Review

X17: Status and Perspectives

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Review

X17: Status and Perspectives

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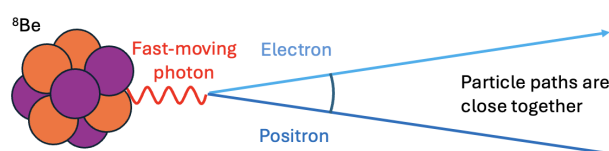carlo.gustavino@roma1.infn.it

Abstract: Recently, a group directed by A. J. Krasznahorkay observed an anomaly in the emission of electron–positron pairs in three different nuclear reactions, namely, the ^{3}H(p,e$^-$e$^+$)^{4}He, ^{7}Li(p,e$^-$e$^+$)^{8}Be, and ^{11}B(p,e$^-$e$^+$)^{12}C processes. Kinematics indicate that this anomaly might be due to the de-excitation of ^{4}He, ^{8}Be, and ^{12}C nuclei with the emission of a boson with a mass of about 17 MeV, rapidly decaying into e$^-$e$^+$ pairs. The result of the experiments performed with the singletron accelerator of ATOMKI is reviewed, and the consequences of the so-called X17 boson in particle physics and in cosmology are discussed. Forthcoming experiments designed to shed light on the possible existence of the X17 boson are also reported.

Keywords: X17; dark matter; nuclear physics

1. Introduction

Three significant anomalies have recently been observed in the electron–positron pairs emitted in the ^{3}H(p,e$^-$e$^+$)^{4}He, ^{7}Li(p,e$^-$e$^+$)^{8}Be, and ^{11}B(p,e$^-$e$^+$)^{12}C reactions [1–3]. These anomalies consist in an excess of e$^-$e$^+$ pairs at a large relative angle. As shown in Figure 1, the excess e$^-$e$^+$ pairs have been interpreted as the signature of a new particle with a mass of about 17 MeV (hereinafter $c = \hbar = 1$), called X17 boson.
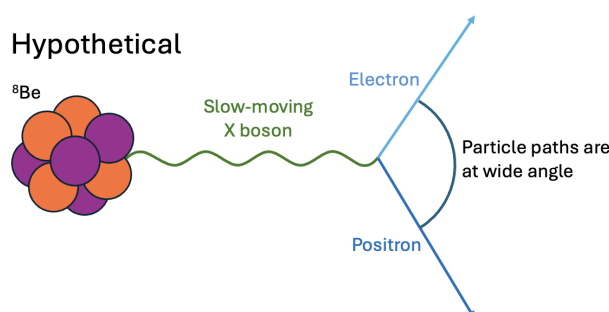
Expected ^{8}Be Transition

Hypothetical

Figure 1. Graphical representation of the ^{7}Li(p,e$^-$e$^+$)^{8}Be process: the creation of the massive X17 boson decaying into an e$^-$e$^+$ pair is deduced by the excess of e$^-$e$^+$ pairs at a large relative angle. The main background is due to the internal pair conversion (IPC) of virtual photons.

If confirmed, the existence of this new particle would be of extraordinary importance in particle physics and in cosmology. In fact, the X17 boson could be a mediator of a fifth force, characterized by a strong coupling suppression of protons compared with neutrons

(protophobic force). Moreover, it could explain existing tensions in the standard model, such as the long-standing (recent) anomaly on the muon (electron) magnetic moment [4,5]. From a cosmological point of view, X17 could be a "portal" between the ordinary matter and the dark sector.

2. The ATOMKI Experiments

Figure 2 shows the setup used to study the ^{3}H(p,e$^+$e$^-$)^{4}He reaction (to study the other two reactions, very similar apparatuses were used). It consists of a tritium target adsorbed on a thin Ti backing. The target is bombarded with a proton beam with an intensity of about 1 μA and an energy of $0.5 \lesssim \mathrm{E}_p(\mathrm{MeV}) \lesssim 1$. The vacuum along the beam line is ensured by a 1 mm thick carbon tube, in correspondence with the target. The detection of the electron–positron pairs is performed with 6 telescopes mounted in a plane orthogonal to the beam line. Each telescope consists of a double-sided silicon strip detector (3 mm wide strips, 0.5 mm thick), coupled with a plastic scintillator ($8.2 \times 8.6 \times 8.0$ cm^3) with a standard energy resolution of about 5% at 20 MeV. The use of a thin backing for the target and of a thin carbon fiber tube limits the spread of the aperture angle of e$^-$e$^+$ pairs due to the multiple scattering. The silicon strips provide the impact point of crossing particles, while the scintillators are used to measure the electron and positron energies. This detector does not provide the tracking and the particle identification, and its acceptance is limited to particles emitted at around 90° with respect to the beam axis.
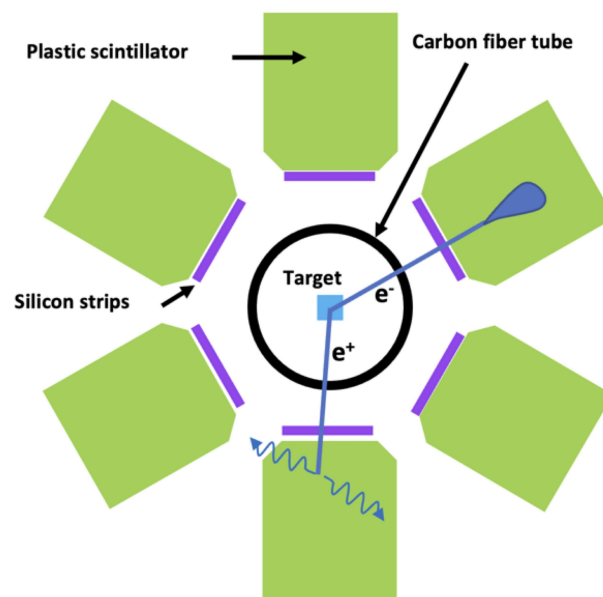

