Letter

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

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Employing the ^{11}B$(p,\gamma)^{12}$C nuclear reaction, the angular correlation of e^+e^- pairs was investigated in the angular range of $40^\circ \leqslant \Theta \leqslant 175^\circ$ for five different proton energies between $E_p = 1.50$–2.5 MeV. At small angles ($\Theta \leqslant 120^\circ$), the results can be well interpreted by the internal pair creation process of electromagnetic radiations with $E1$ and $M1$ multipolarities and by the external pair creation in the target backing. However, at angles greater than 120°, additional count excesses and anomalies were observed, which could be well accounted for by the existence of the previously suggested hypothetical X17 particle. Our results suggest that the X17 particle was generated mainly in $E1$ radiation. The derived mass of the particle is $m_X c^2 = 17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$ MeV. According to the mass, and to the derived branching ratio [$B_x = 3.6(3) \times 10^{-6}$], this is likely the same X17 particle that we recently suggested for describing the anomaly observed in the decay of ^{8}Be and ^{4}He.

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I. INTRODUCTION

Very challenging nuclear physics experiments were initiated in 1978 to detect a new particle, the axion, predicted by Weinberg [1,2]. The quantum chromodynamics axion is one of the most compelling solutions to the strong CP (charge conjugation parity symmetry) problem. Donelly [3] proposed to study the angular correlation of the e^+e^- pairs created in $1^+ \rightarrow 0^+$ nuclear transitions as a signature for the decay of the axion. However, it was quickly ruled out in the MeV/c^2 mass regime.

The later introduced dark photon [4,5] is proposed as a force carrier connected to dark matter. In a minimal scenario, this new force can be introduced by extending the gauge group of the standard model with a new Abelian U(1) gauge symmetry.

Fayet suggested a generalized dark photon model that would produce a light gauge boson with an extra U(1) gauge group already in 1980 [6–8]. Such a generalized dark photon may act as a mediator of light dark matter annihilations, possibly allowing for lighter than GeV/c^2 dark matter particles [9,10]. More recent discussions on the light U boson as the mediator of a new force, coupled to a combination of Q, B, L, and dark matter can be found in Refs. [11,12].

Searches for light particles, especially a 9 MeV/c^2 particle suggested by de Boer and coworkers, have been performed in Frankfurt [13]. These results, although with little confidence, appeared to confirm the existence of the 9 MeV/c^2 particle. However, due to the closure of the accelerator, these experiments could not be continued.

Recently, we studied electron-positron angular correlations for the 17.6 MeV and 18.15 MeV transitions in ^{8}Be and an anomalous angular correlation was observed for the 18.15 MeV transition [14]. This was interpreted as the creation and 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, which is now called X17. The possible relation of the X17 boson to the dark matter problem triggered an enormous interest in the wider physics community [15,16] and hopefully new results on X17 will be published in a few months, in a few different places [17–19].

The first theoretical interpretation of the experimental results was performed by Feng *et al.* [20,21]. They explained the anomaly with a 16.7 MeV, vector gauge boson X17, which may mediate a fifth fundamental force with some coupling to standard model (SM) particles. The theory of the dark photon has been generalized to the fact that the new particle is coupled not only to electric charges but also to quarks.

Constraints on the coupling constants of such a new particle, notably from searches for $\pi_0 \rightarrow Z' + \gamma$ by the NA48/2 experiment [22] was also taken into account by Feng and co-workers [20,21]. Based on their results, the X17 particle couples much more strongly to neutrons than to protons, so the particle was named protophobic.

Zhang and Miller [23] investigated the nuclear transition form factor as a possible origin of the anomaly, but they found the concluded form factor unrealistic for the ^{8}Be nucleus.

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Ellwanger and Moretti suggested another interpretation of the experimental results in view of a light, pseudoscalar particle [24]. They predicted about ten times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV one, which is in nice agreement with our results.

Subsequently, many studies with different models have been performed including an extended two Higgs doublet model [25–27]. They showed that the anomaly can be described with a very light Z_0 bosonic state, with significant axial couplings.

In parallel to these recent theoretical studies, we reinvestigated the ^{8}Be anomaly with an improved experimental setup [28–30].

