

Normalization and filling optimization of the τ SPECT experiment

Dissertation zur Erlangung des Grades
„Doktor der Naturwissenschaften“

am Fachbereich Physik, Mathematik und Informatik
der Johannes Gutenberg-Universität in Mainz

vorgelegt von

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Mainz den 18. Dezember 2025

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Abstract

The free neutron decay is one of the simplest forms of β -decay, and the experimentally measured neutron mean lifetime τ_n is a relevant parameter in astrophysics, cosmology, and particle physics. It can be used in unitarity tests of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and is an essential input to Big Bang Nucleosynthesis (BBN), where it determines the theoretical primordial helium abundance.

To date, two main methods have been established to measure the neutron lifetime: 1. Beam experiments, which determine the neutron decay rate by detecting the decay products of a cold neutron beam and 2. bottle experiments, which confine neutrons with very low kinetic energies, called ultra-cold neutrons (UCNs), and count the number of surviving neutrons after a known storage period. However, the results of those two methods deviate by more than 4σ , a discrepancy known as the “neutron lifetime puzzle”. In order to eliminate systematic effects related to interactions with material walls, recent bottle-type experiments are using magneto-gravitational traps, to confine neutrons by utilizing gravity and magnetic fields.

The τ SPECT experiment aims to deliver the first competitive neutron lifetime measurement based on purely magnetic storage, with a target uncertainty of 0.3 s. The experiment was commissioned at the research reactor TRIGA Mainz in Germany and was relocated to the Paul Scherrer Institute (PSI) in Switzerland in 2023. τ SPECT confines neutrons in a magnetic field which is a superposition of a radial field of a Halbach permanent-magnet octupole and a longitudinal field generated by superconducting coils. The trap is filled by manipulating the spin of incoming neutrons using rf magnetic fields. Filling of τ SPECT can be realized with two different methods: the single spin-flip (sSF) method, and the double spin-flip (dSF) method. In this thesis, the dSF method was refined from prototype stage to an established procedure. This improvement was achieved by an upgrade to the rf circuitry and the implementation of an absolute magnetic-field reference. With the improved dSF method, the number of filled neutrons increased by a factor of 1.94(5) compared to the previously used sSF method.

A second major contribution of this thesis is the development and characterization of an in-beamline neutron detector to measure the UCN flux at the experiment entrance. The detector uses a coincidence scheme for event discrimination, to suppress background caused by dark counts and γ -radiation. In the characterization the monitor detector shows good agreement with a commercial UCN detector, and it can be considered effectively background-free for operation with τ SPECT. Once the detector was integrated into the experiment, it became possible to monitor the UCN source output. This knowledge is key, since extracting the neutron lifetime from τ SPECT measurements requires correcting for fluctuations in the number of initially trapped neutrons.

Using data of the first scientific data run of the experiment in winter 2024, I investigated whether, and how well, the τ SPECT measurements can be normalized using the monitor detector measurements. A promising approach to normalization has been found and is presented in this thesis.

Zusammenfassung

Der Zerfall des freien Neutrons ist eine der einfachsten Formen des β -Zerfalls, und die experimentell bestimmte Neutronenlebenszeit τ_n ist ein wichtiger Parameter in der Astrophysik, der Kosmologie und der Teilchenphysik. Sie kann verwendet werden um die Unitarität der Cabibbo-Kobayashi-Maskawa (CKM) Matrix zu testen und ist ein essenzieller Eingangsparameter für die Big-Bang-Nucleosynthese (BBN), in welcher sie die vorhergesagte primordiale Häufigkeit von Helium bestimmt.

Zum jetzigen Zeitpunkt gibt es zwei Hauptmethoden, um die Neutronenlebenszeit zu bestimmen: 1. Strahlexperimente, die die Neutronenzerfallsrate bestimmen, indem sie Zerfallsprodukte eines Strahls kalter Neutronen detektieren, und 2. Flaschenexperimente, welche Neutronen mit sehr niedriger kinetischer Energie, sogenannte ultrakalte Neutronen (UCNs), speichern und nach einer bekannten Speicherdauer die verbliebenen Neutronen zählen. Die Ergebnisse der beiden Methoden unterscheiden sich um mehr als 4σ , diese Diskrepanz wird auch als “neutron lifetime puzzle” bezeichnet. Moderne Flaschenexperimente nutzen magneto-gravitative Fallen, die die Neutronen mit einer Kombination aus Schwerkraft und Magnetfeldern in der Falle halten, um systematische Effekte, die durch Wechselwirkungen mit Materialwänden entstehen, zu beseitigen.

Das τ SPECT-Experiment hat zum Ziel, die erste konkurrenzfähige, ausschließlich durch Speicherung in Magnetfeldern erreichte Messung der Neutronenlebenszeit zu erbringen. Angestrebt wird eine Präzision von 0.3 s. Das Experiment wurde am Forschungsreaktor TRIGA Mainz in Deutschland entwickelt und in Betrieb genommen bevor es im Jahr 2023 an das Paul Scherrer Institut (PSI) in der Schweiz umgezogen wurde. τ SPECT speichert Neutronen in einem Magnetfeld, welches aus der Kombination eines radialen Feldes, das durch einen Halbach-Oktupol erzeugt wird, und eines Longitudinalfeldes, welches durch supraleitende Spulen erzeugt wird, besteht. Die Falle wird durch Spinmanipulation der Neutronen mit rf-Magnetfeldern gefüllt. Das Befüllen von τ SPECT kann auf zwei unterschiedliche Arten umgesetzt werden: Durch die single spin flip (sSF) und durch die double spin flip (dSF) Methode. Im Rahmen dieser Dissertation wurde die dSF-Methode vom Prototypenstadium zu einem etablierten Verfahren weiterentwickelt. Diese Verbesserung wurde durch ein Upgrade der rf-Schaltung sowie durch den Einbau einer absoluten Magnetfeldreferenz erreicht. Mit der verbesserten dSF-Methode erhöhte sich die Zahl der eingefüllten Neutronen um den Faktor 1.94(5) im Vergleich zu der zuvor genutzten sSF-Methode.

Ein weiterer wesentlicher Teil dieser Dissertation ist die Entwicklung und Charakterisierung eines in der Strahllinie eingebauten Neutronendetektors, welcher den UCN-Fluss am Eingang des Experiments misst. Der Detektor nutzt Koinzidenzen zur Eventbestimmung, um Untergrund durch Dunkelzählungen und γ -Strahlung zu unterdrücken. In der Charakterisierung zeigte sich eine gute Übereinstimmung zwischen diesem Monitordetektor und einem kommerziellen UCN-Detektor. Für den Betrieb mit τ SPECT kann der Detektor als untergrundfrei angesehen werden. Nachdem der Detektor in τ SPECT eingegliedert worden war, war es möglich den Neutronenoutput der UCN-Quelle zu überwachen. Kenntnis über den Neutronenoutput ist essenziell, denn um die Neutronenlebenszeit aus den Messungen berechnen zu können, sind Korrekturen für Schwankungen der Anzahl an ursprünglich gespeicherten Neutronen notwendig.

Als Teil dieser Dissertation habe ich, anhand von Messdaten der ersten wissenschaftlichen Messkampagne des Experiments, untersucht, ob und in wie weit τ SPECT Messungen mit den Messergebnissen des Monitordetektors normalisiert werden können. Ein vielversprechender Ansatz wird in dieser Arbeit präsentiert.

Contents

<i>List of Figures</i>	<i>ix</i>
<i>List of Tables</i>	<i>xiii</i>
<i>List of Abbreviations</i>	<i>xv</i>
1 Introduction	3
1.1 Relevance of the neutron lifetime	4
1.1.1 Unitarity of the CKM Matrix	4
1.1.2 Big Bang Nucleosynthesis	6
2 Neutron lifetime measurements	9
2.1 The beam method	9
2.2 Bottle experiments	10
2.2.1 Ultra-cold neutrons	11
2.2.2 Principle of bottle experiments	12
2.3 The neutron lifetime puzzle	15
2.4 Current status of neutron lifetime measurements	16
3 An introduction to the τSPECT experiment	17
3.1 Description of the experiment apparatus	17
3.2 Overview of the measurement procedure	20
4 Optimization of the double-spin-flip filling procedure	23
4.1 Introduction to the filling procedure	23
4.2 A short introduction to the spin-flip theory	24
4.2.1 AFP spin flip	25
4.2.2 NMR magnetometer	27
4.3 Hardware updates	28
4.3.1 NMR magnetometer	28
4.3.2 Upgrade of spin flipper 1	31
4.4 Double SF measurements	38
4.4.1 Double SF commissioning in 2023	38
4.4.2 Double SF optimization in 2024	41
4.5 Conclusion	46
5 Monitor detector	47
5.1 Motivation	47
5.2 Monitor-detector hardware	48
5.2.1 Ultra-cold neutron detection	48
5.2.2 UCN detection scheme of the monitor detector	50
5.2.3 Monitor-detector electronics	54

5.3	Detector software	65
5.4	Monitor detector version 1 characterization at TRIGA Mainz	67
5.4.1	Measurements directly at the source	67
5.4.2	Characterization measurement campaign	69
5.5	A short introduction of the PSI UCN source	76
5.6	Commissioning of monitor-detector version 2	77
5.6.1	Test setup and initial tests	77
5.6.2	Optimizing settings for operation	80
5.6.3	Performance of the monitor detector	84
6	Operation of the monitor detector with τSPECT	91
6.1	Monitor detector in the experimental setup of τ SPECT	91
6.2	UCN source monitoring	93
6.3	First approaches to normalization	95
6.3.1	Structure and analysis of the 2024 cleaning investigation campaign	96
6.3.2	Structure and analysis of the first science-run data	105
6.3.3	An improved approach to normalization	113
6.4	Summary and outlook	122
7	Summary and outlook	125
A	Additional technical drawings and schematics	127
A.1	Detector flange drawing	127
A.2	Electronics version 2 boards	128
A.3	CASCADE settings	132
A.4	NMR magnetometer setup	133
A.5	Analysis of NMR magnetometer data	133
B	Additional Plots	135
B.1	Additions to normalization	138
C	Software tools	139
C.1	Use of AI-Tools	139
C.2	Note on the software packages used in the analysis	139

List of Figures

1.1	Feynman diagram of the neutron beta decay	3
2.1	Simplified concept of a beam-type neutron lifetime measurement	10
2.2	Simplified concept of a bottle-type neutron lifetime experiment	13
2.3	Overview of relevant neutron lifetime measurement results since 2005	15
3.1	Visualization of the τ SPECT magnetic field	18
3.2	Picture of the τ SPECT apparatus at PSI beamport West-1.	18
3.3	Overview schematic of the τ SPECT apparatus.	19
3.4	Example of a data set of the τ SPECT detector during a measurement at PSI.	21
4.1	Visualization of the energy acceptance of τ SPECT for its two filling modes	24
4.2	Pictures of the NMR magnetometer at SF1.	29
4.3	Plot of the simulated τ SPECT field in the vicinity of the NMR probe and SF1	30
4.4	Plot of a typical spectrum acquired with the installed NMR magnetometer	31
4.5	Pictures of the unmodified SF1	32
4.6	Schematic of the cabling of SF1 before the update.	33
4.7	Picture of SF1 with the added matching boards.	34
4.8	Schematic of the SF1 circuitry after the modifications.	35
4.9	S_{11} measurements of the modified spin flipper.	36
4.10	Comparison of the rf voltage signal in the pick up coil for the internally matched spin flipper, and the externally matched spin flipper.	37
4.11	Comparison of the phase difference between the pickup coil signal and the rf voltage applied to SF1 for multiple SF1 configurations.	38
4.12	Results of an initial frequency scan with the double spin flip method.	39
4.13	Comparison of amplitude scans of SF1 C1 for different magnetic field gradient configurations.	41
4.14	Comparison of amplitude scans performed in 2023 and in 2024 at 0 m height	42
4.15	Comparison of the amount of filled neutrons using the optimal filling method at different heights.	43
4.16	Comparison of SF1 C1 frequency scans for two different gradients within the spin flipper.	44
4.17	Comparison of two amplitude scans using SF1 coil 1 and SF1 coil 2 as the active coil	45
5.1	Visualization of the UCN source fluctuation at the research reactor TRIGA Mainz port D and at port West-1 of the UCN source at PSI	48
5.2	Schematic of the monitor detector's neutron-detection principle	50
5.3	Comparison of the detector's SiPM photon detection efficiency, optical components' transmission as a function of wavelength, and the scintillator's emission spectrum.	52
5.4	Cut view of the monitor flange and photograph of the monitor flange in a test setup.	53
5.5	Picture of the SiPM mount.	54
5.6	Schematic of the adjustable voltage supply used in the monitor-detector electronics	55

5.7	Schematic of the monitor detector's coincidence-logic for event discrimination.	56
5.8	Monitor detector version 1 amplification board	57
5.9	Signal of an α -particle from an α -source acquired using version 1 of the amplification board	58
5.10	Picture of the coincidence board of monitor detector version 1	59
5.11	Housing of the monitor-detector version 1 electronics	60
5.12	Picture of the amplifier board for the SiPM signal used in monitor-detector version 2 and picture of the SiPM amplifiers setup at PSI	61
5.13	Photograph of the monitor-detector version 2 main electronics' housing	62
5.14	Photograph of the version 2 micro-controller circuit board	62
5.15	Photograph of the version 2 amplifier PCB	63
5.16	Photograph of the detector version 2 coincidence circuit board	64
5.17	Frequency response of the detector version 2 coincidence logic	65
5.18	Signal of an α -particle from an α -source acquired using the detector electronics version 2	65
5.19	Plot of the first three seconds of a measurement taken with the monitor detector directly at the UCN source a reactor port D of the TRIGA Mainz	67
5.20	Counts per time section in the close-to-source measurements	68
5.21	Comparison of I-V characteristics of SiPMs used close to the source and those of a new SiPM of the same batch	69
5.22	Schematic of the aluminum bottle setup used for characterization of monitor detector version 1	70
5.23	First 7.5 s of a measurement taken with the monitor detector in front of the aluminum storage bottle	71
5.24	2D color plot of the correlation between the stored UCNs detected with the CASCADE and monitor-detector counts, within the UCN time-window, plotted against the window width and the window start time	72
5.25	Ratio of detector version 1 counts and CASCADE counts plotted against event threshold voltage	73
5.26	Ratio of detector version 1 counts and CASCADE counts plotted against SiPM bias voltage	74
5.27	UCNs counted by CASCADE detector and the monitor detector, plotted against the pulse number of the measurement	75
5.28	Monitor version 1 counts plotted against CASCADE counts	75
5.29	Plot of measurement data taken with the monitor-detector version 1 during operation with τ SPECT at PSI	76
5.30	Setup for test measurements of the monitor detector-version 2 at beamport West-1 at PSI	78
5.31	Time structure of data of a monitor detector and a CASCADE measurement	79
5.32	Plot of a raw neutron signal in the monitor detector	80
5.33	Measurement results of the scan of threshold voltage 2 of the monitor detector version 2	81
5.34	Measurement results of the scan of the amplifier 2 supply voltage of monitor detector version 2	82
5.35	Measurement results of the scan of the SiPM 2 bias voltage of monitor detector version 2	83
5.36	Monitor detector version 2 and CASCADE detector average background per kick	85
5.37	Plot of monitor detector version 2 counts against CASCADE detector counts	86
5.38	Plot of the ratio of monitor counts and CASCADE counts against the measured temperature of the detector flange	87

5.39	Measurement of the influence of the monitor detector's aperture radius on the count ratio	88
5.40	Comparison of the count ratio for the two versions of the monitor detector	89
6.1	Picture of the monitor detector version 1 in operation with τ SPECT at PSI	92
6.2	Counts measured by the monitor detector during a τ SPECT measurement plotted against the time since the kick	93
6.3	Plot of the monitor counts and the stored neutrons in τ SPECT for a measurement campaign in 2024	94
6.4	τ SPECT counts, monitor-detector counts, and their ratio plotted against the measurement date for the first 48 h of measurement block A	97
6.5	Time evolution of the measurement results of measurement block A	99
6.6	Background-corrected counts in τ SPECT plotted against the applied rf frequency of spin flipper 1	100
6.7	Analysis results for measurement block A. Background-corrected τ SPECT counts plotted against the monitor-detector counts with a weighted linear fit	101
6.8	Quantile-quantile plot comparing the quantiles of the fit residuals with the theoretical quantiles of a normal distribution	102
6.9	Analysis results for measurement block B. Background-corrected τ SPECT counts are plotted against the monitor-detector counts with a weighted linear fit	103
6.10	Analysis of measurement block C. Background corrected τ SPECT counts plotted against the monitor-detector counts with a weighted linear fit	104
6.11	Measurement data of the first scientific data-taking phase in winter of 2024	106
6.12	Blinded data run analysis result for frequency block with SF1 frequency set to 29.229 MHz	107
6.13	Time evolution of τ SPECT and monitor counts during the 29.238 MHz SF1 frequency block of the scientific data run	109
6.14	Time evolution of τ SPECT and monitor counts during the 29.24 MHz SF1 frequency block of the scientific data run	110
6.15	Visualization of fluctuations in the 29.24 MHz SF1 frequency block. Comparison of the total monitor-detector counts (integrated from 8 s to 240 s) and the monitor counts recorded during the filling window (from 8 s to 28.86 s)	111
6.16	Combined analysis of all time windows with NLK South open that were not rejected based on their individual fit's χ^2	112
6.17	Time evolution of filling, monitor, and τ SPECT counts during the 2024 scientific data run.	114
6.18	Time evolution of τ SPECT, monitor and filling counts from 8th November to November 11th 2024	116
6.19	Adjusted Pearson residuals of the multiple linear fit performed on data set 1 with a storage time of 21 s, in blinded time, and NLK South open	118
6.20	Visual comparison of the multiple linear fit and simple proportional fit	119
A.1	Technical drawing of the monitor detector flange	127
A.2	Circuit schematic of the powerboard	128
A.3	Circuit schematic of the supply board of monitor detector electronics version 2	129
A.4	Circuit schematic of the coincidence board of monitor detector electronics version 2	130
A.5	Circuit schematic of the micro-controller board of the monitor detector electronics version 2	131
A.6	Meta file containing the CASCADE settings during the commissioning of monitor detector version 2	132
A.7	Schematic of the setup of the readout of the NMR magnetometer	133

B.1	Count ratio of monitor detector and CASCADE detector measurements for a scan of event thresholds of channel 1	135
B.2	Count ratio of monitor detector and CASCADE detector measurements plotted for a scan of the amplifier 1 supply voltage	136
B.3	Plot of the count ratio for a scan of SiPM 1 bias voltage	137
B.4	Plot of S11 reflection measurements of the spin flipper 1 coil 1 circuit throughout winter 2024	138

List of Tables

2.1	Fermi potential for selected materials commonly used in UCN experiments	11
5.1	Absorption mean free path of UCNs in ^{10}B for different kinetic energies	49
5.2	Refractive indices of the optical elements used in the monitor detector	51
5.3	Relevant properties of the MICROFC-60035-SMT SIPM	56
5.4	Table of commands accepted by the micro-controller of the monitor detector.	66
5.5	Chosen operational settings for the monitor detector version 2	84
6.1	Overview of the analyzed measurement blocks of the cleaning investigation campaign	100
6.2	Overview of the analyzed measurement blocks of the scientific data run	108
6.3	Fit results of the multiple linear fit relating monitor and filling counts to the τ SPECT counts	117
C.1	Overview of used AI-tools	139

List of Abbreviations

Abbreviation	Description	Chapter
UCN	Ultra-Cold Neutron	1, 2, 3, 4, 5, 6, 7
PSI	Paul Scherrer Institute	1, 3, 4, 5, 6, 7
BBN	Big Bang Nucleosynthesis	1, 2
CKM matrix	Cabibbo-Kobayashi-Maskawa matrix	1, 2
NIST	National Institute of Standards and Technology	2
LFS	Low-Field Seeker	3, 4, 6, 7
HFS	High-Field Seeker	3, 4, 6, 7
NMR	Nuclear Magnetic Resonance	3, 4, 6, 7, A
rf	radio frequency	3, 4, 6
SF	Spin Flipper	3, 4, 6
SFU	Spin Flip Unit	3, 4
AFP	Adiabatic Fast Passage	3, 4
sSF	single Spin Flip	4, 6
dSF	double Spin Flip	4, 6, 7
FWHM	Full Width at Half Maximum	4, 5
PCB	Printed-Circuit Board	4,5
PLA	Poly lactide	5
ADC	Analog-Digital Converter	5
DAC	Digital-Analog Converter	5
NOA68	Northland-Optical Adhesive 68	5
PDE	Photon Detection Efficiency	5
SPI	Serial Peripheral Interface	5

Abbreviation	Description	Chapter
SMU	Source Measure Unit	5
SiPM	Silicone Photo Multiplier	5
PEEK	Polyether ether keton	5
SPAD	SinglePhoton Avalanche Diode	5
PCC	Pearson correlation coefficient	5
RMS	Root-Mean-Square	5
POM	PolyOxyMethylene	5
OpAmp	Operational Amplifier	5
NLK	NeutronenLeiterKlappe	6
VIF	Variance Inflation Factor	6
FID	Free Induction Decay	A

Acknowledgments

Removed due to data protection reasons.

Nuclear, it's pronounced nuc-u-lar. Homer J. Simpson

Introduction

The neutron is a neutral nucleon, which together with the proton forms the atomic nuclei. While neutrons bound in nuclei can be stable, the free neutron is unstable and undergoes β -decay with a mean lifetime of approximately 15 minutes. Shortly after its discovery in 1932 by James Chadwick [Cha32], mass measurements in 1935 ruled out the hypothesis that the neutron was a bound state of the slightly lighter proton and an electron [Cha+35]. It was therefore assumed to be an elemental particle that decayed into a proton, an electron and an antineutrino, as described by Fermi's theory of nuclear beta decay [Cha+35][Fer34]

$$n \rightarrow p + e + \bar{\nu}_e. \quad (1.1)$$

In modern particle physics, the neutron and its decay are described using the Standard Model (SM). The neutron is composed of three valence quarks: one up quark u and two down quarks d . The β -decay is the weak transition of one of the d quarks into a u quark by emission of a virtual W^- Boson, which decays into an electron and an electron antineutrino $\bar{\nu}_e$. The leading order Feynman diagram of this process is shown in Fig. 1.1.

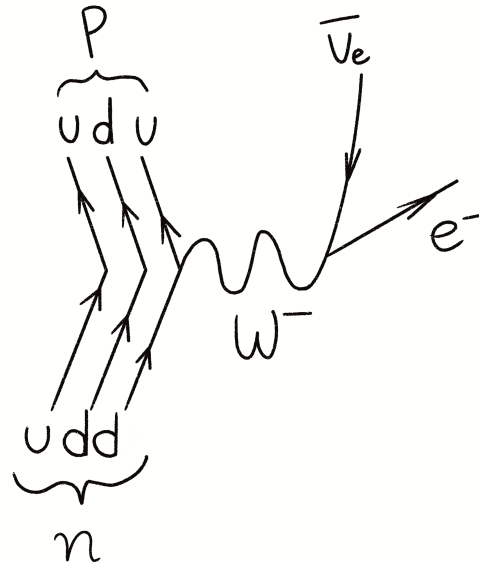


FIGURE 1.1: Feynman diagram of the neutron beta decay. Illustration by Dimitra Kanta.

The free neutron decay is one of the simplest forms of β -decay, as it involves no additional form factors from interactions between nucleons. The neutron mean lifetime τ_n , which characterizes the decay probability, is a relevant parameter in astrophysics, cosmology, and particle physics [Wie18]. It plays a central role in the unitarity test of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and is a key parameter in Big Bang Nucleosynthesis (BBN), since it determines the theoretical primordial helium abundance.

The first experimental determination of τ_n in 1951 had a relatively large uncertainty on the order of minutes [Rob51]. Since then precision has greatly improved with measurements reaching sub-second uncertainties, and two different main experimental methods have been established: 1. Beam experiments, which determine the neutron decay rate by detecting the decay products of a cold neutron beam and 2. bottle experiments, which confine neutrons with very low kinetic energies, called ultra-cold neutrons (UCNs), and count the number of surviving neutrons after various storage times. However, the results of those two methods deviate by more than 4σ , a discrepancy known as the neutron lifetime puzzle. Recent bottle-type experiments are using magneto-gravitational traps, utilizing gravity and magnetic fields to confine the neutrons [Ezh+18][Pat+18]. This thesis was done as part of the τ SPECT experiment, which aims to deliver the first competitive neutron lifetime measurement based on purely magnetic storage, with a target uncertainty of 0.3s. The focus of this work in particular was the improvement of the filling procedure, the design and commissioning of an in-beamline neutron detector for monitoring the incoming neutron flux, and investigating approaches for normalization of τ SPECT measurements. In the remainder of this chapter, I will discuss the motivation for high-precision measurements of the neutron lifetime in more detail.

1.1 Relevance of the neutron lifetime

1.1.1 Unitarity of the CKM Matrix

In 1963 N. Cabibbo proposed the Cabibbo mixing angle in order to describe observed leptonic decays of strange hadrons [Cab63]. This model was included in the quark model and extended to include all three known quark families by M. Kobayashi and T. Maskawa [KM73]. The Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the mixing of the mass states and the weak flavors of quarks [Pur23, p. 339] via

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.2)$$

The squared absolute of a matrix element of the CKM matrix gives the transition probability of one quark to another. In the standard model three generations of quarks exist. If this model is correct then the 3x3 CKM matrix must be unitary and the transition probabilities for one initial quark must sum to 1. Therefore one can search for physics beyond the standard model by testing the CKM matrix for unitarity. Since the CKM matrix is unitary, also the sum of the squared matrix elements for each row and column must be unity. For the first row therefore

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad (1.3)$$

must hold. To test this precise measurements of V_{ud} , V_{us} and V_{ub} are of interest.

V_{us} can be obtained from kaon, hyperon, and tau decays [Sci+07][Mou17][CSW04][Amh+23, pp. 317–320]. The particle data group (PDG) currently quotes $|V_{us}| = 0.22431(85)$ for the first row unitarity

test of the CKM matrix [Nav+24, p. 271], it is obtained from kaon decays. V_{ub} can be extracted from semileptonic B decays [Amh+23, pp. 94–121], the PDG currently gives as an average $|V_{ub}| = 3.82(20 \cdot 10^{-3})$ [Nav+24, p. 272]. Currently the most precise value for V_{ud} is obtained from a set of 15 superallowed $0^+ \rightarrow 0^+$ nuclear β -decays. These depend uniquely on the vector part of the weak interaction [HT20]. From the measured half-life, the transition energy, and the branching ratio of the transition, the vector coupling constant for semi leptonic weak interactions G_V can be calculated. From G_V V_{ud} can be determined via the relation [HT20]

$$G_V = G_F \cdot V_{ud}, \quad (1.4)$$

where G_F is the Fermi constant which is determined through muon decays [Web+11]. However, the calculations of G_V include transition-dependent nuclear and radiative corrections in addition to the transition-independent radiative correction Δ_R^V . The PDG currently quotes [Nav+24, p. 904]

$$|V_{ud}| = 0.97367(11)_{exp}(13)_{\Delta_R^V}(27)_{NS}(32)_{total} \quad (1.5)$$

Here *exp* marks uncertainty due to the experiments, Δ_R^V the uncertainty due to the universal radiative corrections and *NS* the uncertainty due to nuclear structure which are dominant. For the total uncertainty the uncertainties have been added in quadrature.

Currently the PDG quotes for the first row [Nav+24, p. 275]

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984(7). \quad (1.6)$$

This is a 2σ disagreement with unitarity. The PDG currently interprets this as either a problem in V_{ud} theory, so in the calculation of the radiative and nuclear structure corrections, a problem in the determination of V_{us} , or new physics [Nav+24, pp. 905–906].

A different promising way to obtain V_{ud} is from the neutron β -decay. This method has the advantage that there are no nuclear-structure corrections needed. In the SM the decay rate (inverse lifetime) of the neutron is given by [CMS04]

$$\Gamma = \frac{1}{\tau_n} = \frac{m_e^5}{2\pi^3} G_F^2 |V_{ud}|^2 (1 + 3\lambda^2) f(1 + RC) \quad (1.7)$$

Where m_e is the electron mass and G_F is the Fermi constant. The parameter $\lambda = G_A/G_V$ denotes the ratio of the axial-vector to vector nucleon couplings. It can be experimentally determined from angular correlation measurements in the neutron β -decay [JTW57][Wil82]. The factor f accounts for phase-space contributions and RC summarizes radiative corrections. By solving this equation for $|V_{ud}|$, and using the current PDG averages for $\tau_n^{PDG} = 878.4(5) \text{ s}$ [Nav+24, p. 2091] and $\lambda = -1.2754(13)$ [Nav+24, p. 2094] the PDG obtains [Nav+24, p. 904]

$$|V_{ud}| = 0.97441(28)_\tau(82)_\lambda(13)_{\Delta_R}(88)_{total}. \quad (1.8)$$

Here τ marks the uncertainty due to the neutron lifetime, λ the uncertainty due to λ and Δ_R the uncertainty due to radiative corrections. It should be noted that the calculation of V_{ud} is still evolving, as especially the radiative corrections are continuously being refined when higher-order contributions are taken into account. In [Van+25], a new result for those calculations containing the first two-loop input to long-distance corrections is reported as

$$|V_{ud}|^2 = \frac{5263.284(17) \text{ s}}{\tau_n(1 + 3\lambda^2)(1 + \Delta_R^s)(1 + \delta)}. \quad (1.9)$$

Here [Van+25] uses $\Delta_R^s = 45.37(27) \cdot 10^{-3}$ from [Cir+23] as the short- and $\delta = 27.04(7) \cdot 10^{-3}$ includes the long-distance corrections. With the PDG averages for τ_n and λ this results in

$$|V_{ud}| = 0.97424(28)_{\tau}(82)_{\lambda}(13)_{\Delta_R^s}(3)_{\delta_r}(88)_{total}. \quad (1.10)$$

Where δ_R marks the uncertainty due to long-distance radiative corrections. With the most precise measurements for $\tau_n = 877.83 \pm 0.22$ (stat) $^{+0.20}_{-0.17}$ (syst) s [Mus+25] and $\lambda = -1.247641(56)$ [Mär+19] the result is

$$|V_{ud}| = 0.97393(17)_{\tau}(35)_{\lambda}(13)_{\Delta_R^s}(3)_{\delta_R}(41)_{total}. \quad (1.11)$$

The total uncertainties of all these results for $|V_{ud}|$ are limited by the experimental precision. In order to improve the precision and become competitive with the superallowed β -decay results, more precise measurements of λ and τ_n are needed.

1.1.2 Big Bang Nucleosynthesis

The neutron lifetime is also a relevant parameter in cosmology, where it is used as an input parameter in Big Bang nucleosynthesis (BBN), the theory describing the production of the light nuclei in the early universe. With this model the primordial abundance of the light elements ^1H to ^7Li can be predicted [Fie+20][ABG48]. A central quantity in these predictions is the neutron-to-proton ratio $\frac{n_n}{n_p}$. In the early universe, when the energy-equivalent temperature was $T \gtrsim 1$ MeV, weak interactions between neutron and proton [YOF23]

$$n + \nu_e \leftrightarrow p + e^- \quad (1.12a)$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e \quad (1.12b)$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e, \quad (1.12c)$$

maintained a thermal equilibrium [YOF23]. In this equilibrium the neutron-to-proton ratio is given by [BBF89]

$$\frac{n_n(T)}{n_p(T)} = \exp\left(-\frac{\Delta m}{T}\right). \quad (1.13)$$

Here $\Delta m = 1.293\,332\,51(38)$ MeV [Moh+25, p. 47] is the mass difference of the proton and the neutron. The rate of these weak interactions scales with T^5 [YOF23]. As the Universe expanded and cooled down, the interaction rate reduced and eventually dropped below the expansion rate of the universe, breaking the thermal equilibrium and “freezing” the neutron-to-proton ratio. This freeze-out condition is given by [BBF89]

$$G_F^2 T^5 \propto \Gamma_{wk}(T_f) = H(T_f) \propto G_N^{1/2} T^2. \quad (1.14)$$

Here H is the Hubble parameter and G_N is Newton’s constant. According to [YOF23], the freeze out occurs at $T_f \approx 0.84$ MeV, corresponding to an age of the universe of about 1 s. At this time the neutron-to-proton ratio is estimated to be about $\frac{1}{4.66}$ [YOF23]. After freeze out the free-neutron β -decay decreases the ratio over time. This effect is relevant, since nucleosynthesis does not begin until $t_{BBN} \approx 322$ s [YOF23], which is much later than the freeze-out. The reason for this late onset is the low binding energy of the deuteron ($E_b = 2.2$ MeV). Formed deuterons are photo-dissociated immediately as long as the number density of photons above E_b is high enough. This period of time is called the deuterium bottleneck [Esp+99][ST98]. Only when the ratio of photons with energy above E_b to baryons falls below unity at t_{BBN} , deuterium (D) nuclei can form without immediately being destroyed again [Nav+24, p. 474]. At this time the ratio of neutrons and protons has fallen

to about $\frac{1}{7.17}$ [YOF23]. The dominant product of BBN is ${}^4\text{He}$, which makes up about 25% of the baryon mass [YOF23]. Other light elements, like ${}^3\text{He}$ and D , make up fractions on the order of 10^{-5} [YOF23]. To a good approximation, essentially all neutrons end up bound in ${}^4\text{He}$. The primordial helium mass fraction Y_p can then be written as

$$Y_p = 2 \frac{n/p}{1 + n/p} \Big|_{t_{\text{BBN}}}, \quad (1.15)$$

since each ${}^4\text{He}$ nucleus consists of two protons and two neutrons. The neutron lifetime influences the BBN model in two distinct ways [YOF23]. First, it is used to normalize the weak-interaction matrix element for the reactions in Eqs. (1.12), and it thereby affects the freeze-out temperature. Second, it describes the free-neutron β -decay between the weak freeze out and the end of the deuterium bottleneck, thereby influencing the neutron-to-proton ratio. As a consequence, the predicted helium mass fraction Y_p is sensitive to the neutron lifetime. In fact, the uncertainty in τ_n is the dominant contribution to the uncertainty of current estimations of Y_p [YOF23]. According to [YOF23] the effect of the uncertainty in τ_n on Y_p can be estimated as

$$\frac{\Delta Y_p}{Y_p} \approx 0.79 \frac{\Delta \tau_n}{\tau_n}. \quad (1.16)$$

Using the current PDG value of τ_n this corresponds to a relative uncertainty of the prediction using the BBN model of approximately $6 \cdot 10^{-4}$. The abundance of primordial helium can be extrapolated from spectroscopic observation of extragalactic H II regions [ITG14]. The PDG recommends $Y_p = 0.245(3)$ [Nav+24, p. 475]. The relative uncertainty of this result is on the order of $\mathcal{O}(1\%)$, which still exceeds the current uncertainty of the theoretical BBN predictions. Nevertheless τ_n remains the major source of uncertainty in theoretical predictions, implying that more precise measurements of τ_n would further improve the predictions of the BBN model.

2

Neutron lifetime measurements

In the previous section we discussed the motivation for measuring the neutron lifetime. In this chapter I will introduce the two main experimental techniques used to measure the neutron lifetime: the beam method, and the bottle method. After introducing those techniques, their results will be compared and the present status of lifetime measurements will be discussed.

2.1 The beam method

Beam-type neutron lifetime experiments determine the neutron lifetime τ_n by counting the charged decay products originating from a cold neutron beam in a well-defined decay volume. By relating the decay rate dN/dt measured this way to the amount of neutrons in the beam N , τ_n can be extracted using the differential form of the exponential decay function [WG11]

$$\frac{dN}{dt} = -\frac{N}{\tau}. \quad (2.1)$$

A simplified schematic of a beam-type experiment is shown in Fig. 2.1. A cold-neutron beam passes through the decay volume, where the charged decay products are detected by the surrounding detectors. Behind this region a neutron detector measures a fraction of the incoming neutrons to determine the beam intensity.

Not all beam experiments detect the neutrons outside the decay volume. In some setups, such as those reported in [Sch+89] [Sum+21], neutrons are detected within the decay volume by using a time projection chamber filled with ^3He . Over the years, various methods for detecting the charged decay products have been employed. The experiment by [Rob51] used an electrostatic collection system for particle collection, while [Chr+72] used a static magnetic field to guide produced electrons into the detector. [Sch+89] [Sum+21] used projection chambers for the detection of the decay products and [Byr+90][Byr+96][Nic+05] stored the protons produced in the decay in a Penning trap subsequently extracting and detecting them to suppress background events. The decay products are counted at a rate of R_p with an efficiency ϵ_p and the neutrons at a rate of R_n with an efficiency ϵ_n . According to [Nic+05] the neutron lifetime is related to those parameters via

$$\tau_n \propto \left(\frac{R_n}{R_p} \right) \cdot \left(\frac{\epsilon_p}{\epsilon_n} \right). \quad (2.2)$$

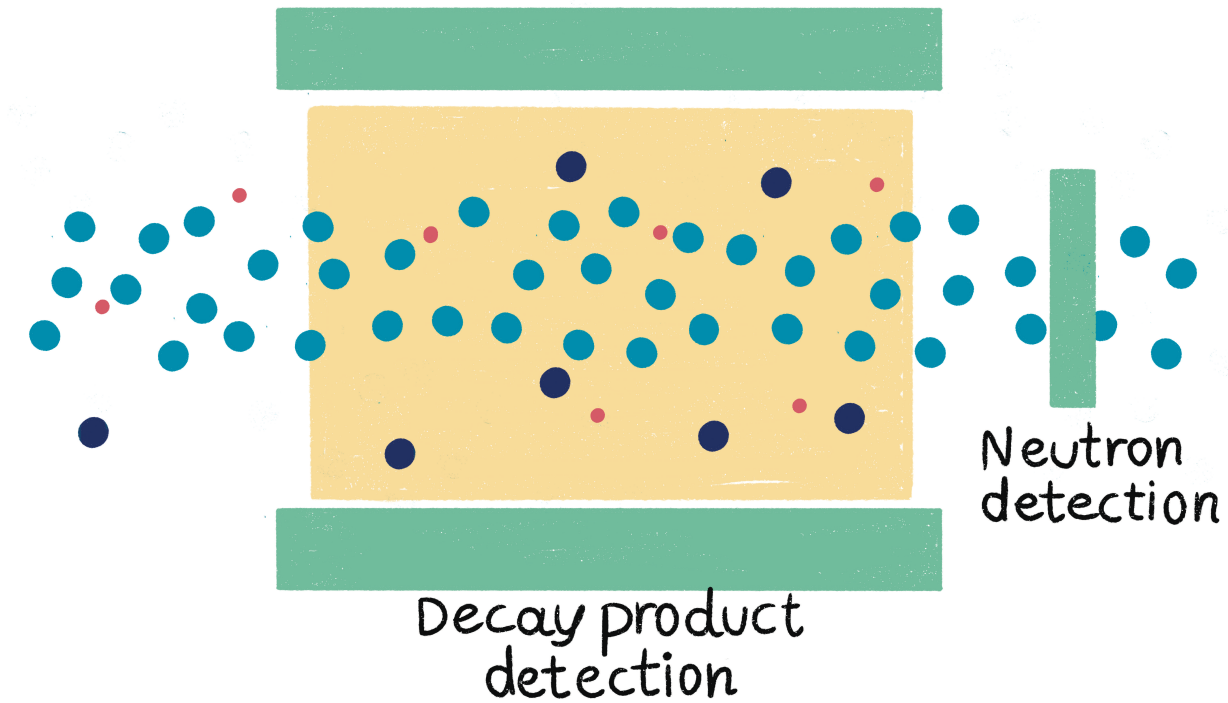


FIGURE 2.1: Simplified schematic of a beam-type neutron lifetime measurement. A beam of cold neutrons (turquoise) passes through a defined decay volume (yellow). Behind the volume, a fraction of the neutrons is detected to determine the beam intensity. Decay products (dark blue, red) coming from decays inside the defined volume are detected using charged-particle detectors. Illustration by Dimitra Kanta.

From this relation it is evident that the absolute detection efficiencies for both the products and the neutrons need to be known precisely. Additional challenges of the beam method include background caused by the neutron beam and the challenge of precisely defining the decay volume. The most precise beam-type measurement to this date was accomplished by the BL1 experiment at the National Institute of Standards and Technology (NIST) giving a result of $\tau_n = (886.3 \pm 1.2 \text{ (stat)} \pm 3.2 \text{ (syst)})\text{s}$ [Nic+05]. The experiment used a segmented Penning trap, which allowed to vary the length of the decay volume. The systematic uncertainty is dominated by the neutron counting. The two main contributions to it were, the areal density of the neutron-absorbing deposit used in the detector and the uncertainty of the corresponding neutron-absorption cross section. Through an absolute calibration of the neutron detector, the detection efficiency was determined independently from the cross section. This significantly reduced the systematic uncertainty and led to an updated result of $\tau_n = (887.7 \pm 1.2 \text{ (stat)} \pm 1.9 \text{ (syst)})\text{s}$ [Yue+13].

2.2 Bottle experiments

Bottle-type lifetime experiments store ultra-cold neutrons (UCN) in a vessel and count the remaining neutrons after a certain storage time, in contrast to beam-type experiments which count the decayed neutrons. Before we discuss bottle-type experiments further, we will first shortly discuss how it is possible to confine neutrons spatially.

2.2.1 Ultra-cold neutrons

Historically ultra-cold neutrons are defined as neutrons which can be stored in closed material vessels [Gol91, p. 2]. This is possible because, when the de Broglie wavelength of a neutron λ_n is much larger than the interatomic spacing of a material, the interaction of a neutron and a material surface can be described by an effective potential U [Gol91]

$$U = V_f - iW. \quad (2.3)$$

Here V_f is the so-called Fermi potential which describes the coherent scattering, while W describes inelastic scattering and absorption [Gol91, p. 24]. For most materials except strong neutron absorbers W is much smaller than V [Gol91, p. 25]. The Fermi potential can be written as

$$V_f = \frac{2\pi\hbar^2}{m}Na. \quad (2.4)$$

Here N is the number density of the material, m is the neutron mass and a is the coherent scattering length of the material [Gol91]. The angle of total reflection for an incident neutron on this potential is given by [Gol91]

$$\sin \theta = \sqrt{\frac{V_f}{E}}. \quad (2.5)$$

Neutrons with kinetic energy smaller than the potential of the material are reflected for all incident angles. The material with the highest Fermi potential currently known is ^{58}Ni with 335 neV. Values of the Fermi potential for some relevant materials are given in Table 2.1.

Material	Fermi potential (neV)	Source
Stainless Steel	190	[Ign90, p. 326]
Aluminium	54	[Gol91, p. 20]
^{58}Ni	335	[Gol91, p. 20]
$^{58}\text{Ni:Mo}$ (85:15)	311	[Kah+17]
Copper	168	[Gol91, p. 20]
Fused Silica	95	[Ign90, p. 326]

TABLE 2.1: Fermi potential for selected materials commonly used in UCN experiments.

The magnitude of the Fermi potential is on the order of up to a few hundred neV. Notably, this is comparable to the energy scales of other fundamental interactions relevant for UCNs. Those are:

Gravity: Due to their mass, neutrons experience Earth's gravitational potential. At the Earth's surface, the energy required for a neutron to rise by a height h can be estimated classically as

$$V_{grav} = \int_{r_e}^{r_e+h} \frac{G_N M_e m_n}{r^2} dr \approx m_n g h \approx 102.5 \text{ neV m}^{-1} \cdot h. \quad (2.6)$$

Here G_N is Newton's gravitational constant, m_n is the neutron mass, r_e is the Earth's radius, and $g \approx 9.81 \text{ m s}^{-2}$ is the gravitational acceleration on the surface. The potential difference per meter is $\approx 102.5 \text{ neV}$ meaning that neutrons with a kinetic energy of 100 neV cannot rise higher than 1 m above their current position. This means that gravity can be used for vertical confinement of UCNs.

Magnetic interaction: The neutron is a spin-1/2 particle and its magnetic moment is anti-aligned with its spin. The interaction of the neutron's magnetic moment with an external magnetic field

can be described by the potential [Gol91, p. 9]

$$V_{mag} = -\vec{\mu}\vec{B} \approx \pm 60.31 \text{ neV T}^{-1} \cdot |B|. \quad (2.7)$$

The sign depends on the relative orientation of the neutron's spin to the magnetic field. In an inhomogeneous magnetic field a neutron will therefore experience a Stern-Gerlach force [Gol91, p. 9]

$$\vec{F} = -\vec{\nabla}V_{mag} = \pm|\mu|\vec{\nabla}|\vec{B}|. \quad (2.8)$$

Depending on the orientation of their spin, neutrons are therefore accelerated into regions of higher field or repelled by them.

- Neutrons with their spin oriented opposite to the field direction are accelerated towards higher fields and are referred to as high-field seekers (HFS).
- Neutrons with their spin oriented parallel to the field are accelerated into lower-field regions and are referred to as low-field seekers (LFS).

This interaction provides the ability to spatially contain spin-polarized neutrons with magnetic fields, if their total kinetic energy is smaller than the magnetic-potential difference they have to surpass. In τ SPECT this is realized by placing LFS inside a magnetic-field well.

2.2.2 Principle of bottle experiments

Having discussed the fundamental interactions which can be used to confine neutrons, we now return to bottle-type experiments. The majority of the first generations of bottle-type neutron lifetime experiments relied purely on the Fermi potential of material walls to confine UCNs. A simplified schematic of a bottle-type experiment employing material wall storage is shown in Fig. 2.2. The basic principle is rather straightforward. Using the shutters the storage volume can be opened either towards the UCN beam line to fill it with neutrons or to the neutron detector to count the remaining UCNs. During the storage phase, both shutters remain closed. Under ideal conditions, the number of neutrons after a time t in the storage vessel is given by an exponential decay

$$N(t) = N_0 \exp(-t/\tau_n). \quad (2.9)$$

Here τ_n is the neutron lifetime and N_0 are the neutrons initially in the trap. By comparing the amount of neutrons after a long t_l and a short t_s storage time one can extract the neutron lifetime via

$$\tau_n = \frac{t_l - t_s}{\ln(N_s/N_l)}. \quad (2.10)$$

Here N_s and N_l are the amount of neutrons after the corresponding storage times. Because both measurements use the same detector, the result is independent of the absolute detection efficiency, in contrast to the beam-type experiments. However, Eq. (2.9) and Eq. (2.10) describe an idealized scenario. In practice, additional effects must be taken into account, two of which will be discussed next.

Fluctuations of initial neutrons: One idealization is that both the long and the short measurement have the exact same initial configuration and, therefore, the same N_0 , while in reality the amount of initial neutrons varies, for example due to changes in the UCN source output. When

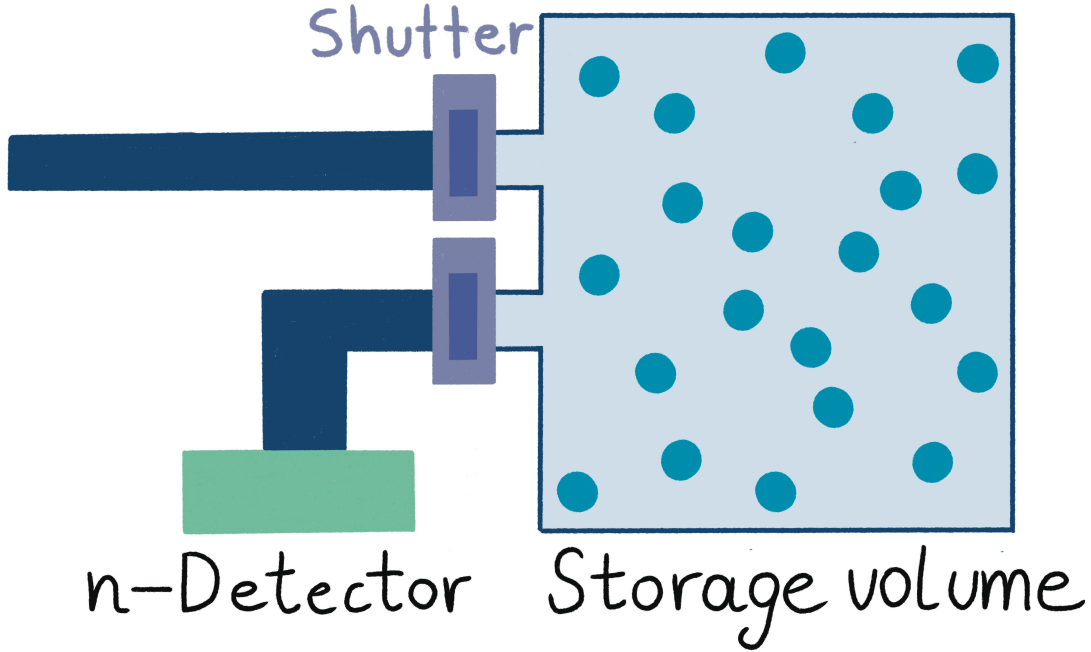


FIGURE 2.2: Simplified schematic of a bottle-type neutron lifetime measurement. The storage vessel is filled with UCNs (blue dots) through the filling beam line. During the storage phase both shutters are closed. To count the surviving neutrons, the bottom shutter is opened to allow the UCNs to reach the detector. Illustration by Dimitra Kanta.

taking this into account, Eq. (2.10) needs to be rewritten as

$$\tau_n = (t_l - t_s) \ln \left(\frac{N_s N_{0l}}{N_l N_{0s}} \right)^{-1}. \quad (2.11)$$

Where N_{0l} and N_{0s} are the initially filled neutrons for the individual measurement. A difference in the initial neutrons can have a significant impact on the measured lifetime, if not corrected for. Just to give an orientation of the order of this effect, we will look at a simplified example. For a hypothetical neutron lifetime of 878.4s, two measurements with storage durations of 50s and 1000s, and $\frac{N_{0l}}{N_{0s}} = 1.01$ (a 1% difference in initial neutrons) the measured lifetime calculates to 870.4s. This is a reduction of .9%, therefore, to avoid systematics, the measurements have to be normalized for the amount of initial neutrons. The τ SPECT experiment is normalizing by monitoring the incoming UCN flux using an in-beamline detector developed as part of this thesis. The detector and its development are discussed in Sec. 5.

Additional loss channels: While Eq. (2.9) describes the idealized case, in which the only loss mechanism during storage is the neutron β -decay, in practice, bottle-type experiments are affected by multiple other loss channels:

- Absorption of neutrons by the wall [WG11] (characterized by a mean loss time τ_{abs}),

- Inelastic scattering of the neutrons on the vessel walls [Wie18] (characterized by a mean loss time τ_{in}),
- Escape of neutrons through small gaps or slits [Wie18] (characterized by a mean loss time τ_{esc}),
- Losses due to interaction with residual gas in the storage vessel [WG11] (characterized by a mean loss time τ_{gas}), and
- Losses of marginally trapped neutrons (neutrons with slightly higher energy than the trap potential) which may survive inside the trap for hundreds of seconds before escaping [Wie18] (characterized by a mean loss time τ_{marg}).

As a first order approximation, all of these loss channels can be combined and give an effective storage time τ_{store} given by

$$\frac{1}{\tau_{store}} = \frac{1}{\tau_n} + \frac{1}{\tau_{abs}} + \frac{1}{\tau_{in}} + \frac{1}{\tau_{esc}} + \frac{1}{\tau_{gas}} + \frac{1}{\tau_{marg}} + \frac{1}{\tau_{other}}. \quad (2.12)$$

Here τ_n is the neutron life time and τ_{other} represents the mean loss time for additional other loss channels. The 2nd, 3rd, and 4th terms arise from interactions between the neutrons and the material walls. Common approaches in material traps to reduce these loss channels include: coating of the storage walls with low-absorption and high-Fermi-potential materials [Mam+89][Nes+92][Arz+00][Ser+05], cooling the surfaces to reduce thermal upscattering [Nes+92][Ser+05], and varying the volume-to-surface ratio of the trap to extrapolate to the limit of storage without wall collisions [Mam+89][Nes+92]. Additionally, marginally trapped neutrons can be removed through cleaning procedures [Nes+92][Pic+10].

The most precise neutron lifetime measurement using material wall storage to date was performed by the Gravitrap experiment, resulting in $\tau_n = (878.5 \pm 0.7 \text{ (stat)} \pm 0.3 \text{ (syst)})\text{s}$ [Ser+05]. Gravitrap used a spherical storage vessel with an opening at the top. By rotating the bottle by a certain angle after filling, the UCN energy spectrum could be varied and marginally trapped neutrons removed. A first result of $\tau_n = (881.5 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (syst)})\text{s}$, measured with an upgraded version of the experiment with a larger storage volume, was published in 2018 [Ser+18].

The current generation of bottle-type experiments eliminate wall interactions by avoiding material walls for storage and contain the neutrons purely using magnetic fields and gravity instead. This way the first three of the loss channels mentioned above can be avoided. So far, two experiments have published competitive measurement results for the neutron lifetime using such a “wall-free” confinement. Both those experiments employ magneto-gravitational traps to store UCNs. While the result of Ezhov et al. $\tau_n = (878.3 \pm 1.6 \text{ (stat)} \pm 1 \text{ (syst)})\text{s}$ [Ezh+18] contains corrections of 3.7 s for loss of UCNs due to depolarization, no such corrections are necessary for the measurement of the UCN τ experiment [Mus+25].

The UCN τ experiment uses an asymmetric bowl-shaped permanent-magnet array to store UCNs. Vertically, the neutrons are trapped by gravity. The asymmetric shape of the Halbach array eliminates closed neutron trajectories. Additional coils provide a holding field to maintain spin polarization [Sal+14]. For counting the neutrons after the storage phase, the experiment uses a detector which can be lowered into the trap for in-situ counting [Mor+17]. Its current result of $\tau_n = (877.83 \pm 0.22 \text{ (stat)} {}^{+0.20}_{-0.17} \text{ (syst)})\text{s}$ [Mus+25] is the overall most precise measurement of the neutron lifetime so far.

2.3 The neutron lifetime puzzle

After outlining the two central measurement techniques, an overview of the relevant neutron lifetime results published since 2005 is given in Fig. 2.3. The measurements are plotted against the publication year. Cross markers denote results which are a reanalysis of an earlier publication. Red points correspond to the beam experiments, while blue data points represent results obtained using the bottle method. The latter have been subdivided into material bottles (light blue) and magneto-gravitational bottles (dark blue). The result of Gonzalez et al. (grey) is included in the publication of Musedinovic et al. The red shaded area represents the weighted mean of the two most precise beam measurements [Yue+13] and [Byr+96] 888.0(21) s [Yue+13]. The blue shaded area represents the weighted mean of the displayed bottle measurements of 878.4(4) s. This average has been calculated according to the PDG procedure of averaging [Nav+24, pp. 15–18]. It differs slightly from the PDG world average 878.4(5) s [Nav+24, p. 2091], since the latter does not yet include the full result of Musedinovic et al., but only the part that has been published earlier in Gonzalez et al. A clear discrepancy exists between the averaged results for bottle and beam methods. For

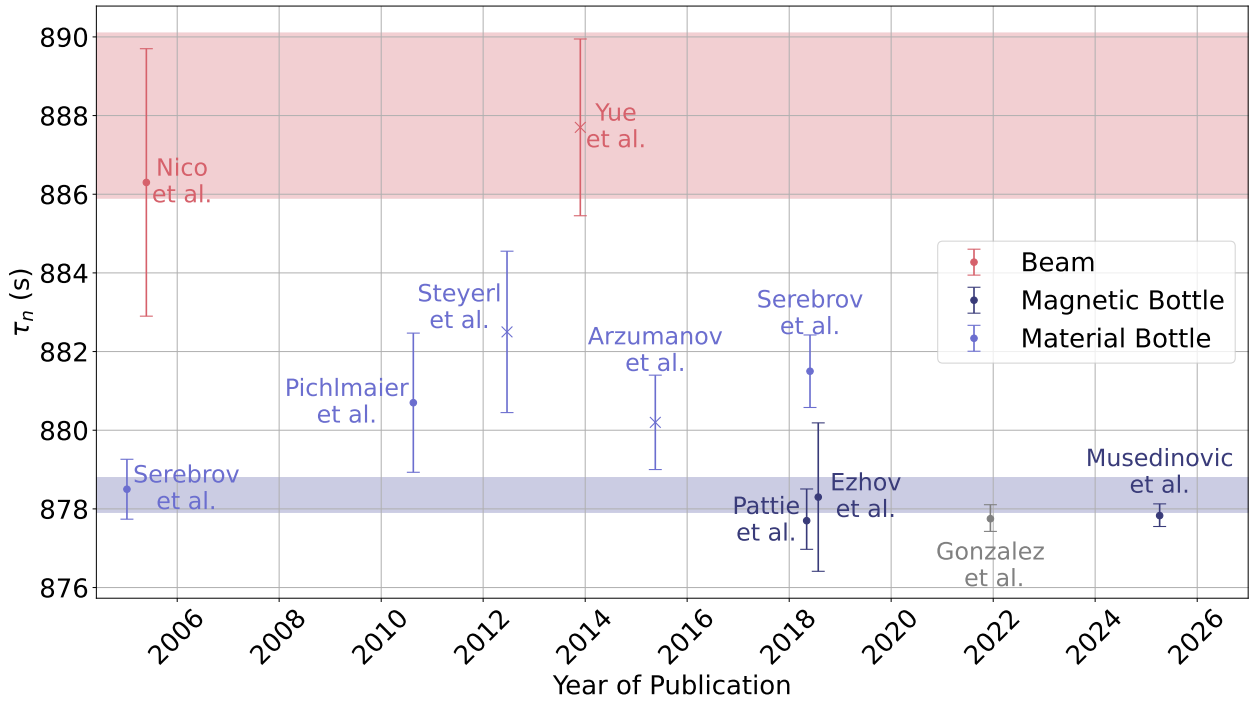


FIGURE 2.3: Overview of relevant neutron lifetime measurement results. Cross markers represent reanalyses of an earlier publication. Red data points were obtained using the beam method, blue data points using the bottle method. Light blue represents material-bottle measurements and dark blue magneto-gravitational bottle measurements. The result of Gonzales et al. (grey) is included in Musedinovic et al. The red shaded area represents the weighted mean 888.0(21) s [Yue+13] of the two most precise beam measurements [Yue+13] and [Byr+96]. The blue shaded area represents the weighted average of the bottle measurements 878.4(4) s. There is a clear difference between the average of the bottle measurements and the beam results. Data has been taken from [Nic+05][Ser+05][Pic+10][Ste+12][Yue+13][Arz+15][Pat+18][Ezh+18][Ser+18][Gon+21][Mus+25]

the averages displayed in Fig. 2.3, the difference corresponds to 4.5σ and even when replacing the bottle average with the PDG average, a tension of 4.4σ remains. No conclusive explanation for this discrepancy has been identified yet, and it is therefore also referred to as the “neutron lifetime

puzzle”. Various possible causes have been proposed, ranging from unaccounted systematic effects to beyond the Standard Model physics, but none have been confirmed so far. In 2021, it was suggested that systematic effects in beam experiments, related to scattering or charge-exchange processes between decay protons and residual gas, could have been underestimated [Ser+21]. This would lead to an underestimation of the decay rate and consequently to an overestimation of the neutron lifetime. However it has been shown that systematic uncertainties were appropriately evaluated and the measured lifetime was not altered [Wie+23]. In 2018 a possible decay channel of the neutron into the dark sector was proposed [FG18] as a explanation of the neutron lifetime puzzle. This hypothesis was tested shortly afterwards and was ruled out [Klo+19][Tan+18][Bay+18].

Further investigation of the neutron lifetime puzzle requires additional high-precision measurements of τ_n . Of particular interest are experiments employing novel approaches to the measurement methods, as they may be subject to different systematic effects. In this context τ SPECT, a purely magnetic trap with a distinct geometry, may offer compelling insights.

2.4 Current status of neutron lifetime measurements

Efforts for further precise measurements of the neutron lifetime are ongoing. The BL2 beam experiment aims to achieve a new measurement with an uncertainty below 2 s and investigates systematics related to the BL1 result. Data acquisition is expected to finish in 2027 [Wie25]. The successor experiment BL3 is planned with a goal of reaching an uncertainty smaller than 0.3 s [Wie25]. At J-PARC, a beam experiment employing a complementary approach, detecting both the electrons from the β -decay and the neutrons using a time projection chamber, is currently in progress. This method has systematic uncertainties distinct from methods detecting the protons of the β -decay [Fuw+24]. The UCNProBe experiment at Los Alamos National Laboratory, which aims to determine the neutron lifetime by detecting the decay products of trapped UCNs to a precision of 2 s, is currently in the commissioning phase [Kri25][Ito25]. The UCN τ collaboration is planning an upgrade to the experiment’s filling procedure, which is expected to improve the number of loaded UCNs by a factor of 5-10 [Mus+25]. This thesis is part of the τ SPECT experiment, which aims for a precision of 0.3 s, and is currently in the data taking phase.

3

An introduction to the τ SPECT experiment

After presenting the motivation for precision measurements of the neutron lifetime and reviewing the main experimental techniques in previous chapters, in this chapter I now introduce the neutron lifetime experiment τ SPECT. I start with a description of the experimental apparatus, followed by a summary of the measurement procedure.

3.1 Description of the experiment apparatus

The purpose of this section is to provide an overview of the experiment and to highlight modifications done to the setup since the most recent publication. More detailed descriptions of the experiment apparatus are presented in [Roß21, pp. 21–51], [Kah20, pp. 67–108], [Aul+24a], and [Aul+25].

