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

A.J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi,
I. Kuti, B.M. Nyakó, L. Stuhl, J. Timár, T.G. Tornyi, and Zs. Vajta

Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T.J. Ketel

Nikhef National Institute for Subatomic Physics,
Science Park 105, 1098 XG Amsterdam, The Netherlands

A. Krasznahorkay

CERN, Geneva, Switzerland and
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

Electron-positron angular correlations were measured for the *isovector magnetic dipole* 17.6 MeV state ($J^\pi = 1^+$, $T = 1$) → 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 deviation from 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 might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of 16.70±0.35 (stat)±0.5 (sys) MeV/c^2 and $J^\pi = 1^+$ was created.

Recently, several experimental anomalies were discussed as possible signatures for a new light particle [1]. Some predictions suggest light neutral bosons in the 10 MeV - 10 GeV mass range as dark matter candidates, which couple to electrons and positrons [2–5], to explain the anomalies. A number of attempts were made to find such particles by using data from running facilities [6–13] or reanalyzing data of preceding experiments [14–18]. 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 [19–24].

In the present work we reinvestigated the anomaly observed previously in the internal pair creation of an isovector (17.6 MeV) and an isoscalar (18.15 MeV) M1 transitions in ^{8}Be [25–30].

The expected signature of the new particle is a very characteristic angular correlation of the e$^+$e$^-$ pairs from its decay [31, 32]. Quantum electrodynamics (QED) predicts [33, 34] that the angular correlation between the e$^+$ and e$^-$ emitted in the internal pair creation (IPC) drops rapidly with the separation angle θ. 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 the two-particle decay (180° in the center-of-mass system) is decreased according to the Lorentz boost in the laboratory system.

To populate the 17.6, and 18.15 MeV 1$^+$ states in ^{8}Be selectively, we used the ^{7}Li(p,γ)^{8}Be reaction at the E_p=0.441, and 1.03 MeV resonances [30]. Angular correlation of the produced e$^+$e$^-$ pairs were detected in the experiments performed at the 5 MV Van de Graaff accelerator in Debrecen. Proton beams with typical current of 1.0 μA impinged on 15 μg/cm^2 thick LiF$_2$ and 300 μg/cm^2 thick LiO$_2$ targets evaporated on 10 μm Al backings.

The e$^+$e$^-$ pairs were detected by five plastic ΔE–E detector telescopes similar to those built by Stiebing and co-workers [35], but we used larger telescope detectors in combination with position sensitive detectors to increase the coincidence efficiency by about 3 orders of magnitude. ΔE detectors of 38×45×1 mm^3 and the E detectors of 78×60×70 mm^3 were placed perpendicularly to the beam direction at azimuthal angles of 0°, 60°, 120°, 180° and 270°. These angles were chosen to obtain a homogeneous acceptance of the e$^+$e$^-$ pairs as a function of the correlation angle. The positions of the hits were registered by multiwire proportional counters (MWPC) [36] 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 [37].

e$^+$e$^-$ pairs of the 6.05 MeV transition in ^{16}O, and of the 4.44 MeV 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. γ rays were also detected for monitoring. A ϵ_{rel}=20% HPGe detector (measured

at 1.33 MeV relative to that of a standard 3"-diameter, 3"-long NaI(Tl) scintillator) was used at 50 cm from the target to detect the 477.61 keV γ ray in the ^{7}Li(p,p'γ) reaction [38], which has a very high cross section and could be used to follow 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 (Γ= 138 keV) 18.15 MeV 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.

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 (MC) simulations of the experiment were performed using the GEANT code. Target chamber, target backing, windows, detector geometries were included in the simulation 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 in the surrounding materials could also be investigated. Beside the IPC process, the background of γ radiation, external pair creation (EPC) and multiple lepton scattering were considered in the simulations to facilitate a thorough understanding of the spectrometer and the detector response [37].

We observed a slight deviation from the simulated internal pair conversion correlation (IPCC) curve at large angles above 110° confirming the results of a previous measurement [27], but the deviation could be explained by admixing some E1 component from the background. Previously, pure M1 transitions from the decay of the 17.6 MeV resonance were assumed [25–27]. It is true for the resonances itself, but not for the underlying background, which is reasonably small (but not negligible) for the 17.6 MeV resonance. The background originates from the direct (non-resonant) proton capture and its multipolarity is dominantly E1 [39], and it adds to the M1 decay of the resonance. 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.

