Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.

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Recently, several experimental anomalies were discussed as possible signatures for a new light particle [1–3]. Some predictions suggest light neutral bosons in the 10 MeV–10 GeV mass range as dark matter candidates, which couple to electrons and positrons [4–7], to explain the anomalies. A number of attempts were made to find such particles [1,8–17]. Since no evidence was found, limits were set on their mass and their coupling strength to ordinary matter. In the near future, ongoing experiments are expected to extend those limits to regions in mass and coupling strength which are so far unexplored. All of them are designed to exploit the radiative production of the so-called dark photons (γ') by a very intense electron or positron beam on a high-Z target [18–23].

In the present work, we reinvestigated the anomalies observed previously in the internal pair creation of isovector (17.6 MeV) and isoscalar (18.15 MeV) $M1$ transitions in ^{8}Be [24–29]. The expected signature of the anticipated particle is a very characteristic angular correlation of the e^+e^- pairs from its decay [30,31]. The angular correlation between the e^+ and e^- emitted in the internal pair creation (IPC) drops rapidly with the separation angle θ [32,33]. In striking contrast, when the transition takes place by emission of a short-lived ($\tau < 10^{-13}$ s) neutral particle decaying into an e^+e^- pair, the angular correlation becomes sharply peaked at larger angles, the correlation angle of a two-particle decay is 180° in the center-of-mass system.

To populate the 17.6, and 18.15 MeV 1^+ states in ^{8}Be selectively, we used the ^{7}Li$(\mathrm{p},\gamma)^8$Be reaction at the $E_p = 0.441$, and 1.03 MeV resonances [29]. Proton beams from a 5 MV Van de Graaff accelerator with typical current of 1.0 μA impinged on 15 μg/cm^2 thick LiF_2 and 700 μg/cm^2 thick LiO_2 targets evaporated on 10 μm Al backings.

The e^+e^- pairs were detected by five plastic $\Delta E - E$ detector telescopes similar to those built by Stiebing and co-workers [34], but we used larger telescope detectors in combination with position sensitive detectors to significantly increase the coincidence efficiency by about 3 orders of magnitude. ΔE detectors of $38 \times 45 \times 1$ mm^3 and the E detectors of $78 \times 60 \times 70$ mm^3 were placed perpendicularly to the beam direction at azimuthal angles of 0°, 60°, 120°, 180°, and 270°. These angles ensured homogeneous acceptance of the e^+e^- pairs as a function of the correlation angle. The positions of the hits were determined by multiwire proportional counters (MWPC) [35] placed in front of the ΔE and E detectors.

The target strip foil was perpendicular to the beam direction. The telescope detectors were placed around the vacuum chamber made of a carbon-fiber tube. A detailed description of the experimental setup is published elsewhere [36].

e^+e^- pairs of the 6.05 MeV transition in ^{16}O, and of the 4.44 and 15.11 MeV transitions in ^{12}C excited in the ^{11}B(p, γ)^{12}C reaction ($E_p = 1.6$ MeV) were used to calibrate the telescopes. A $\epsilon_{rel} = 20\%$ HPGe detector was also used at 50 cm from the target to detect the 477.61 keV γ ray in the ^{7}Li($p, p'\gamma$) reaction [37], to monitor the Li content of the target as a function of time.

In order to check the effective thickness of the targets during the long runs, the shape (width) of the high-energy γ rays was measured by a 100% HPGe detector. In the case of the broad 18.15 MeV ($\Gamma = 168$ keV) resonance, the energy of the detected γ rays is determined by the energy of the proton at the time of its capture (taking into account the energy loss in the target), so the energy distribution of the γ rays reflects the energy distribution of the protons. The intrinsic resolution of the detector was less than 10 keV at 17.6 MeV and the line broadening caused by the target thickness was about 100 keV, allowing us a reliable monitoring.

The raw spectra were continuously monitored during the whole experiment. The counting rates were reasonably low and not challenging the electronics. We observed only a few percent gain shifts of the energy detectors, but otherwise the whole spectrometer was stable during the typically 1 week long experiments performed at each bombarding energy. The targets were changed every 8 h.

The acceptance as a function of the correlation angle in comparison to isotropic emission was determined from the same data set by using uncorrelated e^+e^- pairs of different single electron events [36], and used to determine the angular correlations of different IPC transitions simultaneously.