τ SPECT is a magnetic bottle-type neutron lifetime experiment. Ultra-cold neutrons (UCNs) in the low-field-seeking spin state (see Sec. 2.2.1) are confined in a 3D magnetic trap. A simulation of the magnetic field is shown in Fig. 3.1. The field is a superposition of a longitudinal field and a radial field. The longitudinal field is produced by superconducting coils, the radial field is an octupole field produced by a Halbach array of permanent magnets. The magnetic-trap potential is limited by the magnetic field of the octupole, since its amplitude is smaller than the two maxima of the longitudinal field. When gravity is taken into account, the minimum of the trap potential lies on the surface of the octupole, and has a value of about 48 neV [Aul+25]. Within the storage region, between the two field maxima, a non-zero magnetic field is maintained to preserve neutron polarization. It is referred to as the “holding field”. The lowest magnetic potential experienced by low-field seekers (LFS) inside the trap is determined by the minimum holding field of approximately 0.21 T, corresponding to about 12.5 neV [Aul+25]. A more detailed description of the trapping fields is given in [Aul+24a] and [Aul+25].

Fig. 3.2 shows a picture of the τ SPECT apparatus set up at the beamport West-1 of the UCN source at the Paul Scherrer Institute (PSI). The neutrons are stored inside the cold bore of the τ SPECT cryostat (1), which houses the superconducting coils producing the longitudinal field. The bore itself is evacuated using multiple vacuum pumps, reaching a pressure of about $2 \cdot 10^{-7}$ mbar [Aul+24a] during operation. The cryostat is suspended in an iron yoke (2) to reduce stray fields. Cryostat and yoke are positioned on four truck lifts (3), which can be used to adjust the vertical position

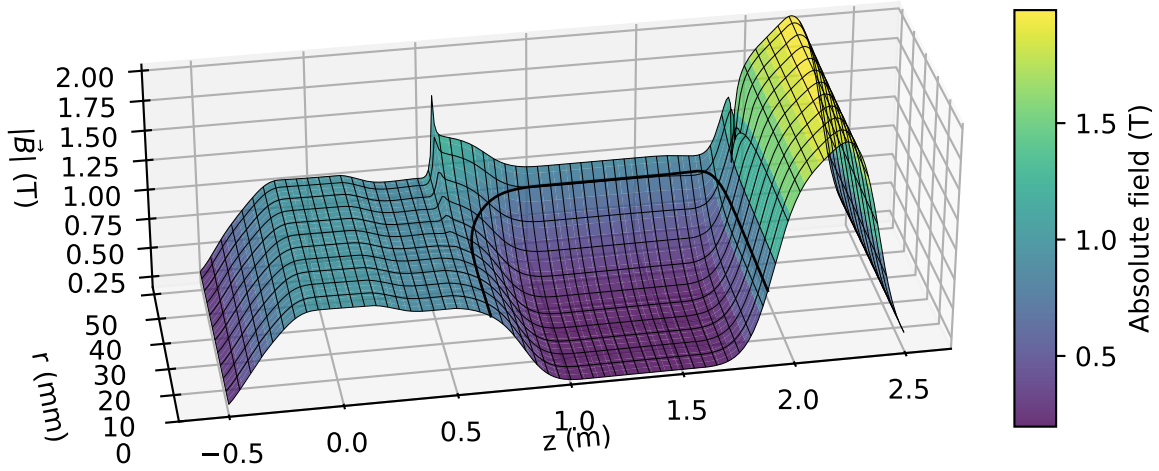


FIGURE 3.1: Calculated absolute magnetic field $|\vec{B}|$ plotted as a function of the longitudinal position z and the radial position r . The longitudinal field is produced by superconducting coils. The majority of the radial field component is produced by a Halbach permanent magnet array arranged as an octupole. The edge of the storage region is marked by a black line.

of the setup with respect to the beamport, and thereby shift the energy spectrum of the neutrons reaching the experiment entrance.

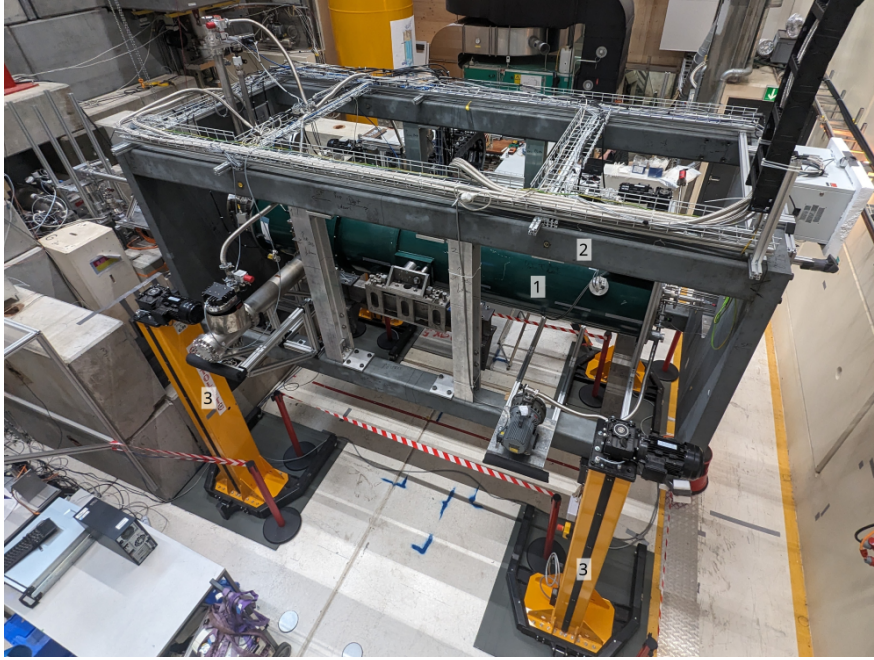


FIGURE 3.2: Picture of the τ SPECT apparatus at PSI beamport West-1. The neutron storage region is inside a cryostat (1), which houses the superconducting coils producing the longitudinal field. The τ SPECT cryostat is suspended in an iron yoke (2) to reduce stray fields. The whole setup is positioned on four truck lifts, two of which are visible in the picture (3). They can be used to adjust the setup's vertical position with respect to the beamport.

Fig. 3.3 shows a cut view of the apparatus. UCNs are guided from the beamport to the experiment entrance shutter via the beamline (1), which consists of stainless steel tubes ($V_f = 190$ neV [Ign90, p. 326], inner diameter $d_i = 66$ mm). For transitions between horizontal and vertical sections $^{58}\text{Ni:Mo}$ (85:15) ($V_f = 311$ neV [Kah+17]) coated plates (1b) mounted at a 45° angle are used. The monitor detector (2), which measures the incoming neutron flux, is located in front of the entrance shutter (3). This detector was designed, built, and characterized as part of this thesis, it is discussed in detail in Ch. 5. Behind the entrance shutter, neutrons are guided into the storage region (9) by a telescopic section consisting of a Teflon-covered stainless steel tube (inner diameter $d_i = 66$ mm) (4) and two fused silica tubes ($V_f = 95$ neV and inner diameter $d_i = 73$ mm) (5). The telescopic section is discussed in detail in [Kah20, pp. 85–91]. As part of an upgrade in 2024, the first fused silica tube was coated with a copper layer ($V_f = 168$ neV [Gol91, p. 20]) from one end to the position of spin flip unit 1 (SFU1) (7). SFU1 and spin flip unit 2 (SFU2) (8) contain the adiabatic fast passage (AFP) spin flippers SF1 and SF2. The spin flippers are mounted concentrically around the fused silica tube. To accommodate SFU2, the second fused silica tube's diameter is reduced to $d_i = 50$ mm.

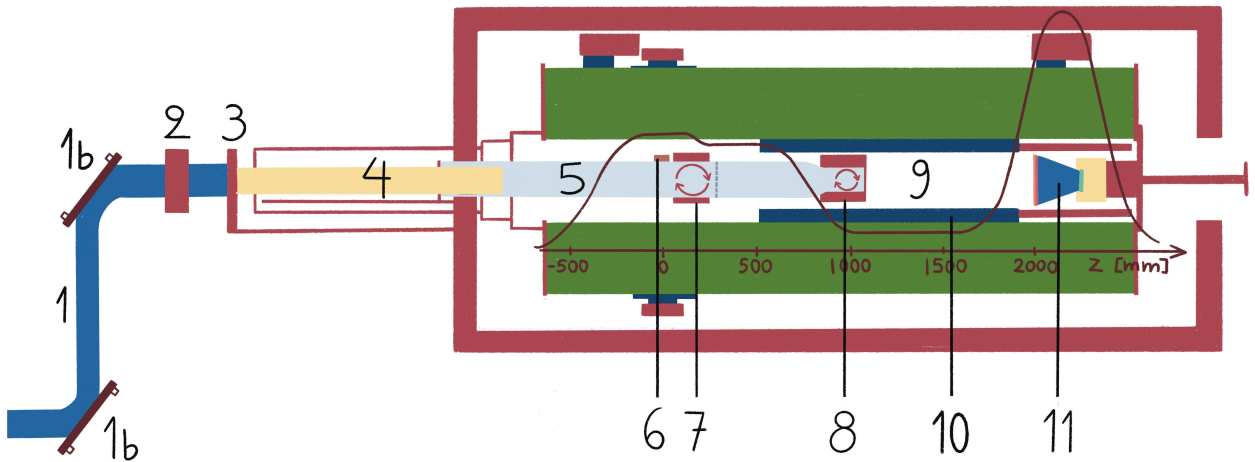


FIGURE 3.3: Cut view of the τ SPECT apparatus. Stainless steel beamline (1), $^{58}\text{Ni:Mo}$ (85:15) ($V_f = 311$ neV [Kah+17]) coated plates (1b), monitor detector (2), experiment entrance shutter (3), telescopic section (4 and 5), Teflon-covered stainless steel pipe (4) and fused silica glass tubes (5), NMR magnetometer (6), spin flip units SFU1 (7) and SFU2 (8), storage region (9), Halbach octupole (10) and τ SPECT detector (11), longitudinal field (dark-red graph). Adapted by D.Kanta from [Roß21, p. 24] with permission of K.Roß.

Using the telescopic section, the fused silica tubes and the SFUs can be moved along the z -axis. This way they can be moved into the trap during the filling of the experiment and retracted from the trap during the storage period. The range of motion is about 70 cm. A detailed description of the SFUs is provided in [Roß21, pp. 81–91, 117–126]. In front of SFU1 a nuclear magnetic resonance (NMR) magnetometer (6) is located. It was mounted in the course of this thesis as a part of an upgrade to SFU1, which is discussed in Sec. 4.3.2. During the filling of the trap the experiment shutter is opened. Incoming neutrons become spin-polarized by the longitudinal magnetic field. The neutrons' spin is flipped, by applying rf magnetic fields using the spin flippers, to obtain LFS with storable energies. There are two different modes of filling the experiment, of which one uses only SF2 and the other uses both SF1 and SF2. I discuss the filling procedures in more detail in Ch. 4. Storable neutrons are confined inside the storage region (9). They are radially confined by the magnetic field of a Halbach octupole (10) and longitudinally by the field (dark-red graph)

produced by the superconducting coils. The τ SPECT main detector (11) can be moved along the experiment's z-axis using a translation stage and a stepper motor. This way it can be positioned inside the trap to detect neutrons and outside of the trap during storage periods. The τ SPECT detector and its moving mechanism are described in detail in [Kah20, pp. 91–108].

3.2 Overview of the measurement procedure

In this section I provide a brief overview of the τ SPECT measurement procedure. The experiment is controlled by a computer, which triggers the actions needed to perform a measurement, such as movement of components or the start of data acquisition, via logic signals. A typical τ SPECT measurement consists out of four phases. The optimal values of the measurement parameters depend on many different conditions, with some important conditions being the vertical position of the trap with respect to the beamport and the filling mode of the experiment. The values given here are the typical values used during measurements in 2024 at a vertical position of 59 cm above the beamport, and when filling τ SPECT using both SFUs. The four phases of the measurement are:

1. **Filling phase:** At the beginning of the measurement, the detector is positioned at the edge of the trap at $z = 1800$ mm. The SFUs are at their filling positions $z_{\text{SF2}}^{\text{fill}} = 980$ mm and $z_{\text{SF1}}^{\text{fill}} = 50$ mm. When the measurement trigger is activated, the experiment's entrance shutter opens, and the SFUs' rf power is turned on. At the end of the filling phase the entrance shutter closes, the SFUs' rf is switched off, and the SFUs start to move out of the trap to their storage positions $z_{\text{SF2}}^{\text{store}} = 400$ mm and $z_{\text{SF1}}^{\text{store}} = -430$ mm. The optimal filling duration depends on the filling method and the vertical position of the experiment. A typical filling duration is about $t_{\text{fill}} = 27$ s.
2. **Cleaning phase:** While the SFUs are retracted from the trap to their storage position, the detector remains at the edge of the trap to remove neutrons with energy slightly above the trap potential. The optimal cleaning position is still under investigation. The position used during the first scientific data run of the experiment was $z_{\text{det}}^{\text{clean}} = 1800$ mm. A typical duration for this phase is $t_{\text{clean}} = 100$ s.
3. **Storage phase:** The detector is completely retracted from the trap to its storage position $z_{\text{det}}^{\text{store}} = 1920$ mm. The start of its movement marks the beginning of the storage period. Typical durations of the storage period are in the range of 20 s to 2000 s. The storage period ends, when the detector starts moving from the storage position to the counting position.
4. **Counting phase:** At the end of the storage time, the detector starts to move into the trap to the counting position $z_{\text{det}}^{\text{count}} = 1605$ mm, where it counts the remaining UCNs in the trap volume. The typical duration of the counting phase is $t_{\text{count}} = 190$ s. Afterwards, the SFUs and the detector move back to their initial positions to ready the setup for the next measurement.

Fig. 3.4 shows an example of a data set of the events detected with the τ SPECT detector during a measurement. The four phases are color coded, dashed lines mark their transitions. During the filling phase (blue), a steep rise in counts can be observed, as the neutrons (UCNs and faster neutrons) arrive at the detector. At the start of the cleaning phase (red), a spike in the counts occurs. This behavior is not fully understood yet. It is assumed that the spike is caused by leftover LFS

in the telescopic section, which reach the detector. Investigations using simulations are currently ongoing. After the spike the count rate decreases by approximately three orders of magnitude, as non-storable neutrons are removed by the detector. During the storage phase (grey), the counts drop to background level. When the detector moves back into the trap during the counting period (orange), a “counting peak”, caused by the detection of the stored UCNs, can be seen. The counts in this window are the ones of interest for the measurement of the neutron lifetime. The background is typically estimated using the storage windows of measurements with long storage durations.

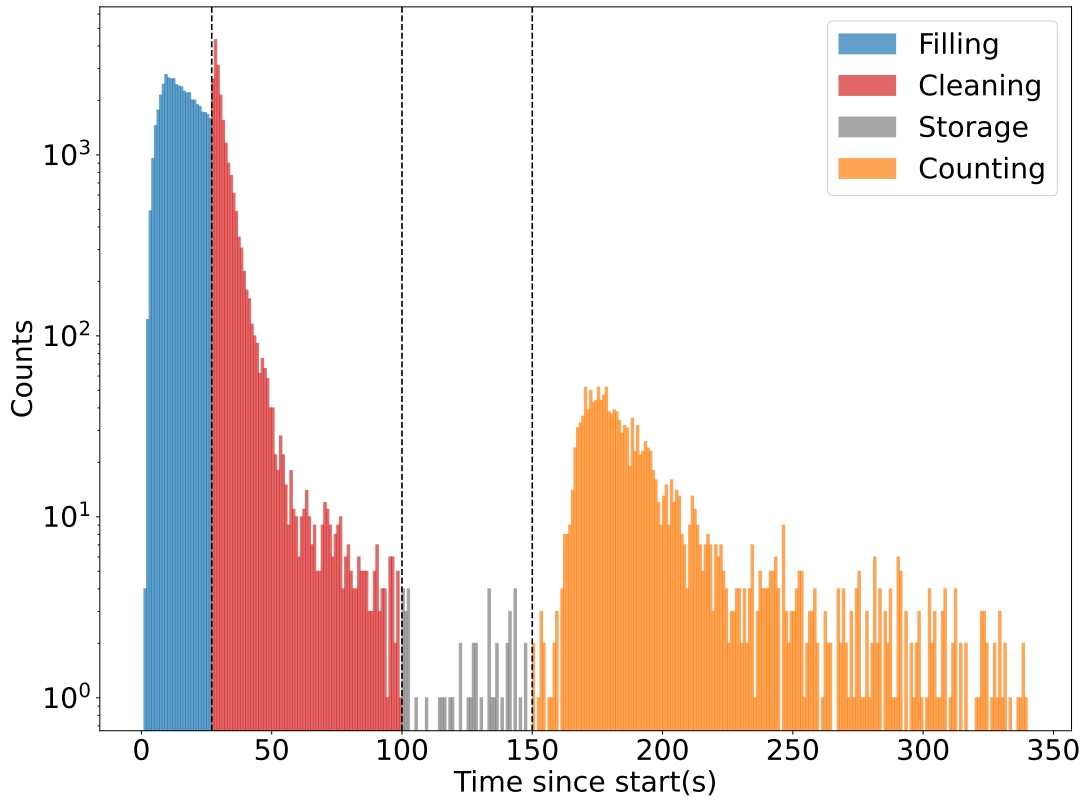


FIGURE 3.4: Example of a data set of the τ SPECT detector during a measurement at PSI for a filling duration of 27 s, a cleaning duration of 100 s, a storage duration of 50 s, and a counting window of 190 s. Events have been binned in 1 s wide bins. The measurement phases are color coded, with dashed lines marking the transitions between them. First, during the filling phase (blue) a steep rise in counts can be observed. During the cleaning phase (red) the count rate reduces by up to three orders of magnitude. During the storage phase (grey) the counts drop to background level. During the counting phase (orange) a “counting peak” occurs as the detector moves into the trap counting the remaining UCNs.

4

Optimization of the double-spin-flip filling procedure

This chapter covers the optimization of the filling of UCNs into τ SPECT using the double spin-flip method. This filling method has been shown as a proof of principle in [Roß21]. In this chapter I will focus on the development of the double spin-flip method from a prototype state into a reliably usable filling method. The chapter provides a brief theoretical background and discusses both hardware upgrades and optimization of the procedure's parameters.

4.1 Introduction to the filling procedure

To successfully fill τ SPECT, the trap volume needs to be populated with neutrons which are in the low-field-seeking spin state, called low-field seekers (LFS) (see Sec. 2.2.1), and have insufficient energy to escape the trap. This can be achieved by using two different filling procedures:

- **Single spin-flip (sSF) procedure:** Initial high-field seekers (HFS) are converted into LFS using SF2, which is the adiabatic fast passage (AFP) spin flipper located at $z_{SF2}^{\text{fill}} = 980$ mm. Initial LFS are simultaneously converted into HFS which cannot be stored in τ SPECT. The sSF procedure and SF2 have been optimized in [Roß21].
- **Double spin-flip (dSF) procedure:** Initial LFS are first converted into HFS using SF1, at $z_{SF1}^{\text{fill}} = 50$ mm and then back into LFS at $z_{SF2}^{\text{fill}} = 980$ mm using SF2. Initial HFS cannot be stored in τ SPECT using this filling procedure.

In addition to targeting two different initial spin states, the two filling procedures also differ in their energy acceptance. This is illustrated in Fig. 4.1, which visualizes the reduction of the kinetic energy of incoming UCNs for both filling methods. When using the sSF procedure (dotted orange line), initial HFS first accelerate as they approach the local field maximum and then decelerate when entering the lower field of the trap region. Due to the holding field of the trap their kinetic energy has increased by approximately 12.5 neV when they reach SF2 at $t_{SF2}^{\text{fill}} = 980$ mm, where they are converted into LFS. In the dSF procedure (dashed orange line), initial LFS lose kinetic energy on their way to the local field maximum and are converted into HFS neutrons at $z_{SF1}^{\text{fill}} = 50$ mm. As HFS they are further decelerated by the decreasing magnetic field on the way into the trap

volume. They are converted into LFS again using SF2 at $z_{SF2}^{\text{fill}} = 980 \text{ mm}$. In the course of the filling procedure their kinetic energy has decreased by about 108 neV.

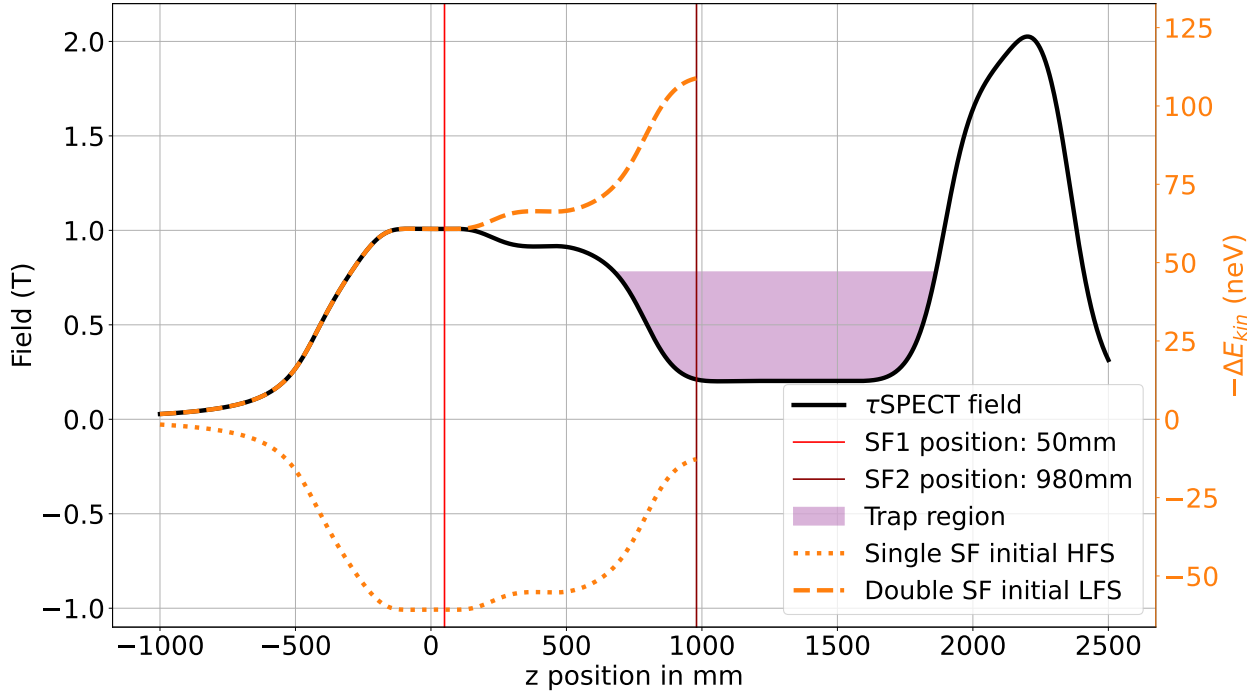


FIGURE 4.1: Visualization of the kinetic-energy reduction ($-\Delta E_{kin}$) of UCNs during the two filling procedures of τ SPECT. The τ SPECT longitudinal magnetic field is represented by the black solid line. The positions of the two spin flippers are marked by vertical lines. The trap region is shaded in purple. During the filling of the trap, UCNs enter from the left. During the sSF procedure (dotted orange line), initial HFS neutrons are accelerated as they enter the magnetic field, and are then slowed down after passing the local field maximum, when entering the lower field region of the trap volume. After conversion into LFS at $z = 980 \text{ mm}$, their kinetic energy has increased by about 12.5 neV relative to its initial value. In the dSF procedure (dashed orange line) initial LFS decelerate when entering the magnetic field and are converted into HFS neutrons at $z = 50 \text{ mm}$. This leads to them also losing kinetic energy on their way into the trap region. They are converted into LFS again using SF2 at $z = 980 \text{ mm}$. In the course of the filling procedure their kinetic energy has decreased by about 108 neV.

We can calculate the conditions for the total initial energy of storable UCNs. When accounting for gravity and the magnetic field at the position of SF2 the resulting energy ranges are $[0 \text{ neV}, 23 \text{ neV}]$ for the sSF procedure and $[108 \text{ neV}, 144 \text{ neV}]$ for the dSF procedure [Aul+25]. One can see that the energy acceptance window for the dSF method is wider by 12.5 neV. This is caused by the additional kinetic energy which the neutrons receive during the sSF method. This wider energy acceptance makes the dSF method an interesting candidate for filling τ SPECT.

4.2 A short introduction to the spin-flip theory

The spin flippers used during the filling of τ SPECT as well as the magnetometer employed in the experiment (see Sec. 4.3.1) rely on methods developed in the field of nuclear magnetic resonance

(NMR). A more detailed explanation of the spin flip is presented in [Roß21]. This section briefly introduces the dynamics of spins in a magnetic field and Sec. 4.2.1 covers the process of the adiabatic fast passage spin flip a bit more in depth. An introduction to the NMR magnetometer is given in Sec. 4.2.2.

In 1970 Lushikov proposed to adapt the adiabatic fast passage method, originally developed in the field of NMR, for UCN experiments [LT84]. This technique enables spin flipping of UCNs in-beam and is also used in τ SPECT. We begin with the dynamics of a single spin $\vec{S}$ in a magnetic field $\vec{B}$, which are given by [Abr83, p. 19]

$$\frac{d\vec{S}}{dt} = \gamma \vec{S} \times \vec{B}. \quad (4.1)$$

Here γ denotes the gyromagnetic ratio. From this equation, it follows that the spin precesses around the field at the Larmor frequency $\omega_L = -\gamma B$. For neutrons the gyromagnetic ratio has the value $\gamma_N = -1.873\,247\,171(43) \cdot 10^8 \text{ T}^{-1} \text{ s}^{-1}$ [Moh+25, p. 58]. Treating the UCNs' spins as isolated spins is appropriate, since the UCN density in experiments is so low that interactions between the neutron spins are negligible. In contrast, NMR typically deals with ensembles of spins due to much higher densities. NMR experiments typically use a dominant static magnetic field $\vec{B}_0$

$$\vec{B}_0 = B_0 \hat{e}_z, \quad (4.2)$$

here chosen to be along the z -axis, together with a much smaller perpendicular field $\vec{B}_1$

$$\vec{B}_1 = B_1 (\cos(\omega_1 t) \hat{e}_x + \sin(\omega_1 t) \hat{e}_y), \quad (4.3)$$

which rotates at the frequency ω_1 in the x - y plane to manipulate the spins. In τ SPECT, the longitudinal trap field serves as B_0 , while the transverse B_1 field is produced by the spin flipper. To better understand the spin dynamics in this configuration, it is useful to consider Eq. (4.1) in a reference frame which rotates around $\vec{B}_0$ at a frequency ω_f . In this rotating frame the spin vector evolves according to

$$\frac{d\vec{S}'}{dt} = \gamma \vec{S}' \times ((B_0 + \frac{\omega_f}{\gamma}) \hat{e}'_z + \vec{B}_1'(t)) = \gamma \vec{S}' \times \vec{B}'_{eff}. \quad (4.4)$$

Here $\vec{S}'$ is the spin vector, $\vec{B}_1'$ is the transversal field, and $\vec{B}'_{eff}$ is the effective field, all expressed in the rotating frame. If one chooses the frame to rotate at the Larmor frequency $\omega_f = -\gamma B_0$, then $\vec{B}_0$ is effectively canceled in the rotating frame. If $\omega_f = \omega_1$ the traverse field $\vec{B}_1'$ will appear as static. For the description of the spin flipper we choose such a reference frame with $\omega_f = \omega_1$.

4.2.1 AFP spin flip

To describe the AFP spin flip method, we consider a magnetic field $\vec{B}_0$ with a strictly monotonic gradient along z , in the region where the transverse field $\vec{B}_1$ is applied, called in this thesis the spin-flipping region. In a reference frame which rotates at $\omega_f = \omega_1$, $\vec{B}_1'$ will appear static and the effective field will be dependent on z :

$$\vec{B}'_{eff}(z) = ((B_0(z) + \frac{\omega_1}{\gamma}) \hat{e}'_z + \vec{B}_1'(z)). \quad (4.5)$$

The angle θ between the effective field and the z -axis is then given by

$$\tan(\theta) = \frac{B_1(z)}{B_0(z) + \frac{\omega_1}{\gamma}}. \quad (4.6)$$

By choosing the correct ω_1 , one can ensure that there exists a point in the spin-flipping region where $\omega_1 = \omega_L$. Since the gradient is monotonic, the z -component of the effective field changes sign within the spin-flipping region. If the condition

$$|B_0(z) + \frac{\omega_1}{\gamma}| \gg |B_1(z)| \quad (4.7)$$

is satisfied at both ends of the spin-flipping region, then the effective field undergoes an overall rotation of 180° across the region. A neutron traversing this region with a velocity v_z , will perceive B'_{eff} as time-dependent. If this field changes orientation much slower than the Larmor precession, the neutron spin will follow the effective field adiabatically. This so-called ‘‘adiabaticity condition’’ is given by [Pow58]

$$|\gamma B'_{eff}| \gg |\dot{\theta}| \text{ or } \alpha = \frac{|\gamma B'_{eff}|}{|\dot{\theta}|} \gg 1. \quad (4.8)$$

Here α is called the adiabaticity parameter. The time differential $\dot{\theta}$ is given by [Hol+12]

$$\frac{d\theta}{dt} = \gamma \frac{\dot{B}_1'(\omega_1 + \gamma B_0) - \gamma \dot{B}_0 B_1'}{(\omega_1 + \gamma B_0)^2 + (\gamma B_1')^2}. \quad (4.9)$$

A simple analytical expression for the spin-flip probability P (the probability of a spin following the rotation of the effective field) is found for the case that α is constant in [Rob71]

$$P = 1 - \frac{1}{1 + \alpha^2} \sin^2(\sqrt{1 + \alpha^2} \frac{\pi}{2}). \quad (4.10)$$

This expression shows that for large α P approaches 1. In practice α is not constant in the spin-flip region, however a lower-bound estimate is presented in [Hol+12]. Under the assumptions of a constant $\vec{B}_0$ gradient, a constant B_1 amplitude, and a constant UCN velocity in the spin flip region, the minimum value of α occurs at resonance and it is given by

$$\alpha = \frac{|\gamma| B_1'^2}{\nabla \vec{B}_0 v}. \quad (4.11)$$

This leads to a lower-bound estimate for P

$$P = 1 - \frac{(\nabla \vec{B}_0 v)^2}{(\nabla \vec{B}_0 v)^2 + (|\gamma| B_1'^2)^2} \sin^2(\sqrt{1 + \frac{|\gamma| B_1'^2}{\nabla \vec{B}_0 v}} \frac{\pi}{2}). \quad (4.12)$$

From this one can see that in this idealized case P approaches 1 as

$$\gamma^2 B_1'^4 \gg (\nabla \vec{B}_0 v)^2. \quad (4.13)$$

This illustrates that a strong B_1 and an appropriate field gradient are both important to achieving a high spin-flip efficiency. However, it should be emphasized, that while this analytical expression can serve as a useful metric in the case of suitable gradients and sufficiently large $\vec{B}_1$, it can fail for spatially varying B_1 and low enough gradients [Hol+12]. Furthermore, this estimation neglects effects from non-idealized neutron trajectories, the influence of gravity, or field gradients along the other axes. Therefore, Monte Carlo simulations are necessary for a complete understanding of the

spin-flip process in τ SPECT. Such simulations are beyond the scope of this work. Initial simulation studies have been carried out in [Roß21, pp. 68–73]. More elaborate simulations of the spin-flip process are currently part of the work of Niklas Pfeifer as part of the τ SPECT simulation framework [Aul+25].

4.2.2 NMR magnetometer

In the course of this thesis an NMR magnetometer was installed as an absolute field reference in τ SPECT. This section will give a brief introduction to the underlying principle. The magnetometer uses an ensemble of nuclear spins. If these spins are placed in a static magnetic field, here chosen to be along the z -axis, the before energetically-degenerate spin states are shifted by the energies [Abr83, p. 27]

$$E_{mag} = -\hbar\gamma m_z B_z. \quad (4.14)$$

Where m_z is the spin magnetic quantum number. At thermal equilibrium the energy states, and therefore the spin states of the ensemble, will be populated according to the Boltzmann distribution. This causes the lower energy states to be more populated than the higher energy states [Lev08, pp. 266–267]. The resulting thermal spin polarization of the sample gives rise to a macroscopic magnetization. The dynamics of this magnetization vector $\vec{M}$ in a magnetic field can be described as [Blo46]

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B} - \hat{e}_x \frac{M_x}{T_2} - \hat{e}_y \frac{M_y}{T_2} - \hat{e}_z \frac{M_z - M_0}{T_1}. \quad (4.15)$$

Here $\hat{e}_i$ are the unit vectors along the corresponding axis, M_0 is the equilibrium value of M_z . T_1 is the longitudinal relaxation time constant, which describes the return to the equilibrium state. T_2 is the transversal relaxation time constant, which describes the decay of the transversal magnetization component [Lev08, p. 35]. Inhomogeneities of the static magnetic field across the sample accelerate the transversal magnetization relaxation. To describe the transversal relaxation including the field variations usually, T_2^* is defined as [Abr83, p. 51]

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^\dagger}. \quad (4.16)$$

Here $T_2^\dagger$ describes the relaxation due to inhomogeneities in the field. In this work the field inhomogeneities are dominating, so $T_2^* \approx T_2^\dagger$. When ignoring the relaxation terms Eq. (4.15) simplifies to

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B}, \quad (4.17)$$

which is the same equation as Eq.(4.1). Therefore, analogous to Eq.(4.5), the dynamics of the magnetization in a static magnetic field $\vec{B}_0$ and a much smaller perpendicular field $\vec{B}_1$, oscillating at a frequency ω_1 can be described in the rotating frame as

$$\frac{d\vec{M}'}{dt} = \gamma\vec{M}' \times ((B_0 + \frac{\omega_f}{\gamma})\hat{e}_z + \vec{B}_1'(t)) = \gamma\vec{M}' \times \vec{B}'_{eff}. \quad (4.18)$$

If now $\omega_1 = \omega_f = -\gamma B_0$, then the effective field in the rotating frame will be just a static field B_1 and the magnetization vector will precess around it. When applying the B_1 field as a pulse the magnetization will precess by a certain angle, which can be controlled by the choice of the pulse amplitude and the pulse duration. This way it is possible to rotate the magnetization into the x - y plane. The reoriented magnetization will precess around B_0 at the Larmor frequency giving rise to a measurable oscillating magnetic signal. By measuring the frequency of this signal the magnetic

field B_0 can then be calculated using the gyromagnetic ratio γ . In reality, this oscillating signal will decay with time due to relaxation. In this work the field inhomogeneities are the dominant cause of relaxation and so the relevant time constant is T_2^* .

4.3 Hardware updates

In the course of this thesis two hardware improvements were done to improve the dSF filling procedure:

- an NMR magnetometer was installed as an absolute field reference,
- the circuitry of SF1 was updated in order to improve the spin-flip efficiency.

In this section I will discuss these two hardware updates. First the NMR magnetometer and its measurement results and then the upgrade of SF1 will be covered.

4.3.1 NMR magnetometer

To successfully flip the neutron spin, the Larmor frequency must match the frequency of B_1 at a position within the spin flipper. Therefore, the magnetic field at the spin flipper needs to be known with sufficient precision. The magnetic field in the region of SF1 is produced by three sets of superconducting coils: the main coils, which produce the main part of the trap field, and two additional gradient coils, labeled C3 and C5. These gradient coils can be used to adjust the field gradient locally at the filling position ($z_{SF1,fill} = 50$ mm) of SF1. At the start of this work the standard current-settings¹ were: $I_{main} = 33$ A, $I_{C3} = 45$ A, $I_{C5} = -20$ A. The field gradient along z was, based on these settings, simulated to be about 0.5 mT cm⁻¹, resulting in a total field range of 3.5 mT covered by SF1. However, after ramping the magnet, fluctuations of the final applied current, cause also field fluctuations. These fluctuations can exceed the field range covered by SF1. As a result, after each ramp, we had to scan a wide range of frequencies to find the correct spin-flip frequency. To address this issue, an absolute magnetic-field reference, with a precision of about 1 mT, was required to determine the neutron Larmor frequency at SF1. An NMR magnetometer was designed to serve as such a reference as a part of the Bachelor Thesis by Viktoria Ermuth. The device measures the magnetic field in τ SPECT by measuring the Larmor frequency of hydrogen nuclei. The magnetometer uses a 1:1 mixture of acetone and ethanol as a sample. This mixture was chosen for operation inside the bore of the cryostat due to its low freezing point. The sample is contained in a capillary with a 3 mm inner diameter and a length of about 30 mm. A probe based on that design was later installed in τ SPECT. It was mounted on the telescopic section of τ SPECT, which allows movement along the z -axis within the field. Fig. 4.2 shows the magnetometer's probe head with the sample on the left and a picture of the magnetometer mounted next to the SFU1 on the right. The probe was mounted 141 mm from the center of SF1. This way it is positioned at $z = -91$ mm, when the spin flipper is at the filling position. This position was chosen, because field simulations predicted the field gradient to be near zero for that position. More detailed studies have shown that there is still some gradient present. Fig. 4.3 visualizes the simulated magnetic field in the region of SF1 and the NMR probe for the initial standard settings. In the top panel,

¹Those settings were adjusted multiple times in the course of this work to improve the spin-flip efficiency, more on that in Sec. 4.4

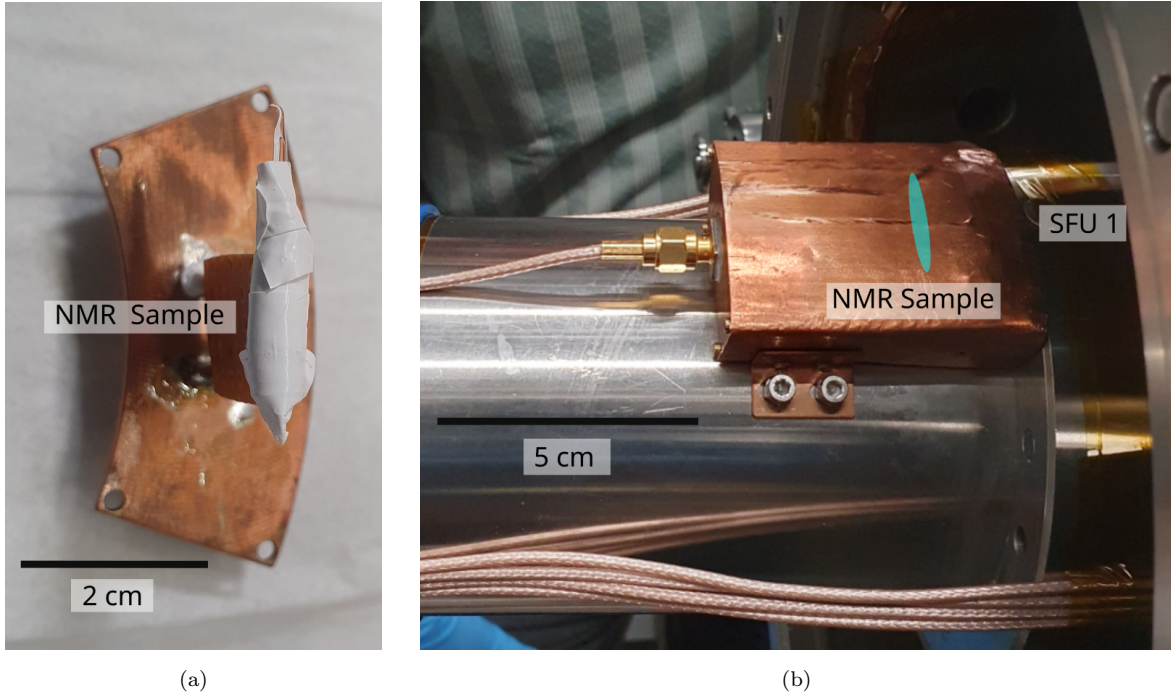


FIGURE 4.2: (a) NMR magnetometer probe head consisting of sample and matching board.(b) Picture taken of the NMR probe mounted in its copper housing next to SFU1 during assembly of τ SPECT in 2025. The approximate position of the sample is highlighted in turquoise.

the z -component of the magnetic field is plotted as a function of z . The field at the center of the beam guide, which represents the field the neutrons experience, is plotted in blue. The field at the NMR probe position, radially offset from the center by about 50 mm, is plotted in orange. The bottom panel shows the gradient $\frac{dB_z}{dz}$ as a function of z with the same color coding. The z -range, covered by SF1 during filling, is marked by red dashed lines and a yellow highlight. The z -position of the NMR probe during filling is indicated by a vertical dashed black line. At this position the gradient is calculated to be approximately 1 mT cm^{-1} . Within the highlighted z -range the field at the NMR offset and in the center of the beam guide are nearly identical. When using the NMR magnetometer to determine the correct spin-flip frequency, measurements can be performed in the standard filling configuration ($z_{nmr} = -91 \text{ mm}$) and the field within SF1 ($z = 50 \text{ mm}$) can then be estimated by finding the corresponding currents in the simulation that match the measured field. Alternatively the NMR probe can be moved to $z_{SF1}^{fill} = 50 \text{ mm}$ and the spin-flip frequency can be estimated from field measurements at that position. Final fine adjustments of the SF1 frequency are performed using neutron-storage measurements, see Sec. 4.4.

Readout of the NMR magnetometer was done using a KEA² spectrometer, provided by and set up with the help of Peter Blümler. A schematic of the readout setup is shown in the Appendix A.4. The signal processing and analysis of the spectrum are discussed in the Appendix A.5. Fig. 4.4 shows a spectrum obtained by accumulating 32 measurements acquired with the spectrometer. A clear resonance is visible, with the centroid of the peak (marked by a dashed-dotted orange line) positioned at $43.9261(2) \text{ MHz}$. The FWHM (marked in gray) of the peak is $6.9(1) \text{ kHz}$, which is used as an upper bound for the sensitivity. To convert the frequencies to magnetic field, the gyromagnetic ratio of a shielded proton $\gamma_p = 42.576\,385\,43(17) \text{ MHz T}^{-1}$ [Moh+25, p. 47] is used. The chemical shifts of acetone and ethanol are on the order of a few parts per million (ppm), which is much

²KEAHF5-40 Kea2 NMR spectrometer by Magritek Holdings Ltd. <https://magritek.com/products/kea/>

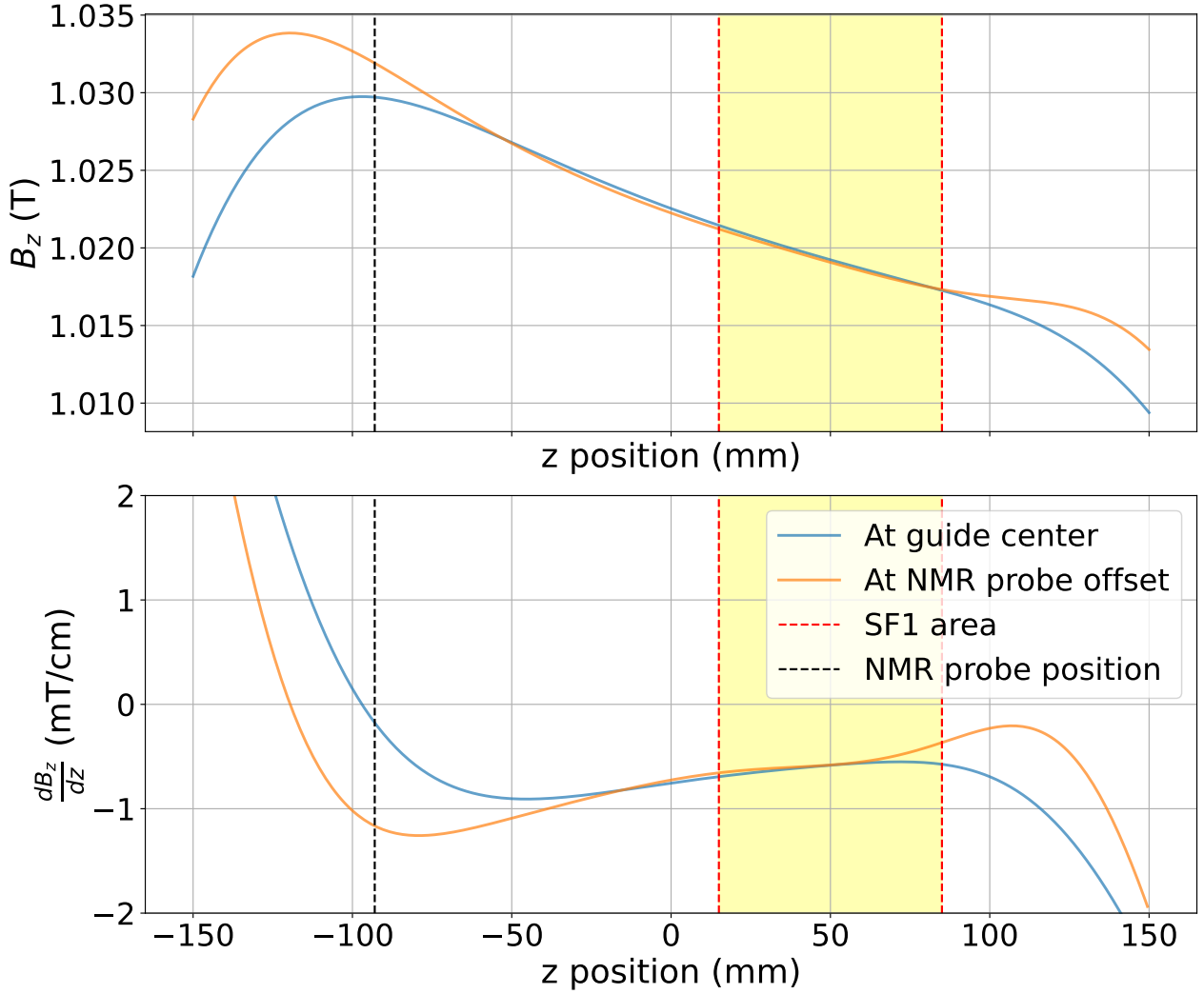


FIGURE 4.3: Simulation of the τ SPECT magnetic field in the region of SF1 for the initial standard settings $I_{main} = 33$ A, $I_{C3} = 45$ A, $I_{C5} = -20$ A. **Top panel:** Amplitude of the magnetic-field component B_z as a function of position along the z -axis. The field calculated for the center of the neutron guide $(x,y) = (0\text{ mm}, 0\text{ mm})$ is represented in blue and the field calculated for the offset of the NMR magnetometer $(x,y) = (0\text{ mm}, 50\text{ mm})$ in orange. **Bottom panel:** The axial field gradient $\frac{dB_z}{dz}$ as a function of z using the same color coding. The z -range covered by SF1 during the filling phase is marked by dashed red lines and highlighted in yellow. The position of the NMR probe during filling is marked by a dashed black line.

smaller than the needed precision and the FWHM and can therefore be neglected. The conversion results in a field value of 1.0317(2) T with the uncertainty given by the FWHM.

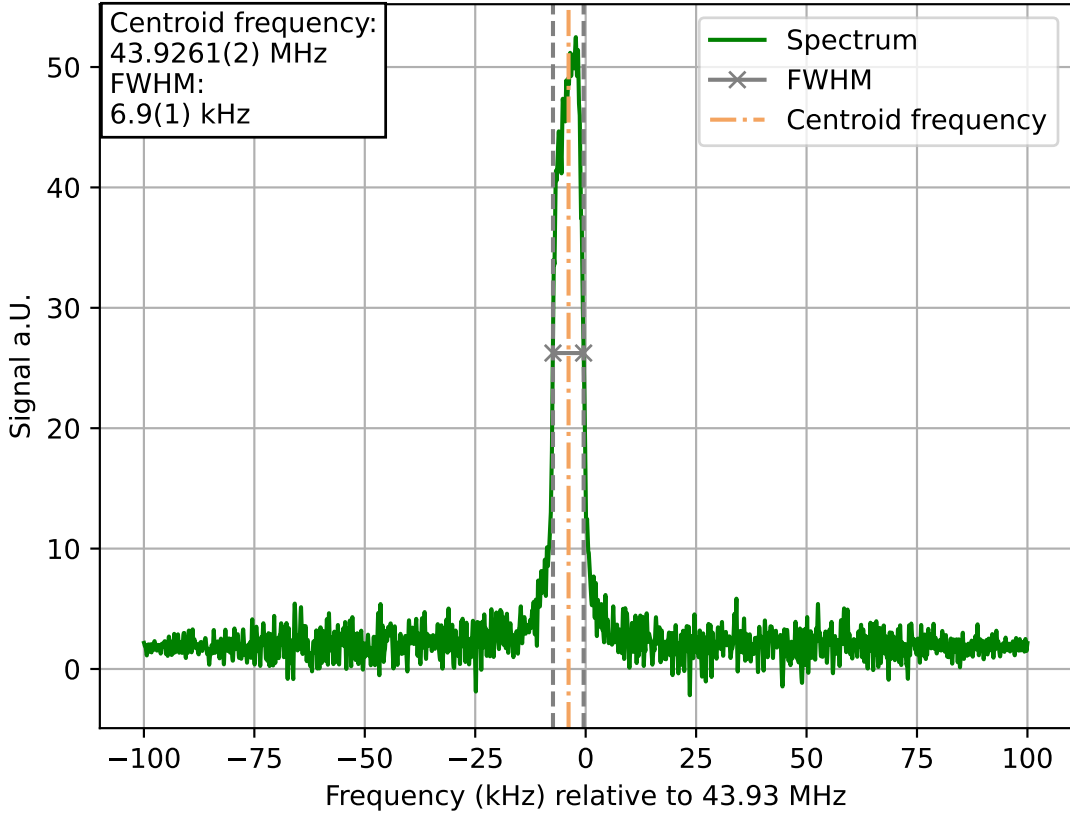


FIGURE 4.4: Typical spectrum acquired with the installed NMR magnetometer. The NMR probe was positioned at $z = -91$ mm and the field settings were $I_{main} = 33$ A, $I_{C3} = 45$ A, $I_{C5} = -20$ A. For this spectrum, 32 measurements have been accumulated. The signal is plotted against the frequency relative to an offset of 43.93 MHz. The spectrum is represented by the green line. The estimated centroid frequency of 43.9261(2) MHz is marked by a orange dash-dotted line. The full width at half maximum is marked in gray.

These measurement results show that the NMR magnetometer provides an absolute field reference with sub-mT precision. This meets the requirements to reliably find the correct spin-flip frequency.

4.3.2 Upgrade of spin flipper 1

Previous measurements using the dSF procedure indicated that the spin-flip efficiency of SF1, as a function of the applied rf power and therefore of B_1 , had not yet reached saturation [Roß21, pp. 124–125]. From Eq. (4.12), it follows that by increasing the rf field amplitude B_1 one can increase the spin-flip probability. To achieve higher B_1 , and thereby store more UCN, we modified SF1 as part of this work. The update was carried out using existing hardware. This section focuses on these modifications. I will first give a brief overview of the original status of SF1 to make the issues addressed with the modification more understandable. A full description of SF1 prior to the upgrade is given in [Roß21, p.119].

Fig. 4.5 presents two photographs of SF1 before the modifications. SF1 consists out of a hollow polyoxymethylene (POM) cylinder with an inner diameter of 84 mm (2), connected to a short stainless steel piece (3) which is used to mount the SF in the translation stage. When installed in τ SPECT the neutron guide passes through the bore of the cylinder. Two saddle-coil pairs (1a, 1b), referred to as coil 1 (C1) and coil 2 (C2), are wound on the POM cylinder, to generate the rf magnetic field required for the spin flip. They each have a height of 80 mm, but are displaced by 10 mm, leading to an overlap of 70 mm. The coil pairs are rotated by 90° with respect to each other. This way they produce two perpendicular fields and by the right choice of phase difference a rotating field (as mentioned in Eq. (4.3)) can be produced. The coils are connected to coaxial wires which are fed through holes in the POM (4). To shield the rest of the experiment from the rf of the spin flipper, a shield (5) made from copper is mounted surrounding the POM cylinder. The shield is grounded by connecting it to the ground of C1 (6) [Roß21, pp. 117–119].



FIGURE 4.5: (a) Picture of SF1 without the rf shield. The saddle coils C1 (1b) and C2 (1a) are wound on the POM cylinder (2). For mounting in the translation stage, the POM cylinder is connected to a short stainless steel piece (3). The saddle coils are connected to coaxial cables which are fed through the POM cylinder (4). (b) Picture of SF1 with the copper rf shield (5) surrounding the POM cylinder. The copper shield is connected to the ground potential of C1 through a screw connection (6).

Fig. 4.6 shows a schematic of the cabling used for the operation of the unmodified SF1. The rf signal for each coil is generated by a function generator, and then amplified in two stages^{3,4}. To match the impedance of the SF1 coils to the $50\ \Omega$ output impedance of the amplifier, two antenna tuners⁵, referred to as tuner boxes, are used. The outputs of these tuner boxes are connected to the spin-flipper coils mounted in the cryostat. The copper shield is grounded through the ground connection of C1. This external matching allows for adjustable and precise matching to $50\ \Omega$ and therefore leads to low reflection into the amplifier output. However, the external matching has one central issue, namely the low transmission from the tuner-box output to the coil. Low transmission means that most of the current will not reach the coil and therefore not contribute to the B_1 field. To investigate the transmission, the input reflection coefficient S_{11} of the circuit behind the tuner box was measured with a vector network analyzer (VNA)⁶ resulting in $-0.05\ \text{dB}$ at the usually used frequency of $29.7\ \text{MHz}$. Additionally, during operation, the incident and reverse voltage at the output of the tuner box were measured using a bi-directional coupler resulting in a ratio of $0.97(3)$. Both results, indicate poor transmission and show that over 90% of the incoming power is reflected. This means that less than 10% of the applied power could actually produce the rf field.

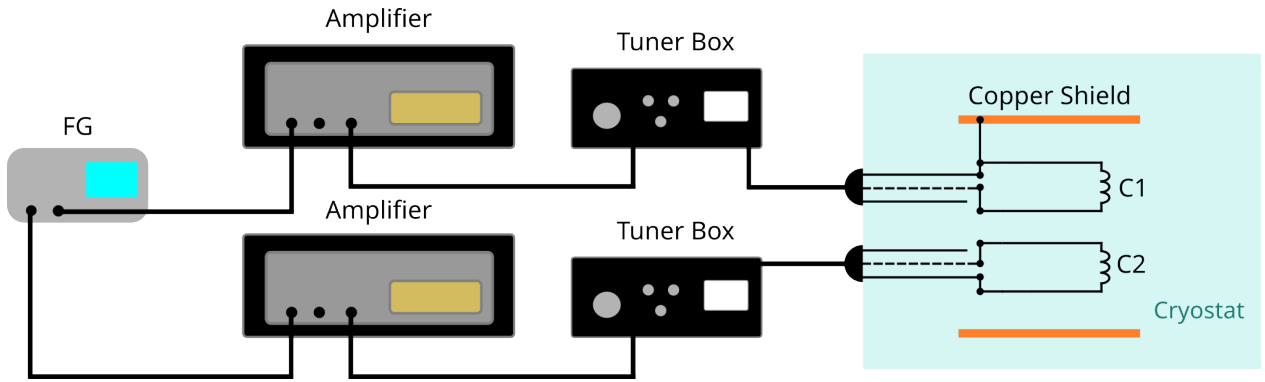


FIGURE 4.6: Schematic of the cabling of SF1 during τ SPECT operation before the update. A function generator (FG) generates an rf voltage signal for each coil, which is then amplified. The spin-flipper circuits are impedance-matched outside of the cryostat to $50\ \Omega$ with a tuner box. The outputs of the tuner boxes are connected to the coils of the spin flipper which is mounted inside the cryostat. The copper shield is grounded via a connection to the ground of C1. All connections outside the cryostat are realized with coaxial cables, but are illustrated as a single line.

In order to improve the transmission to the coils, and thereby increase the rf field amplitude, the impedance of the spin flipper itself had to be matched more closely to $50\ \Omega$. For this purpose, a simple matching circuit was added to each coil of SF1. Each coil was equipped with a matching board containing a parallel capacitor (tuning capacitor) and a serial capacitor (matching capacitor). Two versions of these boards were made. Version 1 was based on a strip board and used in 2023, version 2 is based on a designed printed circuit board (PCB) and was used from the beginning of 2024 onward. Fig. 4.7 shows SF1 with the newly installed version 2 matching boards, which are placed in the gap between the POM cylinder and the copper shield. To avoid short distances between soldering pads, which are a risk for short circuits at high voltages, each matching circuit consists of two PCBs and the capacitors are soldered between those two boards. Since SF1 is not accessible mechanically when mounted in τ SPECT, it was not possible to use variable capacitors

³Pre-amplifier: 10W QRP-99 by KN-Electronic

⁴Main amplifier: HLA 300 Black by RM Italy

⁵MFJ-969 Deluxe Versa Tuner II RF output antenna tuner box by MFJ Enterprises INC© [MFJnd]

⁶Siglent SVA1032X VNA

and fixed ones had to be used instead. The capacitors used are non-magnetic rf capacitors of the ATC 100B Series⁷.

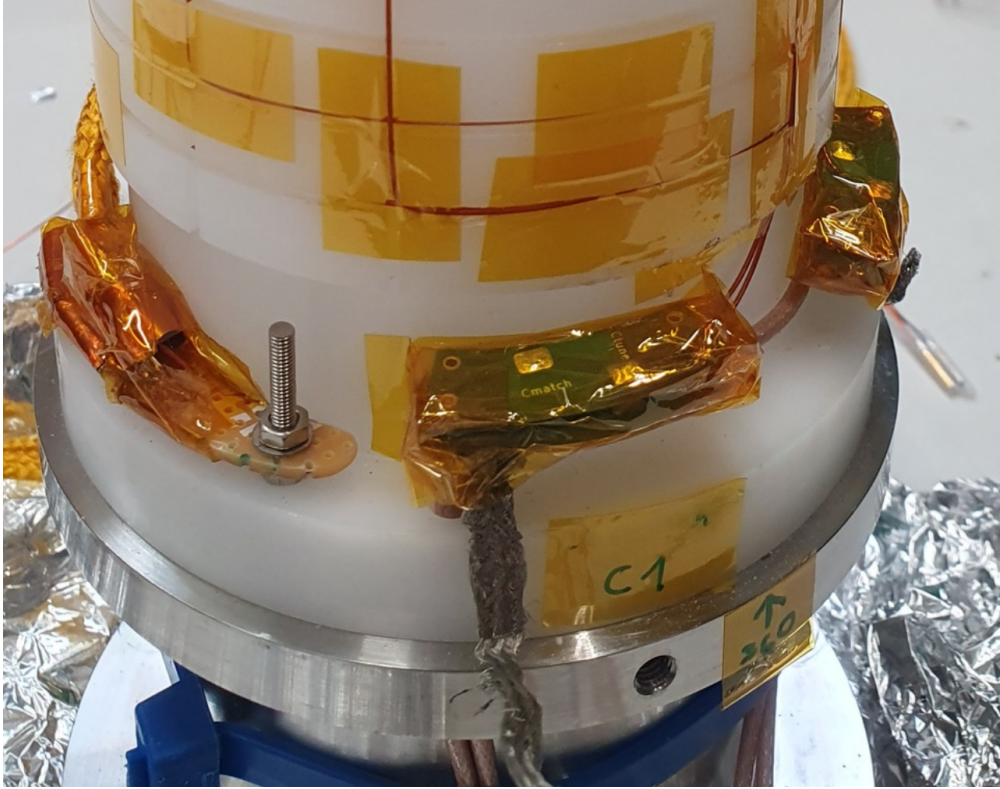


FIGURE 4.7: SF1 with the added matching boards wrapped in kapton tape. The boards are fixed in the space between the POM cylinder and the copper shield (not in picture). Each matching circuit consists of two PCBs. The matching and tuning capacitors are soldered between those boards.

A schematic of the internally-matched SF1 circuit is presented in Fig. 4.8. Since the LC circuits, consisting of the coils and the matching boards, must be electrically shielded from their environment, the ground of both coils is connected to the surrounding copper shield. This connection resulted, as expected, in a strong coupling between the two coils. As a consequence, simultaneous operation of both coils was not feasible, since the crosstalk caused the amplifiers to shut down. To address this, one coil was terminated outside the cryostat with a 300 W $50\ \Omega$ termination resistor. Operation with only a single coil, however, has an inherent drawback: the linearly polarized rf field produced by such a coil can be decomposed into a superposition of two circularly polarized fields of half the amplitude, which are counter rotating. Only the field rotating in the spin precession direction contributes to the spin-flip process [Lev08, pp. 180-181]. This effectively reduces the field amplitude by a factor of two.

In this version of the spin flipper the strong coupling between the coils may lead to an elliptical polarization of the field rather than a linear one. An investigation of the polarization will be shown later in this section.

