EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Searching for the X17 Particle using the novel n+^{3}He Reaction

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Abstract:
We aim to clarify the current scenario in nuclear physics after striking anomalies reported in the electron-positron pairs emitted 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. These anomalies consist of an excess of electron-positron pairs events emitted at large relative angle that have been unfolded as the signature of a new boson with mass of about 17 MeV/c^{2}, the so called X17. We propose to study for the first time the neutron-induced reaction ^{3}He(n, e^{-}e^{+})^{4}He at the n_TOF EAR2 facility, with the aim of investigating the puzzle surrounding the existence of the X17 particle.

Requested protons: 5.0 $\times 10^{18}$ protons on target, (split into 2 runs over 2 years)
Experimental Area: EAR2

Significant anomalies have recently been observed in the emission of electron-positron pairs 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 by a researcher team of ATOMKI, Hungary [1, 2, 3, 4]. These anomalies consist of an excess of electron-positron pairs events emitted at large relative angle that have been interpreted as the signature of the existence of a new boson called X17, with mass $M_{X17} \simeq 16.8$ MeV (here and after $c = \hbar = 1$). The results obtained by the ATOMKI group are summarized in figure 1 (see [1, 2, 3, 4] for more details).

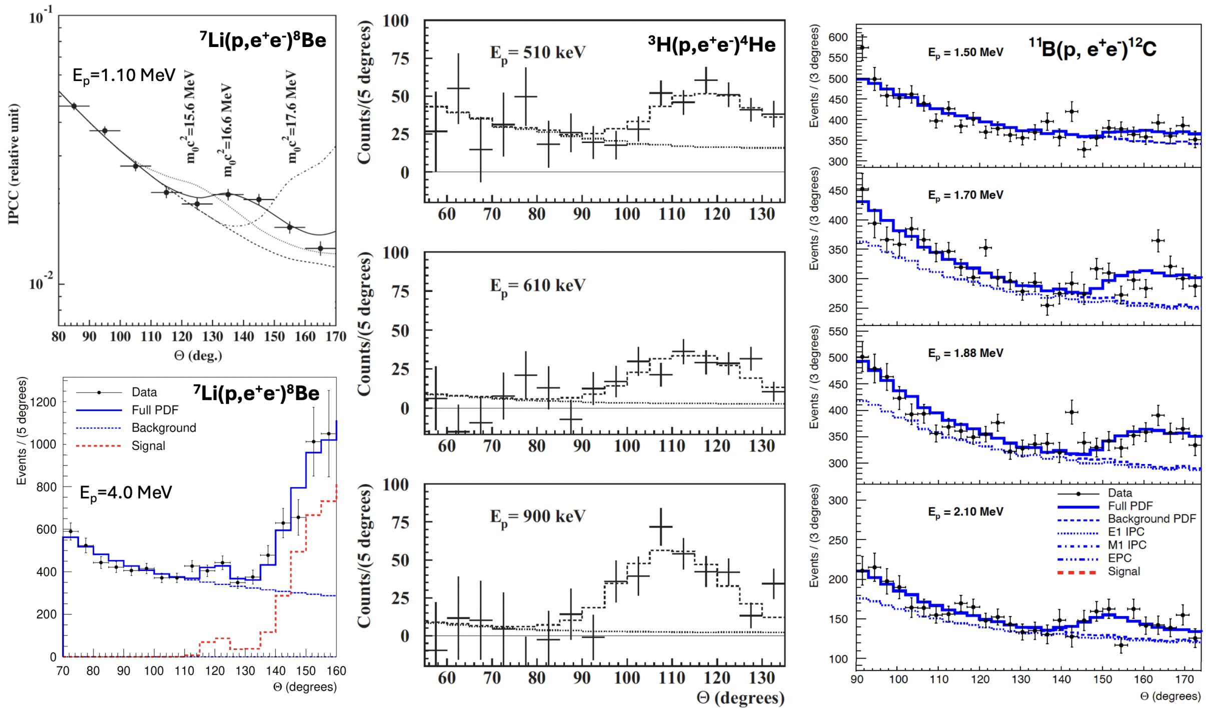

