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An Update of the Hypothetical X17 Particle

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Abstract: 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, our latest results obtained for the X17 particle are presented by investigating the e^+e^- pair correlations in the decay of the Giant Dipole Resonance (GDR) of ^{8}Be. Our results initiated a significant number of new experiments all over the world to detect the X17 particle and determine its properties. In this paper, we will also conduct a mini-review of the experiments whose results are already published, as well as the ones closest to being published.

Keywords: internal pair creation; ^{8}Be anomaly; light boson; X17 particle

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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 $m_X c^2 = 16.70 \pm 0.35(stat) \pm 0.5(sys)$ 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 [6] and resulted in also many other interpretations, which is 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.

We also observed a similar anomaly in ^{4}He [8]. It could be described by the creation and subsequent decay of a light particle during the proton capture process on ^{3}H to the ground state of ^{4}He. The derived mass of the particle ($m_X c^2 = 16.94 \pm 0.12(stat) \pm 0.21(sys)$ MeV) agreed well with that of the proposed X17 particle.

Recently, we studied the E1 ground state decay of the 17.2 MeV $J^{\pi} = 1^-$ resonance in ^{12}C [9]. The angular correlation of the e^+e^- pairs produced in the ^{11}B(p,γ)^{12}C reaction was studied at five different proton energies around the resonance. The gross features of the angular correlations can be described well by the internal pair creation (IPC) process following the E1 decay of the 1^- resonance. However, on top of the smooth, monotonic distribution, we observed significant peak-like anomalous excesses around 155–160° at four different beam energies. The e^+e^- excess could be well described by the creation and subsequent decay of the X17 particle. The invariant mass of the particle was derived to be ($m_X c^2 = 17.03 \pm 0.11(stat.) \pm 0.20$(syst.) MeV), 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] organized in 2022.

Very recently, Barducci and Toni published an updated view on the ATOMKI nuclear anomalies [10]. They have critically re-examined the possible theoretical interpretation of the observed anomalies in ^{8}Be, ^{4}He and ^{12}C nuclei in terms of a beyond standard model boson X with mass ≈17 MeV. Their results identify an *axial vector state* as the most promising candidate to simultaneously explain all three anomalous nuclear decays, while the other spin/parity assignments seem to be disfavored for a combined explanation.

At the same time, the NA62 collaboration was searching for K^+ decays to the $\pi^+e^+e^-e^+e^-$ final state and excluded the QCD axion as a possible explanation for the 17 MeV anomaly [11]. Hostelt and Pospelov reanalyzed some old pion decay constraints [12], ruled out the vector–boson explanations and set limits on the axial vector ones.

The newest experimental searches for the X17 particle performed by Tran The Anh et al. at the Hanoi University of Sciences, Vietnam, confirmed the presence of the X17 anomaly in ^{8}Be [13]. They measured the angular correlation of the e^+e^- pairs at E_p = 1225 keV, which is the off-resonance region 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., at the Joint Institute for Nuclear Research, Dubna, Russia, reported evidence of the observation of X17 in the $\gamma\gamma$ invariant mass spectra in d+Cu collisions at p_{lab} of 3.83 GeV/c per nucleon [14]. 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 also for e^+e^- pairs and observed a significant peak also in their invariant mass spectrum at 17 MeV/c^2 [15]. However, an alternative explanation of the structures reported in the d+Cu experiment may be evidence of the rearrangement or formation of transient energy levels in the nuclei leading to the enhancement of particle production in some energies.

The aim of this paper is to present our latest results obtained for the X17 particle during the investigation of the Giant Dipole Resonance (GDR) decay. We also give a mini-review of the current experiments aiming at studying the X17 particle.

2. Observation of the X17 Anomaly in the Decay of the Giant Dipole Resonance of ^{8}Be at ATOMKI

The experiments were performed in Debrecen (Hungary) at the 2 MV Tandetron accelerator of ATOMKI, with a proton beam energy of E_p = 4.0 MeV. Owing to the rather large width of the GDR (Γ = 5.3 MeV [16–18]), a 1 mg/cm^2 thick $^7Li_2O$ target was used in order to maximize the yield of the e^+e^- pairs. The target was evaporated onto a 10 μm thick Ta foil. The average energy loss of the protons in the target was ≈100 keV. γ radiation was detected by a $3'' \times 3''$ $LaBr_3$ detector, monitoring also for any potential target losses.

The detector was placed at a distance of 25 cm from the target at an angle of 30° to the beam direction. A typical γ energy spectrum is shown as a black histogram in Figure 1.

