X17 Discovery Potential in the $\gamma N \to e^+e^-N$ Process at Electron Scattering Facilities

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We propose a direct search for the X17 particle, which was conjectured to explain the ATOMKI ^{8}Be and ^{4}He anomalies, through the dilepton photoproduction process on a nucleon in the photon energy range below or around the pion production threshold. For the scenarios of either pseudoscalar, vector, or axial-vector quantum numbers of the conjectured X17, we use existing constraints to estimate the X17 signal process. For dilepton invariant mass resolutions which have been achieved in previous experiments, a signal-to-background ratio of up to an order of magnitude is found for a neutron target, and, in particular, for the pseudoscalar and vector X17 scenarios.

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A few years ago, the ATOMKI group measured electron-positron angular correlations for two magnetic dipole transitions to the ground state taking place in ^{8}Be [1]. At large angles the correlation significantly deviated from the expectation for the transition from the predominantly isoscalar excited state at 18.15 MeV to the ^{8}Be ground state, whereas no signal was found in the decay of the predominantly isovector excited state at 17.64 MeV. In a second experiment with an improved and independent setup, the signal for the transition from the 18.15 MeV state was confirmed [2,3]. Furthermore, the same collaboration reported an excess with around 7σ significance in a transition in ^{4}He, around the same e^+e^- invariant mass [4,5]. Both observations were conjectured by the authors as being due to the emission of a new boson with mass around 17 MeV, denoted as X17.

In view of a vigorous program worldwide to search for dark sector particles with a very weak coupling to standard model particles, from sub-eV mass scales to multi-TeV mass scales [6–8], the ATOMKI observations have sparked the prospect that the conjectured X17 might fall in this category. Based on angular momentum and parity conservation in the observed nuclear transitions, the hypothetical X17 could be a pseudoscalar ($J^P = 0^-$) axionlike particle (ALP), a vector particle ($J^P = 1^-$), or an axial-vector particle ($J^P = 1^+$), and a variety of theoretical explanations along these lines have been proposed, see Refs. [9–25] among others. Several of these new physics explanations were challenged however, see, e.g., Refs. [26,27], motivating us to further scrutinize the energy dependence of the nuclear (p,γ) reactions which led to the above observations. On the experimental side, direct searches by the NA64 Collaboration at CERN have not found any X17 evidence so far [28,29], putting constraints on the allowed parameter ranges for new physics explanations. Furthermore, X17 searches are part of an ongoing large scale effort at many facilities in searches for feebly interacting particles; see Ref. [8] for a recent review.

In this Letter, we propose a direct search for the conjectured X17 particle through the dilepton photoproduction on a nucleon, the $\gamma N \to e^+e^-N$ process, in the 100–150 MeV photon energy range, below or around the production threshold for pions, at high-luminosity fixed target electron scattering facilities. Focusing on the scenario of well-defined parity, we take into account either pseudoscalar, vector, or axial-vector quantum numbers for the conjectured X17 in the ATOMKI ^{8}Be anomaly. We use existing constraints to provide an estimate for the X17 signal in the $\gamma N \to e^+e^-N$ process. For each of the three scenarios we compare this signal to the electromagnetic background for both a proton and a quasi-free neutron target, and provide an experimental outlook. For the pseudoscalar scenario we follow the model of Alves and Weiner [13], for the vector case we adopt the model proposed by Feng *et al.* [9,10], and for the axial-vector scenario we rely on the investigation of the ^{8}Be anomaly by Kozaczuk *et al.* [12].

To estimate the possible X17 signal in the $\gamma N \to e^+e^-N$ process (right panel in Fig. 1), we start from the reported ATOMKI value for the ratio of the decay rate via the new boson, denoted by X, to the γ decay rate of the (predominantly) isoscalar transition in ^{8}Be [3]:

$$
\begin{aligned}
&\Gamma[^8\mathrm{Be}(18.15) \to {}^8\mathrm{Be}(\mathrm{g.s.})X] \\
&\quad = (6 \pm 1) \times 10^{-6}\,\Gamma[^8\mathrm{Be}(18.15) \to {}^8\mathrm{Be}(\mathrm{g.s.})\gamma], \\
&\quad = (1.2 \pm 0.2) \times 10^{-5}\ \mathrm{eV}, \qquad (1)
\end{aligned}
$$

