EXPERIMENTS TO DETECT THE HYPOTHETICAL X17 PARTICLE*

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Recently, when examining the differential internal pair creation coefficients of ^{8}Be, ^{4}He, and ^{12}C nuclei, we observed peak-like anomalies in the angular correlation of the $e^{+}e^{-}$ pairs. This was interpreted as the creation and immediate decay of an intermediate bosonic particle with a mass of $m_{X}c^{2} \approx 17$ MeV, receiving the name X17 in subsequent publications. In this paper, I will give a mini-review of the experiments related to X17 the results of which are already published, and the ones closest to being published.

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1. Introduction

We published very challenging experimental results in 2016 [1] indicating the electron–positron ($e^{+}e^{-}$) decay of a hypothetical new light particle. The $e^{+}e^{-}$ angular correlations, measured with a newly built spectrometer [2] for the 17.6 MeV and 18.15 MeV transitions in ^{8}Be, were studied and an anomalous angular correlation was observed for the 18.15 MeV transition [1]. This was interpreted as the creation and immediate decay of an intermediate bosonic particle with a mass of $m_{X}c^{2} = 16.70 \pm 0.35(\text{stat.}) \pm 0.5(\text{sys.})$ MeV, receiving the name X17 in subsequent publications.

Our results were first explained with a new vector gauge boson by Feng and co-workers [3–5], which would mediate a fifth fundamental force with some coupling to Standard Model (SM) particles. The possible relation of the X17 boson to the dark matter problem triggered an enormous interest in the wider physics community as listed in Ref. [6] and resulted in many other interpretations, which are summarized by the community report of the Frascati conference [7] organized in 2022, the complete survey of which is beyond the scope of this paper.

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We also observed a similar anomaly in ^{4}He [8]. The derived mass of the particle ($m_X c^2 = 16.94 \pm 0.12$(stat.)± 0.21(sys.) MeV) agreed well with that of the proposed X17 particle.

Recently, we have studied the E1 ground-state decay of the 17.2 MeV $J^\pi = 1^-$ resonance in ^{12}C [9] ,and the invariant mass of the particle was derived to be ($m_X c^2 = 17.03 \pm 0.11$(stat.) ± 0.20(syst.) MeV), which is also in good agreement with our previously published values.

In conclusion, the well-defined excitation energy of the nucleus after the proton capture is used to create a new particle, and the rest gives kinetic energy for the created particle. The larger the kinetic energy, the smaller the opening angle between the e^+e^- pairs, according to the formulas derived for the two-particle decay of a moving particle. This provides strong kinematic evidence that all results were caused by the same particle as concluded by Feng *et al.* [4].

However, despite the consistency of our observations, more experimental data are needed to understand the nature of this anomaly. For this reason, many experiments all over the world are in progress to look for such a particle in different channels. Many of these experiments have already put constraints on the coupling of this hypothetical particle to ordinary matter. Others are still in the development phase, but hopefully, they will soon contribute to a deeper understanding of this phenomenon as concluded by the community report of the Frascati conference [7].

Every new elementary particle, especially bosons, could be associated with a new force or at least with a new, unknown or unexpected aspect of one of the known forces. In general, the possible existence of a new particle is of paramount importance to particle physics and cosmology. Therefore, our experiments at ATOMKI initiated a significant number of new experiments to detect the light X17 particle, which is inaccessible in high-energy accelerators.

The aim of this paper is to give a short overview of the current experiments aiming at studying the X17 particle.

2. Recently published experimental data supporting the existence of the X17 particle

The newest experimental searches for the X17 particle performed by Tran The Anh *et al.* [13] at the Hanoi University of Sciences, Vietnam confirmed the presence of the X17 anomaly in ^{8}Be. They measured the angular correlation of the e^+e^- pairs at $E_p = 1225$ keV (which is above the $E_p = 1040$ keV resonance) and a significant anomaly ($\geq 4\sigma$) was observed at around 135 degree, in agreement with the ATOMKI results [1].

