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Advances in Dark Matter and Particle Physics

On the creation of the 17 MeV X boson in the 17.6 MeV M1 transition of ^{8}Be

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Abstract. Electron-positron angular correlations were remeasured for the 17.6 MeV ($J^{\pi} = 1^{+} \rightarrow 0^{+}$) ground state transition in ^{8}Be using an improved setup compared to one we used previously. Significant deviations from the internal pair creation was observed at large angles in the angular correlations, which supports that, in an intermediate step, a neutral isoscalar particle with a mass of 17.0±0.5 (stat)±0.5 (sys) MeV/c^2 and $J^{\pi} = 1^{+}$ was created.

1 Introduction

Dark matter is currently one of the greatest unsolved mysteries in physics. It is accepted already that all the ordinary matter we can find accounts for only about 4 percent of the universe. The quest to find the hidden universe is one of the key efforts that has brought cosmologists and particle physicists together. In spite of the great success of the standard model of particle physics (SM), which was crowned by the discovery of the Higgs boson, it is not completely satisfactory. It does not explain dark matter (DM), neutrino masses, the cosmological baryon asymmetry, etc.

Although dark matter has been gravitationally confirmed by astrophysical observations in various ways, one has no information on its properties. Whether it is made up of single, yet undiscovered particle. If yes, what would be its mass and couplings to other particles, and so on.

The leading dark-matter candidates are Weakly Interacting Massive Particles (WIMPs), axions, dark photons, etc. predicted by some physics theories but never detected. WIMPs are kind of like heavy neutrons, with a mass of 10 to 100 times heavier than a neutron. The axion was proposed to ensure that the strong nuclear force treated matter and antimatter on equal footing (so as to agree with observations). There have been dozens of big experiments that have looked for dark matter and found nothing yet.

In various dark matter theories, a kind of popular model includes a light new boson X which mediates between the Standard Model and a dark sector, e.g., Ref. [1, 2].

Very recently, we have observed an anomaly in the nuclear decay of ^{8}Be. This could be a first hint for a 17 MeV X-boson signal [3]. The ^{7}Li(p,γ)^{8}Be reaction was used at the E_p = 0.441 MeV and E_p = 1.03 MeV resonances to populate the excited states in ^{8}Be selectively and the differential internal pair conversion coefficients were studied for the 17.6-MeV, and 18.15-MeV, $J^{\pi} = 1^{+} \rightarrow 0^{+}$, M1 transitions in ^{8}Be. Significant peak-like enhancement of the internal pair creation was observed at large angles in the angular correlation of the 18.15 MeV transition, but not in the 17.6 MeV one [3]. This observation was interpreted as the creation and the subsequent decay of a neutral boson with mass m_0c^2=16.70±0.35(stat)±0.5(sys) MeV. The branching ratio of the e^+e^- decay of such a boson to the γ decay of the 18.15 MeV level of ^{8}Be is found to be 5.8×10^{-6} for the best fit [3].

A theoretical group lead by J. Feng [4] studied our data as well as all other previous experiments in this area and showed that the evidence strongly disfavors dark photons. They proposed a new theory, however, that synthesizes all existing data and determined that the discovery could indicate a fifth fundamental force [4]. If confirmed by further experiments, this discovery of a possible fifth force would completely change our understanding of the universe, with consequences for the unification of forces and dark matter.

The possible relation of the X boson to the dark matter problem as well as the fact that it might explain the (g-2)$_\mu$ puzzle, triggered an enormous theoretical and experimental interest in the particle and hadron physics community.

The protophobic 17 MeV gauge boson can mediate isovector transitions, so there is no dynamical suppression of this decay. However, its mass is near the 17.64 MeV threshold, so that the decay is kinematically suppressed noted Feng et al. [4]. They calculated the suppression factor for particle mass of 17 MeV and 17.4 MeV and obtained values of 2.3 and 5.2, respectively. In spite of that suppression, it would be important to see the anomaly also in the 17.64 MeV transition, since it is a much cleaner case without having any interference effect, so we deceided to

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repeat that experiment with better conditions than before [3].

In the present work we reinvestigated the anomaly observed previously by using a new and more stable Tandetron accelerator of our Institute. The multi wire proportional counters were replaced with silicon DSSD detectors as well as the complete electronics and data acquisition system from CAMAC to VME.

