OBSERVATION OF ANOMALOUS INTERNAL PAIR CREATION IN ^{8}Be*

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The electron–positron angular correlation was measured for the isoscalar magnetic dipole 18.15 MeV transition in ^{8}Be. Significant, peak-like deviation was observed from the internal pair creation at $\Theta \approx 140^\circ$ in the angular correlation. 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.

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1. Introduction

The leading theory for dark matter used to be WIMPs (weakly interacting massive particles) that only interacted via gravity and the weak force, making them very hard to detect. Following recent research results, though, a new theory of dark matter actually postulates bosons in the 10 MeV to 10 GeV range [1]. A number of attempts were made to find such particles by using data from running facilities or reanalysing data of preceding experiments, but no evidence has been found yet [1, 2]. In the near future, many ongoing experiments are expected to extend those regions in mass and coupling strength which are so far unexplored [3–5].

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In the present work, we reinvestigated the anomaly observed previously in the internal pair creation of a 17.6 MeV and a 18.15 MeV M1 transitions in ^{8}Be [6–11], where the angular correlation gave some hint on the existence of a light neutral isoscalar particle.

2. Experiments

We used the $^{7}\mathrm{Li}(p,\gamma)^{8}\mathrm{Be}$ reaction at the $E_p = 0.441$, and 1.03 MeV resonances [9] to populate the 17.6, and 18.15 MeV 1^+ states in ^{8}Be selectively. Angular correlations 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 the typical current of 1.0 μA impinged on 300 μg/cm^2 thick LiO$_2$ targets evaporated on 10 μm Al backings.

The e^+e^- pairs were detected by five plastic scintillator ΔE–E detector telescopes similar to those built by Stiebing and co-workers [12], however, we used larger telescope detectors in combination with position-sensitive multiwire proportional counters (MWPC) [13], which enabled an increase of the coincidence efficiency by about 3 orders of magnitude.

The ΔE detectors of $52 \times 52 \times 1$ mm^3 size and the E detectors of $82 \times 86 \times 80$ mm^3 size 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 precise detection positions were measured by the MWPC detector placed in front of the ΔE and E detectors.

The ^{7}Li target was evaporated onto a 10 μm Al strip foil, which was spanned between 3 mm thick Perspex rods to minimize the scattering and external pair creation in the vicinity of the target. The target foil was placed perpendicularly to the beam direction in a vacuum chamber made of a carbon fiber tube. A detailed description of the experimental set-up is to be published elsewhere [14].

2.1. Monte Carlo simulations

In order to model the detector response to e^+e^- pairs and gamma rays, Monte Carlo (MC) simulations of the experiment were performed using the `GEANT` code. The target chamber, target backing, windows and detectors with their geometries were included in the simulation. The scattering of the electrons and positrons, as well as the effect of the external pair creation in the surrounding materials were also investigated. In order to facilitate a thorough understanding of the spectrometer and the detector response [14], the background of gamma radiation, external pair creation (EPC) and multiple lepton scattering were also considered besides the IPC process.

3. Results

To demonstrate the reliability of the spectrometer, we investigated a 17.2 MeV pure E1 transition in ^{12}C and a 17.6 MeV pure M1 transition in ^{8}Be. The ^{12}C resonance is populated in the $^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$ reaction at 1.6 MeV beam energy. The ^{8}Be resonance at 17.6 MeV is populated in the $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ reaction at 441 keV proton beam energy.

The acceptance of the spectrometer 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 [14]. With this experimental acceptance, the angular correlations of different IPC lines were determined simultaneously.

The experimental angular correlations could be well described with the simulations performed for pure E1 and M1 transitions. Their r.m.s. differences were less than 2.8% and 5.5% for the M1 and E1 transitions, respectively [14].

We investigated the isoscalar M1 transition originated from the decay of the 18.15 MeV resonance in ^{8}Be. Figure 1 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.

