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Anomalous Internal Pair Conversion Signaling Elusive Light Neutral Particles

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Abstract. In this paper we report on a systematic search for a neutral boson in the mass range between 5 and 15 MeV/c^2 in the decay of highly excited nuclei. Its signature is found a deviation in the angular correlation of the e^+e^- pairs from conventional internal pair conversion (IPC) resulting from of its two-body decay kinematics. With an e^+e^- pair-spectrometer, a number of transitions has been investigated in the α–nuclei ^{8}Be, ^{12}C and ^{16}O, following light ion induced reactions at low bombarding energies, first at IKF in Frankfurt and during the last years at ATOMKI in Debrecen. Startlingly, in all isoscalar transitions excess e^+e^- pairs are found at large angles with branching ratios with respect to the total yield ranging from 10^{-2} to 10^{-6}. If these deviations are all related to the two-body decay of an X-boson, this observation implies plural X-bosons. An analysis of all angular spectra with a boson search program, yields a pandemonium of more than ten candidate bosons.

Introduction

Elusive neutral X-bosons can be emitted in a nuclear transition within the constraints of spin-parity, isospin and energy-momentum conservation. Superallowed (*L=0)* emission is expected for a *pseudoscalar* 0^- particle in a $0^-\rightarrow 0^+$ M0 transition, a *scalar* particle 0^+ in an $0^+\rightarrow 0^+$ E0, an *axial vector* 1^+ in an M1 and a *vector* 1^- particle in an E1 transition. Allowed (*L=1*) emission occurs for 0^+ and 0^- particles in E1 and M1 respectively, and for 1^+ and 1^- in E1, M1 but also in E2 and M2 transitions. The signature of X-boson emission is expected to be the two-body decay into e^+e^- pairs superposed on conventional internal pair conversion (IPC) [1], but with a marked difference in the distribution of the e^+e^- opening angle.

Since some time a search is carried out for such a neutral particle in high-energy transitions in self-conjugate α-nuclei. Since 1990, experiments have been performed at the 'small' Van de Graaff accelerator of the Institut für Kernphysik in Frankfurt, Germany and since the year 2000 at the AVF cyclotron and the Van de Graaff accelerator at ATOMKI in Debrecen, Hungary. In all experiments the same compact spectrometer was used, consisting of eight E-ΔE detectors, allowing a good compromise between angular granularity, stopping power, range and pair- efficiency [2].

A signal which could originate from a boson with an invariant mass of 9 MeV/c^2 has been observed in the M1 transitions depopulating the 17.64 MeV, 1^+ level in ^{8}Be to the ground- and first excited state. In Table 1 of refs. [6, 5, 7], the results are collected which are relevant to this anomaly for the α-nuclei ^{4}He to ^{20}Ne, like the branching ratio B_X, the width Γ_X, the coupling strength α_X and the m_X for the different transitions. It appears

that isoscalar magnetic transitions and a possible $0^- \rightarrow 0^+$ transition exhibit an excess of e^+e^- pairs at large opening angles, whereas no deviations occur in isovector E1 and M1 transitions. The deviations in isoscalar M1 transitions indicate an isoscalar character for such a boson with spin-parity 0^- or 1^+, and coupling strength α_X proportional to the isoscalar strength of the M1 transition. The sensitivity of these X-boson searches—expressed in the ratio of Γ_X to Γ_γ–varies between 10^{-6} and 10^{-2}.

In order to test this X-boson scenario, we started a dedicated search of e^+e^- angular correlations in isoscalar magnetic transitions with inelastic proton scattering experiments on ^{12}C and ^{16}O, the (p,α) reaction on ^{19}F and the $(^3He, pe^+e^-)$ reaction on ^{10}B and ^{14}N targets. The first aim was to check the signal observed [7] for the isoscalar M1 ground state transition from the T=0 level at 12.71 MeV in ^{12}C at a high level of significance and the second aim to look for the 9 MeV/c^2 boson in the 'forbidden' $0^- \rightarrow 0^+$ (M0) transition at 10.96 MeV in ^{16}O. The mere observation of e^+e^- decay to the ground state imposes a straightforward bound on an X-boson emission width.