As shown in Fig.1b, the slope of the E1 angular correlation is much smaller than the slope of the M1 one, so by adding even a small contribution of E1 radiation, the angular correlation at large angles is modified considerably. The dashed simulated curve in Fig. 1b is obtained by fit-
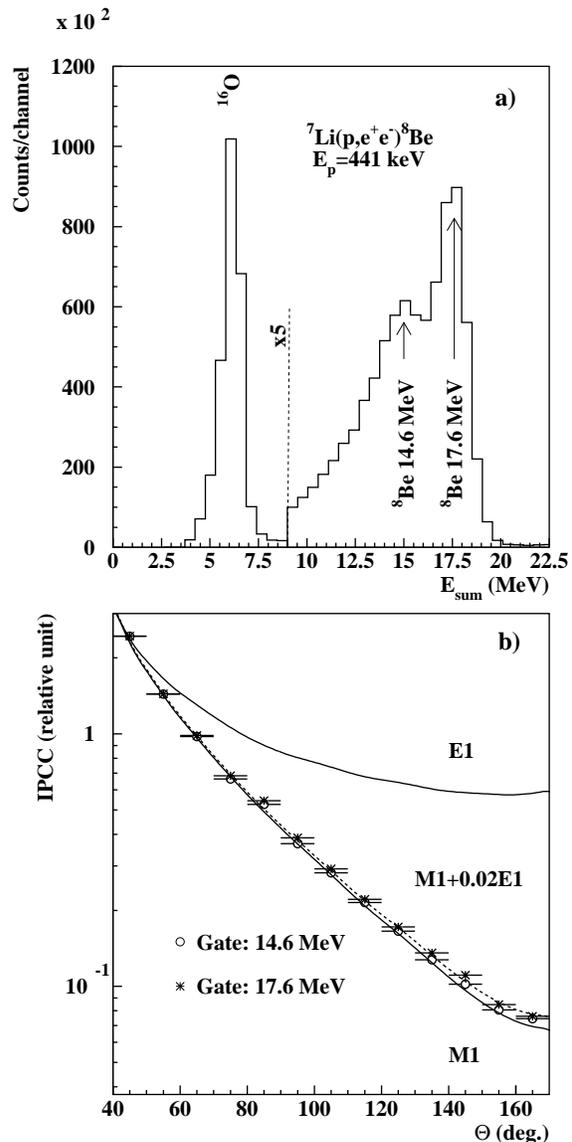
FIG. 1. *Measured total energy spectrum (a) and angular correlation (b) of the e^+e^- pairs originated from the decay of the 17.6 MeV resonance compared with the simulated angular correlations [37] assuming M1 (full curve) and M1+2%E1 mixed transitions (dashed line).*

ting a small (1.4%) E1 contribution to the dominant M1 one, which describes the experimental data reasonably well.