Recently, we also observed a similar anomaly in ^{4}He [29,31]. The signal 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 the ^{4}He nucleus. The derived mass of the particle [$m_X c^2 = 16.94 \pm 0.12(\text{stat.}) \pm 0.21(\text{syst.})$ MeV] agreed well with that of the proposed X17 particle. It was also shown, that the branching ratios of the X17 particle compared to the γ decay are identical within uncertainties for three beam energies, proving that the X17 particle was most likely formed in direct proton capture, which has a dominant multipolarity of $E1$. Our results obtained for ^{4}He at different beam energies agree well with the present theoretical results of Viviani *et al.* [32].

Referring to our paper [31], Feng and co-workers have communicated a work very recently with the title of "Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies" [33], in which they propose to study the $E1$ ground state decay of the 17.2 MeV $J^\pi = 1^-$ state in ^{12}C in order to determine if X17 has a vector or axial-vector character.

In the present work, we investigated the 17.2 MeV $1^- \rightarrow 0^+$ transition of ^{12}C to search for signatures of the creation of the X17 particle.

II. EXPERIMENTAL METHODS

The experiments were performed in Debrecen, Hungary at the 2 MV Tandetron accelerator of ATOMKI. The $E_x = 17.23$ MeV ($J^\pi = 1^-$) [34] state of ^{12}C was excited by the ^{11}B$(p, \gamma)\,^{12}$C nuclear reaction. Due to its large cross section, the reaction is also widely used for detector calibrations. The resonant proton energy is $E_p = 1.388$ MeV [34,35].

Owing to the rather large level width ($\Gamma = 1.15$ MeV [34]), a 2 mg/cm^2 thick ^{11}B target was applied to maximize the yield of the e^+e^- pairs. The target was evaporated onto a 5 μm thick Ta foil. The average energy loss of the protons in the target was ≈ 300 keV. To compensate for the energy losses, the energy of the protons was chosen to be $E_p = 1.50$, 1.70, 1.88, 2.10, and 2.50 MeV. The proton beam was impinged on a ^{11}B target with a typical current of 2 μA for about 50 h at each beam energy. To achieve a more efficient cooling of the target and thus to reduce its degradation, we replaced the previously used [14,36] plexiglass support rods by Al rods. However, in turn, our data suffered a bit larger signal background from Al induced by the γ rays as shown in Fig. 1 than before (Fig. 9 of Ref. [17]).

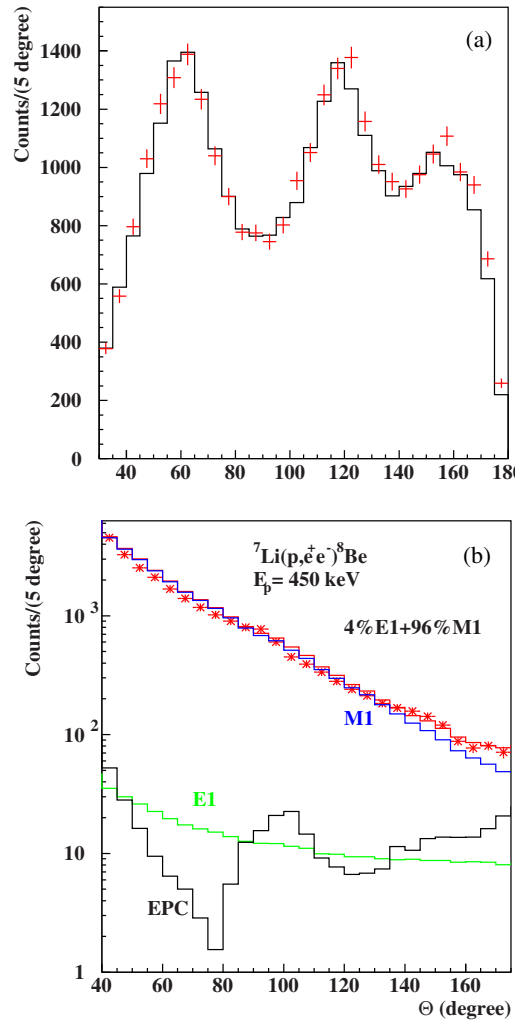

FIG. 1. (a) Detector response for the setup as a function of correlation angle (θ) for isotropic emission of e^+e^- pairs (red crosses) compared with the results of the Monte Carlo simulations (black line histogram) as explained in the text. b) e^+e^- angular correlations obtained for the 17.6 MeV transition of ^{8}Be by using thin target backing compared to the simulations performed for $E1$ and $M1$ IPC, as well as for the EPC created by the γ-rays on the different materials around the target.

Our previous detector setup [14,36] has recently been upgraded. The details of the upgrade are described in [31]. In the present experiment, the time and energy signals of the scintillators, as well as the time, energy and position signals of the DSSD detectors were recorded.