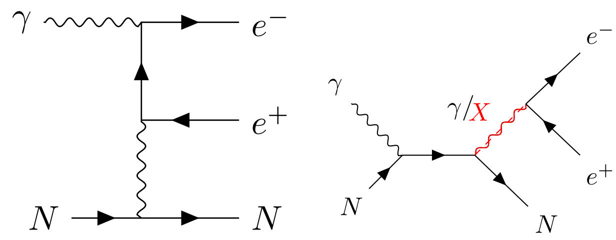

FIG. 1. Right panel: Direct tree-level Feynman diagram for the signal process $\gamma N \to e^+e^-N$ via a new physics particle X. The process on the right panel with a photon (γ) instead of X and the Bethe-Heitler process on the left panel are the main QED background processes. The crossed diagrams are not shown explicitly.

assuming a branching ratio $BR(X \to e^+e^-) = 1$, and using the reported value of the new boson mass [3]

$$m_X = 17.01(16)\ \text{MeV}. \quad (2)$$

For $BR(X \to e^+e^-) = 1$, the X17 signal in the $\gamma N \to e^+e^-N$ process depends solely on the X coupling to the nucleon, which we discuss subsequently for the three possible X quantum number scenarios.

Following Alves and Weiner [13] for the pseudoscalar ALP scenario, the coupling of an ALP X to the nucleon isospin doublet N is described by

$$\mathcal{L}_{PS} = i\bar{N}\gamma_5(g^{(0)}_{XNN} + g^{(1)}_{XNN}\tau_3)NX, \quad (3)$$

with τ_3 the isospin Pauli matrix, and $g^{(0)}_{XNN}$ ($g^{(1)}_{XNN}$) the isoscalar (isovector) coupling constants, respectively. The latter can be expressed as

$$g^{(1)}_{XNN} = \frac{m_N}{f_\pi}(\Delta u - \Delta d)\theta_{X\pi}, \quad (4)$$

with nucleon mass m_N, pion decay constant $f_\pi \approx 92.4$ MeV, isovector combination of axial charges $\Delta u - \Delta d \simeq 1.27$, and ALP-$\pi^0$ mixing angle $\theta_{X\pi}$. For the latter, searches for the decay $\pi^+ \to e^+\nu_e X \to e^+\nu_e e^+e^-$ by the SINDRUM Collaboration [30] put the very strong constraint $|\theta_{X\pi}| \lesssim (0.5-0.7)\times 10^{-4}$ [13], leading to the bound $|g^{(1)}_{XNN}| \lesssim 0.6 \times 10^{-3}$. The isoscalar coupling $g^{(0)}_{XNN}$ is then constrained by the ATOMKI results. The ratio of ALP to M1 photon emission rates with isospin change $\Delta T = 0$, 1 was calculated by Donnelly *et al.* [31] as

$$\left.\frac{\Gamma_X}{\Gamma_\gamma}\right|_{\Delta T} = \frac{1}{2\pi\alpha}\left(\frac{g^{(\Delta T)}_{XNN}}{\mu^{(\Delta T)} - \eta^{(\Delta T)}}\right)^2\left[1 - \left(\frac{m_X}{\Delta E}\right)^2\right]^{3/2}, \quad (5)$$

where $\alpha \approx 1/137$ is the fine-structure constant, ΔE is the excitation energy of the corresponding nuclear level, and the parameters μ and η are the form factor values at momentum transfer $\sim\mathcal{O}(17\ \text{MeV})^2 \approx 0$, which are related to nuclear magnetic moments and the ratio of convection to magnetization currents, respectively. They have been estimated as $\mu^{(0)} = 0.88$, $\mu^{(1)} = 4.7$, $\eta^{(0)} = 1/2$, while $\eta^{(1)}$ can be neglected compared to $\mu^{(1)}$ as a first estimate [31].

Because of isospin mixing of the ^{8}Be excited states at 18.15 (predominantly isoscalar) and 17.64 MeV (predominantly isovector), the comparison with the measured decay rates involves an isospin mixing angle θ_{1^+}, which we take as $\sin\theta_{1^+} = 0.35(8)$, following the analysis of Ref. [12]. The ATOMKI value for the transition ratio of the 18.15 MeV state, given in Eq. (1), then yields for the isoscalar coupling $g^{(0)}_{XNN}$ the range shown in Table I. Furthermore, the value of the transition ratio for the 17.64 MeV state in ^{8}Be is found to be

$$\left.\frac{\Gamma_X}{\Gamma_\gamma}\right|_{^8\text{Be}(17.64)} \approx (0.4-9.3)\times 10^{-8}, \quad (6)$$

which is 1–2 orders of magnitude smaller than the one for the 18.15 MeV state, and consistent with the ATOMKI nonobservation of an X particle in the 17.64 MeV → g.s. transition in ^{8}Be.