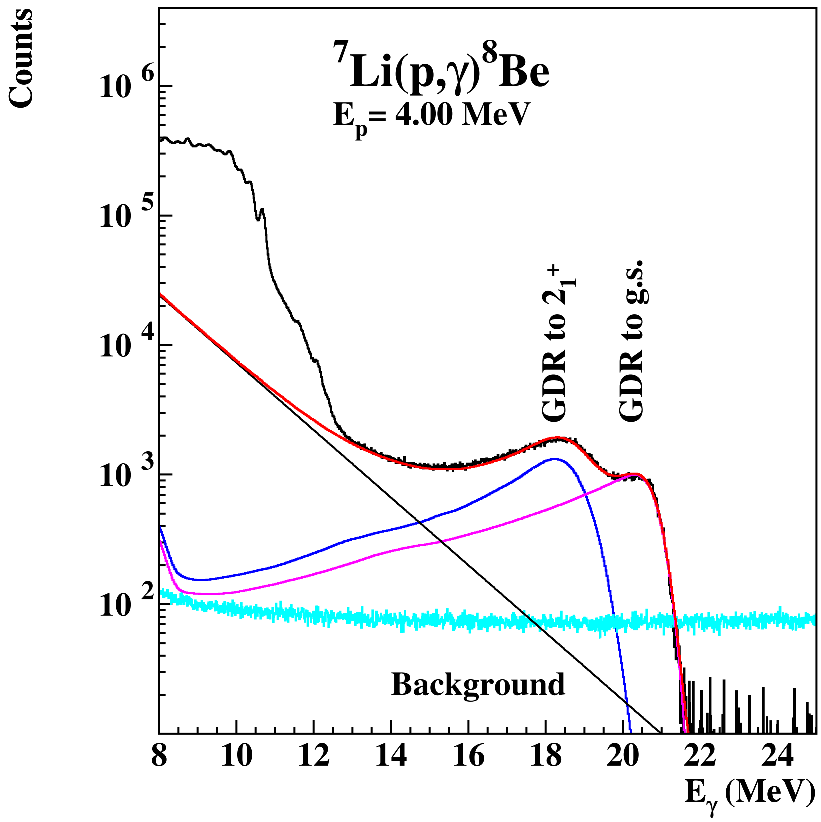

Figure 1. Typical γ-ray spectrum measured for the ^{7}Li(p,γ)^{8}Be nuclear reaction at E_p = 4.0 MeV.

The figure clearly shows the transitions from the decay of GDR to the ground and first excited states in ^{8}Be. The cosmic ray background is shown in cyan and was already subtracted from the signal distribution. It was found to be low, and reasonably uniform.

The simulated spectra for the ground-state and first-excitation-state transitions, including their natural widths and the resolution of the detector, are shown in red and blue, respectively. The remaining background, coming mostly from neutron capture on the surrounding materials, was estimated by an exponential curve and used to fit the γ-spectrum between 14 and 22 MeV, together with the simulated response curves. The result of the fit is shown in red in Figure 1. The intensity ratio of the peaks, obtained from the fit, is I(GDR→ g.s.)/I(GDR→ 2_1^+) = 0.88 ± 0.09 at E_p = 4.0 MeV and θ = 30°. It is consistent with the results of Fischer et al. [16].

2.1. The e^+e^- Spectrometer

For our first experiments [1], an electron–positron pair spectrometer was constructed for precise angular correlation measurements of high-energy (6–18 MeV) nuclear transitions. Five plastic ΔE-E telescopes were used together with Multiwire Proportional Counter (MWPC) detectors for the identification of the particles, for measuring their energies, and for measuring the position of the hits [2].

The spectrometer was upgraded for studying the angular correlation of the e^+e^- pairs from the decay of highly excited states of ^{4}He [8]. The scintillators were replaced with EJ200 ones and PM tubes by Hamamatsu 10233-100 ones. The sizes of the scintillators were 82 × 86 × 80 mm^3 each. As another improvement, the MWPC detectors were replaced by novel double-sided silicon strip detectors (DSSDs), placed very close to the front face of the scintillators, to enhance the efficiency of the experimental setup and its homogeneity. The positions of the hits were registered by the DSSDs having sizes of 50 × 50 mm^2 , strip widths of 3 mm and a thickness of 500 µm. The telescope detectors were perpendicular to the beam direction, each at 60° to its neighbors, around a vacuum chamber made of a carbon fiber tube with a wall thickness of 1 mm.

Pleased with the successful experiments performed with the double-arm e^+e^- spectrometer in Hanoi [13], we built a similar spectrometer also at ATOMKI. The simpler geometry of such a spectrometer, and the smooth acceptance curve as a function of the relative angle of the e^+e^- pairs avoided non-trivial possible artifacts which might be connected to the spectrometer itself [19].

With such a new spectrometer, we studied the X17 creation and the e^+e^- pair emission from the decay of the Giant Dipole Resonance (GDR) [16–18] excitations of ^{8}Be.

In the present experiment, two detector telescopes consisting of Double-sided Silicon Strip Detectors (DSSDs) and plastic scintillators were used, placed at an angle of 110° with respect to each other as shown in Figure 2.