The tuning and matching capacities were determined in an iterative process to bring the resonance frequency of the LC circuit close to the SF operation frequency of 29.67 MHz. This work was

⁷This series is no longer produced. Its successor is the 100B Series Porcelain Superchip® by Kyocera AVX [Kyond]

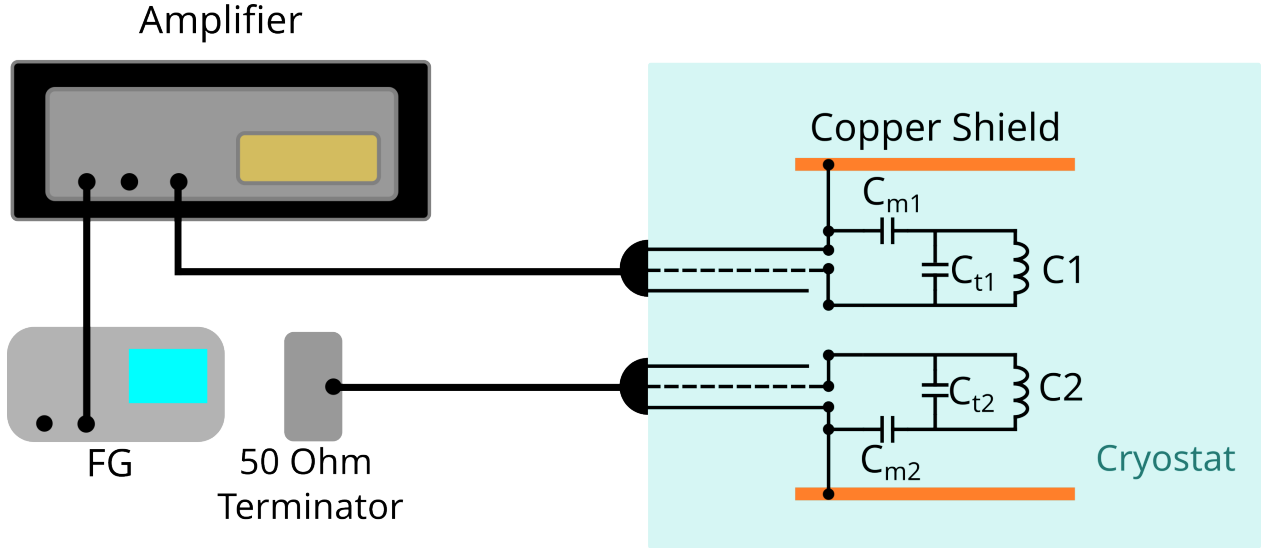


FIGURE 4.8: Schematic of the SF1 circuitry after the modifications. A matching capacitor (C_m) and a tuning capacitor (C_t) have been added to each of the spin-flipper coils. Both circuits are electrically connected to the copper shield. One coil (Coil 2 in this sketch) is terminated using a $50\,\Omega$ termination resistor outside of the cryostat, the other coil is connected to an rf amplifier. The tuner box is not needed in this setup. All connections outside the cryostat are realized with coaxial cables, but are illustrated as a single line.

done together with Viktoria Ermuth. To estimate the effects of the cool down of the circuit in the cryostat, the spin flipper was cooled down using a liquid nitrogen bath. These tests indicated a frequency shift of approximately 500 kHz toward higher frequencies when cooled to liquid nitrogen temperature. Based on these results, values of 30 pF for the tuning capacitor and 2.7 pF for the matching capacitor were selected. Fig. 4.9 shows the S_{11} measurements for SF1 coil C1 with the spin flipper installed in τ SPECT. The resonance curves are shown for the cryostat at room temperature (blue) and at operating temperature (orange). At room temperature the minimal S_{11} is -13.2 dB at 28.7 MHz and after the cool down it has visibly shifted to -14.1 dB at 29.0 MHz. The asymmetry of the curves is likely caused by the coupling of the two coils. The resonance frequency is lower than the operation frequency in Mainz. It is possible to compensate this by a small change of the magnetic field in τ SPECT (more on this in Sec. 4.4). A S_{11} value of -14.1 dB corresponds to only about 4% of the incident power being reflected, a substantial improvement compared to more than 90% reflection before implementing internal matching.

To investigate whether the upgraded SF1 produced a higher field amplitude after the internal matching, the field amplitudes for both the internally matched and the pre-upgrade versions were measured using a pickup coil described in [Roß21, pp. 145–147]. These measurements were performed at room temperature outside of the cryostat. The pickup coil was mounted in SF1 using a 3D-printed holder and its voltage was read out with an oscilloscope⁸.

Figure 4.10 shows the pickup coil signals for the unmodified SF1 using only coil 1, as well as for both modified versions of SF1, plotted against the function generator output. The internally matched versions were operated at 28.7 MHz, and the externally matched version was operated at 29.67 MHz. The measured amplitudes were corrected for frequency dependencies of the pickup coil. For the unmodified SF1, increasing the function generator amplitude was limited by the voltage reflected back into the amplifier. This sent the amplifier into protection mode for amplitudes larger than

⁸Sigilent SDS5104X

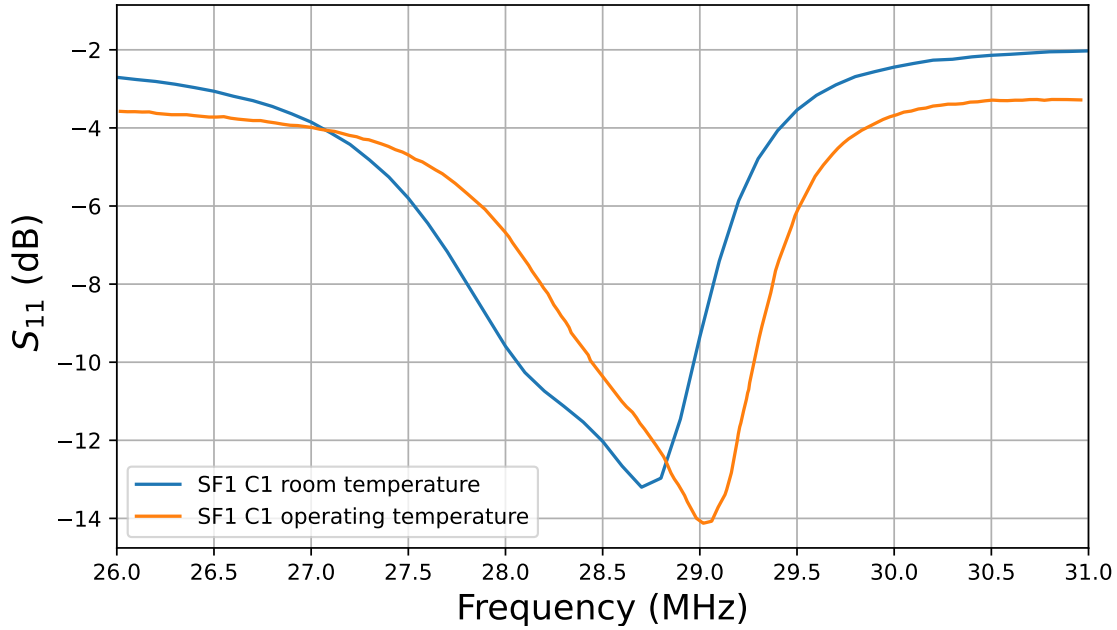


FIGURE 4.9: S_{11} measurement of SF1, while it was mounted in τ SPECT at PSI in 2023. The VNA was connected at the point where the amplifier is normally attached. The blue curve shows the measurement with the cryostat at room temperature, the orange curve corresponds to a measurement done when the cryostat was cooled down to operating temperature. At room temperature the minimum of S_{11} is -13.2 dB at 28.7 MHz. After the cool down the minimum shifts to -14.1 dB at 29.0 MHz. The asymmetry of the curves is likely caused by the coupling of the two coils.

250 mV peak-to-peak. To avoid damages to the boards for version 1 the input signal was limited to 160 mV peak-to-peak when operating the spin flipper in the evacuated cryostat. For version 2 this limit was increased to 200 mV beyond which the boards and the coils showed signs of heating up. When taking into account the limits for operation in the cryostat, the upgraded version 1 produces a pickup voltage larger by an estimated factor 2.43(5) than the unmodified SF1 C1 and for version 2 the pickup voltage is larger by a factor 2.87(5). Under the assumption that the upgraded SF1 produces a purely linearly polarized field, and that the unmodified SF1 functioned as an ideal two-coil spin flipper, meaning it is generating a purely circularly polarized rf field, the “worst-case” effective-field increase corresponds to a factor 1.22(3) for version 1 and 1.44(3) for version 2. However, since the field amplitude contributes to the spin-flip probability with its fourth power (see Eq. (4.12)), even this increase could result in a significant improvement. It should also be noted that earlier phase-scan measurements with the unmodified SF1 yielded results that deviated from the expectations for an idealized two-coil spin flipper [Roß21, pp. 121–122]. The interpretation of the data was complicated by the low statistics. In [Roß21, pp. 121–122] the proposed interpretation was that the observed behavior could have originated by a mixture of neutrons filled with the single and double spin flip during the filling process. From the perspective of this present work, however, it appears equally plausible that SF1 did not operate as an ideal two-coil spin flipper.

To investigate the polarization of the rf field generated by the modified SF1, the pickup coil was placed in the center of the spin flipper and then rotated clockwise in discrete steps. After each step the phase difference between the pickup-coil signal and the forward voltage at the SF1 input was recorded. Fig. 4.11 compares the results of these measurements for the unmodified SF1 (with

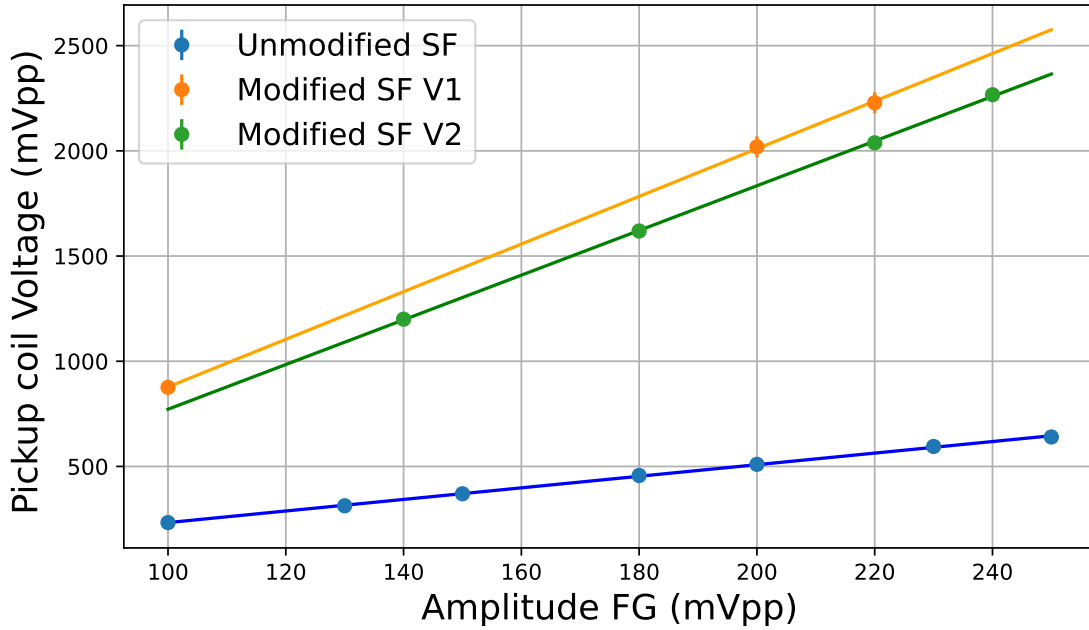


FIGURE 4.10: Comparison of the pickup coil voltage signal for the internally matched spin flipper (blue) and the externally matched spin flipper as a function of the output signal of the function generator. Most points are larger than the errorbars. The internally matched spin flipper has been measured at 28.7 MHz, the externally matched at 29.67 MHz. The measured amplitudes have been adjusted for frequency dependence of the pickup coil. As a guide to the eye, linear slopes have been fitted to the measurement points. One can clearly see that the adjusted pickup signal for the internally matched SF is higher than for the externally matched setup at the same input voltage. To avoid damages to the boards for version 1 the input signal was limited to 160 mV peak-to-peak when operating the spin flipper in the evacuated cryostat. For version 2 this limit was increased to 200 mV.

only C1 driven) and for version 1 of the upgraded spin flipper. In all cases, the non-active coil was terminated. For the unmodified configuration the results are consistent with a linearly polarized field. The phase remains constant and jumps twice by 180° which is caused by the pickup coil switching orientation with respect to the field. In contrast, the measurements with the modified spin flipper show a continuous phase shift as the pick up coil is rotated. For C2 the phase difference increases with the rotation angle, whereas the dependency is reversed for C1. This behavior is a strong indication for an elliptical polarization. The sign difference for the two coils is most likely caused by the elliptical polarizations rotating in opposite directions depending on which coil the signal is applied to. This suggests that one coil may perform better when used as the active coil due to the polarization of the field.

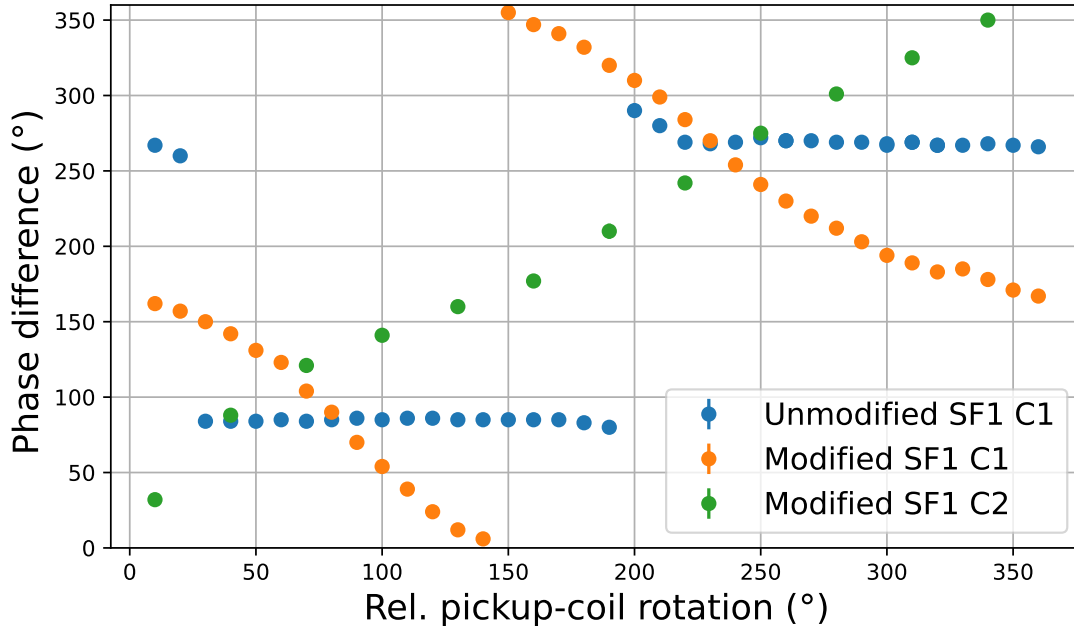


FIGURE 4.11: Comparison of the phase difference between the pickup coil-signal and the rf voltage applied to SF1 as a function of the pickup coil-rotation. Measurement results obtained with the unmodified C1 (blue), the modified C1 (orange) and the modified C2 (green) are depicted. The inactive coil was terminated by a $50\ \Omega$ resistor during the measurements. Error bars are smaller than the data points. For the unmodified coil, the phase difference remains constant except for two 180° jumps. For the modified coils, the phase difference shifts continuously depending on the rotation: for C2 it follows the rotation, while for C1 it has the opposite orientation.

4.4 Double SF measurements

In this section I present the measurement results we obtained with the dSF procedure. First, I discuss the commissioning and optimization measurements done in 2023. Subsequently I present, the 2024 measurements taken with the optimized settings, including a direct comparison between the dSF and sSF procedures.

4.4.1 Double SF commissioning in 2023

The measurements for the initial investigations of the dSF method at PSI were carried out in December 2023. Measurements discussed in this section used version 1 of the matching circuit. The cryostat was put to a vertical position of 0 m relative to the beamport, meaning the center of the beamport and the center of the experiment's entrance shutter were at the same height. This was done to simplify the interpretation of the measurement results. At the PSI UCN source, a 0.1 mm thick AlMg3 foil supported by a stainless steel grid is installed between the beamport and the storage vessel [Bis+20]. Consequently, only UCN with kinetic energies above the foil's Fermi potential of 52 neV [Rie22, p. 36] can come out of the beamport. Since the sSF method can only store neutrons with initial energies in the range of [0 neV, 23 neV] (see Sec. 4.1), it follows that at

this height no storable neutrons can be filled using the sSF. Therefore, at a height of 0 m, all stored neutrons must have been filled using the double spin flip.

All measurements discussed in this section were done with a measurement sequence consisting of a 30 s long filling phase, no cleaning phase, 50 s storage duration, a 80 s long counting window, and a background window of 90 s. To fit the field better to the the resonance frequency of the S_{11} measurement results shown in Fig. 4.8, the currents of the field coils were set such that, according to the field simulations, the field at SF1 corresponded to a neutron Larmor frequency of about 29.0 MHz. This was realized with settings of $I_{main} = 32.28$ A, $I_{C3} = 15$ A, and $I_{C5} = -10$ A. For these settings, the average field gradient in the spin flip region at the center of the guide was calculated to be -0.31 mT cm $^{-1}$. Measurements with the NMR probe at $z = -91$ mm resulted in a resonance at 42.585(2) MHz. The field simulations had predicted 42.685 MHz. The difference between simulation and measurement was larger than 2 mT which highlights the necessity of the NMR magnetometer. Using those measurements, the corresponding spin-flip frequency was estimated to be 29.01 MHz.

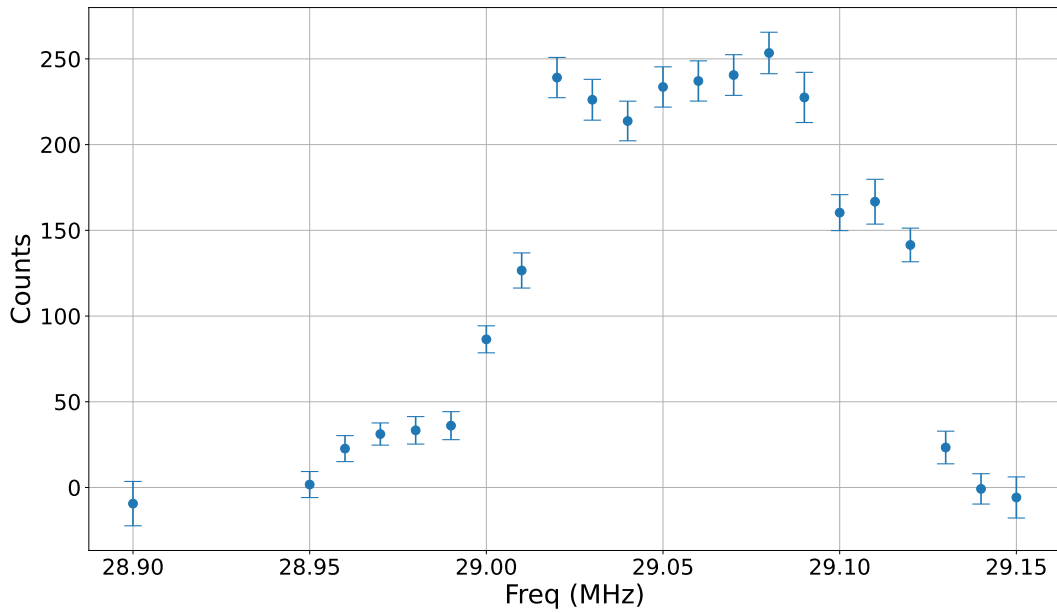


FIGURE 4.12: Results of an initial frequency scan with the double spin-flip method. This measurement was done at a height of 0 m and with a function-generator amplitude of 140 mV peak-to-peak. Background-corrected counts are plotted against the SF1 C1 frequency. Data points represent the weighted mean and error bars represent the standard error of the weighted mean. Negative count values are caused by background correction. A clear resonance with a plateau of more than 200 counts can be observed between 29.02 MHz and 29.09 MHz. On either side of that plateau the counts decrease rapidly.

To determine the optimal spin-flip frequency, storage measurements (measurements which include a storage phase for the neutrons) were performed and the rf frequency of SF1 was changed in between those measurements. For these measurements, the background counts were estimated by measuring the count rate after the end of the counting window and multiplying it with the duration of the counting window. Afterwards, the background counts were subtracted from the counts measured during the counting window. This method likely lead to an overestimation of the background. This

bias does not significantly influence the results discussed in this section. In 2024 the background estimation was improved to avoid this bias.

Fig. 4.12 shows the results of the storage measurements for the frequency scan. The weighted mean of the background-corrected counts is plotted against the applied frequency. A clear resonance can be observed with a plateau of up to 250 counts extending between 29.02 MHz and 29.09 MHz. On either side of that plateau the counts decrease rapidly. Below 28.95 MHz and above 29.14 MHz the counts are consistent with 0. The plateau's width is related to the field covered by the spin flipper. The field simulation predicts that SF1 C1 covers about 2.2 mT (about 64 kHz), which is comparable to the width of the plateau.

This measurement confirmed that filling with the dSF using the modified SF1 was working and neutrons could indeed be stored. However the number of stored UCNs was not sufficient for lifetime measurements yet. Moreover, the number of stored UCNs did not reach saturation at the maximum of the applied rf amplitude, which indicates that the spin-flip probability was not yet maximized. Since the spin-flip efficiency depends on the gradient of B_0 , see Sec. 4.2.1, the field gradients were subsequently adjusted. This was realized by iteratively changing the currents in the gradient coils C3 and C5, starting from values for which the field simulations predicted small gradients. The highest counting statistics were obtained for $I_{main} = 32.24$ A, $I_{C3} = 12$ A, and $I_{C5} = 8.5$ A. It should be noted that, according to the field calculations, the absolute gradient at this setting is below 0.05 mT cm^{-1} , although the precision of the calculations at this level is uncertain.

Figure 4.13 shows a comparison of scans of the applied rf amplitude for the initial gradient configuration (blue) and the optimized gradient configuration (orange). The single spin flip is given as a reference in green. To account for variations in source yield, the background corrected counts N_c were rescaled as follows:

$$N_r = \frac{N_c}{N_m} \bar{N}_m. \quad (4.19)$$

Here N_m are the monitor counts of the individual measurements and $\bar{N}_m$ is the mean of the monitor counts of all measurements. The monitor detector is covered in detail in Sec. 5. The error was estimated using Gaussian error propagation for uncorrelated variables. This probably overestimates the error, since N_m and N_c are likely correlated, but the data set was not large enough to calculate a meaningful correlation. In practice, the error is dominated by the measurement error on the stored neutrons. The corrected counts are plotted against the output voltage of the function generator. Each data point corresponds to the weighted mean of multiple measurements. For the initial gradient, a linear increase in counts with the applied signal can be observed. In contrast, for the optimized gradient setting the counts first rise steeply, increasing by more than a factor 6 when the function generator output is raised from 50 mV to 70 mV peak-to-peak. At higher amplitudes the growth rate decreases and for voltages above of 130 mV peak-to-peak the counts agree within their errors, indicating that the spin-flip efficiency approaches saturation. At the maximum applied amplitude of 160 mV peak-to-peak, with the optimized gradients, a factor 4.9(2) more neutrons were stored than with the initial gradient configuration.

These results demonstrate that with a suitable choice of field gradients the amount of stored UCNs can be significantly increased. However, it should be noted that reducing the gradient in the spin-flip region strongly affects the frequency response of the dSF. This will be discussed in a comparison between two gradient settings done in 2024 in the following section.

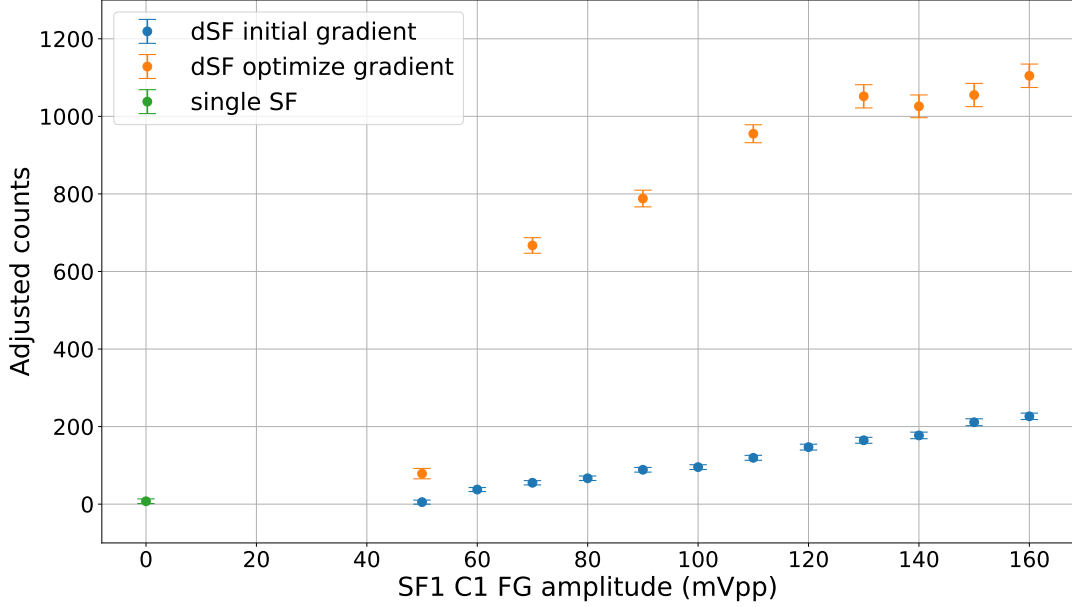


FIGURE 4.13: Comparison of amplitude scans of SF1 C1 for different gradient configurations. Measurements were performed at a height of 0m relative to the beam port and with 50s of storage time. Background-corrected counts are plotted against the function-generator amplitude. Depicted are the sSF method (green) and the dSF method for the initial (blue) and the optimized gradient settings (orange). Counts have been adjusted to correct for changes in source yield. Markers represent the weighted mean of multiple measurements and the error bars represent the standard error of the weighted mean. Markers are often larger than the error bars. Filling with optimized gradients increased the number of stored neutrons by a factor of 4.9(2). For amplitudes above 130 mV peak-to-peak the counts seem to saturate for the optimized gradient, whereas measurements taken with the initial gradients continue to increase approximately linearly.

4.4.2 Double SF optimization in 2024

For the 2024 beamtime, two hardware modifications were implemented. First, version 1 of the matching boards was replaced by version 2 allowing for an increased applied signal of up to 200 mV peak-to-peak. This change resulted in a slight shift of the S_{11} of the SF1 circuit. The new minimum reached -17 dB at a frequency of 29.3 MHz. Second, the first fused-silica neutron guide of the telescopic section (see Sec. 3) was replaced by a partially copper-coated guide. In the coated region the Fermi potential was thereby increased from 95 neV (fused silica) to 168 neV (copper). This modification was done to reduce transmission losses of the storable UCNs filled with the dSF method. Since these neutrons have initial energies in the range [108 neV, 144 neV], which are above the Fermi potential of fused silica, but below the potential of copper, they have enough energy to escape the uncoated guide but not the coated one. To investigate the effect of those modifications on the amount of stored UCNs, the measurements at a vertical position of 0 cm were repeated. For those measurements the field gradient was optimized again, the most counts were obtained at $I_{main} = 32.51$ A, $I_{C3} = 12$ A and $I_{C5} = 8.0$ A.

Fig. 4.14 shows a comparison of amplitude scans at those settings, in green, with the measurements done in 2023 (also presented in Fig. 4.13), in blue and orange. The 200 mV measurement of the 2024

data has been adjusted to compensate for changes in source performance. A significant increase in counts from 2023 to 2024 can be observed. Over 3000 neutrons were stored during a single measurement at optimized settings.

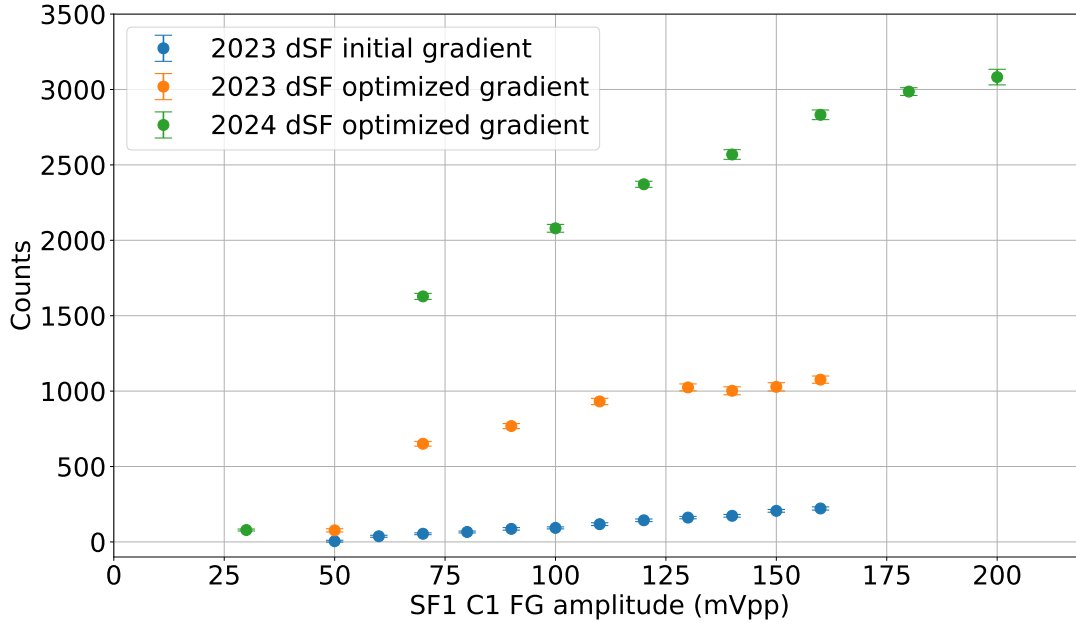


FIGURE 4.14: Comparison of amplitude scans performed in 2023 (blue and orange) and in 2024 (green) at 0 m height. Counts have been adjusted to correct for changes in source performance. The counts are plotted against the applied rf frequency. Markers represent the weighted mean of multiple measurements. Error bars represent the standard error of the weighted mean. A significant increase in counts can be observed between 2023 and 2024.

Due to this significant improvement, the dSF method became a legitimate option as filling method for the 2024 scientific data run.

To determine the optimal filling method, a measurement campaign was conducted comparing the different filling methods at several heights. By changing the height, the energy distribution of the incoming UCNs is shifted. This is a crucial parameter to optimize, since the energy distribution of the UCNs at port West-1 is not uniform. In fact, simulations show that it peaks at about 200 neV [Aul+25]. For all heights, except for 0 m, the beamline described in Sec. 3.1 was used. For the measurements at a height of 0 m a straight piece of beamline with a wider diameter of 200 mm and a length of 60 cm was connected to the beamport. The beamline diameter was then reduced in front of the monitor detector. The filling parameters, such as the spin-flipper frequency and the filling time, were optimized at each height. Both the sSF and dSF method were evaluated using measurements without cleaning and with 50s storage. Across all investigated heights, one filling method clearly outperformed the other. The smallest difference was at a height of 0.8 m where the dSF method filled about 70(5)% more UCN than the sSF method. The dSF performed better for heights of 0.8 m and lower and the single spin flip for heights above 1.25 m. This is most likely caused by the energy spectrum of the UCNs and the different energy-acceptance windows of the filling methods. At each height the preferable method was investigated in more detail by performing measurements with cleaning. After the filling, a 150 s long cleaning window was implemented, during which the detector was positioned at $z = 1800$ mm. This window was then immediately

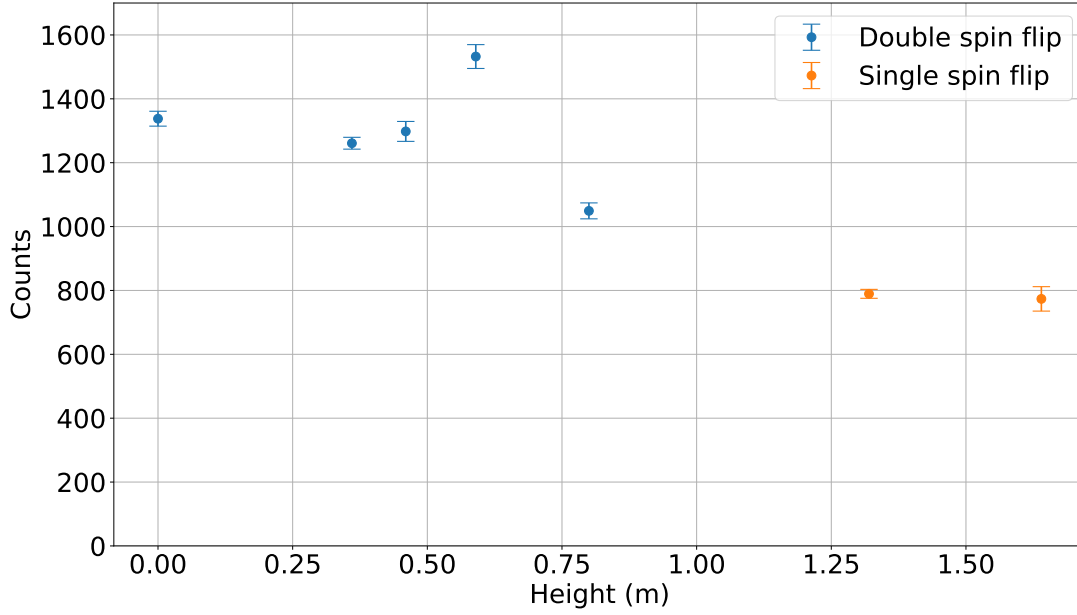


FIGURE 4.15: Comparison of the optimal filling method at different heights. Measurements were performed with 150s of cleaning and without storage. Background-corrected counts are plotted against the height of the τ SPECT entrance in respect to the beamport. Data points represent the weighted mean of measurements and error bars represent the estimator for the standard error of the mean. Results obtained using the dSF method are depicted in blue, the ones obtained with the sSF method in orange. The double spin flip performed overall better than the single spin flip. The most neutrons were filled at a height of 0.59 m using the double spin flip.

followed by the counting phase, which lasted 170 s. The detector background was estimated using dedicated background measurements at each height. For the heights of 0.36 m and 0.8 m no dedicated background measurements were performed. Instead, I used the mean of all background rates for those measurements in this analysis. Since the background rates differ by maximal 0.18 s^{-1} , this substitution is not expected to significantly affect the results.

Fig. 4.15 summarizes the results of those measurements. Background-corrected counts are plotted against the elevation of the τ SPECT entrance in respect to the beamport. Results obtained using the double spin flip are depicted in blue, the ones obtained with the single spin flip in orange. The highest counts were achieved with the dSF method at a height of 0.59 m with 1530(40) counts. This is a factor of 1.94(5) more than the best single spin-flip result of 790(12).

As mentioned in Sec. 4.4.1 the changing of the gradient has a significant effect on the dSF frequency response. Fig. 4.16 shows the amount of stored neutrons against the applied spin-flip frequency for two different gradients. The field settings of $I_{\text{main}} = 32.51 \text{ A}$, $I_{C3} = 36 \text{ A}$, and $I_{C5} = -18 \text{ A}$ resulted in a 0.5 mT cm^{-1} gradient and they are depicted in blue, while the optimized gradient settings are shown in orange. The gradient at the optimized settings was calculated to be smaller than 0.05 mT cm^{-1} . Both measurements were taken in 2024, at a height of 0 m and with an applied amplitude of 140 mV peak-to-peak.

The difference between the two measurements is clearly visible. For the larger gradient, a plateau of about 700 counts with a width of 120 kHz can be observed. In contrast, the optimized gradient

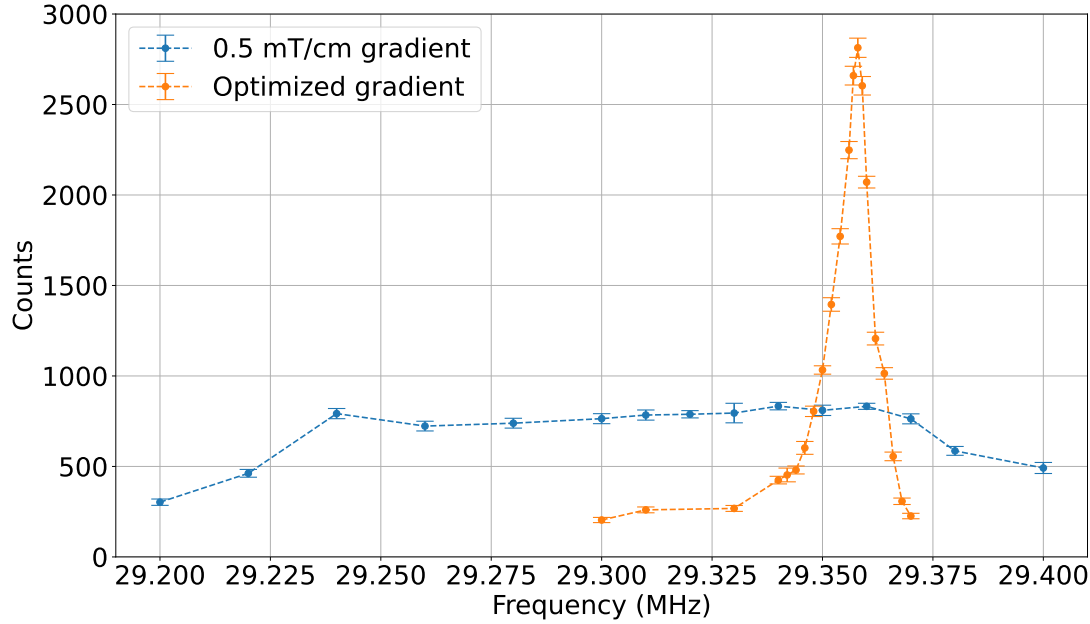


FIGURE 4.16: Comparison of SF1 C1 frequency scans for two different gradients within the spin flipper. Measurements done with a gradient of about 0.5 mT cm^{-1} are depicted in blue, measurements done with the gradient optimized for the amount of filled neutrons (simulated to be smaller than 0.05 mT cm^{-1}) are depicted in orange. The background-corrected counts are plotted against the applied frequency. Markers represent the weighted mean of multiple measurements. Error bars represent the standard error of the weighted mean. A clear difference in the shape of both curves can be observed. While the blue curve shows a plateau of about 700 counts with a width of 120 kHz, for the optimized gradient the counts show a sharp peak with a maximum of about 2800 counts and a FWHM of about 10 kHz.

results in a sharp peak of up to 2800 counts with a full width half maximum of about 10 kHz. The width of the plateau in the high-gradient case can be mostly attributed to the gradient. The gradient is expected to stay relatively constant throughout the spin flipper, meaning that there are no big differences in spin-flip efficiency to be expected in the center of the spin flipper. In contrast, the shape of the resonance at the optimized gradient setting is more complex. While an increase in counts and a sharper resonance are expected when reducing the gradient, the exact shape is likely influenced by additional factors. At such a small longitudinal gradient, the radial gradients could have an influence on the resonance shape. Additionally, in this configuration, the longitudinal gradient is, according to the simulations, no longer necessarily monotonous. Detailed measurements of the field and Monte Carlo simulations based on those measurements are required for quantitative understanding. Those are beyond the scope of this work. The narrow resonance at the optimized settings indicates that reducing the gradient is not purely advantageous. Although the spin-flip efficiency improves and more neutrons can be stored, the system becomes more sensitive to changes in the rf frequency and drifts in the static magnetic field B_0 . For future operation it is therefore of interest to further increase the applied field amplitude B_1 , to maintain a high spin-flip efficiency also at larger gradients and thereby reduce the sensitivity to frequency and B_0 changes.

The improved statistics after the upgrade in 2024 allowed to investigate whether using SF1 C1 or SF1 C2 as active coil affects the filling performance. A dedicated comparison measurement was

done in December 2024. An amplitude scan was performed for both coils. The same frequency of 29.216 MHz was used for both. The experiment was at a height of 0.59 m. The measurements were performed with cleaning during the first 50 s at $z = 1800$ mm and a storage duration of 50 s.

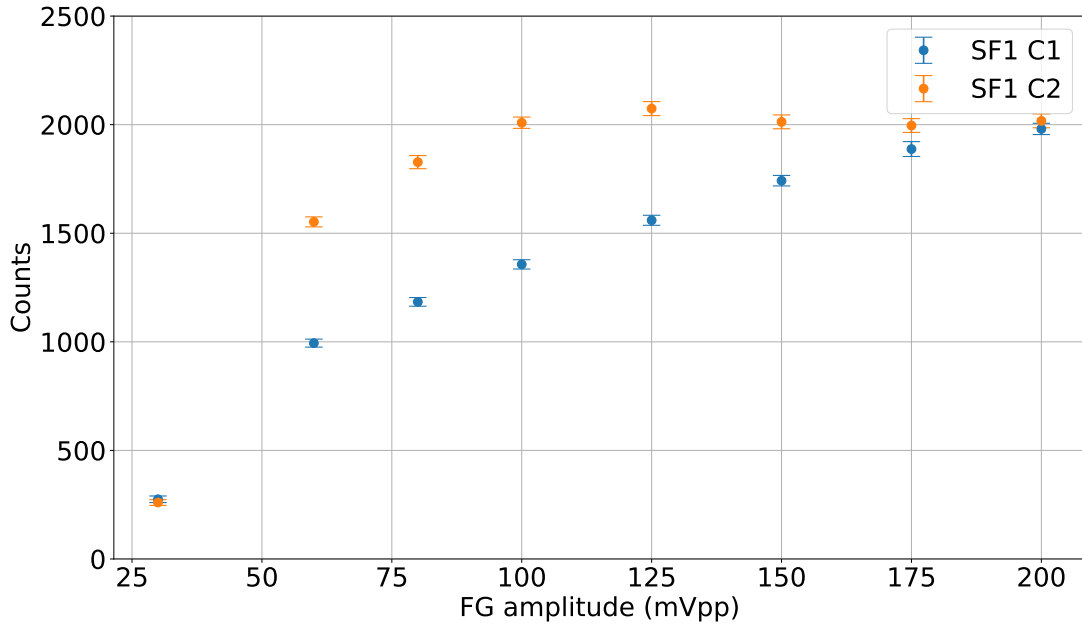


FIGURE 4.17: Comparison of two amplitude scans using SF1 C1 (blue) and SF1 C2 (orange) as the active coil. Measurements were performed at a height of 0.59 m. Background-corrected counts are plotted against the output amplitude of the function generator. Counts have been adjusted to correct for changes in source yield. Data points represent the weighted mean of multiple measurements, and the error bars represent the standard error of the weighted mean. The curve measured using C2 rises more rapidly and levels off at about 2000 counts for applied amplitudes of 100 mV and higher, while the curve measured with C1 saturates much slower and reaches 2000 counts only at double the amplitude.

Fig. 4.17 shows the results of those two scans. The measurements, with C1 as active coil, are displayed in blue. The measurements, with C2 as active coil, are displayed in orange. The curve obtained using C2 rises faster than the one measured with C1 as active coil. It levels off at about 2000 counts for applied amplitudes of 100 mV and higher, while the measurement done with C1 saturates much more slowly and reaches 2000 counts only at roughly double the amplitude. Several factors could contribute to this difference. It is possible that the rf-field polarization is one of the causes: Since the polarization is rotating in opposite directions for C1 and C2 (see Fig. 4.11), it would be possible that C2 applies a higher effective field for the same field amplitude. However, it is also possible that C2 applied an overall higher field amplitude for the same applied voltage. For better understanding of the difference between the two coils in the future, monitoring of the field amplitudes during operation is necessary.

4.5 Conclusion

In the course of this work the dSF filling method has been advanced from a proof-of-principle stage to the used filling procedure for acquiring scientific data with τ SPECT. Two central issues were addressed. First, the difficulty of reliably identifying the correct spin-flip frequency was resolved by the installation of an NMR magnetometer. Secondly, the low spin-flip efficiency has been brought to near saturation by a hardware upgrade to the spin flipper and by optimizing the field gradients. The dSF method has proven to fill a factor 1.94(5) more neutrons than the previous sSF method: a crucial increase in counting statistics.

Looking ahead, the dSF can be further improved by increasing the rf-field amplitude even more and thereby making the filling method more stable against field drifts. Additionally, equipping the spin flipper with an tunable matching circuit would allow us to adjust the spin-flipper-resonance frequency. This way we could compensate for changes to the resonance frequency during the cool down. Finally, implementing continuous monitoring of the rf-field amplitude would help with diagnostics of the system.

5

Monitor detector

5.1 Motivation

As mentioned in Sec. 2.2.2, bottle-type lifetime experiments like τ SPECT are sensitive to changes in the amount of initially trapped neutrons of each measurement cycle. These changes can be caused by fluctuations of the output of the UCN source. The output fluctuations can originate from variations of the incoming neutron flux, often produced by a reactor or a spallation target. Another cause can be changes of the efficiency of the process which converts those neutrons to UCNs. During the course of this thesis, τ SPECT was operated at two sources: the UCN source at beamport D of the research reactor TRIGA Mainz and at port West-1 of the UCN source at Paul Scherrer Institute (PSI). Both sources use a solid deuterium (sD_2) crystal in the conversion process. Both sources do not produce a continuous flow of incoming neutrons, but they are operated in a pulsed mode.

It has been shown that the yield of those sources is strongly influenced by the physical condition of that crystal [Rie22]. During operation, heat is deposited by neutrons and gamma rays into the crystal which changes the performance of the source with every pulse [Ang+18]. For example, a reduction of UCN output by 30% over the first 30 pulses has been observed for the source in Mainz [Kah+17] and a reduction of 50% over 63.5 h of operation has been reported for the source at PSI [Doo24]. A visualization of the output fluctuations is shown in Fig. 5.1.

The UCN flux at the entrance of the τ SPECT experiment has to be measured, to monitor those output fluctuations. For this purpose, I developed an in-beamline UCN detector as part of this thesis. This detector is referred to as the monitor detector. In this chapter I will present the detector's design and present the results of the characterization measurements of the monitor detector.

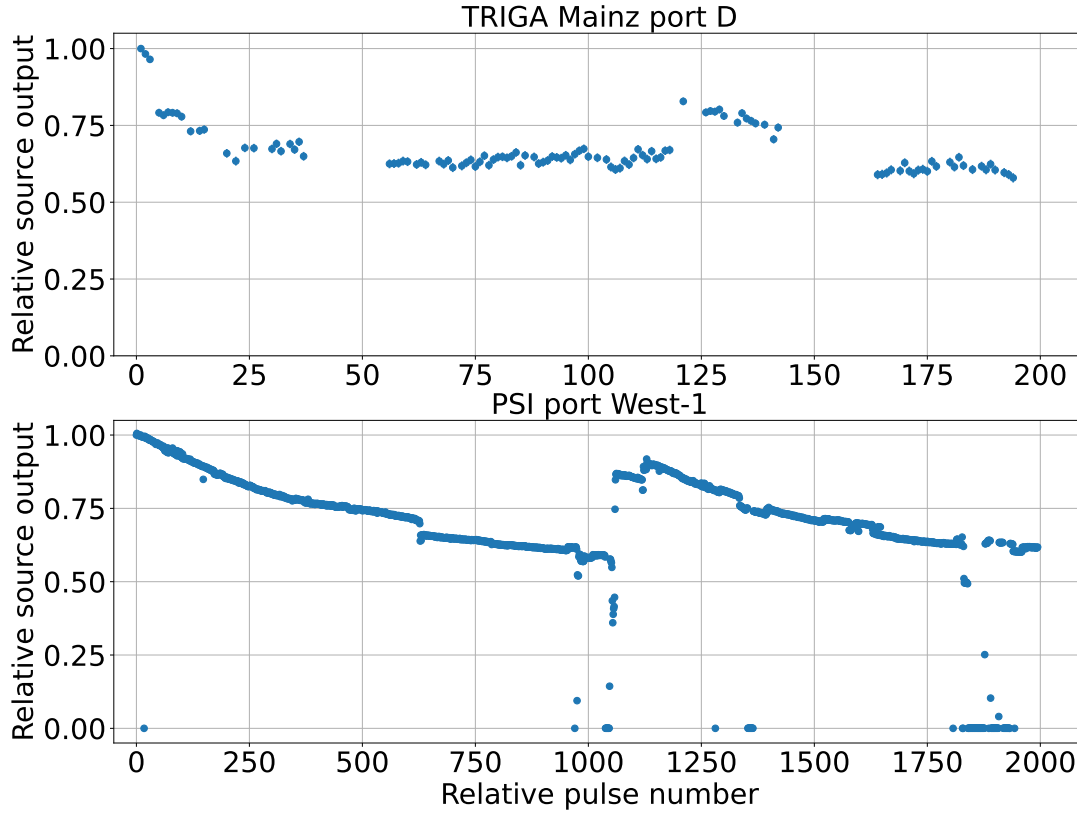


FIGURE 5.1: Visualization of the output fluctuations of the UCN source at the research reactor TRIGA Mainz port D (top) and at port West-1 of the UCN source at PSI (bottom). The measured source outputs have been rescaled to the first measurement. Error bars have been calculated assuming a Poisson distribution, but are mostly covered by the markers. Both data sets cover about a week of operation.

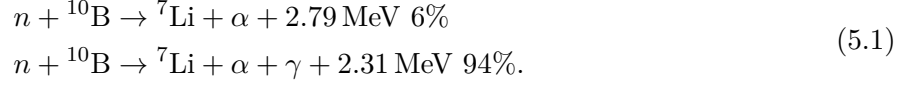
5.2 Monitor-detector hardware

Throughout this thesis I developed two versions of the monitor detector based on the same detection principle. The second version is an upgrade of the first one. I will first give an introduction into the theoretical background of UCN detection, then discuss the general detection scheme and the hardware components of both versions.

5.2.1 Ultra-cold neutron detection

Before discussing the detector itself, it is helpful to introduce some basic principles of UCN detection. Direct detection of electrically-neutral particles, like the neutron, is difficult. Therefore, neutrons are typically converted into charged particles, which are then detected. This works as follows: Neutron-capture reactions produce charged particles or γ -rays, which then can be detected using ionization chambers or scintillation detectors. Some examples of used capture reactions are:

$^3\text{He}(n,p)^3\text{H}$ [Mor+09], $^6\text{Li}(n,\alpha)^3\text{H}$ [Jak+09] and $^{10}\text{B}(n,\alpha)^7\text{Li}$ [Aul+24a]. We use ^{10}B for the monitor detector, because it is affordable, chemically stable, does not require an entrance window, and by mixing it with ^{11}B one can reach low or even zero Fermi potential for the detector's surface. The $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction has two branches with different probabilities:



The neutron-capture reaction is destructive and the energy released by this process is at least 13 orders of magnitude larger than the kinetic energy of the UCN. So the reconstruction of the UCNs kinetic energy by measuring the energy of the products is not feasible. The efficiency of a neutron detector depends on the probability of a neutron being absorbed while traversing the converter material. In an idealized scenario, in which absorption is the only interaction between UCNs and the material, the intensity of a UCN beam traveling through a material can be written as [Ste20, p. 91]

$$I(l) = I_0 \exp(-N_m \sigma_{UCN} \cdot l) = I_0 \exp(-\frac{l}{l_a}). \quad (5.2)$$

Here, l is the distance traveled through the medium, N_m is the number density of the material, and σ_{UCN} is the absorption cross-section of the material for UCNs. The expression can also be written using the UCN absorption mean free path l_a . Neglecting resonance effects, the neutron absorption cross-section is, to first order, proportional to the inverse of the neutron's velocity v_N [Sea82], [Gol91, p. 24], [Ign90, p. 306]

$$\sigma_N \propto \frac{1}{v_N}. \quad (5.3)$$

This means that the absorption mean free path for UCNs can be expressed as [Wan+15]

$$l_a = \frac{1}{N_m \sigma_{UCN}} = \frac{v_{UCN}}{N_m \sigma_{th} v_{th}} = \tau_a \cdot v_{UCN}. \quad (5.4)$$

Here σ_{th} is the thermal neutron absorption cross-section in the material, v_{th} is the velocity of a thermal neutron, and τ_a is the neutron absorption time. Using the number density $N_B = 0.22 \text{ mol cm}^{-3}$ of ^{10}B , the absorption cross-section $\sigma_{th} = 3835 \text{ barn}$ of ^{10}B [Sea92], and $v_{th} = 2200 \text{ m s}^{-1}$ the velocity of thermal neutrons [Sea92], one finds $\tau_a = 9 \text{ ns}$. For a neutron with a kinetic energy of 100 neV , this corresponds to l_a of 40 nm . Calculated values of l_a for several UCN energies are presented in Table 5.1.

UCN kinetic energy neV	UCN velocity m/s	l_a nm
50	3.1	28
100	4.4	40
200	6.2	56
250	6.9	63
300	7.6	69

TABLE 5.1: Calculated values of UCN velocities and the absorption mean free path l_a in ^{10}B for different UCN energies.

If we again assume an idealized system, where absorption is the only interaction between the UCNs and the material, more than 95% of the UCNs are captured after $3l_a$. This can be used as a benchmark when choosing the thickness of the boron layer. Additionally, one has to consider that the lithium-ion and the α -particle must be able to pass through the boron layer to be detected. Therefore, the ranges of the charged particles in ^{10}B have to be considered. They have been

calculated in [Wan+14] using Stopping and Range of Ions in Matter code (SRIM) [Ziend]. The results are in a range of $1.8\mu\text{m}$ (for the lower energy ^7Li) to $4.4\mu\text{m}$ (for the higher energy α -particle). The charged particles can be detected using an ionization chamber or a scintillator and a photodetector. We are using the latter option, converting the light of a thin $\text{ZnS}(\text{Ag})$ scintillator into an electrical signal, which then can be amplified.

5.2.2 UCN detection scheme of the monitor detector

After introducing the relevant fundamentals, I will now describe the detection scheme of the monitor detector. In Fig. 5.2 the detection principle is summarized. The monitor detector uses a boron coated¹ $\text{ZnS}(\text{Ag})$ scintillator to convert the UCNs into an optical signal. This signal is detected using two silicon photo multipliers (SiPMs), which are placed on a UV fused silica prism so that light can reach both SiPMs. By using two separate SiPMs it is possible to use coincidences between their signals in event discrimination. This way, the detector is less affected by background. The details of the readout logic are covered in Sec. 5.2.3.

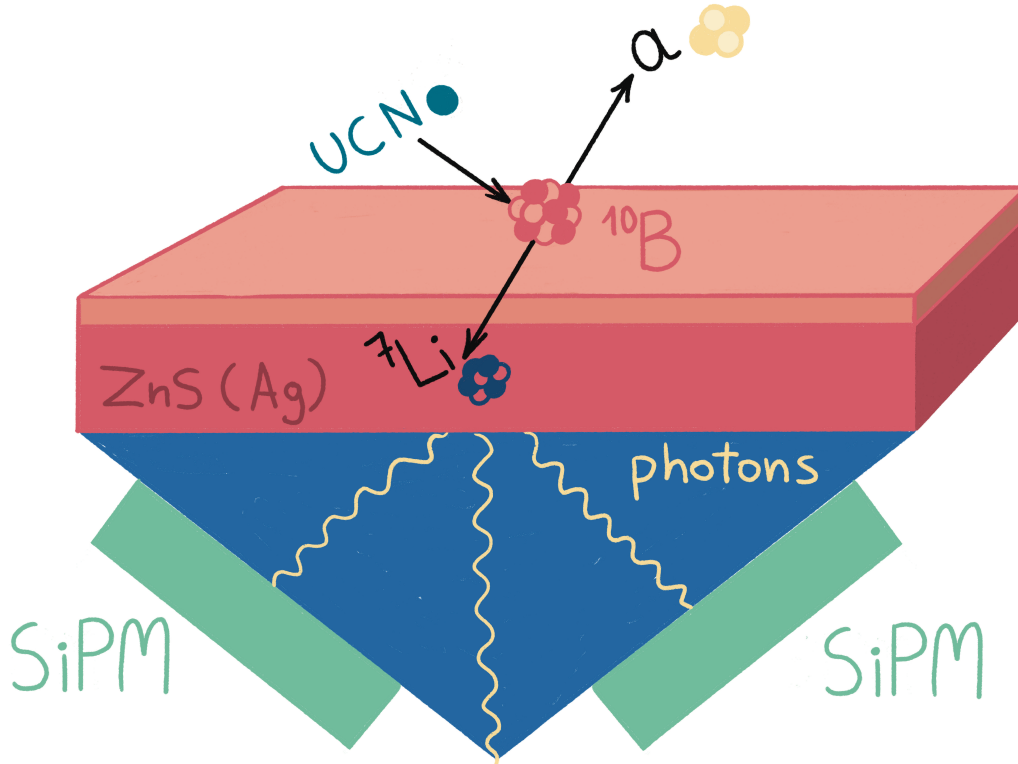


FIGURE 5.2: Schematic of the monitor detector's neutron-detection principle. The detector consists out of a 200 nm thick ^{10}B layer on top of a $7.9(6)\mu\text{m}$ thick $\text{ZnS}(\text{Ag})$ scintillator. When a UCN gets absorbed, the neutron-capture reaction produces an α -particle and a ^7Li -ion. One of those charged particles hits the scintillator and causes it to emit light. The scintillator is glued, using a UV-cured optical adhesive, on top of a rectangular UV fused silica prism, which transmits the photons to two SiPMs. Illustration by Dimitra Kanta.

¹The coating was done by CDT CASCADE Detector Technologies GmbH, <https://n-cdt.com/>

The available thickness of boron coating for this work was 200 nm. For UCNs with energies below 250 neV and therefore the full energy range of UCNs storable in τ SPECT, l_a is smaller than 200 nm (see Table 5.1). For neutrons with a kinetic energy of 350 neV the ideal absorption probability is still 93%. Note that the Fermi potential of ^{10}B has a non-zero real part $V_F = -3.4$ neV, which would lead to UCNs being reflected at the detectors surface. To reach a Fermi potential of $V_F \approx 0$, the ^{10}B layer contains small amounts ($<4\%$)² of ^{11}B and therefore l_a will be slightly ($<4\%$) longer than for pure ^{10}B . The effect of the additional ^{11}B on the absorption probability is less than 1%. The boron layer is still significantly shorter than the ranges of the charged particles in boron, see Sec. 5.2.1. In conclusion, the boron-layer thickness of 200 nm is well suited for the purposes of this work. The thickness of the scintillator is $7.9(6) \mu\text{m}^3$ and it is coated on a 0.25 mm thick polyester sheet. ZnS(Ag) has a relatively high light yield of about 49000 photons per MeV (given as 30% higher than NaI:TI in [Kno10]), the peak intensity is at $\lambda_{peak} = 450$ nm and the decay constant is 200 ns [Elj21a], which is rather long compared to other typical scintillators. The polyester sheet is glued onto the prism using the Norland optical adhesive 68 (NOA68) [Nornd]. The UV fused silica prism has both a side length and thickness of 10.0(2) mm [Thonda]. The optical contact between the SiPMs and the prism was initially established by a standard silicone high-viscosity vacuum grease. In version 2 of the detector, it was replaced by the EJ-550 optical grease by Eljen Technology [Elj21c] to ensure optimal coupling. The photosensors are the MICROFC-60035-SMT SiPM Sensors by onsemiTM with an active area of 6 mm×6 mm [Sem22]. The optical components have been chosen to reduce losses due to absorption or reflection.

Fig. 5.3 shows the ZnS(Ag) scintillator emission spectrum (red), the SiPM photon detection efficiency (PDE) at 2.5 V overvoltage and the transmission of both the UV fused silica (green) and the UV optical adhesive (blue). The transmission of the UV fused silica is given for a thickness of 10 mm and the optical grease's transmission for a thickness of 0.1 mm. Both the transmissions of the fused silica and the one of the UV adhesive are above 90% across the whole scintillator emission spectrum. The optical grease's transmission was only given for wavelengths below 500 nm for the range of 320 nm to 500 nm it is above 95% . The combined transmission at 450 nm is above 88%. The SiPM PDE reaches its maximum at about 415 nm and remains above 20% for most of the emission spectrum. Thus, the SiPMs are well suited to detect light in the range of the scintillator emission spectrum.

Optical element	Refractive index
EJ-600 scintillator [Elj21b]	2.356
Polyester sheet[Bil84]	1.52-1.57
NOA 68 Optical adhesive [Nornd]	1.54
UV fused silica (at 450 nm)[Thonda]	1.47
EJ-550 Optical grease [Elj21c]	1.46
SiPM(at 420 nm) [Sem22]	1.59

TABLE 5.2: Refractive indices of the optical elements used in the monitor detector, sorted by their order in the lights path from scintillator to SiPM. If a wavelength-specific value is given by the source, the wavelength is noted. The refractive index of the polyester foil was not given by the manufacturer, therefore a literature value for polyester was taken.

The refractive indices of the optical components can be found in Table 5.2. They have been sorted by the position of the optical element in the light's path from scintillator to SiPM. The relevant

²The ^{10}B enrichment is determined by the base material used for coating and is guaranteed by CDT CASCADE Detector Technologies GmbH to be $>96\%$

³The thickness has been calculated using the surface density of $\rho_{sf} = 3.25(25)\text{mg cm}^{-2}$ [Elj21a] and the density of the scintillator $\rho = 4.09\text{g cm}^{-3}$ [Elj21b], both given by the manufacturer.

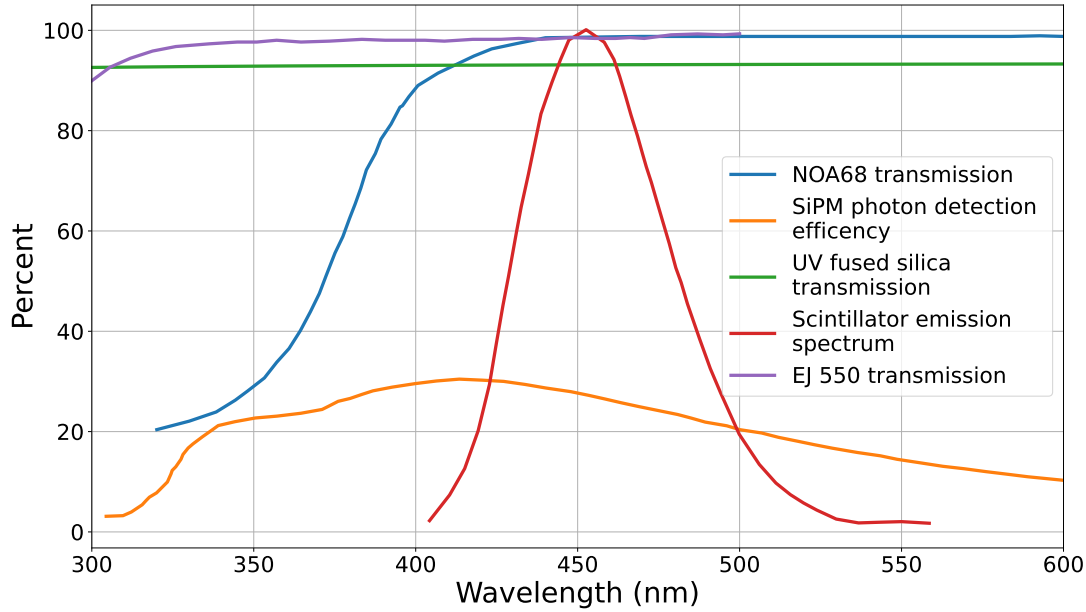


FIGURE 5.3: Comparison of the ZnS(Ag) scintillator's emission spectrum (red) [Elj21a], the SiPM photon detection efficiency (PDE) at 2.5 V overvoltage as a function of wavelength [Sem22] (orange), and the transmission spectra of the UV fused silica (green)[Thondb], the UV optical adhesive (blue) [Nornd], and the optical grease [Elj21c]. Data for the plot was taken from the cited data sheets. The PDE as function of wavelength was only given for the MICROFC-30035-SMT sensor by the manufacturer. However, since that sensor has the same micro-cell size as the used SiPM, the PDE is expected to be the same. The transmission of the UV fused silica is given for a thickness of 10 mm and the optical grease's for a thickness of 0.1 mm. One can see that the transmissions of the fused silica and the UV glue are above 90% for the whole range of the scintillator's emission spectrum. The optical grease's transmission is above 95% from 320 nm to 500 nm. The SiPM PDE spectrum overlaps well with the emission spectrum. It reaches its maximum at about 415 nm and stays above 20% for the majority of the emission spectrum.

index of refraction for the choice of optical components is the one of polyester, while the refractive index of the scintillator is given for the sake of completeness.