Figure 1 shows the total energy spectrum of e^+e^- pairs measured at the proton absorption resonance of 441 keV (a) and the angular correlations of the e^+e^- pairs originated from the 17.6 MeV $1^+ \rightarrow 0^+_1$ *isovector* $M1$ transition and the 14.6 MeV $1^+ \rightarrow 2^+_1$ transition (b).

The Monte Carlo simulations of the experiment were performed using the GEANT code. Target chamber, target backing, windows, and detector geometries were included in order to model the detector response to e^+e^- pairs and γ rays. The scattering of the e^+e^- pairs and the effects of the external pair creation (EPC) in the surrounding materials were also investigated. Besides the IPC process, the background of γ radiation, EPC, and multiple lepton scattering were considered in the simulations to facilitate a thorough understanding of the spectrometer and the detector response [36].

For the 17.6 MeV transition we observed a slight deviation from the simulated internal pair conversion correlation (IPCC) curve at angles above 110°, but without any structure, and the deviation could be fully explained by admixing some $E1$ component typical for the background. The background originates from the direct (nonresonant) proton capture and its multipolarity is dominantly $E1$ [38], and it adds to the $M1$ decay of the resonance. Previously, pure $M1$ transitions from the decay of the 17.6 MeV resonance were assumed [24–26], which is reasonable for the resonance itself, but not for the underlying background. The contribution of the direct capture depends on the target thickness if the energy loss of the beam in the target is larger than the width of the resonance. The dashed simulated curve in Fig. 1(b) is obtained by fitting a small (2.0%) $E1$ contribution to the dominant $M1$ one, which describes the experimental data reasonably well.

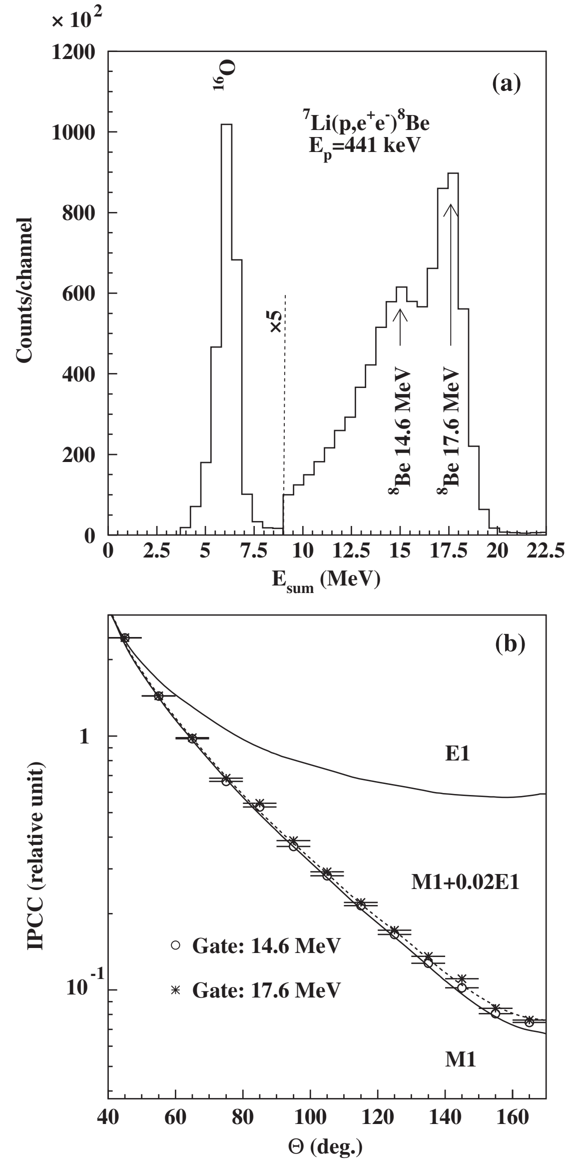

FIG. 1. Measured total energy spectrum (a) and angular correlation (b) of the e^+e^- pairs originated from the decay of the 17.6 MeV resonance compared with the simulated angular correlations [36] assuming $M1$ (full curve) and $M1 + 1.4\%E1$ mixed transitions (dashed line).

The 18.15 MeV resonance is *isoscalar* and much broader ($\Gamma = 168$ keV) [29], than the one at 17.6 MeV ($\Gamma = 12.2$ keV) [29] and its strength is more distributed.