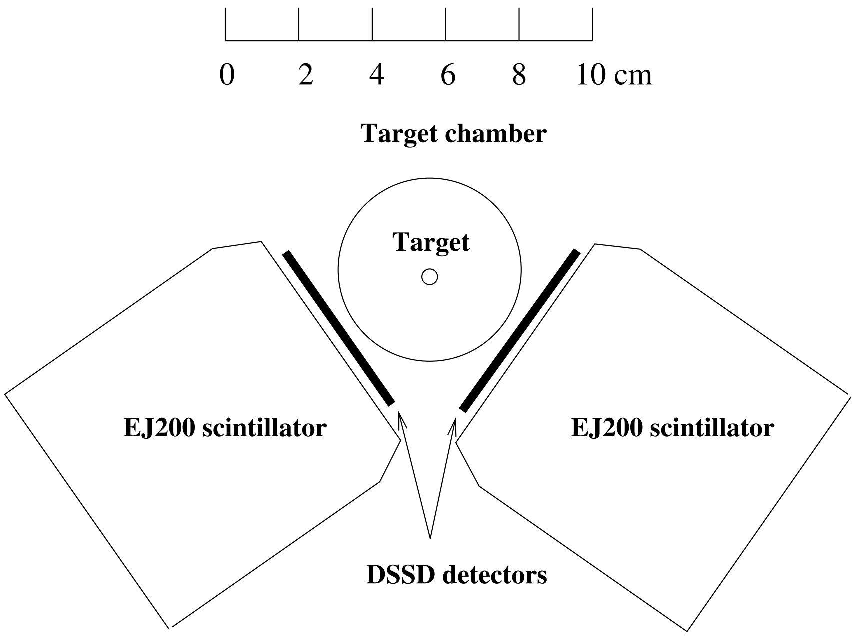

Figure 2. Schematic diagram of the e^+e^- spectrometer.

The diameter of the carbon fiber tube of the target chamber was reduced to 48 mm to allow a closer placement of the telescopes to the target. This way, we could cover a similar solid angle to our previous setups, which had more telescopes.

The two detector telescopes were placed at azimuthal angles −35° and −145° with respect to the horizontal 0° angle. This meant that cosmic rays, predominantly arriving vertically, would have a very low chance of hitting both telescopes at the same time.

The DSSDs were used to measure the energy loss of the e^+e^- particles and their directions. They consisted of 16 sensitive strips on the junction side and 16 orthogonal strips on the ohmic side. Their element pitch was 3.01 mm for a total coverage of 49.5 × 49.5 mm^2.

The dimensions of the EJ200 plastic scintillators were 82 × 86 × 80 mm^3, each connected to Hamamatsu 10233-100 PMT assemblies. In order to place the detectors as close as possible to the target, their front sides were trapezoidally shaped.

During our previous measurements, we examined the decay of excited states for which the emission of neutrons was not an allowed process. In this way, we did not have to worry about radiation damage to our DSSD detectors. However, at the proton energy of E_p = 4.0 MeV, the (p,n) reaction channel was open (E_{thr} = 1.88 MeV), generating neutrons and low-energy γ rays with a large cross-section, which could destroy the DSSD detectors in our setup. We estimated 9–10 orders of magnitude more neutrons produced than the e^+e^- decays of the X17 particle. Other reaction channels were also open, but their cross-sections were much smaller and their influence on our experiment was much weaker.

The maximum neutron energy (E_n = 1.6 MeV) induced only a 300 keV electron equivalent signal in the plastic scintillator due to the quenching effect. Such a small signal fell well below the CFD thresholds that we used. The low-energy neutrons did not produce any measurable signal in the DSSD detectors either. The maximum energy that could be transferred in the elastic scattering on the Si atoms was only ≈50 keV, which is below the detection threshold.

To actively shield against the effect of cosmic radiation, we used 13 plastic scintillators measuring 100 × 4.5 × 1 cm^3, which were placed above the spectrometer. The signals from these detectors were fed into CFD discriminators and then into TDCs. If one of these detectors fired, that event was omitted from the offline data analysis. Since the efficiency of the cosmic shielding was only 50%, after the measurements, we also performed a cosmic background measurement for the same amount of time as we had with the beam on target. The cosmic events collected in this way were subtracted from our spectra.

2.2. Calibration of the Acceptance of the Spectrometer

Besides the e^+e^- coincidences, down-scaled single events were also collected during the whole run of the experiment for making acceptance/efficiency calibrations. An event-mixing method explained in Ref. [8] was used to experimentally determine the relative response of the spectrometer as a function of the correlation angle by using the single telescope triggered events. Uncorrelated lepton pairs were generated from subsequent single events, and their correlation angle was calculated like that for the coincident events. The resulting angular correlation for the uncorrelated events gave us the experimental response curve.

Reasonably good agreement was obtained between the efficiencies measured in the data and the Monte Carlo simulations as presented in Figure 3. The average difference between the two was within ≈7.0% in the 70°–170° range.