As we learned in Sec. 5.2.1 UCN detection is destructive, therefore the monitor detector should only count a small fraction of the neutrons during the filling of τ SPECT to not significantly reduce the amount of filled neutrons. This is realized by making it relatively unlikely for neutrons to reach the detector. The top of Fig. 5.4 shows a cut view of the so called detector flange, which is built into the beamline and houses the optical components of the detector. The detector flange (dark grey)(1) is mounted in between two steel beamline pieces (black) (2, 3) by two connector rings (light grey) (4, 5). The beamline can be pumped to vacuum through the pumping port of the flange (6). The actual detection takes place in the top cavity. Only a small fractions of UCNs in the beamline will pass the 4 mm diameter aperture (7) and hit the ^{10}B coated scintillator (red) (8). The UV fused silica prism is shown in blue, the SiPMs (9) in green. The SiPMs and the prism are fixed in the cavity using a mount (10). The aperture size can be changed by replacing the aperture insert. More detailed technical drawings of the flange are presented in Fig. A.1 in appendix A.1.

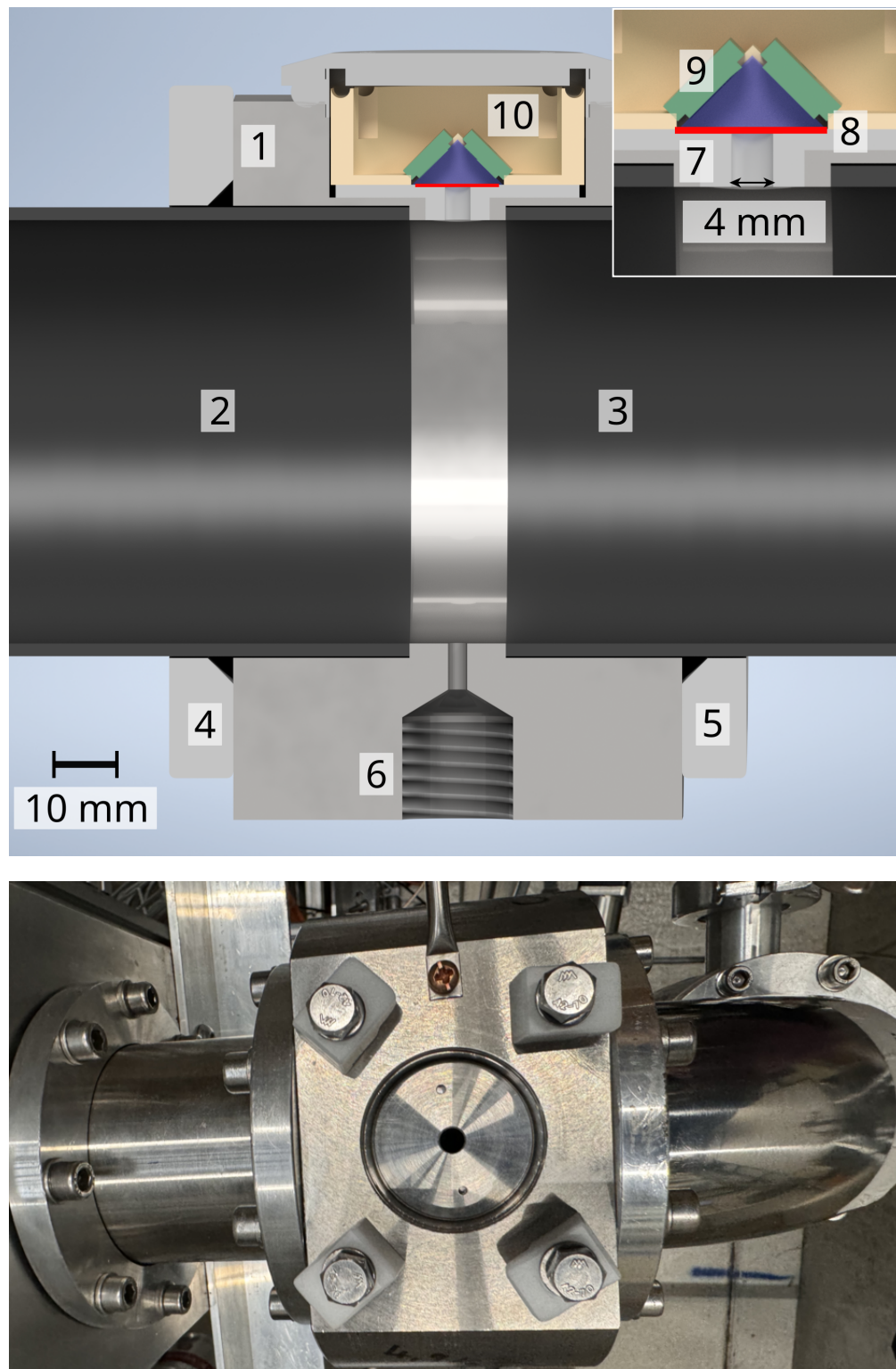


FIGURE 5.4: Top: Cut view of the detector flange when built into the beamline. The detector flange (dark grey) (1) is mounted in between two stainless steel beamline pieces (black) (2, 3) by two connector rings (light grey) (4, 5). The beamline can be pumped to vacuum through the pumping port of the flange (6). A small fraction of UCNs will go through the 4 mm diameter aperture (light grey) (7) and hit the ^{10}B coated scintillator (red) (8) glued to the UV fused silica prism (blue). The produced light is detected using SiPMs (green) (9). The SiPMs and the prism are fixed in the cavity using a mount (10). The aperture size can be changed by replacing the aperture insert. The top of the cavity can be sealed using standard KF 40 components. Bottom: Monitor flange build into the beamline of a test setup.

A photograph of the 3D-printed mounting structure is shown in Fig. 5.5. The left image displays the bottom side, which faces the UCNS, with the boron covered scintillator, while the right image shows the top side with the SiPM mounts and the cabling used in version 1. The SiPMs are soldered onto the backside of the printed circuit boards (PCBs), which are screwed to the mount. In version 1, the SiPM connections are routed to a feedthrough using twisted pair wires, whereas in version 2 RG318 coaxial cables are used. The mount is made from polylactide (PLA). For future versions, a material more suitable for vacuum applications, such as polyether ether ketone (PEEK), should be used to reduce outgassing. In detector version 1 the mounting structure is fixed in the cavity using an o-ring positioned between the mount and the KF 40 sub-D feedthrough. In version 2 the mount is glued inside the cavity.

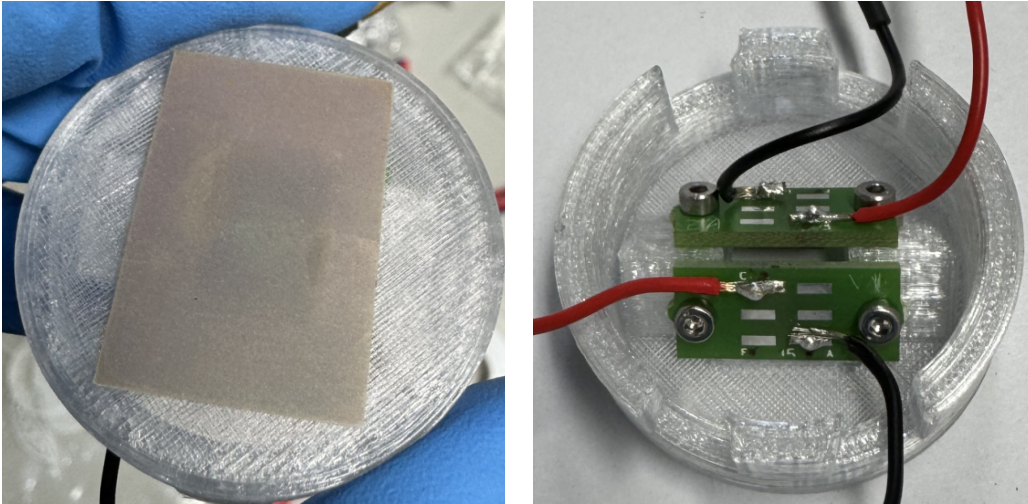


FIGURE 5.5: Left: bottom view of SiPM mount. One can see the boron covered scintillator, Right: Top view of the mount (without prism and scintillator). In version 1 the SiPM signals are fed to a feedthrough using twisted pair wires (not twisted in picture yet) in version 2 RG318 coaxial cables are used.

5.2.3 Monitor-detector electronics

In the previous section, the conversion of a UCN to an optical signal has been discussed. This section covers the subsequent steps: the conversion of the optical signal to an electric one, the signal processing, and the event discrimination, all of which are performed by the detector's readout electronics. While the overall principle is the same for both designs of the detector, there are significant differences in the hardware layout and components of the two versions of the electronics. For this reason, I will first discuss some general concepts that both have in common and then give a more detailed description of each version.

Electronics concept

Both versions of the electronics are controlled by the TeensyTM4.1⁴, a micro-controller board with a fast CPU and a large number of digital and analog inputs and outputs. In Sec. 5.2.2 I discussed the conversion of a neutron into an optical signal. I now continue the description with the detection of

⁴TeensyTM4.1 micro-controller by PJRC.COM, LLC., <https://www.pjrc.com/store/teensy41.html>

the optical signal using SiPMs. SiPMs consists of many single-photon avalanche diodes (SPADs). SPADs are p-n or n-p junctions operated at a reverse bias voltage larger than the breakdown voltage V_{br} . This mode of operation is called Geiger mode. When a photon is absorbed in the sensitive volume, it creates an electron-hole pair. These charge carriers experience a strong local electric field, due to the applied voltage, and are accelerated, creating an avalanche, strongly amplifying the initial signal to a macroscopic current (Geiger discharge). During the discharge, it is not possible to detect further photons. In order to reduce the deadtime of the SPAD, the current is stopped by a quenching resistor in series to the diode (passive quenching). In an SiPM each SPAD has its own quenching resistor, and the unit of both of them together is referred to as a “microcell”. Each microcell can fire individually, leading to a proportionality between the incoming photon flux and the generated current [Sem23].

In contrast, to a photomultiplier tube, SiPMs can be operated in magnetic fields and do not need high supply voltages. The main noise source in SiPMs are dark counts, which are caused by a thermal excitation of an electron-hole pair causing a microcell to fire. To quantify the dark counts, the dark-count rate is quoted or, to quantify them in a continuous way, the dark current. Both versions of the monitor detector use the MICROFC-60035-SMT sensor. Some important parameters of that sensor type are listed in Table 5.3. The SiPMs need to be supplied with a voltage between 25.2 V and 29.7 V. The SiPMs’ gain and photon detection efficiency both depend on the overvoltage. For version 2 of the detector, SiPMs have been selected such that their breakdown voltages differ as little as possible. The breakdown voltages have been measured by Konrad Franz to be 24.787(2) V and 24.784(2) V at 30 °C. To be able to control the gain and the photon detection efficiency, the bias voltage has to be adjustable.

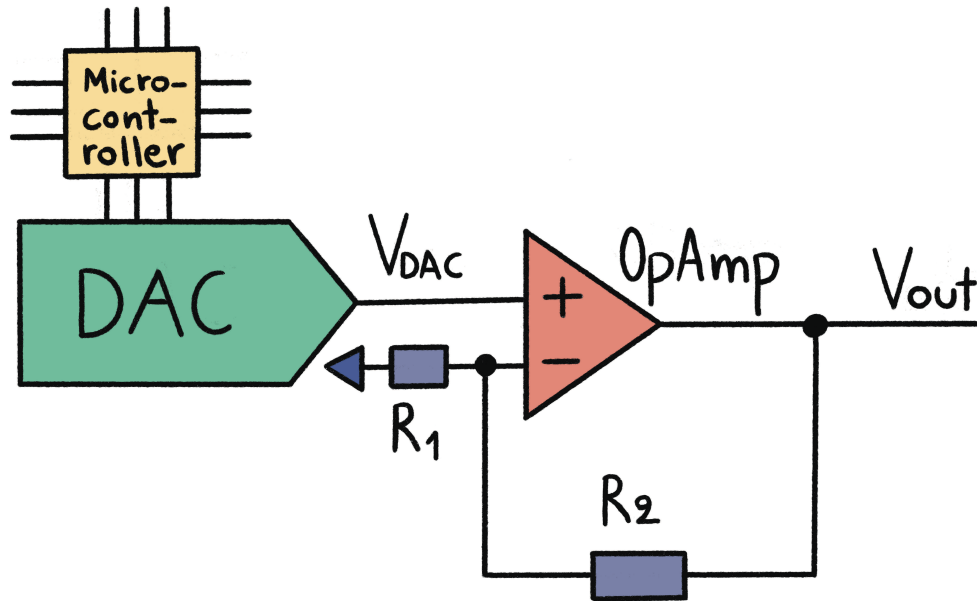


FIGURE 5.6: Schematic of the adjustable voltage supply used in the monitor-detector electronics. The output voltage (V_{DAC}) of a digital-to-analog converter (DAC) is set using the micro-controller through a Serial Peripheral Interface (SPI) bus. V_{DAC} is then amplified by a constant factor to V_{out} using an operational amplifier (OpAmp) as a non-inverting amplifier. V_{out} is used to drive the load. An example for a load is an SiPM. Illustration by Dimitra Kanta.

Parameter	Value
Number of microcells	18980
Breakdown voltage(V_{br})	24.2 V-24.7 V
Temperature dependence of V_{br}	21.5 mV °C ⁻¹
Overvoltage range	1 V- 5 V
Dark-count rate at 2.5V overvoltage	1200 kHz
Dark current at 2.5V overvoltage	618 nA
Gain at 2.5V overvoltage	3×10 ⁶
Temperature dependence of the gain (21 °C)	−0.8 % °C ⁻¹

TABLE 5.3: Relevant properties of the MICROFC-60035-SMT SiPM taken from [Sem22]

In the monitor electronics, such adjustable voltage supplies are achieved using the circuit shown in Fig. 5.6. The output voltage of a digital to analog converter (DAC) V_{DAC} is set by the micro-controller using a Serial Peripheral Interface (SPI) bus. V_{DAC} is then amplified to V_{out} using an operational amplifier (OpAmp) as a non-inverting amplifier. V_{out} is given by

$$V_{out} = V_{DAC} \cdot \left(1 + \frac{R_2}{R_1}\right). \quad (5.5)$$

Here R_1 and R_2 are the resistances of the resistors used in the circuit. V_{out} is then used to supply a load, for example an SiPM.

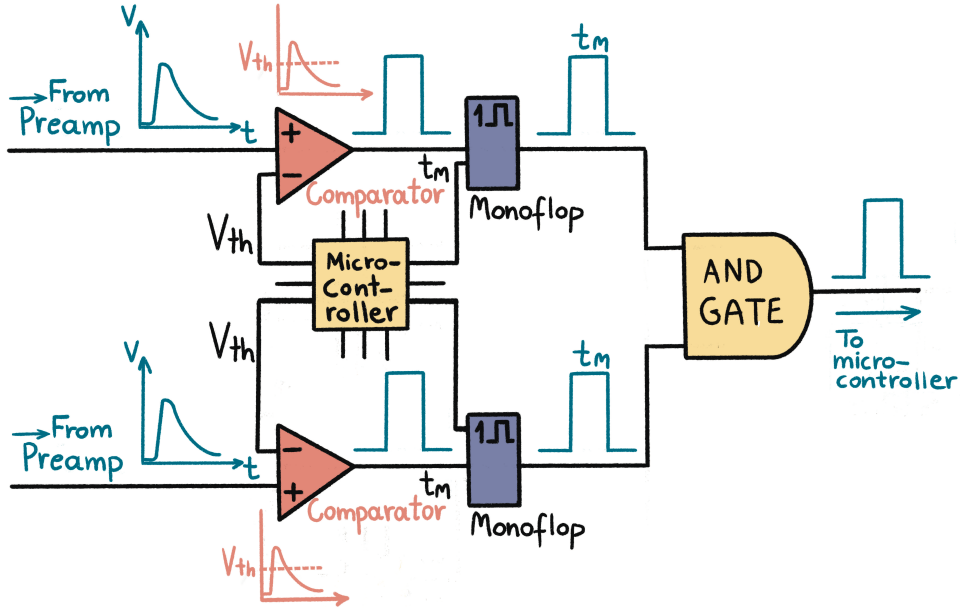


FIGURE 5.7: Simplified schematic of the coincidence-logic circuit. The amplified SiPM signals are each fed into the non-inverting input of a comparator. If the signal height exceeds the threshold voltage V_{th} , set by the micro-controller, the comparator gives out a logic high. The comparator output is fed into a monostable multivibrator, which gives out a well-defined pulse of the duration t_M . The outputs of both monostable multivibrators are fed into an AND gate. This way the AND gate will only give out a high, if the threshold voltage was surpassed in both comparators within t_M . These events are counted using the micro-controller. Illustration by Dimitra Kanta.

The SiPM signal is subsequently amplified before event detection. To suppress electronic noise being falsely recorded as an event, a hardware-based coincidence logic is part of the event identification. Fig. 5.7 shows a schematic drawing of the coincidence-logic circuit. The two amplified SiPM signals are fed into the non-inverting inputs of two comparators. If the signal height exceeds the threshold voltage V_{th} , set by the micro-controller, the comparator gives out a logic high. The comparator output is fed into a monostable multivibrator, which gives out a well-defined pulse of the duration t_M . The outputs of both monostable multivibrators are fed into an AND gate. This way, the AND gate will only give out a high, if the threshold voltage was surpassed in both comparators within t_M . Behind the AND gate is a third monostable multivibrator (not illustrated here) to give the output of the AND gate a well defined shape. These events are counted using the micro-controller.

Version 1 electronics prototype

Version 1 of the detector electronics was supplied by a single 6 V DC power supply. The electronics

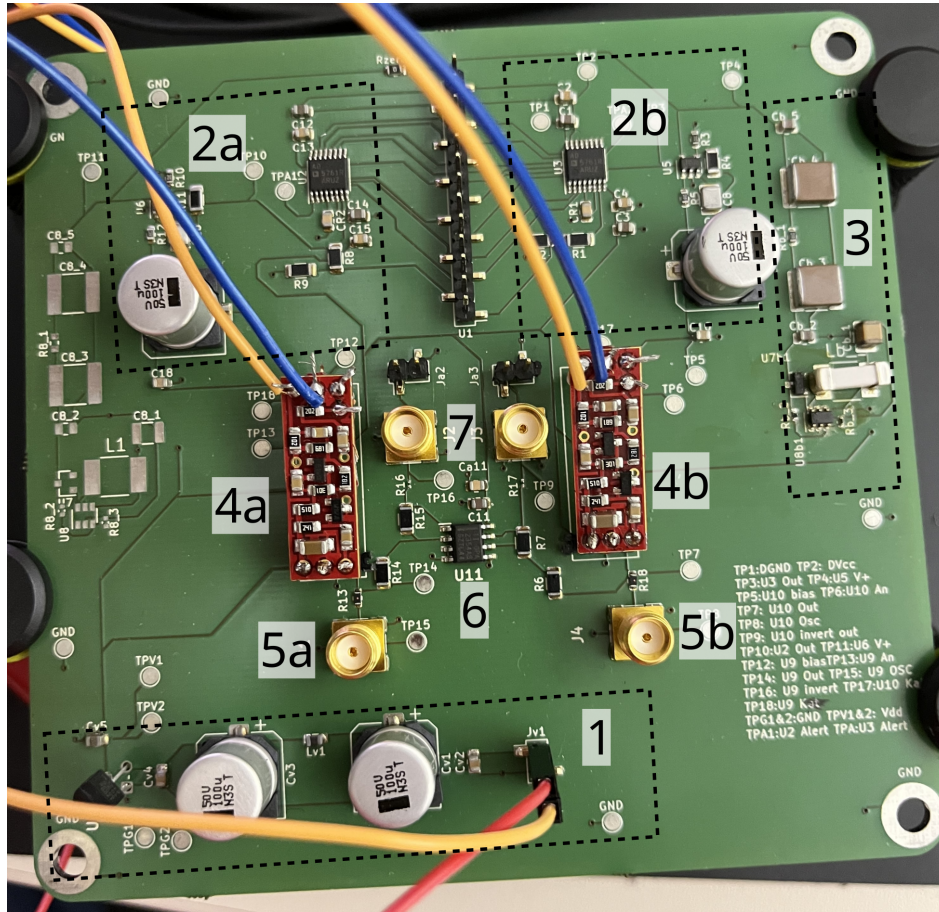


FIGURE 5.8: Picture of the amplification board. The 5 V supply voltage is produced from an external voltage using a low-dropout voltage converter and an LC-lowpass filter (1). The adjustable SiPM bias voltages are provided by non-inverting amplifier circuits with 16-bit DACs as references (2a, 2b). The necessary 30 V are produced on board by a DC-DC boost converter (3). The SiPM output is amplified by the SiPM preamplifiers (4a, 4b), which invert the signal, which can be monitored using the monitoring outputs (5a, 5b). The signal is then inverted again by a second inverting amplifier (6) producing the signal used for event detection. This signal can be accessed through the signal outputs (7).

consist of two separate $110\text{ mm} \times 114\text{ mm}$ PCBs: one supplying the SiPMs and amplifying the SiPM signal and one containing the coincidence circuit. The first PCB is referred to as the amplification board and the second PCB is referred to as the coincidence board. Each board converts the supplied 6 V to a stable 5 V supply voltage using an LC-lowpass filter and the MCP1700-5002E/TO low-dropout voltage regulator [Mic20]. The micro-controller is powered through its USB connection to the control PC. A picture of the amplification board is shown in Fig. 5.8. The low-dropout voltage converter and the LC-lowpass filter are marked by (1). The adjustable SiPM bias voltages are provided by the non-inverting amplifier circuits (2a, 2b) discussed in Fig. 5.6. These circuits use the AD5761R 16-Bit DAC [Ana14] and the LT 6015 rail-to-rail operational amplifier [Lin15]. The necessary 30 V supply voltage are produced on board by the Max5028 DC-DC boost converter (3), which can supply up to 4 mA [Max09]. A second boost converter can be installed if more current is needed. The SiPM output is amplified using advatech AMP-0611 [Advnd] SiPM preamplifiers (4a, 4b). Their output signal has negative polarity and can be monitored using the monitoring outputs (5a, 5b). This signal is then inverted by using the OPA2354 [Tex18a] operational amplifier as a unity-gain inverting amplifier (6). The inverted signals are used for event detection. They can be accessed through the signal outputs (7).

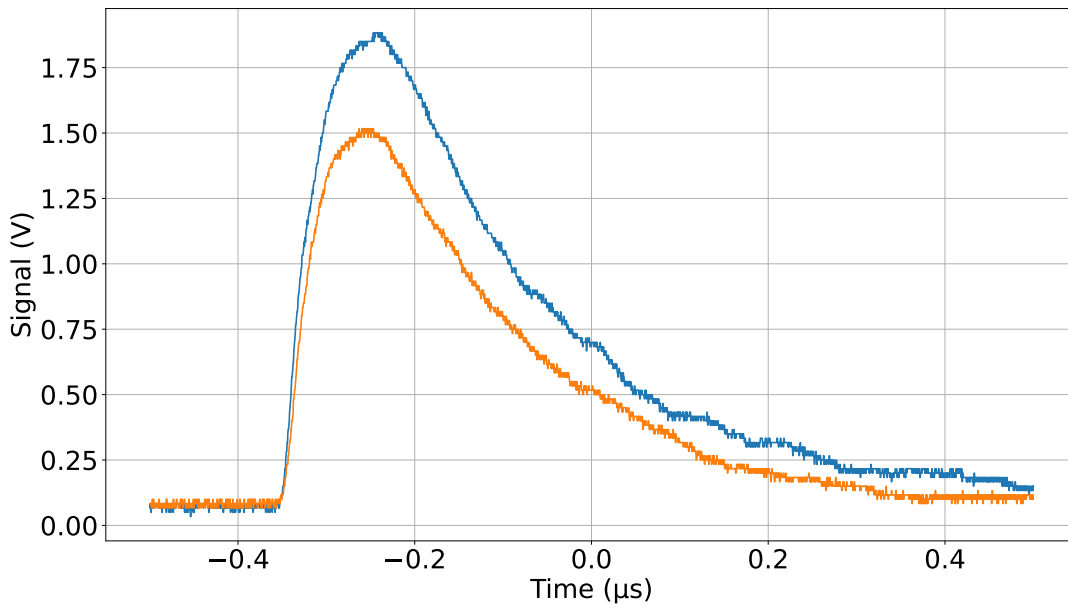


FIGURE 5.9: Signal of an α -particle from an ^{241}Am α -source. The signal was acquired using the optical part of the detector and the amplification board.

The amplification board was tested together with the optical part of the detector in a light tight enclosure. To simulate the charged particles, produced by the neutron-capture reaction, we used α -particles from an ^{241}Am source. The ^{241}Am was deposited by Dennis Renisch on top of a piece of uncoated scintillator, which replaced the boron coated scintillator during the test measurements. The signal output of the amplification board was connected to an oscilloscope to acquire the signals. Fig. 5.9 shows a signal acquired during those tests and a clear signal can be seen in both channels. This shows that the amplification board is working. Note that the kinetic energy of the α -particles is 5.4 MeV [Bé+10], which is more than a factor 3 higher than the kinetic energy of the charged particles produced by the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction. Consequently, the signal caused by a neutron is expected to be smaller by that factor.

A picture of the coincidence board is shown in Fig. 5.10. The board houses the event detection circuit discussed in Fig. 5.7. Two comparators (TLV3201, 2a, 2b), with a low propagation delay of 40 ns [Tex24a], were used. Their shared threshold is provided by an AD5761R 16-Bit DAC (3) [Ana14].

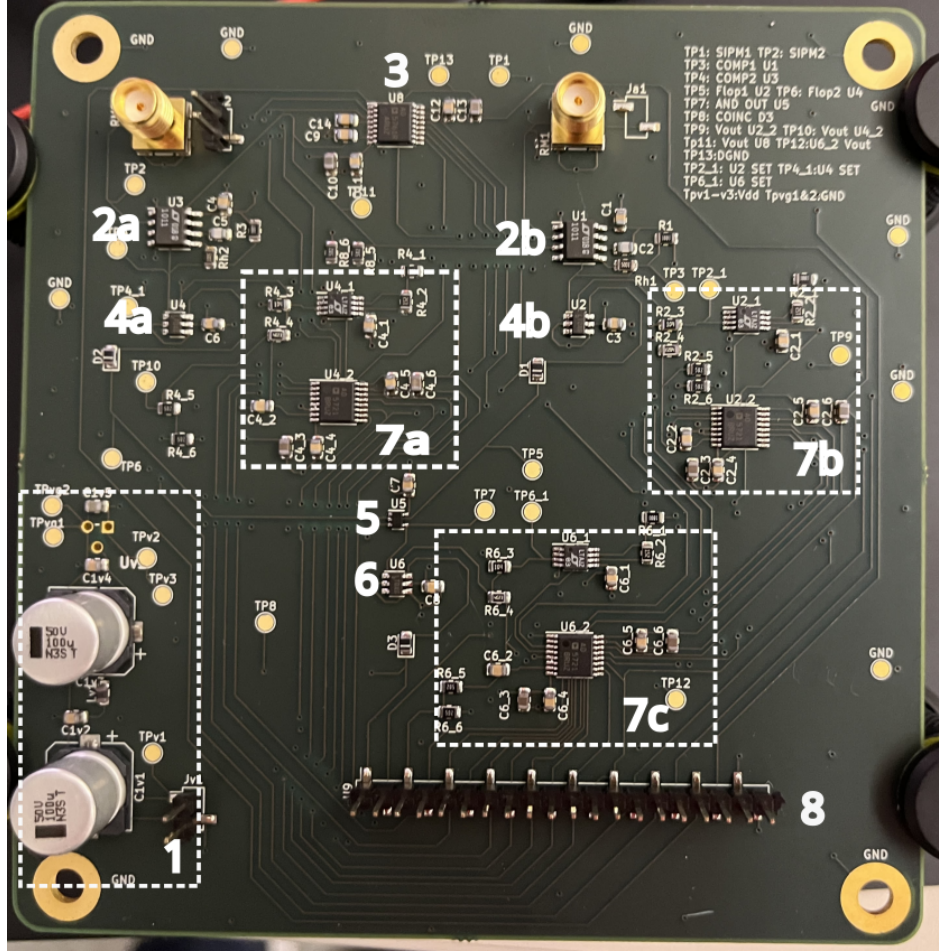


FIGURE 5.10: Picture of the coincidence board of monitor detector version 1. The 5 V supply voltage is produced from an external voltage using a low-dropout voltage converter and a LC-lowpass filter (1). The comparators (2a, 2b) produce a logic high if the signal exceeds the threshold voltage. The threshold voltage is set using a DAC (3). Monostable multivibrators (4a, 4b, 6) are used to produce pulses of well-defined lengths. The pulse widths are digitally controlled for each multivibrator by reference-voltage circuits (7a, 7b, 7c). The AND gate (5) produces an event signal if both comparators are triggered within the coincidence window. This event signal as well as the SPI bus are connected to the micro-controller via the pinheader line (8).

For the monostable multivibrators (4a, 4b, 6) the model LTC6993-1 was chosen. The pulse width is digitally controlled using the LTC6078 operational amplifier and a DAC, as recommended in the data sheet [ANA20]. Connections to the micro-controller are implemented via pin headers (8). Through those connections the micro-controller receives the event signal, can set the DACs, and can measure the used voltages. When testing the amplification board and the coincidence board simultaneously, it was discovered that the monitoring output of the amplification board does not give out a signal while the coincidence board is connected. The cause for this malfunction could not be clearly identified, but an impedance mismatch between the output and the amplifiers is considered a likely explanation. In version 2 of the electronics, a different amplifier model is used

and the monitoring output functions as intended. Both boards are put into an aluminum electrical housing. The connection to the SiPMs was realized using a shielded control line. In order to avoid electrical contact between the shield and the beamline, the shield was cut shortly before the KF feedthrough.



FIGURE 5.11: Housing of the monitor-detector version 1 electronics. Both PCBs and the micro-controller are inside the housing. The SiPMs are connected to the front using a sub-D type connector and a shielded multi-wire cable. 6 V supply voltage is connected at the back using banana plugs. The connection from the PC is done via a USB-cable. Ports at the side of the housing can be used to measure the SiPM supply voltage directly.

Detector electronics version 2

Version 1 of the monitor detector was a working prototype. Based on the experience gained with it, I developed an improved version of the electronics. Additionally, the move of τ SPECT from the research reactor TRIGA Mainz to the UCN Source at PSI in 2023, meant the detector would be operated in a less temperature-controlled environment. I addressed this issue by adding a temperature sensor to measure the detector's temperature during operation. Version 2 consists of the main electronics in a rack-mountable housing and the SiPM amplifiers in their own housing. This way the SiPM amplifiers can be kept close to the detector flange, while the main electronics can be mounted into a rack up to 10 m away.

The circuit of the SiPM amplifiers used in version 2 was designed at PSI by U. Greuter [Cat+14]. The amplifier PCBs were designed by Konrad Franz. One of the amplifier PCBs is shown in Fig. 5.12(a). The SiPM is connected to the input (1). The gain can be controlled by a potentiometer (2) and by the supply voltage at the supply input (3). The amplified signal can be accessed at the output (4). The SiPM bias voltage is connected at (5).

In order to reduce noise coupling into the signal before amplification, the connections from the SiPMs to the amplifiers were realized with coaxial cables. To fit the larger insulated coaxial feedthrough, the monitor-detector flange was extended with a KF40 I-piece. Fig. 5.12(b) shows the modified detector flange and the amplifier housing during measurements at PSI. The two amplifiers inside

their housing (2) are connected to the modified detector flange (1) via a 1 m coaxial cable. The supply inputs and outputs are connected to the main electronics with 10 m coaxial cables. A PT100 temperature sensor (3) has been mounted to the detector flange to monitor its temperature.

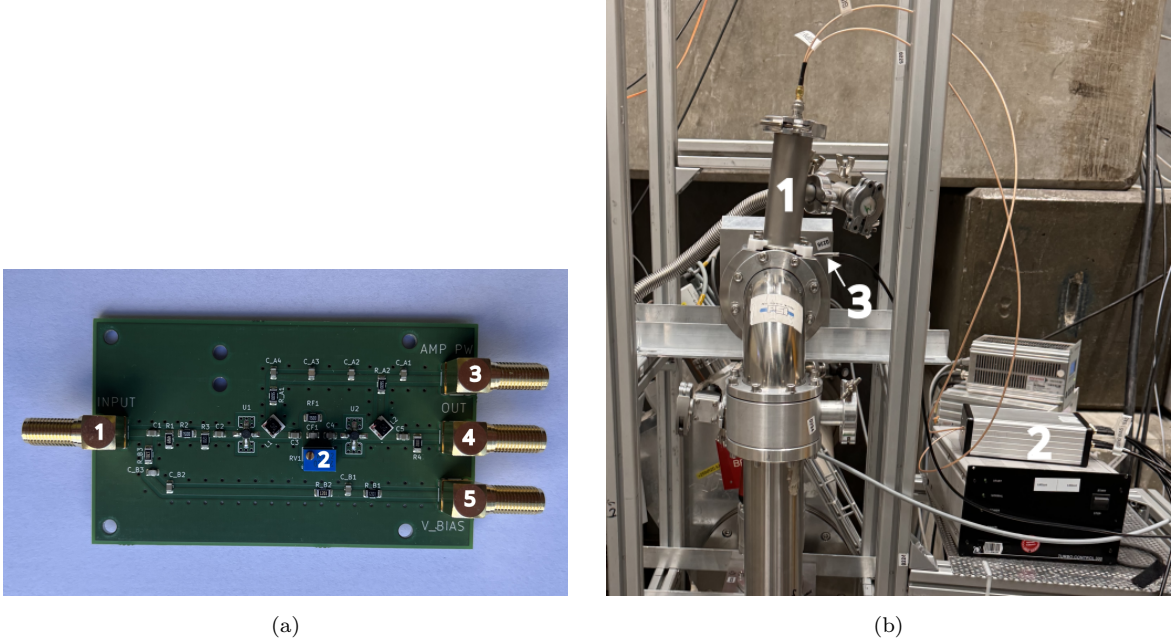


FIGURE 5.12: **(a)**: Amplifier board for the SiPM signal used in version 2 of the monitor-detector electronics. The SiPM is connected to the input (1). The gain can be controlled by a potentiometer (2) and by the supply voltage at the supply input (3). The amplified signal can be accessed at the output (4). The SiPM bias voltage is connected at (5). **(b)**: SiPM amplifiers setup at PSI. The two amplifiers inside their housing (2) are each connected to the modified detector flange (1) via a 1 m coaxial cable. The supply inputs and the outputs are connected to the main electronics via 10 m coaxial cables. A PT100 temperature sensor (3) has been mounted to the detector flange.

The main electronics are shown in Fig. 5.13. The housing is designed to fit in a standard 19-inch rack and it contains four interconnected Eurocard format PCBs. These boards are: The supply board (1), which provides the supply voltages for the amplifiers and the SiPMs, as well as the readout of the added temperature sensor, an updated version of the coincidence board (2), the micro-controller board (3), and the power board (4). The power board produces the supply voltages of -5 V , 5 V , 12 V , and 30 V from the standard AC line power. Circuit schematics of all boards can be found in A.2.

The micro-controller board is shown in Fig. 5.14. Connection to the back plane is realized via a 96-pin DIN 41612 connector (1). The micro-controller (2) is attached to the board via pinheaders. It can be reset by pressing the reset button (3). For communication through TCP/IP in the future, the micro-controller can be connected to Ethernet using the socket (4). For now, communication is still done by using a USB feedthrough in the front panel (not on board). The micro-controller is powered through the backplane connector and therefore the power wire of the USB cable was cut. External trigger signals can be applied to the two trigger inputs (5, 6). The two inputs are optically isolated from the micro-controller.

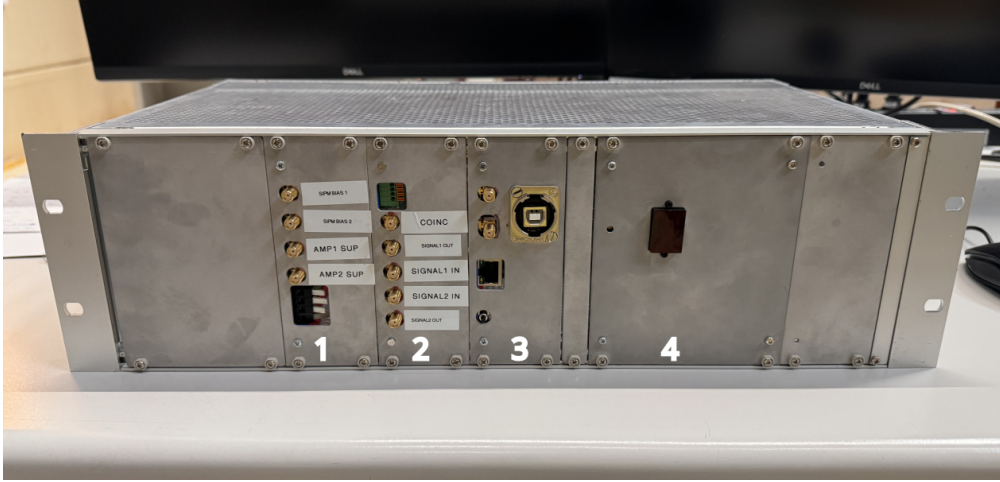


FIGURE 5.13: Main electronics of monitor-detector version 2. The housing is rack mountable in standard 19-inch racks. It contains four interconnected Eurocard-format PCBs which can be accessed through the front panels. These boards are the supply board (1), an updated version of the coincidence board (2), the micro-controller board (3), and the power board (4). The device is powered by connecting it to a standard power outlet.

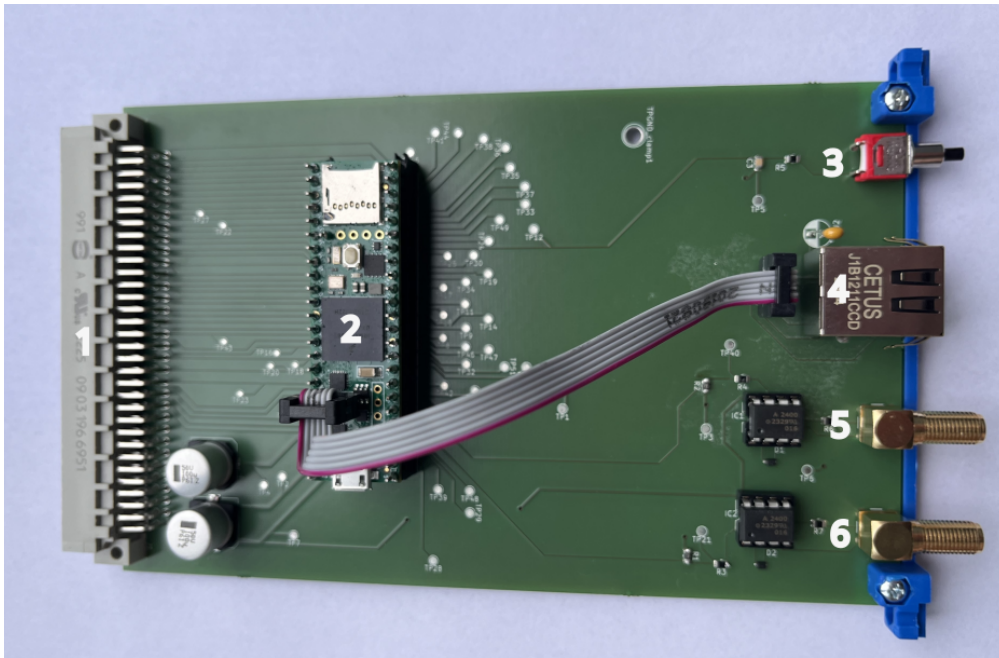


FIGURE 5.14: Picture of the micro-controller board. Connection to the back plane is realized via a 96-pin DIN 41612 connector (1). The micro-controller (2) is attached to the board via pinheaders. It can be reset by pressing the reset button (3). The micro-controller can be connected to Ethernet using the socket (4). External trigger signals can be applied to two trigger inputs (5, 6).

The supply board is shown in Fig. 5.15. The board contains a readout circuit⁵(2) for four-terminal

⁵This circuit is based on the SparkX Qwiic PT100 by SparkFun Electronics® and it is available at <https://www.sparkfun.com/qwiic-pt100-ads122c04.html> and licensed under CC BY-SA 4.0. The layout of the components has been adapted to the needs of the PCB. The connection ports for (I²C) have been replaced by connections to the DIN 41612 connector.

sensing of a PT100 temperature sensor, which can be connected to the latch terminal. The sensor is read out with the ADS122C04 24-bit ADC [Tex18b]. Communication with the micro-controller is realized through the Inter-Integrated Circuit (I²C) bus⁶. Supply voltages of up to 12 V for the SiPM amplifiers are generated by circuit (3) using the OPA992 operational amplifier [Tex24b]. Although designed to supply voltages up to 12 V in steps of 3 mV, during testing it was discovered that the maximum output voltage was 11.3 V. This limitation is likely caused by the high capacitive load, which the circuit has to drive, and can be fixed in a future iteration by switching to a line-driver circuit. This has no influence on the overall functionality of the electronics, aside from a slight reduction in amplifier gain ($\approx 10\%$). The SiPM bias voltages of up to 30 V and a current of up to 25 mA are provided by circuit (4) using the LT6015 operational amplifier [Lin15]. The voltages can be adjusted in steps of 7.3 mV. Both circuits are using the scheme discussed in Fig. 5.6.

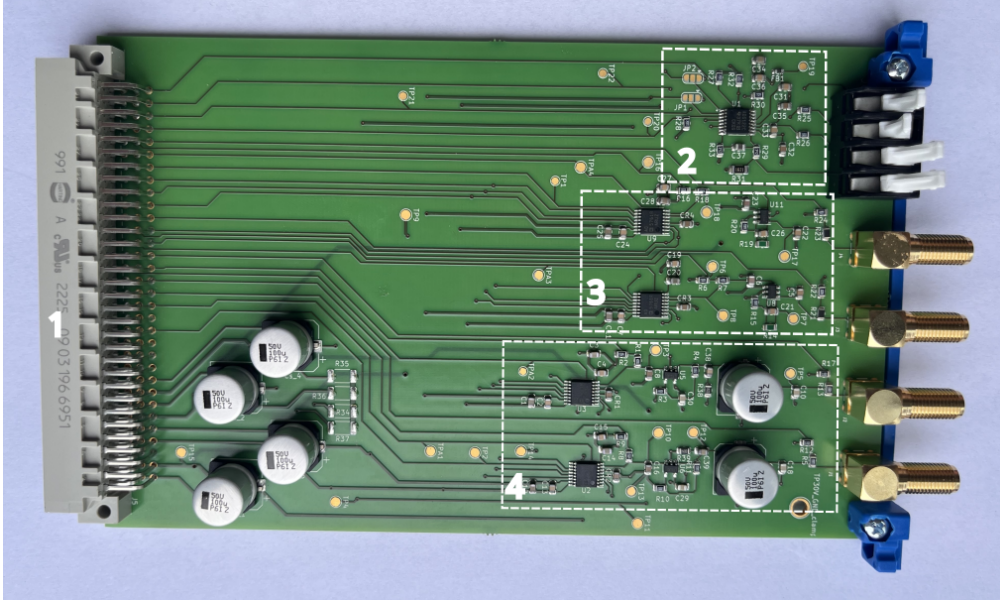


FIGURE 5.15: Picture of the supply board. Connection to the back plane is realized via a 96-pin DIN 41612 connector (1). A PT100 temperature sensor connected to the latch terminal is read out using a 24-bit ADC (2). The supply voltages for the SiPM amplifiers are produced by circuit (3) and the SiPM bias voltages are supplied by circuit (4). All DAC outputs and all supply voltages can be measured by the micro-controller over voltage dividers.

The coincidence board is shown in Fig. 5.16. The amplified SiPM signals are connected to the SMA connectors (3a, 3b). The signal is also inverted on this board using the AD8066 operational amplifier (6) [Ana19]. The inverted signals are sent to the comparators and can be accessed through the signal monitoring outputs (2a, 2b). Unlike in the previous version, each comparator now receives an individual threshold voltage from the 16-bit DACs (8a, 8b). In order to prevent output oscillations of the comparators, two resistors were added to the comparators leading to hysteresis of the threshold. This hysteresis reduces the voltage required to switch back to the low state by 5 mV. The threshold voltages are measured by the micro-controller over voltage dividers and can be accessed via the latch terminal (5). The digital controls of the monostable multivibrators' pulse width have been replaced by resistors, fixing the pulse width to 1 μ s. The event signal is produced by an AND gate (9) and can be accessed via the event monitoring output (4).

⁶Using the SparkFun ADS122C04 ADC Arduino Library, Copyright ©2020 SparkFun Electronics under the MIT License, available at https://github.com/sparkfun/SparkFun_ADS122C04_ADC_Arduino_Library/tree/main.

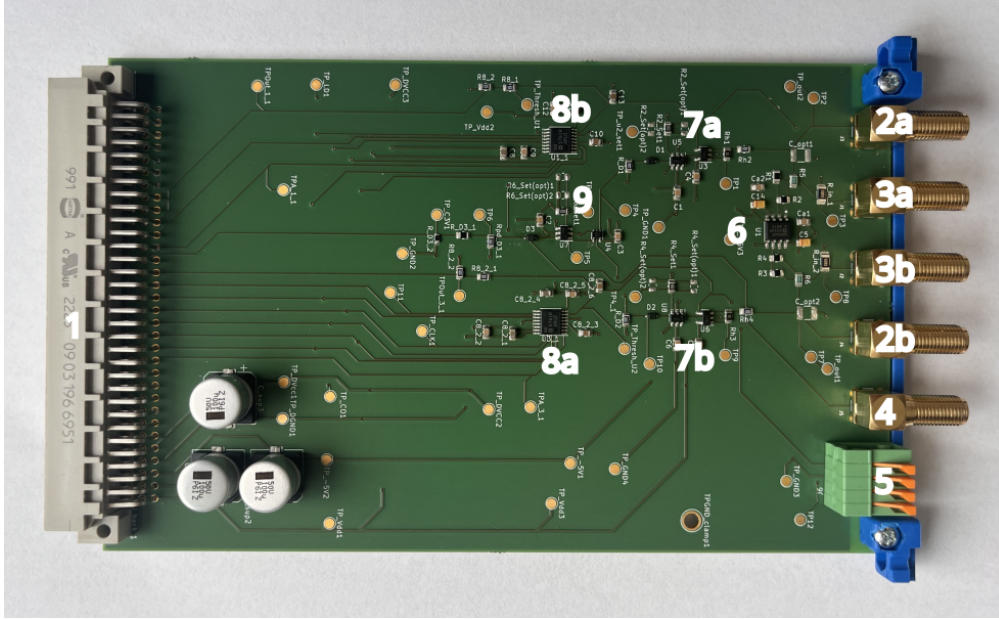


FIGURE 5.16: Picture of the version 2 coincidence board. All connections to the micro-controller boards and the power supply are done via a 96-pin DIN 41612 connector (1). The SMA connectors 3a and 3b are the inputs for the amplified SiPM signals. A operational amplifier (6) inverts the signal. The inverted signal can be accessed using the signal monitoring outputs (2a, 2b). Comparators (7a, 7b) compare the signal to their reference voltages provided by 16-bit DACs (8a, 8b). The reference voltages are measured by the micro-controller over a voltage divider and can be accessed manually through a latch terminal (5). The event signal is produced by an AND gate (9). The event signal can be accessed through the event monitoring output (4).

I tested the frequency response of the coincidence board by applying rectangular pulses to the board inputs using a Rigol DG1032Z function generator at various frequencies. The pulses had an amplitude of -150 mV (keep in mind that the incoming signal is inverted) and the detection threshold was set to 120 mV . Fig. 5.17 shows the results of those measurements. For frequencies up to 750 kHz , the coincidence board correctly identifies each pulse as an event. At frequencies of 1 MHz and above, only half of the pulses were detected. This behaviour was expected since the set coincidence-window length of $1\text{ }\mu\text{s}$ is longer than the period of the applied signal. When in operation at the PSI UCN source, the detector is experiencing peak count rates of about 45 kHz , which is certainly within the frequency range the board can handle.

I tested the main electronics and the new amplifiers in Mainz with: SiPMs of the same model, scintillator from the same batch as used in the optical part of the detector, and an ^{241}Am source. The event threshold was set to 114 mV (100 DAC units), the SiPM bias voltages were set to 28.5 V and the amplifier supply voltage was set to 10 V . The signal outputs of the amplifiers were connected to the main electronics using 10 m coaxial cables, to use the same cable length as used at PSI. The amplified SiPM signals were acquired with an oscilloscope, which was connected to the signal monitoring outputs of the coincidence board. The oscilloscope was triggered on the event monitoring output. Fig. 5.18 shows a signal acquired during those measurements. These signals indicated that the electronics were working as intended. Characterization of the detector can be found in Sec. 5.6.

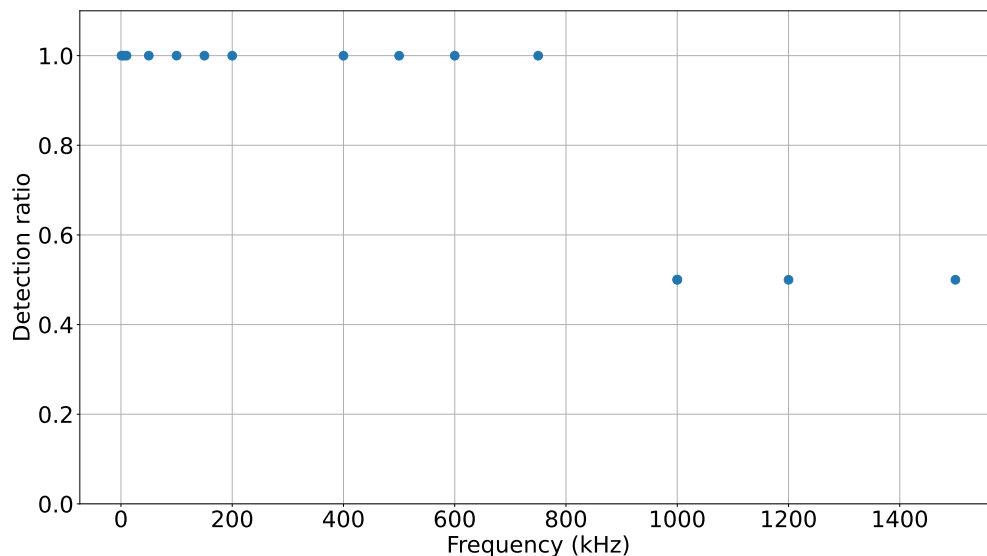


FIGURE 5.17: Response of the coincidence board to pulses applied with a function generator at different frequencies. Uncertainties on both frequency and detection ratio are smaller than the marker size. For frequencies up to 750 kHz the coincidence board correctly identifies each pulse as an event. At frequencies of 1 MHz and above only half of the pulses were detected.

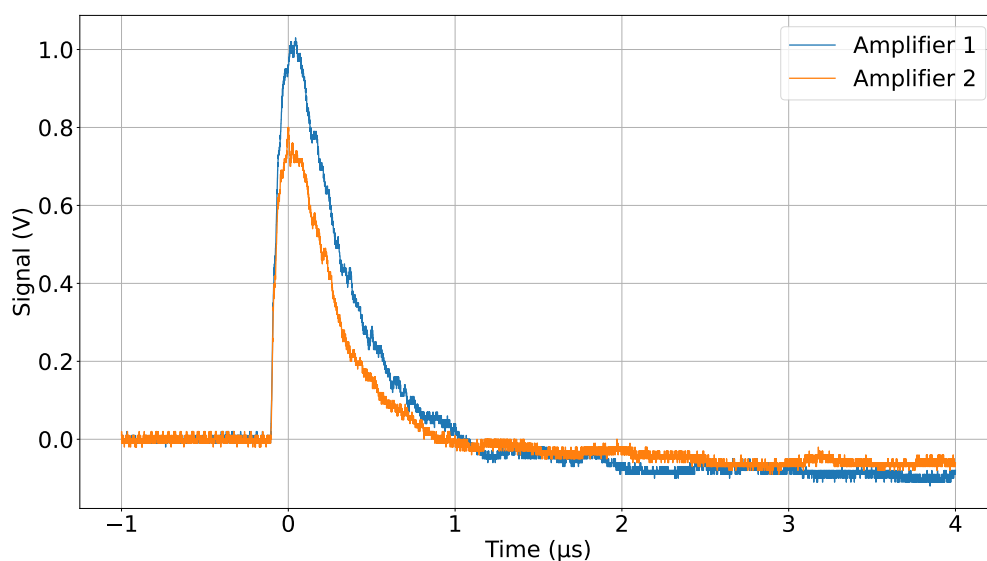


FIGURE 5.18: Signal of an α -particle from an ^{241}Am α -source. The signal was acquired using version 2 of the electronics. Zero on the time axis corresponds to the rising edge of the event signal.

5.3 Detector software

The detector electronics are controlled by a C++ script, which is running on the micro-controller. Communication, via a serial connection with the micro-controller, is handled by a python script on a user PC. By entering commands in the terminal window, the user can set and readout the detector parameters such as threshold and supply voltages, the measurement mode, the duration of

a measurement and the bin width of the time bins. All commands accepted by the micro-controller are given in Table 5.4.

Parameter command	Function
rc/rp	Readout voltages on the coincidence/supply board
wc#1,#2	Set threshold voltage 1 (#1) and threshold voltage 2 (#2) in DAC units
wp#1,#2,#3,#4	Set supply voltages for SiPM1 (#1), SiPM2 (#2), amplifier 1 (#3) and amplifier 2 (#4) in DAC units
seglength#	Set time bin width in ms
measTime#	Set measurement length for manual and self-triggered measurement in ms
trigThresh#	Set threshold for start of measurement in self-triggered mode in counts
status	Get full system status report all settings and voltages and detector temperature
Measurement command	Function
coinc	Start manual one time measurement
coinc_self	Start self-triggered measurement mode
hard_trig	Start hardware-triggered measurement mode

TABLE 5.4: Commands accepted by the micro-controller of the monitor detector. Parameter commands must be entered in the terminal using the write function of the Python script (`write(command)`). Measurement commands can be entered in the terminal as they are.

When a measurement is started, the micro-controller sends a status report of the detector to the PC which saves the report in the header of the measurement file. This report includes all settings, all measured voltages and the temperature of the detector. During a measurement, the micro-controller bins the counts into time bins and sends the counts and a timestamp for each bin to the PC, which writes them into the measurement file. Currently, the filename of the measurement file and the sum of all counts in the measurement are forwarded to the experiment control software and are written into the experiment's data base.

The detector can take measurements in three different ways, which mainly differ in how the measurement is started: manual measurement, self-triggered mode and hardware-triggered mode. A manual measurement is started by sending a command from the PC. The detector will then immediately start to measure for a fixed duration. Since, in this mode, the measurement is started by hand, it is mainly used during testing, troubleshooting and noise measurements. For operation in parallel to τ SPECT the two triggered modes were implemented. In those modes, the detector stays idle and waits for a trigger condition to be fulfilled to start a measurement. In the self-triggered mode, the detector constantly writes counts into a ring buffer. When the counts in the last bin have surpassed a threshold, a measurement of a set duration is started. This mode was developed for operation at the TRIGA Mainz where the sharp thermal-neutron peak could be used as a clear start signal. It was then adapted to the PSI source using an integrating approach, to compensate for a broader neutron peak. Detector electronics version 2 can also use the hardware-triggered mode. In that mode, a measurement can be started by applying a TTL signal to trigger input 1 on the micro-controller board. The measurement is taken for as long as the input is kept at high level. The hardware-triggered mode is the standard mode of operation of the detector, as part of the τ SPECT experiment, since September 2024. Both the self-triggered and hardware-triggered mode are initiated and ended by the user using commands on the user PC.

5.4 Monitor detector version 1 characterization at TRIGA Mainz

In the previous section, I have introduced the two hardware versions of the monitor detector. In this section, I will discuss the first measurements with version 1 and its characterization. The characterization of version 2 is covered in Sec. 5.6.

Version 1 of the monitor detector was characterized at the UCN source at the beamport D of the research reactor TRIGA Mainz. The UCN source converts thermal neutrons coming from the reactor core to UCNs. A more detailed discussion of the source is given in [Kah+17] and [Fre+07]. During UCN production, the reactor is operated in pulsed mode, producing pulses with a full width half maximum (FWHM) of 30 ms at a rate of 5 h^{-1} .

5.4.1 Measurements directly at the source

The first measurements using the monitor-detector version 1 were done in parallel to test measurements of the τ SPECT detector. The monitor-detector flange was positioned directly at the output of the UCN source. The detector was operated in the self-triggered mode, taking a 180 s long measurement every time it triggered. Fig. 5.19 shows the first three seconds of such a measurement. The monitor-detector counts are binned in 10 ms wide time bins. The measurement can be separated into 3 sections.

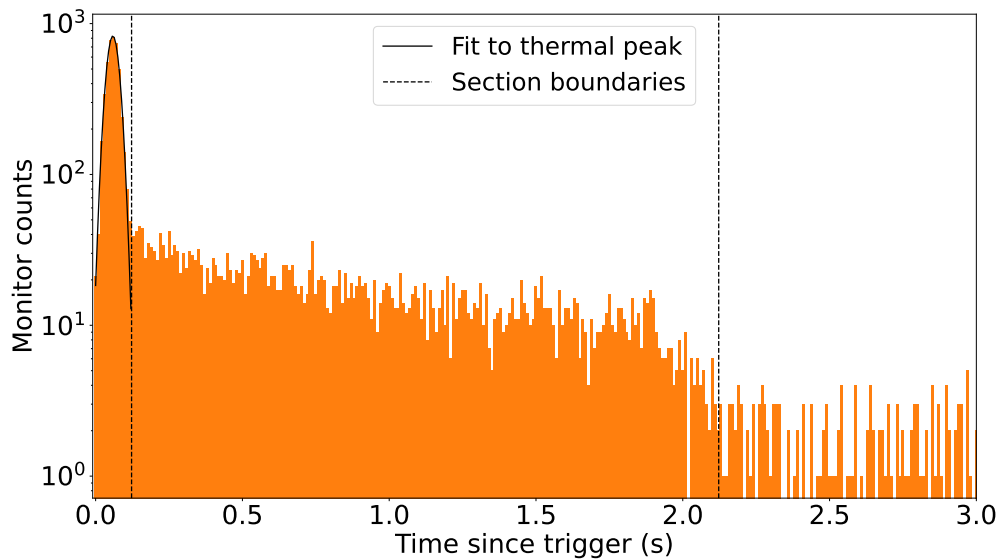


FIGURE 5.19: Plot of the first three seconds of a measurement taken with the monitor detector directly at the UCN source. The monitor-detector counts are binned in 10 ms wide time bins. The data is separated into three different sections, marked by the dashed lines. The first section is given by the thermal peak of the reactor pulse. To determine the width of that section, a Gaussian, shown in black, was fitted to it. Section 1 was then defined from the start of the measurement till three times the Gaussian’s RMS width after the center of the peak. Section 2 was defined as the 2 s after the first section. Section 3 covers the remaining data.

First, there is a sharp peak in counts, then comes a section with a medium count rate (more than 10 counts per bin) followed by a drop in counts and then a third section with low count rate. The peak in counts is caused by thermal neutrons produced during the reactor pulse and is referred to as “thermal peak” in this work. The second section is expected to contain the majority of the UCNs produced during the reactor pulse, which reach the monitoring detector during this time window. The sharp pulse is broadened in time due to the velocity differences of the UCNs. Counts during the third section are likely leftover UCNs which cannot escape the beamline.

To define the boundary between the thermal peak and section 2, a Gaussian $g(t)$ was fitted to the thermal peak:

$$g(t) = a \cdot e^{-\frac{(t-m)^2}{2c^2}}. \quad (5.6)$$

Here, a is the amplitude of the Gaussian, c is the root-mean-square (RMS) width, m is the center time, and t is the time since the trigger. The boundary between the thermal peak and section 2 was then defined to be at $t = m + 3c$, which resulted in about 120 ms. Section 2 has a fixed length of 2 s and section 3 covers the rest of the measurement data.

Fig. 5.20 shows the evolution of the counts in every section during the measurement campaign in May 2022. The counts decrease throughout the measurement campaign in all three sections. Since the counts within the thermal peak were also affected, it was unlikely that the observed reduction was caused by the yield of the UCN source. Therefore, I investigated the hardware of the monitor detector to find the cause of this drift.