Figure 1: Angular correlations for the e^{-}e^{+} pairs measured in the ^{7}Li(p, e^{-}e^{+})^{8}Be, ^{3}H(p, e^{-}e^{+})^{4}He and ^{11}B(p, e^{-}e^{+})^{12}C reactions. The experimental data show a clear excess of e^{-}e^{+} events at large relative angle over the smooth distribution of e^{-}e^{+} pairs due to standard physics. For all the reactions the excess is consistent with the creation of a new boson with mass $M_{X17} \simeq 17$ MeV, rapidly decaying into e^{-}e^{+} pairs (see [1, 2, 3, 4]).

Overall, 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 to neutrons (protophobic force) [5, 6]. Moreover, it could explain existing tensions in the standard model, such as the long-standing (recent) anomaly on the muon (electron) magnetic moment [7, 8]. From the cosmological point of view, the X17 could be a "portal" between the ordinary matter and the dark sector.
The claim of the existence of a new particle triggered several experimental activities. For instance, the collaboration of the NA64 experiment at CERN investigated the possible production of X17 in the bremsstrahlung reaction by a high energy beam. The NA64 collaboration reported no evidence of its subsequent decay into pairs, thus constraining part of the space parameter favored by the X17 anomaly [9]. On the other hand, the MEG II

collaboration at PSI exploited their spectrometer designed to study the $\mu^+ \to e^+\gamma$ decay to investigate the existence of the X17 particle, using protons from a Cockroft-Walton accelerator and Li-based targets. Although more data would be needed to improve statistics, the data does not show a significant evidence of the X17 particle, providing a 6.2% (1.5 σ) p-value for the ATOMKI X17 hypothesis [10]. In summary, so far there is no yet clear independent confirmation or exclusion of the ATOMKI claim, and the lack of independent experiment calls for new initiatives (see [4] for a review).

