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SEARCHING FOR A LIGHT NEUTRAL AXIAL-VECTOR BOSON IN ISOSCALAR NUCLEAR TRANSITIONS

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Abstract

The electron-positron angular correlations within the pairs created in the decay of the 17.6-MeV ($J^\pi = 1^+$, $T = 1$) and the 18.12-MeV ($J^\pi = 1^+$, $T = 0$) *isovector and isoscalar magnetic dipole* transitions in ^{8}Be were measured. A sharp maximum was found at large angles in the isoscalar transition(s), which indicates that, in an intermediate step, a neutral isoscalar particle with a mass of 13.45(30) MeV/c^2 and $J^\pi = 1^+$ was created with a confidence level of 3σ. This particle may be identified with U, the supersymmetrical gauge boson, and may be related to dark-matter particles in the **u**niverse.

1 Introduction

In a recent series of papers the intriguing possibility was explored that the cosmic dark matter consists of new elementary particles with masses in the MeV range, which could be searched for in nuclear physics laboratories. Such particles are not excluded by any obvious laboratory measurements or astrophysical arguments. There are even some experimental indications for a light neutral boson with a mass of around 9 MeV/c^2.

The signature of the new particle is the very characteristic angular correlation of the e^+e^- pairs from their decay. Quantum electrodynamics (QED) predicts [1, 2] 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 annihilating into an e^+e^- pair, the angular correlation becomes sharply peaked at larger angles. In the center-of-mass system this emission takes place back to back at 180°. In the laboratory system the angle is smaller due to the Lorentz boost.

A light and weakly coupled neutral spin-1 gauge boson U was predicted by Fayet [3] and revisited by Boehm and Fayet [4]. It was argued by Boehm *et al.* [5], by Fayet [6] and Beacom [7] that light dark-matter particles decaying through such bosons into e^+e^- pairs may be the source of the observed 511-keV emission line in the galactic bulge [8]. In a renormalizable theory, some particle must mediate $\chi\ \bar{\chi} \to e^+e^-$ annihilation. The simplest possibility is to introduce a light, spin-1 boson, coupling to both e^+e^- and $\chi\bar{\chi}$ states. In a recent paper the mass of such a dark matter candidate was estimated to be $\mathrm{m}_e \leq \mathrm{m}_\chi \leq 20$ MeV/c^2 [9].

In 1988 de Boer and van Dantzig [10] analysed emulsion data obtained from relativistic heavy ion reactions in which e^+e^- pairs were observed at short but non-zero distances from the interaction vertices. These events were attributed to the emission and subsequent decay of a light neutral boson with a mass of around 9 MeV/c^2 and lifetime of about 10^{-15} s. These parameters fall within the allowed mass–lifetime window: 5 MeV/$c^2 \leq m_X \leq 20$ MeV/c^2, 10^{-16} s $\leq \tau \leq 10^{-13}$ s [11]. This finding motivated a systematic search for anomalous IPC in transitions between the levels of ^{8}Be and ^{12}C [14]. The e^+e^- pair decay from ^{8}Be*(17.6, 18.15) $J^\pi = 1^+$ and the ^{12}C*(17.2) $J^\pi = 1^-$ levels was measured. Whereas for the E1 decay (^{12}C) at large correlation angles no deviation is found from internal pair conversion (IPC), surprisingly the M1 angular correlation deviated from IPC at the 4.5σ level. While an anomaly is seen in the pair production, the overall results are not consistent with the involvement of a neutral boson [12, 13, 14]. A limit of $\leq 4.1\times10^{-4}$ was obtained for the boson to γ-ray branching ratio [12, 13, 14, 15] .

The aim of the present work is to re-evaluate the anomaly that de Boer et al. observed in pair production and to search for signatures of the assumed boson.

2 Experiments

To populate the 17.6, and 18.12 MeV 1^+ states in ^{8}Be strongly and selectively, we used the ^{7}Li(p,γ)^{8}Be reaction at E_p=0.44, and 1.03 MeV [15], and detected the angular correlation of the the e^+e^- pairs. The experiments were performed at the 5-MV Van de Graaff accelerator of ATOMKI with a typical beam current of 1.0 μA. LiF_2 and LiO_2 of about 1-mg/cm^2 targets were used on a thin 40-μg/cm^2 C backing.