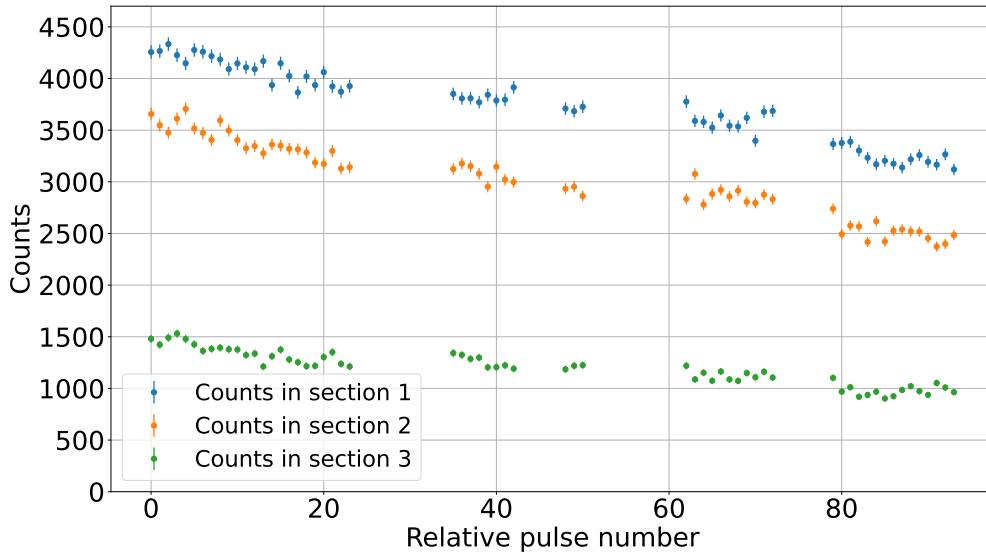


FIGURE 5.20: Counts in the respective sections plotted against the relative pulse number of the measurement campaign. Error bars represent the Poisson error. All sections show a decrease in counts with increasing pulse number.

To inspect the SiPMs, I measured the voltage-current characteristic of the used SiPMs with a Keithley 2450 source measure unit (SMU). I mounted the SiPMs in a light-tight enclosure and supplied them using the SMU via a feedthrough. Fig. 5.21 shows the result of those measurements for the SiPMs used in the monitor detector and for a new SiPM, of the same batch, for comparison. At the usual operation voltage of 28.5 V, the dark currents of the used SiPMs are multiple orders of magnitude higher than that of the new SiPM. The dark current also vastly exceeds the maximum value given by the datasheet of 1.7 μ A at 2.5 V overvoltage [Sem22]. We suspect radiation damages to the SiPMs as the cause for the increased dark current. Another SiPM based detector, which was

mounted near the monitor detector, also showed decline in performance, likely caused by radiation damages [Aul+24b]. The drift in counts is likely caused by the radiation damages accumulating and the dark current increasing. The detector electronics cannot supply the current needed to maintain the operation voltage, and so the supplied voltage drops. This leads to a reduction in gain, which in turn results in fewer events measured by the detector.

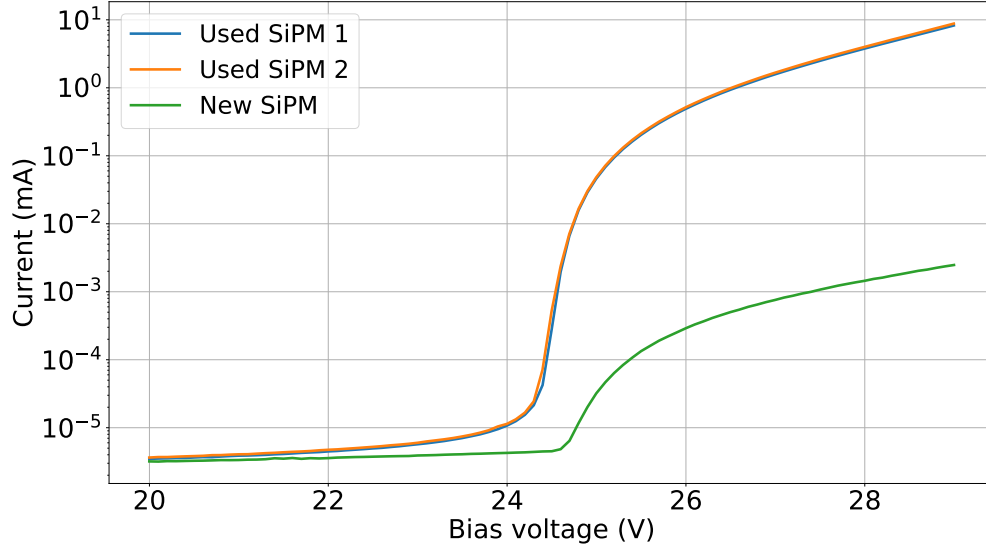


FIGURE 5.21: Comparison of the I-V characteristics of the SiPMs that were used in the monitor detector at the UCN source, and the characteristic of an unused SiPM of the same batch. Errors in sourced voltage and measured current are negligible compared to the line thickness. The dark currents of the used SiPMs vastly exceed the dark current of the new SiPM. At the usually used operation voltage of 28.5 V, the dark current is increased by more than three orders of magnitude.

The damaged SiPMs were replaced. During all later measurements at TRIGA Mainz the monitor detector was positioned farther away from the source and outside of the direct line of sight to the reactor core, to prevent radiation damages.

5.4.2 Characterization measurement campaign

The detector was characterized in a measurement campaign of 150 pulses at the TRIGA Mainz. The campaign had two main goals: identifying the UCNs within the time structure of the detector data and finding good detector settings for UCN detection. A picture and a sketch of the setup used for those measurements is shown in Fig. 5.22.

The neutrons are transported using a 66 mm-inner-diameter stainless steel beamline. After passing an approximately 80 cm long horizontal section at the source output, the UCNs are directed upward by a ⁵⁸Ni:Mo (85:15) coated reflective surface to a height of 152.5 cm (center-to-center of the beamline pieces) above the source output. At this point a second plate redirects them back into horizontal direction. The monitor detector (1) is mounted behind that vertical section and about 1 m in front of the aluminum storage bottle (2). Behind the bottle a 87 cm long Ni:Mo coated vertical glass guide leads the UCNs downwards into a CASCADE-U⁷ detector. The 87 cm drop

⁷UCN Detector by CDT CASCADE Detector Technologies GmbH, <https://n-cdt.com/>

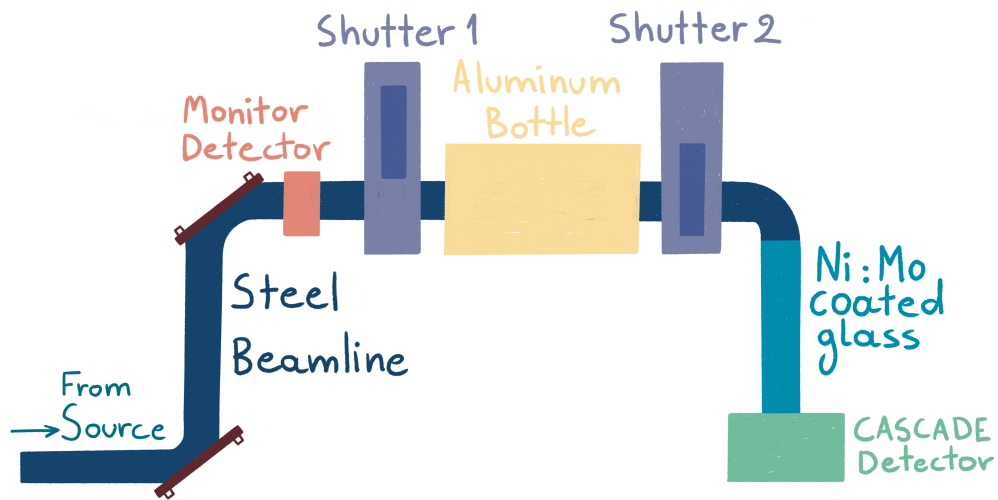
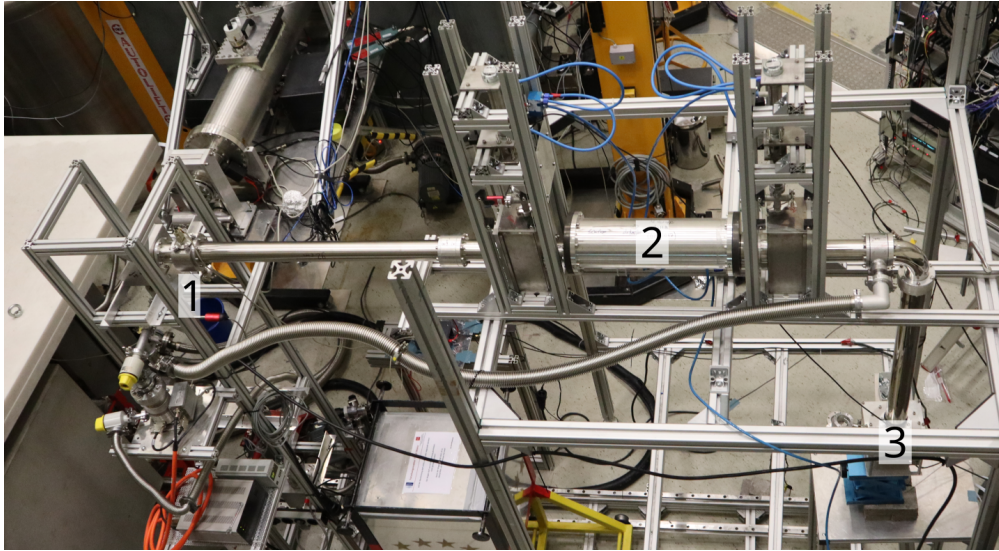


FIGURE 5.22: Picture (top) and sketch (bottom) of the test setup used for characterization of the version 1 of the monitor detector at TRIGA Mainz. The UCNs are guided from the source to a height of 152.5 cm above the center of the beamport using a 66 mm-inner-diameter stainless steel beamline and two $^{58}\text{Ni:Mo}$ (85:15) coated reflective surfaces. The monitor detector (1) is mounted on that height and about 1 m in front of the aluminum storage bottle (2). Behind the bottle, a CASCADE detector (3) is mounted at the end of a 87 cm-long Ni:Mo coated vertical glass guide. The sketch shows the bottle state during the counting phase. Illustration by Dimitra Kanta.

accelerates the UCNs so that they can overcome the Fermi potential of the CASCADE's vacuum separation foil made of aluminum. The CASCADE detector uses an argon-carbon dioxide mixture (82:18) as counting gas.

A measurement consists out of three phases: the filling phase, the storage phase, and the counting phase. During the filling phase the front shutter of the bottle is kept open for the first 5.5 s after the pulse. The bottle is then kept closed for 20 s during the storage phase. After storage, the back shutter is opened to empty the bottle towards the CASCADE detector during the counting phase. By identifying only events during the counting phase as UCNs, UCNs can be distinguished

from faster neutrons detected by the CASCADE. The monitor detector was operated in the self-triggered mode taking a 180 s long measurement at every pulse, while the CASCADE detector was triggered using the reactor pulse trigger of the TRIGA Mainz. Based on previous experience the monitor detector was initially operated using an SiPM bias voltage of 28.5 V (3900 DAC units) and a threshold voltage of 54 mV (50 DAC units). To determine an optimal operational setting the event threshold and the SiPM bias voltage were varied during the measurement campaign.

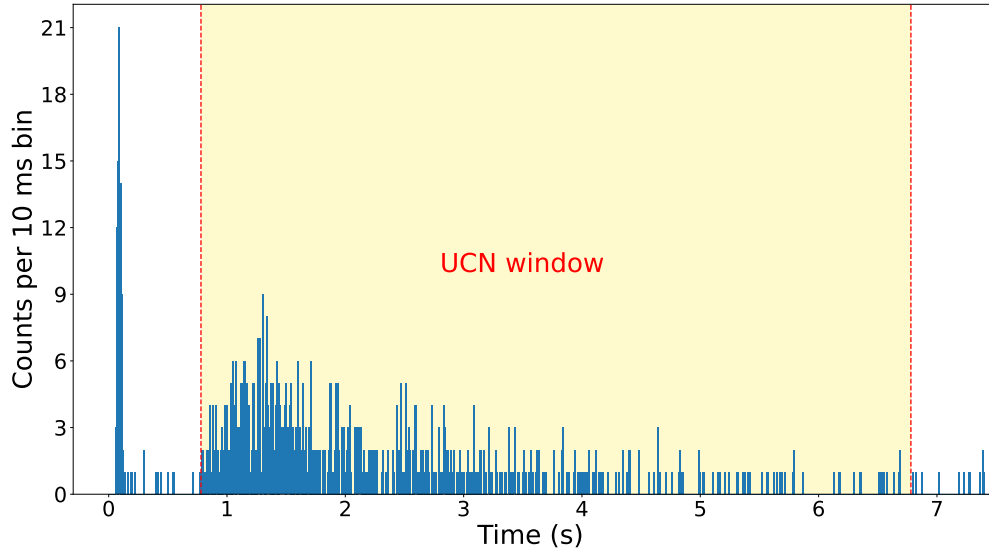


FIGURE 5.23: First 7.5 s of a measurement taken with the monitor detector in front of the aluminum storage bottle. The counts are binned in 10 ms wide time bins. Only counts within the acceptance window, here shaded in yellow, are identified as UCNs. The window is defined by its start time t_s , which is given as the time since the thermal-peak maximum, and its width Δt . The window shown here has the parameters $t_s = 0.7$ s and $\Delta t = 6$ s.

Before discussing any effects caused by the values of those voltages, I will cover the identification of UCNs in the monitor detector data. Fig. 5.23 shows the first 7.5 s of a measurement taken with the monitor detector. The thermal peak of the reactor is clearly visible shortly after the measurement start. About a second after the thermal peak, a broad peak is visible. This peak is likely caused by UCNs produced at the source during the thermal peak, which is broadened due to velocity differences in the UCNs. After that peak, counts are registered only occasionally. Those are likely UCNs which are still trapped in the beamline.

UCNs are identified using their time of arrival. Only counts N_m within a specific time window are registered as UCNs. This window is defined by its start time t_s , which is given as the time since the thermal peak maximum, and by its width Δt . A first guess for the start time can be estimated using simplified assumptions. From their production in the source until they reach the monitor detector, the UCNs have to cover a distance of about 6.5 m (4.4 m of this distance in the source [Kah+17]). The fastest UCNs ($E_{kin} = 335$ neV) have a velocity of about 8 m s^{-1} . Therefore, they need at least 0.8 s to reach the monitor detector. Since thermal neutrons have a velocity of 2200 m s^{-1} , the time they need from the source to the monitor detector is negligible and we can assume that the UCNs are at the source when the thermal peak reaches the monitor detector. Since t_s is defined as the time since the thermal peak's maximum, I will account for the width of the thermal peak to estimate the earliest possible arrival time of UCNs. To do so, I subtract 0.1 s, which is about three times the thermal peak's FWHM, from the 0.8 s needed to reach the monitor detector. This results in

an estimation of $t_s = 0.7$ s. In Fig. 5.23 the time window with $t_s = 0.7$ s and $\Delta t = 6$ s is shaded in yellow.

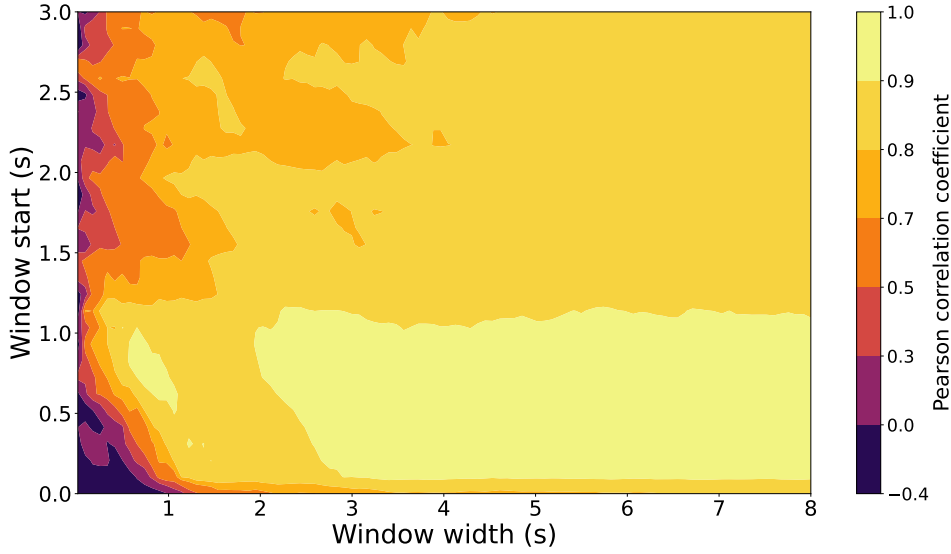


FIGURE 5.24: Correlation of the stored UCNs detected with the CASCADE and the events detected with the monitor detector within the UCN time window plotted against the window's width and the window's start time. The correlation was calculated using 27 measurements done with a threshold voltage of 54 mV and a bias voltage of 28.5 V. For a window width larger than 3 s and a window start time of 0.2 s to 1.2 s, a broad region, with a correlation coefficient higher than 0.9, can be observed.

For a window containing mainly UCNs, N_m should be highly correlated with the number of UCNs detected with the CASCADE N_c . To test the choice of the window parameters, the Pearson correlation coefficient (PCC) $p_{N_m N_c}$ was calculated for multiple t_s and Δt . The PCC for a sample of n measurement pairs (x_i, y_i) is given by

$$p_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}, \quad (5.7)$$

where $\bar{x}$ and $\bar{y}$ are the means of the respective measurements. Fig. 5.24 shows a contour plot of the PCC as a function of start time and window width. For this plot, the largest data set containing the same detector settings was used. It consists of 27 measurements which were done with a SiPM bias voltage of 28.5 V (3900 DAC units) and a threshold of 54 mV (50 DAC units). One can see a broad region of very high correlation (>0.9) for a window width longer than 3 s and a start time between approximately 0.2 s and 1.2 s. This agrees with the initial assumption that the broad peak contains mainly UCNs. The initially guessed window parameters, $t_s = 0.7$ s and $\Delta t = 6$ s, result in a correlation of 0.93(3) and lie well within the high correlation area. This indicates that the correlation is robust against small timing fluctuations for this choice of parameters. They were therefore used in the further analysis. For the sake of completeness, it should be noted that, due to the sample size of 27 measurements the correlation has a non-negligible uncertainty. The estimator for the standard error of the PCC proposed by Soper [Sop13]

$$\sigma_p = \frac{1 - p^2}{\sqrt{n - 1}} \quad (5.8)$$

results in $\sigma_p = 0.037$ for a sample size of 27 and $p = 0.9$.

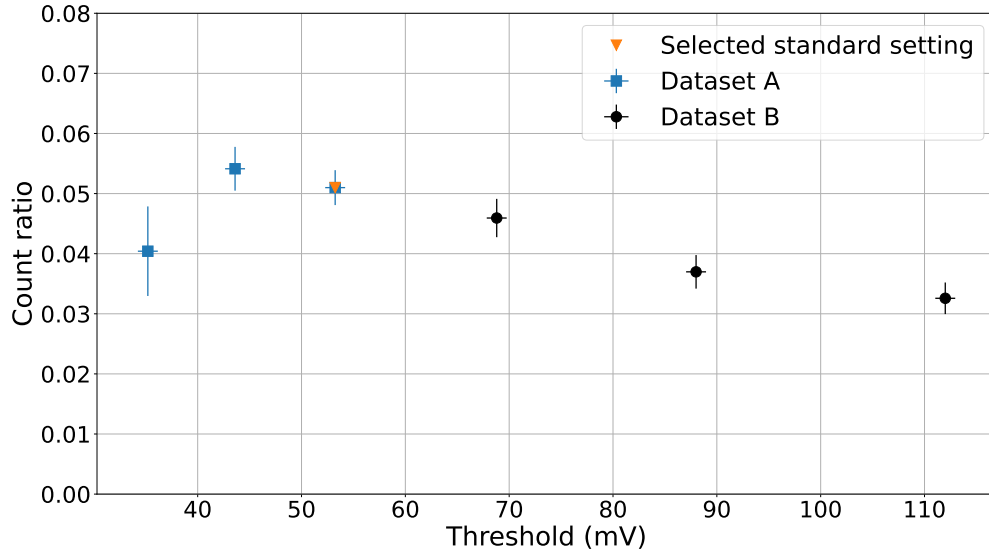


FIGURE 5.25: Count ratio plotted against the threshold voltage. Data points represent the weighted mean of the measurements. Error bars represent the estimator for the standard deviation. The voltage error bar represents the standard deviation of measured voltages. The count-ratio error bars represent the estimator for the standard deviation. For dataset A (blue), the standard deviation was calculated from the sample data set and for the low statistics dataset B (black, $N=2$), the error of the ratio was used as the estimator. The count ratio increases with lower threshold, but then plummets for a threshold of 35 mV. The voltage threshold of 54 mV (orange triangle) was chosen as standard setting for future operation.

Measurements at different settings were analyzed and compared. To reduce the effect of source fluctuations, the ratio r of N_m and the Cascade counts N_c was used

$$r(N_m, N_c) = \frac{N_m}{N_c}. \quad (5.9)$$

The uncertainty of this ratio can be calculated using the propagation of error for correlated variables

$$(\delta f(x_1, \dots, x_N))^2 = \sum_{i,j=1}^N \frac{\delta f}{\delta x_i} \frac{\delta f}{\delta x_j} V_{ij}. \quad (5.10)$$

Here, V_{ij} are the elements of the covariance matrix. In the case of r , this results in

$$\delta r(N_m, N_c) = \left(\left(\frac{\sigma_m}{N_c} \right)^2 + \left(\frac{\sigma_c N_m}{N_c^2} \right)^2 - 2\sigma_m \sigma_c p_{mc} \frac{N_m}{N_c^3} \right)^{\frac{1}{2}}, \quad (5.11)$$

when writing the covariances using the correlation coefficient p_{mc} and the standard deviations σ_m and σ_c of the respective counts.

Fig. 5.25 shows the dependence of the count ratio on the threshold voltage. Due to the limited amount of measurements, statistic was only accumulated for the more interesting settings (dataset A, blue), while for the others only one or two measurements were conducted (dataset B, black). Data points represent the weighted mean of the measurements. Error bars represent the estimator of the standard deviation.

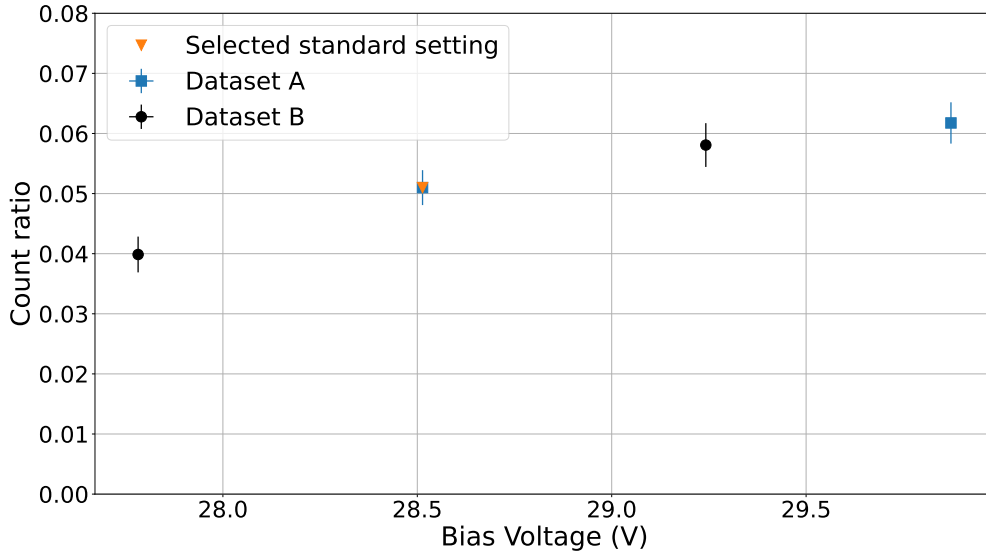


FIGURE 5.26: Count-ratio dependence on SiPM bias voltage. Data points represent the weighted mean of the measurements. Error bars represent the estimator of the standard deviation. The voltage error-bars, represent the standard deviation of the measured voltage. They are smaller than the markers. The count-ratio error-bars represent the estimator of the standard deviation. For dataset A (blue) the standard deviation was calculated from the sample data set, while for the low statistics dataset B (black, $N=2$), the error for the ratio, see Eq. (5.11), was used as the estimator. The count ratio increases with increasing bias voltage. The bias voltage setting of 28.5 V (3900 DAC units), here measured as 28.51(5) V, was chosen as standard setting for future operation.

The standard deviation for the threshold voltage was estimated using voltage log files of the detector, since, due to a software bug, the voltages in the measurement files were only updated once per new setting not once per measurement. The standard deviation of the count ratio was estimated in two different ways. For dataset A, the standard deviation was calculated from the dataset. For the low statistics dataset B, with $N=2$, the standard deviation was estimated using Eq. (5.11). For dataset B no meaningful correlation could be calculated. Instead, I assumed the same correlation for dataset B as the one calculated for a threshold voltage of 54 mV and a bias voltage of 28.5 V. The error estimated this way is about 25% smaller than in the case of independent variables. The count ratio increases with lower threshold, but then plummets for a threshold of 35 mV. This might be caused by reaching the electronic noise floor. The voltage threshold of 54 mV (50 DAC units) was chosen as the standard setting for future operation, to keep higher count-ratio while staying above the noise floor.

Fig. 5.26 shows the dependence of the count ratio on the SiPM bias voltage. Data points represent the weighted mean of the measurements. Error bars represent the estimator for the standard deviation. Standard deviations were estimated the same way as for the threshold voltages. The bias voltage setting of 28.5 V (3900 DAC units), here measured as 28.51(5) V, was chosen as standard setting for future operation.

The capability of the monitor detector to monitor the source was further investigated using the data taken with the standard settings. Fig. 5.27 shows the UCNs counted by the CASCADE detector and the monitor detector, plotted against the pulse number in the measurement campaign.

One can clearly see a trend in both counts. This trend is most likely caused by the source. The monitor-detector counts following the trend is a good indicator that source monitoring is working.

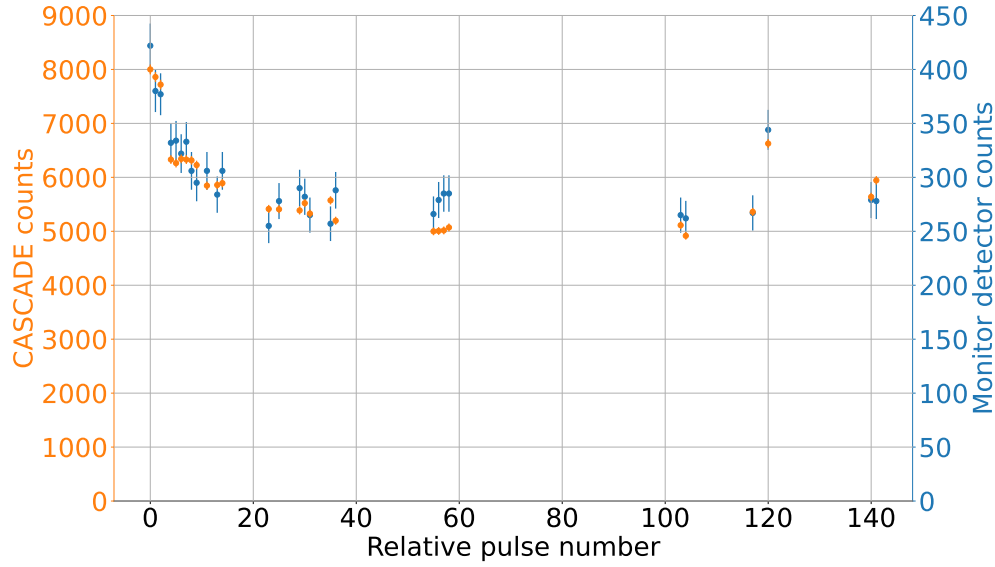


FIGURE 5.27: UCNs counted by the CASCADE detector and the monitor detector, plotted against the pulse number of the measurement. Only data taken with standard detector settings is plotted here. Error bars represent the Poisson error. For the CASCADE counts the error bars are often smaller than the markers. One can see the counts reducing from pulse number 0 to 60.

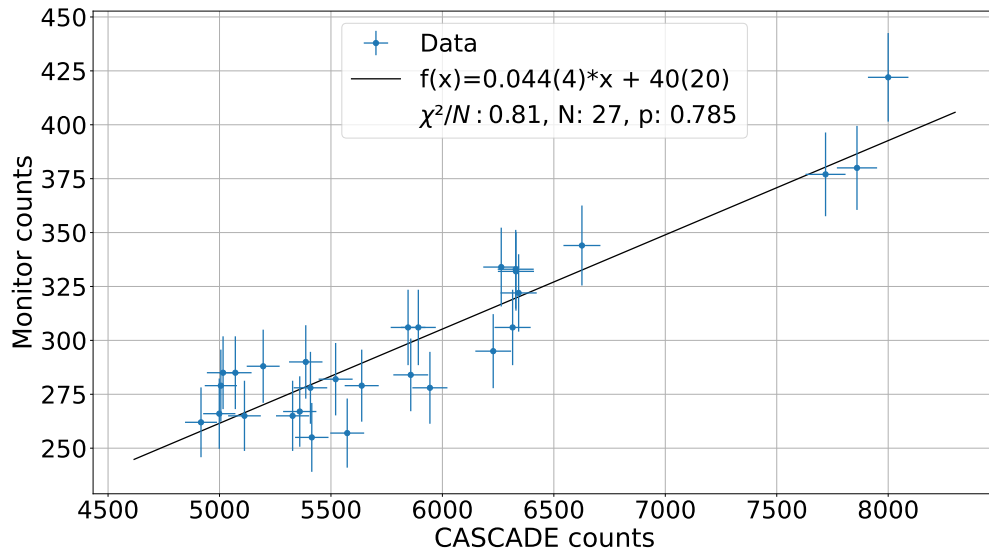


FIGURE 5.28: Monitor counts plotted against CASCADE counts. Error bars have been calculated assuming that the counts follow a Poisson distribution. A linear fit to the data is shown in black.

Next, I checked whether the monitor detector data can be used to normalize the amount of stored UCNs. Fig. 5.28 shows the monitor counts plotted against the CASCADE counts. A linear correlation between the two was assumed and is visualized by the black line representing a linear fit. While the fit is not rejected by the χ^2 , one can see that the uncertainties, especially of the monitor counts, limit the interpretation of the data. It is possible that there is a linear correlation, but more statistics are needed both in total counts and in the number of measurements to make a reliable statement.

To conclude, using the data from the measurement campaign, I determined standard operational settings for the monitor-detector version 1. Additionally, I found a time window for UCN identification for this specific setup. Comparison with CASCADE data shows that the monitor detector follows the source trend and can be used for source monitoring. Strong correlation of the monitor counts with the UCNs stored in the aluminum bottle hints towards the possibility of normalization using the monitoring detector. However, this normalization is limited by the amount of UCNs detected with the monitor detector.

5.5 A short introduction of the PSI UCN source

In the summer of 2023, the τ SPECT experiment was relocated from the research reactor TRIGA Mainz to PSI in Switzerland. Testing of the monitor-detector version 2 as well as all measurements discussed in Ch. 6 were performed at PSI. The UCN source at PSI differs quite a bit from the source in Mainz. In this section I will give a short overview of the differences and how they affect the monitor-detector measurements. More detailed descriptions of the PSI UCN are given in [Rie22, pp. 25–41] and [Bis+22].

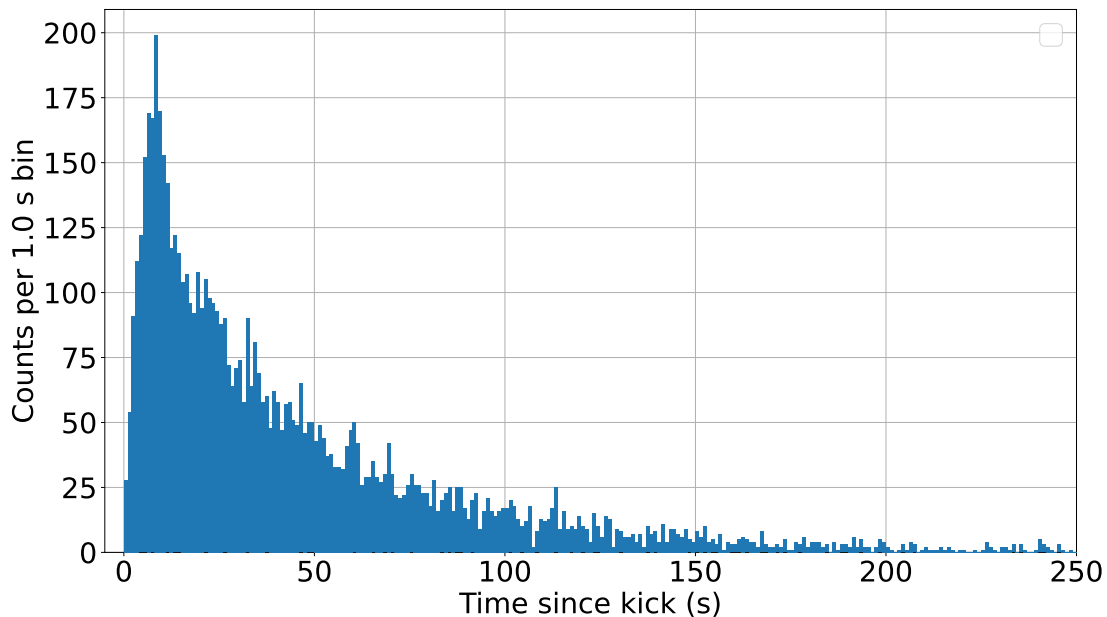


FIGURE 5.29: Example of measurement taken with the monitor-detector version 1 during operation with τ SPECT at PSI. Events counted by the monitor detector are plotted against time. The counts are binned into bins of a width of 1 s. The monitor detector was positioned at a height of 107 cm above the center of the source’s beamport. At the start of the measurement one can see a rise in counts as the UCNs are produced. The counts then slowly reduce over time and after 50 s about 50 counts per second are detected.

While the source in Mainz uses a reactor for neutron production, the PSI source uses a spallation target, which is irradiated with a proton beam. The maximum duty cycle are pulses of 8 s every 300 s. Such a pulse is referred to as a “kick” in this work. This means, the duration of neutron production is about 300 times longer than the sharp peak produced by the TRIGA Mainz. Additionally, in

contrast to the UCN source in Mainz, the source at PSI has a storage volume between the sD_2 crystal and the output port. Both these differences lead to a much broader time structure of the UCN output than in Mainz. Fig. 5.29 shows a measurement with the monitor-detector version 1 during operation with τ SPECT at PSI. The monitor detector was positioned at a height of 107 cm above the center of the source's beamport. At the start of the measurement, the counts rise as the UCNs are produced. The counts then slowly reduce over time and after 50 s still about 50 counts per second are detected. This is a lot different than the output of the UCN source at the TRIGA Mainz, where the significant amount of UCNs were counted in a window of a few seconds.

It should also be noted, that combination of the storage volume and a vacuum separation foil lead to a low-end cutoff of the energy spectrum of the UCNs at the PSI UCN source. A 0.1 mm thick AlMg3 foil supported by a stainless steel grid is installed between the storage vessel and the beamport [Bis+20]. UCNs with kinetic energies below the Fermi potential of 52 neV [Rie22, p. 36] cannot pass the foil. This leads to the low-end cutoff of the energy spectrum of the UCNs at the beamport.

5.6 Commissioning of monitor-detector version 2

The monitor detector upgrade was finished in August 2024. I conducted a three week long measurement campaign in September 2024 at PSI to test the new version (see Sec. 5.2.3), select proper parameters for UCN detection and evaluate the detector's performance. In this chapter I introduce the measurement setup and discuss the measurements and their results.

5.6.1 Test setup and initial tests

In order to commission version 2 of the monitor detector, the detector was installed in a test setup at beamport West-1 of the PSI UCN source. This is the same beamport at which the τ SPECT experiment is currently positioned. The test setup is shown in Fig. 5.30. The UCNs were guided upwards by the beamline (inner diameter $d_i = 66$ mm) to a height of 59 cm above the beamport, where the monitor detector is positioned. This is done to shift the energy spectrum of the UCNs which reach the monitor detector, so that it starts from 0 neV instead of 54 neV, as mentioned in Sec. 5.5. Behind the monitor detector, the beamline drops to the level of the beamport, where a CASCADE-U detector⁸ was mounted. This drop gives the UCNs enough kinetic energy to pass through the CASCADE's vacuum separation foil, which is made from aluminum. In front of the CASCADE the beamline diameter is adapted to 110 mm to fit the CASCADE's flange.

The CASCADE detector was operated at a voltage of 1.5 kV, and a gas mixture of 82% Ar and 18% CO₂ was used as counting gas. For more information on the settings of the CASCADE detector a metadata file is provided in Fig. A.6 in the appendix. The CASCADE detector was measuring in parallel to the monitor detector and was used as a reference to account for changes in source performance. Fig. 5.31 shows the data taken by the CASCADE and the monitor detector for the same kick. The counts are accumulated in bins of 1 s width.

The counts in both detectors follow the same time distribution: first a sharp rise, then an exponential decay of the counts. The sharp rise is caused by the UCN production of the source. After 8 s, the production stops, the beamline acts as a storage vessel, and the UCN count rate follows an

⁸UCN Detector by CDT CASCADE Detector Technologies GmbH, <https://n-cdt.com/>



FIGURE 5.30: Setup for test measurements of the monitor-detector version 2 at beamport West-1 at PSI: UCNs enter the beamline through the beamport (1). The beamport can be closed using the vacuum shutter (2). Behind the shutter, the beamline (3) rises to a height of 59 cm above the center of the beamport, where the monitor detector is positioned (4). A close-up of the detector flange is shown in the top left corner. Inside the detector flange, a pinhole allows only a fraction of the UCNs to reach the detection surface. Behind the monitor detector, the beamline (5) goes down to the beamport height again, where the CASCADE detector (6) detects the majority of the UCNs.

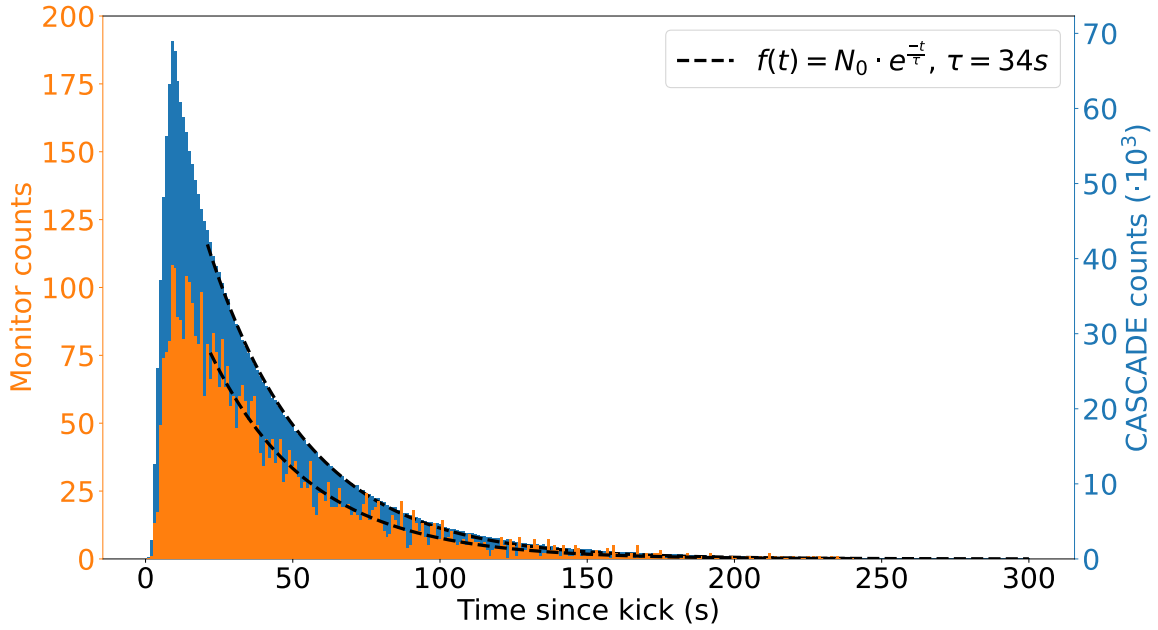


FIGURE 5.31: Counts measured with the monitor detector (orange, left y-axis), and with the CASCADE detector (blue, right y-axis), plotted against the time after the kick. Counts were binned in 1 s-wide time bins. The monitor detector measured for 240 s after the kick, the CASCADE detector for 300 s. Two dashed lines, representing an exponential decay with an exponential time constant of 34 s, have been plotted as a guide to the eye on the right flanks of the signals.

exponential decay. Using the dashed lines in the plot as a guide to the eye, one can see that the right flanks of both data sets fit well to an exponential decay with a time constant of 34 s. The monitor detector measured for 240 s after the kick, which is the standard measurement duration for operation with τ SPECT and the CASCADE detector measured for 300 s. While the CASCADE data does not contain a significant amount of counts in the last 60 s, they are discarded when comparing measurements of the two detectors. The total CASCADE-detector counts were measured to be on the order of $2 \cdot 10^6$ neutrons per kick, while the monitor-detector counts are on the order of $4 \cdot 10^3$. The CASCADE detector's background was measured to be on the order of 10^3 counts per kick and is not taken into consideration. The background of the monitor detector is discussed in more detail in Sec. 5.6.3. When comparing measurements, I used the ratio r of monitor counts N_m divided by the CASCADE counts N_c

$$r = \frac{N_m}{N_c}. \quad (5.12)$$

This ratio will be stable against fluctuations of the UCN source, assuming that N_m and N_c are proportional. I will show in Sec. 5.6.3 that this assumption is reasonable. The uncertainty of the ratio was calculated using propagation of uncertainty for correlated variables, see Sec. 5.4.

To examine the signal shape and verify that the monitor detector was working, the analog signals going into the detector were measured using a Siglent SDS 1202X-E oscilloscope. The two signal outputs of the detector electronics were connected to the oscilloscope and it was triggered using the coincidence output of the monitor detector. An example for a signal induced by a neutron is shown in Fig. 5.32.

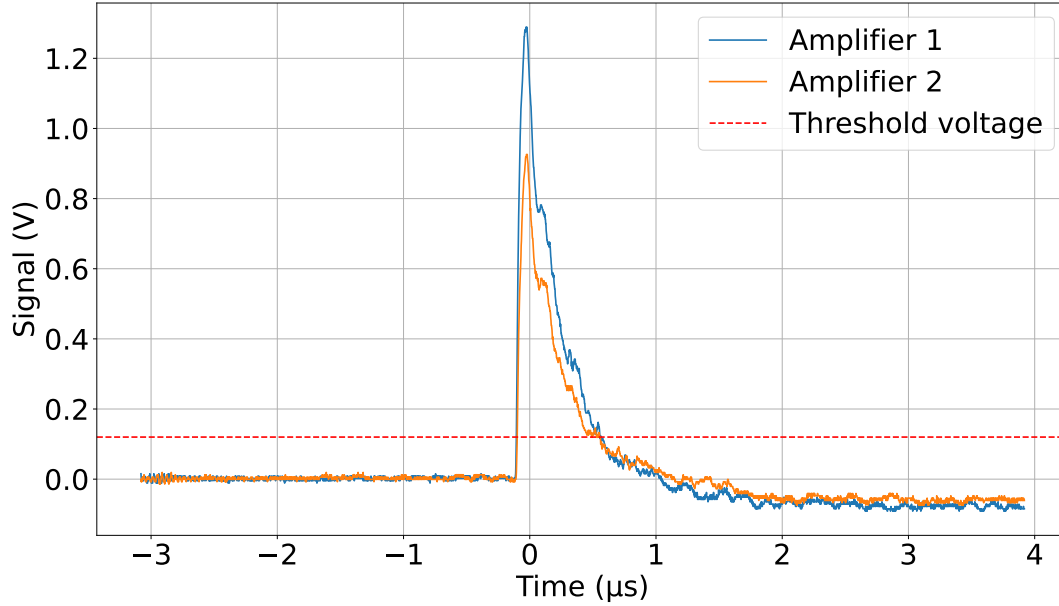


FIGURE 5.32: Signal induced by a neutron in the monitor detector. The two inverted amplifier output signals produced by the monitor-detector electronics are plotted. The event threshold of 120 mV is marked by a red dotted line. Zero on the x-axis corresponds to the rising edge of the detector’s event trigger. There is a clear coincidence between both signals.

The signals in both channels can be clearly distinguished from noise and a clear coincidence between them is observed. Since the signal shapes correspond to the expected pulse form and the event distribution is consistent with that of the CASCADE detector, it was concluded that the detector was working.

5.6.2 Optimizing settings for operation

After I verified that the detector was working, the next step was to find suitable settings for long term operation of the monitor detector. Suitable settings maximize the count ratio while keeping the background of the monitor detector low. The parameters for which the suitable settings had to be determined are the two SiPM bias voltages, the two event thresholds and the two amplifier supply voltages. The effects of the SiPM bias voltages and the event thresholds on the signal have been covered before in Sec. 5.4. However, each channel of version 2 has its own threshold voltage, instead of a common one for both channels. The amplifier supply voltages are additional parameters introduced in version 2. By adjusting them, one can change the amplifier gain and therefore the signal amplitude.

In order to optimize the settings, the voltages were scanned by varying their values between measurements. To simplify this process, I decided to not scan each value individually, but to keep the voltages of one setting pair (e.g. the threshold voltages) at the same value. Since the hardware is the same for both channels, this should not significantly affect the resulting settings. Initially, the SiPM bias voltages were set to 28.5 V. The same value had been used for version 1 of the monitor detector. The event thresholds were set to 114 mV (100 DAC units), and the amplifier

supply voltages were set to 10 V (the same settings as during the tests with ^{241}Am , see Sec. 5.2.3). Since the charged particles emitted from the $^{10}\text{B}(n,\alpha)^7\text{Li}$ neutron-capture reaction have less kinetic energy than the α -particles of the ^{241}Am - α decay, it was expected that signals caused by neutrons would be smaller than the ones observed during the tests. A full scan of all parameter combinations would have been too time consuming. Because of that, I chose an iterative approach. I first scanned the amplifier supply voltage, while keeping the other two parameters fixed at their initial values. Afterwards, I scanned the SiPM bias voltage, while keeping the amplifier supply voltage at a promising setting found in the previous step and the threshold voltage at its initial value. Finally, I scanned the event thresholds, while keeping the other two parameters at the settings determined from their parameter scans. As a result SiPM bias voltages were left at 28.5 V, the event thresholds were lowered to 54 mV (50 DAC units) and the amplifier supply voltages were increased to 10.6 V. A lower threshold and a higher gain fit well to the expectation of smaller signal amplitudes, caused by the lower energies of the charged particles. At those settings more detailed scans were performed.

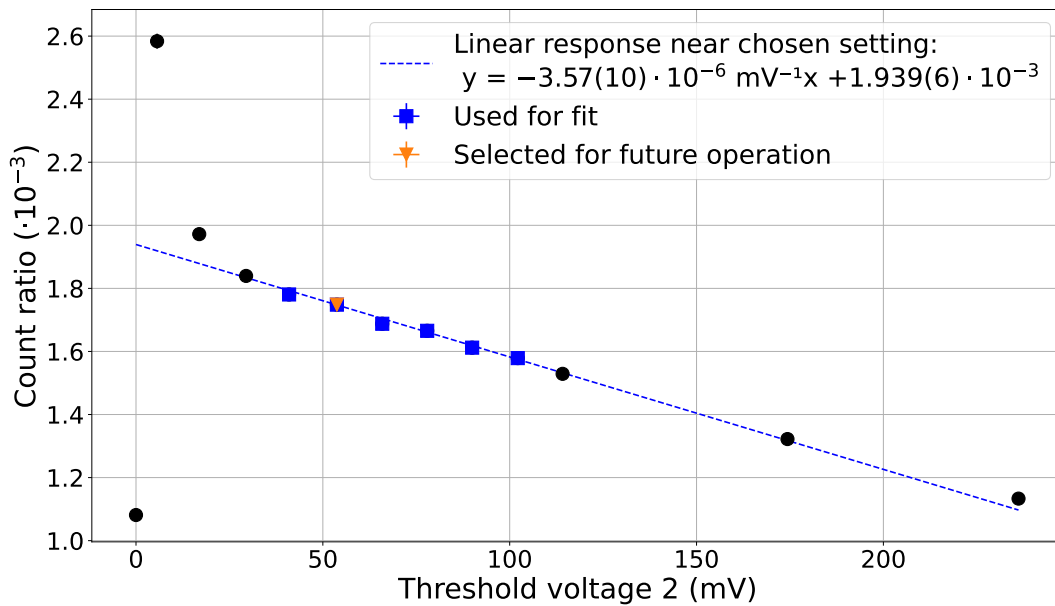


FIGURE 5.33: Ratio of monitor-detector counts and CASCADE-detector counts for a scan of event thresholds. The amplifier supply voltage and the SiPM bias voltage were fixed at 10.6 V and 28.5 V. The x-axis displays the threshold voltage of channel 2 measured by the micro-controller. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean, but are often entirely covered by the markers. For thresholds close to zero a strong nonlinearity in the count ratio can be observed. 54 mV (marked by an orange triangle) has been chosen as the setting for future operation. In order to estimate the response of the system around the chosen setting, a line (dotted blue) has been fitted to selected points marked in blue.

Fig. 5.33 shows the count ratio plotted against the event threshold of channel 2. At thresholds below 30 mV, a strong non-linear behavior of the count ratio can be observed: it first sharply rises and then plummets. The sharp rise is likely caused by the threshold entering the electronic noise floor, which leads to noise being registered as events. When decreasing the threshold voltage even further, the noise level surpasses the threshold for most of the time, and since the system does not retrigger, this likely leads to the observed reduction in count rate. For thresholds of 40 mV and higher, the count ratio decreases approximately linearly with the threshold voltage. The threshold of 54 mV

(orange triangle) was chosen as setting for operation, because it has a sufficient distance to the non-linear region, while maintaining a high count ratio of $1.747(1) \cdot 10^{-3}$. In Sec. 5.6.3, I will show that noise is not an issue for the detector at this chosen setting. To estimate the response of the system near the chosen setting, I applied a linear fit to selected data points around the chosen setting (blue squares), represented by a blue dotted line. The slope of the fit $m = -3.57 \cdot 10^{-6} (\text{mV})^{-1}$ gives the response of the count ratio to changes in the threshold voltage. The threshold voltage is read out by the 12-Bit ADC of the micro-controllers MIMXRT1062DVJB processor [NXP24]. The measured voltage exhibits fluctuation and it has a standard deviation of about 1.6 mV. If this was caused by an actual fluctuation of the threshold voltage, it would correspond to an additional variation of the monitor counts by 0.3% of the counts. However, because the standard deviation is on the same order as the least significant bit (LSB) of the micro-controller's ADC, I assume that the fluctuations mainly originate from the resolution of the ADC and I neglect them in this work. The corresponding plot for the threshold voltage of channel 1 is shown in Fig. B.1 in Appendix B. It exhibits the same behavior as Fig. 5.33 and the fitted slope and offset agree with their values for channel 2 within their uncertainty.

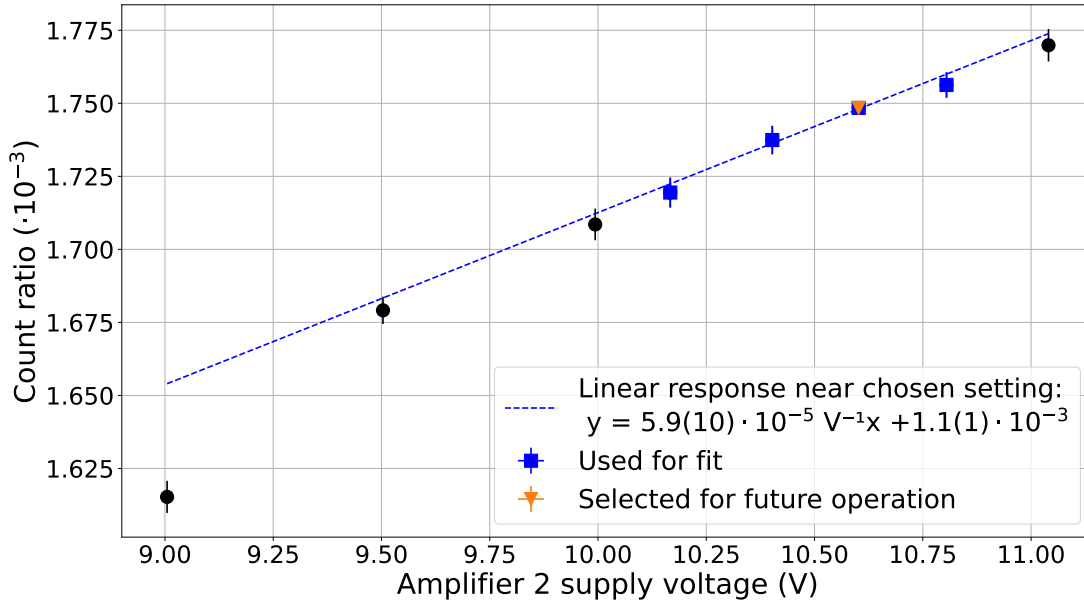


FIGURE 5.34: Count ratio of monitor detector and CASCADE detector, plotted for a scan of the amplifier supply voltage. The event threshold voltage and the SiPM bias voltage were fixed at 54 mV and 28.5 V. The x-axis displays the supply voltage of amplifier 2 measured with the micro-controller. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean. For voltages higher than 9.5 V, the count ratio increases linearly with the supply voltage. 10.6 V (marked by an orange triangle) were chosen as the setting for future operation. In order to estimate the response of the system around the chosen setting, a line (dotted blue) has been fitted to selected points marked in blue.

Fig. 5.34 shows the count ratio for a scan of the amplifier supply voltage. For supply voltages above 9.5 V the count ratio increases linearly with the supply voltage. For both amplifiers a supply voltage of 10.6 V, marked in orange, was chosen for future operation, to maximize the count ratio while maintaining a safety margin to the maximum supply voltage of 11.3 V. To estimate the system's response to voltage fluctuations, a line was fitted to selected points marked in blue. The slope of

the fit is $m = 5.9(10) \cdot 10^{-5} \text{ V}^{-1}$ and the fluctuation of the measured voltage is $\sigma_V = 6.4 \text{ mV}$. The count ratio fluctuation is estimated as $3.8(6) \cdot 10^{-7}$ which corresponds to a relative fluctuation of $0.022(3)\%$. This effect is small enough to be neglected. The plot for channel 1 can be found in Fig. B.2 in the Appendix B. The fit values for the slope and the offset are the same within the error.

The dependence of the count ratio on the SiPM bias voltage is shown in Fig. 5.35. For the points marked in blue, the count ratio depends linearly on the bias voltage. For higher voltages, the response seems to flatten out. While this possible plateau at 29.2 V would be a tempting choice for the operational setting because of the flat voltage response, I decided to use the lower bias voltage of 28.5 V instead, to stay well within the maximum 5 V overvoltage given by the data sheet (see Sec. 5.2.3). To estimate the system's response to voltage fluctuations a linear fit was performed on the selected points marked in blue. The slope of the fit is $m = 1.24(10) \cdot 10^{-4} \text{ V}^{-1}$, and the standard deviation of the measured voltage is $\sigma_V = 11.72 \text{ mV}$. This corresponds to a fluctuation in count ratio of $1.5(1) \cdot 10^{-6}$ or $0.084(6)\%$ relative fluctuation, which is so low that it can be neglected. The plot for channel 1 shows similar behaviour, and the fit results for slope and offset are consistent with the values obtained for channel 2 within their uncertainties. The plot is shown in Fig. B.3 in Appendix B.

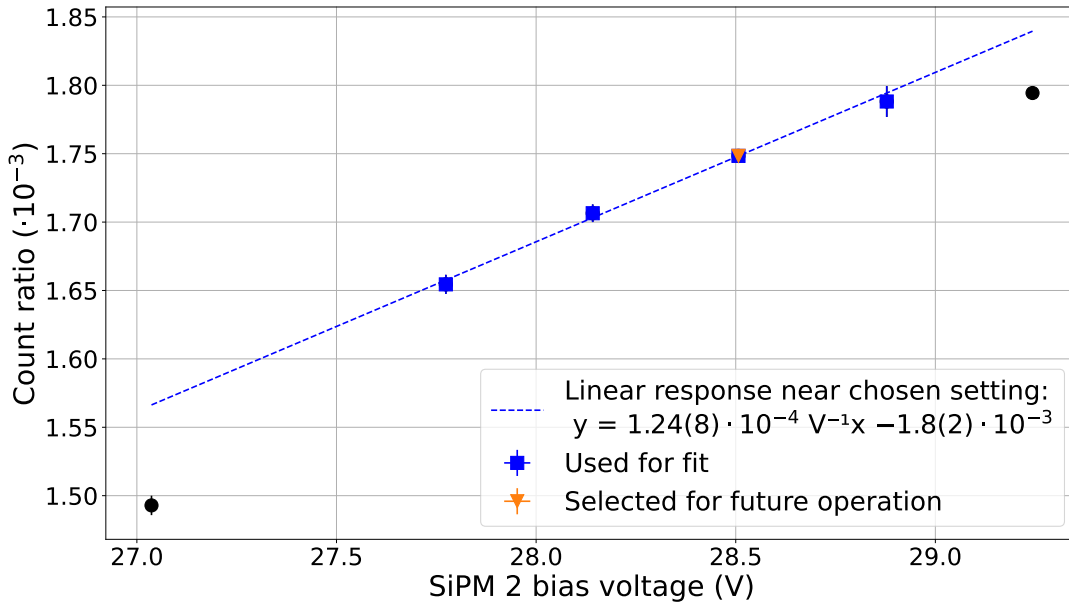


FIGURE 5.35: Plot of the count ratio for a scan of SiPM bias voltage, the event threshold voltage and the amplifier supply voltage were fixed at 54 mV and 10.6 V . The x-axis displays the bias voltage of SiPM 2 measured with the micro-controller. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean. 28.5 V (marked by an orange triangle) has been chosen as the setting for future operation. In order to estimate the response of the system around the chosen setting, a line (dotted blue) has been fitted to selected points marked in blue.

The chosen operational settings are summarized in Table 5.5 and were used in all following measurements discussed in this work.

Setting	DAC setting	Measured voltage
Threshold 1	50	54 mV
Threshold 2	50	54 mV
SiPM 1 bias voltage	3900	28.5 V
SiPM 2 bias voltage	3900	28.5 V
Amp 1 supply voltage	3820	10.6 V
Amp 2 supply voltage	3650	10.6 V

TABLE 5.5: Table containing the optimized settings of monitor detector version 2. DAC settings are the DAC units set by the user. Measured voltages are the corresponding voltages measured with the micro-controller. Note that the voltage supply of Amplifier 1 was supplying less voltage than expected and therefore the setting had to be adjusted to compensate.

5.6.3 Performance of the monitor detector

In this section I cover the detector’s performance at the chosen operational settings. One important parameter is the amount of non-UCN events detected during one measurement. For accurate monitoring of the sources output, this amount should be much smaller than the amount of UCNs detected. To measure the amount of non-UCN events, I took 27 measurements with the source’s vacuum shutter and the beamline flap closed. This prevents UCNs from entering the beamline, but is not an obstacle to γ -rays, which are likely the dominant background source. Fig. 5.36 shows the average time structure of those measurements for both the CASCADE (blue) and the monitor detector (orange). The counts are binned per second and are plotted for the first 50 s after the kick. The shape of the background of both detectors is similar. The majority of the events is detected within the first 8 s after the kick, when the proton beam still hits the spallation target. The remaining events happen shortly thereafter. The mean background is 4.3(3) counts in the monitor detector and 1237(18) counts in the CASCADE detector. Both backgrounds are negligible compared to the total events in a measurement with those detectors.

The γ -radiation at the position of the monitor detector was measured with a Radiacode[®] 103 detector⁹ during the kick. This detector uses a cubic 1 cm³ CsI:Tl crystal. The measurement resulted in up to 870 counts per second. This confirms that the monitor detector exhibits low sensitivity to the γ -radiation produced during the kick. To estimate the monitor detector’s intrinsic background, I took a 10⁵ s long measurement during a period without neutron production, which resulted in 7 counts. Using the upper limit for the mean of a Poisson variable [Nav+24, pp. 707], the 95% upper bound for the background rate was determined to be $1.315 \cdot 10^{-4} \text{ s}^{-1}$. This rate corresponds to significantly less than one count per 240 s measurement window. Therefore, both the intrinsic detector background and the background due to radiation from the spallation target, are negligible compared to the total number of events, which were about $4 \cdot 10^3$ during characterization and up to $3.5 \cdot 10^4$ in operation with τ SPECT (see Sec. 6). This demonstrates that the chosen threshold voltage is appropriate for low-noise operation, and that the detector can be considered background-free in this work. Low background is essential for reliable source monitoring and for using the monitor detector to normalize τ SPECT, as the recorded events accurately reflect the number of neutrons in the beamline, and the measurement result will be largely insensitive to changes of the γ -background.