The expected signature of the new particle is a very characteristic angular correlation of the e^+e^- pairs from its two-particle decay, as shown in Fig.1. The predicted [5, 6] angular correlation between the e^+e^- pairs emitted in the internal pair creation (IPC) process however drops rapidly with the separation angle θ, as shown in Fig.2.

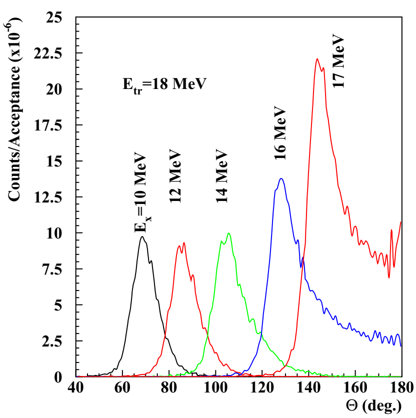

Figure 1. *Simulated angular correlations of IPC and of 1% boson decay e^+e^- pairs for boson masses indicated with the different curves.*

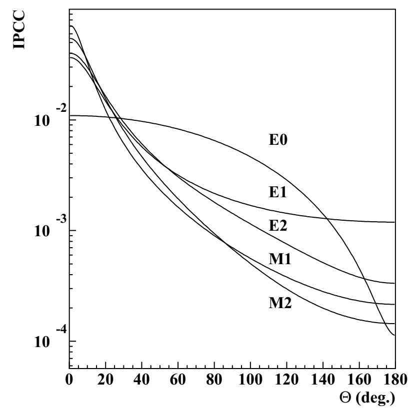

Figure 2. *Simulated angular correlations of IPC for different multipolarity nuclear transitions*

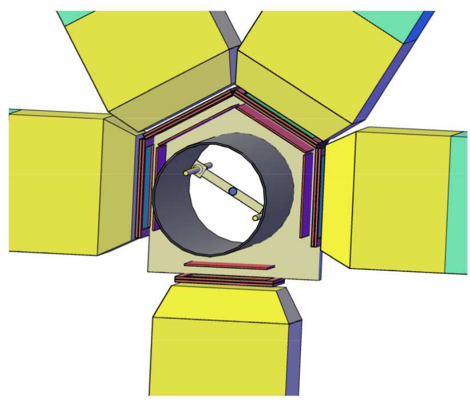

Figure 3. *CAD drawing of the e^+e^- spectrometer with five DSSD+$\Delta E - E$ detector telescopes. The target (blue spot in the center of the figure) is evaporated onto 10 μm Al strip foil spanned between 3 mm thick perspex rods to minimize the scattering and external pair creation in the vicinity of the target. The beam pipe is shown in black around which the ΔE and the DSSD detectors are arranged. The 1 mm thick ΔE detectors are shown in violet and red, while the E scinillators in yellow and their light guides are in blue.*

2 Experiments

To populate the 17.6 MeV 1^+ states in ^{8}Be selectively, we used the ^{7}Li(p,γ)^{8}Be reaction at the E_p=441 keV resonance [7]. The experiments were performed at the 2 MV Tandetron accelerator in Debrecen. A proton beam with a typical current of 1.0 μA impinged on 15 μg/cm^2 thick LiF target evaporated on 10 μm thick Al backing.

The e^+e^- pairs were detected by five plastic scintillator ΔE–E detector telescopes placed perpendicularly to the beam direction at azimuthal angles of 0°, 60°, 120°, 180° and 270° [8]. The positions of the hits were registered by double sided silicon strip detectors having a strip widths of 3 mm. The target strip foil was perpendicular to the beam direction. The telescope detectors were placed around the vacuum chamber made of a carbon fiber tube with a wall thickness of 1 mm. The arrangement of the detectors is shown in Fig.4.

γ rays were also detected for monitoring purposes. A ϵ_{rel}=100% HPGe detector (measured at 1.33 MeV relative to that of a standard 3”-diameter, 3”-long NaI(Tl) scintillator) was used at 25 cm from the target to detect the 17.6 MeV γ rays in the ^{7}Li(p,γ)^{8}Be reaction. Typical γ-ray spectra measured at E_p=441 keV is shown in Fig.4.