Figure 2. Sketch of the experimental setup used at ATOMKI to study the ^{3}H(p,e$^-$e$^+$)^{4}He reaction.

The main background for the electron–positron pairs produced by the X17 decay is due to the internal pair conversion (IPC) of virtual photons (see Figure 1). The IPC rate is a factor 10^{-3} lower with respect to the rate of real γ's, and it smoothly decreases with the electron–positron aperture angle θ_{ee}. Figure 3 shows the rate of e$^-$e$^+$ pairs as a function of their aperture angle θ_{ee} for the ^{7}Li(p,e$^-$e$^+$)^{8}Be reaction at a proton energy $\mathrm{E}_p = 1.10$ MeV. The counting excess at $\theta_{ee} \simeq 140°$ is clearly visible and corresponds with a boson with a mass $\mathrm{M}_{X17} \simeq 17$ MeV. The plot also shows the expected rate in which the decay of a boson is added to those of IPC pairs for different boson masses (see [1] for more details). Figure 4 shows the θ_{ee} angle distributions for the ^{3}H(p,e$^-$e$^+$)^{4}He reaction at $\mathrm{E}_p = 0.51, 0.61, 0.9$ MeV. Additionally, in this case, the excess of events at large θ_{ee} is visible for all the three energies. Remarkably, the excess moves towards smaller angles, increasing the energy, in good agreement with the de-excitation of ^{4}He to the ground state with the production of a particle with a mass of 17 MeV [2]. Finally, Figure 5 shows the distributions relative to

the ^{11}B(p,e$^-$e$^+$)^{12}C process at E$_p$ = 1.5, 1.7, 1.88, and 2.1 MeV. Additionally, for this process, there is an excess compatible with the creation of a particle with a mass of 17 MeV for all the beam energies [3]. In summary, all the three experiments provide an excess of several standard deviations in the θ_{ee} distribution. The observed anomalies are all compatible with the creation of a particle with a mass $M_{X17} \simeq 17$ MeV. The branching ratio compared with the γ-decay is B$_x \sim 10^{-5}$, while the lifetime of the boson with the observed coupling strength is expected to be of the order of $\tau = 10^{-14}$–10^{-12}s. The corresponding flight distance is about 0.03–3 mm, corresponding with a very narrow resonance ($\Gamma \lesssim 0.07$ eV).
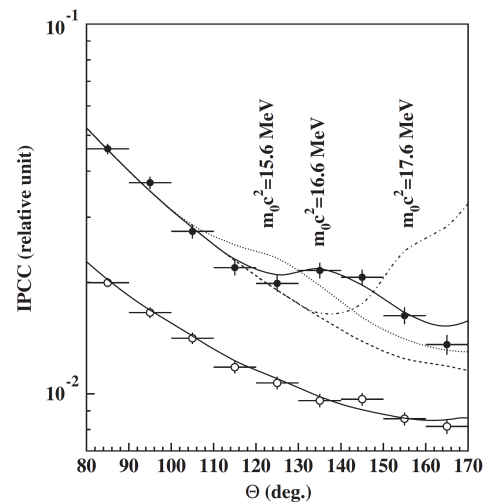

Figure 3. Angular correlations for the e$^-$e$^+$ pairs measured in the ^{7}Li(p,e$^-$e$^+$)^{8}Be, ^{3}H(p,e$^-$e$^+$)^{4}He, and ^{11}B(p,e$^-$e$^+$)^{12}C reactions. The experimental data show a clear excess of e$^-$e$^+$ at a large relative angle. Also shown are the expected angular distribution of e$^-$e$^+$ pairs based on standard physics (dotted lines) and the data fit assuming $M_{X17} \simeq 17$ MeV [1].

