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A new anomaly observed in ^{4}He supporting the existence of the hypothetical X17 particle

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Abstract. Recently, we observed an anomalous peak-like excess of internal e^+e^- pairs at around 140° for the M1 transition depopulating the 18.15 MeV isoscalar 1^+ state in ^{8}Be. The deviation from the theoretical prediction can be described by GEANT simulations assuming the creation and subsequent decay of a new, light boson with a mass of 16.7 MeV/c^2. In order to reduce the possible systematic errors from the experimenntal data, we re-investigated the ^{8}Be anomaly with an improved setup and confirmed the anomaly within the statistical uncertainties. We also studied the angular correlation of the electron-positron pairs created in the M0 transition depopulating the 21.01 MeV 0^- state in ^{4}He, and observed an anomalous excess of e^+e^- pairs at a significantly smaller angle of 115°. Since the transition energy was higher in this case, the observed anomaly could be described by assuming the creation and subsequent decay of the same light particle in the simulations.

1. Introduction

Recently, we measured electron-positron angular correlations for the 17.6 MeV and 18.15 MeV, $J^\pi = 1^+ \rightarrow J^\pi = 0^+$ M1 transitions in ^{8}Be and an anomalous angular correlation, a significant peak-like enhancement relative to the internal pair creation was observed at large angles in the angular correlation spectrum of the 18.15 MeV transition [1]. This was interpreted as the creation and decay of an intermediate particle X(17) with a mass of m_0c^2=16.70±0.35(stat)±0.5(sys) MeV.

Zhang and Miller [3] investigated the possibility to explain the anomaly within nuclear physics. They explored the nuclear transition form factor as a possible origin of the anomaly, and found the required form factor to be unrealistic for the ^{8}Be nucleus.

The data were explained by Feng and co-workers [4, 5] with a 16.7 MeV, $J^\pi = 1^+$ vector gauge boson X17, which may mediate a fifth fundamental force with some coupling to Standard

Model(SM) particles. The X17 boson is thus produced in the decay of an excited state to the ground state, ^{8}Be$^* \rightarrow ^8$Be + X17, and then decays through the X17 $\rightarrow e^+e^-$ process.

Constraints on such a new particle, notably from searches for $\pi_0 \rightarrow Z' + \gamma$ by the NA48/2 experiment [6], require the couplings of the Z' to up and down quarks to be protophobic, i.e., the charges $e\epsilon_u$ and $e\epsilon_d$ of up and down quarks, written as multiples of the positron charge e, satisfy the relation $2\epsilon_u + \epsilon_d \leq 10^{-3}$ [4, 5]. Subsequently, many studies of such models have been performed including an extended two Higgs doublet model [7].

At the same time, Ellwanger and Moretti made another possible explanation of the experimental results through a light pseudoscalar particle [8]. Given the quantum-numbers of the ^{8}Be* and ^{8}Be states, the X17 boson could indeed be a $J^\pi = 0^-$ pseudoscalar particle, if it was emitted with L = 1 orbital momentum. They predicted about ten times smaller branching ratio in case of the 17.6 MeV transition compared to the 18.15 MeV one, which is in nice agreement with our results.

The QCD axion is one of the most compelling solutions to the strong CP problem. There are major current efforts in searching for an ultra-light, invisible axion, but visible axions with decay constants at or below the electroweak scale are believed to have been long excluded by laboratory searches. Considering the significance of the axion solution to the strong CP problem, Alves and Weiner [9] revisited experimental constraints on QCD axions in the O(10 MeV) mass window. In particular, they found a variant axion model that remains compatible with existing constraints. This model predicts new particles at the GeV scale coupled hadronically, and a variety of low-energy axion signatures, including nuclear de-excitations via axion emission. This reopens the possibility of solving the strong CP problem at the GeV scale. Such axions or axion like particles (ALPs) are expected to decay predominantly also by the emission of e^+e^- pairs.

Delle Rose and co-workers [10] showed that the anomaly can be described with a very light Z_0 bosonic state, stemming from the U(1)0 symmetry breaking, with significant axial couplings so as to evade a variety of low scale experimental constraints. They also showed [11] how both spin-0 and 1 solutions are possible and describe the Beyond the Standard Model (BSM) scenarios that can accommodate these. They include BSM frameworks with either an enlarged Higgs, or gauge sector, or both.