The energy calibration of the telescopes, the energy and position calibrations of the DSSD detectors, the Monte Carlo (MC) simulations as well as the acceptance calibration of the whole e^+e^- coincidence pair spectrometer were explained in Ref. [31]. Reasonably good agreement was obtained between the experimental acceptance and results of the MC simulations, as presented in Fig. 1. The average difference is within $\approx$3.0% in the angular range of 40°–170°.

In order to validate the accuracy of the MC simulations, we performed measurements also on the ^{7}Li$(p, \gamma)\,^8$Be reaction.

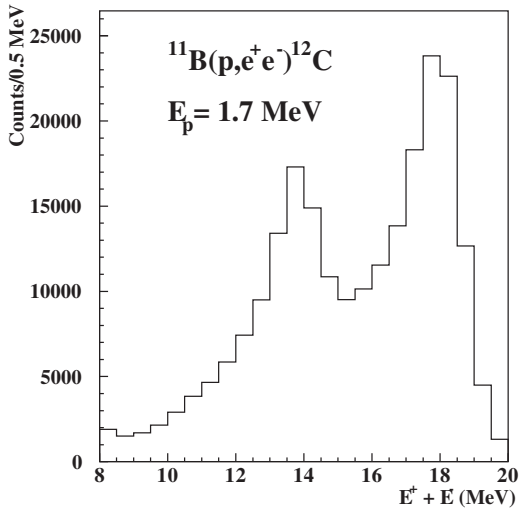

FIG. 2. Total energy spectrum of the e^+e^--pairs from the ^{11}B(p, e^+e^-) ^{12}C nuclear reaction.

The experimental results for the angular correlations from this data taking on the $E_p = 441$ keV resonance (red dots with error bars) are shown in Fig. 1(b), together with the corresponding Monte Carlo simulation (histogram) of the IPC process stemming mostly from the $M1$ nuclear transition. The contribution of the external pair creation (EPC) process of the 17.6 MeV γ rays is also shown by a black histogram. We note here that the direct-capture contribution is negligible compared to the $M1$ IPC due to the large resonance capture cross section and the thin target.

As it can be seen in Fig. 1, the simulation of the IPC process manages to describe the shape of the data distribution accurately, and the contribution of EPC created on the different parts of the spectrometer is reasonably low.

In order to search for the assumed X17 particle, both the sum-energy spectrum of the e^+e^- pairs measured by the telescopes, and their angular correlations, determined by the DSSD detectors, have been analyzed. Since the counting rates in the detectors were low (≈150 Hz in the scintillators and (≈25 Hz in the DSSD detectors) and the coincidence time window was sharp (≈10 ns) the effect of random coincidences was negligible. In the followings we show only the real coincidence gated spectra.

In the GEANT simulations, both e^+e^- pairs generated by internal pair creation in the target and the e^+e^-- pairs generated by external pair creation in the Ta backing were taken into account. A more detailed description of the simulations can be found in Ref. [31].

III. EXPERIMENTAL RESULTS AND DISCUSSION

The total energy spectrum of the e^+e^--pairs produced in the decay of the $E_x = 17.2$ MeV ($J^\pi = 1^-$) state of ^{12}C at $E_p = 1.7$ MeV is presented in Fig. 2. In addition to the $E1$ ground state transition, this state decays to the $E_x = 4.44$ MeV ($J^\pi = 2^+$) level with an $E = 12.76$ MeV $E1$ transition, which is also present the energy spectrum. The intense, 4.44 MeV ground state transition was discarded by setting a proper hardware threshold in order to reduce the high count rate of the data acquisition system.

