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An Update on the Hypothetical X17 Particle

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Abstract

Angular correlation spectra of e^+e^- pairs produced in the ^{7}Li(p,γ)^{8}Be nuclear reaction were first studied in 2016 and oserved an anomalous peak like behaviour at around 140 degree in case of the 18.15 MeV transitions of ^{8}Be. We also observed a similar anomaly in ^{4}He at around 115 degrees for transition energy of about 20.3 MeV, and in ^{12}C at around 160 degrees for transition energy of about 17.3 MeV. Comparing these experimental data with the corresponding simulations we could get kinematical evidence for the two body decay of a new particle with a mass of about 17 MeV/c^2.

Recently, the ^{7}Li(p,γ)^{8}Be nuclear reaction was also studied at a proton beam energy of $E_p = 4.0$ MeV, which corresponds to the excitation energy of the Giant Dipole Resonance (GDR) in ^{8}Be. The e^+e^- spectrum measured show a peak-like anomaly at 120° and a broader anomaly also above 140°. Both anomalies could consistently be described by assuming that the same hypothetical X17 particle was created both in the ground-state transition and in the transition going to the broad (Γ=1.5 MeV), first excited state in ^{8}Be. The invariant mass of the particle, which was derived to be $m_X c^2 = 16.95 \pm 0.48(stat.) \pm 0.35$(syst.) MeV, agrees well with our previously published results.

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 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 decay of an intermediate bosonic particle with a mass of $m_X c^2$=16.70±0.35(stat)±0.5(sys) MeV, which is now called X17.

Our data were first explained with a vector gauge boson, X17 by Feng and co-workers [2, 3, 4], 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 [5]. New results will hopefully be published soon on the X17 particle from a few different experiments [6].

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.)±0.21(syst.) 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]. The angular correlation of the e^+e^- pairs produced in the ^{11}B(p,γ)^{12}C reaction were 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 excess around 155-160° at four different beam energies. The e^+e^- excess can 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 decay kinematics of the X17 particle into e^+ and e^- particles is shown in Fig 1. As a function of the kinetic energy of the X17 the opening angles at which anomalous peaks were found in the e^+e^- spectra are shown as circles with error bars. After proton capture the excitation energy of the nucleus is well defined. This energy 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. The results of such calculations are also shown in Fig. 1. as full curves by assuming $m_0 c^2$= 16, 17 and 18 MeV for the rest mass of the decaying particle. All our measured opening angles so far follow these simple theoretical lines well. This providides strong evidence that all results were

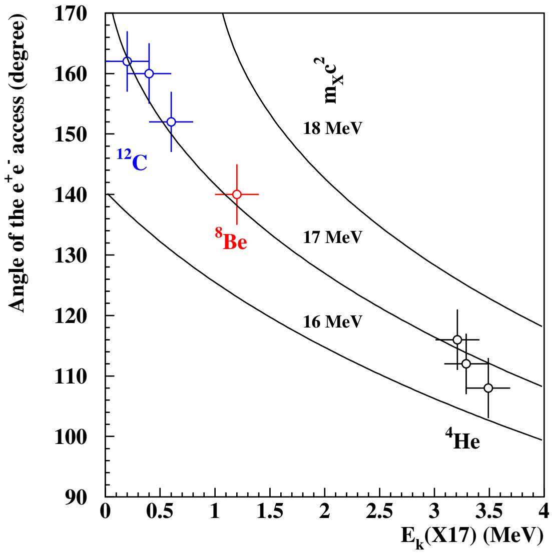

Figure 1: Two-body e^+e^- decay kinematics of the hypothetical X17 particle. The angle of the observed anomaly is shown as a function of the kinetic energy of the X17 particle created in different nuclear reactions, as labelled in the figure.

caused by the same particle.

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 [6].

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 the three anomalous nuclear decays, while the other spin/parity assignments seems 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 of the 17 MeV anomaly [11]. Hostelt and Pospelov reanalysed some old pion decay constraints [12], ruled out the vector-boson explanations and set limits on axial-vector ones.

The aim of this paper is to use a simpler geometry of the spectrometer to avoid nontrivial possible artefacts, which may be connected to the spectrometer itself [13].

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) [15, 16, 17] excitations of ^{8}Be.

2 Experimental methods

The e^+e^- pair spectrometer used in our first measurements was previously described in detail [7]. We also described the method of Monte-Carlo simulations performed with the Geant3 particle-detector interaction simulation library for the interpretation of the information provided by the detectors.

However, after our first publication, the gas-filled Multi-Wire Proportional Counter (MWPC) detectors of the spectrometer, which were used to measure the positions of the e^+e^- pairs in laboratory coordinates as they left the target were replaced by semiconductor Double Sided Silicon strip Detectors (DSSD). At the same time, we upgraded the spectrometer's electronics and data acquisition system as well.