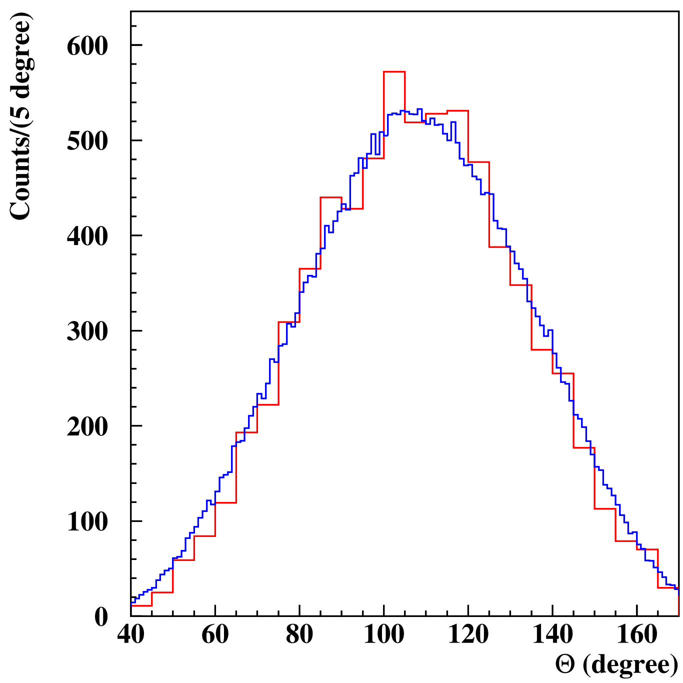

Figure 3. Experimental acceptance of the spectrometer as a function of correlation angle (θ) for consecutive, uncorrelated e^+e^- pairs (red line histogram) compared with the results of the MC simulations (blue line histogram) as explained in the text.

It was crucial for the precise angular correlation measurements to measure and understand the response of the whole detector system to isotropic e^+e^- pairs as a function of the correlation/opening angle.

The detectors measured continuous e^+e^- spectra, and the sum of the energies were constructed offline. Due to the energy loss in the wall of the vacuum chamber and in the DSSD detectors, as well as the finite thresholds of the discriminators (CFD), the low-energy part of the spectrum was always cut out. Since we measured e^+e^- coincidences, such a low-energy cut also meant a high-energy cut for the particles detected in coincidence. Thresholds were set to have similar efficiencies in the different telescopes. After a proper energy calibration of the telescopes, this was performed in the analysis software. The response curve was found to depend primarily on the geometrical arrangement of the two detector telescopes.

Due to the very tight geometry, the DSSD position data, and therefore the e^+e^- angular distribution, experienced an enhanced dependence on the beam spot size and position. According to previous measurements and MC simulations of the present setup, we could take this effect into account properly.

2.3. Results for the Angular Correlation of the e^+e^- Pairs

The energy sum spectrum of the two telescopes is shown in Figure 4.

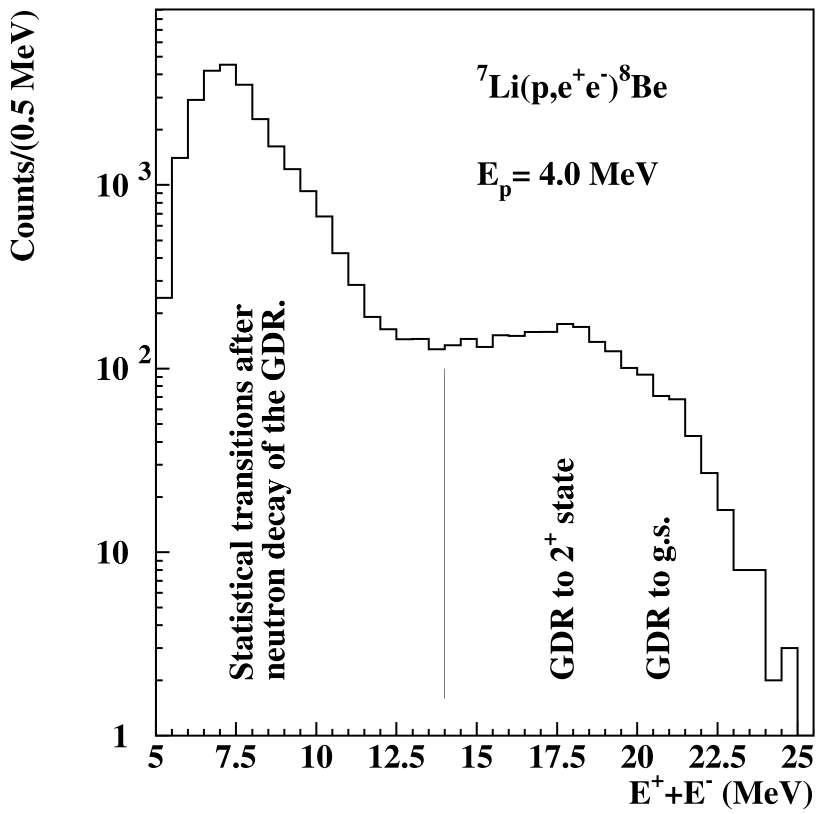

Figure 4. Total energy spectrum of the e^+e^- pairs from the ^{7}Li(p,e^+e^-)^{8}Be nuclear reaction.

The angular correlation spectra of the e^+e^- pairs for the different energy sum regions were then obtained for symmetric $-0.5 \leq \epsilon \leq 0.5$ pairs. Here, the energy asymmetry parameter, ϵ, was defined as $\epsilon = (E_1 - E_2)/(E_1 + E_2)$, where E_1 and E_2 denoted the kinetic energies of the leptons measured in telescopes 1 and 2, respectively.

The angular correlation gated by the low-energy-sum region (below 14 MeV), as marked in Figure 4, is shown in the left side of Figure 5. The measured counts were corrected for the acceptance obtained as described in Section 2.2. It is a smooth distribution without showing any anomalies. It could be described by assuming E1 + M1 multipolarities for the IPC process and a constant distribution, which may originate from cascade transitions of the statistical γ decay of the GDR appearing in real coincidence. In such a case, the lepton pair may come from different transitions, and thus their angles are uncorrelated. This smooth curve reassured us that we were able to accurately determine the efficiency of the spectrometer. The angular correlation of the e^+e^- pairs gated by the GDR energy region (above 14 MeV), as marked in Figure 4, is shown in the right side of Figure 5.