To compare the measurement results of the monitor detector to the ones of the CASCADE detector, I used all data taken with the optimized settings during this campaign. Fig. 5.37 shows the monitor

⁹Geiger counter from Radiacode LTD <https://www.radiacode.com/de>

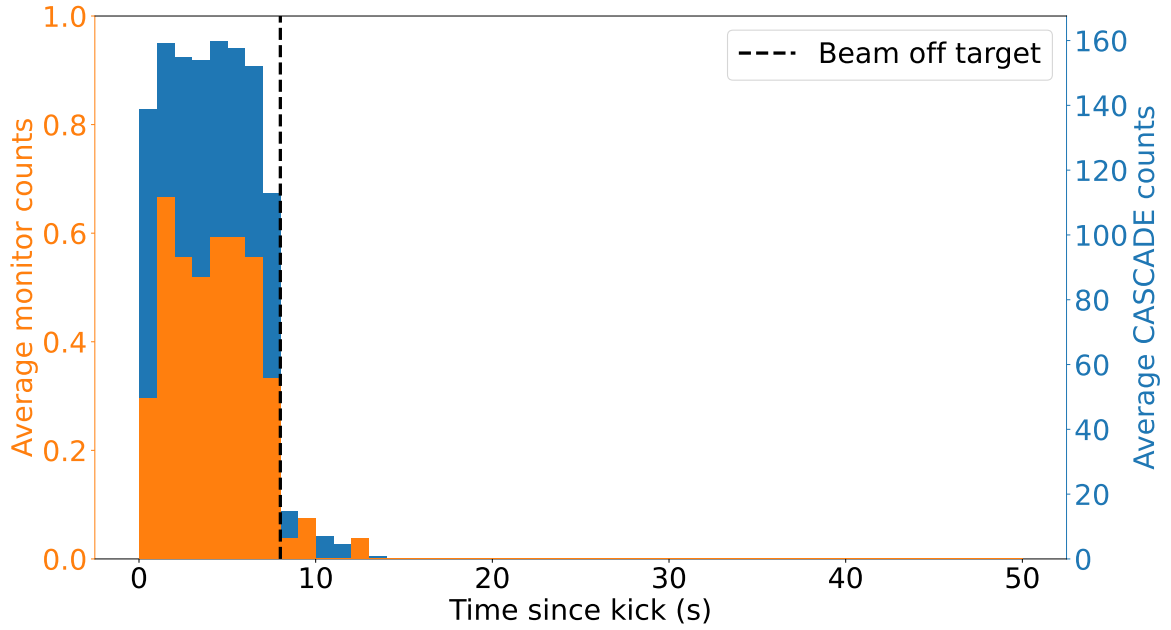


FIGURE 5.36: Average counts of 27 background measurements with the vacuum shutter and the beamline flap closed. The monitor counts are plotted in orange and the CASCADE counts in blue. The bars represent the mean counts per 1 s. Both detectors register most events in the first 8 seconds (marked by dashed line), which coincides with the duration of the proton beam hitting the spallation target. The monitor detector did not register any events later than 13 seconds after the kick in any of these measurements. The mean background counts are 4.3(3) for the monitor detector and 1237(18) for the CASCADE detector.

counts plotted against the CASCADE counts and a weighted linear fit with offset in the top panel. The residuals of the fit are shown in the bottom panel. The measured counts cover a wide range, which is caused by the decline of the source's performance over time. The counts of the two detectors are highly correlated with a correlation coefficient of $\rho = 0.9946$. The fit's reduced χ^2 is slightly larger than 1 indicating either missing components of the fit or that the error variance has been underestimated. However the Pearson residuals, which are the residuals divided by their estimated standard deviation, do not show any obvious higher-order dependencies and their mean of 0.009 does not indicate any bias. I therefore assume that the model is appropriate and that the measurements fluctuate slightly more than expected from pure Poisson statistics. The fit's offset is 10(20), which is compatible with zero. Thus, the dependence between the detectors is essentially proportional and the ratio can be used to compare measurements. The good agreement with a commercial detector confirms the reliability of the monitor detector. Possible contributions to the increased fluctuation of the monitor counts include the voltage fluctuations mentioned in Sec 5.6.2, but their effect is not big enough to be the sole explanation. Additional factors could be temperature effects, which are investigated in the following paragraph, or slight differences in the energy dependency of the detectors' detecting efficiencies.

As noted in Sec. 5.2 the gain of the SiPMs decreases with temperature. This likely reduces the number of events seen by the monitor detector. To investigate this dependency, version 2 of the monitor detector documents the temperature at the detector flange for each triggered measurement. Fig. 5.38 shows the count ratio plotted against that measured temperature. The set of measurements

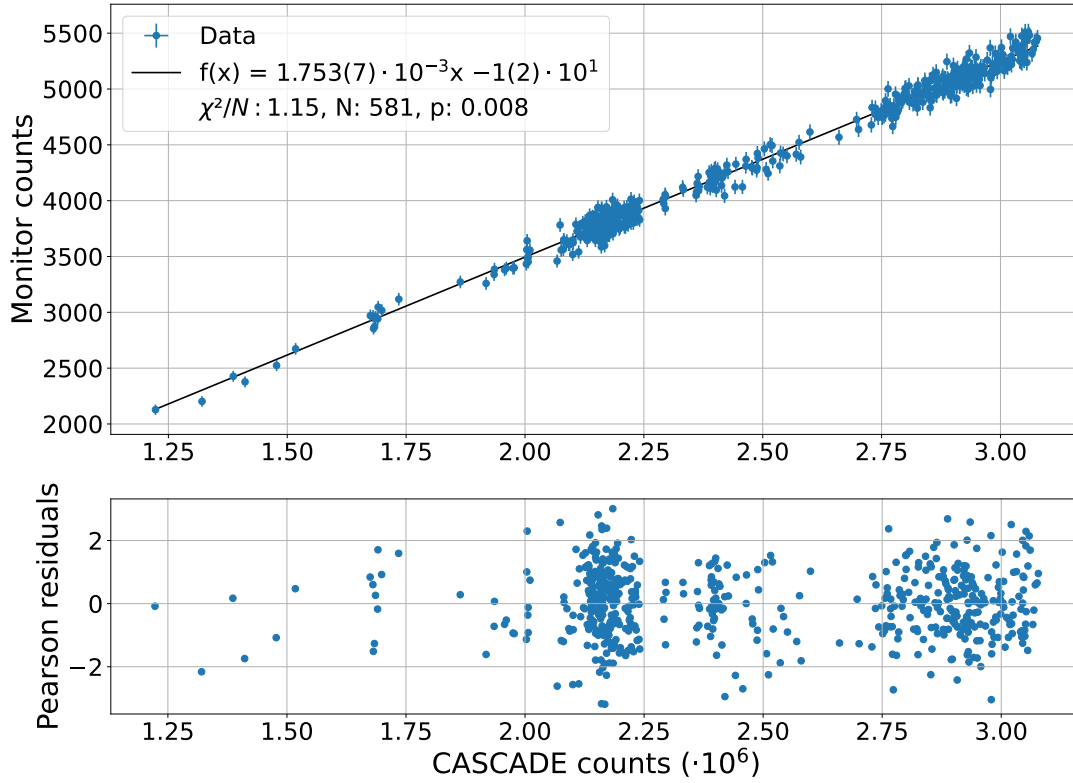


FIGURE 5.37: Counts in the monitor detector plotted against CASCADE counts with a weighted linear fit (top) and the Pearson residuals (residuals divided by uncertainty estimator) of that fit (bottom). The error bars of the points represent the Poisson error. The plot includes all measurements taken during the test beamtime, operated at the optimized settings (see Table 5.5). The wide range of counts is caused by the drift of the UCN source performance. One can clearly see the linear dependence between the counts of the two detectors and the offset of the fit is compatible with zero. The reduced χ^2 of the fit is larger than 1, but the Pearson residuals do not show any obvious higher-order dependency and almost no bias, with a mean of 0.009.

is the same as the one displayed in Fig. 5.37. The measurements were binned by temperature into bins with a width of 0.5°C . The data points represent the weighted means of the temperature and the count ratio in those bins. The temperature error bars represent the standard deviation, while the error bars on the count ratio represents the standard error of the mean. There is a visible reduction of the count ratio with temperature. In general, a reduction would fit to a decreasing SiPM gain, however it is not trivial to determine on what level the SiPM gain contributes, since the count ratio is influenced by both detectors. Additionally, it should be noted that the measured temperature follows a day-night cycle, so other effects, which are not directly caused by the temperature but correlate with the day-night cycle, might affect this result. Over the whole temperature range of $5.69(4)^\circ\text{C}$, the count ratio decreases by $5.2(10) \cdot 10^{-5}$, a relative reduction of about $3.0(6)\%$. For small temperature differences this effect gets much smaller. While the observed effect is relatively small, it is larger than the possible effect of voltage fluctuations. The effect over the full temperature range is comparable to a change of 0.4 V in SiPM bias voltage. To conclude, a slight reduction

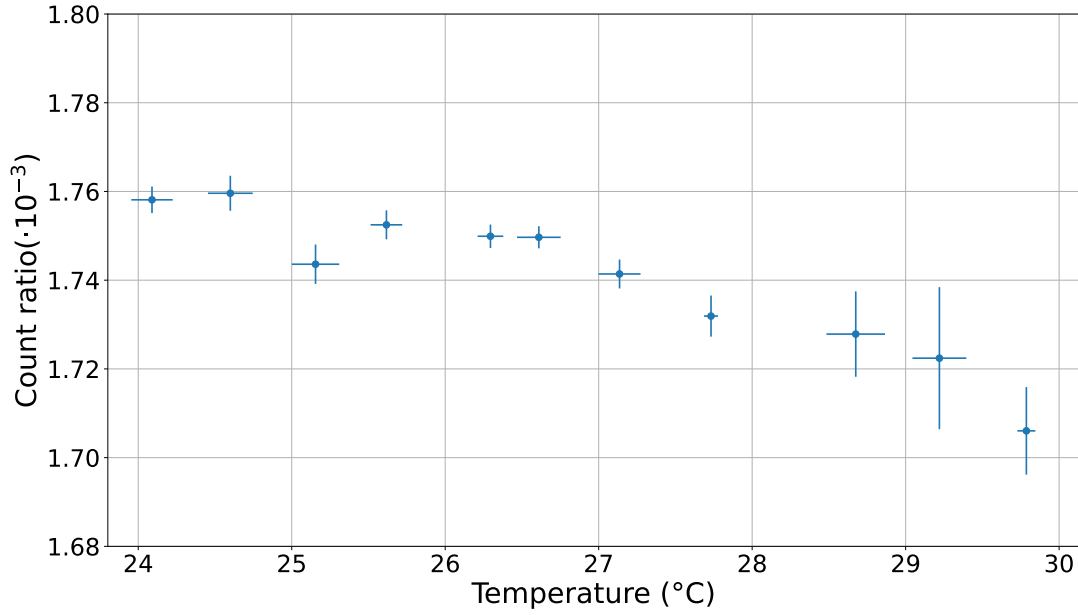


FIGURE 5.38: Plot of the count ratio against the measured temperature of the detector flange. Measurements were binned by temperature into bins with a width of 0.5°C . Data points represent the weighted means of temperature and count ratio within those bins. The error bars on the temperature represent the standard deviation and the error bars on the count ratio represent the standard error of the mean. All measurements for this plot were taken using the optimized settings, see Table 5.5. No dedicated temperature scan was done, the temperature changes are caused by environmental temperature. One can observe a decrease in count ratio with increasing temperature.

of the count ratio with rising temperature can be observed. This effect could contribute to the slightly raised reduced χ^2 reported in Fig. 5.37. Since the ambient temperature normally does not fluctuate rapidly, this effect does not have significant influence when comparing measurements taken close together in time. However, especially for longer measurement campaigns in not-temperature-stabilized environments, it could become relevant. To reduce the effect in the future, one can compensate for the temperature dependence of the SiPMs breakdown voltage, by readjusting the bias voltage based on the temperature readings. This can be implemented easily in the software. The safer and more general approach would be to temperature stabilize the detector or its environment.

All measurements discussed so far were performed with an aperture of 2 mm radius. To investigate the influence of the aperture size on the counts, I measured using three different aperture radii. Fig. 5.39 shows the resulting count ratios. The naive expectation that the count ratio increases proportional with the active detector area (quadratic with the radius) is visualized by a dashed line. However, the measured count ratio rises faster than this expectation. A possible explanation is that the aperture's thickness of 6 mm (see Sec. 5.2) is comparable to its radius. Therefore, increasing the radius does not only increase the active detector area, but also the solid angle for neutron trajectories which hit the detection area directly without touching the aperture surface first. For example, for a neutron at the center of the aperture, the unobstructed solid angle is 0.014π for a radius of 1 mm, and 0.105π for a radius of 3 mm. This is an increase in solid angle by a factor of 7.5. Since there is some probability to lose a UCN whenever it touches a material

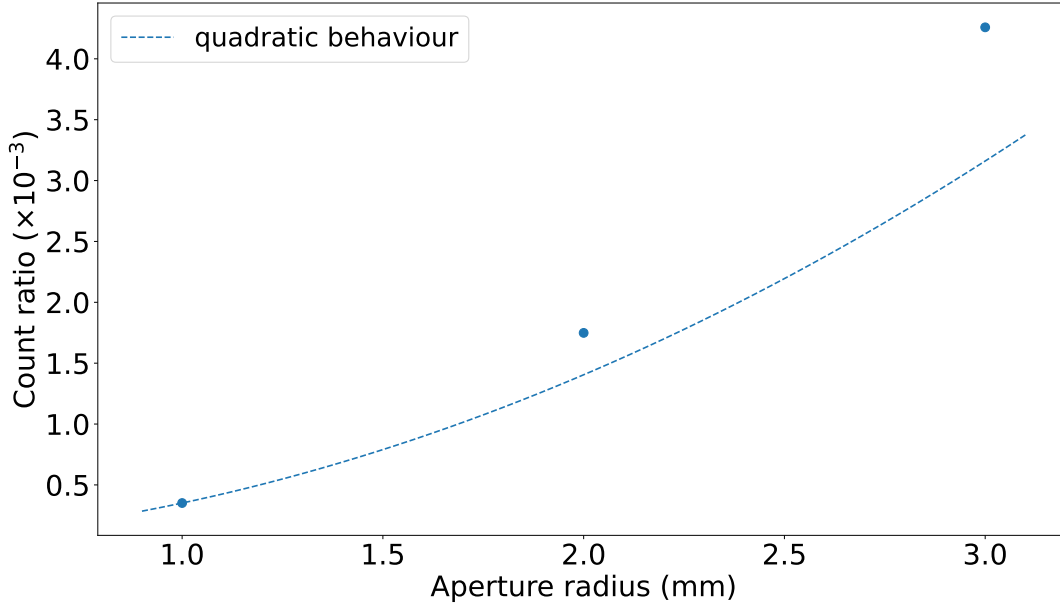


FIGURE 5.39: Count ratio plotted for different aperture radii. Data points represent the mean and measurements error bars represent the standard error. Error bars are mostly covered by the markers. A dashed blue line represents the naive estimation of a quadratic increase of the count ratio with the radius. The count ratio increases faster than this estimation.

surface, the increase in solid angle leads to additional neutrons reaching the detection surface. For future operation with τ SPECT, the aperture with the largest radius (3 mm) was selected in order to maximize the counting statistics.

To compare the performance of the two monitor-detector versions, I took a set of reference measurements using version 1 of the detector electronics. Fig. 5.40 shows a histogram of the relative occurrences of the count ratio for both versions. Both versions were operated at their operational settings and both versions used the 2 mm radius aperture. As a guide to the eye, normal distributions with the mean and standard deviation of the respective datasets are plotted. The mean count ratio of version 1 (blue, on the left) is $1.373(2) \cdot 10^{-3}$ and of version 2 (orange, on the right) is $1.749(1) \cdot 10^{-3}$. This is an increase of 27% from version 1 to version 2. The standard deviation increased by only about 4% from $2.8 \cdot 10^{-5}$ to $2.9 \cdot 10^{-5}$. In conclusion, the upgraded detector detects significantly more neutrons with lower relative fluctuation.

To summarize, version 2 of the monitor detector has been commissioned successfully. At its optimized settings, the detector is basically background-free and its measurements are in strong agreement with the results of the CASCADE detector. Version 2 has an improved detection efficiency and counts 27% more neutrons than the previous version. At this point the detector is ready for operation with τ SPECT.

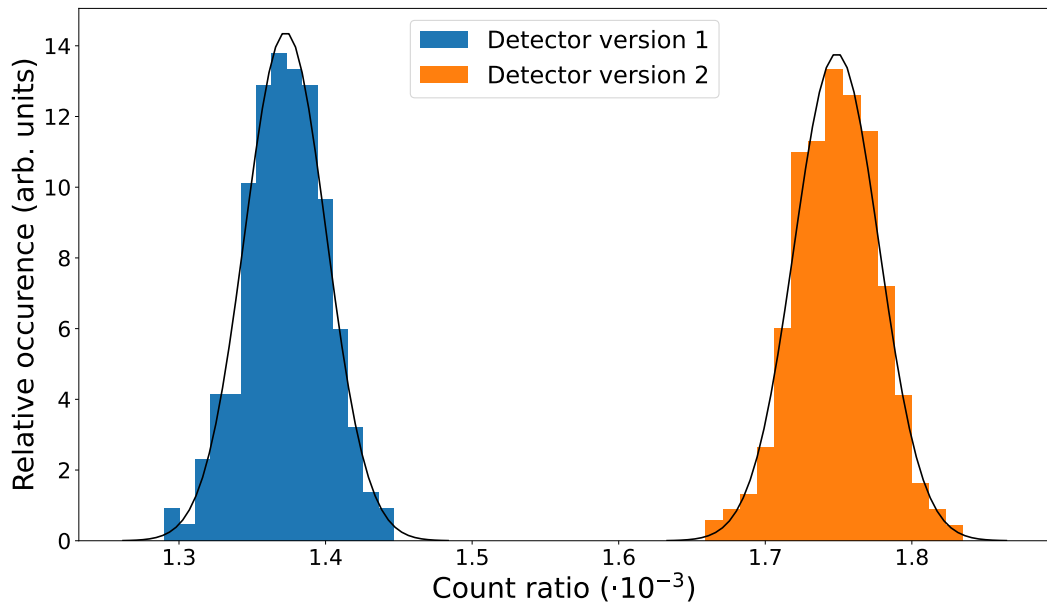


FIGURE 5.40: Comparison of relative occurrence of the count ratio for version 1 (blue, left) and version 2 (orange, right) of the detector. Both versions used their optimal settings. Histograms have been rescaled such, that the area under the histograms integrates to 1. As a guide to the eye normal distributions have been plotted in black using the mean and the standard deviation of the respective datasets. Version 2 has a significantly higher count ratio with a mean of $1.749(1) \cdot 10^{-3}$ compared to $1.373(2) \cdot 10^{-3}$ for version 1. The standard deviations are comparable at $2.8 \cdot 10^{-5}$ for version 1 and $2.9 \cdot 10^{-5}$ for version 2.

6

Operation of the monitor detector with τ SPECT

In chapter 5, I discussed the development and characterization of both versions of the monitor detector. This chapter focuses on the operation of the monitor detector in conjunction with the τ SPECT experiment. Since the start of the operation of τ SPECT at beam port West-1 of the UCN source at Paul Scherrer Institute (PSI) a monitor detector was operated in parallel to the experiment. Initially, version 1 was used and since September 2024 version 2 has been in operation. In this chapter, I will first describe the installation of the monitor detector on the τ SPECT apparatus and its application for source monitoring. I will then present two approaches of normalizing τ SPECT measurements using data from the monitor detector.

6.1 Monitor detector in the experimental setup of τ SPECT

The typical setup of the monitor detector with τ SPECT can be seen in Fig. 6.1. The entrance shutter of the experiment (1) is connected to the detector flange (3) by a horizontal 66 cm long piece of beamline (2). The detector flange is mounted to the top of the vertical beamline section (4). The bottom of the vertical beamline section is connected to the beamport (not visible because of the concrete block). $^{58}\text{Ni:Mo}$ (85:15)-coated plates mounted at a 45° angle are used to direct the neutrons through the 90° angles on top (4a) and bottom (not visible) of the vertical beamline section. All beamline pieces are made from stainless steel ($V_F = 190 \text{ neV}$, [Alt+08]) and have an inner diameter of 66 mm. The beamport has an inner diameter of 180 mm.

The horizontal configuration stays the same for all measurements discussed in this chapter. When the τ SPECT cryostat is moved vertically, only the length of the vertical section is modified. This ensures that the detector flange is always on the same height as the entrance shutter. This setup complicates comparison of measurements taken with τ SPECT at different vertical positions, because the monitor detector moves with the cryostat. However, it has the advantage that the monitor detector always gives information on the neutron flux which reaches the height of the experiment entrance. Additionally, mounting the detector flange to the top of the vertical beamline allows for easier adjustments of the vertical beamline in the future. An example for such an adjustment would be the increase of the beamline diameter.



FIGURE 6.1: Picture of the monitor detector version 1 in operation with τ SPECT at PSI. The entrance shutter of the experiment (1) is connected to the detector flange (3) by a horizontal 66 cm long piece of beamline (2). The detector flange is mounted to the top of the vertical beamline section (4). The bottom of the vertical beamline section is connected to the beamport. $^{58}\text{Ni:Mo}$ (85:15)-coated plates mounted at a 45° angle are used to direct the UCNs through the 90° angles on the top (4a) and bottom (covered by the concrete block) of the vertical beamline. The monitor-electronics version 1 (5) can be seen in the foreground. When the experiment cryostat is moved to another height, the length of the vertical section is adjusted.

A typical measurement result taken with version 2 of the monitor detector positioned in front of τ SPECT is shown in Fig. 6.2. In this setup, the center of the experiment's entrance shutter was located 59 cm above the center of the beamport. All measurements presented in this chapter were taken at that same height. The counts are binned in 1 s intervals, and the monitor detector recorded data for 240 s after each kick. We expect a similar time structure as observed in the testing of monitor version 2 (See Fig. 5.31) and in the measurement with version 1 at PSI with τ SPECT presented in Fig. 5.29: a strong rise in counts in the first 10 s followed by an exponential decline over time. This expected behaviour is visible, but an additional feature appears at about 30 s, where the counts increase again, forming a second peak. This second peak is caused by the closing of the experiment's entrance shutter, which is marked by the dashed line in the figure. Once the shutter is closed, UCNs which would have entered τ SPECT, are now reflected by the shutter instead. This likely leads to an increased neutron density in the beamline. The feature is absent in the test measurements of version 2, since they were conducted without τ SPECT and therefore

without the experiment’s entrance shutter. The feature is present in Fig. 5.29, but it is much less pronounced due to lower counting statistics. This effect has to be considered in the analysis, since it indicates that the shutter opening duration can influence the monitor measurement. In this work the issue is addressed by only comparing data taken with identical shutter open durations. A more detailed analysis of this effect is possible in future studies.

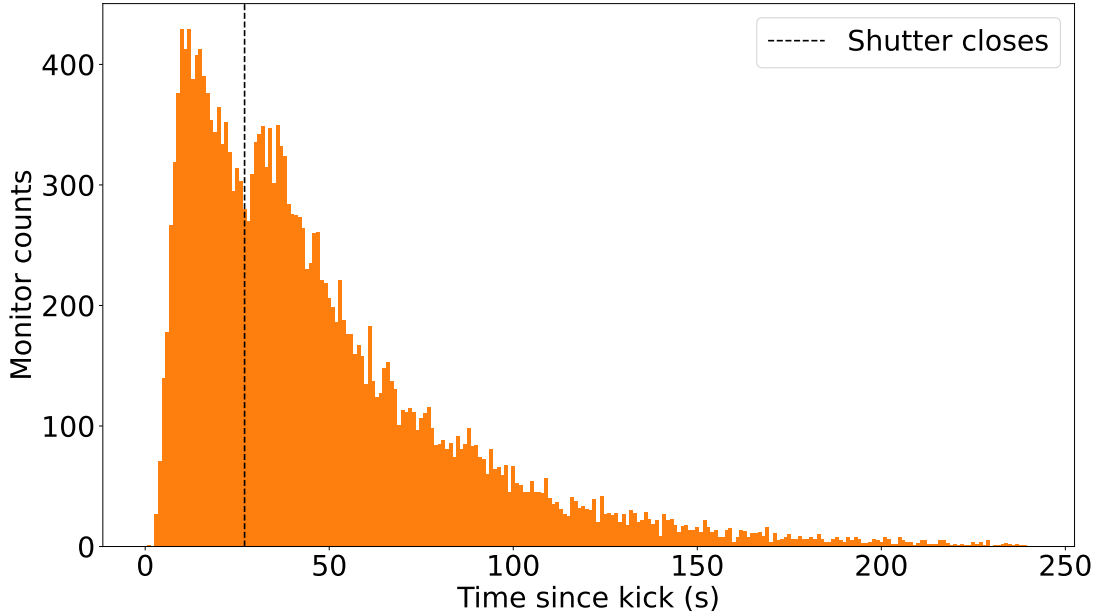


FIGURE 6.2: Counts measured by the monitor detector plotted against the time since kick. This measurement was taken with version 2 of the monitor detector, the center of the experiment shutter was at a height of 59 cm above the center of the beamport. Counts have been binned into 1 s wide bins. The monitor detector measured for 240 s after the kick. The dashed line represents the time at which the experiments entrance shutter closes. After the kick, a steep rise in counts can be observed, the counts then start to reduce with time. Shortly after the entrance shutter closes a second peak in counts can be observed.

6.2 UCN source monitoring

The most immediate use of the monitor detector running in parallel to τ SPECT was to identify outliers in the source output. This way, measurements during which the source was not operating properly can be flagged.

In addition, the monitor detector is used to detect two regularly occurring changes to the source state. The first change, called “source conditioning”, is a procedure to recover the UCN yield of the source [Bis+22]. At PSI, conditioning is usually repeated on the order of days and the process takes about 1 h. Conditioning can be carried out in parallel to the source operation and therefore also in parallel to operation of τ SPECT and the monitor detector. However, during conditioning a drop in source output has been observed ([Doo24], page 53). The second regularly occurring change to the source state is the change of the state of the Neutronenleiterklappe (NLK) (neutron-guide flap) at the port South of the UCN source, which will be referred to as “NLK South” in this work.

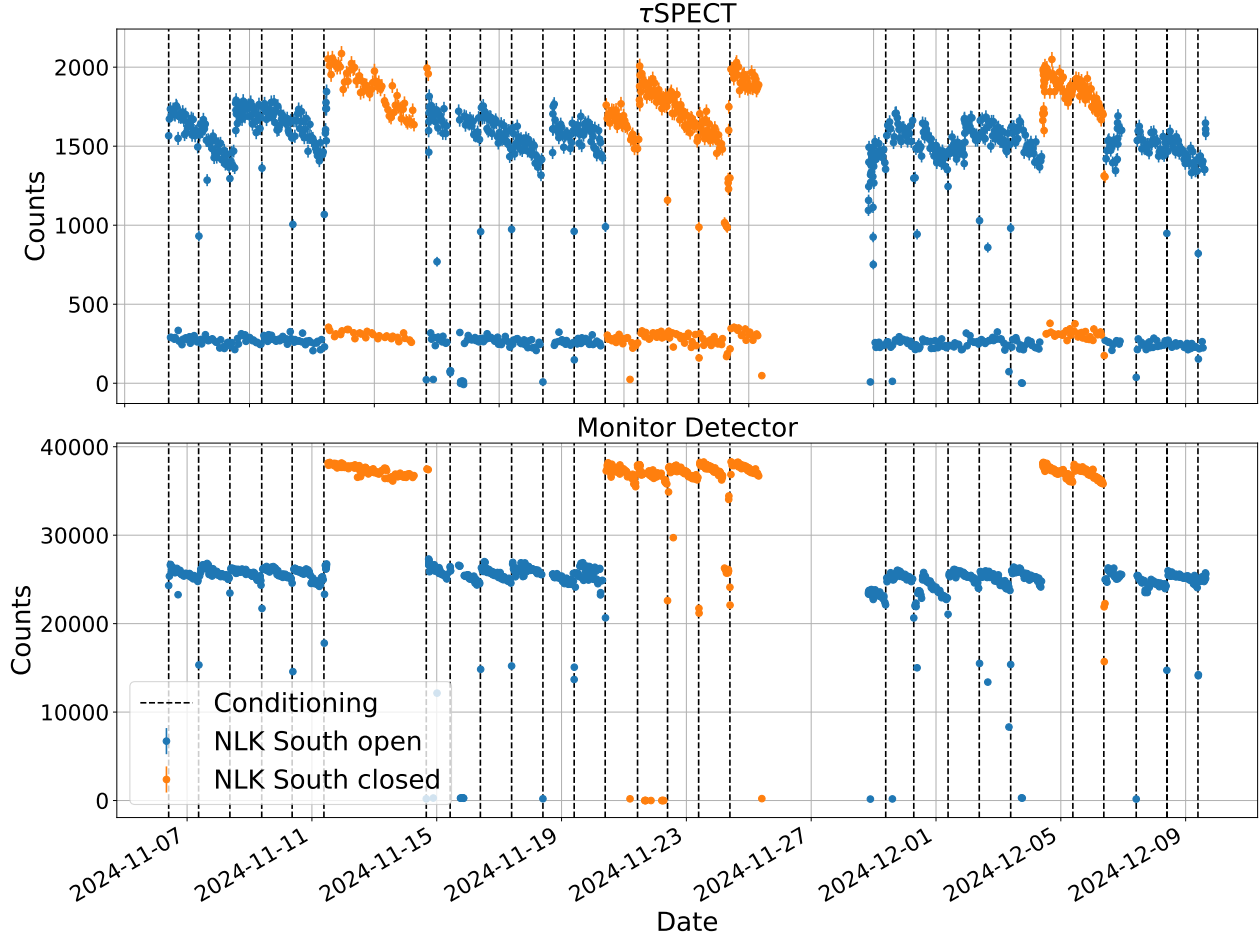


FIGURE 6.3: Data acquired during a measurement campaign in 2024. The top plot shows the counts measured with τ SPECT. The bottom plot shows the measurement results of the monitor detector. Measurements taken while NLK South was open are colored in blue and while it was closed in orange. The dashed black lines represent the times of the source conditioning. The horizontal bands in the top plot are caused by different neutron storage times. Closing NLK South leads to a clearly visible increase in monitor counts. Measurements taken during conditioning show reduced counts. Measurements without any counts are caused by malfunction of τ SPECT, the monitor detector, or the source.

The UCN source at PSI has three beamports: port West-1, West-2, and South, all are connected to the same storage vessel. τ SPECT is positioned at port West-1. Port South is used by the n2EDM experiment. When n2EDM does not require UCNs, NLK South is closed. In this state, the UCN output at port West-1 increases compared to when NLK South is open. Port West-2 is elevated 2.3m above the other two beam ports. So far no significant impact of the state of West-2 on the UCN flux at port West-1 has been observed [Rie22, pp. 35–36].

Fig. 6.3 shows data acquired during a measurement campaign in 2024, to visualize the discussed effects. The top panel shows the counts measured by τ SPECT. The τ SPECT data contains a drift which I will discuss in more detail in Sec. 6.3.1. The bottom plot shows the measurement results of the monitor detector. Measurements with NLK South open are represented in blue and with NLK South closed in orange. The dashed black lines represent the times of the source conditioning. The horizontal bands in the top plot are caused by different storage durations. Closing NLK South causes a clearly visible increase in the monitor counts of about 30%. The effect is harder to see in

the τ SPECT counts. Measurements taken during conditioning show reduced counts. The monitor counts show a sawtooth pattern which is caused by the periodical conditioning (more details can be found in Sec. 6.3.1). Measurements without any counts are caused by a malfunction of τ SPECT, the monitor detector, or the source and are discarded.

The monitor detector has proven to be a useful tool for detecting changes of the source and for excluding outliers caused by irregularities in the UCN production.

6.3 First approaches to normalization

As discussed in Sec. 5.1, a central objective of employing the monitor detector is to correct τ SPECT measurements for variations in the UCN source output. In this section I cover the analysis done on data of two measurement campaigns. I discuss the normalization approach, identify its main challenge, and introduce two methods to address it.

I have already demonstrated in this work, by comparison of measurements of the monitor detector with the measurement results of a CASCADE detector (see Sec. 5.6.3), that the monitor detector gives an reliable representation of the UCN output of the PSI source. For the purpose of normalization I make the simplifying assumption that the number of UCNs stored in τ SPECT is proportional to the source output and therefore to the monitor-detector counts. Under this assumption, normalization can be done simply by dividing the τ SPECT counts, N_τ , by the monitor counts N_m

$$r(N_m, N_\tau) = \frac{N_\tau}{N_m}. \quad (6.1)$$

The statistical uncertainty of this ratio is given by

$$\sigma r(N_m, N_c) = \left(\left(\frac{\sigma_\tau}{N_m} \right)^2 + \left(\frac{\sigma_m N_\tau}{N_m^2} \right)^2 - 2\sigma_m \sigma_\tau p_{m\tau} \frac{N_\tau}{N_m^3} \right)^{\frac{1}{2}}, \quad (6.2)$$

where σ_τ and σ_m are the standard deviations of N_τ and N_m and $p_{m\tau}$ is their correlation coefficient.

It should be mentioned that, unlike in the measurements with the CASCADE detector in Sec. 5.6.3, the monitor detector and τ SPECT do not sample the same energy spectrum of neutrons. With the center of the experiment's entrance shutter as reference height, the monitor detector is able to detect UCNs independent of their kinetic energy (apart from a lower cut-off at about 5 neV due to gravitational potential). τ SPECT, on the other side, can only store neutrons which reach the center of the entrance shutter with kinetic energies within specific ranges. When filling using a single spin flip (sSF), neutrons in the energy range of [0 neV, 18.9 neV] can be stored and when filling using the double spin flip (dSF), kinetic energies in the range of [108 neV, 144 neV] are needed, see Sec. 4.1. This means that shifts in the energy spectrum of the source output can affect the number of stored neutrons and the monitor detector differently, which could lead to systematic effects. This issue is planned to be addressed beyond this thesis by adding additional monitor detectors at different heights along the beamline, which will give information on the energy spectrum of the UCNs.

To evaluate the effectiveness of a normalization approach, a data set is needed in which τ SPECT repeatedly performs the same measurement using identical settings. This allows the assumption that the dominant factor responsible for changes in the amount of stored neutrons are the changes

in the neutron-source output. These changes can then be accounted for by using data from the monitor detector. In this thesis I analyze two such data sets from:

1. A measurement campaign conducted in October 2024 to investigate the cleaning process of τ SPECT.
2. The first scientific data run of τ SPECT at PSI, done in November and December 2024.

Both campaigns used the version 2 of the monitor detector, operated at the standard parameters (see Table 5.5). In both cases τ SPECT was filled using the dSF technique (see Ch. 4). I will first analyze data of the cleaning investigation campaign. Insights from that analysis will then be applied to the scientific run, which is the larger data set and contains blinded measurement data.

6.3.1 Structure and analysis of the 2024 cleaning investigation campaign

I will first give a short overview on how the cleaning investigation measurement campaign in October 2024 was structured. To understand the following description, one should first become familiar with the τ SPECT measurement procedure, a description of that procedure is presented in chapter 3. The October 2024 campaign consists of multiple measurement blocks, which are named alphabetically A, B and C. Between these blocks the duration of the cleaning procedure t_{clean} and/or the position of the detector during the cleaning procedure were changed. For the analysis that simply means that different measurement blocks cannot be compared regarding normalization. During each block measurement pairs consisting of a measurement with a short storage duration $t_{st1} = 50$ s and a measurement with a long storage duration $t_{st2} = 1250$ s were measured repetitively for several days.

At this point, I will introduce how the τ SPECT counts and the monitor-detector counts were calculated for the analysis. The raw τ SPECT detector counts were adjusted by subtracting an estimate for the τ SPECT detector background. I estimated the detector background by summing the counts in the detector data during the storage period of the long measurements. However, the background estimation is further complicated by periodic increases of the background. Those increases have two main causes: 1. The proton pulses on the spallation target of the UCN source, which occurred at the pulse repetition rate of 400 s^{-1} , and 2. increased radiation from the source's cooling water system which occurs about 55 s after the kick and repeats with the circulation time of the system which is 52 s [Jor09, p. 50]. The counting window has been chosen such that it is unaffected by these contaminations, but they periodically increase the background during storage. Therefore, I defined several exclusion windows and calculated the background using only counts outside of those windows. To estimate the τ SPECT detector background, I assumed that the background has a constant rate throughout the whole measurement campaign and one common background rate $\rho_b = 0.872(2) \text{ s}^{-1}$ was calculated.

The background-corrected τ SPECT counts are then given by

$$N_\tau = N_c - \rho_b \cdot t_c, \quad (6.3)$$

where N_c are the counts within the counting window and $t_c = 190$ s is the length of the counting window. An estimator for the statistical uncertainty of the background-corrected counts is given by

$$\sigma_{N_\tau} = \sqrt{N_c + (\sigma_{\rho_b} \cdot t_c)^2 + (\rho_b \cdot \sigma_{t_c})^2} \approx \sqrt{N_c}. \quad (6.4)$$

This term is dominated by the Poisson error on N_c , because the uncertainty of the background rate and the uncertainty of the duration of the counting window σ_{t_c} are comparatively small. The background of the monitor detector has been discussed in Sec. 5.6.3 and electronic background and background due to γ -radiation can be considered negligible for the purpose of these measurements. Nonetheless, in this analysis, I discard the first 8 s of each monitor data set, to reduce potential contamination by neutrons with slightly higher energies than UCNs in the beamline. The error of the monitor counts is estimated to be the Poisson error. The correlation between the monitor counts and the τ SPECT results is only investigated for the short-storage duration measurements, since their counting statistic is significantly better than the one of the measurements with a longer storage duration. To ensure data quality, only measurements with more than 30,000 monitor counts were considered when NLK South was closed, and only those with more than 20,000 monitor counts were considered when NLK South was open. This way 13 of a total of 355 measurements were rejected.

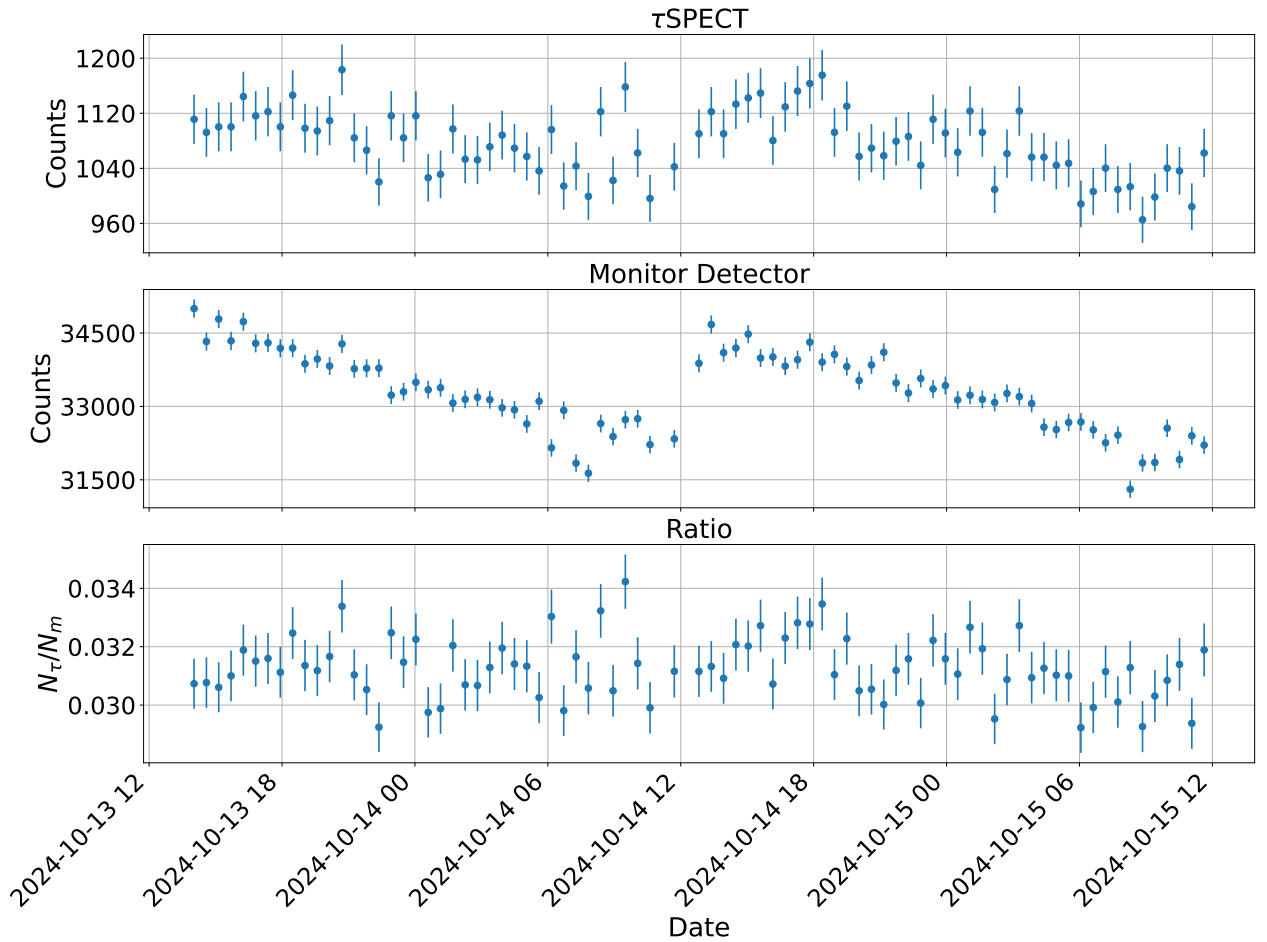


FIGURE 6.4: Data taken in the first 48 h of measurement block A. τ SPECT counts (top), monitor-detector counts (middle), and their ratio (bottom) plotted against the measurement date. Error bars on the τ SPECT measurements represent the error derived in Eq. (6.4). Error bars on monitor-detector counts represent the Poisson error. The error for the ratio has been calculated as in Eq. (5.11). The monitor counts show a clear 24h pattern, which is caused by the daily source conditioning and the reduction in source yield over time. The same pattern can be seen in the τ SPECT counts. The ratio remains approximately constant over the whole time period

Fig. 6.4 shows the measurement results of the first 48 h of the 96 h of measurement block A. During

this block NLK South was open. The background-corrected τ SPECT counts, the monitor-detector counts, and their ratio are plotted against the measurement date. The monitor counts show a clear decline over the first 24 h, followed by a sudden increase, after which the decline starts again. This pattern reflects the typical behavior of the source. The decline is caused by the reduction in source yield over time and the sudden jump is caused by the source conditioning which recovers lost source yield. This trend is also reflected in the τ SPECT counts. The ratio remains approximately constant over time which is an indicator that the normalization approach corrects for changes in the source output.

Fig. 6.4 shows only a subset of block A. The complete data set is shown in Fig. 6.5, where the previously displayed 48 h window is marked by dashed lines. As before, the τ SPECT counts, the monitor-detector counts, and their ratio are plotted against the measurement date. The characteristic pattern caused by the source conditioning can be seen again in both monitor and τ SPECT counts throughout the complete data set. Additionally, a reduction in τ SPECT counts and count ratio can be observed after 48 h. This reduction is resolved when the rf frequency of spin flipper 1 (SF1) is changed from 29.3505 MHz (blue) to 29.348 MHz (orange).

This reduction was first observed during this measurement campaign. Subsequently, the cause was found to be a drift of τ SPECT's main magnetic field. Although the superconducting main coils are in persistent mode, the field slowly decreases over time. The drift was measured using the NMR probe mounted near SF1, which was introduced in Sec. 4.3.1. A linear regression of multiple measurements taken over 45 h resulted in a drift of $1.08(5) \mu\text{T h}^{-1}$ [Pfe24], corresponding to about $26(1) \mu\text{T d}^{-1}$. A change in the main field results in a shift of the neutron Larmor frequency within the spin flipper. Using the neutron gyromagnetic ratio $\gamma_N = 29.164\,693\,5(69) \text{ MHz T}^{-1}$ [Moh+25, p. 48], the field drift is equivalent to a decrease of about $0.76(3) \text{ kHz d}^{-1}$ in neutron Larmor frequency. This shift causes the frequency of the applied rf magnetic field to deviate from the optimal spin-flip frequency, which reduces the effectivity of the dSF-filling method and, thus, the amount of neutrons stored in τ SPECT. This time-dependent effect presents a significant challenge, as it violates the assumption that the source's fluctuations are the dominant cause for changes in stored neutrons. In principle, normalization for source effects using the monitor detector is still possible. However, making a quantitative statement about the quality of that normalization is difficult, as it is not possible to distinguish whether variations in the τ SPECT counts are due to source effects that the monitor detector is not affected by, or due to changes in the performance of τ SPECT itself. To be able to make a such statement, the normalization analysis has to be restricted to a time window in which the effect of the field drift remains comparably small.

To find such a window we have to estimate the dependence of the amount of stored neutrons on the field change. Under the assumption that a change in field is equivalent to a detuning of the spin flipper frequency, we can use the results of a frequency scan for this estimation. Before each measurement block the frequency of SF1 was shortly scanned to find the optimal frequency. These scans were done with a storage time of 50 s and without cleaning. Fig. 6.6 shows this scan for measurement block A. This measurement was taken at October 13, just before the data set shown in Fig. 6.5. The τ SPECT counts are plotted against the applied frequency of SF1. Note, that the amounts of counted neutrons are higher overall, because these measurements were done without cleaning. A clear nonlinear dependence of counts with frequency can be seen. The counts reach a maximum for a frequency of 29.3505 MHz, so this frequency was chosen for operation. When the frequency is detuned by 2.5 kHz the amount of stored neutrons reduces by more than 10%. In order to define a frequency window in which the influence of the field drift is not a dominant factor, we estimate a frequency window in which the count reduction is comparable to statistical fluctuations.

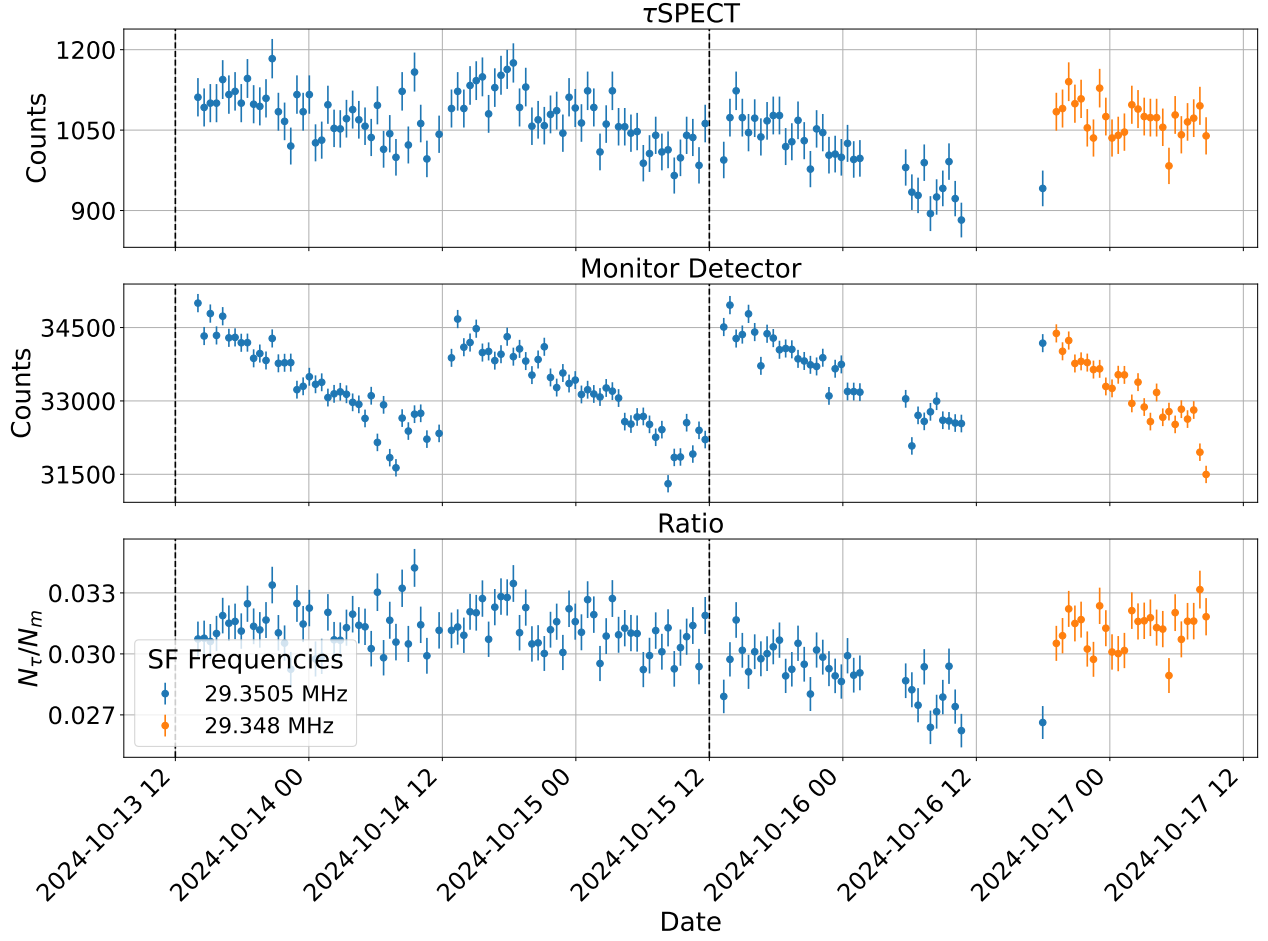


FIGURE 6.5: Time evolution of the measurement results of measurement block A. τ SPECT counts (top), monitor-detector counts (middle) and their ratio (bottom) are plotted against the measurement date. Different colors indicate different frequencies applied to SF1. The dashed lines mark the window displayed in Fig. 6.4. Error bars on the τ SPECT measurements represent the error derived in Eq. (6.4). Error bars on monitor-detector counts represent the Poisson error. The error for the ratio has been calculated as in Eq. (5.11). A clear 24 h pattern is visible in the monitor counts. It is caused by the daily source conditioning and the reduction in source yield over time. The same pattern can be seen in the τ SPECT counts. A decline in count ratio and τ SPECT counts becomes noticeable especially after about 70 h. This reduction is not standing out in the first 48 h. A recovery in both τ SPECT counts and ratio occurs when the rf frequency of SF1 is changed from 29.3505 MHz (blue) to 29.348 MHz (orange).

For this, we define the Z-score of the difference of counts N to the maximum counts N_0 .

$$Z(N) = \frac{N_0 - N}{\sqrt{\sigma_N^2 + \sigma_{N_0}^2}} \approx \frac{N_0 - N}{\sqrt{2\sigma_{N_0}^2}}, \quad (6.5)$$

where σ_{N_0} and σ_N are the estimators for the standard deviation of N_0 and N . For similar counting statistic we can assume that $\sigma_{N_0} \approx \sigma_N$. If the Z-score is smaller than 2, we consider the effect to be comparable to the statistical fluctuation. We define the frequency window as the difference of the operation frequency to the smallest frequency with a Z-score smaller than 2. The shaded area in Fig. 6.6 marks the counts for which the Z-score is smaller than 2. For measurement block A, the

frequency difference is 1.5 kHz, which corresponds to a field drift over about 47(2) h. Therefore, it is assumed that the field drift has a small influence on the amount of stored neutrons within 47 h after the frequency scan. Table 6.1 gives an overview of the measurement blocks and their calculated time windows.

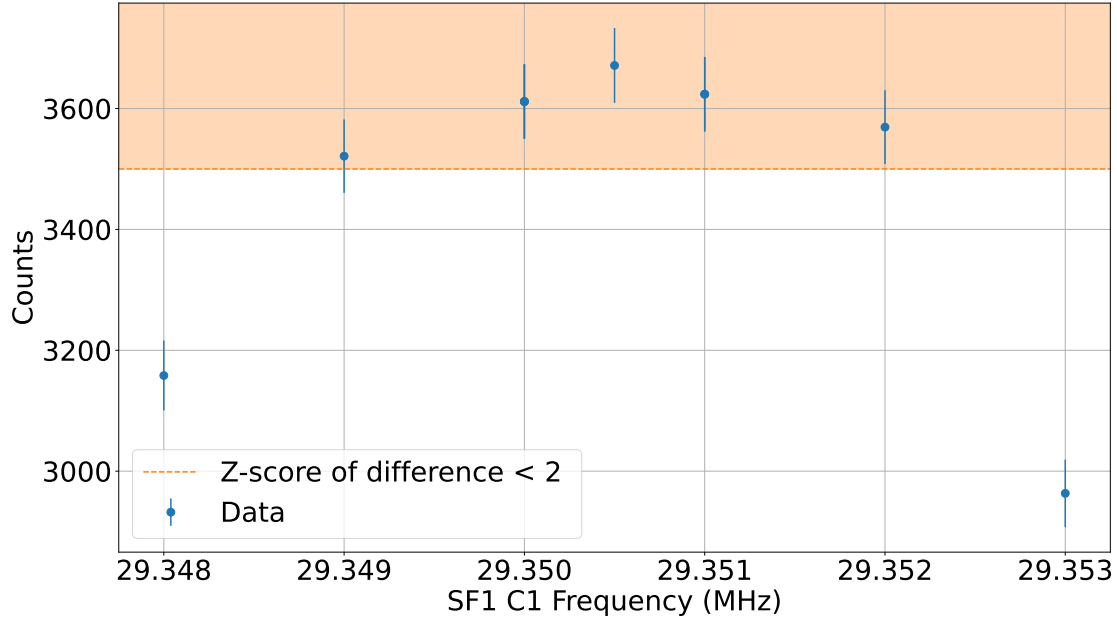


FIGURE 6.6: Background-corrected counts measured with τ SPECT plotted against the applied rf frequency of SF 1. These measurements were done without cleaning and with a 50 s storage duration. The error bars represent their estimated standard deviation, see Eq. (6.4). The counts reach a maximum for 29.3505 MHz. Detuning from the optimal frequency by 2.5 kHz already leads to a reduction of stored neutrons larger than 10%. The shaded area marks counts for which the Z-score of the difference to the maximum is smaller than 2.

Block	SF1 frequency (MHz)	Time window (h)	NLK South state	Measurement date
A	29.3505	47(2)	closed	2024-10-13
B	29.356	32(1)	open	2024-10-7
C	29.353	47(2)	mixed	2024-10-9

TABLE 6.1: Overview of the investigated measurement blocks. Given are: the used SF1 frequency, the time window for which the effect of the field drift is considered small, the state of NLK South, and the date of the first measurement.

The data within those time windows was then analyzed for each measurement block. To test the hypothesis of proportionality between the τ SPECT and the monitor measurements, a weighted linear regression without offset was performed for each data set. The inverse of the variance of N_τ was used for the weights. The χ^2 of the fit was calculated using the effective variance, this means by propagating the x -error into the total variance. The 1σ confidence interval of the fit was estimated using error propagation

$$\sigma_f(N_m) = \sqrt{(\sigma_m \cdot N_m)^2 + (m \cdot \sigma_{N_m})^2}, \quad (6.6)$$

where N_m are the monitor counts, m is the slope of the fit, and σ_m is the standard deviation of the slope. The 1σ prediction interval additionally includes the estimated uncertainty of the τ SPECT

counts

$$\sigma_p(N_m) = \sqrt{\sigma_f(N_m)^2 + \sigma_{N_\tau}(N_m)^2}. \quad (6.7)$$

The confidence interval of the fit quantifies the uncertainty of the expected value $E(N_\tau)$ of a future measurement, whereas the prediction interval is the range in which individual future measurements are expected to lie [FTL09, pp. 134–138]. In this work, the confidence interval is used to evaluate the uncertainty of the normalization, while the prediction interval is used to visualize the expected spread of data around the fit.

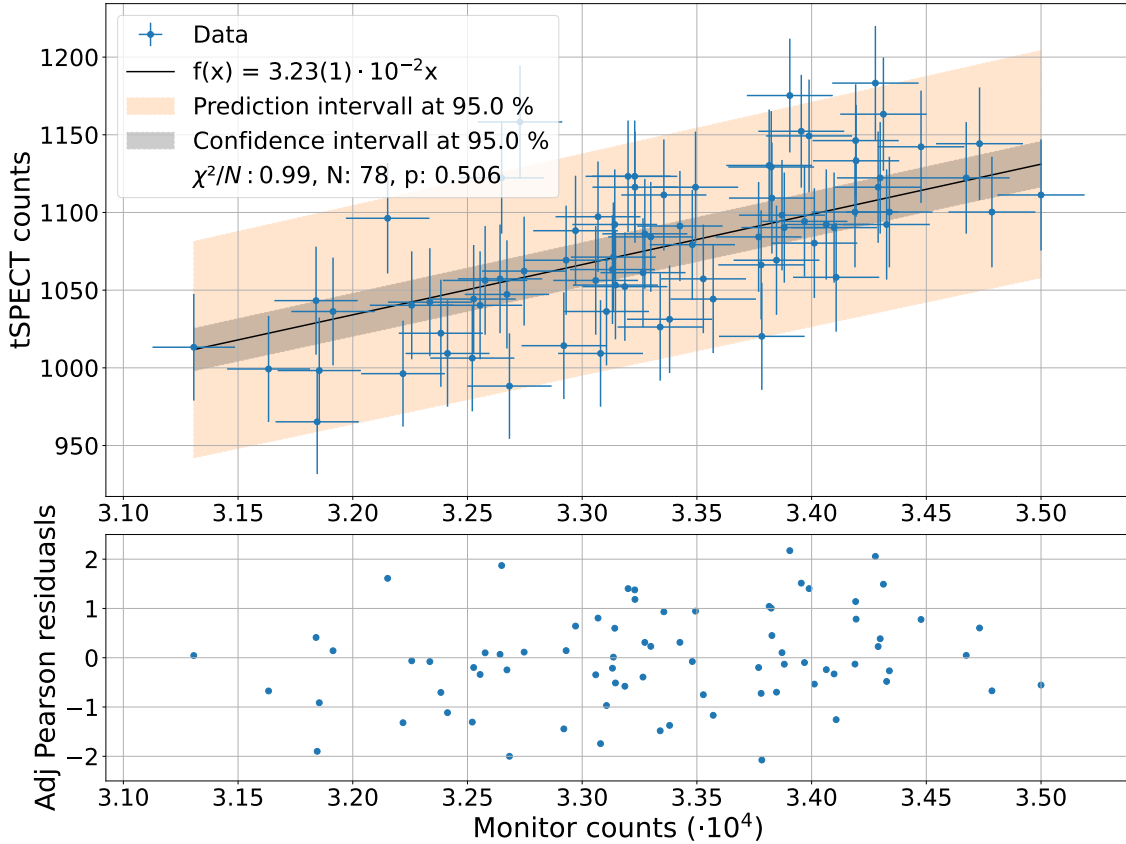


FIGURE 6.7: Analysis result for measurement block A. Background-corrected τ SPECT counts are plotted against the monitor-detector counts in the top panel. The weighted linear fit is represented by a black line. The adjusted Pearson residuals of that fit are shown in the bottom panel. Error bars for the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The dark-shaded region represents the confidence interval of the fit at a confidence level of 95%. The light-shaded region represents the prediction interval at a confidence level of 95%. The adjusted reduced χ^2 is close to 1. The residuals have a mean of 0.012 and a standard deviation of 1.0. They do not show any obvious bias.

Fig. 6.7 shows such a fit applied to the data of measurement block A. In the top panel the τ SPECT counts are plotted against the monitor-detector counts with a weighted linear fit represented by a black line. The dark-shaded region represents the confidence interval of the fit at a confidence level of 95%. The light shaded region represents the prediction interval at a confidence level of 95%. The width of the confidence interval at 33000 monitor counts is about 29 counts and the width of the prediction interval 144 counts. This shows that the prediction interval is dominated by the uncertainty on the τ SPECT counts. The reduced χ^2 is 0.99, resulting in a p-value of 0.506. In the bottom panel, the adjusted Pearson residuals of the fit are plotted. The adjusted Pearson

residuals are calculated by dividing each residual by the estimated effective standard deviation of that measurement. The mean of the residuals is 0.012 and the standard deviation is 1.0. They do not show any obvious bias.

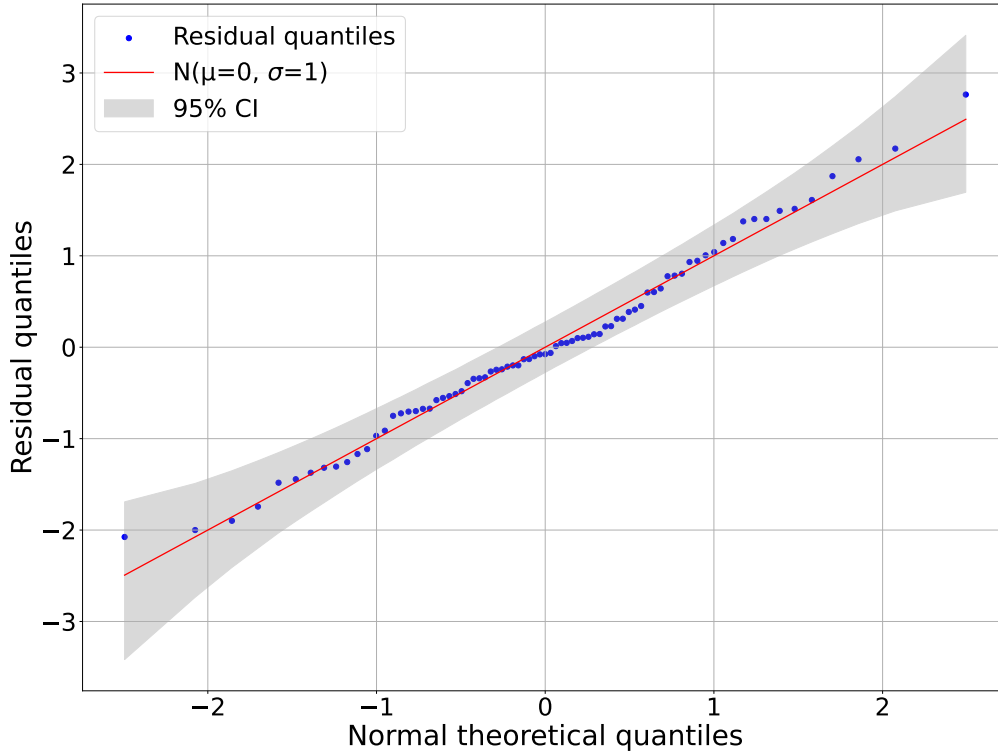


FIGURE 6.8: Quantile-quantile plot comparing the quantiles of the fit residuals with the theoretical quantiles of a normal distribution with mean = 0 and standard deviation 1. The red line represents expected quantiles for a normal distribution with $\mu=0$ and $\sigma=1$. The grey shaded area is the confidence interval at 95%, which was estimated using Monte Carlo methods. The residuals approximately follow the red line and lie within the confidence interval.