All our results published after 2017 were obtained with spectrometers upgraded in this way, with only the number of detector telescopes and their positions differing between some of the experiments.

2.1 The e^+e^- spectrometer

In the present experiment two detector telescopes consisting of Double-sided Silicon Strip Detectors (DSSD) and plastic scintillators were used, placed at an angle of 110° with respect to each other. The diameter of the carbon fiber tube of the target chamber has been reduced from 70 mm to 48 mm to allow a closer placement of the telescopes to the target. This way we could cover a similar solid angle as our previous setups with more telescopes.

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

The DSSD's were used to measure the energy loss of the e^+e^- particles and their directions. They consist of 16 sensitive strips on the junction side and 16 orthogonal strips on the ohmic side. Their element pitch is 3.01 mm for a total coverage of 49.5 x 49.5 mm^2.

The dimensions of the EJ200 plastic scintillators were chosen 82 × 86 × 80 mm^3 and 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 trapesoidally 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, the GDR examined in our present work decays primarily by the emission of neutrons, which can destroy the DSSD detectors in our setup. We estimate 9-10 orders of magnitude more neutrons produced, than e^+e^- decays of the X17 particle.

To actively shield against the effect of cosmic radiation, we used 13 plastic scintillators measuring 100x4.5x1 cm, 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, that we had with beam on target and the cosmic events collected in this way subtracted from our spectra.

A very similar experimental setup was used recently in Hanoi [18] for checking the the ^{8}Be anomaly. The experimental details and the calibration of the detectors are described in their recent report [18].

3 Experimental results

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 [15]), 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 radiations were detected by a 3"x3" LaBr3 detector monitoring also any potential target losses. The detector was placed at a distance of 25 cm from the target at an angle of 90 degrees to the beam direction.

A typical γ energy spectrum is shown as a black histogram in Fig 2. 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 hown in cyan and was already subtracted from subtracted from that. It is reasonably low and flat.

The simulated spectra for the ground-state and first excitation state transitions, including their natural widths and the resolution of the detector is shown in red and blue, respectively. The remaining backgrund, coming mostly from neutron capture on the sorrounding materials was estimated by an exponential curve and used to fit the gamma spectrum between 14 and 22 MeV together with the simulated response curves. The result of the fit is shown in red in Fig 2. The intensity ratio of the peaks was obtained from the fit: I(GDR→ g.s.)/I(GDR→ 2_1^+)=0.88±0.09 at E_p= 4.0 MeV bombarding energy.

At the proton energy of E_p= 4.0 MeV, the (p,n) reaction channel is open (E_{thr}=

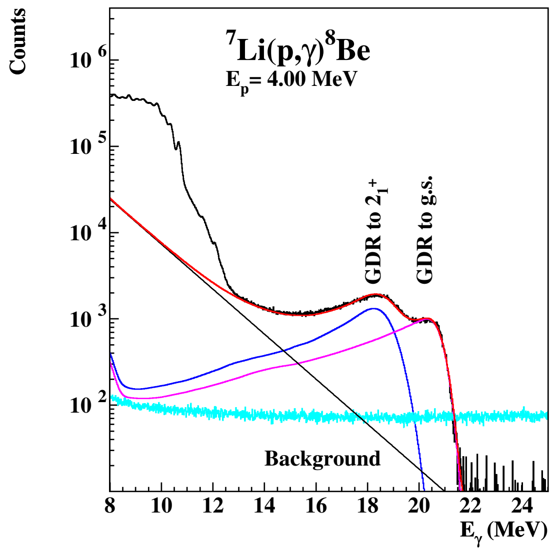

Figure 2: Tipical γ-ray spectrum measured for the ^{7}Li(p,γ)^{8}Be nuclear reaction at E_p= 4.0 MeV

1.88 MeV) and generated neutrons and low-energy γ rays with a large cross section. (Other reaction channels are also open, but their cross sections are much smaller and their influence on our experiment is much weaker.) The maximum neutron energy E_n = 1.6 MeV, which induces 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 since the maximum energy that can be transferred in elastic scattering on Si atoms is only ≈50 keV, which is below the detection threshold.

3.1 Calibration of the acceptance of the spectrometer

The acceptance calibration of the whole e^+e^- coincidence pair spectrometer was performed in a similar way as described in Ref. [8]. 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 measure continuous e^+e^- spectra and the sum of the energies are constructed off-line. 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 is always cut out. Since we measure e^+e^- coincidences, such a low energy cut also means 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 done in the analysis software. The response curve was found to depend primarily on the geometrical arrangement of the two detector telescopes.