In parallel to these recent theoretical studies, we re-investigated the ^{8}Be anomaly with an improved setup. We have confirmed the anomaly, and constrained the mass of the hypothetical particle ($m_\mathrm{X}c^2$ = 17.01(16) MeV) and branching ratio compared to the γ-decay ($B_x = 6(1) \times 10^{-6}$) [12, 13]. We also re-investigated the e^+e^- pair correlation in the 17.6 MeV transition of ^{8}Be, in which a much smaller deviation was observed [14]. We have conducted a new search also for the X17 particle in the 21.01 MeV $0^- \rightarrow 0^+$ transition of ^{4}He. Emission of a $m_\mathrm{X}c^2$ = 17 MeV vector boson (J^π=1^+) or pseudoscalar particle (J^π=0^-) is allowed in this transition with orbital angular momentum 1 or 0, respectively. In this proceedings we report on anomalous angular correlation of electron-positron pairs in this transition, which is in good agreement with the scenario of their decay from the assumed X17 particle.

2. Experiments

To populate the 17.6 and 18.15 MeV 1^+ excited states in ^{8}Be selectively, we used the ^{7}Li(p,γ)^{8}Be reaction at the E_p=441 keV and the E_p=1030 keV resonances [15]. The experiment was performed at the new 2-MV Tandetron accelerator at MTA Atomki. A proton beam with a typical current of 1.0 μA impinged on 15 μg/cm^2 LiF (used at the E_p=441 keV resonance) and 300 μg/cm^2 thick Li target evaporated on 20 $\mu g/cm^2$ thick carbon foils (used at the E_p=1030 keV resonance). The average energy loss of the protons in the targets were 9 keV and 70 keV, so the actual proton energy were 450 and 1100 keV. In contrast to our previous experiment [1, 17], we used a much thinner ^{12}C backing and we increased the number of telescopes (from 5 to 6), which resulted in a different pair detection efficiency as a function of the correlation angle. As a considerable improvement, we replaced the gas-filled MWPC detectors with a double-sided silicon strip detector (DSSD) array. The e^+e^- pairs were detected by six plastic scintillator + DSSD detector telescopes placed in a plain perpendicular to the beam direction. Their relative angles were 0°, 60°, 120°, 180° 240° and 300°. The size of the scintillators was $82\times86\times$ 80 mm^3. The positions of the hits were registered by the DSSD detectors having strip widths of 3 mm. The telescope detectors were placed around the vacuum chamber made of a carbon fibre tube with a wall thickness of 1 mm.

γ rays were also detected for monitoring purposes. A ϵ_{rel}=100% HPGe detector was used at 25 cm from the target to detect the 18.15 MeV γ rays produced in the ^{7}Li(p,γ)^{8}Be reaction.

In order to populate the wide (Γ = 0.84 MeV) 0^- second excited state (E$_x$= 21.1 MeV) in ^{4}He [16], we used the ^{3}H(p,γ)^{4}He reaction at E_p=0.900 MeV bombarding energy, which is below the threshold of the (p,n) reaction (E$_{thr}$=1.018 MeV). This state overlaps with the first excited state in ^{4}He (J$^\pi$=0$^+$, E$_x$=20.21 MeV, Γ=0.50 MeV), which was also excited at the same time and deexcited by an E0 transition.

The target used for the measurements was a tritiated titanium disk with a thickness of 3.0 mg/cm^2 evaporated previously on a 0.4 mm thick Mo disk. The concentration of the tritium atoms was 2.66×10^{20} atoms/cm^2. The disk was cooled down to liquid N$_2$ temperature to prevent the evaporation of ^{3}H.

3. Efficiency calibration of the e^+e^- spectrometer

The well-known, strong 6.05-MeV IPC transition ($0^+ \to 0^+$, E0) following the $^{19}\mathrm{F}(\mathrm{p}, \alpha e^+e^-)^{16}\mathrm{O}$ reaction was applied to perform the energy calibration of the spectrometer.

The pair correlation efficiency of the telescopes was calibrated by using the same dataset but with uncorrelated e^+e^- pairs of consecutive events.

The efficiency curve differs considerably for the present and previous setups, therefore, the present results could be considered as an independent measurement in the sense that any geometry-related systematic effect is eliminated from the measured data.

4. Results for the ^{8}Be transitions

Figure 1 shows our experimental results for the sum energy spectrum of coincidence events (a), and the angular correlation (b) of e^+e^- pairs measured at the proton absorption resonance at E$_p$= 441 keV.

In order to check the efficiency of the experimental setup we used the angular correlation determined for the 6.05 MeV E0 transition following the ^{19}F(p,α)^{16}O reaction. It is shown in the upper curve of Fig.1b together with the simulated results for an E0 transition.