The 18.15 MeV resonance is much broader, Γ= 138 keV [30], than the one at 17.6 MeV, Γ= 10.7 keV 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 [27]. 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 total energy spectrum of the e^+e^- pairs measured at the proton absorption resonance of 1041 keV and the angular correlation of the e^+e^- pairs emitted in the 18 MeV $1^+ \to 0_1^+$ isoscalar M1 transition and in the 15 MeV $1^+ \to 2_1^+$ transition.
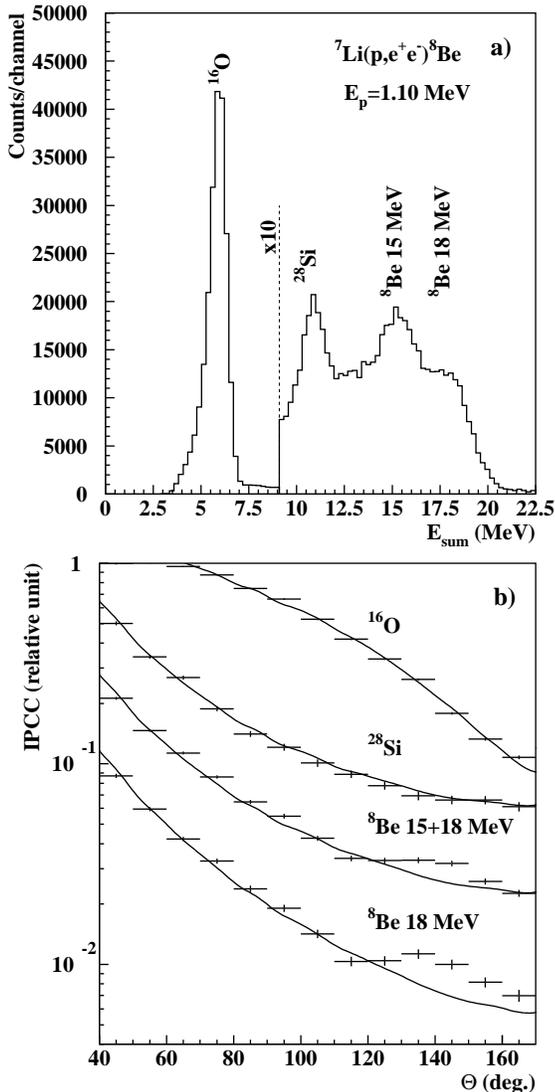
FIG. 2. *Measured total energy spectrum (a) and angular correlations (b) of the e^+e^- pairs created in the different transitions labelled in the figure, compared with the simulated angular correlations assuming E0 (from the ^{16}O peak) and M1+E1 mixed transitions from the other peaks.*

The spectra were obtained for symmetric $-0.5 \le y \le 0.5$ pairs, where the disparity (y) parameter 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 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 [37]. With this experimental acceptance, the angular correlations of different IPC lines in Fig. 2a were determined simultaneously.

The 6.05 MeV E0 transition in ^{16}O is due to the ^{19}F$(p,\alpha)^{16}$O reaction on a target contamination. The 11 MeV peak contains M1 and E1 transitions in ^{28}Si. As shown in Fig. 2 both the ^{16}O and the ^{28}Si angular correlations can be well explained 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 can not be explained by any amount of E1 mixing.

The angular correlation of the e^+e^- pairs arising from the $\approx$18 MeV IPC transitions to the ground state excited in the ^{7}Li$(p,\gamma)^8$Be reaction was measured at different bombarding energies. The results are presented in Fig. 3.
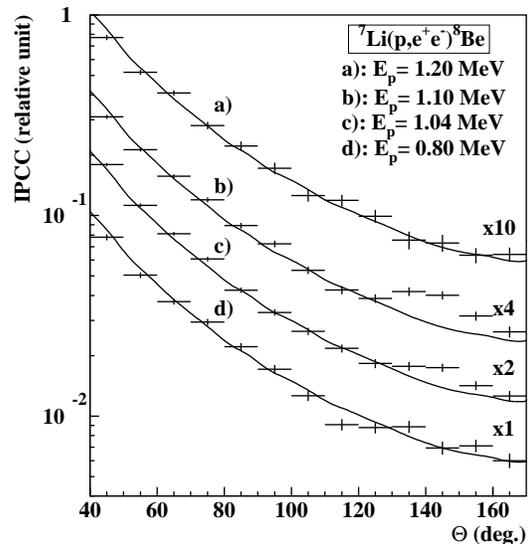
FIG. 3. *Measured angular correlations of the e^+e^- pairs originated from the ground state decay of the $^7Li(p,\gamma)^8Be$ reaction (dots with error bars) compared with the simulated ones (full curves) assuming M1+E1 mixed transitions with the same mixing ratio for all curves at different beam energies.*

The pair correlation spectra measured at different bombarding energies are multiplied with different factors (indicated in the figure) for better separation. The full