Beside 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 as for the coincident events. The resulting angular correlation for the uncorrelated events gave us the experimental response curve.

Reasonably good agreement was obtained to the results of the Monte Carlo simulations, as presented in Fig. 3. The average difference is within $\approx 7.0\%$ in the 70° - 170° range.

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

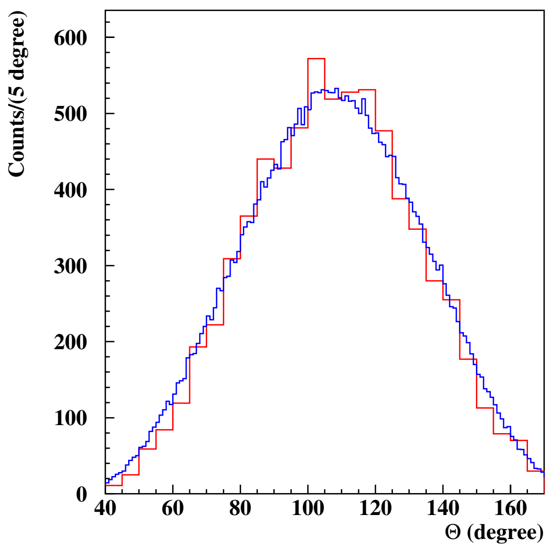

Figure 3: Experimental acceptance of the spectrometer as a function of correlation angle (θ) for consecutive, uncorrelated e^+e^- pairs (red line histogram) compared with the results of the MC simulations (blue line histogram) as explained in the text.

3.2 Results for the angular correlation of the e^+e^- pairs

The energy sum spectrum of the two telescopes are shown in Fig. 4. The angular correlation spectra of the e^+e^- pairs for the different energy sum regions were then obtained for symmetric $-0.5 \le \epsilon \le 0.5$ pairs, where the energy asymmetry parameter ϵ is defined as $\epsilon = (E_1 - E_2)/(E_1 + E_2)$, where E_1 and E_2 denote the kinetic energies of the leptons measured in telescope 1 and telescope 2, respectively.

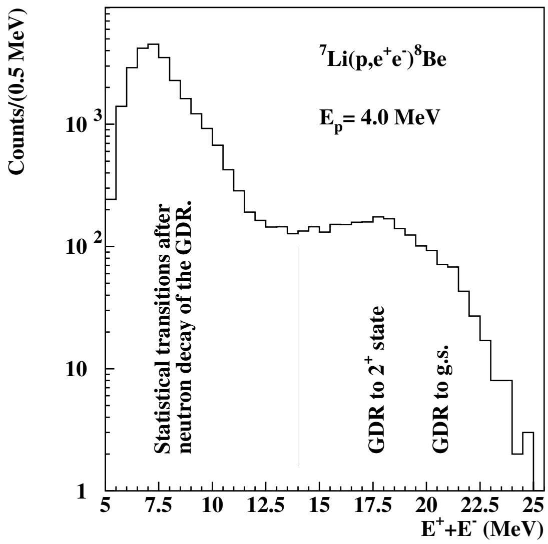

Figure 4: Total energy spectrum of the e^+e^--pairs from the ^{7}Li(p,e^+e^-)^{8}Be nuclear reaction.

The angular correlation gated by the low energy-sum region (below 14 MeV), as marked in Fig. 4, is shown in the left side of Fig. 5. The measured counts were corrected for the acceptance obtained from the raw data collected for the whole experiment in the similar way as described previously [8]. 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 Fig. 4, is shown in the right side of Fig. 5.

The experimental data corrected for the acceptance of the spectrometer is shown as red dots with error bars. The simulated angular correlation for the E1 internal pair creation