To graphically investigate the residuals for normality a quantile-quantile (Q-Q) plot was done and is shown in Fig. 6.8. Here the residuals, sorted by value, are plotted against the theoretical quantiles of the standard normal distribution. The theoretical quantiles were estimated as

$$Q\left(\frac{k - 0.5}{n}\right) = x_k, \quad (6.8)$$

where x_k is the k -th order statistic, n is the sample size and Q is the inverse of the cumulative distribution function of the standard normal distribution. The red line represents expected quantiles of a standard normal distribution ($\mu=0$, $\sigma=1$). The grey shaded area indicates the estimated 95% confidence interval for quantiles drawn from that distribution. It has been estimated using a Monte Carlo simulation by sampling the distribution for the number of residuals 10^5 times. The residuals approximately follow the red line and lie within the confidence interval, suggesting that the residuals are consistent with the assumed normal distribution.

The residuals were additionally investigated for normality by performing a Kolmogorov-Smirnov test for normal distribution, resulting in a test statistic of 0.075 and a p-value of 0.73, which agrees with the result of the Q-Q plot. Overall, the good agreement between fit and data, the χ^2 and the normality of the residuals, indicate that the proportional model adequately describes the

relationship between the monitor-detector counts and the τ SPECT counts within the time window, for measurement block A.

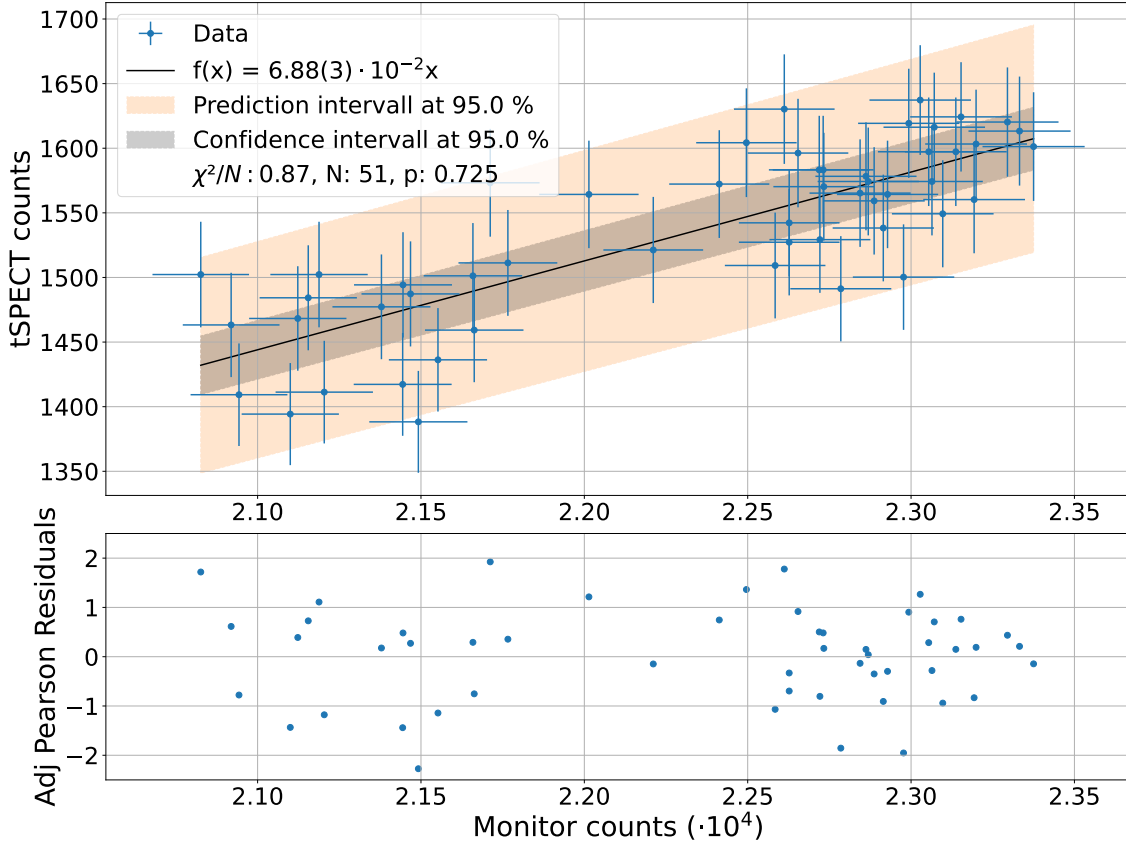


FIGURE 6.9: Analysis results for measurement block B. Background-corrected τ SPECT counts are plotted against the monitor-detector counts in the top panel. A weighted linear fit is depicted by a black line. The adjusted Pearson residuals of that fit are displayed in the bottom panel. Error bars of the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The dark-shaded region represents the confidence interval of the fit at a confidence level of 95%. The light-shaded region represents the prediction interval at a confidence level of 95%. The adjusted reduced χ^2 results in a p-value of 0.725. The residuals have a mean of 0.011 and a standard deviation of 0.95. They do not show any obvious bias.

Fig. 6.9 depicts the fit for measurement block B. In the top panel, the τ SPECT counts are plotted against the monitor-detector counts and the fit is represented by a black line. The dark-shaded region represents the confidence interval of the fit at a confidence level of 95%. The light-shaded region represents the prediction interval at a confidence level of 95%. The width of the confidence interval is about 48 counts and the width of the prediction interval 176 counts. This means that the prediction interval is dominated by the uncertainty of the τ SPECT counts in this measurement block as well. The reduced χ^2 is 0.87, resulting in a p-value of 0.725. In the bottom panel, the adjusted Pearson residuals of the fit are plotted. The mean of the residuals is 0.011 and the standard deviation is 0.95. The residuals do not show any obvious bias. A Kolmogorov-Smirnov test for normal distribution of the residuals resulted in a test statistic of 0.12 and a p-value of 0.45, indicating normality of the residuals.

The good agreement between fit and data, the χ^2 and the normality of the residuals indicate that the proportional model adequately describes the relationship between the monitor-detector counts

and the τ SPECT counts within the time window for measurement block B.

During measurement block C the state of NLK South was changed from open to close. I therefore use this data set to investigate whether measurements with different NLK South states can be grouped together in analysis. Fig. 6.10 depicts the data within the corresponding time window. In the top panel, the τ SPECT counts are plotted against the monitor-detector counts, the fit is represented by a black line. The two NLK states are color coded and they are clearly separated in the plot.

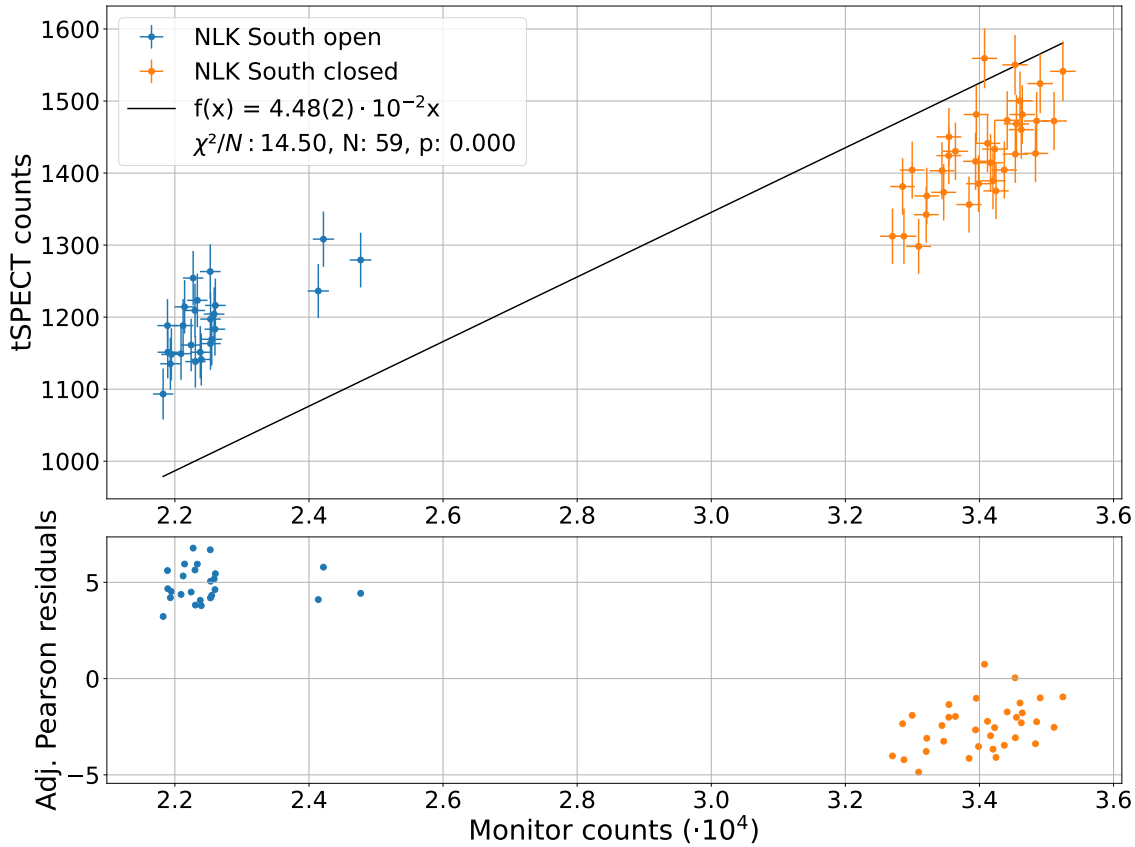


FIGURE 6.10: Analysis of measurement block C. Background-corrected τ SPECT counts are plotted against the monitor-detector counts. The weighted linear fit is represented by a black line. The adjusted Pearson residuals of that fit are shown in the bottom panel. The color of the data points represents the state of NLK South, blue represents open and orange represents closed. Error bars of the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The proportional fit fails to properly describe the combination of the two data sets.

The proportional fit cannot adequately describe both data sets simultaneously. The τ SPECT counts increase by about 25% when the NLK is closed, while the monitor counts increase by about 50%. It can be clearly seen from the residuals that the fit underestimates the τ SPECT counts for NLK South open and overestimates them for NLK South closed. A possible cause for the NLK state affecting the τ SPECT counts and the monitor counts differently, could be that the storage time of the beam-line system differs depending on the NLK state. This could then affect the monitor counts stronger than the τ SPECT counts. The results presented above show that, at least when using a proportional approach, measurements with different NLK states must be analyzed separately.

To conclude, in this section I discussed the effect of the slow decrease of the main magnetic field of τ SPECT, which leads to a progressive reduction in τ SPECT's performance. I estimated time windows in which this effect can be considered small. I then demonstrated that, within those time windows, the τ SPECT counts are proportional to the monitor counts. This validates the monitor detector as a tool for normalization under stable experiment conditions. However, it was also shown that this proportional correlation does not hold if measurements with different NLK South states are combined. The analysis was limited to the lengths of the time windows, which were tens of hours and therefore it was not possible to investigate effects on larger time scales. Studying such long-term effects would require combining the analysis of multiple time windows. This is not possible for data from this measurement campaign, since the measurement blocks differ in cleaning parameters. Studying long-term effects will be part of the analysis of a larger more complex data set, which I present in the next section.

6.3.2 Structure and analysis of the first science-run data

In this section I present my investigation of the normalization of τ SPECT using data from the first scientific data run. The analysis generally follows the approach outlined in Section 6.3.1, with a few important differences between the data sets, which I discuss below.

A key difference is the introduction of blinding. To avoid bias during later analysis of the neutron lifetime, measurements were done in blinded time. The blinding was done by Julian Auler. In this thesis, only aspects of the blinding relevant for the normalization analysis are considered. In the blinding procedure, the timestamps of both the raw detector data and all experiment-related time variables (e.g. filling duration) have been multiplied by an unknown factor between 0.975 and 1.025. Additionally, the experiment-related time variables have an unknown offset of $\pm 2.5\%$. The actual values remain unknown until unblinding. All analysis in this thesis was done without unblinding, so all times given in this section are in blinded time. The common background rate is calculated in blinded time analogously to Sec. 6.3.1. The time windows, which exclude the periodic background increases, have been adjusted to the blinding. Importantly, the monitor-detector-data timestamps were also blinded, but with a different factor between 0.975 and 1.025. To reduce potential contamination by neutrons with slightly higher energies than UCNs in the beamline, the first 8 s in blinded time of each monitor measurement were discarded.

A second major difference is the lower repetition rate of measurements with the same storage time compared to the cleaning-investigation run. In the cleaning-investigation campaign, pairs of short and long storage measurements were taken repeatedly, resulting in 81 short-storage measurements within 49 h (see, Fig. 6.7). The science data run, however, contains measurements with 5 different storage times:

- Two short storage durations S1 (20.28 s) and S2 (28.392 s)
- One medium storage duration M1 (401.554 s)
- Two long storage durations L1 (1204.632 s) and L2 (1608.204 s)

The measurements followed a fixed repeating pattern:

S1 L1 M1 S2 L2 S1 L2 M1 S2 L1 S2 L1 M1 S1 L2 S2 L2 M1 S1 L1.

The PSI source was operating at a kick repetition time of 400 s. It took about 5.8 h or 52 kicks to complete one cycle of the pattern. This means that, within 46.4 h, maximally 32 measurements with the same storage time were done, which is about a factor of 2.5 less than in the cleaning-investigation measurement campaign.

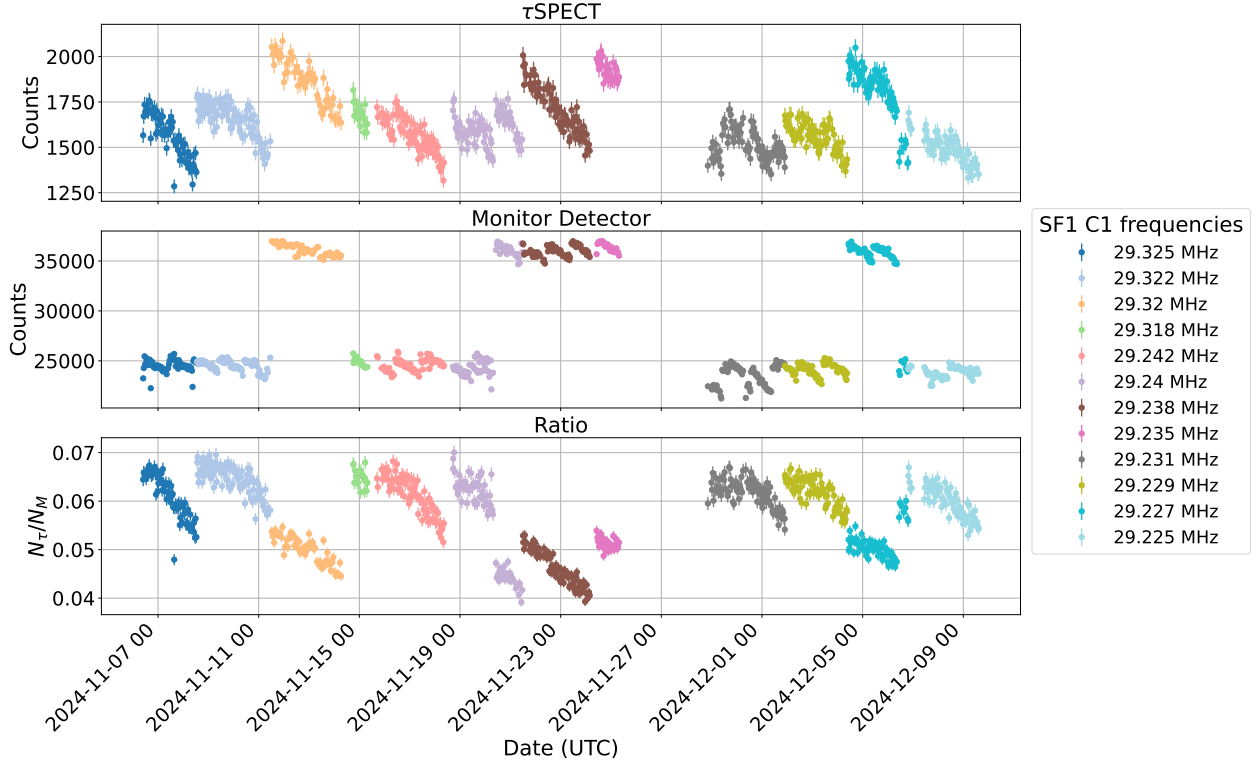


FIGURE 6.11: Data of the first scientific data taking phase in winter of 2024. The τ SPECT counts (top), the monitor-detector counts (middle) and their ratio (bottom) are plotted against time. Only measurements with the short storage times S1 and S2 are depicted. The different SF1 frequencies are represented using different colors. Error bars of the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The error for the ratio has been calculated as described in Eq. (5.11). The monitor counts show the characteristic seesaw behavior caused by the periodical source conditioning. Changes to the state of NLK South cause clearly visible jumps in the monitor counts. For each frequency, the τ SPECT counts and the ratio reduce with time. When readjusting the frequency the counts recover

This reduced rate poses a challenge for the normalization analysis, since a reliable statistical conclusion requires a minimum amount of measurements. Since the field drift can only be neglected for relatively short time spans (typically about 40 h) this constraint becomes significant. To increase the usable data within each time span, I combine measurements with both short storage durations (S1 and S2) for the analysis. From an estimation of the effect of the different storage durations we can see that the effect of combining those data sets is small. If we assume the same amount of initial neutrons, the expected ratio of surviving neutrons in τ SPECT, after the respective storage times t_{S1} and t_{S2} , is given by

$$\frac{N_{S2}}{N_{S1}} = \exp\left(\frac{t_{S1} - t_{S2}}{\tau_{store}}\right), \quad (6.9)$$

where $\tau_{store} = 859(16)$ s is the most recent published storage time constant of τ SPECT [Aul+24a]. The difference in storage-time for S1 and S2 is on the order of 10 s leading to a ratio of 0.9884(2). The influence of the storage-time difference on the counts is on the order of 1%. This is smaller

than the estimated uncertainty of the counts, which is typically about 2.5 %. Therefore, we can assume that the combination of measurements with storage durations S1 and S2 does not have a significant influence on the normalization analysis.

Fig. 6.11 shows the data of those measurements. Cuts due to monitor-detector counts or irregularities in the measurements have been applied already. The background-corrected τ SPECT counts, the monitor-detector counts, and their ratio, are plotted against the measurement date. The different SF1 frequencies are represented using different colors. The monitor counts show the characteristic seesaw behavior caused by the periodical source conditioning. Changes to the state of NLK South cause clearly visible jumps in the monitor counts. For each frequency, the τ SPECT counts and the ratio reduce with time. This is caused by the field drift. When readjusting the frequency, a recovery of the reduction is visible. Each of those frequency blocks was analyzed individually. Based on the frequency-scan measurements, time windows could be estimated for ten of the twelve blocks. Of those ten, eight contained a sufficient amount of measurements to allow for a meaningful fit.

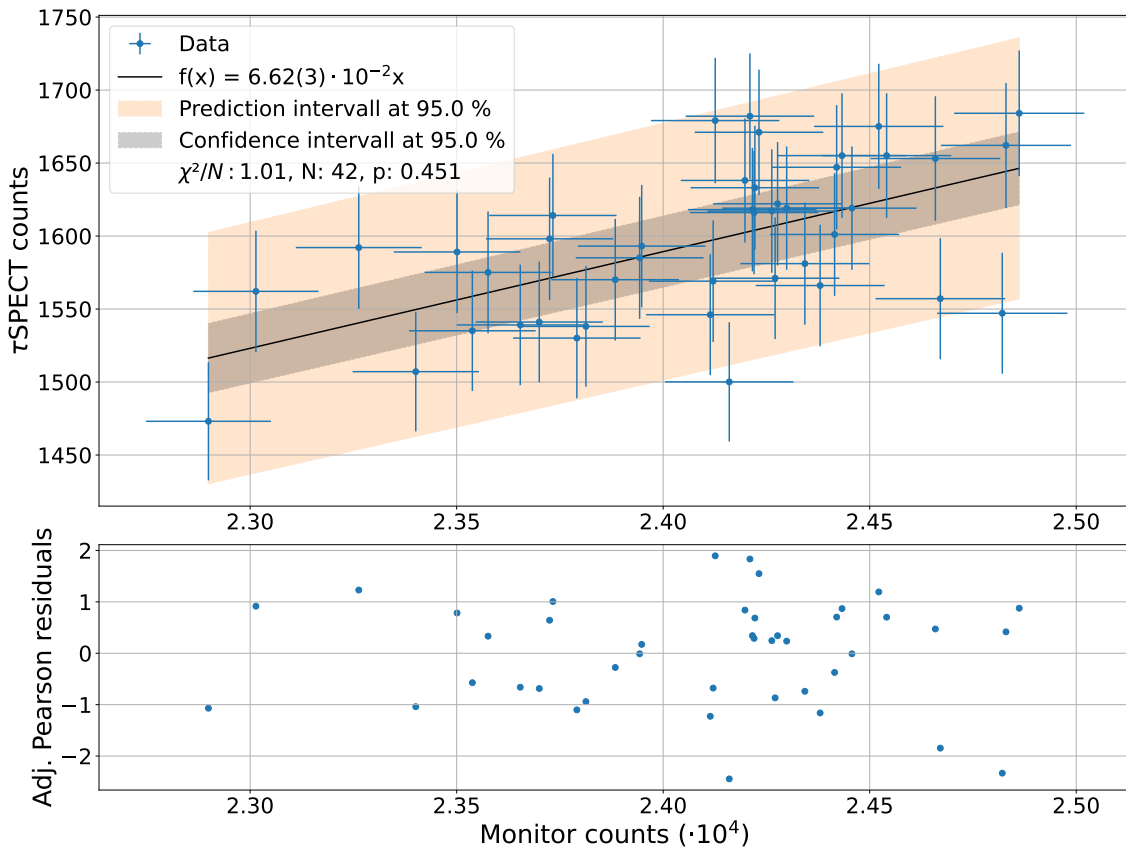


FIGURE 6.12: Analysis results for the frequency block with SF1 frequency set to 29.229 MHz. Measurements with short storage durations (S1 and S2) have been combined. To minimize the influence of the main field drift, only measurements within 32 h of the start of the measurement block were included. The background-corrected τ SPECT counts are plotted against the monitor-detector counts with a weighted linear fit (top) and the adjusted Pearson residuals of that fit (bottom). Error bars for the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The dark shaded area is the confidence interval of the fit at a confidence level of 95%, the light shaded region is the 95% prediction interval. The fit results in an adjusted reduced χ^2 of 1.01 corresponding in a p-value of 0.451. The residuals have a mean of 0.013 and a standard deviation of 0.99 and do not show any obvious bias.

Fig. 6.12 shows the results of such a fit for a SF1 frequency of 29.229 MHz. In the top panel, the τ SPECT counts are plotted against the monitor-detector counts. The weighted linear fit is represented by the black line. The dark shaded area represents the confidence interval of the fit at a confidence level of 95%, and the light shaded area represents the 95% prediction interval. The reduced χ^2 is 1.01, resulting in a p-value of 0.451, which indicates good agreement between the model and the data. In the bottom panel, the adjusted Pearson residuals of the fit are shown. They have a mean of 0.013 and a standard deviation of 0.99. They do not show any obvious bias or systematic deviations.

An overview of the frequency blocks, their time windows, and the results of the fits is given in Table 6.2. For the majority of the analyzed blocks, the linear fit describes the data well. However, for two frequencies, 29.24 MHz and 29.238 MHz, the resulting χ^2 indicates a poor fit. To identify potential causes, those two data sets will be investigated in more detail in the following section.

SF1 frequency (MHz)	Time window (h)	NLK South	χ^2/N	N	slope a
29.325 ^a	32(1)	open	-	-	-
29.322 ^b	-	open	-	-	-
29.32 ^c	-	closed	-	-	-
29.318 ^d	32(1)	open	-	-	-
29.242	32(1)	open	1.26	37	6.71(3)
29.24	32(1)	open*	2.26	43	6.58(3)
29.238	32(2)	closed	3.13	34	5.06(2)
29.235	32(1)	closed	0.94	29	5.28(2)
29.231	32(1)	open	1.17	38	6.57(3)
29.229	32(1)	open	1.01	42	6.62(3)
29.227	32(1)	closed*	1.16	43	5.25(2)
29.225	32(1)	open	1.07	27	6.53(3)

^a The frequency scan was done 17 h before the first measurement and as a result the time window does not contain enough measurements for a meaningful analysis.

^b The frequency scan did not contain a frequency for which the z-value was smaller than 2.

^c During the frequency scan the beam current of the proton accelerator HIPA was fluctuating. The frequency scan is therefore considered not reliable.

^d Data set did not contain enough measurements for a meaningful analysis.

* Data set contains multiple NLK states, but only data of the written state was used in analysis.

TABLE 6.2: Overview of the frequency blocks during the science data run. Given are the SF1 frequency, the duration of the time window for which the field drift is considered small, the state of NLK South, the adjusted reduced χ^2 of the fit, the degrees of freedom (N), and the fitted slope a.

Fig. 6.13 shows the data taken at a SF1 frequency of 29.238 MHz. Plotted are the τ SPECT counts (top panel), the monitor counts (middle panel), and their ratio (bottom panel) against the measurement date. The vertical dashed lines mark the time window used for the fit. As expected, the monitor counts follow a seesaw pattern. In contrast, the τ SPECT counts show a decline, which immediately begins at the start of the measurement and results in a drop of the count ratio throughout the data set. Unlike other data sets (see Fig. 6.5 for comparison), there is no initial plateau with a constant ratio. A straightforward explanation for this behavior is that the effect of the magnetic-field drift was already significant at the start of the measurement block. Sec. 6.3.3 will present a

strong indicator supporting the hypothesis that this reduction is primarily caused by a change in τ SPECT performance. However, it remains unclear why the field drift's effect would be significant so early in the measurement block. One possible reason could be that statistical fluctuations during the frequency scan resulted in the selection of a SF1 frequency which was already slightly detuned from the true resonance center. Alternatively, a sudden change of the main magnetic field after the frequency scan could be the reason.

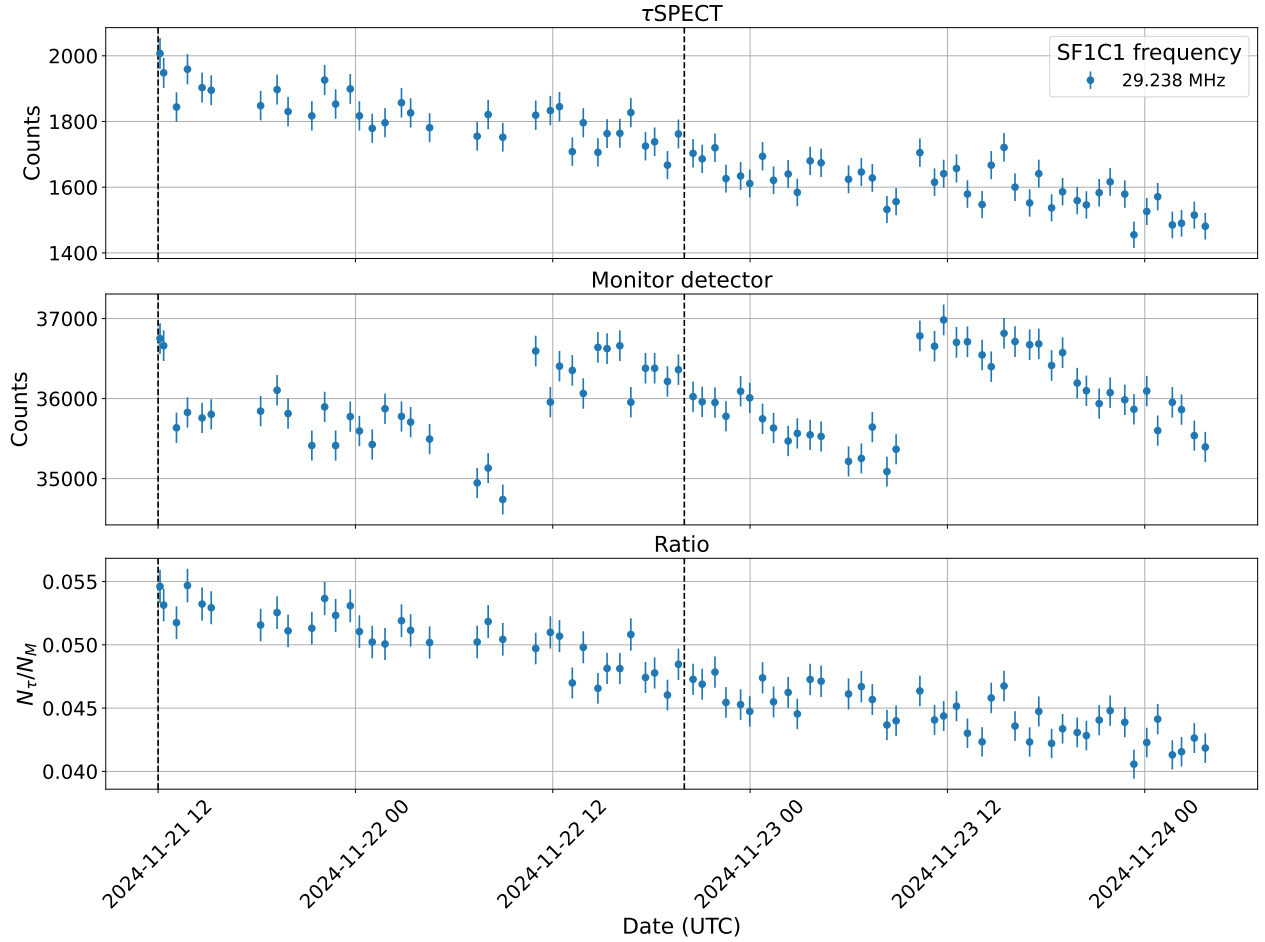


FIGURE 6.13: Time series of the measurements taken at a SF1 frequency of 29.238 MHz. The τ SPECT counts (top), the monitor counts (middle), and their ratio (bottom) are plotted against the measurement date. Measurements with short storage durations (S1 and S2) have been combined. Error bars of the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The error for the ratio has been calculated as in Eq. (5.11). The dashed lines indicate the time window used for the analysis. While the monitor counts show the characteristic pattern caused by the regular source conditioning, a continuous reduction of the τ SPECT counts and the ratio can be observed from the beginning of the measurement block.

Fig. 6.14 shows a time series of the measurements taken at a SF1 frequency of 29.24 MHz. The τ SPECT counts (top panel), the monitor counts (middle panel), and their ratio (bottom panel), are plotted against the measurement date. The vertical dashed lines mark the time window used for the fit. Two irregularities can be observed in the data: First, a few initial measurements show significantly higher τ SPECT counts than the later measurements, resulting in an increased ratio. Currently, there is no clear explanation for this, it may simply be due to statistical fluctuations.

The second irregularity is more relevant as it affects a larger portion of the data. Beginning at 2024-11-19 at about 12:00, the monitor counts show fluctuations by up to 10% of the total counts. This leads to a noticeable increase in the scattering of the ratio.

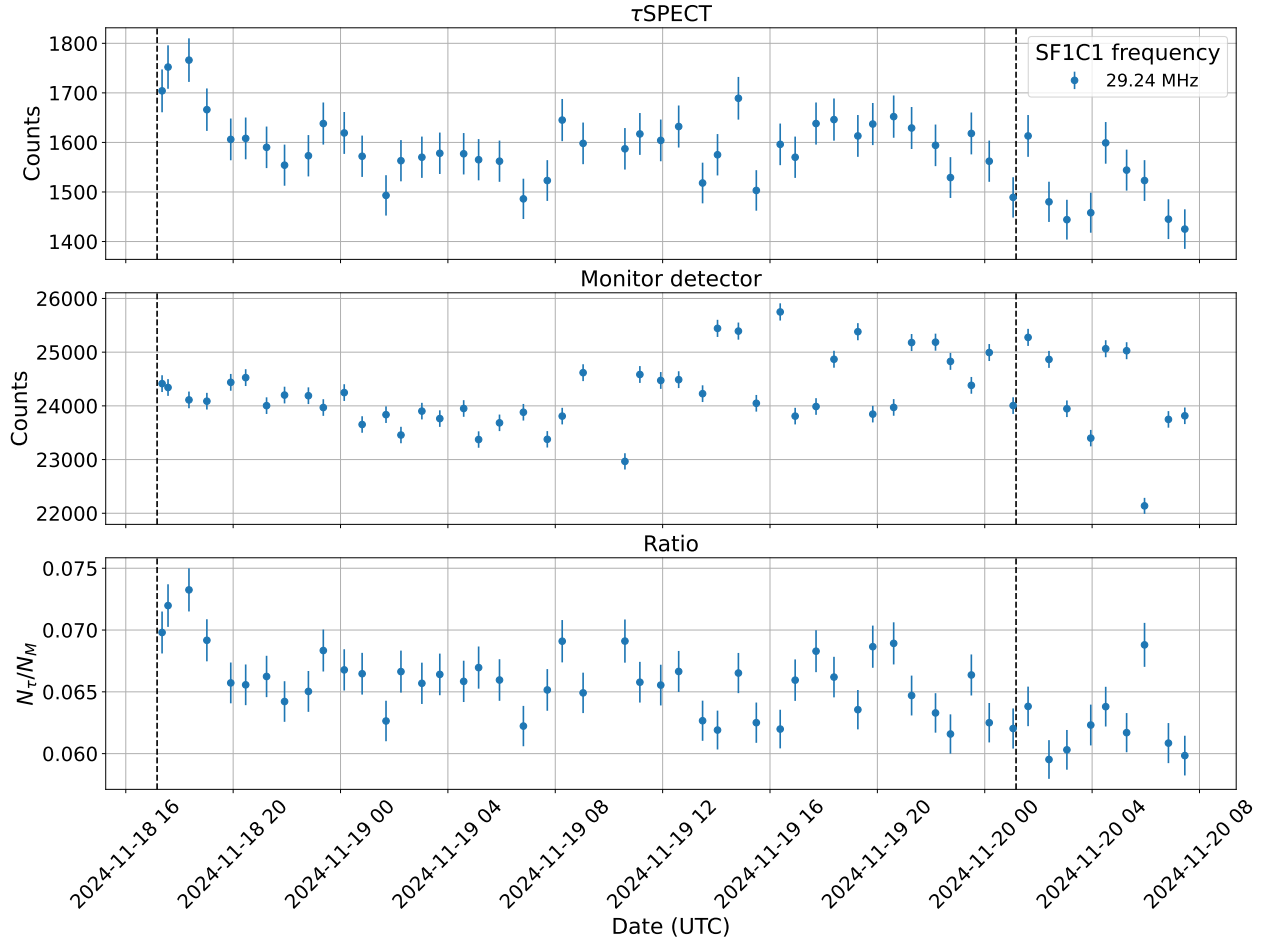


FIGURE 6.14: Data of measurements taken at a SF1 frequency of 29.24 MHz. τ SPECT counts (top), monitor counts (middle), and their ratio (bottom) are plotted against the measurement date. Measurements with both short storage durations (S1 and S2) have been combined. Error bars for the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The error for the ratio has been calculated as in Eq. (5.11). The dashed lines represent the time window which has been used for analysis. The first few measurements contain significantly more τ SPECT counts than the later measurements leading to a higher ratio. From the 2024-11-19 at about 12:00, the monitor counts show an increased fluctuation by up to 10% of their value.

I investigated the behavior of the monitor counts further. Fig. 6.15 presents a comparison between the total monitor counts (integrated from 8 s to 240 s) and the monitor counts during the filling window (from 8 s until the experiment shutter closes at 25.86 s). Both those counts are plotted against the measurement date. The increased fluctuations seen in the total monitor counts can not be observed in the monitor counts during the filling window. This indicates that the fluctuation primarily affects neutrons which reach the detector after 25.86 s. A possible explanation for this behavior would be changes to the setup behind NLK South. Such changes would affect only UCNs which leave the source through beam port South, re-enter the source, then exit it through beamport West-1 and reach the monitor detector. Those UCNs will naturally need additional time to reach

the monitor detector. Indeed, the n2EDM experiment performed measurements involving a scan of the magnetic field of their polarization magnet, which is positioned behind NLK South, from 0 T to 5 T, between the 19th of November at 11:00 till the 20th of November at 7:30 (UTC). The timing of these measurements matches very well with the time window of the observed fluctuations and they are therefore considered the most likely cause.

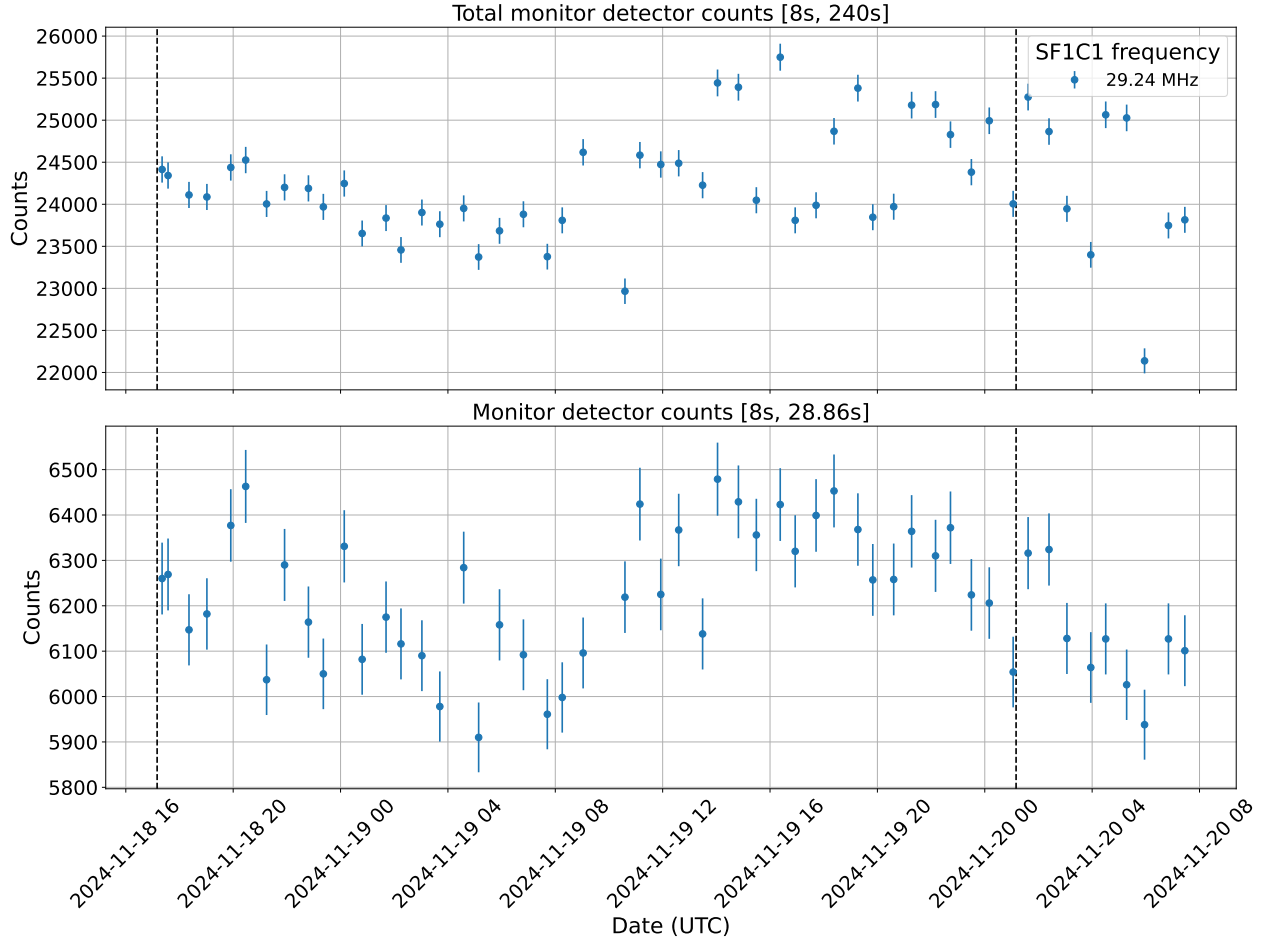


FIGURE 6.15: Comparison of the total monitor-detector counts (integrated from 8 s to 240 s) and the monitor counts recorded during the filling window (from 8 s until the experiment shutter closes at 28.86 s). Measurements with both short storage durations (S1 and S2) have been combined. Error bars represent the Poisson error. The dashed lines represent the time window which has been used for analysis. From about 2024-11-19 at 12:00 increased fluctuation of up to 10% can be observed in the total monitor counts. Those fluctuations cannot be observed in the ones recorded during the filling window.

For both data sets for which the fit was rejected, plausible explanations have been identified and none of them indicate any malfunction of the monitor detector. In the course of this investigation it was demonstrated that the monitor detector is sensitive even to relatively minor variations of the source configuration, and that influences on the beamline and source must be carefully considered when running τ SPECT.

I used the non-rejected measurement blocks to see whether the relationship between the τ SPECT counts and the monitor counts was stable over the course of the measurement campaign. An initial hint that this may not be the case is given by the fitted slope a in Tab. 6.2, which varies by multiple standard deviations between comparable measurement blocks. Fig. 6.16 (top panel) shows the data

of all time windows during which NLK South was open and for which the individual fits were not rejected by their χ^2 based on a two sided 95% confidence interval. A single linear fit was applied to the combined data. In the bottom panel, the fit residuals have been plotted against the SF1 frequency in blue. The mean of the residuals binned by frequency is presented in black. The fit yields a reduced χ^2 of 1.24, corresponding to a p-value of 0.02. This indicates that the linear model and the assumed uncertainties do not fully capture the scatter of the data. Furthermore, the mean of the frequency-binned residuals differs significantly from zero for two frequencies. On average, the fit underestimates measurements taken at 29.242 MHz by 24(8) counts and overestimates measurements taken at 29.242 MHz by 18(8) counts. This suggests that the relation between the τ SPECT counts and the monitor counts could vary between measurement blocks or change slowly with time.

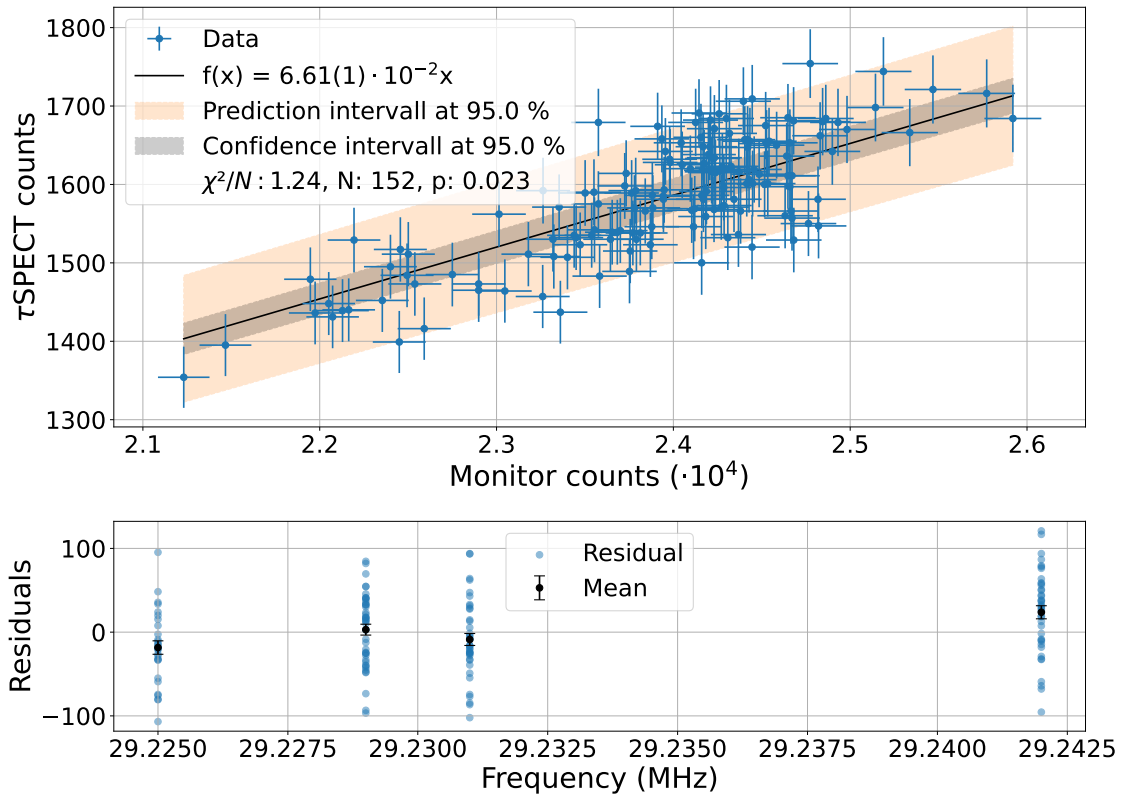


FIGURE 6.16: Combined analysis of all time windows with NLK South open that were not rejected based on their individual fit's χ^2 . The background-corrected τ SPECT counts are plotted against the monitor-detector counts. The weighted linear fit is represented by a black line. The fit residuals and their mean are plotted against the SF1 frequency in the bottom panel. Error bars for the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. Error bars of the residual means represent the standard error of the mean. The dark-shaded region represents the confidence interval of the fit at a confidence level of 95%. The light-shaded region represents the prediction interval at a confidence level of 95%. The adjusted reduced χ^2 of 1.24 results in a p-value of 0.02. The residuals show differences depending on the frequency.

Several potential causes for small systematic changes like the ones mentioned above can be considered:

1. Spin-flip-efficiency variations: It is possible that the spin-flip efficiency of SF1 does not return to exactly the same value after adjusting the frequency. This may result from:
 - Changes of the magnetic-field gradients due to drift of the main magnetic field within the spin-flipper region.
 - Degradation or changes of the spin flipper itself over time. Post-campaign inspections revealed damage to the SF1 unit, although it remains unclear when this damage occurred. Multiple S11 reflection measurements were taken throughout the campaign, to check SF1 these are presented in the appendix (B.4) and show minor fluctuations but no significant changes.
 - Varying offsets of the spin flipper's operating frequency from the optimal frequency at the start of each measurement block.
2. Variations of the τ SPECT background: The analysis assumes a constant rate for the τ SPECT detector background throughout the campaign. However, this assumption may not hold in practice and could lead to a bias.
3. Changes of the UCN spectrum: It is also possible that the UCN energy spectrum varied over time due to changes in the source conditions. This could affect the monitor detector and the number of stored UCN in τ SPECT differently.

To conclude, I have demonstrated that during the scientific data run, the monitor detector can be used to describe the τ SPECT counts by a proportionality. The primary limiting factor is currently the stability of the filling process of the experiment. The monitor detector has proven sensitive to changes to the source complex. When I extended the analysis across multiple time windows, I found that the residuals fluctuate about 11% more than statistically expected. Additionally, small systematic differences (on the order of 2% of the counts) between measurement blocks have been observed.

6.3.3 An improved approach to normalization

In the previous sections I have established the proportional dependence of the τ SPECT counts on the monitor counts, for time windows in which other systematics, especially the main field drift, stayed negligible. In this section I introduce an approach to account for both the fluctuations of the source's performance and changes to the filling efficiency of the experiment.

An interesting observable, which might contain additional information on the filling process, are the events counted by the τ SPECT detector during the filling phase of the experiment. In this work, these counts will be referred to as "filling counts" or N_{fill} . They are defined as the background-corrected counts integrated from the start of the τ SPECT detector $t_0=0.5$ s until the spin flipper is turned off and the experiment shutter is closed at $t_{sf}=25.856$ s (blinded time). During this time, the detector is positioned at $z_{det}^{clean} = 1800$ mm (see Ch. 3). The background correction and the estimator for the uncertainty are calculated analogously to the background corrected τ SPECT counts (see Eqs. (6.3) and (6.4)) leading to

$$N_{fill} = \int_{t_0}^{t_{sf}} N_{det}(t) - \rho_b dt \quad (6.10)$$

and

$$\sigma_{fill} = \sqrt{N_{fill} + (\sigma_b \cdot (t_{sf} - t_0))^2}. \quad (6.11)$$

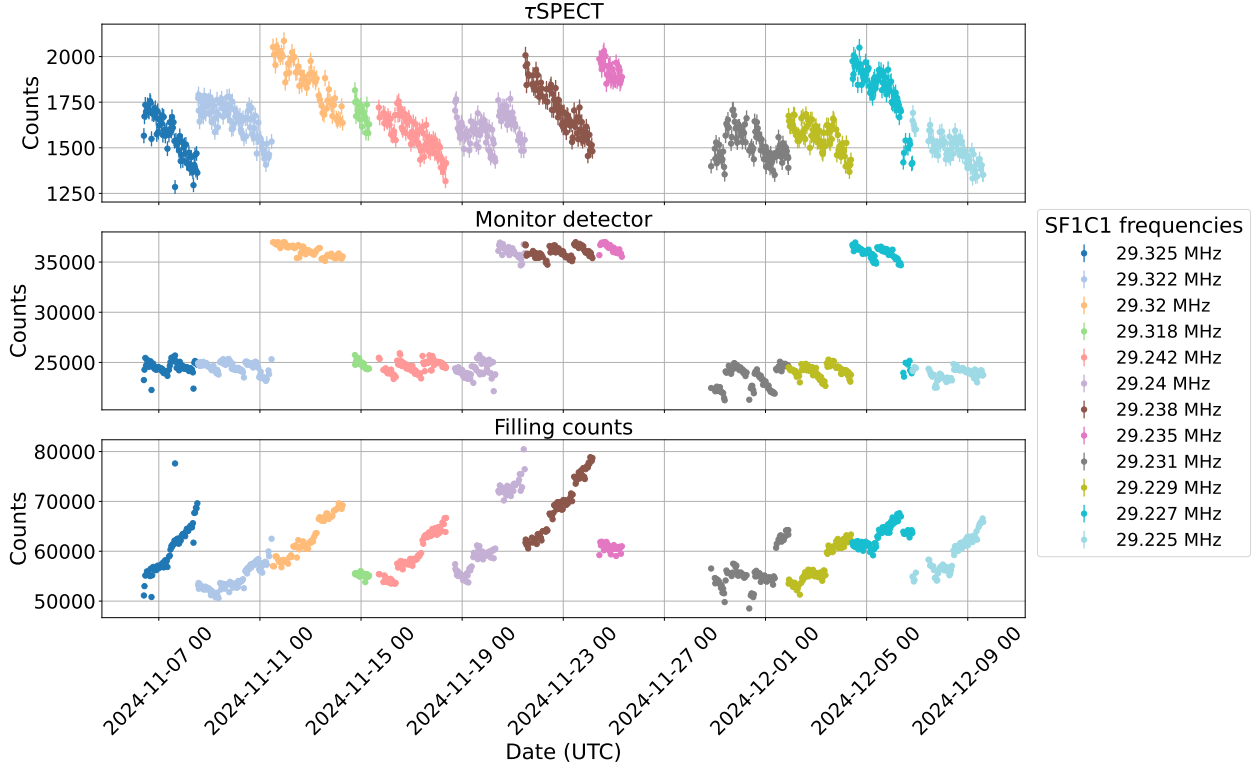


FIGURE 6.17: Time evolution of the background-corrected τ SPECT counts, monitor counts, and filling counts. Measurements with short storage times (S1 and S2) are depicted. Error bars of the τ SPECT counts represent the uncertainty derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The error bars of the filling counts represent the error calculated in Eq. (6.11). Different SF1 frequencies are color coded. While the monitor-detector counts follow the conditioning pattern, the τ SPECT counts show a decline with time at a fixed frequency. In contrast, the filling counts show the opposite behavior, increasing with time during each frequency block and then returning to a lower baseline when the SF1 frequency is adjusted. When NLK South is closed, the filling counts show a slight increase.

Fig. 6.17 shows these filling counts, the monitor counts, and the τ SPECT counts, plotted against the measurement date. The monitor counts follow the pattern of the daily source conditioning. The τ SPECT counts show the decreasing trend within each frequency block which has been attributed to the loss in spin-flip efficiency caused by the magnetic field drift. Notably, the filling counts show an inverse behavior compared to the τ SPECT counts: they increase over time for a fixed frequency and drop back to a base level when the SF1 frequency is readjusted. The underlying mechanism is still under investigation and the effect is currently studied using simulations. A hypothetical explanation for the behaviour of the filling counts is that a reduction in spin-flip efficiency of SF1 leads to an increased amount of low-field seeking UCNs with kinetic energy above the trap potential entering the storage region. These neutrons are able to reach the τ SPECT detector which could lead

to more filling counts. The filling counts also increase when NLK South is closed which indicates a dependence on the incoming neutron flux.

To show the behavior of the filling counts in more detail and compare it to the τ SPECT and monitor counts, Fig. 6.18 depicts data of a specific frequency (29.322 MHz) block which was taken between the 8th of November and the 11th of November 2024. The monitor counts show the characteristic 24 h periodic pattern, caused by the daily source conditioning. During the first 24 h period, the filling counts follow the monitor counts' decrease, reducing by about 8%. The conditioning at the 9th of November at around 12:00 can be clearly seen in the filling counts. During that time window the τ SPECT counts do not yet show a visible drift. Over the second 24 h-period, the filling counts do not decrease, but a jump due to source conditioning can still be observed. During this period the τ SPECT counts are reducing slightly. Over the third 24 h-window, the filling counts increase visibly by about 20%, while the τ SPECT counts decrease.

The current interpretation is that the filling counts depend on both the general source output and the filling efficiency of τ SPECT, with the latter becoming increasingly dominant as the SF1 frequency differs from the optimal spin-flip frequency.

This shows that the filling counts are a promising measure for the changes of the spin-flip efficiency. But their dependence on the neutron flux has to be kept in mind.

Next, I analyzed if the filling counts can be used to estimate the changes in the filling procedure and by doing so recover the assumed proportionality between τ SPECT counts and monitor counts for significant field drifts. To combine the filling N_{fill} and the monitor counts N_m to describe the τ SPECT counts N_τ a multiple linear fit with an offset b was used:

$$f(N_m, N_{fill}) = a_1 \cdot N_m + a_2 \cdot N_{fill} + b. \quad (6.12)$$

This is of course still a simplified approach to a complex system. It assumes that the field drift is the single mayor contributor to the change in τ SPECT filling efficiency. It also assumes that the monitor counts and the filling counts are (mostly) independent parameters.

However, since the filling counts and the monitor counts show some correlation (see Fig. 6.18). This correlation, as well as the variance inflation factor (VIF) were calculated for each data set to check for independence and problematic collinearities. The VIF for a co-variable x_j is given by

$$\text{VIF}_j = \frac{1}{1 - R_j^2}. \quad (6.13)$$

Here, R_j is the coefficient of determination of x_j by the other variables [FTL09]. Usual thresholds for problematic collinearities are at a VIF of 10 [FTL09].

To test the multiple linear fit, I applied it to the data set taken at a SF1 frequency of 29.238 MHz (see Table 6.2), which is shown in Fig. 6.13. The VIF for this data set was 1.4, so there were no problematic collinearities. The multilinear fit results in an adjusted reduced $\chi^2/N = 1.18$. This is a reduction by a factor of about 2.6 compared to the result of the fit which considered just the monitor counts ($\chi^2/N = 3.13$). This indicates that the observed reduction in counts in this data set can be described using the filling counts, suggesting that the reduction was caused by a change in τ SPECT performance.

After this test, the analysis was extended to the full measurement campaign. The measurements were separated into four groups based on storage time and state of NLK South. Additionally, measurements in two time intervals were excluded, due to parallel changes to the n2EDM side of

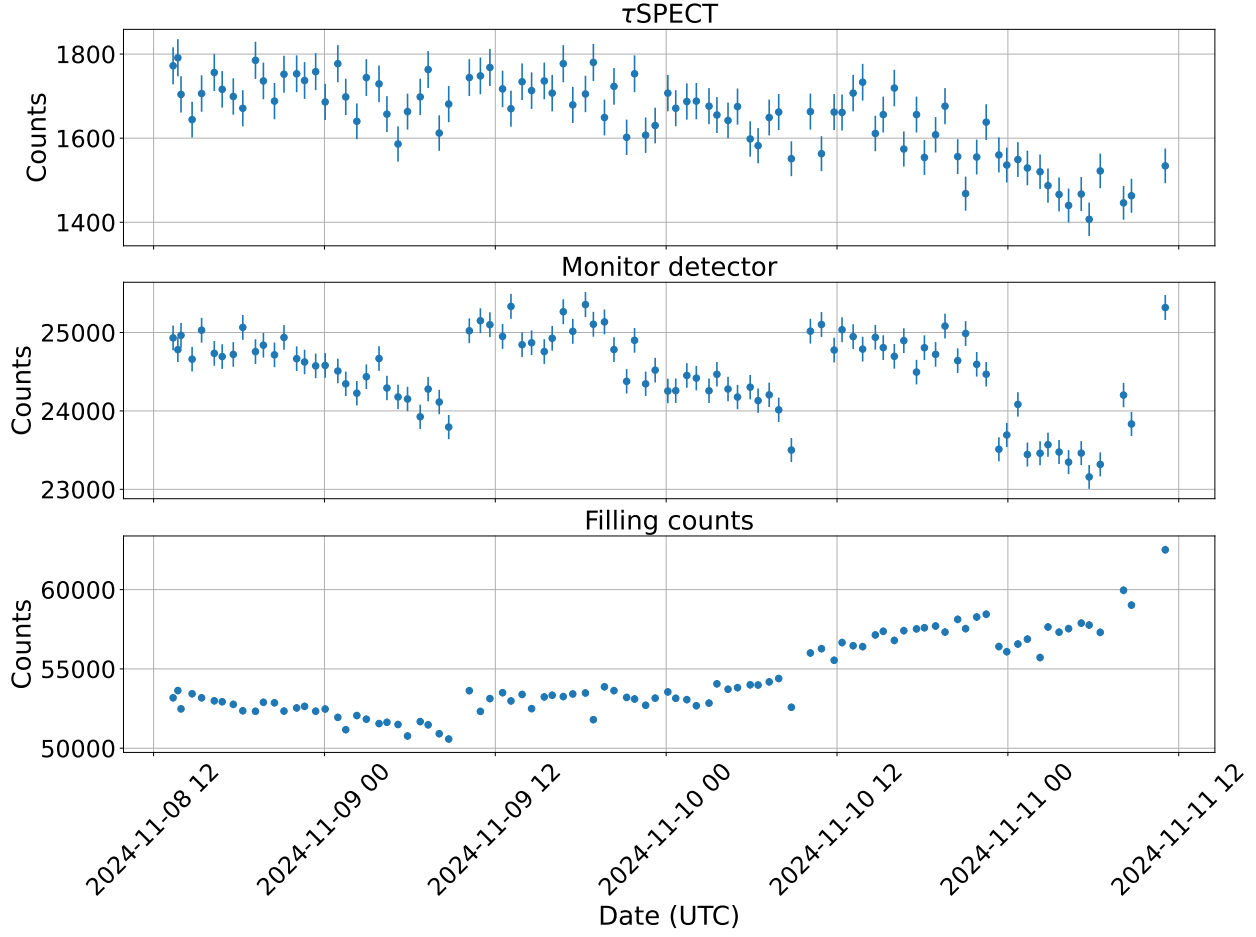


FIGURE 6.18: Zoom-in on the evolution of τ SPECT, monitor and filling counts from 8th November to 11th November 2024. All measurements were done with a SF1 frequency of 29.322 MHz with short storage durations (S1 and S2). Error bars of the τ SPECT counts and filling counts represent the errors derived in Eqs. (6.4) and (6.11). Error bars of the monitor counts represent the Poisson error. One can clearly see the 24h periodic pattern in the monitor counts, caused by the daily source conditioning. During the first 24h, the filling counts follow the monitor counts' decrease, the conditioning at November 9th around 12:00 can be clearly seen in the filling counts. As the τ SPECT counts start to decrease, the filling counts exhibit an anti-correlated behaviour and gradually increase.

the source, which likely caused increased fluctuation of the monitor counts. Those time windows are:

- 2024-11-19 8:20 (UTC) till 2024-11-20 6:30 (UTC), which has been discussed in section 6.3.2 (see Fig. 6.14) and
- 2024-11-17 10:10 (UTC) till 2024-11-17 19:10 (UTC).

The multilinear fit was then performed on the four data sets. For each of these, the correlation coefficient between N_{fill} and N_m was below 0.33, and the VIF was below 1.12. This indicates that there were no problematic collinearities.

The fit results for each data set are presented in Tab. 6.3. For data sets with the same NLK state, but different storage times, all three fit parameters are compatible within their errors. However, the parameters differ significantly for different NLK states. This fits the assumption that the difference in the amount of stored neutrons between the two short storage times is small and with the observation that measurements with different NLK states cannot be combined (see Sec. 6.3.1). Data sets 3 and 4 yield adjusted χ^2/N values of 1.15 and 1.02, which do not lead to significant p-values for a two sided 95% confidence interval. However, for data sets 1 and 2, the fit results in slightly elevated adjusted χ^2/N values of 1.24 and 1.32 and the corresponding p-values lie outside a two sided 95% confidence interval. These slightly increased values could indicate either that the model does not fully describe the data or that the assumed uncertainties have been underestimated. Assuming that the uncertainties were indeed underestimated, the 1σ confidence and prediction intervals of the fit were calculated using the uncertainties rescaled by $(\chi^2/N)^{\frac{1}{2}}$ to compensate for this underestimation. Since the intervals depend on N_m , N_{fill} , and N_τ , the minimum and maximum results for each data set are listed in Tab. 6.3.