Figure 4. Angular correlations for the e$^-$e$^+$ pairs measured in the ^{3}H(p,e$^-$e$^+$)^{4}He reaction at three different energies. The excess at a large relative angle is very visible and in good agreement with the production of a boson with a mass $M_{X17} \simeq 17$ MeV. See [2] for more details.
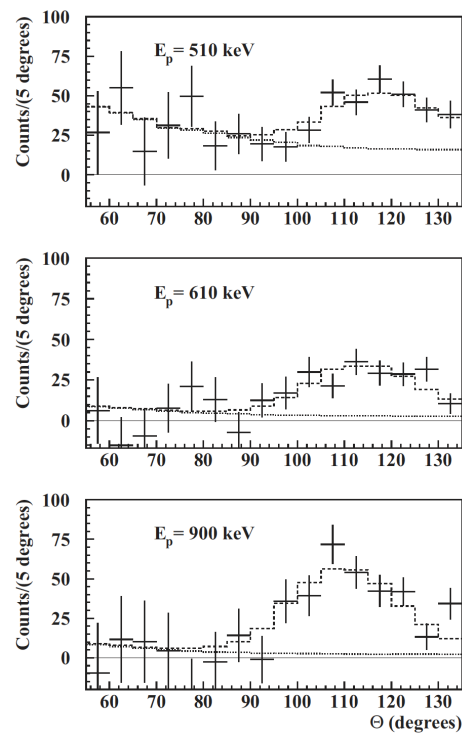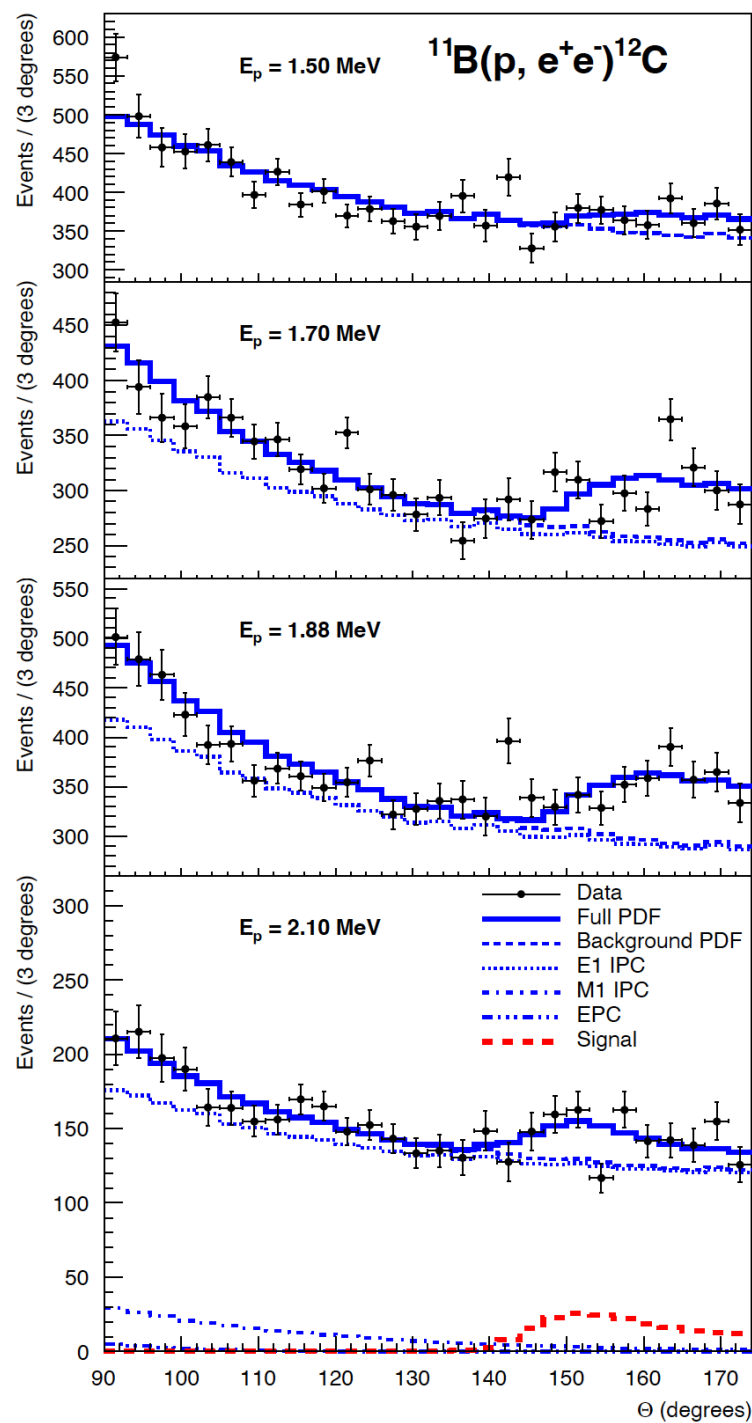
Figure 5. Angular correlations for the e^-e^+ pairs measured in the ^{11}B(p,e^-e^+)^{12}C reaction at three different energies. Additionally, in this case, data are consistent with the production of a boson with a mass $M_{X17} \simeq 17$ MeV. See [3] for more details.