The $E1$ contribution is expected to be larger than that of the 17.6 MeV resonance and, indeed, the deviation observed previously was much bigger in the 75°–130° angular region [26]. In the present work we extended the angular range to 170° and improved the statistics to check if the previously observed deviation can be explained with some $E1$ mixing also in this case. Figure 2 shows the angular correlations of the e^+e^- pairs measured at the proton capture resonance of 1.03 MeV. The spectra were obtained for symmetric $-0.5 \le y \le 0.5$ pairs, where the disparity parameter y is defined as $y = (E_{e^-} - E_{e^+})/(E_{e^-} + E_{e^+})$, where E_{e^-} and E_{e^+} denote the kinetic energies of the electron and positron, respectively.

The 6.05 MeV $E0$ transition in ^{16}O is due to the ^{19}F$(p,\alpha)^{16}$O reaction on a target contamination. As shown in Fig. 2 their angular correlation can be well described by the simulations.

The angular correlation for $M1$ transitions in ^{8}Be in the 15–18 MeV region (wide gate) shows a clear deviation from the simulations. If we narrow the gate around 18 MeV the deviation in the angular correlation at around 140 degrees is even larger, so the deviation can be associated with the 18 MeV transition, and cannot be explained by any amount of $E1$ mixing.

The γ spectrum showed no peaks above 11 MeV, due to possible impurities in the target. The $E0$ decay of the 20.2 MeV, 0^+, $\Gamma = 720$ keV ^{8}Be state did not effect the measured e^+e^- angular correlation. Mixing in some $E0$ component into the simulations did not improve the quality of the fit.

The angular distributions for all different multipolarities vary gradually as a function of the angle and, consequently, the mixed distribution also follow that pattern and cannot explain the peaklike anomaly we observed as a function of the correlation angle.

Since the 18.15 MeV transition has a very large (8:1) forward-backward anisotropy [39,40], which is caused by the interference of the $E1$ amplitude from direct capture, and the $M1$ amplitude of the 441 keV and 1.03 MeV resonances, we investigated their effects on the angular correlation of the e^+e^- pairs. It is known that the anisotropic angular distribution of the γ rays with mixed multipolarities may affect the angular correlation of the e^+e^- pairs [41]; however, placing the detectors in the plane at the target perpendicular to the beam, like in the case of our spectrometer, the above interference can be minimized. The forward-backward anisotropy peaks at $E_p = 1.1$ MeV (70 keV above the resonance) and remains almost constant at around $E_p = 1.2$ MeV. In this way, the forward-backward anisotropy does not follow the shape of the 1.03 MeV resonance, which vanishes at that energy [40].

In order to check experimentally that the measured anomaly of the angular correlation is related (or not) to the above anisotropy we performed a systematic measurement at different bombarding energies. The results are presented in Fig. 3.

The full curves show the IPC background ($M1 + 23\%E1$). We carried out the experiment at $E_p = 1.15$ MeV as well (not shown in Fig. 3), slightly above the resonance and obtained about 60% anomaly of the one observed below the resonance at $E_p = 1.04$ MeV.

The proton beam energy dependent shape of the measured deviation from IPC is in good agreement with the

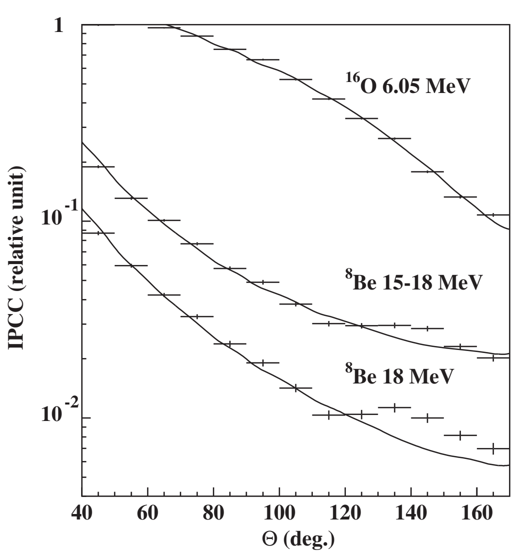

FIG. 2. Measured angular correlations ($E_P = 1.10$ MeV) of the e^+e^- pairs created in the different transitions labeled in the figure, compared with the simulated angular correlations assuming $E0$ and $M1 + E1$ mixed transitions.