Abramyan *et al.* [14] at the Joint Institute for Nuclear Research, Dubna, Russia reported evidence on the observation of X17 in the $\gamma\gamma$ invariant mass spectra in $d + \mathrm{Cu}$ collisions at p_{lab} of 3.83 GeV/c per nucleon. The γ-rays were detected by 32 lead glass scintillation spectrometers, which were placed 300 cm from the target. The significance of the peak observed at 17 MeV/c^2 was better than 6σ. The presented evidence of both X17 and E38 suggests that there might be several new particles below the mass of the π^0 particle. The experiment was repeated for the e^+e^- pairs and observed a significant peak also in their invariant mass spectrum at 17 MeV/c^2 [15].

3. Overview of experiments (under construction and/or data acquisition) searching for the X17 particle

3.1. The MEG II (Muon Electron Gamma) experiment

To verify the existence of the X17 particle, experiments were carried out at the Paul Scherrer Institute with the MEG II (Muon Electron Gamma) superconducting solenoid spectrometer [7], using the $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ nuclear reaction.

Feasibility studies, performed with a complete detector simulation and including realistic background models, suggest that a 5σ sensitivity could be reached with that setup. The analysis of the results of the experiment performed in 2023 is already in its last phase. Their results are expected to become public soon.

Recently, Papa [16] presented their latest experimental results at the ICHEP 2024 conference in Prague. She reported on the status of this search with the MEG II apparatus, presenting the collected data, the analysis strategy, and the current results.

She concluded that the analysis is well advanced and ready to report the results soon for the background regions, but not for the signal region yet. A new X17 data collection, fully exploiting the 1030 keV resonance, is foreseen during the first part of 2025 (Physics Run 2025).

3.2. The Mu3e experiment, using the MEG II setup

Another channel that will be investigated with the Mu3e experiment is $\mu^+ \to e^+X$ in which X is an axion-like particle [17]. The sensitivity of the Mu3e experiment in phase I exceeds the limits set by TWIST [17] by two orders of magnitude in a large range of X masses and will be further improved in phase II. These limits indicate that the weak interaction does not play a significant role in the creation and decay of the X17 particle, so it is probably not an axion-like particle.

3.3. The PADME (Positron Annihilation for Dark Matter Experiment)

Experiments using positron beams impinging on fixed targets offer unique capabilities for probing new light dark particles weakly coupled to the e^+e^- pairs that can be resonantly produced from positron annihilation on target atomic electrons.

A study of the resonant production of the X17 with a positron beam started at Laboratori Nazionali di Frascati (LNF) in 2022 [7]. The year 2023 was dedicated to the analysis of the data collected in Run III for the X17 campaign and the latest results were published at the ICHEP 2024 conference by Kozhuharov [18].

The main background to the X17 $\rightarrow e^+e^-$ signal is the elastic (Bhabha) electron–positron scattering. The expected peak-to-background ratio (assuming a vector particle) is only about 0.6–2.0% for the allowed coupling constant region, making it very challenging to find this resonance. The Run III analysis is in its final track. Public results from the experiment are expected by the end of the year 2024.

They are planning to have another run (Run IV) in early 2025 with an upgraded detector. They want to have 4 times higher statistics per scan point with beam intensity higher by a factor of 2 and with fewer scan points due to the widening of the X17 lineshape because of the electronic motion. Such improvements will hopefully allow for probing the full unexplored region for the X17 particle.

3.4. Searching for the X17 particle with a highly efficient e^+e^- spectrometer in Montreal

At the Montreal Tandem accelerator, an experiment is being set up to measure the electron–positron pairs from the decay of the X17 particle, using the same $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ nuclear reaction that was studied in [1], for an independent observation of the X17 particle [19]. They are using long multiwire proportional chamber and scintillator bars surrounding a target. The beam travels along the symmetry axis of the spectrometer with the target located in the middle. The most important feature of their spectrometer is its nearly 4π solid angle coverage. The $^7\mathrm{LiF}$ target will be mounted on an Al foil and water-cooled in a thin carbon fiber section of the beamline. Presently, they are still in the process of setting up the apparatus.

