LEPTON PAIRS FROM A FORBIDDEN M0 TRANSITION: SIGNALING AN ELUSIVE LIGHT NEUTRAL BOSON?*

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Electron–positron pairs have been observed in the 10.95 MeV $0^- \rightarrow 0^+$ decay in ^{16}O. This magnetic monopole (M0) transition cannot proceed by γ-ray decay and is, to first order, forbidden for internal pair creation. However, the transition may also proceed by the emission of a light neutral 0^- or 1^+ boson, which might play a role in the current quest for light dark matter in the Universe.

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1. Introduction

When an excited nuclear level does not decay by γ radiation or by conventional internal pair creation (IPC) [1], an emission of a light neutral particle which in turn decays into an e^+e^- pair is still a possible form of the deexcitation. Such a light boson might be identified with a light and very weakly coupled neutral spin-1 gauge boson U, introduced by Fayet [2] more than two decades ago and revisited by Boehm and Fayet [3].

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In 1997 de Boer *et al.* [4] observed some deviations between the measured and predicted IPC angular correlations of e^+e^- in isoscalar magnetic transitions and explained it as a consequence of the formation and decay of a short lived isoscalar neutral boson with spin-parity (pseudo scalar) 0^- or (axial vector) 1^+ and with a mass of about 9 MeV/c^2.

The possibility of the existence of such 9 MeV/c^2 boson provided the motivation to investigate the 10.95 MeV $0^- \rightarrow 0^+$ g.s. electromagnetically forbidden transition in ^{16}O. Earlier, Eklund and Bent [5] and Alburger [6] searched for that transition by measuring the e^+e^- decay of the 10.95 MeV state but a really sensitive search for those transitions remained to be made.

2. Experimental methods

In order to populate strongly and selectively the 0^- state, we used the $^{14}\mathrm{N}(^3\mathrm{He},p)^{16}\mathrm{O}$ reaction at $E(^3\mathrm{He}) = 2.4$ MeV [7], and performed the experiment in coincidence with the proton group populating the 0^- state. TaN target produced at the KVI with an approximate thickness of 4 mg/cm^2 on a 5 μm thick Ta backing was used, allowing a beam current of 0.5 μA without considerable target damage during the course of the experiment. The Ta backing served also as an absorber for the ^{3}He beam particles.

A plastic scintillator disk with a diameter of 45 mm and a thickness of 6 mm was used behind the target to get large solid angle and high count-rate capabilities for detecting the protons. A solid angle of about 2 sr and an energy resolution of about 1 MeV was achieved for protons with such a detector when populating the 0^- state.

For high-statistics measurements of the e^+e^- pairs, $\Delta E - E$ detector telescopes from the IKF spectrometer constructed by Stiebing *et al.* [8] with large solid angles were used. The two largest telescopes (ΔE detector: $38 \times 40 \times 1$ mm^3 and E detector: $80 \times 60 \times 70$ mm^3) telescopes were set at 90 degrees. In order to increase our sensitivity for searching the boson, we improved the angular resolution by inserting a standard MWPC detector between the ΔE and E detectors of the telescopes.

The x, y position of the hits could be measured with an accuracy of 5 mm, which results in an angular resolution with FWHM $= 8.5^\circ$ between the electrons and positrons in the 60–120° angular range. The actual angular resolution of the telescopes was somewhat worse because of the scatterings on the plastic ΔE detectors.

The target was inclined by an angles of 45 degrees with respect to the beam direction. The telescope detectors were placed outside the vacuum chamber. To minimize the amount of the material around the target, a 24 cm long electrically conducting carbon fiber tube with a radius of 3.5 cm and a wall thickness of 0.8 mm, as well as thin aluminum target frames held by thin rods were used.

The γ-rays were also measured in coincidence with the protons. A highly efficient (120 %) clover type Ge detector equipped with a BGO anticoincidence shield [9] was used perpendicular to the beam and at a distance of 25 cm from the target.

3. Results

Fig. 1. shows a γ-ray and an $e^+ + e^-$ sum spectrum measured in coincidence with the protons populating the 10.95 MeV 0^- state. The 3.84 MeV γ-ray transition as well as a less intense $e^+ - e^-$ line at 10.95 MeV depopulating the 0^- state can be clearly seen, while no γ-rays could be observed at 10.95 MeV.