Although the kinematics of ATOMKI experiments are quite convincing, the properties of the X17 boson are not clear enough. As an example, for $E_p = 0.8$ MeV, no excess has been observed in the ^{7}Li(p,e^-e^+)^{8}Be reaction [1]. This circumstance is debated; in particular, it is unclear whether the absence of an excess is due to some X17 property or indicates that the anomaly seen at $E_p = 1.10$ MeV is due to some systematics [6]. On the other hand, the existence of the X17 boson is still not confirmed or rejected by other groups or

experiments. Therefore, an adequate theoretical and experimental effort is highly desirable to shed light on the X17 anomaly.

3. Discussion

The first theoretical interpretation of the experimental results was performed by Feng et al. [7,8]. They explained the anomaly by a 17 MeV vector gauge boson, which may mediate a fifth fundamental force with some coupling to standard model (SM) particles. In their work, the X17 boson has a peculiar coupling with electrically charged particles and quarks because the search of $\pi^0 \to A' + \gamma$ by the NA48/2 experiment provided a null result [9]. Based on these experimental results, the X17 particle must couple more strongly to neutrons than to protons, so the particle was defined as "protophobic". Figure 6 shows the beryllium experiment result (red line), together with the excluded area of parameter space (gray area). The coupling constant ϵ_e is essentially constrained by the X17 decay length. Figure 6 also shows that a protophobic boson with a mass $M_{X17} = 17$ MeV is not excluded by the present experimental results (gray area). The contours show the sensitivity of several experiments to "dark photons" (but without the protophobicity assumption [7]).
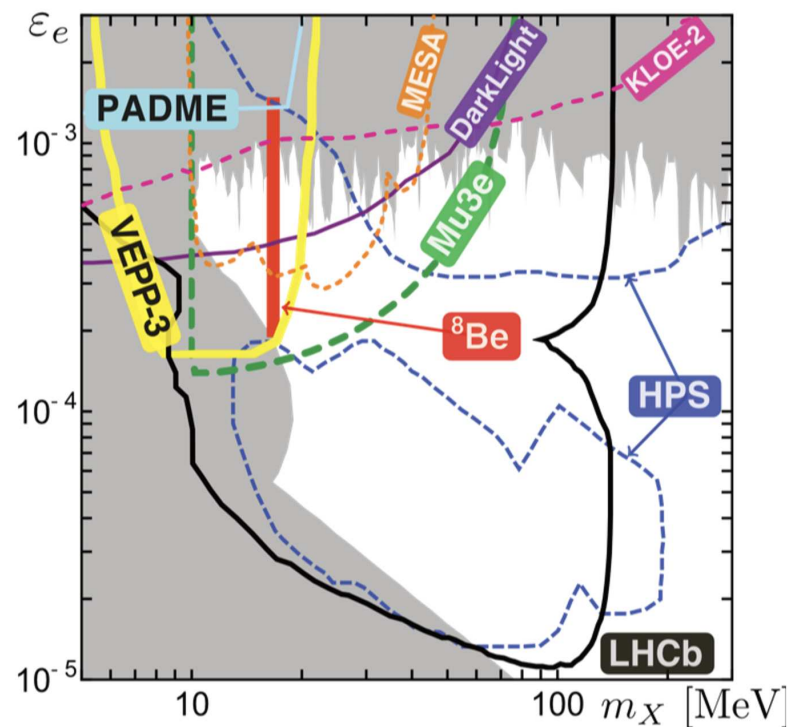

Figure 6. The ^{8}Be signal region (red line) in the (M_{X17}, ϵ_e) plane. The excluded parameter space assuming a protophobic coupling is also shown (gray area). The contours show the sensitivity for the dark photon search of several experiments. Reproduced from [7] published by American Physical Society, with permission.