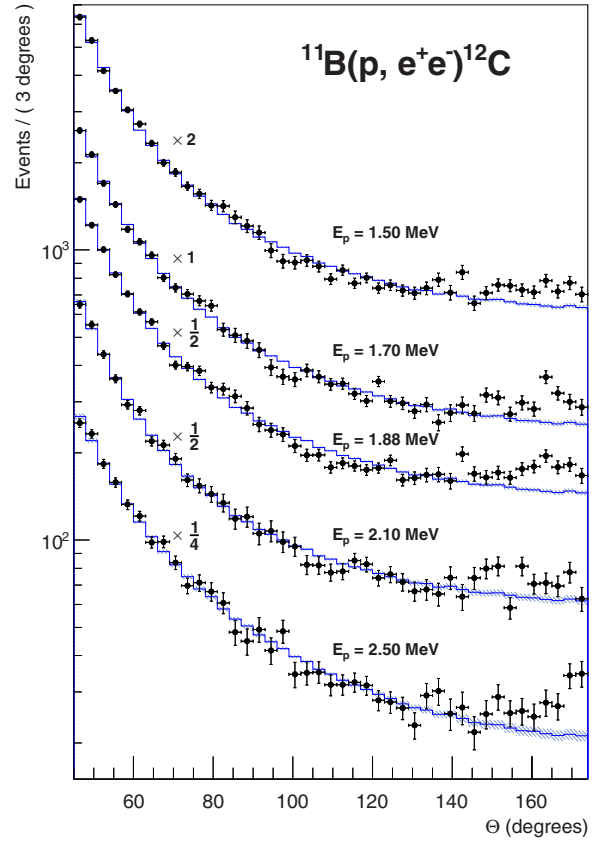

FIG. 3. (a) Experimental angular correlations of the e^+e^- pairs measured in the ^{11}B(p, e^+e^-) ^{12}C reaction at the vicinity of the $J^\pi = 1^+$ resonance for different proton energies.

The experimental efficiency of the e^+e^- spectrometer was determined with uncorrelated e^+e^- pairs by taking the e^- and e^+ data from consecutive events as previously described in Refs. [14,28,30,31]. The gated and efficiency-corrected e^+e^- angular correlation in the 17.2 MeV ($J^\pi = 1^- \rightarrow 0^+$) transition is shown in Fig. 3 for proton energies of $E_p = 1.5$, 1.7, 1.88, 2.1 and 2.5 MeV.

As show in Fig. 3, a combination of the MC simulated IPC distributions of $E1$ and $M1$ radiations together with a small contribution of simulated external pair creation (EPC) in the Ta backing can describe the experimental distributions below $\Theta = 140^\circ$ reasonable well. However, we observe significant deviations at large angles ($>140^\circ$) at a few proton energies.

The measurements presented here were performed without interruptions or target changes. Thus, the experimental setup did not change during the measurements. The experimental data measured at different proton bombarding energies were also processed with the same analysis.

In the case of the lowest bombardment energy (1.5 MeV), when the average excitation energy—taking into account the loss of proton energy in the target—was below 17 MeV, a very weak anomaly was observed. Due to the use of a

TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [31]	5.1	16.94(12)	
Predicted [33]	3.0		

thick target, our excitation function—determined by measuring γ rays—showed a maximum at $E_p = 1.7$ MeV. Significant anomalies were observed at $E_p = 1.7$, 1.88, and 2.10 MeV. When we increased the bombarding energy to 2.5 MeV (off-resonance region), the strength of the anomaly decreased significantly.

The above behavior seems to support the existence of X17 and their creation in the decay of the $J^\pi = 1^-$ resonance.

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 peak.

The fit was performed with RooFit [37] by describing the e^+e^- angular correlation with the following intensity function (INT):

$$\mathrm{INT}(e^+e^-) = N_{Bg}\mathrm{PDF(exp)} + \mathrm{N_{Sig}PDF(sig)}, \qquad (1)$$

where PDF(exp) was determined from a separate fit for the background region, was simulated by GEANT for the two-body decay of an X particle as a function of its mass, and N_{Bg} and N_{Sig} are the fitted numbers of background and signal events, respectively.

The signal PDF was constructed as a two-dimensional model function of the e^+e^- opening angle and the mass of the simulated particle. To construct the mass dependence, the PDF linearly interpolates the e^+e^- opening angle distributions simulated for discrete particle masses.

Using the intensity function described in Eq. (1), we first performed a list of fits by fixing the simulated particle mass in the signal PDF to a certain value, and letting RooFit estimate the best values for N_{Sig} and N_{Bg}. Allowing the particle mass to vary in the fit, the best fitted mass is calculated and the corresponding fit is shown for each studied beam energy in Fig. 4.

A significant background is obtained from the $E1$ transition, but the contribution from the assumed particle decay is also significant at large angles.

The measured invariant masses of the hypothetical X17 and the branching ratios (B_x) of its e^+e^- decay to the γ decay, as derived from the fits are summarized in Table I. The values are compatible for each fitted parameter within 1σ error bars. Their average values are also highlighted.