The e^+e^- pairs were detected by five plastic ΔE–E detector telescopes similar to those built by Stiebing *et al.* [16], but we used larger telescope detectors in combination with position sensitive detectors to increase the coincidence efficiency by about a factor of 600. ΔE detectors of $38\times45\times1$ mm^3 and the E detectors of $78\times60\times70$ mm^3 were used perpendicular to the beam direction and at azimuthal angles of 0°, 60°, 120°, 180° and 270° around the beam pipe. These angles were chosen to obtain a homogeneous acceptance as a function of the correlation angle of the e^+e^- pairs. The positions of the hits were registered by a multiwire proportional counters (MWPC) [17] inserted between the ΔE and E detectors. The anode plane of the MWPC was a set of parallel 10-μm thick gold-plated tungsten wires put equidistantly by 2 mm. There were two cathode planes spanned by 0.1-mm thick silver-plated copper wires separated by 1.27 mm. The two cathode planes, with wirings perpendicular to each other to detect the x and y coordinates, flanked the anode plane at distances of 7 mm. Delay-line read-out (2 ns/taps) was used for the signal (cathode) wires. Ar(50%)+C_2H_6(50%) counting gas was flowing across the detector volume at an atmospheric pressure. The accuracy of the (x, y) coordinates implies an angular resolution of FWHM$\leq$2° in θ in the 70°–110° angular range. The angular resolution of the set-up is increased by multiple scattering of low energy electrons in the wall of the vacuum chamber and in the plastic ΔE detectors.

The target was tilted by 45° with respect to the beam direction. The telescope detectors were placed around the vacuum chamber made of a carbon fiber tube [16]. Apart from e^+e^- pairs, also γ rays were detected. A Ge clover detector with active volume of about 470 cm^3 and equipped with a BGO anti-coincidence shield [18] was put perpendicular to the beam and at a distance of 25 cm from the target.

The electron energy calibration was made with respect to 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 with the same setup.

3 Experimental results

Figure 1 shows γ-ray spectra measured at proton absorption resonances at E$_p$=0.441 MeV and 1.03 MeV.

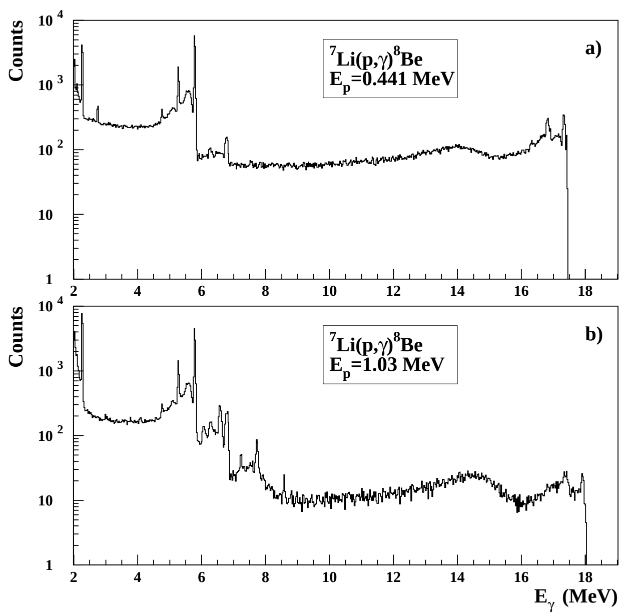

Figure 1: *γ-ray spectra measured at E_p= 0.441 MeV (a) and E_p=1.03 MeV (b).*

The 17.6 ($1^+ \rightarrow 0^+$) and 18.12 ($1^+ \rightarrow 0^+$) MeV photopeaks and their single escape peaks are clearly visible. The double escape peaks are suppressed by the anti-compton shield. The broad peaks at 14-15 MeV correspond to transitions to the first excited 2^+ level at E_x = 3.0 MeV, which has a width of Γ = 1.5 MeV [15]. This broad peak is more prominent with the 18.1 MeV excitation at E_p=1.03 MeV. The branching ratios of γ-transition to the ground state and to the 2^+ are, respectively, about 30% and 70% for the 18.15 MeV 1^+ state and 70% and 30% for the 17.6 MeV 1^+ state [15].