Figure 2 shows our experimental results (red dots with error bars) for the recent angular correlation of e^+e^- pairs together with our previous results (blue dots with error bars) [1] measured at the proton absorption resonance at E$_p$= 1030 keV. There is a very good agreement between the two independent sets of experimental data.

5. Fitting the measured angular correlations

The shape of the background, originated mostly from the internal pair creation process, as well as the shape of the signal originated from the two particle decay of the hypothetical particle are obtained from GEANT simulations as a function of the mass of the particle.

The fit was performed with RooFit [19] by describing the e^+e^- angular correlation distribution with the following probability density function (PDF):

$$PDF(e^+e^-) = N_{Bkgd} * PDF(IPC) + N_{Sig} * PDF(signal)\ , \tag{1}$$

where N_{Bkgd} and N_{Sig} are the fitted number of background and signal events, respectively.

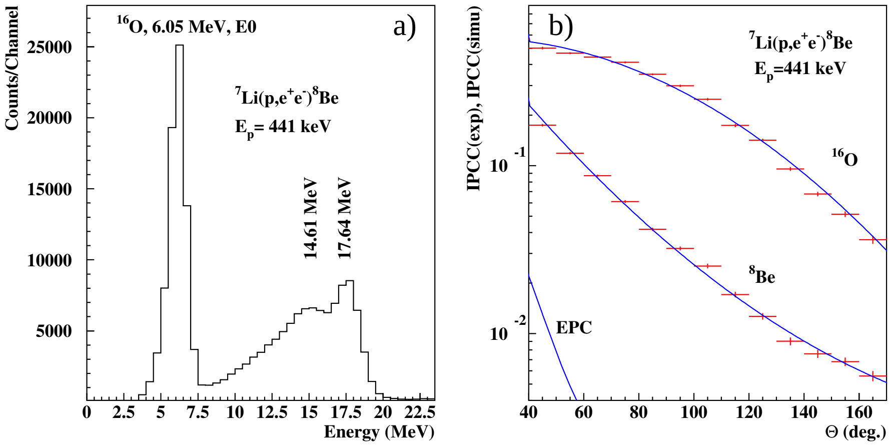

Figure 1. Measured sum energy spectrum (a) and angular correlation (b) of the e^+e^- pairs originated from the decay of the 17.6 MeV resonance compared with the simulated angular correlations [17] assuming M1+1.0%E1 mixed transitions (full blue curve). The contribution of external pair creation in the simulations caused by the 17.6 MeV γ-rays is shown at the bottom of the figure marked by EPC.

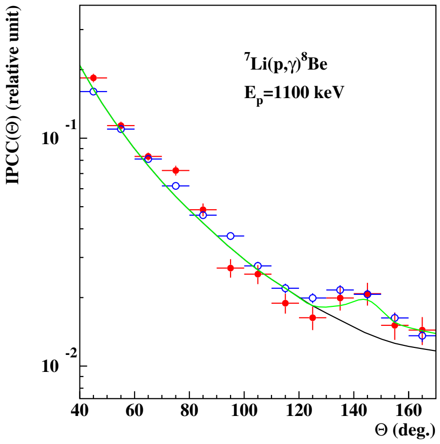

Figure 2. Measured angular correlations published previously [1] (blue circles) and the present results (red dots) of the e^+e^- pairs originated from the decay of the 18.15 MeV ground state transition in ^8Be. The black line represents the background, while the green one is the sum of the signal and background.

The signal PDF was constructed as a 2-dimensional model as a function of the e^+e^- opening angle and the mass of the simulated particle. To construct the mass dependence, the PDF linearly interpolates the e^+e^- opening angle distributions simulated for discrete particle masses.

Using the composite PDF described in Equation 1 we first performed a list of fits, by fixing the simulated particle mass in the signal PDF to a certain value, and letting RooFit estimate the best values for N_{Sig} and N_{Bkgd}. The best fitted values of the likelihood used to minimise the fit.

Letting the particle mass lose in the fit the best fitted mass and the branching ratio of the

e^+e^- decay of such a boson to the γ-decay is calculated for the best fit. The results of the two fits are summarized in Table 1.

The first column shows our published results in Ref. [1], while the second one was obtained also for the data of Ref. [1], but fitted with the method described above.

Table 1. Results of the new fit for Exp1, which was published earlier [1] and for Exp2, which is the present experiment.