Experiments

Experiments are carried out at ATOMKI, in Debrecen, Hungary at the cyclotron and at the Van de Graaff accelerator. The first four experiments (DEB1-DEB4) were dedicated to the $^{12}\mathrm{C}(p,p'e^+e^-)^{12}\mathrm{C}^*$ and the the $^{16}\mathrm{O}(p,p'e^+e^-)^{16}\mathrm{O}^*$ reaction at 16.5 MeV at the cyclotron using only the six 'small' detectors. For calibration the $^{19}\mathrm{F}(p,\alpha e^+e^-)^{16}\mathrm{O}^*$ reaction was used at 3.5 and 5.5 MeV. In the DEB5-run, the $^{14}\mathrm{N}(^3He, pe^+e^-)^{16}\mathrm{O}^*$ reaction was studied at 2.3 MeV together with the $^{19}\mathrm{F}(p,\alpha e^+e^-)^{16}\mathrm{O}^*$ reaction at 3.5 MeV using the complete eight detector set. The DEB7 experiment was performed in an 'asymmetric' arrangement with five telescopes (two large and three small ones) and an additional detector for proton detection. The $^{10}\mathrm{B}(^3He, pe^+e^-)^{12}\mathrm{C}^*$ reaction was measured followed by the $^{14}\mathrm{N}(^3He, pe^+e^-)^{16}\mathrm{O}^*$ reaction for comparison. These reactions were found to favor the population of unnatural parity states [8, 9]. In this experiment a thin proton detector with an 11% efficiency was implemented downstream. In coincidence with the populating proton group, e^+e^- pairs from the different levels could be distinguished.

In comparison with the p-capture spectra obtained at IKF where the decay of only one level is selected by the choice of the bombarding energy, the (p,α), $(^3He,p)$ and (p,p') reactions have several entrance channels in the final nuclei. The resulting e^+e^- sum-spectra are composite, but nevertheless different sum-peaks can be distinguished. We clearly observe deviations in the angular correlation spectra of transitions with energies below 9 MeV, the aimed boson mass, which energetically cannot decay by this particle. In the particle scenario with $(m_X \sim E \cdot sin(\omega/2))$, these deviations have to be explained by the emission of different particles with lower mass. With the observation of several deviations, a number of new particles has to be postulated. This also opens the exciting possibility of multiple boson emission in one transition.

Analysis of the presumably composite spectra with the number of bosons, their mass and strength as free parameter is not trivial and time-consuming. We have solved this problem in an indirect approach. We converted the angular spectrum in a 'quasi'-mass

spectrum by comparing the ratio of experimental data-points, divided by the simulated IPC distribution, with the ratio obtained by simulation of e.g. 10^8 bosons divided by an equal number of IPC's. Normalization was obtained by requiring an equal content of simulated to experimental X/IPC events by multiplying the theoretical ratio with a factor u, the transmission or inverse efficiency for boson emission. Boson masses were fitted from threshold to the transition energy in e.g 64 channel bins using a χ^2 procedure. The inverse of the χ^2 was taken to be the transition probability: $P = (\chi^2/(N-1))^{-1}$, where N is the number of detector combinations. The value P can then be plotted as a function of assumed m_i, testing the likelyhood of a particle with the given mass being present in the spectrum. An upper limit for the branching ratio is obtained by multiplying P with the 'transmission' u. For three detector geometries 10^7 or 10^8 events have been generated for some 40 to 70 boson masses, with and without energy disparity (y) cuts, for transition energies of 6.05, 8.87, 10.96, 12.71 14.64, 17.23 and 17.64 MeV. Also for the IPC (E0, E1, E2, M1 and M2) distributions, generally up to 10^9 events were simulated with and without y-cuts. It was found that a proportional scaling between boson masses and transition energies could be applied, except for the low masses, where the transition from backward decay to forward two-body decay at $\beta_{CM} = \beta_{lab}$ is not scaled correspondingly. A detailed description of the program will be published elsewhere [13].