Ellwanger and Moretti suggested another interpretation of the experimental results, assuming a light, pseudoscalar particle [10]. They predicted a branching ratio that was about ten times smaller in the case of the 17.6 MeV transition compared with the one with 18.15 MeV, which is in nice agreement with the ^{7}Li(p,e$^-$e$^+$)^{8}Be experiment. Subsequently, many studies with different models have been performed, including an extended two-Higgs-doublet model [11–13]. They showed that the anomaly can be described with a very light Z_0 bosonic state, with significant axial couplings. Zhang and Miller investigated the form factor as a possible origin of the anomaly, but they concluded that this hypothesis is unrealistic for the ^{8}Be nucleus [14]. Finally, a vector X17 boson is compatible with the anomalous magnetic moment of an electron and a muon [4,5]. Figure 7 shows the exclusion area in the (ϵ, M_{X17}) space for the X17 boson. Figure adapted from [5].
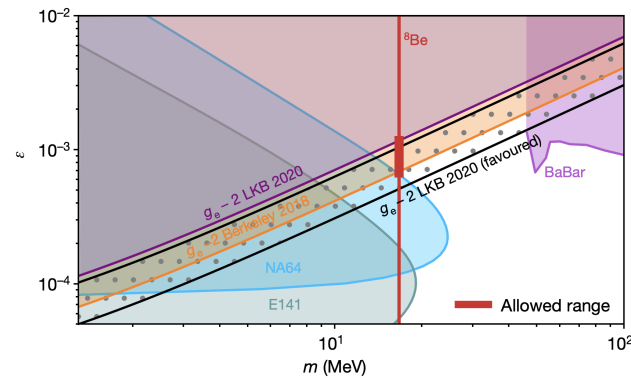
Figure 7. Exclusion area in (ϵ, M_{X17}) space for the X17 boson. The green, red and yellow regions are ruled out by the E141, NA64 and BaBar experiments, respectively. A test based on the magnetic moment of the electron rules out the orange region when using the previous (Berkeley) measurement and the purple region when using the most recent and accurate result for the electron magnetic moment [5]. Disregarding the Berkeley measurement, the remaining allowed range at 16.7 MeV is depicted by the thick violet. The zone favoured by [5] is shown in dark green. Reproduced from [5] published by Springer Nature, with permission from SNCSC.

4. New Experimental Approaches

The ATOMKI data are clearly compatible with the production of a particle with a mass of 17 MeV. Although the statistical evidence of this anomaly is of many standard deviations, it is worth pointing out that all the three experiments were carried out by the same group of researchers, in which very similar apparatuses were used. Recently, the ^{7}Li(p,e$^-$e$^+$)^{8}Be anomaly was confirmed by a Vietnamese group [15]. However, This work was carried out in collaboration with the ATOMKI group, using an apparatus and an analysis technique similar the one described in [1–3].

A possible confirmation of the X17 boson is provided by a series of tests on the production of photon pairs at JINR, using ions of several GeV on carbon and copper targets [16]. The analysis provides anomalies of the invariant mass of photon pairs at about 17 and 38 MeV, although further investigations are necessary.

To confirm (or otherwise explain) the ATOMKI anomaly, it is of primary importance to perform independent measurements by other groups and with different approaches. Following the nuclear road (i.e., experiments based on the de-excitation of nuclei), new experiments should provide more precise information on the X17 properties, such as its coupling with ordinary matter and its quantic numbers J^π. This objective can be achieved by measuring the charge and 4-momenta of electron–positron pairs, performing measurements in a wide energy region, and using an apparatus with a large acceptance. In this regard, a theoretical calculation was performed considering the ^{4}He de-excitation, assuming the standard model (in which only IPC pairs are produced) and also considering the production of a 17 MeV scalar (S), pseudoscalar (P), vector (V), or axial (A) boson decaying into e$^-$e$^+$ pairs, with M = 17 MeV [17]. The calculations were normalized to the ATOMKI data of the ^{3}H(p,e$^-$e$^+$)^{4}He process at E$_p$ = 0.9 MeV, in which only pairs at about 90° with respect to the beam axis were detected. Figure 8 shows the cross section for the ^{3}H(p,e$^-$e$^+$)^{4}He and ^{3}He(n,e$^-$e$^+$)^{4}He processes at six different energies for the incident nucleons. By inspecting Figure 8, it is apparent that the strength of the excess as a function of the projectile energy strongly depends on the X17 quantic numbers, according to the level scheme of the ^{4}He nucleus [17]. Similarly, the X17 momentum and parity affect the angular distribution of emitted pairs. Figure 9 shows the cross section for the ^{3}H(p,e$^-$e$^+$)^{4}He process (E$_p$ = 0.9 MeV) as a function of the e$^-$e$^+$ aperture angle. The first quadrant reproduces the ATOMKI conditions, in which only pairs at about 90° with respect to the beam axis ($\theta_{e^-} = \theta_{e^+} = 90°$) are detected. The theoretical curves of the first quadrant for scalar (S), pseudoscalar (P), vector (V), and axial (A) are normalized to the data. The other three quadrants of Figure 9) show the predictions for $\theta_{e^-} = \theta_{e^+} = 80°$, 70°, and 60°, respectively. As expected,