In Table I, only the statistical errors are indicated. The systematic uncertainties were estimated to be $\Delta m_X c^2(\mathrm{syst.}) =$

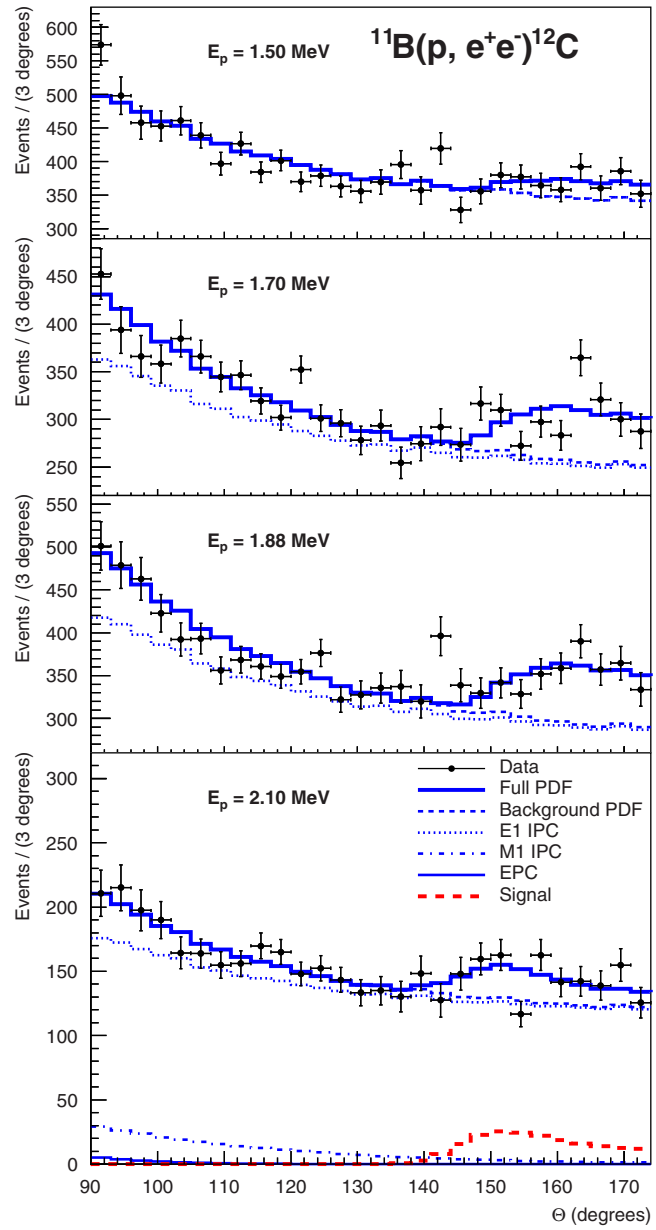

FIG. 4. Experimental angular correlations of the e^+e^- pairs measured at different proton energies. The full curves for each proton energy shows the results of the fit, using simulated angular distributions.

± 0.20 MeV by employing a series of MC simulations as presented in one of our previous works [31]. It mostly represents the uncertainty of the position of the beam spot, which was found to be shifted by about ± 2 mm in one measurement run.

The extracted invariant mass agrees well with the values published earlier for the ^{8}Be [14] and the ^{4}He [31] experiments, which provides a convincing kinematic verification of the existence of the X17 particle. The branching ratio of the X17 decay differs from the previous data, but, on the other hand, agrees well with the theoretically predicted value [33].

IV. SUMMARY

We have studied the $E1$ ground state decay of the 17.2 MeV $J^\pi = 1^-$ state in ^{12}C. The energy-sum and the angular correlation of the e^+e^- pairs produced in the ^{11}B$(p,e^+e^-)^{12}$C reaction were measured at proton energies of $E_p = 1.50$, 1.70, 1.88, 2.10, and 2.50 MeV. The gross features of the distributions of these quantities can be described well by the IPC process following the decay of the 1^- resonance and by considering a small contribution of external pair creation process induced by the high-energy γ rays. However, on top of the smooth, monotonic distribution of the angular correlation of e^+e^- pairs, 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, which we have recently suggested [14,31]. The invariant mass of the particle was derived to be $[m_X c^2 = 17.03 \pm 0.11(\text{stat.}) \pm 0.20(\text{syst.})$ MeV], which agrees well with our previously published values. The branching ratio of the e^+e^- decay of X17 to the γ decay was found to be $3.6(3) \times 10^{-6}$. The present observation of the X17 particle in an $E1$ transition supports its vector character, as suggested by Feng *et al.* [33].

Given the present results on the X17 creation in $E1$ transitions, we consider to search for X17 in the decay of giant dipole resonance excitations of different nuclei.

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