Parameter	Data Set 1	Data Set 2	Data Set 3	Data Set 4
NLK South	open	closed	open	closed
Storage time (s)	20.28	20.28	28.392	28.392
Slope a1	$9.8(4) \cdot 10^{-2}$	$6.2(8) \cdot 10^{-2}$	$9.7(4) \cdot 10^{-2}$	$6.4(7) \cdot 10^{-2}$
Slope a2	$-2.06(6) \cdot 10^{-2}$	$-2.23(7) \cdot 10^{-2}$	$-2.03(6) \cdot 10^{-2}$	$-2.20(7) \cdot 10^{-2}$
Offset b	$3.9(2) \cdot 10^2$	$1.0(3) \cdot 10^3$	$3.8(3) \cdot 10^2$	$9.4(26) \cdot 10^2$
Sample size	271	128	275	130
N	268	125	252	127
Adj. χ^2/N	1.24	1.32	1.15	1.02
p_χ	$4 \cdot 10^{-3}$	0.01	0.06	0.42
Adj. Pearson μ_r	$1.8 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$
Adj. Pearson σ_r	1.11	1.14	1.07	1.00
1σ Conf. interval	17.9-19.6	15.4-18.6	17.0-21.7	14.0-18.1
1σ Pred. interval	46.7-53.2	49.4-57.3	44.8-50.4	44.0-50.3

TABLE 6.3: Results of the multiple linear fit for the four analyzed data sets. The sets are categorized by the NLK South status and the storage time. The three fit parameters a1, a2, and b, the sample size, the adjusted reduced χ^2 , the degrees of freedom N , and the corresponding p-value p_χ are shown. Also included are the mean of the adjusted Pearson residuals μ_r , and their standard deviation σ_r . The 1σ confidence and prediction intervals of the fits are also given. They have been calculated using the uncertainties rescaled by $(\chi^2/N)^{\frac{1}{2}}$. The maximum and minimum values of the intervals are given for each data set.

In order to look into whether the elevated χ^2 is caused by shortcomings of the used model, I examined the fit residuals. Fig. 6.19 shows the adjusted Pearson residuals, the fit of data set 1 plotted against monitor counts, filling counts, SF1 frequency, and the fitted values. The residuals do not show any obvious trends or structures which would indicate issues with the model. When binning the residuals by frequency and calculating the mean within each bin, the means for two frequencies deviate more than two standard errors of the mean from zero. However, these deviations do not show a frequency-dependent pattern, which could suggest an unaccounted frequency dependency. Therefore the increased χ^2 is primarily attributed to a slight underestimation of the data fluctuations. In the most affected data set (data set 2), the observed standard deviation of the residuals is only about 14%, or about 7 counts, larger than the assumed uncertainty. Potential causes for additional fluctuations include variations in the τ SPECT detector background and shifts in the energy spectrum of the UCN source output.

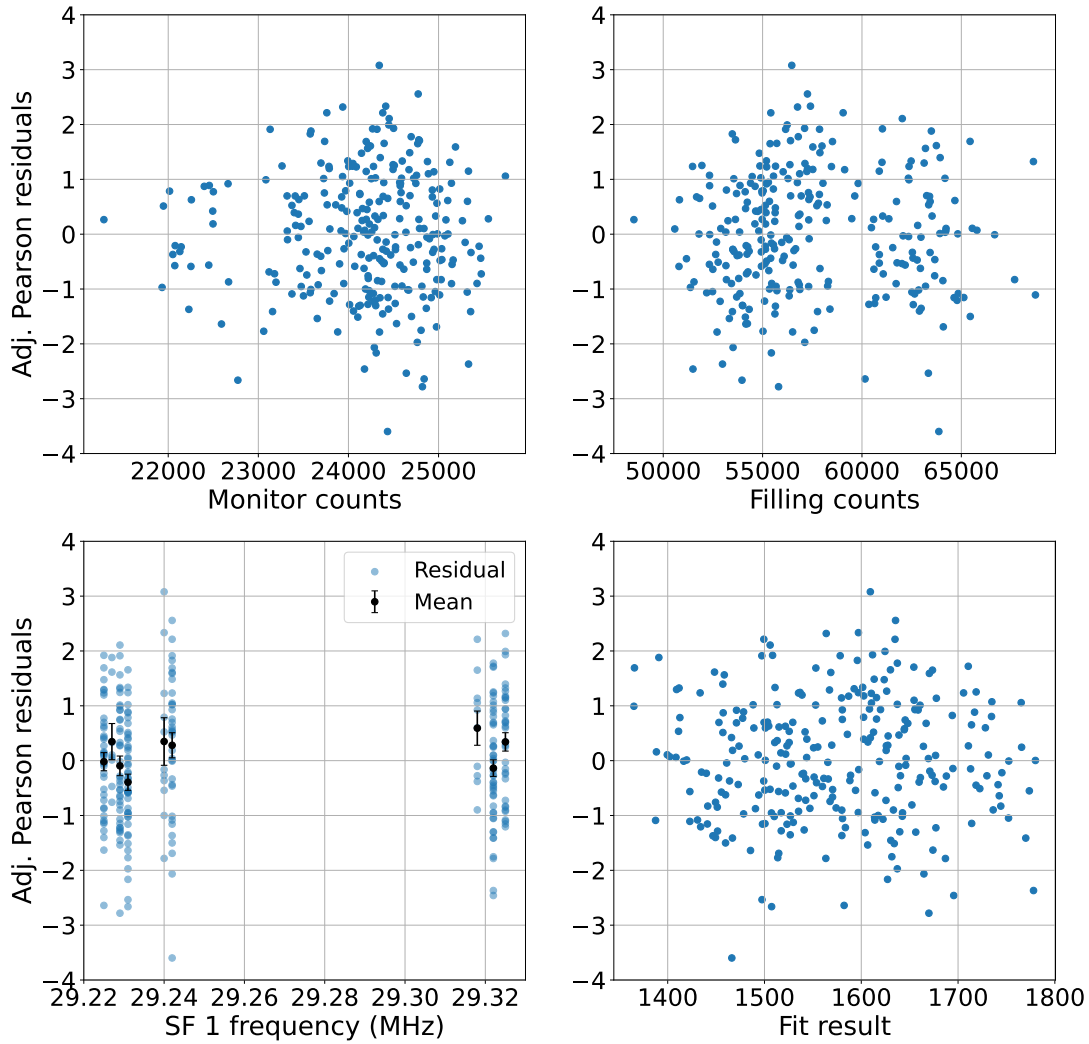


FIGURE 6.19: Adjusted Pearson residuals of the multiple linear fit performed on data set 1 with a storage time of 21 s, in blinded time, and NLK South open. Top left: Residuals plotted against monitor counts. Top right: Residuals plotted against filling counts. Bottom left: Residuals plotted against the SF1 frequency (blue) along with the mean residuals binned by frequency (black). Error bars represent the standard error of the mean. While several means differ significant from zero no systematic trend is observed. Bottom right: Residuals plotted against the result of the multiple linear fit. No systematic structure can be seen in any of the panels.

Overall, the multiple linear approach has proven to be a promising and robust candidate for normalizing τ SPECT measurements. I will conclude this section with a visualization of the improvement achieved with the multiple linear fit compared to the simple proportional fit, and with an estimate of the impact of this normalization on the statistical uncertainty of a lifetime measurement.

Visual comparison of the fit methods

To visually compare the two models, the simple proportional fit using only the monitor counts was performed on data set 1 (storage time = 20.28 s, NLK South open). The multiple linear fit was performed on the same data set in a transformed coordinate system given by the transformation

$$N'_m = N_m - \bar{N}_m, \quad N'_{fill} = N_{fill} - \bar{N}_{fill}, \quad (6.14)$$

where $\bar{N}_m$ and $\bar{N}_{fill}$ are the means of the monitor and filling counts. Since the transformation is a shift by constant, the slopes a_1 and a_2 , the residuals, fit quality (e.g. the χ^2) and statistical significance remain unchanged, while the offset b is affected and the covariances between the slopes and the offset are reduced. To visualize the contribution of the monitor counts to the multiple linear model, the variable N_τ^* is introduced

$$N_\tau^* = N_\tau - a_2 N'_{fill} - b, \quad (6.15)$$

where N_τ are the measured τ SPECT counts, and a_2 and b are parameters of the multiple linear fit.

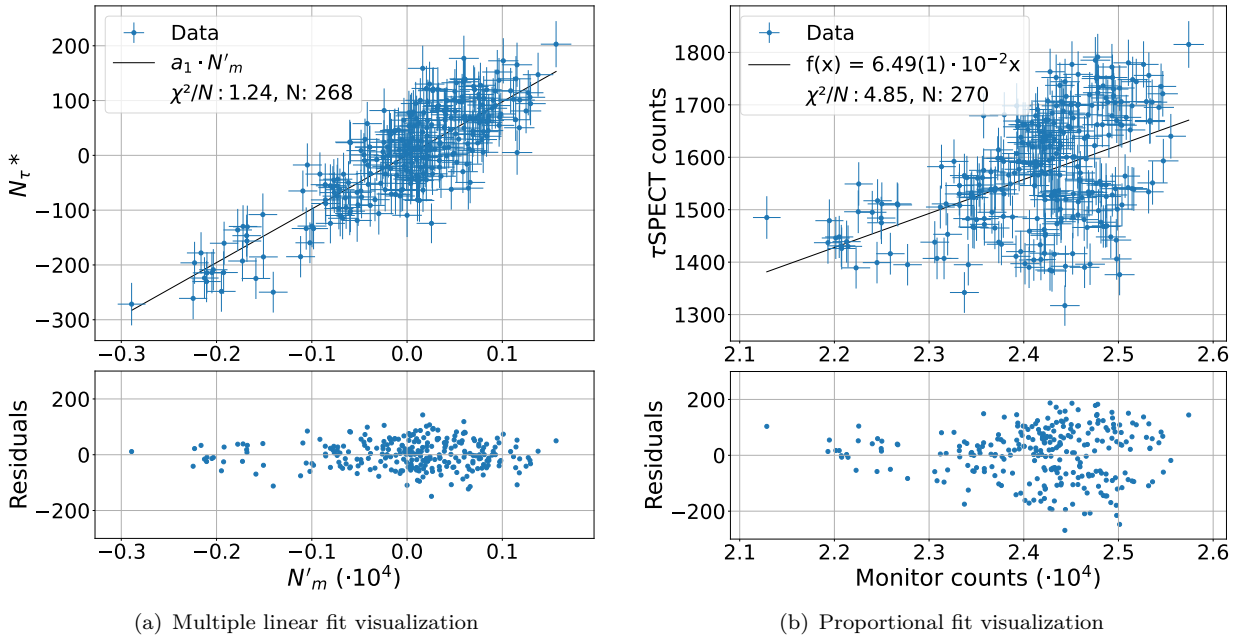


FIGURE 6.20: Visual comparison of the multiple linear fit and simple proportional fit for data set 1 (storage time = 20.28 s, NLK South open). **(a)**: The x-axis represents the monitor counts after the coordinate transformation described in Eq. (6.14). The y-axis shows N_τ^* (see Eq. (6.15)). The black line represents $a_1 N'_m$, which is the component of the multiple fit which depends on the monitor counts. The y-error bars represent the uncertainties as given in Eq. (6.16), and the x-error bars represent the uncertainties of the monitor counts. The lower panel shows the residuals. **(b)**: τ SPECT counts plotted against monitor counts, with the proportional fit represented by a black line. Error bars of the τ SPECT counts represent the error derived in Eq. (6.4). Error bars of the monitor counts represent the Poisson error. The fit results in a relatively large χ^2/N of 4.85 and the data points exhibit significant scatter, making it hard to see a linear dependence. The residuals show significantly more spread than in (a).

The uncertainty for N_τ^* was calculated using uncertainty propagation for correlated variables

$$\sigma_{N_\tau^*} = (\sigma_{N_\tau}^2 + \sigma_{a_2}^2 N_{fill}^2 + \sigma_{N_{fill}}^2 a_2^2 + \sigma_b^2 + 2N_{fill}' \sigma_{a_2 b} - 2a_2 \sigma_{N_\tau N_{fill}}')^{1/2}. \quad (6.16)$$

Both fits are presented in Fig. 6.20. Fig. 6.20(a) on the left, shows the result obtained using the multiple linear fit. In the top panel, N_τ^* is plotted against N_m' . The black line corresponds to the term $a_1 N_m'$, representing the component of the multiple linear fit that depends on the monitor counts. The bottom panel shows the residuals of the fit. Fig. 6.20(b) on the right, shows the result obtained using the proportional fit. The top panel shows the τ SPECT counts plotted against the monitor counts for the same data set. The black line represents the proportional fit and the residuals are shown in the bottom panel. The data points exhibit significant scatter, making a clear linear dependence hard to identify. This is reflected in the relatively large χ^2/N of 4.85. In contrast, the data points and residuals in Fig. 6.20(a) show much less spread and the linear dependence is much clearer. This is also reflected in the χ^2/N of 1.24, highlighting the improvement achieved with the multiple linear approach. The clearer linear behaviour can be interpreted as the proportionality between the monitor-detector counts and the τ SPECT counts being “recovered” by accounting for variations in the τ SPECT performance using the filling counts.

Estimation of the normalization's contribution to the statistical uncertainty

To estimate the contribution of the normalization to the statistical uncertainty of a measured neutron lifetime, I consider a single measurement pair. For such a measurement pair, consisting of of a short and a long storage time, the neutron lifetime can be estimated as

$$\tau = (t_l - t_s) \ln \left(\frac{N_s N_{0l}}{N_l N_{0s}} \right)^{-1}. \quad (6.17)$$

Here t_l and t_s are the long and the short storage times, N_l and N_s are the background-corrected τ SPECT counts after those storage durations, and N_{0l} and N_{0s} are the corresponding estimated mean counts after the short storage duration. N_{0l} and N_{0s} are obtained from the multiple linear fit. To estimate the statistical uncertainty of τ , I use Gaussian error propagation. For this purpose the following simplifying assumptions are made:

- The uncertainties of the storage times, t_l and t_s , are assumed to be negligible.
- The variables are assumed to be independent, except for N_{0s} and N_s , which are correlated by the fit.

Under these assumptions we receive the estimator of σ_τ to be:

$$\sigma_\tau^2 = \left(\frac{d\tau}{dN_s} \sigma_{N_s} \right)^2 + \left(\frac{d\tau}{dN_l} \sigma_{N_l} \right)^2 + \left(\frac{d\tau}{dN_{0s}} \sigma_{N_{0s}} \right)^2 + \left(\frac{d\tau}{dN_{0l}} \sigma_{N_{0l}} \right)^2 + 2 \frac{d\tau}{dN_s} \frac{d\tau}{dN_{0s}} \text{Cov}(N_s, N_{0s}). \quad (6.18)$$

Here σ_{N_s} , σ_{N_l} , σ_{N_s} , σ_{N_l} are the uncertainties of the respective parameters and $\text{Cov}(N_s, N_{0s})$ is the covariance of N_s and N_{0s} .

The partial derivatives of the lifetime estimator are

$$\frac{d\tau}{dN_s} = -\frac{1}{N_s}(t_l - t_s)\ln\left(\frac{N_s N_{0l}}{N_l N_{0s}}\right)^{-2}, \quad (6.19a)$$

$$\frac{d\tau}{dN_{0l}} = -\frac{1}{N_{0l}}(t_l - t_s)\ln\left(\frac{N_s N_{0l}}{N_l N_{0s}}\right)^{-2}, \quad (6.19b)$$

$$\frac{d\tau}{dN_l} = \frac{1}{N_l}(t_l - t_s)\ln\left(\frac{N_s N_{0l}}{N_l N_{0s}}\right)^{-2}, \quad (6.19c)$$

$$\frac{d\tau}{dN_{0s}} = \frac{1}{N_{0s}}(t_l - t_s)\ln\left(\frac{N_s N_{0l}}{N_l N_{0s}}\right)^{-2}. \quad (6.19d)$$

All derivatives share the factor

$$A = (t_l - t_s)\ln\left(\frac{N_s N_{0l}}{N_l N_{0s}}\right)^{-2}. \quad (6.20)$$

Since we only want to approximate the relative contribution to the uncertainty and not the absolute uncertainty, one can factor out A and work with

$$\sigma_\tau^2 \propto \left(\frac{\sigma_{N_s}}{N_s}\right)^2 + \left(\frac{\sigma_{N_l}}{N_l}\right)^2 + \left(\frac{\sigma_{N_{0s}}}{N_{0s}}\right)^2 + \left(\frac{\sigma_{N_{0l}}}{N_{0l}}\right)^2 - \frac{2}{N_s N_{0s}} \text{Cov}(N_s, N_{0s}) \quad (6.21)$$

The covariance term can be estimated by using the fact that the covariance between the i -th measured value and the i -th predicted value of a linear fit can be estimated as [Ize13, pp. 163–165]

$$\text{Cov}(\hat{y}_i, y_i) = \sigma_y^2 h_{ii}. \quad (6.22)$$

Here, σ_y is the estimator for the variance of the measurements and h_{ii} are the leverages of the individual data points. For the multiple linear fits in this thesis, h_{ii} are on the order of 10^{-2} . The covariance term in Eq. (6.21) is therefore small compared to the other terms and can be neglected in this estimation. What remains is that σ_τ^2 is proportional to the sum of the squared ratios of the uncertainty and the counts

$$\sigma_\tau^2 \propto \left(\frac{\sigma_{N_s}}{N_s}\right)^2 + \left(\frac{\sigma_{N_l}}{N_l}\right)^2 + \left(\frac{\sigma_{N_{0s}}}{N_{0s}}\right)^2 + \left(\frac{\sigma_{N_{0l}}}{N_{0l}}\right)^2. \quad (6.23)$$

For the numerical evaluation of this equation, the values for N_s , N_{0s} , N_l , N_{0l} , and their uncertainties are then estimated in the following way: A typical τ SPECT measurement result from data set 2, and its uncertainty are used for $N_s = 1549$ and $\sigma_{N_s} = 41$. The result of the multiple linear fit for that measurement is used for $N_{0s} = 1522$. The value of N_l is estimated from N_s by assuming an exponential decay between the two storage times $t_s = 20.28$ s (S1) and $t_l = 1204.632$ s (L1)

$$N_l = N_s \exp\left(-\frac{t_l - t_s}{\tau_n}\right) \approx 402, \quad (6.24)$$

where for τ_n the PDG average $\tau_n^{PDG} = 878.4(5)$ s [Nav+24, p. 2091] was used. N_{0l} is assumed to be the same as N_{0s} . The uncertainties $\sigma_{N_{0s}} = 17$ and $\sigma_{N_{0l}} = 17$ are given by the confidence interval of the fit. The uncertainty of the long-storage measurement is estimated as $\sigma_{N_l} = \sqrt{N_l + N_{bg}} \approx 24$. Using these values the contributions to the statistical uncertainty result in

$$\sigma_\tau \propto \sqrt{(0.027)_{N_s}^2 + (0.059)_{N_l}^2 + 2(0.011)_{N_{0s}}^2} = 0.067. \quad (6.25)$$

This result shows that the estimated contribution of the normalization to the statistical uncertainty

is small. It contributes only about 6% of the total variance. The short storage measurement contributes roughly 16% to the variance, while the dominant contribution comes from the long storage measurement which is responsible for approximately 78% of the total variance. Consequently, the normalization can be used without significantly reducing the statistical sensitivity of the experiment.

Conclusion on normalization using monitor and filling counts

In this section, I introduced the filling counts as an additional observable that can be used to monitor the filling efficiency of τ SPECT. I analyzed data from the first scientific data run using a multilinear fit that models the τ SPECT counts using both the monitor counts and the filling counts. The results are promising. For two out of four data sets, the resulting χ^2 values indicate a good fit. For the remaining two data sets the χ^2 values are slightly elevated. The standard deviation of the residuals exceeds the expectation by at most 14%, or about 7 counts. No clear systematic effects were found in the residuals. Therefore, it was assumed that the increased χ^2 values are caused by a slight underestimation of statistical uncertainties. Notably, the application of the multilinear fit, enabled correction for the changes in the filling efficiency. This way the assumed linear dependence of the τ SPECT counts on the monitor counts could be recovered and confirmed for the entire data set. Overall, the multiple linear fit has proven to be a promising candidate for normalizing τ SPECT data. An estimate of the normalization's influence on the statistical uncertainty shows that it does not significantly reduce the statistical sensitivity of τ SPECT.

6.4 Summary and outlook

In this chapter, the operation of the monitor detector with τ SPECT has been discussed. Since the start of the operation at PSI in the summer of 2023, a monitor detector has been running in parallel to τ SPECT. It has proven effective in identifying changes to the source, such as the state of NLK South, source conditioning, as well as issues with the source itself. Depending on the NLK South state, the monitor detector records up to 35000 neutrons per kick. I investigated the feasibility of using the monitor counts for normalization by using data from the first scientific data run of τ SPECT. A key challenge for this analysis was a slow drift in the main magnetic field of the experiment, which caused a drift in the filling efficiency of τ SPECT. The monitor detector is insensitive to the resulting decline of stored UCNs. Two different approaches were taken to address this issue.

- A simple proportional fit between τ SPECT and monitor counts, performed only on data on which the field drift had a small influence.
- A multiple linear fit, using counts of the τ SPECT main detector during the filling period, to model the influence of the drift on the data.

Both approaches confirmed a linear dependence between the τ SPECT counts and the monitor counts. Especially, the multilinear approach has proven to be a promising candidate for normalizing τ SPECT data in the future, demonstrating that the monitor detector is an important tool for normalization. In both approaches, the residuals fluctuated by up to about 15% more than expected. It is likely that the statistical uncertainties of the τ SPECT, the monitor and/or the filling counts were underestimated. Possible sources of increased fluctuations could, for example, be variations of the τ SPECT detector background or shifts in the energy spectrum of the UCN source's output.

An estimate of the normalization's influence on the statistical uncertainty shows that it does not significantly reduce the statistical sensitivity of τ SPECT.

Several ways exist to improve future analysis. The τ SPECT detector background could be evaluated more locally, instead of calculating one global background rate for the measurement campaign, to better account for potential drifts in the background. Furthermore, the selection of the time windows, for both filling and monitor counts, can be optimized and time weighting the counts is a possible option. This could reduce the sensitivity of the selected monitor counts to changes of the n2EDM setup. Finally, to investigate potential shifts in the energy spectrum, additional detectors, based on the design presented in this thesis, are currently planned and one is already being constructed. By placing those at different vertical positions in the beamline, information about the UCN energy distribution can be obtained. This will enable a more detailed characterization of, and correction for, energy-dependent systematics.

Summary and outlook

This work provides two main contributions to the τ SPECT experiment: the advancement of the double spin-flip (dSF) method from a proof-of-principle stage to the routinely used filling procedure, and the development and construction of an in-beam line monitoring detector for the monitoring of the UCN source performance and the normalization of τ SPECT measurements to the source yield.

During the implementation of the dSF method, two central issues were addressed. First, the difficulty of reliably identifying the correct spin-flip frequency was resolved by the installation of an NMR magnetometer. Second, the low spin-flip efficiency was improved to near saturation by implementing a parallel matching circuit at SF1 and by optimizing the magnetic field gradients in the spin-flipping region. An increase of the filled neutrons by a factor 1.94(5), in comparison to the previously used single spin-flip method, has been demonstrated, providing a crucial increase in counting statistics.

I developed and characterized two iterations of the monitor detector. Both rely on hardware-based coincidence logic for event identification. The second iteration is an upgraded version, developed based on the experience gained with the prototype and achieves a 27% higher detection efficiency. Commissioning measurements of the upgraded detector show good agreement with a commercial UCN detector. The measured electronic background corresponds to a 95% upper bound of $0.1315 \cdot 10^{-3} \text{ s}^{-1}$, and the low response to non-UCN events of 4.3(3) events per kick means that the detector can be considered effectively background-free for τ SPECT measurements. The detector has been integrated into the τ SPECT experiment, and depending on the source state, it records up to 35000 neutrons per kick. It has proven effective for identifying changes to the source, such as the state of NLK South, source conditioning, and issues with the source itself. Moreover, the detector has shown sensitivity to changes of the setup at the other port of the UCN source.

I investigated the feasibility of normalization with the monitor-detector data using measurements from the first scientific data run of τ SPECT in 2024. A key challenge in this analysis was a drift in the filling efficiency of τ SPECT, caused by a slow drift of the main magnetic field of the experiment. The monitor detector is insensitive to the resulting decline of stored UCNs. Two different approaches were taken to address this issue.

- A simple proportional fit between τ SPECT and monitor counts, performed only on data on which the field drift had a small influence.
- A multiple linear fit, additionally using counts of the τ SPECT main detector during the filling period, to model the influence of the drift on the data.

Both approaches confirmed a linear dependence between the τ SPECT counts and the monitor counts. Especially, the multilinear approach has proven to be a promising candidate for normalizing τ SPECT data in the future, highlighting the monitor detector as an important tool for this purpose. Since the residuals of the multiple linear fit fluctuated by up to 14% more than expected, it is likely that the statistical uncertainties of the τ SPECT, the monitor and/or the filling counts were slightly underestimated. Possible sources of increased fluctuations could, for example, be variations of the τ SPECT detector background or shifts in the energy spectrum of the UCN source's output. An estimate of the normalization's influence on the statistical uncertainty shows that it does not significantly reduce the statistical sensitivity of τ SPECT, as it contributes only about 6% to the total variance.

Outlook

The dSF procedure can be further optimized. Increasing the rf field amplitude further would improve the stability of the spin-flip efficiency against small amplitude variations. Additionally, equipping the spin flipper with an adjustable matching circuit would provide the flexibility to adjust the resonance frequency of the circuit, allowing to adapt it to temperature effects or changes in the main field. Finally, implementing continuous monitoring of the rf field amplitude would help with the system diagnostics. An improved design for higher field amplitude due to an improved matching circuit is currently being worked on. The use of piezo motors for the realization of an adjustable matching circuit is being considered. To reduce sensitivity to the constant magnetic field drift, an adjustment of the SF1 frequency over time has been implemented in the software for the 2025 data run. In the long term, an active field stabilization using an NMR magnetometer as reference is planned. The corresponding NMR magnetometer is currently being tested.

Several approaches to further improve the normalization of τ SPECT data can be explored. To investigate potential shifts in the UCN energy spectrum, additional detectors, based on the design presented in this thesis, are currently planned and one is already being constructed. By placing these at different vertical positions along the beamline, information about the UCN energy distribution can be obtained. This will enable a more detailed characterization of, and correction for, energy-dependent systematic effects. A better understanding of factors influencing the background rate of the τ SPECT detector is also of interest. Currently, an investigation of the effect of temperature on the background rate of the τ SPECT detector is ongoing.

Appendix A

Additional technical drawings and schematics

A.1 Detector flange drawing

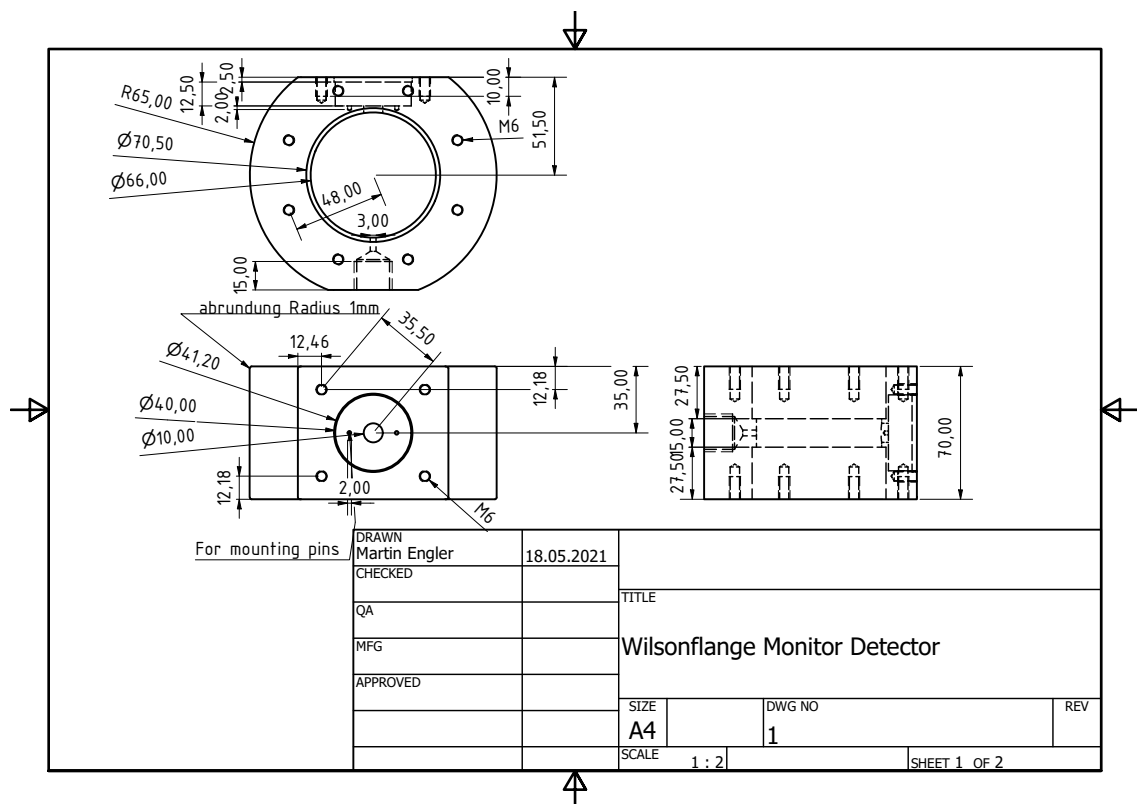


FIGURE A.1: Technical drawing of the monitor detector flange. All length are given in mm. The M6 threaded holes visible on the front view are used to mount the flange within the beamline using connector rings. The M6 threaded holes visible in the top are used to mount claw clamps for mounting a KF 40 piece. The 15 mm diameter hole in the bottom a thread was cut and then a KF 16 piece was screwed and glued in. The mounting pins ended up not being used. Sheet 2 of 2 contained a rendering of the flange and is not presented in this work.

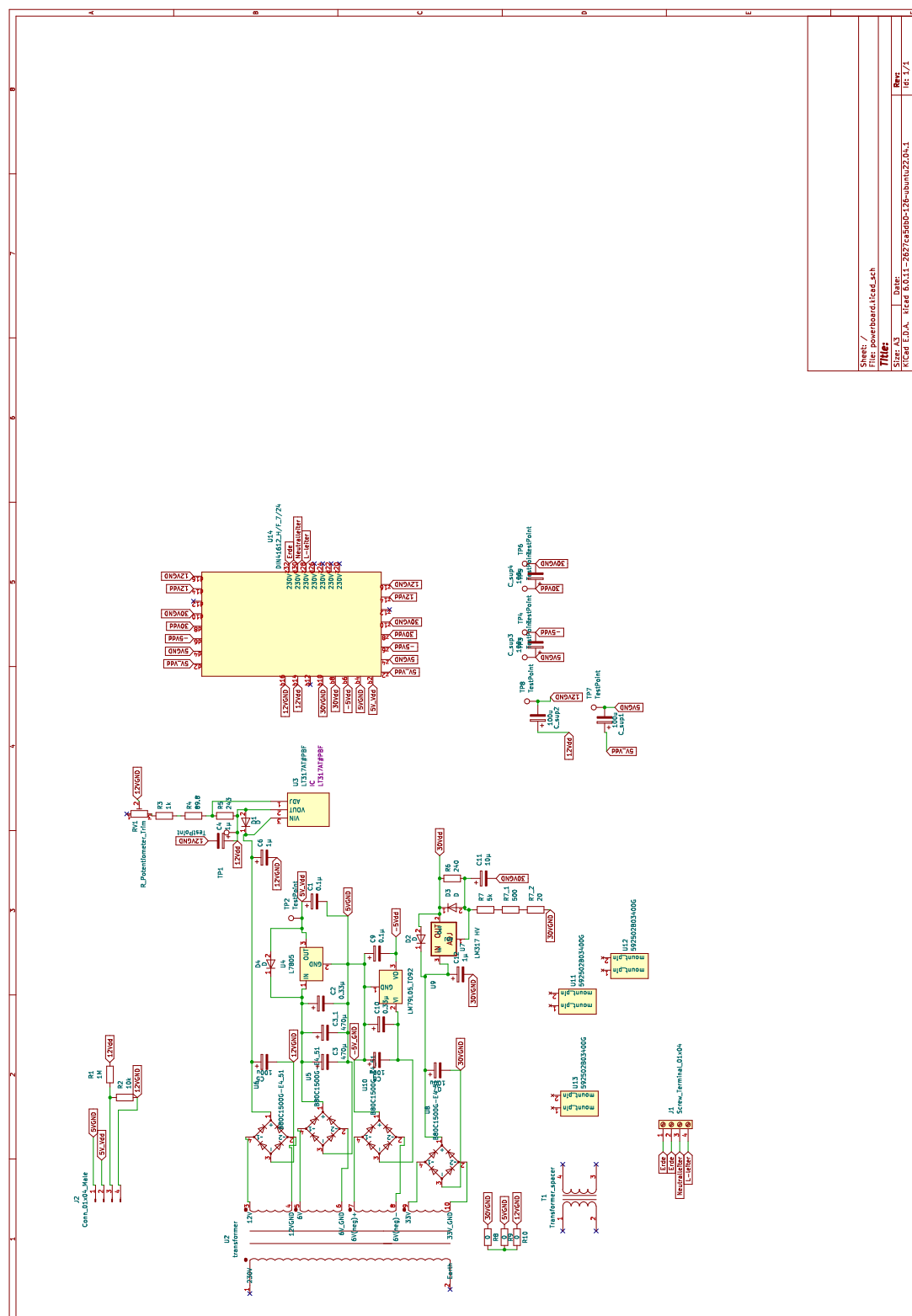


FIGURE A.2: Circuit schematic of the powerboard of monitor detector electronics version 2

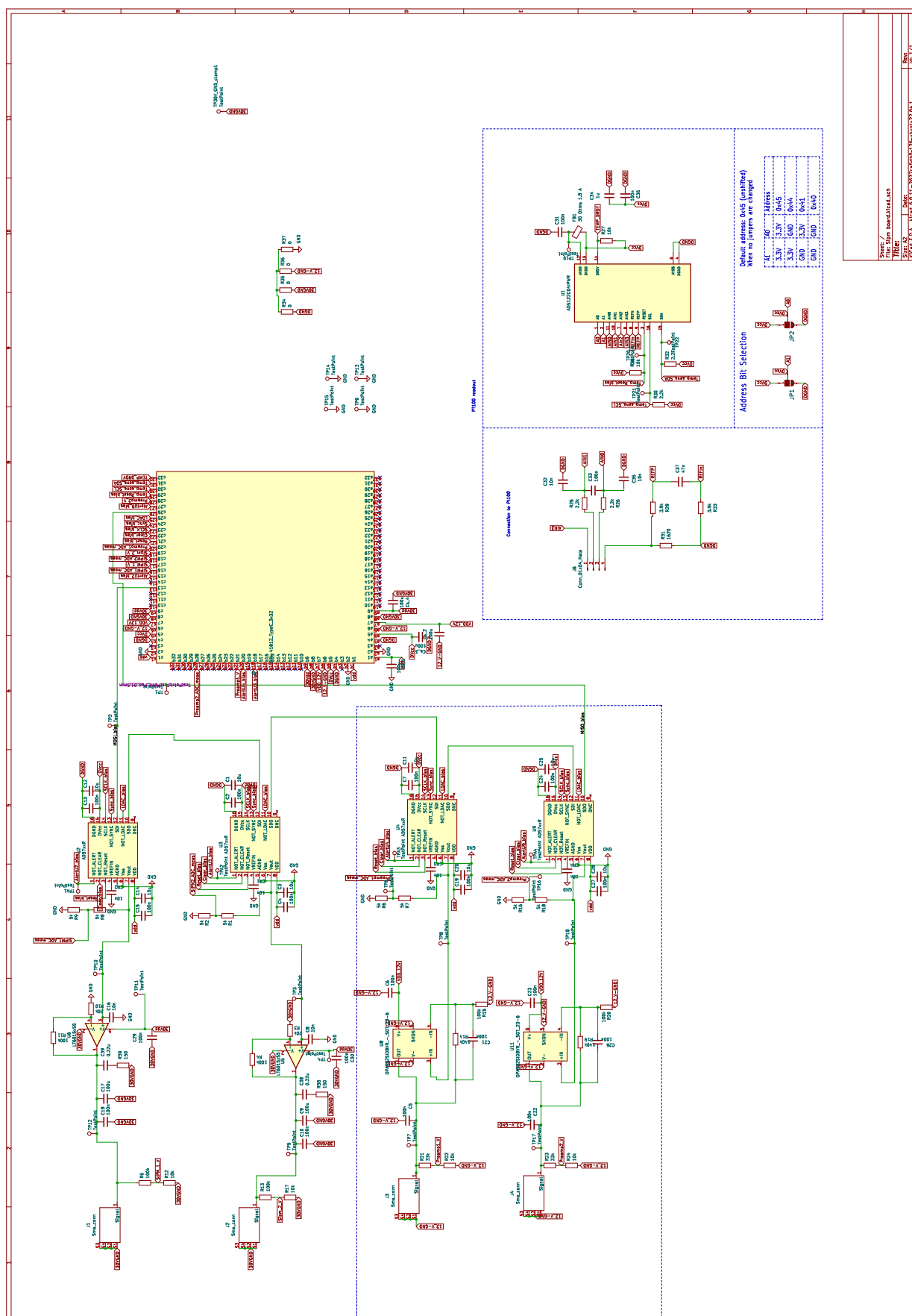


FIGURE A.3: Circuit schematic of the supply board of monitor detector electronics version 2

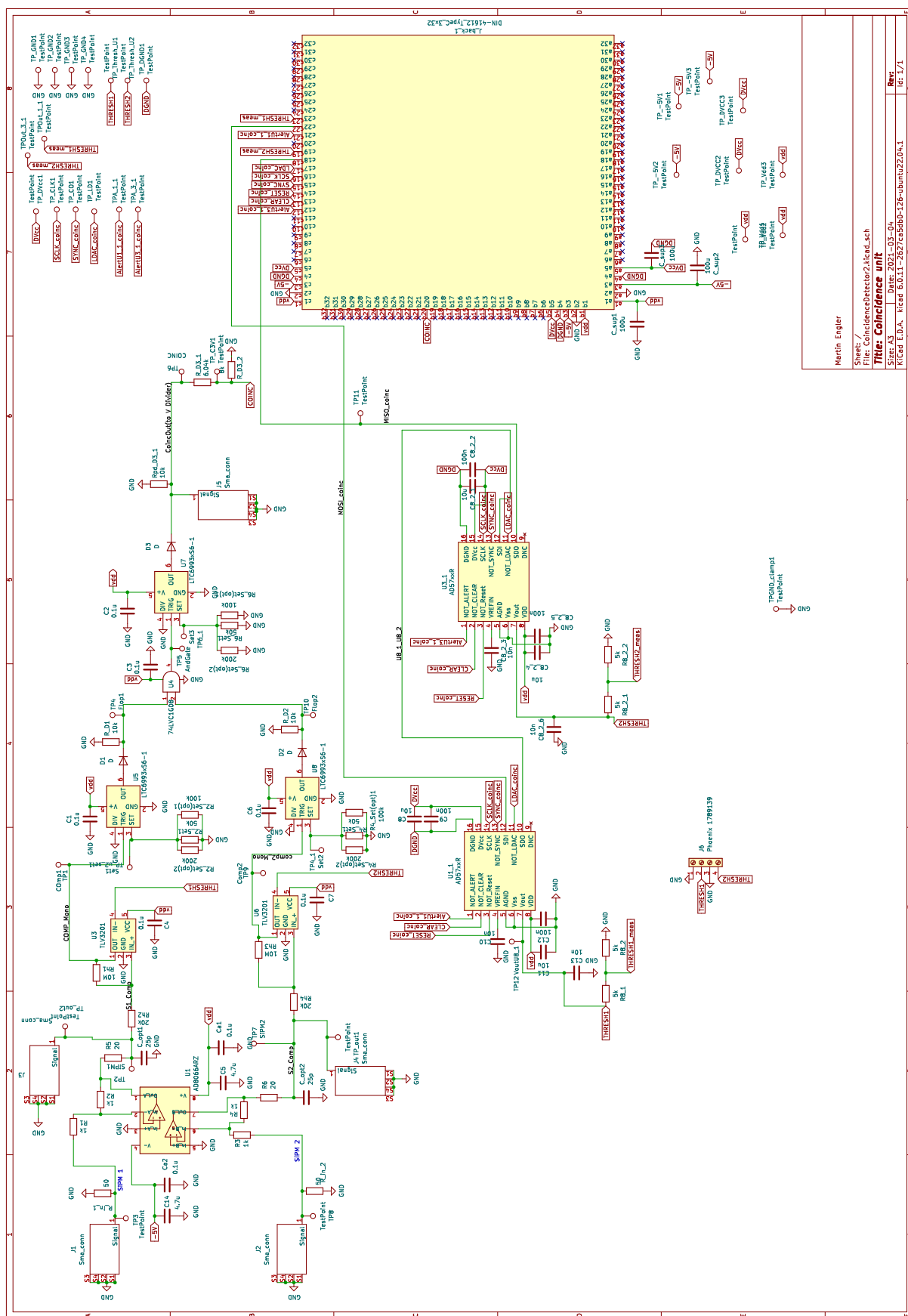


FIGURE A.4: Circuit schematic of the coincidence board of monitor detector electronics version 2



FIGURE A.5: Circuit schematic of the micro-controller board of the monitor detector electronics

A.3 CASCADE settings

```
File Name : T020924_0065.tof
CDT Detector Control : Version 10.2 (Build: Aug 20 2021), CASCADE Hardware Library 5.3 (Build: Aug 20 2021),
Optimized for firmware beyond DAQBox 3.2 and CDR 10.2
```

```
Detector Name : West-2
DAQBox Serial Number : ELZ62XYZEY
Readout Structure : 2D Pixel
No of X Stripes or Pixel : 8
No of Y Stripes or Pixel : 8
```

```
Type of Readout : 2D Pixel
X Resolution : 8
Y Resolution : 8
```

```
Type of Display : 2D Pixel
X Resolution Display : 1
Y Resolution Display : 1
```

```
Sum Column : 1
Data file binary : 0
Data file format (binary): [ Time-Bin [ Y-Channel [ X-Channel ] ] ]
Data file format (ascii, per row): Time-Bin, (Sum), [ Y-Channel, [ X-Channel ] ]
Dwell Time : 1000000
No of Bins : 3000
Break Mode : 1
Nominal No of Sweeps : 1
```

```
Start Time : 18:58:11 082
Nominal Time : 277:46:40
Real Time : 00:04:59
Stop Time : 19:03:10 768
Absolute Time : 2990143967
No of Counts : 2747370
Count Rate : 9188.09
Count Rate Error : 5.54
Actual No of Sweeps : 1
```

```
History:
DAQBox firmware 3.2 from 08.10.2015
CIPix: X0
Ipre: 200
Isha: 20
Ibuf: 40
Icomp: 20
Idriver: 40
Vfp: 140
Vfs: 150
Vref0: 110
Vref1: 110
Voffset: 50
Analog Out: 0
TpReg: 1
CIPixReg: 1
FSetup: 0x37330422
Delay Demux: 4
Mask Registers:
0xffffffff 0xffffffff
Event-Filter Configuration: 0x1040
Max. Event Size: 3
Max. Event Length: 5
Max. Event Skew: 1
: 60, 25, 2, 0, 13, 0 (1909317 Si, 789364 Db, 49534 Tr, 0 Mu, 423401 Iv, 0 Mh)
: 7, 52, 38, 3, 0 (200931 T1, 1415845 T2, 1041048 T3, 90391 TM, 201 TI)
0 Corner, 0 All
DX AS 0, DX AS-PAT 0x0000, DX T0-FW 0, DDP 10, EB Events 2747370, EB DL 0, ED DL 4565, HB DL 0
```

```
Part of batch job: asdf.job
```

FIGURE A.6: Meta file containing the CASCADE settings during the commissioning of monitor detector version 2

A.4 NMR magnetometer setup

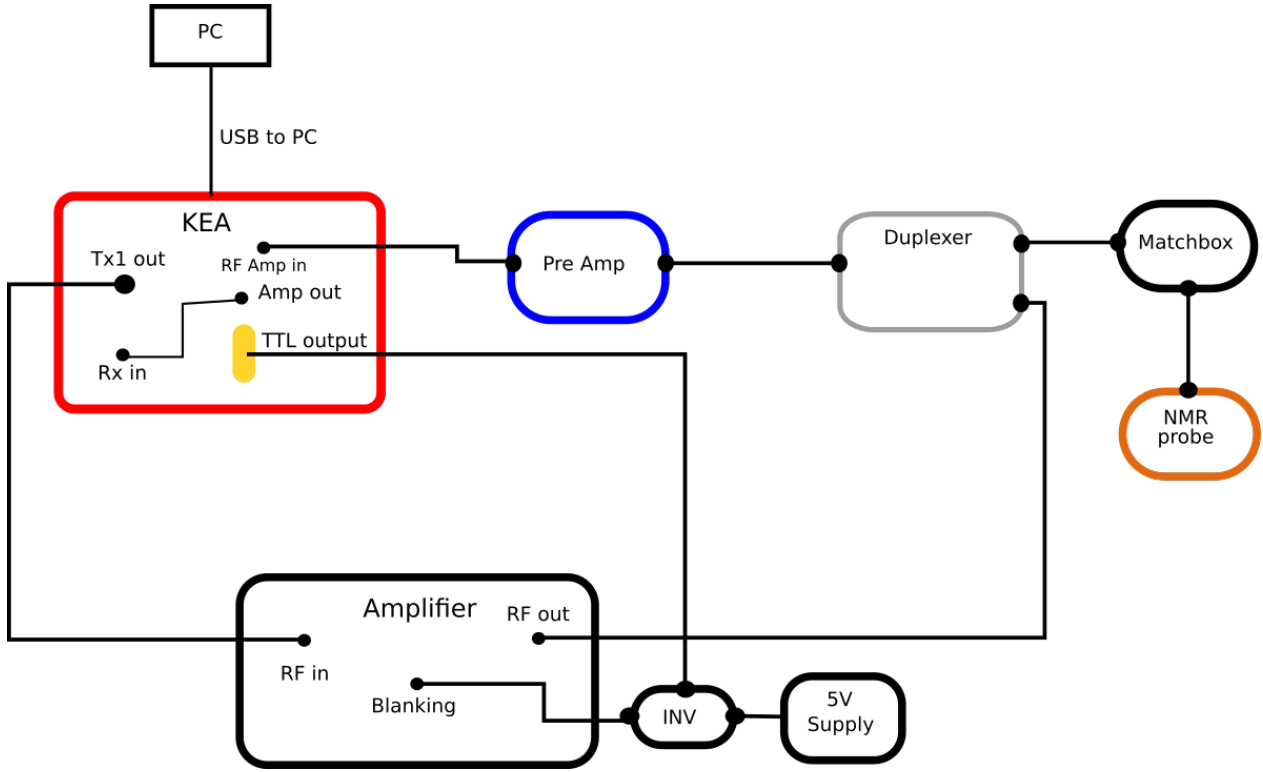


FIGURE A.7: Schematic of the setup of the readout of the NMR magnetometer. The KEA spectrometer is controlled by a user PC via USB. The rf excitation signal is sent from the TX1 out port of the KEA spectrometer to the rf in port of the Amplifier. The blanking input is controlled by the KEA via TTL pulses which are inverted by an inverter due to the inverse logic of the rf amplifier. The rf excitation signal is then transmitted to the NMR probe through a duplexer and an external matchbox. The NMR probe signal is sent to the spectrometer by the duplexer (a passive switch depending on the input voltage using crossed diodes) it is amplified twice, once by the external preamplifier and once by the internal amplifier of the spectrometer, which is connected to the signal input of the KEA (Rx in).

A.5 Analysis of NMR magnetometer data

This section briefly discusses how the free induction decay (FID) measured with the KEA spectrometer is analyzed to obtain the frequency-domain spectrum, as well as the FWHM and the centroid frequency of the peak. The complex time-domain data is first adjusted using a zero-order phase correction, implemented as a rotation in the complex plane by a constant angle θ to turn the real part of the signal fully absorptive [MV90, pp. 83-85]. The angle θ is determined from the first point of the FID s_0 as

$$-\theta = \arctan\left(\frac{\Im(s_0)}{\Re(s_0)}\right). \quad (\text{A.1})$$

The time-domain data is then zero padded to 8192 points, to increase the digital resolution of the discrete spectrum obtained with the discrete Fourier transform [MV90, p. 80]. Because the

quality of the obtained raw data was sufficient for the purpose of the measurement no further data manipulation (e.g. apodization) was done. A fast Fourier transform (FFT) is subsequently applied, and only the real part of the spectrum is used to estimate of the center of the resonance. The full width half maximum (FWHM) is estimated by identifying the leftmost point where the signal crosses from below to above the half of its maximum amplitude, and the rightmost point where it crosses back below. The frequency difference between those points gives the estimate for the FWHM. The uncertainty on the FWHM maximum is estimated as

$$\sigma_F^2 = \left(\frac{\sigma_n}{m_l}\right)^2 + \left(\frac{\sigma_n}{m_r}\right)^2 + 2\left(\frac{f_{bin}}{2}\right)^2 \quad (\text{A.2})$$

Here σ_n is the estimated standard deviation the noise floor, m_l and m_r are the estimators for the slope at the FWHM at the left and the right side, and f_{bin} is the frequency bin width. The slopes were estimated by linear interpolation. The resonance center is estimated by calculating the centroid of the peak, considering only data points within the FWHM of the resonance

$$f_c = \frac{\int f S(f) df}{\int S(f) df}. \quad (\text{A.3})$$

Where $S(f)$ is the amplitude spectrum. This is done by numeric integration using the trapezoidal rule to approximate the definite integral of a function $h(x)$ as

$$\int_a^b h(x) dx = \sum_{i=1}^N \frac{h(x_{i-1}) + h(x_i)}{2} \Delta x_i. \quad (\text{A.4})$$

Where Δx_k is the distance between x_{k-1} and x_k . The uncertainty on the centroid frequency is then estimated as

$$\sigma_c^2 = \sigma_n^2 \left(\frac{AB - C}{B^2} \right)^2, \quad (\text{A.5})$$

where

$$A = \sum_{i=1}^N f_i, B = \sum_{i=1}^N S_i, C = \sum_{i=1}^N f_i S_i. \quad (\text{A.6})$$

Appendix B

Additional Plots

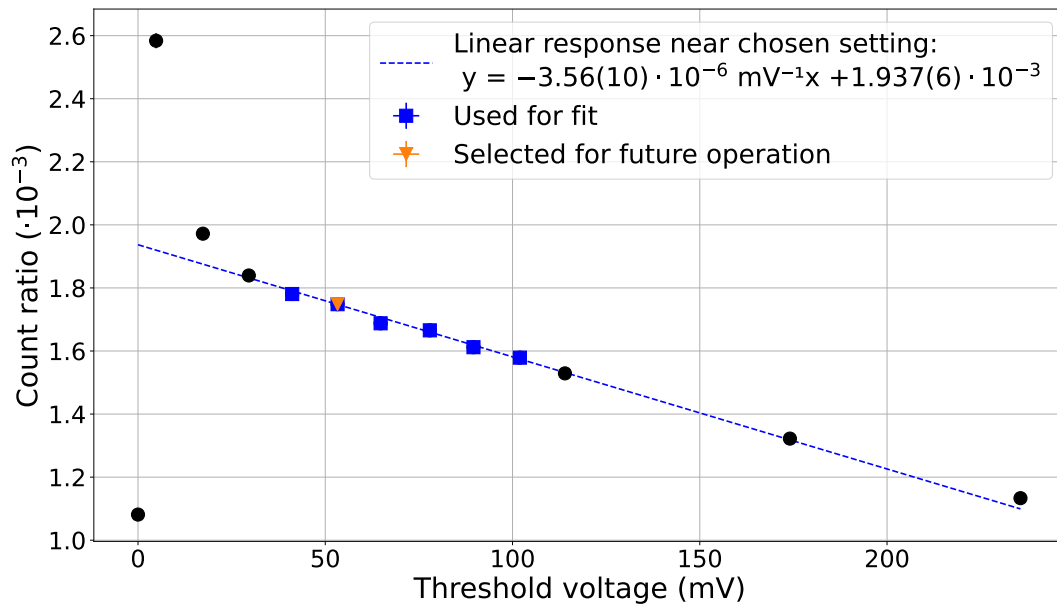


FIGURE B.1: Count ratio of monitor detector and CASCADE detector for a scan of event thresholds of channel 1. The amplifier supply voltage and the SiPM bias voltage were fixed at 10.6 V and 28.5 V. The x-axis displays the threshold voltage of channel 2 measured by the microcontroller. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean but are often entirely covered by the markers. For thresholds close to zero a strong nonlinearity in the count ratio, caused by the threshold entering the noise floor, can be observed. As a setting for future operation 54 mV marked by an orange triangle has been chosen. In order to estimate the response of the system around the chosen setting a line (dotted blue) has been fitted to selected points marked in blue.

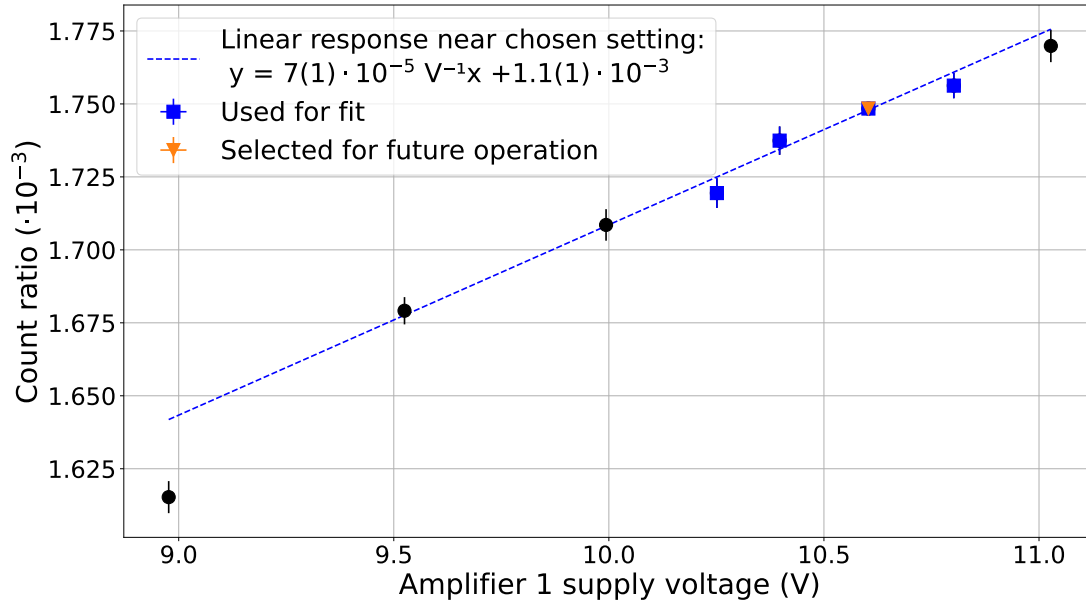


FIGURE B.2: Count ratio of monitor detector and CASCADE detector plotted for a scan of the amplifier 1 supply voltage, the event threshold voltage and the SiPM bias voltage were fixed at 54 mV and 28.5 V. The x-axis displays the supply voltage of amplifier 1 measured with the Teensy. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean. For voltages higher than 9.5 V the count ratio increases linearly with the supply voltage. As a setting for future operation 10.6 V marked by an orange triangle has been chosen. In order to estimate the response of the system around the chosen setting a line (dotted blue) has been fitted to selected points marked in blue.

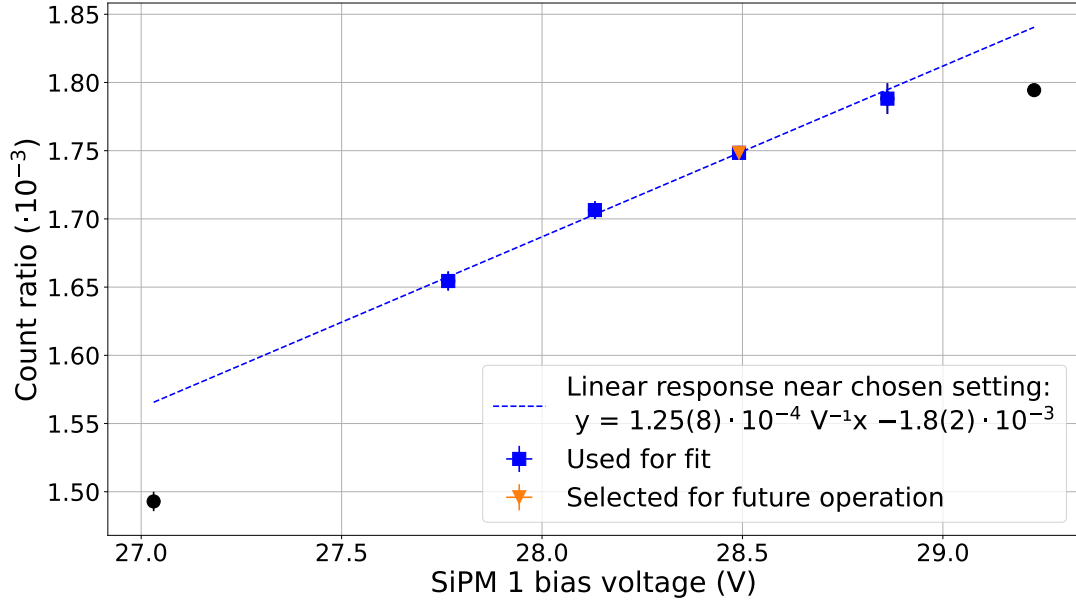


FIGURE B.3: Plot of the count ratio for a scan of SiPM 1 bias voltage. The event threshold voltage and the amplifier supply voltage were fixed at 54 mV and 10.6 V. The x-axis displays the bias voltage of SiPM 1 measured with the Teensy. Points represent the weighted mean of multiple measurements, error bars represent the standard error of the mean. As a setting for future operation 28.5 volt marked by an orange triangle has been chosen. In order to estimate the response of the system around the chosen setting a line (dotted blue) has been fitted to selected points marked in blue.

B.1 Additions to normalization

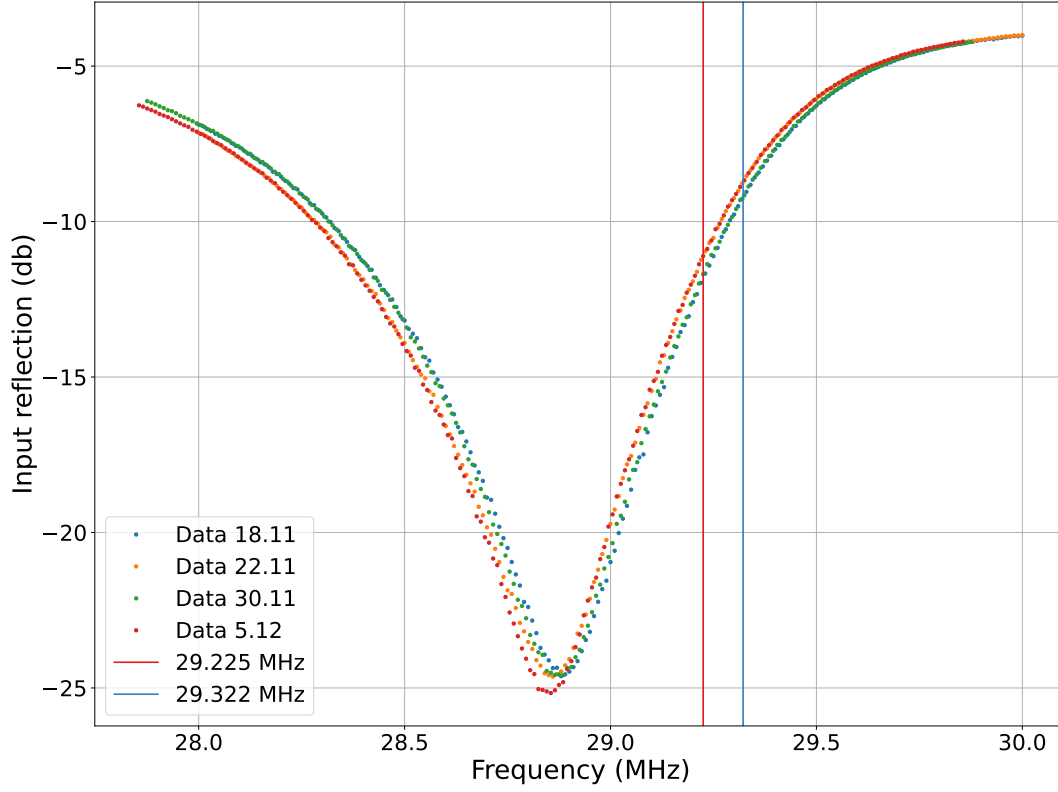


FIGURE B.4: Plot of S11 reflection measurements of the spin flipper 1 coil 1 circuit. The measurements were done at different dates within the blinded data run in winter 2024. The vertical lines represent the highest and lowest frequency which were applied during the data run. Small variations of the shape and the center of the resonance can be seen.

Appendix C

Software tools

C.1 Use of AI-Tools

AI-Tool	Usage	Reason for use	Part of the Thesis
Chat GPT, Le Chat	Produce Python and C++ code examples	Improve code quality, fixing of bugs	Throughout the whole thesis
Chat GPT, Le Chat	Restructure Python and C++ code	Improve code quality and code structure	Throughout the whole thesis
Chat GPT	Search for grammatical errors and missing punctuation	Improve readability of the thesis	Throughout the whole thesis
Chat GPT, Le Chat, JGU Chat	Polish and improve formulation of draft texts	Improve readability of the thesis	Throughout the whole thesis

TABLE C.1: Overview of the AI-tools used for this thesis.

C.2 Note on the software packages used in the analysis

The analysis in this thesis, unless stated otherwise, has been done using the following python packages: numpy [Har+20], scipy [Vir+20], pandas [McK10][tea24] and sklearn [Ped+11]. The plots presented in this work have been done with matplotlib [Hun07] version 3.10.0.

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