The IKF experiments revisited

To test the validity of the program we have first applied it to the earlier results at IKF. Spectra from the $^7\mathrm{Li}(p, e^+e^-)^8\mathrm{Be}^*$ reaction at 0.44 and 1.03 MeV and the $^{11}\mathrm{B}(p, e^+e^-)^{12}\mathrm{C}^*$ reaction at 1.6 MeV proton energy were considered. All 28 correlation angles were used in the fits. The mass distributions perfectly confirm the 9 MeV/c^2 boson hypothesis with the peak at 9.23 MeV in Fig. 1c. The second peak at 10.95 MeV corresponds with the emission of the 9 MeV/c^2 boson in the 14.64 MeV transition to the first excited state, being at 9.09 MeV/c^2 in the 14.64 MeV laboratory system. No significant peak is seen at 9 MeV/c^2 in Fig. 1a. The P-value for ^{8}Be at 9 MeV/c^2 is indeed a factor five larger than for ^{12}C as observed in the angular distributions. However, we also see peaks at the higher masses of 12.50 and 14.23 MeV/c^2 masses.

A different picture is found for the isoscalar transition at 18.15 MeV. Here, the dominant peaks are at 12.42 and 14.55 MeV/c^2. They are a factor 20 stronger than in the isovector M1, whereas the strength of the 9.23 MeV/c^2 peak is about the same. The masses in Fig. 1 are indicated using the ground state transitions as two-body decay frame. Applying the transformation to 14.64, the masses become 2.99, 7.55, 9.26, 10.52 and 11.86 respectively and in Fig. 1f (with 15.15) of 3.21, 4.78, 8.22, 10.37 and 12.15 MeV. The emission of the same 9 MeV/c^2 boson in the 17.64 (9.10) and in the 14.64 MeV (9.23) was already suggested in [6] where approximately the same branching was deduced for this boson. Figs. 1b, 1d and 1f show the branching ratios B_X for boson to γ-ray emission. Integration over 9 MeV/c^2 yields respective values of $1.9{\cdot}10^{-5}$, $1.2{\cdot}10^{-4}$ and $4.0{\cdot}10^{-4}$ within 1σ in accord with the values of $\leq 2.3{\cdot}10^{-5}$, $(1.1\pm0.3){\cdot}10^{-4}$ and $(5.8\pm2.2){\cdot}10^{-4}$ given in [3, 6, 5, 7]. The mass distributions for the transitions after applying symmetry cuts to the spectra. show dramatically larger variations than in Fig. 1