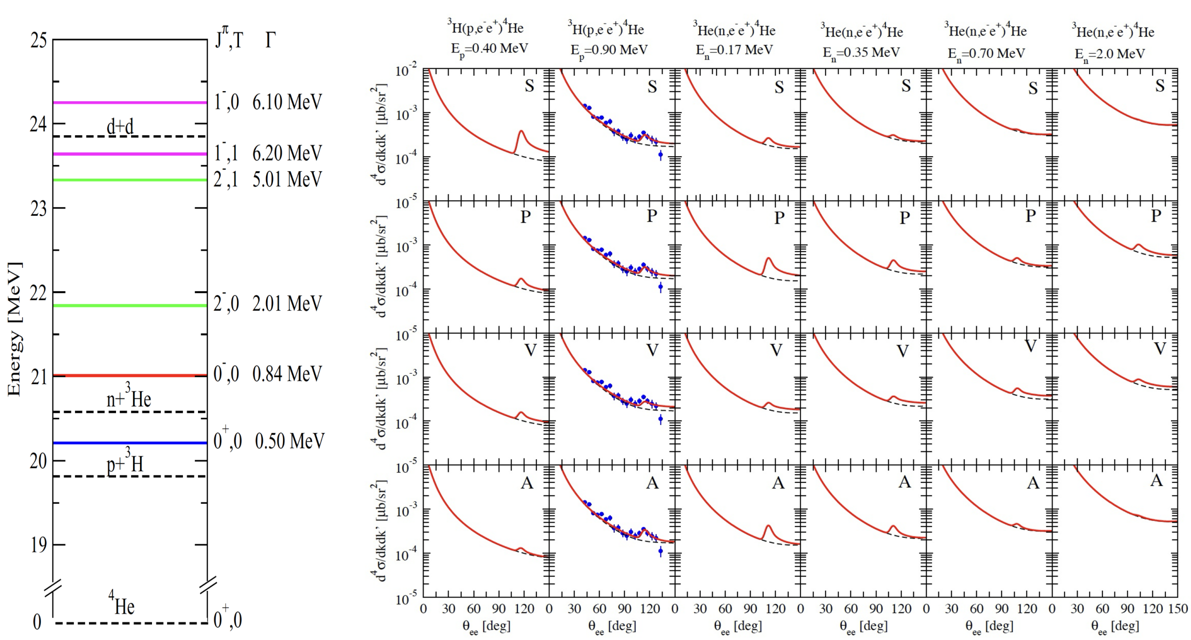

Figure 2: Left: Level scheme of ^{4}He. Right: Cross section for the ^{3}H(p, e$^-$e$^+$)^{4}He and ^{3}He(n, e$^-$e$^+$)^{4}He processes at six different incident nucleon energies, as function of the relative angle θ_{ee} between e$^-$e$^+$ pairs. Predictions for a Scalar (S), Pseudoscalar (P), Vector (V) and Axial (A) with a boson with mass = 17 MeV are shown. The calculations are normalized to the ATOMKI data (blue dots).

1 Probing the X17 boson by using the n_TOF neutron beam

The aim of this proposal is to probe the X17 existence and properties through the novel ^{3}He(n, e$^-$e$^+$)^{4}He reaction, by using the n_TOF neutron beam facility at CERN. In this regard a quantitative calculation was performed by some of us in which the Internal Pair Conversion (IPC) of virtual photon into e$^-$e$^+$ pairs is considered, as well as the production of a 17 MeV boson rapidly decaying into e$^-$e$^+$ pairs, for several J$^\pi$ quantic numbers. Specifically, it has been investigated the BSM production of scalar (S), pseudoscalar (P), vector (V) or axials (A) bosons [11]. In this calculation, X17 cross section was normalized to the ATOMKI data of the ^{3}H(p, e$^-$e$^+$)^{4}He process at E$_p$=0.9 MeV [2]. Figure 2 shows the cross section for the ^{3}H(p, e$^-$e$^+$)^{4}He and ^{3}He(n, e$^-$e$^+$)^{4}He processes as a function of the relative angle between pairs, at six different beam energies (columns) and different J^π for the X17 boson (rows). It is apparent that the excess of pairs at large relative angle over the IPC background depends on the projectile energy and on the X17 quantic numbers, accordingly with the level scheme of the ^{4}He nucleus. Similarly, the X17 momentum and parity strongly affects the angular distribution of emitted pairs [11]. The EAR2 area of n_TOF beam is particularly well suited for this experiment because of its high intensity and wide energy range. The search of X17 boson suggests a detector with low sensitivity to neutrons and γs, with large angular acceptance and capable to reconstruct direction and charge of e$^-$e$^+$ pairs. In this concern, it is worth to point out that the ATOMKI detector did not provide the tracking and particle identification, furthermore its acceptance was limited to particle emitted around 90° with respect to the beam axis. Count-rate estimations show that the neutron intensity at EAR2 is high enough to carry out a conclusive experiment with 3×10^{18} protons on target (pot). However, the estimation of beam-induced background and optimization of the geometry setup could require additional 3×10^{18} pot.