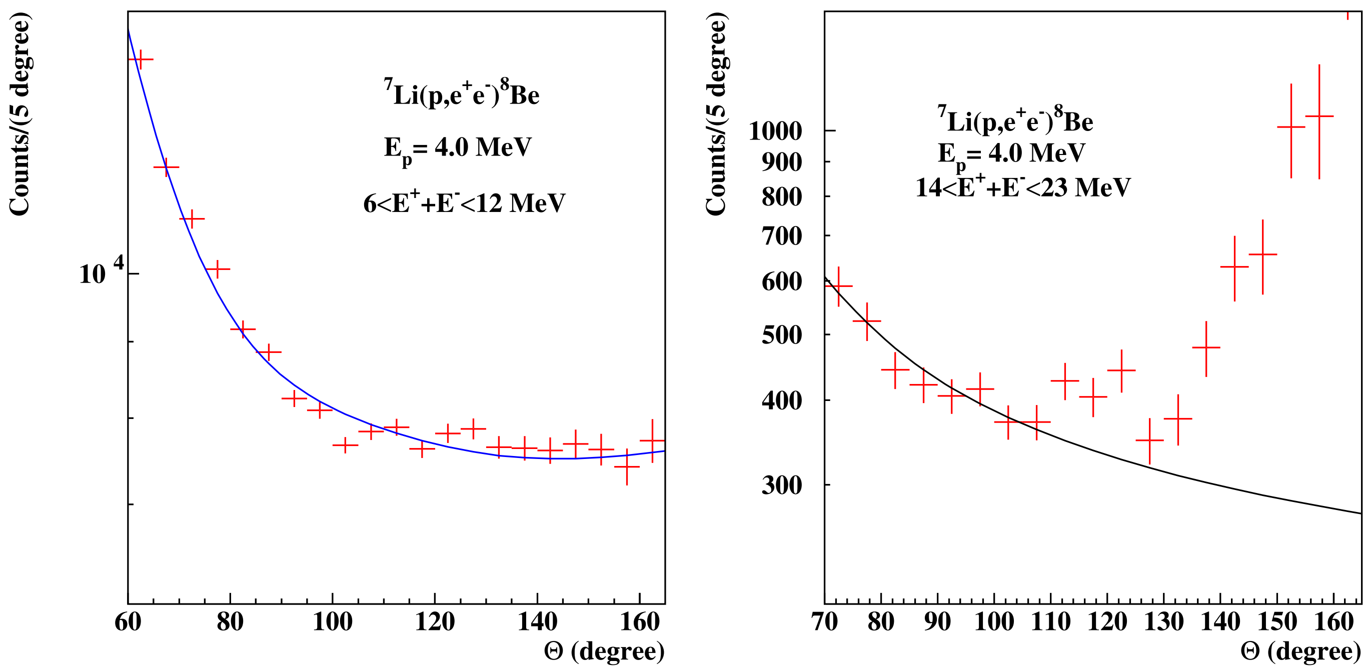

Figure 5. Left side: Experimental angular correlations of the e^+e^- pairs measured in the $^7B(p,e^+e^-)^8Be$ reaction at E_p = 4.0 MeV for low-energy ($E_1 + E_2 \leq 14$ MeV) transitions. Right side: the same for the high-energy (GDR) region ($14 < E_1 + E_2 \leq 25$ MeV).

The experimental data corrected for the acceptance of the spectrometer are shown as red dots with error bars. The simulated angular correlation for the E1 internal pair creation is indicated as a black curve. Significant deviations were observed: first of all, a peak-like deviation at 120° but also an even stronger deviation at larger angles.

The measured angular correlation was fitted from 70° to 160° with the sum of simulated E1, M1 and X17 contributions calculated for both the GDR to ground state and for the GDR to 2_1^+ state transitions. The simulations concerning the decay of the X17 boson in the transition to the ground state of ^{8}Be were carried out in the same way as we did before [1,8,9] and could describe the anomaly appearing at around 120°.

However, based on Figure 1 and previous measurements [16], the γ-decay of GDR to the first excited state was stronger than its decay to the ground state. According to that, we assumed that the X17 particle was created in the decay of GDR to both the ground state and to the first excited state. Based on the energy of that transition (17.5 MeV), we would expect a peak around 150°. However, the first excited state is very broad (Γ = 1.5 MeV), so the shape of the expected anomaly is significantly distorted. The simulations were then performed as a function of the X17 mass from 10 MeV/c^2 to 18 MeV/c^2 for both transitions.

To derive the invariant mass of the decaying particle, we carried out a fitting procedure for both the mass value and the amplitude of the observed peaks. The fit was performed with RooFit [20] in a similar way to what we described before [8,9].