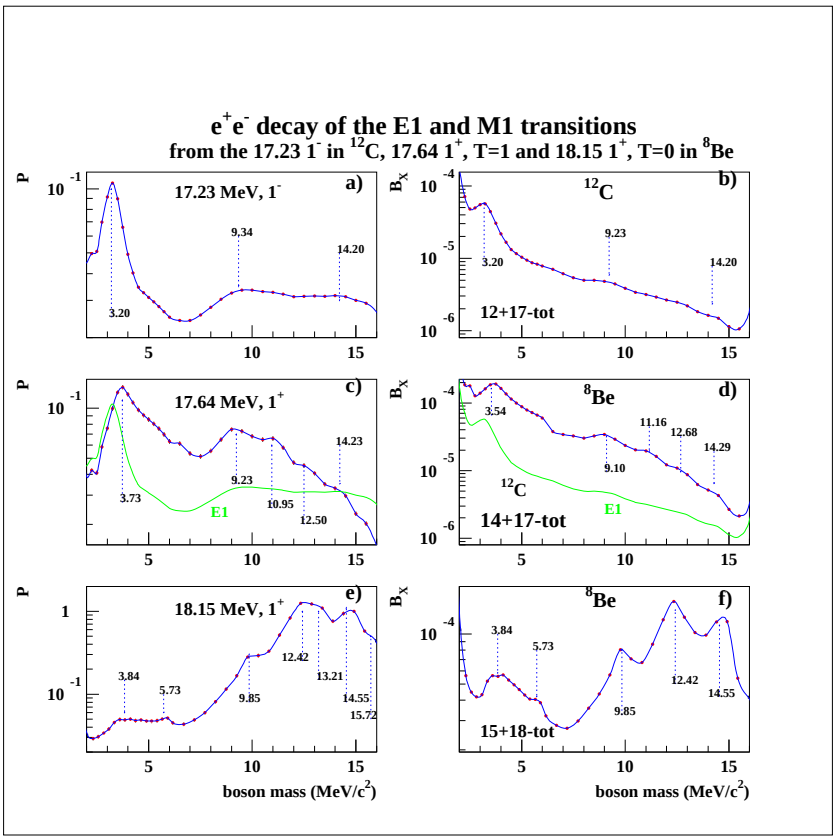

FIGURE 1. *Figs. 1a, 1c and 1e show the probability distributions of bosons in the decay of the 17,23* 1^-*, the 17.64* 1^+ *and the the 18.15 MeV* 1^+ *levels following the* $^{11}B(p,e^+e^-)^{12}C^*$ *reaction at 1.6 MeV and the* $^7Li(p,e^+e^-)^{16}O^*$ *reactions at 0.44 respectively 1.03 MeV as measured at IKF in 1992 and 1998 [3, 7]. Figs. 1b, 1d and 1e show the corresponding* B_X*-values i.e. branching ratios for boson to γ-ray emission. The dashed lines in Figs. 1c and 1d correspond with the E1 distributions from Figs. 1a and 1b.*

at 9.0, 12.5 and 14.5 MeV/c^2, in agreement with the expectations for two-body decay where the symmetrical decay is enhanced with respect to the primarily asymmetrical decay of M1-IPC at large angles. Integration at 9 MeV/c^2 yields B_X values of about half of those obtained from Fig. 1, in agreement with the expectations for two-body decay.

It appears that the boson search program adequately describes the IKF-results by reproducing the previously found signal at 9 MeV/c^2. However, surprisingly, it also finds signals for particles at the masses of 12.5 MeV/c^2 and 14.5 MeV/c^2. In the calibration runs: $^{19}F(p,\alpha e^+e^-)^{16}O^*$ at 0.72 and 0.84 MeV just below and above threshold for the 8.87 MeV 2^- level, two boson candidates are observed at 5.0 and 5.38 MeV/c^2 with branching ratios as large as several percent.

Back to ATOMKI and further

Because of the apparent feasibility of transformation of the angular spectra to mass-spectra and the unbiased character of the program we have systematically converted all available angular spectra from IKF and from ATOMKI and other sources into mass spectra. The oldest investigated spectrum was the celebrated angular correlation measurement of the E0 transition at 6.05 MeV in ^{16}O dated back to 1949 [10] and the most recent one: the study of the e^+e^- decay of the giant resonance decay at 22.23 MeV and the 15.11 MeV isovector M1 decay in ^{12}C at Stony Brook [11] in 2003.

The 4.44, 6.05, 7.66, 8.87, 10.96 and 12.71 MeV transitions

In this paragraph, we discuss the mass-distributions of six different transitions in ^{12}C and ^{16}O, selected from results of the $^{12}\mathrm{C}(p,p'e^+e^-)^{12}\mathrm{C}^*$ and the $^{16}\mathrm{O}(p,p'e^+e^-)^{16}\mathrm{O}^*$ reactions at 16.5 MeV and from the $^{19}\mathrm{F}(p,\alpha e^+e^-)^{16}\mathrm{O}^*$ reaction used for calibration.

The mass-distributions for symmetrical (S) pairs are shown in Fig. 2, with the *P*-distribution in the left column and the branching ratio in the right. In all shown data, disparity cuts of $y\leq 0.5$ have been applied. For every transition more than one spectrum is available showing in essence the same features as Fig. 2. In particular, for the 6.05 MeV E0 transition, data from twelve experiments have been analyzed. Eight of them show strong peaks at 5.0 and 5.3 MeV/c^2. The four spectra where they are absent, stem from experiments where the maximum correlation angle is smaller than 110^0.