2 Experimental setup at EAR2

The wide energy range of EAR2 neutron beam allows to excite simultaneously the first levels of ^{4}He*. The use of a "light" detector allows to minimize its sensitivity to γs produced by the ^{3}He(n, γ)^{4}He reaction or induced by (n, n'γ) processes. On the other hand (n, p) processes do not represent an important source of background. In particular, the protons produced by the ^{3}He(n, p)^{3}H process (Q=764 keV) do not exit the capsule containing ^{3}He. A light detector is also useful to minimize the External Pair Creation (EPC) events due to the interaction of photons with the material surrounding the target. In any case, EPC pairs are produced at small relative angle, far away from the X17 signal region. Instead, the IPC pairs have a distribution with a longer tail towards large angles, although the relative angle distribution is peaked at about 10°. The effect of this irreducible background can be only limited by minimizing the broadening of the X17 excess due to electron and positron multiple scattering on the materials surrounding the ^{3}He target. Figure 3 shows a sketch of the proposed setup for the ^{3}He(n, e$^+$e$^-$)^{4}He experiment. It consists of a quasi-cylindrical ^{3}He target with a diameter of 2 cm and a volume of about 10 cm^3. The nominal pressure of the ^{3}He gas is 358 bar, corresponding to a density of approximately 10^{22} atoms/cm^3 at room temperature.
A target has been produced in order to reduce multiple scattering. The pressurized ^{3}He is contained in a 3D printed SCALMALLOY capsule 0.5 mm thick: the role of this container is to prevent ^{3}He leaks. 0.9 mm thick high modulus (T1200H) pre-preg carbon fiber is wrapped around the Al container in order to achieve the mechanical strength to sustain 358 bar pressure at 300 K. A similar target has been successfully used in another n_TOF experiment [12]. A prototype of the capsule was constructed and approved by the CERN safety group to work at 300 bars. Moreover, it was filled with ^{4}He at the 200 bar, so far without any drop in pressure (i.e. after about 5 months of testing).
As shown in figure 3, the target is surrounded by 4 μRwells gasdetectors [13] equipped

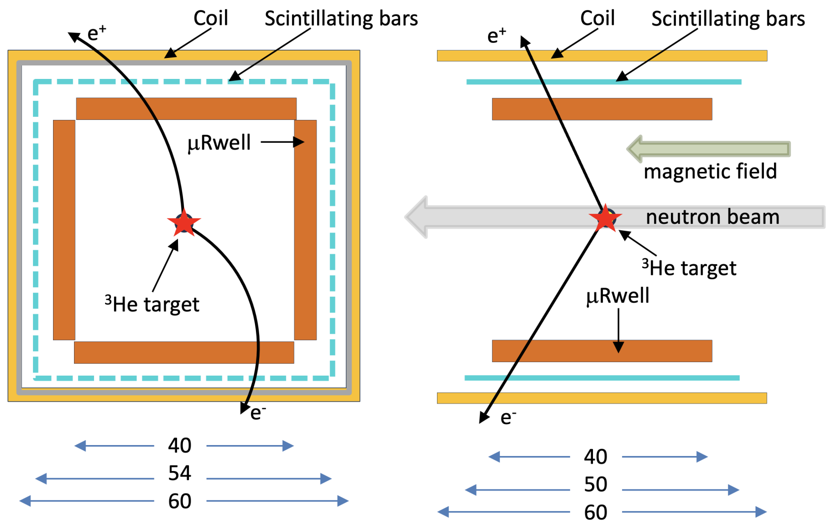

Figure 3: Sketch of the X17 detector setup. Dimensions are in cm.

with orthogonal readout strips, with an active surface of 380×460 mm^2 each. The drift distance between the cathode and μRwell plane is 30 mm. Therefore, it is possible to make a 3D reconstruction of electrons and positrons tracks, operating the μRwells in the μTPC mode. The trigger for the μRwells is provided by 4 planes of scintillating bars. Each plane is made of 32 bars of $3 \times 17 \times 500$ mm^3. The bars also provide the time of flight of neutrons to deduce their energy. The solid angle acceptance is about 80%. The target and the active detectors are inserted into a coil with a square section which provides a magnetic field of 50 mT (see figure 3), to reconstruct the charge and the momentum of e^+e^- pairs. The solenoid will be realized by four sectors, each one 15 cm deep. One sector has already been built and tested showing in the central volume a magnetic field of 50 mT with a radial uniformity of about 2%, with a dissipated maximum power of less than 400 Watt (386 Watt measured). The magnetic field at 60 cm far outside from the center of the square section is reduced by a factor 3 with respect to the value in the middle of the coil. The magnetic field lateral dispersion is negligible (less than 6 mT at 1 m distance). The performance of the detector has been evaluated by using a demonstrator composed by a single μRwell backed with a set of scintillator bars. This demonstrator has been tested: i) at EAR2, to verify the background induced by the neutron beam impinging the capsule that will be used to contain the ^{3}He target; ii) with the proton beam of ATOMKI bombarding a lithium target, to produce electron-positron pairs [14, 15, 16]. As an example, figure 4 shows the 3D track generated by an electron (or positron) in the μRwell equipped with standard APV25 electronics. Details about the detector performance are reported in the conceptual design report (CDR) [16], in which the results obtained with a GEANT4 simulation are also discussed. The experimental setup, the characteristics of the EAR2 neutron beam and the creation of IPC and X17 pairs are considered, accordingly with the ATOMKI results and the theoretical analysis in [11].