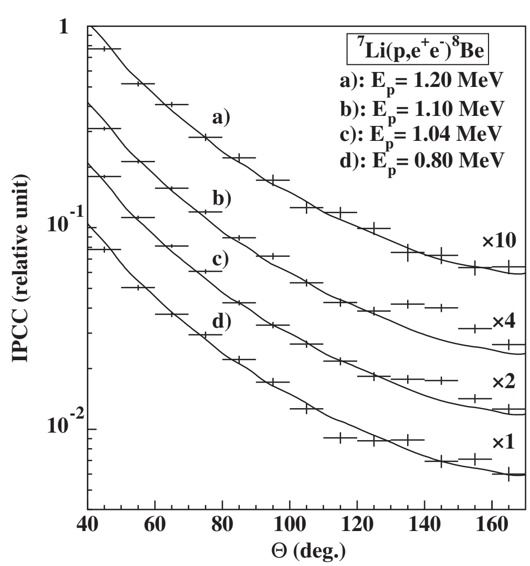

FIG. 3. Measured angular correlations of the e^+e^- pairs originated from the 18 MeV transition of the ^{7}Li$(p,\gamma)^8$Be reaction (dots with error bars) compared with the simulated ones (full curves) assuming $M1 + E1$ mixed transitions with the same mixing ratio for all curves at different beam energies. The pair correlation spectra measured at different bombarding energies are multiplied with different factors for better separation.

shape of the resonance [40], but it is definitely different from the shape of the forward or backward asymmetry [40]. Therefore, the above experimental data make the interpretation of the observed anomaly less probable as being the consequence of some kind of interference effects.

The deviation cannot be explained by any γ-ray related background either, since we cannot see any effect at off resonance, where the γ-ray background is almost the same. To the best of our knowledge, the observed anomaly can not have a nuclear physics related origin.

The deviation observed at the bombarding energy of $E_p = 1.10$ MeV and at $\Theta \approx 140°$ has a significance of 6.8 standard deviations, corresponding to a background fluctuation probability of 5.6×10^{-12}. On resonance, the $M1$ contribution should be even larger, so the background should decrease faster than in other cases, which would make the deviation even larger and more significant.

The e^+e^- decay of a hypothetical boson emitted isotropically from the target has been simulated together with the normal IPC emission of e^+e^- pairs. The sensitivity of the angular correlation measurements to the mass of the assumed boson is illustrated in Fig. 4.

Taking into account an IPC coefficient of 3.9×10^{-3} for the 18.15 MeV $M1$ transition [32], a boson to γ branching ratio of 5.8×10^{-6} was found for the best fit and was then used for the other boson masses in Fig. 4.

According to the simulations, the contribution of the assumed boson should be negligible for asymmetric pairs with $0.5 \le |y| \le 1.0$. The open circles with error bars in Fig. 4 show the experimental data obtained for asymmetric

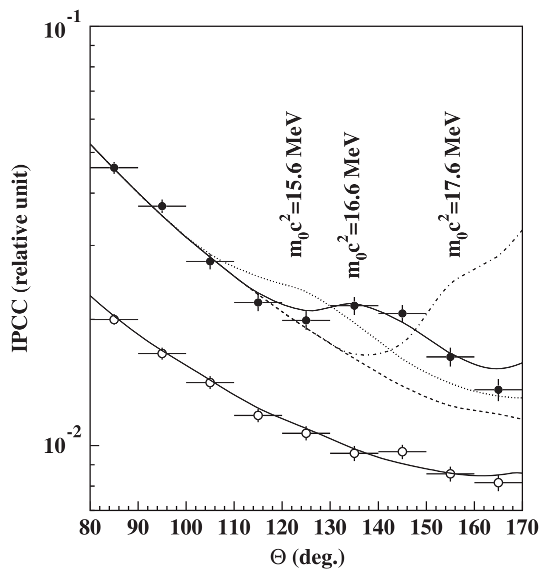

FIG. 4. Experimental angular e^+e^- pair correlations measured in the $^7\mathrm{Li}(p, e^+e^-)$ reaction at $E_p = 1.10$ MeV with $-0.5 \le y \le 0.5$ (closed circles) and $|y| \ge 0.5$ (open circles). The results of simulations of boson decay pairs added to those of IPC pairs are shown for different boson masses as described in the text.

pairs (rescaled for better separation) compared with the simulations (full curve) including only $M1$ and $E1$ contributions. The experimental data do not deviate from the normal IPC. This fact supports also the assumption of the boson decay.