curves show the IPC background (M1+23%E1). The deviation observed at the bombarding energy of E_p=1.10 MeV (b) 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 (b) the M1 contribution should be 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.
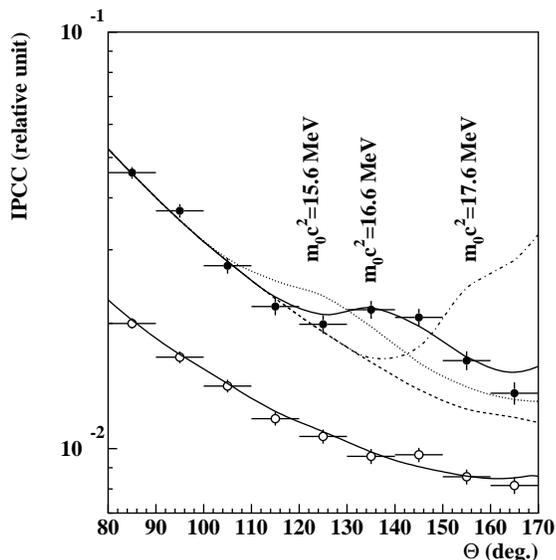
FIG. 4. *Experimental angular e^+e^- pair correlations measured in the $^7Li(p,e^+e^-)$ reaction at E_p=1.10 MeV with -0.5 $\leq y \leq 0.5$ (closed circles) and $|y| \geq 0.5$ (open circles). The results of simulations of boson decay pairs added to those of IPC pairs are shown for different boson masses as described in the text.*

Figure 4 shows the experimental angular correlation of the e^+e^- pairs in the narrow E_{sum} = 18 MeV region and with -0.5 $\leq$ y $\leq$ 0.5 (full circles) together with the results of the simulations assuming boson masses of m_0c^2 = 15.6 (dotted line), 16.6 (full curve) and 17.6 MeV (dash-dotted line), and the simulation without assuming any boson contribution (dashed line).

Taking into account an IPC coefficient of 3.9×10^{-3} for the 18.15 MeV M1 transition [33], a boson to γ branching ratio of 5.8×10^{-6} was 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 $\leq |y| \leq$ 1.0. The open circles with error bars in Fig. 4 show the experimental data obtained for asymmetric pairs (setting a wide, 15+18 MeV gate to get more statistics, as shown in Fig. 2b, and rescaled for better separation) compared with the simulations (full curve) including only M1 and E1 contributions.

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. The reduced χ^2 values as a function of the particle mass are shown in Fig. 5.
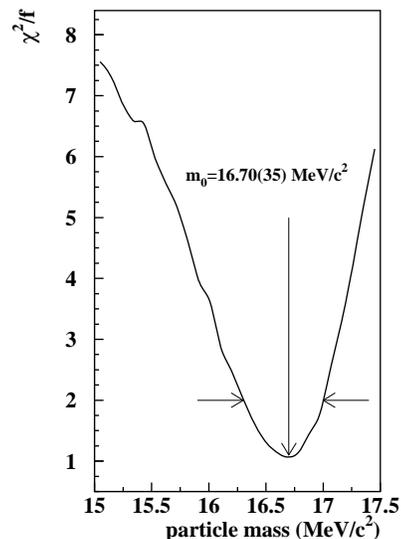
FIG. 5. *Determination of the mass of the new particle by the χ^2/f method, by comparing the experimental data with the results of the simulations obtained for different particle masses.*

As a result of the χ^2 analysis, we determined the boson mass to be m_0c^2 = 16.70±0.35 (stat) MeV. The minimum value for the χ^2/f was 1.07. 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.

In conclusion, we have measured the e^+e^- angular correlation in internal pair creation for the the M1 transitions depopulating the 17.6 and 18.15 MeV states in ^8Be, and observed anomalous IPC in the latter transition. The observed deviations from the M1 IPC in case of the 17.6 MeV transition could be explained by the contribution of the direct proton capture which presumably induce E1 transitions. However, E1 mixing alone cannot explain the measured anomaly in the 18 MeV pair correlation. The deviation between the experimental and theoretical angular correlations is significant and can be

described by assuming the creation and subsequent decay of a boson with mass m_0c^2 =16.70±0.35(stat)±0.5(sys) MeV/c^2 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 [2], or the light mediator of the secluded WIMP dark matter scenario [3] or the dark Z (Z$_d$) suggested for explaining the muon anomalous magnetic moment [5]. The coupling constant (ϵ^2) of the dark Z having a mass of 18 MeV is predicted to be in the 10^{-6} range for explaining the g-2 anomaly [5], which could fairly well explain the boson to γ-decay branching ratio measured in the present work. The lifetime of the boson with the above coupling strength is expected to be in the order of 10^{-14} s [4]. This gives a flight distance of about 30 μm in the present experiment, and would imply a very sharp resonance ($\Gamma \approx 0.07$ eV) in the future e^+e^- scattering experiments.

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* kraszna@atomki.hu

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