the angular distribution of e^+e^- pairs strongly depends on the momentum and parity of the X17 boson. The study of the ^{4}He de-excitation produced through the ^{3}He(n,e$^+$e$^-$)^{4}He process has been recently proposed by using the n_TOF facility at CERN [18]. This facility provides a pulsed, broadband neutron beam, in which the neutron energy is deduced with the time-of-flight (ToF) technique [19]. The experimental setup is shown in Figure 10. It consists of a ^{3}He target of a few cm^3 inside a 1 mm thick carbon fiber at a pressure of 380 bar at room temperature, corresponding to a density of 1.04×10^{22} atoms/cm^3. The detector is composed of 4 TPCs equipped with μRwell readout planes [20] to provide the 3D reconstruction of electron and positron tracks. The detector is also equipped with a set of scintillator bars and a coil with a square cross section, generating a magnetic field of about 500 Gauss (the square section of the coil is solely due to mechanical constraints of the device). The detector has a large solid angle acceptance, fulfills the requirement of the 4-momenta reconstruction of e^+e^-, and provides the charges. Moreover, it is rather insensitive to γs emitted by the ^{3}He(n,γ)^{4}He reaction (B = $n_{X17}/n_\gamma \sim 10^{-5}$) or photons induced by the scattered neutrons.

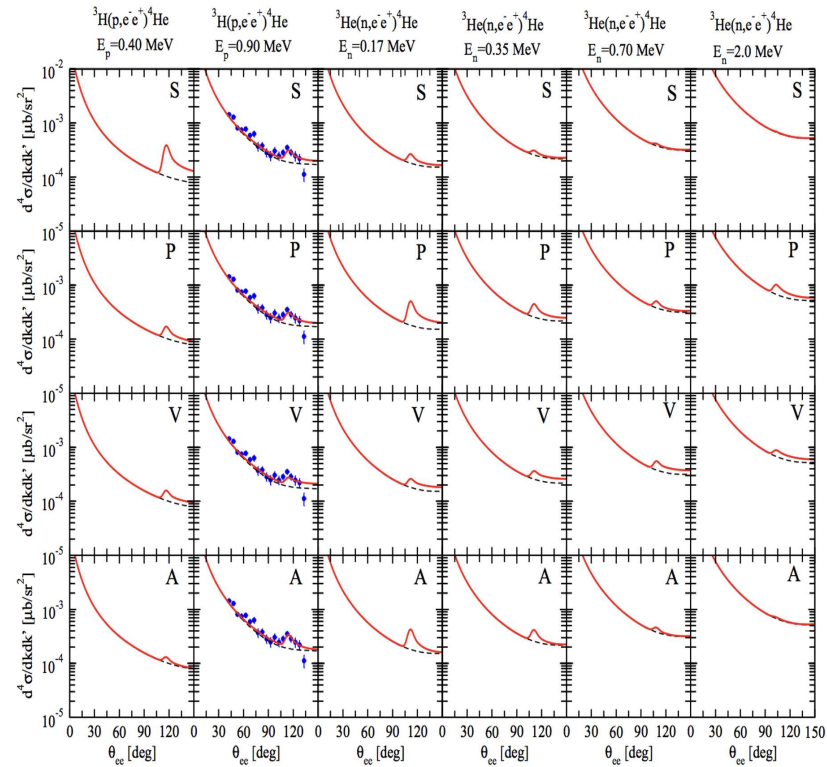**Figure 8.** Cross section for the ^{3}H(p,e$^-$e$^+$)^{4}He and ^{3}He(n,e$^-$e$^+$)^{4}He processes at six different incident nucleon energies as a function of the relative angle θ_{ee} between e$^-$e$^+$ pairs. Predictions for scalar (S), pseudoscalar (P), vector (V), and axial (A) with a boson with a mass of 17 MeV are shown. The calculations are normalized to the ATOMKI data (blue dots). See text.

Figure 11 shows the result of a simulation in which the ^{3}He(n,e$^+$e$^-$)He^4 process is reproduced (E$_n$ = 0.347 MeV). The simulation reproduces the experimental conditions in which Bremsstrahlung and multiple scattering are taken into account. The kinematics of electron–positron pairs (due to IPC and the decay of a vector X17 boson) are calculated in [17] according to the ATOMKI result. The figure shows the electron–positron aperture angle (radiant) θ_{ee} as a function of the energy asymmetry Y = (E$_{e^-}$ − E$_{e^+}$)/(E$_{e^-}$ + E$_{e^+}$), where E$_{e^-}$ and E$_{e^+}$ are the kinetic energies of the electron and the positron, respectively. A "moon-shaped" excess of pairs at a large angle, due to the X17 decay into e$^+$e$^-$ pairs, is clearly visible over the IPC pairs' background (the ratio between IPC and X17 pairs is B = n_{IPC}/n_{X17} = 40), despite of the excess smearing due to the multiple scattering and the Bremsstrahlung affecting electrons and positrons. The n_TOF program also foresees