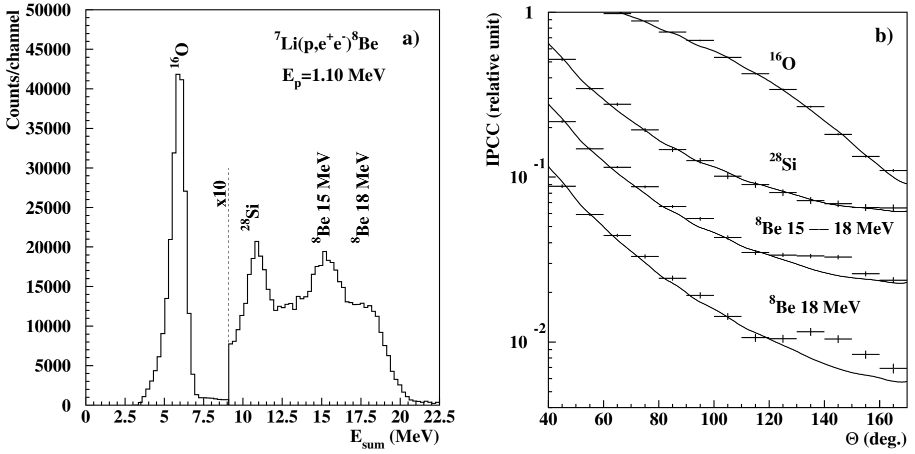

Fig. 1. Measured total energy spectrum (a) and angular correlations (b) of the e^+e^- pairs created in the different transitions labelled in the figure, compared with the simulated angular correlations assuming E0 (from the ^{16}O peak) and M1+E1 mixed transitions from the other peaks.

The spectra were obtained for symmetric $-0.5 \leq y \leq 0.5$ 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 6.05 MeV E0 transition from ^{16}O is present due to the $^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$ reaction on the fluorine content of the target. The 11 MeV peak contains M1 and E1 transitions in ^{28}Si. As shown in Fig. 1, both the ^{16}O and the ^{28}Si angular correlations 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° is even larger, so the deviation can be associated with the 18 MeV transition. Since the angular distributions for all different multipolaries vary slowly as a function of the angle and consequently the mixed distribution also follows that pattern, we cannot explain the peak-like anomaly observed as a function of the correlation angle.

We were trying to understand the origin of the observed anomaly within nuclear physics. It is known that the 18.15 MeV transition has a very large (8:1) forward–backward anisotropy [16, 17], which is caused by the interference of the E1 amplitude due to the direct capture process and the M1 amplitude of the 441 keV and 1030 keV resonances. We investigated their possible effects on the angular correlation of the e^+–e^- pairs as well.

The anisotropic angular distribution of the γ-rays with mixed multipolarities may affect the angular correlation of the e^+–e^- pairs [18]. However, placing the e^+ and e^- detectors in the plane through the target perpendicular to the beam, like our spectrometer was designed, the above interference can be minimized.

The measured forward–backward anisotropy peaked at $E_p = 1.1$ MeV (70 keV above the resonance) and remained almost constant above the resonance at $E_p = 1.2$ MeV, unlike the M1 cross section, which decreases at that energy by about a factor of 3 [17].

In order to check experimentally that the measured anomaly of these e^+–e^- angular correlations is related (or not) to the above anisotropy, we have measured the anomaly at different beam energies. The results are shown in Fig. 2.

The pair correlation spectra measured at different bombarding energies are multiplied with different factors for better separation. The full curves show the most appropriate (fitted) IPC background of M1+23% E1.

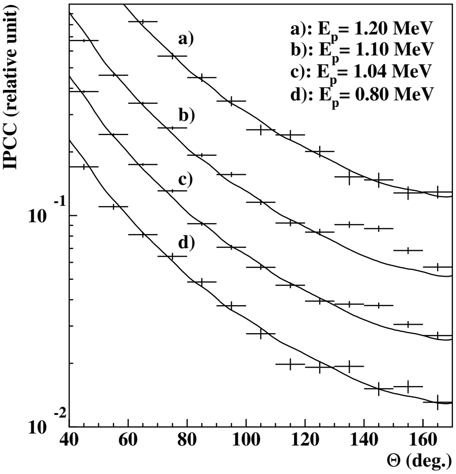

Fig. 2. Measured angular correlations of the e^+e^- pairs originated from the ground state decay of the ^{7}Li$(p,\gamma)^8$Be reaction (dots with error bars) compared with the simulated ones (full curves) assuming M1+E1 mixed transitions with the same mixing ratio for all curves at different beam energies.

By getting maximal anomaly at the resonance and no effect at $E_p = 1.2$ MeV (off-resonance), we could prove experimentally that the observed anomaly is not related to the M1/E1 interference. It cannot be explained by any γ-ray related background either. We cannot see any anomaly at off-resonance where the γ-ray background is almost the same. To the best of our knowledge, no other nuclear physics related origin of the measured anomaly could be considered.