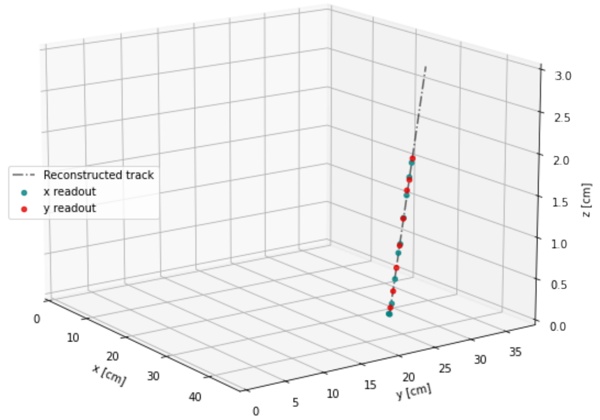

Figure 4: Example of an electron track reconstructed with the large μRwell operated in μTPC mode. The electron is produced by the ^{7}Li(p, e$^+$e$^-$)^{8}Be reaction at $E_p = 0.450$ MeV.

3 Expected count rate

In this proposal we present a measurement able to reconstruct tracks of e$^-$e$^+$ pairs with the aim of testing the existence of X17, and possibly measuring with better precision the mass and establishing its nature. In table 1 the expected count rate is reported.

Table 1: Expected count rate of X17 production in EAR2 using 9 cm^3 volume (worst condition) of 358 bar ^{3}He gas at T=300 K. Neutron energy ranges, corresponding time of flight, and average number of neutrons per pulse are reported in the first three columns. The fourth column shows the expected ^{3}He(n, γ)^{4}He reactions per single pulse, assuming $7{\times}10^{12}$ protons on target (pot) per pulse. The last two columns show the number of expected ^{3}He(n, IPC)^{4}He and ^{3}He(n, X17)^{4}He reactions per 10^{18} pot assuming a vector X17 boson, respectively.

Neutron energy	ToF (μs)	neutrons/pulse	γ's/pulse	IPC/10^{18}pot	X17/10^{18}pot
1 -10 eV	411 - 1300	3.0×10^5	2	128	3
10 – 100 eV	130 -411	3.3×10^5	2	141	4
0.1 – 1 keV	41 - 130	3.7×10^5	2	159	4
1 – 10 keV	13 – 41	5.8×10^5	3	257	6
10 – 100 keV	4 - 13	2.8×10^6	4	1601	40
0.1 – 1 MeV	1.3 - 4	1.5×10^7	33	23117	578
1 – 10 MeV	0.41 – 1.3	7.8×10^6	24	10876	272
Total		2.7×10^7	70	36278	907

Summary of requested protons: $5.0{\times}10^{18}$ protons on target (split into 2 runs over 2 years).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
SIMON	☒ To be used without any modification ☐ To be modified
μRwells, plastic scintillators	☒ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
DAQ	☒ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☒	358 bar
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	
Electrical Safety	Electrical equipment and installations	☐	
	High Voltage equipment	☐	
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	
	Toxic/Irritant	☐	
	Corrosive	☐	
	Oxidizing	☐	
	Flammable/Potentially explosive atmospheres	☐	
	Dangerous for the environment	☐	
Non-ionizing radiation Safety	Laser	☐	
	UV light	☐	
	Magnetic field	☒	0.05 T
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			