The experimental e^+e^- angular correlation was fitted with the following intensity function (INT) simulated as a function of the invariant mass:

$$\begin{aligned} INT(e^+e^-) = \\ & N_{E1} * PDF(E1) + N_{M1} * PDF(M1) + \\ & N_{Sig} * \alpha_{ground} * PDF(sigground) + \\ & N_{Sig} * (1 - \alpha_{ground}) * PDF(sig2plus)\,, \end{aligned} \tag{1}$$

where $PDF(X)$ represents the MC-simulated probability density functions. $PDF(E1)$ and $PDF(M1)$ were simulated for internal pair creation having electromagnetic transitions with E1 and M1 multipolarity. $PDF(sigground)$ and $PDF(sig2plus)$ were simulated for the two-body decay of an X17 particle as a function of its mass created in the GDR to the ground state and GDR to 2_1^+ transitions, respectively. N_{E1}, N_{M1}, and N_{Sig} are the fitted numbers of background and signal events, respectively. α_{ground} is the fraction of X17 decays detected in the GDR to the ground state transition, with respect to the total number of detected X17 decays. We assumed the same mass for the X17 particle created in the two transitions. The result of the fit is shown in Figure 6 together with the experimental data.

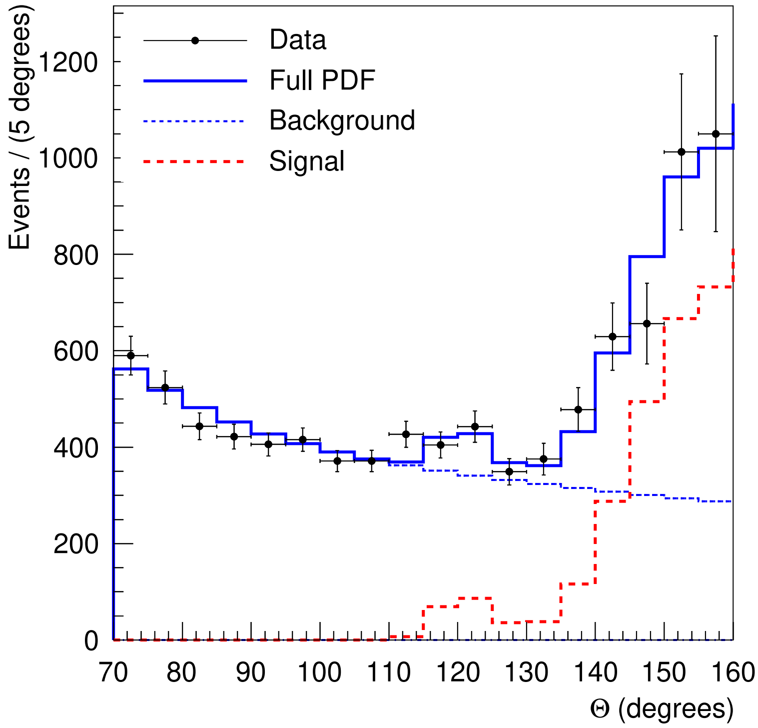

Figure 6. Experimental angular correlations of the e^+e^- pairs fitted by the contributions from the E1 IPC and from the contributions coming from the e^+e^- decay of the X17 particle.

As shown in Figure 6, the simulation can describe the experimental distributions from $\Theta = 70°$ to $160°$ well. The fit results in a >10σ probability for the X17 hypothesis.

The measured invariant mass of the hypothetical X17 particle was determined as the value with which the above INT function provided the best fit to the experimental data. The obtained value for the invariant mass is $m_X c^2$ = 16.94 $\pm$ 0.47(stat.) MeV/c^2, which agrees well with the invariant masses that we obtained previously [1,8,9].

The systematic uncertainties were estimated to be $\Delta m_X c^2$(syst.) $=$ $\pm$0.35 MeV by employing a series of MC simulations as presented in one of our previous works [8]. It mostly represents the uncertainty of the position of the beam spot, which was found to be shifted by about $\pm$3 mm in one measurement run.

The intensity ratio of the X17 particle emission to the ground state ($J^\pi = 0^+$) and to the first excited state $J^\pi = 2^+$ was found to be

$$\frac{B_{X17}(GDR \rightarrow g.s.)}{B_{X17}(GDR \rightarrow 2_1^+)} = \frac{\alpha_{ground}}{1 - \alpha_{ground}} = 0.08 \pm 0.08\,. \quad (2)$$

The spins and parities of the nuclear states examined in our experiments are well known. For ^{8}Be, for example, the 18.15 MeV state has $J^\pi = 1^+$ spin and parity. Based on this, we could think that the X17 particle, which was created during the decay from these states to the ground state, has spin and parity $J^\pi = 1^+$, i.e., a so-called axial vector particle.

However, the anomaly was also observed in the $1^- \rightarrow 0^+$ transition of ^{12}C, when a $J^\pi = 1^-$ vector-type particle with L = 0 orbital momentum could exit the nucleus. However, it is also possible in this case to exit with the L = 1 orbital angular momentum. Then, $J^\pi = 1^+$ axial vector particles could also leave the nucleus.

Currently, we have no experimental information on the orbital momentum of the X17 particle in either case. Thus, we cannot say whether the X17 particle is of a vector or an axial vector type.

The orbital angular momentum of the particles leaving the nucleus is usually determined based on the angular distribution measured with respect to the direction of the particle (proton) that created the nuclear reaction. In the case of exit with L = 0, this angular distribution is expected to be isotropic, and in the case of L = 1, it is expected to be anisotropic.