Figure 2 shows the total energy spectra of e^+e^- pairs measured at the proton absorption resonances at E_p=0.441 MeV and 1.03 MeV.

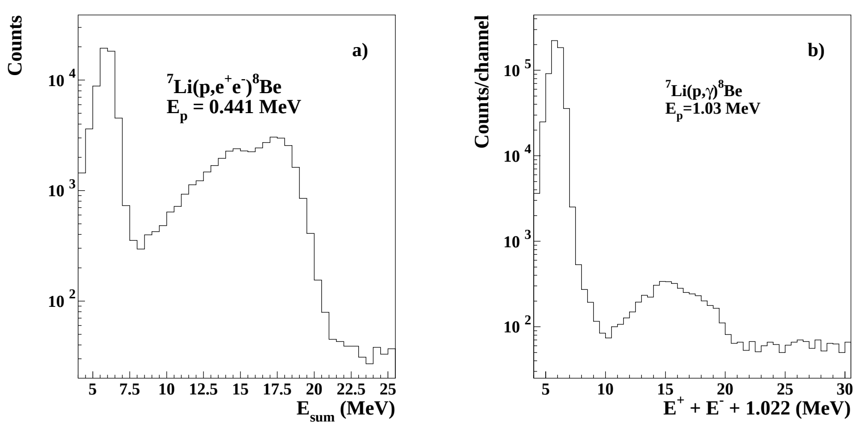

Figure 2: *Total energy spectra of e^+e^- pairs measured at E_p= 0.441 MeV (a) and E_p=1.03 MeV using LiF_2 targets.*

The spectra, especially measured at E_p=1.03 MeV, are dominated by a strong 6.05-MeV peak from the $^{19}F(p,\alpha)^{16}O$ reaction followed by the 100% IPC transition ($0^+ \rightarrow 0^+$, E0). Later on we prepared LiO_2 target with only a thin layer of LiF_2 cover to keep the 6.05-MeV peak at reduced counting rate for energy calibration and for efficiency monitoring of the detector system.

The γ-ray background in the E detectors originating from the target is suppressed by a factor of about 10^{-4} by requiring ΔE–E coincidences in addition to the coincidence between the two telescopes.

The efficiency calibration of the telescopes was made by using the same dataset but with uncorrelated e^+e^- pairs coming from different events. In order to check the calibration, the IPC line of the 6.05-MeV transition in ^{16}O, which is a pure E0 transition, was investigated in the ^{19}F(p,α)^{16}O reaction, and compared to the results of the simulation in Fig. 3.

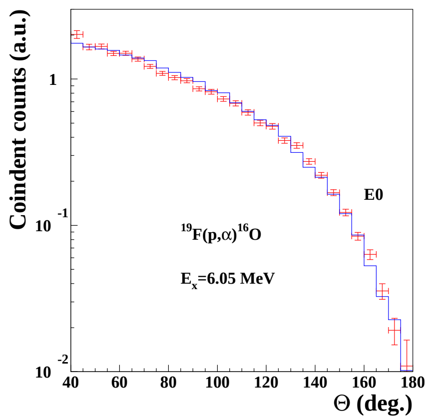

Figure 3: *Measured angular correlation of the* e^+e^- *pairs originated from the 6.05 MeV* $0^+ \rightarrow 0^+$ *E0 transition excited in* ^{16}O *by the* $^{19}F(p,\alpha)$ *reaction (red) compared to the simulated one (blue).*

4 Monte-Carlo simulations

In order to investigate deviations from normal internal pair conversion, a thorough understanding of the spectrometer and the detector response are needed. Besides the IPC process, the background of γ-radiation, external pair creation (EPC) and multiple lepton scattering were considered in extended simulations and calibration procedures.

Extensive Monte Carlo (MC) simulations of the experiment were performed using the GEANT3 code with target chamber, target backing, windows, detector geometries included, in order to model the detector response for e^+e^- pairs and also for γ-rays. In this way the scattering of e^+e^- pairs and the effects of the external pair creation in the surrounding materials could also be investigated. The event files created by the simulation were analysed with the same codes as the experimental data. The efficiency of the setup was calculated from single electron measurements and the results of the simulations was always normalized to that efficiency curve. Very nice agreement has been obtained between the experimental data and the simulations as shown in Fig. 3, indicating our understanding of the set-up.