	Previous res. [1]	Exp1	Exp2	Average
$m_0c^2(MeV)$	16.70(51)	16.86(6)	17.17(7)	17.01(16)
B_x	5.8×10^{-6}	$6.8(10)\times10^{-6}$	$4.7(21)\times10^{-6}$	$6(1)\times10^{-6}$
Significance	6.8σ	7.37σ	4.90σ	

The discrepancy in the particle masses of the two data sets could be a result of the unstable beam position in our previous experiment. According to MC simulations, such a mm order of beam position variation can cause a systematic uncertainty that cannot be neglected.

The particle masses deduced from the two data sets differ more than the statistical errors. It may be caused by the uncertainty of the beam position on the target, or some misalignment of the detectors which effects the angle determination.

6. Results for the ^{4}He transitions

Fig.3 shows our experimental results (red asterisks with error bars) for the angular correlation of e^+e^- pairs gated by the total energy for the signal region (19.5 MeV$\leq E_{tot} \leq$22.0 MeV), and the asymmetry parameter ($-0.5 \leq y \leq 0.5$) as defined in Ref.[1].

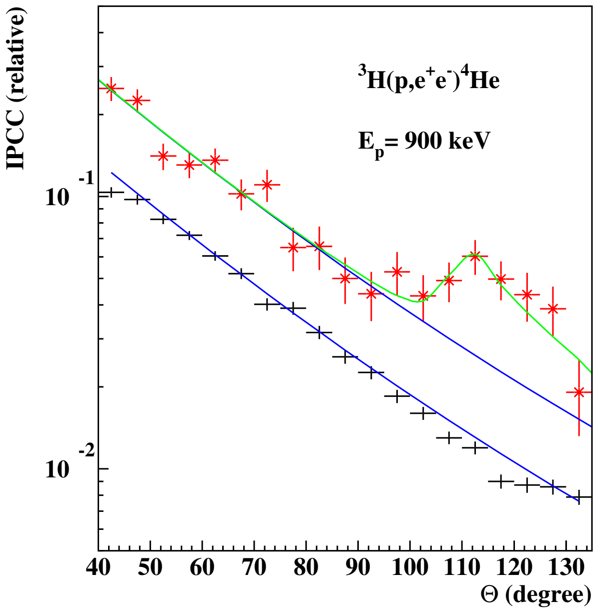

Figure 3. *Angular correlations for the* e^+e^- *pairs measured in the* $^3H(p,\gamma)^4He$ *reaction at* E_p*=900 keV.*

Black dots with error bars show the angular correlation of e^+e^- pairs for the background region (5 MeV$\leq E_{tot} \leq$19 MeV and $-0.5 \leq y \leq 0.5$), originated mostly from external pair creation. These data were fitted by a 4-th order exponential polynomial and the result is shown in blue. This blue curve was rescaled to fit the background of the angular correlation shown in red in the range of $40^\circ \leq \theta \leq 90^\circ$. The green full curve shows the simulated angular correlation including the decay of the X17 particle.

The background of the e^+e^- angular correlation is described by the above exponentially falling (4-th order exponential polynomial) distribution modeled after the external pair creation simulation, while the signal distribution is modeled from the simulation of a boson decaying to e^+e^- pairs.

The fit was performed also with RooFit [19] and the result is shown in green in Fig. 3. The mass of the hypothetical particle derived from the fit is: m_xc^2=16.92±0.16 MeV. The significance of the peak observed in the e^+e^- angular correlation was found to be 7.1σ. The mass of the hypothetical particle derived from the fit is: m_xc^2=17.00±0.13 MeV.

7. Conclusions

In order to significantly reduce the possible systematic errors from the experimenntal data, we have remeasured the e^+e^- angular correlation for the M1 transition depopulating the 18.15 MeV state in ^{8}Be and we could reproduce the peak-like deviation from the predicted IPC. The interpretaion of the anomaly was done by assuming a new hypothetical X(17) particle with mass of $m_xc^2 = 17.01(16)$ MeV and branching ratio compared to the γ-decay: $B_x = 6(1) \times 10^{-6}$. We have observed anomalous excess of e^+e^- pairs as well from an electro-magnetically forbidden M0 transition depopulating the 21.01 MeV 0^- state in ^{4}He. The energy sum of the pairs corresponds to the energy of the transition. The measured e^+e^- angular correlation for the pairs shows a peak at 115° which can be explained by the creation and decay of the X17 particle with mass of m_xc^2=16.84±0.16($stat$)±0.20($syst$) MeV. This mass agrees nicely with the value of m_xc^2=17.01 ±0.16 MeV we derived previously in the ^{8}Be experiment. We are expecting more, independent experimental results to come for the X17 particle in the coming years.

8. Acknowledgements

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