The data are discussed from bottom to top. right to left. In the 12.71 MeV transition, we clearly recognize the boson at 9 MeV/c^2, the original goal for the experiments in Debrecen. The branching ratio is about $8{\cdot}10^{-4}$ in agreement with the results of [6, 5, 7]. However, there are two new candidates at 10.39 and 11.19 MeV/c^2, which are stronger than the one at 9 MeV/c^2. The M1 data are compared (bottom left) with a measurement of the angular distribution of the *forbidden* $0^+\rightarrow 0^+$ M0 transition at 10.96 MeV in ^{16}O, where a strong signal is seen at 7.85 MeV/c^2. The X/IPC value is as large as 0.8 and for the ($y\leq 1$) cut (not shown here) it is even 2, suggesting that the decay via the 7.85 MeV/c^2 boson is the dominant decay mode in this M0 transition. The two peaks at 8.99 and 9.84 MeV can be ascribed to reflection from bosons of 7.35 and 7.85 MeV/c^2 both occurring in the decay of the neighboring 8.87 MeV/c^2 which could experimentally not be completely resolved from the 10.96 MeV sum-peak. It seems appropriate to assign, from the superallowed decay, the 7.85 MeV/c^2 as a pseudoscalar particle and for the same reason the signals at 9.23 and 10.39 MeV/c^2 as axial vector particles. A vector character would be preferred for the 11.19 MeV/c^2 signal.

In the 8.87 MeV M2 transition we see a boson candidate at 7.35 with the spin 1^- and possibly the 7.85 0^-. The 6.32 MeV/c^2 peak could be due to reflection of the 7.85 in the 10.96 transition. However, the signals at 2.25. 3.38 and 5.04 MeV/c^2 in this transition are all viable boson candidates. Also in the mass-distributions of the two E0 transitions at 6.05 and at 7.65 MeV, multiple resonances are displayed. A candidate boson at 3.36 MeV/c^2 is seen in all spectra, The occurrence in the E0, E2 and M2 transitions (allowed decay) could only be compatible with the spin-parity of 1^- for this particle. With the