3.5. The New JEDI (Judicious Experiments for Dark sectors Investigations) experiment at GANIL

At GANIL France, they plan to develop a long-term research program in the MeV *terra incognita* energy range at the new SPIRAL2 facility (Caen, France) that will deliver unique high-intensity beams of light and heavy ions, and neutrons in Europe.

For measuring the electron–positron angular correlations, a set of Double-sided Silicon Strip Detectors (DSSDs) of the New JEDI (Judicious Experiments for Dark sectors Investigations) setup will provide energy losses and angles of the detected electrons and positrons [20].

In addition, sets of plastic detectors will be used to measure the residual energy of electrons and positrons, and to veto external background events. To start off, they plan to populate "excited" non-resonant states in ^{3}He around 18 MeV using the high-power pulsed proton beam of the LINAC impinging onto a thin CD_2 target.

3.6. A new experimental setup at LNL, Legnaro

The building block of the setup discussed in Ref. [7, p. 20] at is a plastic scintillator ΔE–E telescope composed of three detector layers. The E stage is built using a $5 \times 5 \times 10$ cm^3 EJ200 scintillator read out by a Silicon PhotoMultiplier (SiPM). The ΔE stage has two (x and y) sub-layers: each one is made of 10 EJ200 strips, read out by an array of SiPMs allowing for the measurement of both (x and y) coordinates of a particle's entry positions into the telescope.

The telescopes are organized in groups of 4, forming a clover held by a plastic cage. The project plans to produce and use a minimum set of five clovers, placed at different angular positions to get as uniform of an acceptance as possible. The device can be operated in vacuum, making it possible to minimize the amount of matter seen by the particles before reaching the first detection layer. The project is still under construction.

3.7. X17 experiments of the nTOF (neutron Time of Flight) Collaboration at CERN

An Italian group is engaged to carry out a first series of measurements at nTOF, where the excited levels of ^{4}He can be populated via the conjugated $^3\mathrm{He}(n, e^- e^+)^4\mathrm{He}$ reaction using the spallation neutron beam EAR2 at CERN [21, 22]. They propose a detection setup based on TPC trackers of rectangular shape ($50 \times 50 \times 5$ cm^3). Part of this setup was successfully tested recently in ATOMKI, Debrecen.

3.8. The search for X17 at the Czech Technical University in Prague

The Czech group proposes finalizing an existing spectrometer composed of six small TPCs equipped with multiwire proportional counters and an inner tracker based on Tpx3 detectors. It would consist of a cylindrical vessel, divided into sextants, separated by strong permanent magnets. The spectrometer could easily be installed into or removed from the beamline [23]. The momentum of the particles would finally be measured by the TPCs in a toroidal magnetic field.

3.9. Particle and Nuclear Physics at the MeV scale in Australia

An international group intends to employ the Pelletron accelerator in Melbourne to initiate proton capture nuclear reactions for producing the e^+e^- pairs and to build a low-mass, high-precision Time Projection Chamber (TPC) to track the pairs in a homogenous magnetic field created by a superconducting solenoid [24]. In addition, the very large acceptance, and excellent angular and energy resolution of the TPC would enable qualitatively more sensitive investigations of Nuclear Internal Pair Conversion decays.

3.10. Other experiments

It will be possible to search for the X17 at the PRad electron scattering experiment (E12-21-003) approved at Jefferson Lab [25], the FASER [27] at CERN, DarkLight [28] and HPS [29] at JLAB, VEPP-3 [30] at Novosibirsk, and the MAGIX and DarkMESA experiments foreseen at the MESA accelerator complex in Mainz [31]. In addition, searches in charmed meson and J/Ψ decays have been proposed [32, 33] that can be explored at Belle II (SuperKekB), BESIII (BEPCII), and LHCb (CERN).

4. Summary

The ATOMKI anomalies still constitute an open question in nuclear and low-energy particle physics. New, independent confirmations will be very welcome in strengthening the ATOMKI observation, and possibly confirming the particle-like explanation of the anomalous angular distributions observed so far. In this paper, we have discussed several experimental efforts ongoing in different international laboratories in order to reproduce the observation using the same or similar techniques.

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