The χ^2 analysis mentioned above to judge the significance of the observed anomaly was extended to extract the mass of the hypothetical boson. The simulated angular correlations included contributions from bosons with masses between $m_0c^2 = 15$ and 17.5 MeV. As a result of the χ^2 analysis, we determined the boson mass to be $m_0c^2 = 16.70 \pm 0.35(\mathrm{stat})$ MeV. The minimum value for the χ^2/f was 1.07, while the values at 15 and 17.5 MeV were 7.5 and 6.0, respectively. A systematic error caused by the instability of the beam position on the target, as well as the uncertainties in the calibration and positioning of the detectors is estimated to be $\Delta\Theta = 6°$, which corresponds to 0.5 MeV uncertainty in the boson mass.

Since, in contrast to the case of 17.6 MeV isovector transition, the observed anomalous enhancement of the 18.15 MeV isoscalar transition could only be explained by also assessing a particle, then it must be of isoscalar nature.

The invariant mass distribution calculated from the measured energies and angles was also derived. It is shown in Fig. 5.

The dashed line shows the result of the simulation performed for $M1 + 23\%E1$ mixed IPC transition (the mixing ratio was determined from fitting the experimental angular correlations), the dotted line shows the simulation for the decay of a particle with mass of 16.6 MeV/c^2 while the dash-dotted line is their sum, which describes the experimental data reasonably well.

In conclusion, we have measured the e^+e^- angular correlation in internal pair creation for the $M1$ transition depopulating the 18.15 MeV state in ^{8}Be, and observed a peaklike deviation from the predicted IPC. To the best of

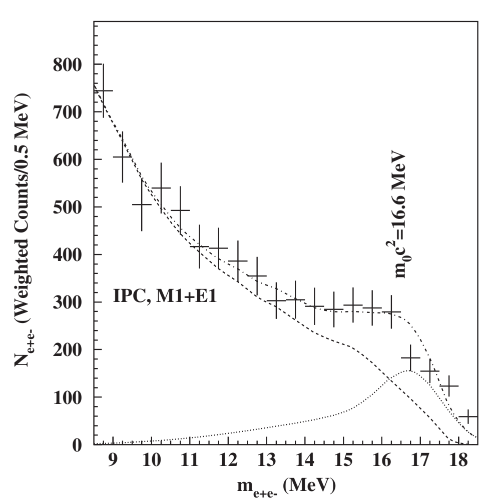

FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.

our knowledge, no nuclear physics related description of such deviation can be made. The deviation between the experimental and theoretical angular correlations is significant and can be described by assuming the creation and subsequent decay of a $J^\pi = 1^+$ boson with mass $m_0c^2 = 16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV. The branching ratio of the e^+e^- decay of such a boson to the γ decay of the 18.15 MeV level of ^{8}Be is found to be 5.8×10^{-6} for the best fit.

Such a boson might be a good candidate for the relatively light $U(1)_d$ gauge boson [4], or the light mediator of the secluded WIMP dark matter scenario [5] or the dark Z (Z_d) suggested for explaining the muon anomalous magnetic moment [7].

Very recently dark photon (DP) signals were searched for in the $\pi^0 \to \gamma e^+e^-$ decay [2]. No signal was observed, and the obtained upper limits ruled out the DP as an explanation for the muon (g-2) measurement under the assumption that the DP couples to quarks and decays predominantly to standard model fermions. However, in the case of the dark Z, the predominant decay to e^+e^- is not assumed [42].

Our observed branching ratio can also be related to the mixing parameter ϵ^2 [2]. A somewhat similar calculation was performed by Donnelly *et al.* [43] for nuclear deexcitations via axions. When we use Eq. 22a of that article, our experimental branching ratio gives an ϵ^2 in the 10^{-7} range, which is already below the best upper limit published recently [2]. If we consider a vector or axial vector dark Z particle, which decays only with 10% branching to e^+e^- pairs, than our ϵ^2 is consistent with the description of the g-2 anomaly [7].

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