the use of this detector to an improved study of the ^{3}H(p,e$^-$e$^+$)^{4}He, ^{7}Li(p,e$^-$e$^+$)^{8}Be, and ^{11}B(p,e$^-$e$^+$)^{12}C reactions, as well as the study of new processes. Of particular interest is the study of the ^{2}H(p,e$^-$e$^+$)^{3}He and ^{2}H(n,e$^-$e$^+$)^{3}H reactions, which are well suited for detailed ab initio calculations (see [21] and references therein). For both processes, X17 would be created by the de-excitation of the A = 3 nuclei (^{3}He and ^{3}H) into the ground state. It is worth pointing out that ^{3}He and ^{3}H have a different content of neutrons and protons. From the measurements of both cross sections, one could extract information about the isospin dependence of the X17–nucleon interaction [22]. Moreover, the X17 boson can be created only by exceeding an invariant mass of 17 MeV, i.e., with proton or neutron beams with an energy above $\sim$ 16 MeV.
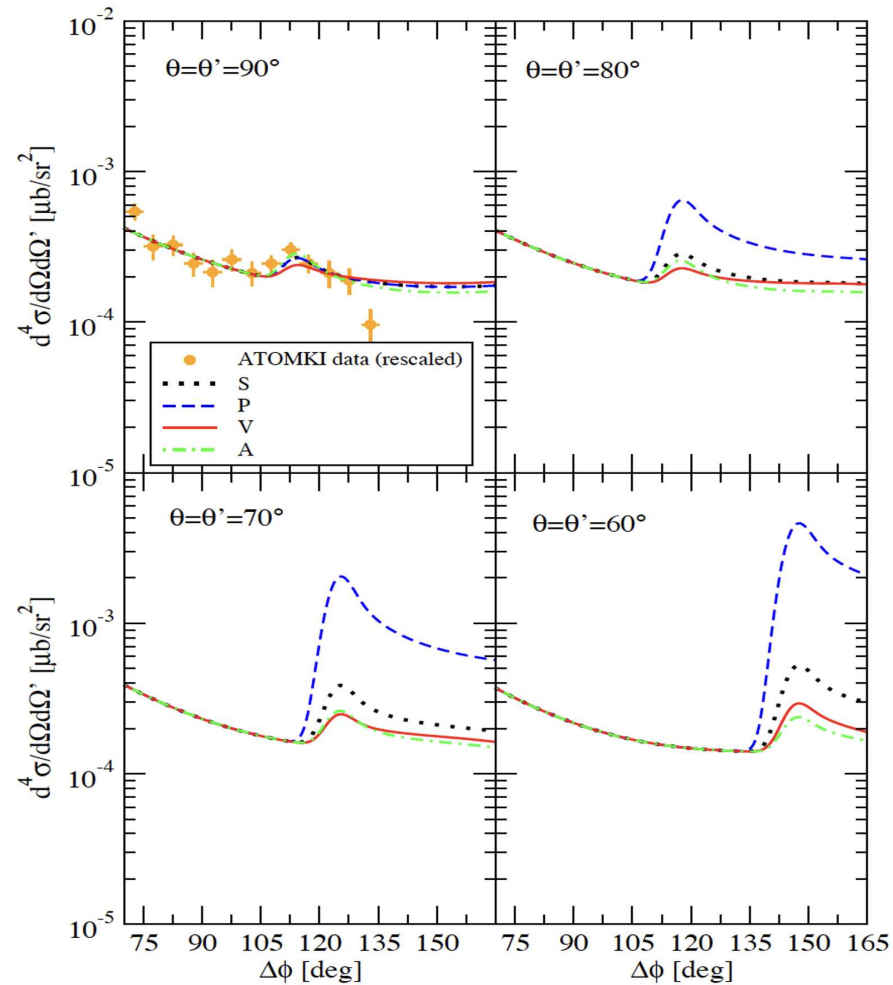