In a later work [22], Alves used a similar estimate from Ref. [31] for the $0^- \to 0^+$ transition in ^{4}He and found that the model can consistently explain both anomalies. On the other hand, for a non-ALP nonderivative pseudoscalar coupling, the production of an X particle in a relative p-wave state (for the ^{8}Be $1^+ \to 0^+$ transition) versus s-wave state (for the ^{4}He $0^- \to 0^+$ transition) leads to a decay width ratio of ^{8}Be vs ^{4}He as third power vs first power of the momentum of X, resulting in a strong suppression of order 10^{-6} [21]. This scenario of a non-ALP pseudoscalar seems therefore ruled out.

We next discuss the vector scenario for the X particle, proposed in Refs. [9,10], which is described by

$$\mathcal{L}_V = -eX_\mu\sum_q \varepsilon_q\bar{q}\gamma^\mu q. \quad (7)$$

The nucleon couplings are then obtained from the quark couplings as $\varepsilon_p = 2\varepsilon_u + \varepsilon_d$ and $\varepsilon_n = \varepsilon_u + 2\varepsilon_d$. In the limit of no isospin mixing or breaking, the nuclear part of the matrix element in the decay rate ratio Γ_X/Γ_γ cancels out, simply yielding for the isoscalar state,

$$\left.\frac{\Gamma_X}{\Gamma_\gamma}\right|_{^8\text{Be}(18.15)} = (\varepsilon_p + \varepsilon_n)^2\left[1 - \left(\frac{m_X}{18.15\ \text{MeV}}\right)^2\right]^{3/2}, \quad (8)$$

which constrains the sum $(\varepsilon_p + \varepsilon_n)$. The expression becomes slightly more complicated when including isospin mixing and isospin breaking. In our numerical analysis we follow Ref. [10], using their breaking parameter $\kappa = 0.549$, and the above mentioned isospin mixing parameter θ_{1+}. The constraint provided by the NA48/2 experiment, which

TABLE I. The values for the X coupling constants to the nucleon in the three discussed scenarios of J_X^P quantum numbers. The left column shows the couplings using the central value for the X mass, the right column the values using a 1σ variation on the m_X value.

J_X^P	$m_X = 17.01$ MeV	1σ uncertainty in m_X
0^-	$\lvert g_{XNN}^{(1)}\rvert = (0 - 0.6) \times 10^{-3}$	
	$g_{XNN}^{(0)} = (3.0 - 4.0) \times 10^{-3}$	$g_{XNN}^{(0)} = (2.7 - 4.4) \times 10^{-3}$
1^-	$\lvert\varepsilon_p\rvert = (0 - 0.12) \times 10^{-2}$	
	$\lvert\varepsilon_n\rvert = (1.2 - 1.7) \times 10^{-2}$	$\lvert\varepsilon_n\rvert = (1.1 - 1.9) \times 10^{-2}$
1^+	$a_{p,n} = (1.9 - 5.9) \times 10^{-5}$	$a_{p,n} = (1.8 - 6.1) \times 10^{-5}$

looked for the decay $\pi^0 \to \gamma(X \to e^+e^-)$ [32], leads to the protophobia condition ($\varepsilon_p \ll \varepsilon_n$) [10]: $|\varepsilon_p| \lesssim 1.2 \times 10^{-3}$. The ATOMKI decay rate for the 18.15 MeV transition then provides a lower limit on the X coupling to the neutron ε_n, as given in Table I.