The currently running experiments, having large acceptance, can provide information on the angular momentum of the exiting X17 particle, so we eagerly await their results.

3. Overview of Experiments (Under Construction and/or Data Acquisition) Searching for the X17 Particle

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.

More 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.

3.1. The MEG II (Muon Electron Gamma) Experiment

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

Inside the solenoid, a special drift chamber was used to determine the four-momenta of the electrons and positrons moving on spiral paths emitted from the Li target, placed in the center of the solenoid. Feasibility studies, performed with a complete detector simulation and including realistic background models, suggest that a 5σ sensitivity could be reached with this 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. Their plans and the description of their spectrometer have been presented at several conferences so far, and a PhD thesis is being prepared from them.

Recently, Papa [21] 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.

They did not use any analyzing magnet after the Cockroft–Walton accelerator, and in this way, the beam contained a reasonable amount ($\approx$25%) of H_2 molecules, making the measurement on resonance more complicated. Moreover, they used a $\approx$ 7 µm thick LiPON target in which the beam was fully stopped and both the 440 keV and 1030 keV resonances would be excited simultaneously with an unfavorable intensity ratio of 79.2% and 20.8% from the 440 keV and 1030 keV resonances, respectively. In this way, they could not study the resonances individually, which could have resulted in a reduced background. Having a low background is very important, especially for the 1030 keV resonance, the decay from which we observed the anomaly earlier. Even worse, they took care of the target cooling with a massive target frame and support rod, which produced a large background from external pair creation.

Within the above conditions, the expected signal-to-background ratio of their results is much lower compared to the one we observed in ATOMKI before, which may prevent the detection of the anomaly.

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 from a broken flavor symmetry like a familon or Majoron that leaves the detector unseen [22]. For this purpose, the Mu3e data acquisition is adapted to accommodate online histogramming of the track fit results such as the momenta and emission angles of events with single positrons on the event filter farm. The current limits on $\mu^+ \to e^+ X$ were set by Jodidio Perrevoort et al., B($\mu^+ \to e^+ X$) < 2.6×10^{-6} at 90 % CL for massless X [22], and by the TWIST collaboration at <9×10^{-6} for X with masses between 13 MeV and 80 MeV. The sensitivity of the Mu3e experiment in phase I exceeds the limits set by TWIST by two orders of magnitude in a large range of X masses and will be further improved in phase II due to a twenty-times-larger number of observed muon decays and enhanced detector performance. 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 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 Venelin Kozhuharov [23].

Taking advantage of the unique opportunity to have positrons in the energy range 250–450 MeV, PADME is in an ideal position to produce the X17 state in a resonant mode and subsequently detect it via its decay to an e^+e^- pair. The PADME Run-III (from October to December 2022) consisted of an energy scan of the X17 mass region. The main background to the X17 $\to e^+e^-$ signal is the elastic (Bhabha) electron–positron scattering. While the t-channel is peaked at high energies for the scattered positron, the s-channel has the same signal kinematics. 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. The number of positrons on target is determined with various cross-calibration procedures with an uncertainty < 1%. The signal acceptance and background estimation are reported to be under control with the systematics of O(1%). Public results from the experiment are expected by the end of this year.

They are planning to have another run (RUN IV) in early 2025 with an upgraded detector. A major improvement to the PADME setup for RUN IV includes precise $e^+e^-/\gamma\gamma$ discrimination with a Micromegas tracker. They want to have four-times-higher statistics per scan point with a higher beam intensity by a factor of two and with fewer scan points due to the widening of the X17 lineshape because of the electronic motion. Such improvements will hopefully allow 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}Li(p,γ)^{8}Be nuclear reaction studied in [1], for an independent observation of the X17 particle [24]. They are using a 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}LiF target will be mounted on an Al foil and water-cooled in a thin carbon fiber section of the beamline. Assuming the ATOMKI evaluation of the electron-pair production rate from X17, Geant4 simulation predicts the observation of a clear signal after about 2 weeks of data taking with a 2 µA proton beam. 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 [25].

In addition, sets of plastic detectors will be used to measure the residual energy of electrons and positrons, and to veto external background events. The detection system is coupled to new generation NUMEXO2 digitizers. A specific charge integration firmware and a coincidence cross-check mode have been developed for the project. It is worth noting that the New JEDI detection system appears to be close to the new version of the spectrometer developed in our ATOMKI group. With the geometry chosen at GANIL, it is more focused on the detection of X17-like 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] on p.20 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 EJ200 scintillator read out by a Silicon PhotoMultiplier (SiPM). The ΔE stage has two sublayers: each one is made of 10 EJ200 strips of dimensions $0.5 \times 0.2 \times 5$ cm, read out by an array of 2×2 mm SiPMs. By placing the bars of the second layer orthogonally with respect to the first one, a grid is obtained, allowing the measurement of both coordinates of a particle's entry positions into the telescope.