Figure 9. Cross section of the ^{3}H(p,e$^-$e$^+$)^{4}He process as a function of the relative angle between e$^-$e$^+$ pairs for an incident proton energy E$_p$ = 0.9 MeV. Calculations are made for a scalar (S), pseudoscalar (P), vector (V), and axial (A) boson with a mass of 17 MeV. The case of pairs emitted at 90° with respect to the beam axis (first quadrant) has been used to normalize the calculations to the ATOMKI data (yellow dots). Also considered are the case of e$^+$e$^-$ pairs emitted at 80° (2nd quadrant), 70° (3rd quadrant), and 60° (4th quadrant).
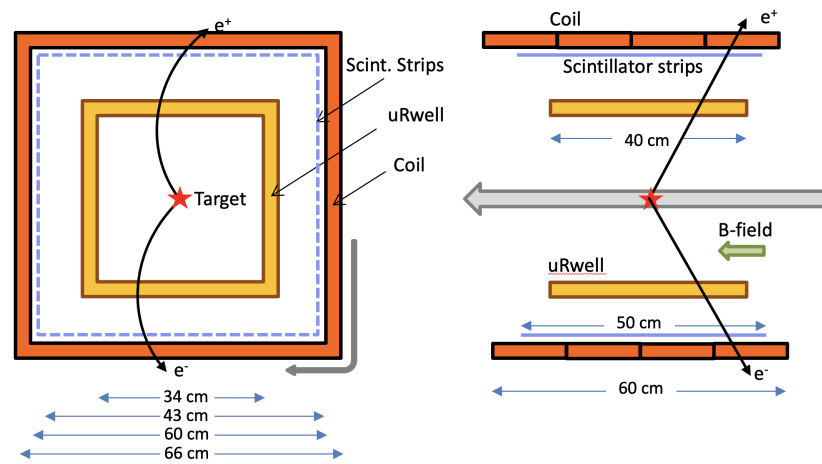
Figure 10. Setup for the study of the ^{3}He(n,e$^+$e$^-$)^{4}He. It consists of 4 large µRwells, surrounded by an array of scintillating bars. The detectors are inside a coil with a squared section, providing a magnetic field up to 500 Gauss. See text.
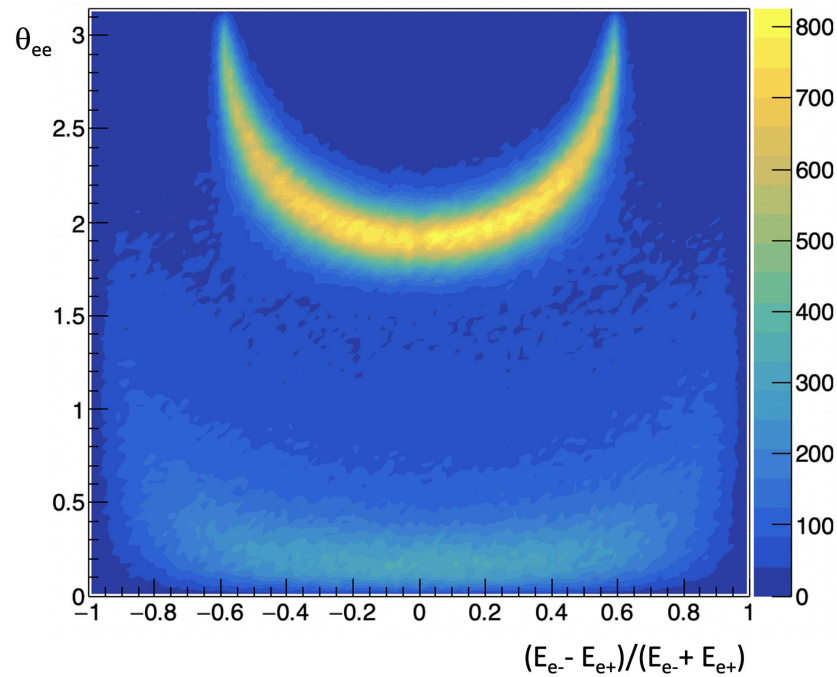

Figure 11. Electron–positron angle θ_{ee} as a function of electron–positron energy asymmetry $Y = (E_{e^-} - E_{e^+})/(E_{e^-} + E_{e^+})$, where E_{e^-} and E_{e^+} are the kinetic energies of the electron and the positron, respectively. The plot refers to the ^{3}He(n,e$^+$e$^-$)^{4}He reaction at E_p = 0.347 MeV, using a detector immersed in a magnetic field of 500 Gauss. In this simulation is considered the multiple scattering due to the material surrounding the target. The kinematics of electron–positron pairs are calculated for IPC and for the X17 vector boson. The counting excess due to the X17 decay is very visible (see text).

Presently, the ^{7}Li(p,e$^-$e$^+$)^{8}Be reaction is also studied with the MEG2 experiment at GSI, in which the tracking and particle identification is performed with a detector based on a Multi-Wire Projection Chamber (MWPC), an intense magnetic field, and a calorimeter [18]. A similar approach was performed by the Montreal X17 project.

Besides the nuclear approach, many experiments are suited for probing the X17 existence, such as the experiments searching for dark photons [18]. As an example, the PADME collaboration has proposed the X17 search by using a positron beam impinging on a diamond target. If X17 exists, an excess of pairs would be observed due to the

$e^+e^- \Rightarrow X17 \Rightarrow e^+e^-$ reactions at $E_{e+} \simeq 250$ MeV, i.e., at the invariant mass of the X17 boson. In this approach, the main background is represented by the Bhabha scattering. Other new proposals and ideas to probe the X17 anomaly can be found in [18], in which a more extensive review of experiments is reported.

5. Conclusions

Although the possible existence of X17 is very suggestive, caution is obviously mandatory for the claim of X17 discovery. However, the experiments proposed to probe its existence would have an adequate sensitivity to provide in a few years a sure answer to this issue. The hunting of the new X17 particle by means of nuclear experiments offers a chance to look for new physics. Even in the case of a negative result, these experimental efforts will shed light on IPC phenomena that represent a primary probe to test ab initio nuclear calculations [22]. If confirmed, the X17 discovery could deeply change the present knowledge of particle physics and cosmology.

Conflicts of Interest: The authors declare no conflict of interest.

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