Third, we also discuss the scenario where the X boson has purely axial-vector interactions with quarks:

$$\mathcal{L}_A = -X_\mu \sum_q g_q \bar{q}\gamma^\mu \gamma_5 q. \tag{9}$$

Kozaczuk *et al.* calculated the decay widths for the transition from the 1^+ states to the 0^+ g.s. in ^{8}Be via such an axial-vector boson as [12]

$$\Gamma_X = \frac{|k_X|}{18\pi}\left[2 + \left(\frac{\Delta E}{m_X}\right)^2\right]|a_n\langle 0\|\sigma^n\|1\rangle + a_p\langle 0\|\sigma^p\|1\rangle|^2, \tag{10}$$

with $|k_X| = \Delta E[1 - (m_X/\Delta E)^2]^{1/2}$, and where the nucleon couplings are expressed as

$$a_{p,n} = \sum_{q=u,d,s} \Delta q^{(p,n)} g_q, \tag{11}$$

where Δq are the known axial charges.The reduced nuclear matrix elements $\langle 0\|\sigma^{p,n}\|1\rangle$ for the states at 18.15 and 17.64 MeV were estimated by Kozaczuk *et al.*, using isospin mixing $\sin\theta_{1^+} = 0.35$, as [12]

$$\begin{aligned}&\langle 0\|\sigma^p\|17.64\rangle = 0.100(18), \quad \langle 0\|\sigma^p\|18.15\rangle = -0.044(13),\\ &\langle 0\|\sigma^n\|17.64\rangle = -0.070(11), \quad \langle 0\|\sigma^n\|18.15\rangle = -0.130(21).\end{aligned} \tag{12}$$

Similar to the vector scenario, the ^{8}Be ATOMKI experiment constrains roughly the (isoscalar) sum of nucleon couplings. Assuming $a_p = a_n$ in this work (corresponding with $g_u = g_d$), we then derive a bound on its value from the observed decay rates from the ATOMKI experiment for the 18.15 and 17.64 MeV states in ^8Be, and the corresponding values for $a_{p,n}$ are shown in Table I.

Within the three discussed scenarios, we next estimate the signal for the photoproduction of X17 in the $\gamma N \to e^+e^-N$ reaction, with N either a proton or neutron, see Fig. 1 (right panel). For photon energies below and around the pion production threshold, the Feynman diagrams for the two leading background processes are also shown in Fig. 1: the Bethe-Heitler process (left) as well as the Born process (right), which has the same topology as the signal process, with X replaced by a photon.

The $\gamma N \to e^+e^-N$ cross section is given by

$$\frac{d\sigma}{dt dm_{ee}^2 d\Omega^*} = \frac{1}{64}\frac{1}{(2\pi)^4}\frac{1}{(2m_N E_\gamma)^2}\overline{|\mathcal{M}|^2}, \tag{13}$$

with E_γ the lab photon beam energy, t the four-momentum transfer to the nucleon, and m_{ee} the invariant mass of the dilepton pair. θ^* is the electron polar angle in the e^+e^- rest frame with respect to the lab momentum direction of the e^+e^- pair, and ϕ^* is the azimuth angle of the e^+e^- decay plane with respect to the plane of the incoming photon and the lab direction of the dilepton pair momentum. Furthermore, $\overline{|\mathcal{M}|^2}$ is the squared matrix element averaged over initial and summed over final spins.

Figure 2 shows the angular dependence of the differential cross section for $E_\gamma = 0.15$ GeV and $-t = 0.04$ GeV^2 with angles $\phi^* = 45°(180°)$ that allow maximizing the signal-to-background-ratio for a proton (neutron) target. The X signal cross section is averaged over a bin $\Delta m_{ee} = 0.2$ MeV around $m_{ee} = m_X$, as such energy resolution in the e^+e^--invariant mass was already achieved at a dark photon search experiment at MAMI [33]. The QED background process is depicted in black, while the signal process is shown for the pseudoscalar (green), vector (blue), and axial-vector (red) scenarios. Both plots in Fig. 2 show two consecutive error bands graded by color. The darkest inner bands correspond with the couplings in the left column of Table I, which were obtained by fixing $m_X = 17.01$ MeV and varying over the range of the ATOMKI ^{8}Be decay rate of Eq. (1). The outer bands were obtained by also considering a 1σ variation of the mass m_X according to Eq. (2), corresponding to the couplings in the right column of Table I. The correlation between the assumed mass and the best-fit decay rate was neglected here. One notices from Fig. 2, that for a proton target and for $\Delta m_{ee} = 0.2$ MeV, the signal is at best of the order of the background for the pseudoscalar or axial-vector X17 scenario around $\theta^* = 90°$, while the signal of a protophobic vector boson cannot be expected to be measurable. For a neutron target, however, the background is considerably smaller in the same kinematical configuration due to the absence of a charge coupling to the neutron, and all three X17 scenarios could leave a significant signal, with the vector scenario nearly an order of magnitude above the background around