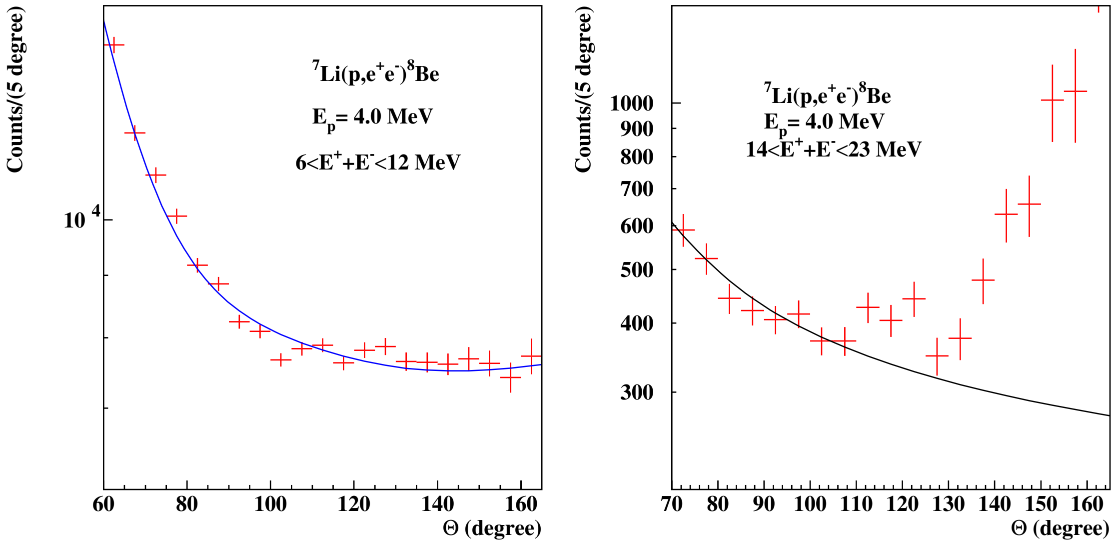

Figure 5: Left side: Experimental angular correlations of the e^+e^- pairs measured in the ^{7}B(p,e^+e^-)^{8}Be reaction at E$_p$=4.0 MeV for low-energy (E$^+$+E$^-$ $\leq$14 MeV) transitions. Right side: the same for the high energy (GDR) region of E$^+$+E$^-$ 14 MeV $\leq$25 MeV.

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 degrees to 160 degrees 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 Fig 2 and previous measurements [15], the γ-decay of GDR to the first excited state is 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 degrees. 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 [19] in a similar way as 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:

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

where PDF(X) represents the MC-simulated probability density functions. $PDF(E1), PDF(M1)$ were simulated for Internal Pair Creation having electromagnetic transitions with E1 and M1 multipolarity. $PDF(sigground), PDF(sig2plus)$ 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 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 Fig. 6 together with the experimental data.

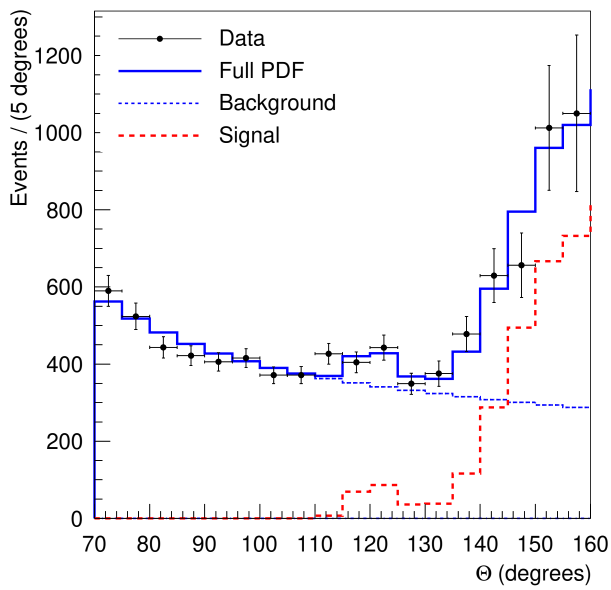

Figure 6: Experimental angular correlations of the e^+e^- pairs fitted by the contributions from the E1 IPC and from the contributions coming from the e^+e^- decay of the X17 particle.

As shown in Fig. 6, the simulation can describe the experimental distributions from $\Theta = 70°$ to $160°$ well. The significance of the fit is larger than 10σ.

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 vaue for the invariant mass is: 16.94 ± 0.47 MeV(stat)/c^2, which agrees nicely with the invariant mass we obtained previously [1, 8, 9].

The systematic uncertainties were estimated to be $\Delta m_{\rm X} c^2$(syst.) = ±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 ±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:

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

4 Summary

We reported on a new direction of the X17 research. For the first time, we successfully detect this particle in the decay of the 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 described well by the IPC process following the decay of the GDR. However, on top of the smooth, monotonic distribution of the angular correlation of e^+e^- pairs, we observed significant anomalous excess at about 120° and above 140°.

The e^+e^- excess can be well-described by the creation and subsequent decay of the X17 particle, which we have recently suggested [1, 8, 9]. The invariant mass of the particle was measured to be ($m_{\rm X}c^2$ = 16.95 ± 0.48(stat.)±0.35(syst.) MeV), which agrees well with our previous results.

The present observation of the X17 particle in E1 transitions support its vector or axial vector character if it is emitted with L=0 or L=1 angular momentum, respectively.

At the 52nd International Symposium on Multiparticle Dynamics (ISMD 2023) the existence of X17 has been confirmed also by Russian and Vietnamese experimental groups and several other groups reported on the construction of control experiments to cross-check the existence of X17.

5 Acknowledgements

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