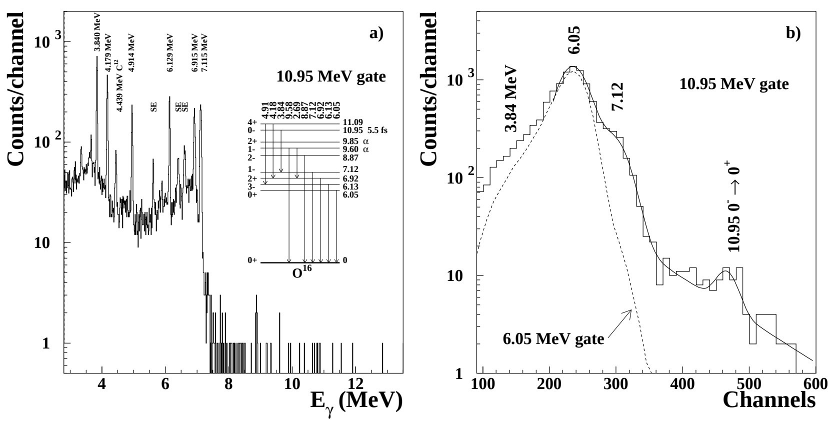

Fig. 1. γ-ray (a) and internal pair creation (b) spectra obtained from the $^{14}N(^{3}He,p)^{16}O$ reaction. See text for details.

The energy calibration of the setup was performed with pairs of the 6.05 MeV transition and of the 4.44 MeV and 15.1 MeV transitions measured in the $^{10}B(^{3}He,p)^{12}C$ reaction with the same setup. The insert in the γ spectrum of Fig. 1(a) shows a level scheme of ^{16}O up to 11 MeV, presenting the relevant γ transitions, which are also indicated in the γ spectrum. No gamma peak is observed above 9 MeV.

In the $e^+ + e^-$ sum energy spectrum with an energy resolution of FWHM ≈ 1.2 MeV for the 6.05 MeV transition a peak is observed at about 11 MeV, which corresponds to the $0^- \to 0^+$ 10.95 MeV transition in ^{16}O.

The γ-ray background in the E detectors originating from the target is very well suppressed by requiring $\Delta E - E$ coincidences in addition to the coincidence between two telescopes. In ^{16}O the 3.84 MeV (M1) and 7.12 MeV (E1) $\gamma - \gamma$ cascade depopulating the 10.95 MeV state may produce high energy electrons by Compton scattering in both ΔE detectors. These events will produce similar coincidence signals as the e^+e^- pairs. Their energy sums add up to a broad spectrum with a sharp edge at 10.95 MeV and thus simulate the IPC process.

In order to estimate the contribution of such kind of background, measurements were performed by using ΔE detectors with 3 mm thicknesses instead of the 1-mm ones. With the thicker ΔE detectors we expected 9 times larger contributions from Compton–Compton coincidences. The results of these measurements confirmed our hypothesis that Compton–Compton coincidences contribute to the background. This kind of background drops at about 1 MeV above the e^+e^- peak allowing a reliable background estimation.

As shown in Fig. 1, the e^+e^- spectrum was fitted with an exponentially falling background and using 3 Gaussians corresponding to the 6.05 MeV transition, the peaks around 7 MeV and the 10.95 MeV e^+e^--line. The intensity ratio obtained for the 10.95 MeV and 7 MeV lines is: $R_e = I(10.95\,\mathrm{MeV})/I(7\,\mathrm{MeV}) = 0.045 \pm 0.012$.

The 7 MeV lines contain the 7.12 MeV transition, which perfectly measures the excitation of the 10.95-MeV state as it decays by 100 % branching ratio to that level, and also the 6.92 MeV, $2^+ \to$ g.s. transition.

The intensity ratio of the 6.92 and the 7.12 MeV γ-lines was deduced from the γ-spectrum: $R = I(7.12)/I(6.92) = 1.20$. The branching ratio B of the e^+e^- decay was obtained for the 0^- state as:

$$B = \frac{R_e}{R}\,\alpha(6.92) + R_e\,\alpha(7.12) = (2 \pm 0.5) \times 10^{-4}\,, \tag{1}$$

where $\alpha(7.12)$ and $\alpha(6.92)$ denote the theoretical internal pair creation coefficients [10] of 2.56×10^{-3} and 1.96×10^{-3} for the 7.12 MeV E1 and the 6.92 MeV E2 transitions, respectively. As the lifetime of the 0^- state is known [11] to be 8 ± 5 fs, the partial lifetime of the e^+e^- transition will be $(4 \pm 2) \times 10^{-11}$ s. This lifetime is comparable to the lifetime of a second-order electromagnetic process and in this sense agrees with the estimate for a pseudoscalar boson.