The instantaneous e^+e^- decay of a hypothetical boson emitted isotropically from the target has also been simulated together with the normal IPC emission of e^+e^- pairs. Figure 4 shows the results of these simulations for the 17.6 MeV M1 transition.

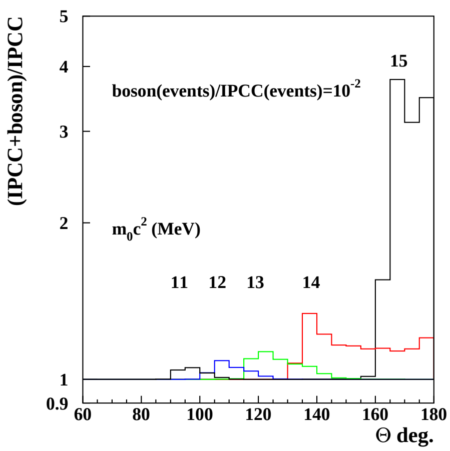

Figure 4: *Simulated angular correlations of IPC and of 1% boson decay* e^+e^- *pairs for boson masses indicated with the different curves.*

The numbers of simulated events are 10^8 for IPC and 10^6 for the decay of the boson. Even for this (very) small branching ratio the effect of the boson is clearly seen, as the IPC correlation drops (very) fast with angle. In this way the method is very sensitive to any boson contribution. The sensitivity is the largest if the mass of the boson is close to the energy of the transition.

5 Experimental results for the angular correlations

The results obtained for the e^+e^- angular correlation at the E_p= 0.441 MeV resonance for the total energy range including the broad resonance at 14 MeV and the 17.6 MeV (both 14.7 and 17.6 MeV M1 transitions in ^{8}Be) is shown in Fig. 5a together with the simulated distribution for M1 IPC. One can observe relative excess intensities compared to the simulations at large angles above 110° as it was also mentioned by de Boer et al. [14].

In Fig. 5b the excess is even larger for the transitions deexciting the E_p= 1.03 MeV resonance. This resonance at 18.1 MeV is much broader, Γ= 138 keV [15], than the one at 17.6 MeV, Γ= 10.7 keV and its strength is more distributed.

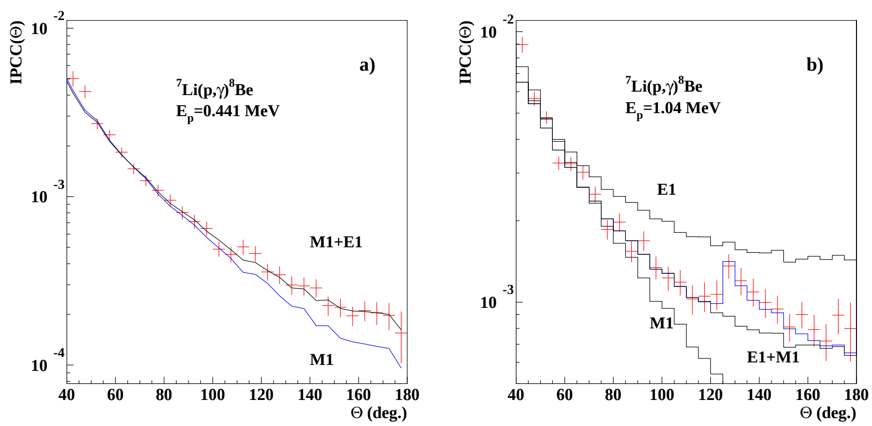

Figure 5: *Measured angular correlation of the e^+e^- pairs originated from the decay of the 17.6 MeV resonance (a) and from the 18.15 MeV resonance (b) (red dots with error bars) compared with the simulated ones assuming pure M1 and E1 transitions and M1+E1 mixed transitions. The contribution of a 13.5 MeV boson is shown in blue.*

De Boer et al. [12, 13, 14] assumed always pure M1 transitions from the decay of the 17.6 and 18.15 MeV resonances. It is fine for the resonances itself, but not for the underlying direct background, which is reasonably small (but not negligible) for the 17.6 MeV resonance, but much larger for the 18.15 MeV one. The background originates from the direct (non-resonant) proton capture and its multipolarity is (mostly) E1. It is mainly due to the low-energy tail of the giant dipole resonance [19] and it adds to the M1 decay of the resonances. The contribution of the direct capture depends on the target thickness, if the energy loss in the target is larger than the width of the resonant state. It is especially the case for the 17.6 MeV state.