The anomaly observed at the beam energy of $E_p = 1.10$ MeV (b) and at $\Theta \approx 140^\circ$ has a significance of 6.8 standard deviations, corresponding to a background fluctuation probability of 5.6×10^{-12}.

3.1. Interpretation of the results by introducing a new particle

The e^+e^- decay of a hypothetical gauge boson [19–21] emitted isotropically from the target has been simulated together with the normal IPC emission of e^+e^- pairs (M1+23% E1). The sensitivity of the angular correlation measurements to the mass of the assumed boson is illustrated in Fig. 3.

Figure 3 (a) shows the experimental angular correlation of the e^+e^- pairs in the narrow $E_{\text{sum}} = 18$ MeV region (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).

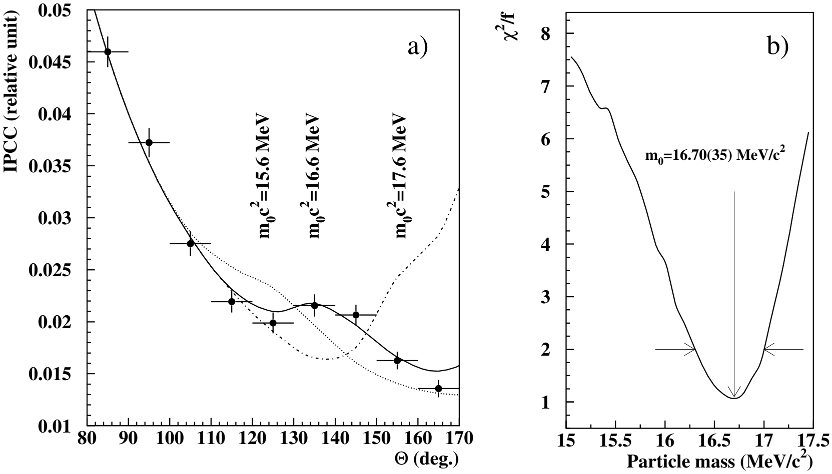

Fig. 3. (a) Experimental angular e^+e^- pair correlations measured in the ^{7}Li(p,e^+e^-) reaction at $E_p = 1.10$ MeV with $-0.5 \leq y \leq 0.5$ (closed circles). The results of simulations of boson decay pairs added to those of IPC pairs are shown for different boson masses as described in the text. (b) Determination of the mass of the hypothetical particle by the χ^2/f method, by comparing the experimental data with the results of the simulations obtained for different particle masses.

Taking into account an IPC coefficient of 3.9×10^{-3} for the 18.15 MeV M1 transition [15], a boson to γ branching ratio of 5.8×10^{-6} was found for the best fit. That branching ratio was then used for the other boson masses as well, which is shown in Fig. 3.

To extract the mass of the hypothetical boson, χ^2 analysis was performed as a function of the mass. 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. 3 (b).

As a result of the χ^2 analysis, we determined the boson mass to be $m_0c^2 = 16.70 \pm 0.35$ (stat.) MeV. 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 0.5 MeV uncertainty in the boson mass.

The measured boson/γ branching ratio can also be related to the mixing parameter ϵ^2 [3]. Earlier, Donnelly *et al.* [22] performed somewhat similar calculation for nuclear deexcitations via axions. Using Eq. (22a) in their article, our experimental branching ratio gives an ϵ^2 in the 10^{-7} range, which does not contradict with the best upper limit published recently [3].

4. Conclusion

We have measured the e^+e^- angular correlation for the isoscalar M1 transition depopulating the 18.15 MeV state in ^{8}Be, and observed a significant peak-like deviation from the predicted IPC. To the best of our knowledge, no nuclear physics related description of such deviation can be made. However, the deviation between the experimental and theoretical angular correlations can be described by assuming the creation and subsequent decay of an isoscalar, $J^\pi = 1^+$, neutral boson with mass $m_0c^2 = 16.70 \pm 0.35(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})$ MeV. The mixing parameter ϵ^2 estimated from the branching ratio of the e^+e^- decay of such a boson to the γ decay is consistent with the theoretical expectations.

Such a boson might be a good candidate for the relatively light $\mathrm{U}(1)_d$ gauge boson [19], or the light mediator of the secluded WIMP dark matter scenario [20] or the dark Z (Z_d) suggested for explaining the muon anomalous magnetic moment [21].

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