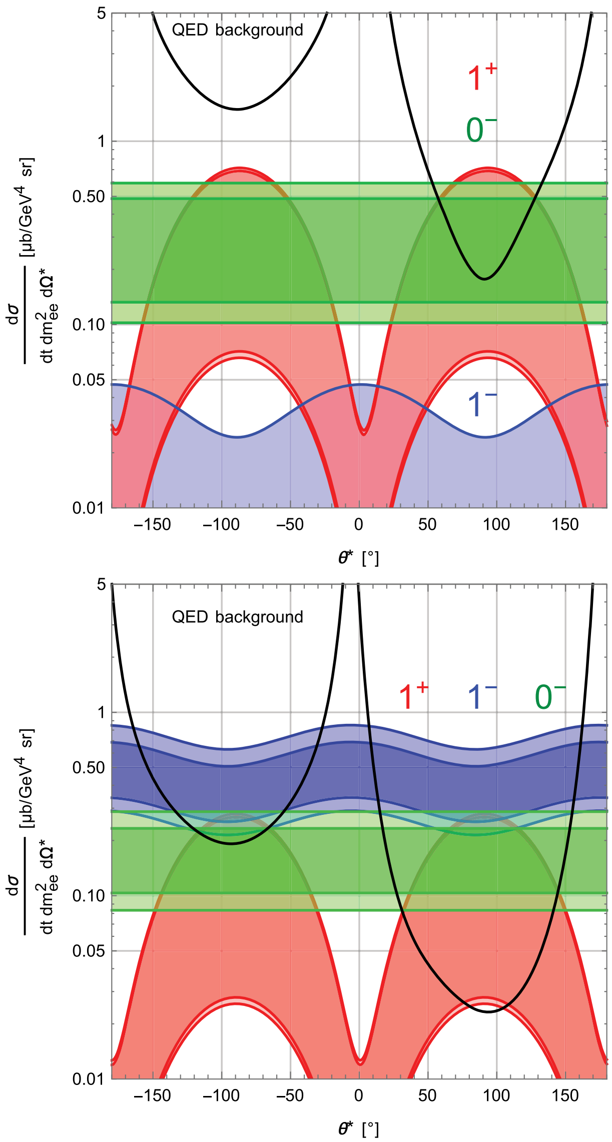

FIG. 2. Cross section estimate of the X17 angular distribution in the $\gamma N \to e^- e^+ N$ reaction for photon energy $E_\gamma = 0.15$ GeV and momentum-transfer to nucleon $-t = 0.04$ GeV^2, with $N = p(n)$ at $\phi^* = 45°(180°)$ in the upper (lower) panel. The signal cross section is averaged over a bin of 0.2 MeV around $m_{ee} = m_X$ and is shown for three X17 scenarios: as a pseudoscalar ALP (green), as a vector state (blue), and as an axial-vector state (red), together with the QED background (black curve). The inner (outer) bands depict the uncertainty due to the ^{8}Be decay width (X17 mass).

$\theta^* = 90°$. One can optimize such a search experiment, and further increase the signal-to-background ratio by a better energy resolution. The different angular dependencies for the three scenarios would allow us to determine the quantum numbers of an X particle thus produced. Note that the above methods can also be extended for the case of an X particle which does not have a well-defined parity, and could, e.g., be a linear combination of a vector and axial-vector particle, as considered in Ref. [15].

In conclusion, we proposed a direct search for the X17 particle, which was conjectured to explain the ATOMKI ^{8}Be and ^{4}He anomalies, through the dilepton photoproduction on a nucleon in the photon energy range below or around the pion production threshold. We analyzed the discovery potential for three J_X^P quantum number scenarios of an X17. For the cases of a pseudoscalar, vector, and axial vector, we calculated the signal process by estimating the coupling constants from the observed ^{8}Be decay rate value. The $\gamma N \to e^+ e^- N$ signal cross section was compared to the expected background for a dilepton mass resolution which has been achieved before. A discovery potential was found when considering the process for a neutron target, and, in particular, for the pseudoscalar and vector scenarios for an X17. This process can be accessed experimentally by studying the X17 production on a quasi-free neutron for a deuteron target, by tagging the recoiling neutron. Such a search experiment can be performed at electron accelerators such as, e.g., MAMI or MESA.

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