The telescopes are organized in groups of four, forming a clover held by a plastic cage. The clovers will be placed at 15 cm from the center of the target, with the ΔE layer facing it. The project plans to produce and use a minimum set of five clovers, placed at different angular positions to obtain 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 in carrying out a first series of measurements at nTOF, where the excited levels of ^{4}He can be populated via the conjugated ^{3}He(n,e^-e^+)^{4}He reaction using the spallation neutron beam EAR2 at CERN [26,27]. Their preliminary theoretical studies indicate a much higher cross-section when neutron transitions are observed with respect to the ones of protons (protophobic scenario). This approach has two relevant advantages: (i) for the first time, the X17's existence would be investigated through neutron-induced reactions exploiting the unique properties of the EAR2 beam and (ii) the experimental setup is completely different from to the one used by our ATOMKI group. To measure the kinematics of the created particles, reaching a high level of particle identification in a wide energy range and to optimize the signal-to-noise ratio, they propose a detection setup based on two TPC trackers of rectangular shape ($50 \times 50 \times 5$ cm) placed at both sides of the target, backed by $50 \times 10 \times 10$ cm long EJ200 slabs. Part of this setup was successfully tested recently in ATOMKI, Debrecen. The goal of that experiment was to establish the capability of the demonstrator of a new e^+e^- spectrometer to measure the four-momenta of IPC e^+e^- pairs generated in the ^{7}Li(p,e^-e^+)^{8}Be reaction. They may still need a few years to obtain experimental results at CERN.

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

The Chech group proposes finalizing an existing spectrometer composed of six small TPCs equipped with multiwire proportional counters (MWPCs) at their entrance windows, and its upgrade with 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 beam line [28].

Each sextant of the spectrometer could be operated as a separate detector, and be composed of three sensitive layers. The first layer would be a Tpx3 detector with a very thin Si sensor (50 µm) and its ASIC. Its 55 µm spatial resolution would provide an excellent angular resolution and a very precise determination of the source vertex of the detected particles. The second layer is planned to be inside the gas volume and consist of a MWPC that would provide some redundancy in the angular determination of the system. It would also be used to correct the energy as a function of the scattering angle of the particles in the Tpx3 detectors and the vacuum tube wall. 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 e^+e^- pairs and to build a low-mass, high-precision Time Projection Chamber (TPC) to track the pairs, with world-first capabilities [29]. The invariant mass resolution of the TPC for the e^+e^- final state is expected to be 0.1 MeV. This would provide a substantially more sensitive search for anomalous e^+e^- production than any other experiment and be 200 times more sensitive than experiments performed at ATOMKI. Accordingly, they will either observe the ATOMKI anomaly on the Pelletron or exclude it at a very high significance. Following this, they propose a program to search for anomalous e^+e^- production with world-leading sensitivity in the 5–25 MeV mass region. 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. This capability would allow for a range of novel nuclear physics investigations.

3.10. The PRad Experiment at JLab

A new electron scattering experiment (E12-21-003) has been approved at Jefferson Lab to verify and understand the nature of hidden sector particles, with particular emphasis on the X17 particle [30]. The proposed direct detection experiment will use a magnetic–spectrometer-free setup (the PRad apparatus) to detect all three final state particles in the visible decay of a hidden sector particle for an effective control of the background and will cover the proposed mass range in a single setup. The use of the well-demonstrated PRad setup allows for an essentially ready-to-run and uniquely cost-effective search for hidden sector particles in the 3–60 MeV mass range with a sensitivity of 8.9×10^{-8} to 5.8×10^{-9} in the square of the kinetic mixing interaction constant between hidden and visible sectors.

Other experiments where it will be possible to search for the X17 are FASER [31] at CERN, DarkLight [32] and HPS [33] at JLAB, VEPP-3 [34] at Novosibirsk and the MAGIX and DarkMESA experiments foreseen at the MESA accelerator complex at Mainz [35]. In addition, searches in charmed meson and J/Ψ decays have been proposed [36,37] that can be explored at Belle II (SuperKekB), BESIII (BEPCII) and LHCb (CERN).

4. Summary

We reported on a new direction of the X17 research. For the first time, we successfully detected this particle in the decay of a Giant Dipole Resonance (GDR). Since this resonance is a general property of all nuclei, the study of GDR may extend these studies to the entire nuclear chart.

We have studied the GDR ($J^{\pi} = 1^{-}$) E1-decay to the ground state ($J^{\pi} = 0^{+}$) and to the first excited state ($J^{\pi} = 2^{+}_{1}$) in ^{8}Be. The energy sum and the angular correlation of the $e^{+}e^{-}$ pairs produced in the ^{7}Li(p,$e^{+}e^{-}$)^{8}Be reaction was measured at a proton energy of E_{p} = 4.0 MeV. The gross features of the angular correlation can be well described by the IPC process following the decay of the GDR. However, on top of the smooth, monotonic distribution of the angular correlation of the $e^{+}e^{-}$ pairs, we observed significant anomalous excesses at about 120° and above 140°.

The $e^{+}e^{-}$ excesses can be well described by the creation and subsequent decay of the X17 particle, which we recently suggested [1,8,9]. The invariant mass of the particle was measured to be ($m_{X}c^{2} = 16.95 \pm 0.48$(stat.) $\pm$ 0.35(syst.) MeV), which agrees well with our previous results. The present observation of the X17 particle in E1 transitions supports its vector or axial vector character if it is emitted with an L = 0 or L = 1 angular momentum.

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 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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