Assume that a short-lived boson with mass m_u is created in such a nuclear transition with transition energy E and decays into an e^+e^- pair. In the center of mass system of the boson the e^+ and e$^-$ are emitted under 180°. In the laboratory system the opening angle will be smaller than 180° and depends on the e^+ and e^- energies. By assuming an isotropic emission of the e^+e^- pairs in the c.m. system, the angular correlation of the pairs can be calculated. The correlation has always a sharp maximum (FWHM $\leq 2°$) and the invariant mass m_x is determined by the scattering angle Θ, measured in the laboratory system as follows [4]:

$$m_u^2 \approx (1 - y^2) E^2 \sin^2 \left(\frac{\Theta}{2} \right) , \tag{2}$$

where the transition energy is calculated as $E = E^+ + E^- + 1.022$ MeV in which, $E^{+(-)}$ denotes the kinetic energy of the positron (electron) and $y = (E^+ - E^-)/(E^+ + E^-)$ is the disparity, all is given in the laboratory system. As an example, for the 10.95 MeV transition and a 9 MeV/c^2 boson we find a correlation angle Θ of about 111°. By measuring the angular correlation pattern of the e^+e^- pairs the mass of the new boson can in principle be deduced.

Figs. 2 (a) and (b) show the results of the angular correlation measurements obtained for the 6.05 MeV and for the 10.95 MeV transitions, respectively. As the angular correlation for the 6.05 MeV E0 transition is varying smoothly (almost linearly) in the investigated angular range Fig. 2(a) shows the effective solid angle of the telescopes as a function of the correlation angles. In Fig. 2(b) the counts have already been corrected for the effective solid angle of the telescopes determined from Fig. 2(a).

As the angular correlation pattern expected from the decay of a boson is sharper than the angular resolution of our telescopes, we expect a Gaussian like distribution with a width determined by the experimental angular resolution. Using a Gaussian with free parameters, we fit the experimental angular correlation. The result is shown in Fig. 2(b) with solid curve. We obtained $\Theta \approx 103°$ from the fit, which gives $m_u \approx 8.6$ MeV/c^2 for the mass of the boson.

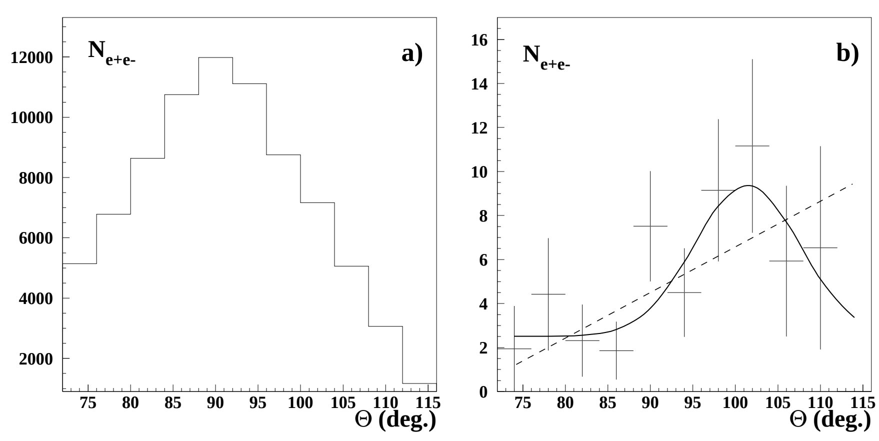

Fig. 2. The angular correlation of the e^+e^- pairs obtained from the decay of the 6.05 MeV (a) and from the 10.95 MeV (b) transitions in ^{16}O.

However, as shown in Fig. 2(b) the angular correlation can also be fitted (with about the same χ^2/f) with a linear function. According to a new experiment performed very recently with 3 telescopes covering an angular range of $60^\circ < \Theta < 170^\circ$ we observed a more pronounced peak at $\Theta = 130^\circ$ on a slowly rising background (Fig. 2(b)), which might be explained by assuming a boson with a mass of $m_u \approx 10\,\mathrm{MeV}/c^2$.

4. Conclusion

We observed for the first time the 10.95 MeV $0^- \to 0^+$ decay in ^{16}O by measuring e^+e^- pairs. The energy sum of the pairs corresponds to the energy of the transition (10.95 MeV), and the branching ratio $B = (20 \pm 5) \times 10^{-5}$ agrees with that of the expected boson. The angular correlation of the pairs might be described by assuming the decay of a boson with a mass of $m_u \approx$ 9–10 MeV/c^2. New experiments with better statistics are needed to settle the question and to determine the mass of the boson more precisely.

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