As shown in Fig. 5 b), the slope of the E1 angular correlation is much smaller compared to the slope of the M1 one, so by mixing in even a small amount of E1 radiation the angular correlation at large angles can be modified considerably. The black simulated curve in Fig.5 a) is calculated by assuming a small (≈5%) E1 contribution to the dominantly M1 one, which explains well the experimental data.

The situation is more complicated in case of the 18.15 MeV resonance. The black (M1+E1) curve in Fig. 5 b) describes the experimental data only up to $\approx 120°$. The deviations at larger angles might be explained by creation and subsequent decay of a new particle, introduced in Ref. [10]. The blue curve in Fig. 5 b), which fits the data well, is calculated by assuming the contribution of a boson as well to the IPC process with 13.5 MeV energy and with a branching ration of 3.0×10^{-5} compared to the γ-decay.

The results of the full χ^2 analysis as a function of the mass of the assumed particle is shown in Fig. 6. The experimental results can be explained best if the mass of the particle is 13.45 ± 0.30 MeV/c^2.

6 Conclusion

We have measured the differential internal pair creation coefficients for the the M1 transitions depopulating the 17.6 and 18.12 MeV states in ^{8}Be. Similar deviations were observed at large opening angles, especially in case of the 18.12 case like de Boer [14] did.

The deviations could mostly be explained by the contribution of the direct proton capture which creates mostly E1 transitions. As the angular dependence of the IPC process for E1 transition is much less, compared to the M1 transition, a small mixing of E1 radiation can modify the the IPCC drastically at large angles.

Taking into account the E1 mixing properly, the IPCC of the 17.6 MeV

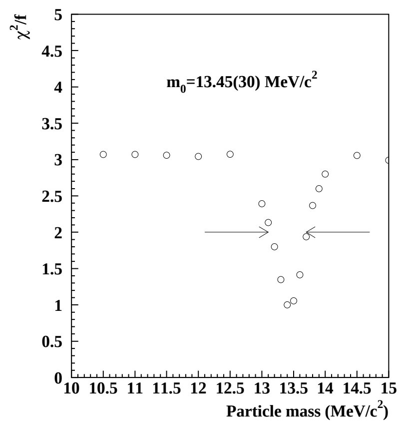

Figure 6: *Determination of the mass of the new particle by the χ^2/f method, by comparing the experimental data with the results of the simulations obtained for different masses.*

transition could be well explained. However, it was not the case for the 18.12 MeV transition. The deviation between the experimental and theoretical IPC shows peak like structures in that case, which can be explained only by assuming the creation and decay of a 13.45(30) MeV boson. The branching ratio of the boson creation compared to the γ-decay should be about 3.0×10^{-5} to explain the deviations. Such branching ratio is about 10 times smaller than de Boer [14] published earlier. The detailed χ^2/f analysis showed a 3σ confidence for the new particles. More precise (at least 3 times more statistics) experimental data is needed to clarify the existence of such assumed particles.

7 Outlook

The recent challenges created by astrophysical observations and theoretical predictions for the existence of a low-mass neutral particle motivated us to search for such particles in nuclear transitions. It turned out, however, that presently no spectrometer exists which could be used for serious searches. That is the reason why we started to build a compact positron-electron spectrometer (COPE), by using EU FP7 ENSAR supports, for studying the internal pair creation process of high energy nuclear transitions precisely.

The electrons and positrons will be bent in a toroidal magnetic field created by strong ($Nb_2Fe_{14}B$) permanent magnets and their bending radius will be measured by special time projection chambers like at the ATLAS Experiment at the CERN Large Hadron Collider, but at a 100 times smaller scale.

The energy and angular resolution of such spectrometer is expected to be much better than the present one, which would allows us to make our search more sensitive in the close future.

8 Acknowledgements

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