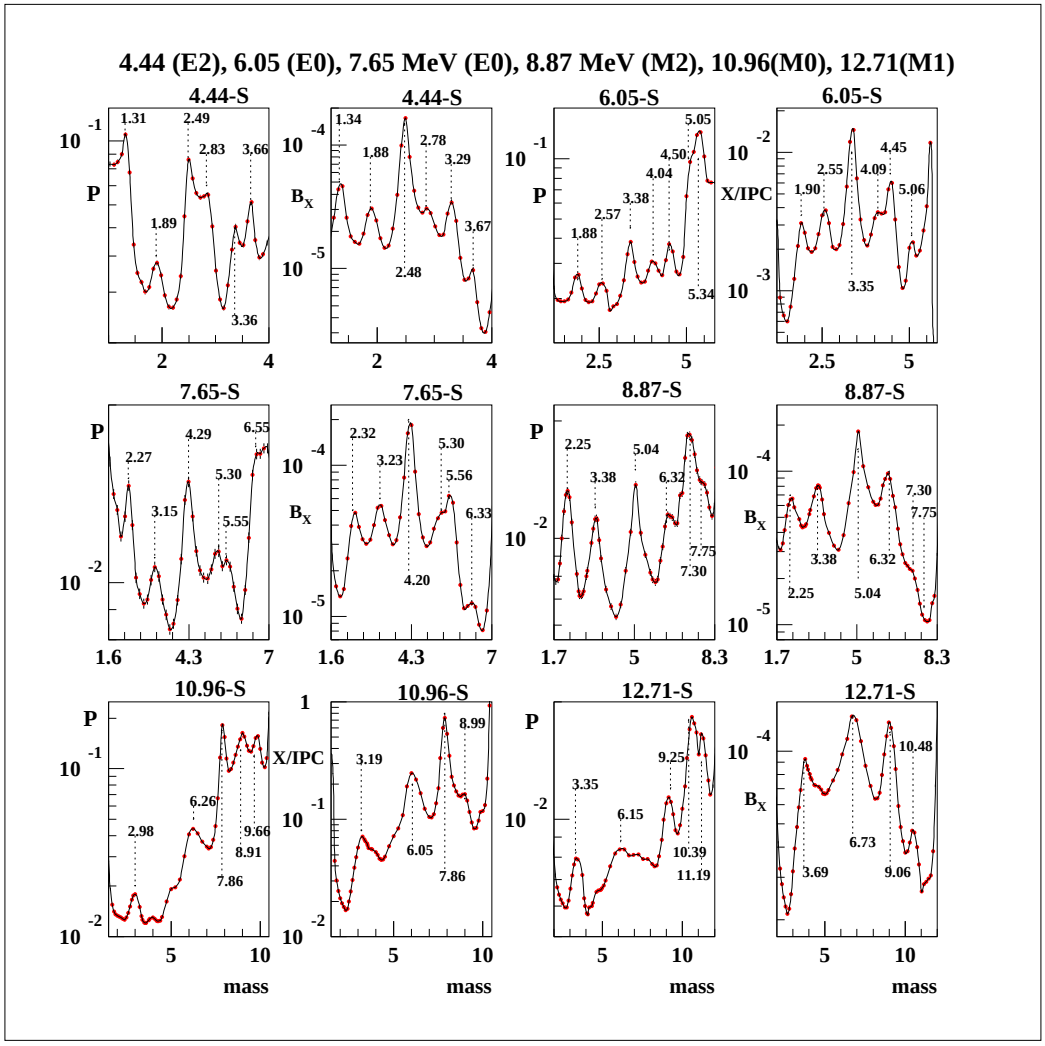

FIGURE 2. *From top to bottom (left) are shown the probability distributions of symmetrical (S) pairs in the 4.44 (E2), 6.05 (E0), 7.65 (E0) and 8.87 (M2), 10.96 (M0) and 12.71 (M1) transitions in ^{12}C and ^{16}O. Right are shown the corresponding branching ratios for boson emission with respect to E0-IPC (X/IPC) for the 6.05 MeV E0 and the 10.96 MeV (M0) transitions and to γ-rays for the E2 at 4.44 MeV, the M2 at 8.87 and the M1 at 12.71 MeV. The B_X-value for the 7.65 MeV E0 is shown with respect to the parallel $0^+ \rightarrow 2^+$ 3.20 MeV E2-γ-ray.*

simultaneous presence of the candidates below 4 MeV in the E0 and E1 transitions the spin is restricted to 1^-. Likewise, the resonance at 5 MeV/c^2 must, from its presence in the E0's and the M2 transition, have spin-parity 1^-. With its appearance in both E0 transitions and its absence in the M2, the 4.48 MeV/c^2 candidate must have a scalar 0^+ character since a 1^- particle would also have shown up in the M2 transition. With some optimism, this figure indicates the existence of two scalar *X*-bosons at 4.5 and 5.3 MeV/c^2 and six vector bosons at 2.5, 3.3, 4.0, 5.0, 6.3 and 7.3 MeV/c^2.

Conclusion and the future

It appears that in every isoscalar transition considered with energies from 4.44 to 12.71 MeV deviations from IPC are observed. This anomaly is explained in an isoscalar particle scenario which would require a multitude of bosons. The finding could have the bizarre consequence of a new type of light neutral matter instead of or/and the discovery of a new gauge boson.

A second generation of dedicated experiments is required to test this exciting possibility. The properties of every boson candidate have to be checked in great detail. A first experiment in that direction [13] has been undertaken in the DEB7 run, where the two-body decay properties of the bosons were verified, by mounting the central detector combination at an asymmetrical position. An alternative approach is being performed [14] at ATOMKI to study the angular correlations with an order of magnitude higher angularity, using wire chambers in front of the dE/dx-detectors.

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