The 17.6 ($1^+ \to 0^+$) photopeak and their single and double escape peaks are clearly visible. 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 [7]. The branching ratios of γ-transition to the ground state

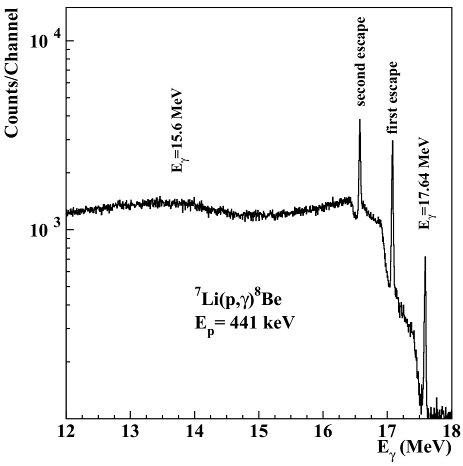

Figure 4. *A typical γ-ray spectrum measured at E_p= 441 keV.*

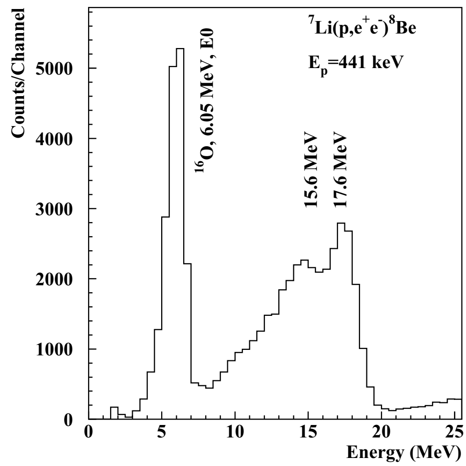

Figure 5. *Total energy spectra of e^+e^- pairs measured at E_p= 441 keV.*

and to the 2^+ are about 70% and 30% for the 17.6 MeV 1^+ state [7].

The excitation function of the reaction was also measured around the 441 keV resonance in order to check the target thickness. The measured width of the resonance was found to be 15 keV compared to the real width of Γ=12.2 keV taken from the literature [7]. From this we concluded that the energy loss of the protons in the target was sufficienly small (8.7 keV). In this way we can be sure that the multipolarity of the transition is dominated by M1. The contribution of the direct capture process gives a small background with multipolarity of E1, but according to the excitation function measurements their contribution is less than 1% [10].

Figure 5 shows the total energy spectrum of e^+e^- pairs measured at the proton absorption resonance at E_p=441 keV.

The strong 6.05-MeV peak comes from the ^{19}F(p, α)^{16}O reaction followed by the 100% IPC transition ($0^+ \rightarrow 0^+$, E0). This transition was used for energy calibration of the spectrometer and also for checking their efficiency calibration, since the angular correlation of the e^+e^- pairs coming from this transition is well known.

The efficiency calibration of the telescopes was made by using the same dataset but with uncorrelated e^+e^- pairs coming from different events.

The energy dependence of the calibration was simulated by the GEANT3 simulation code and taken also into account.

Fig.6 shows our experimental results for the angular correlation 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 calculated the angular correlation also for the 6.05 MeV E0 transition coming from ^{16}O. It is shown in the upper curve of Fig.6a together with the simulated results for an E0 transition.

For the 17.6 MeV transition we observed a slight deviation from the simulated pure M1 internal pair conversion correlation (IPCC) curve at large angles. A smoothly increasing difference could be originated from the direct (non-resonant) proton capture, the multipolarity of which dominates E1 [9], and it adds to the M1 decay of the resonance. The contribution of the direct capture depends on the target thickness if the energy loss of the beam in the target is comparable to the width of the resonance. The full simulated curve in Fig. 6b is obtained by adding a small E1 contribution (2.0%) to the dominant M1 one, which describes the experimental data reasonably well, but not a peak-like deviation observed at about 150 degree.

The e^+e^- decay of a hypothetical boson with mass of 17 MeV/c^2 emitted isotropically from the target has been simulated together also with the normal IPC emission of e^+e^- pairs. The results of the angular correlation measurements together with such simulations in a magnified angular range is illustrated in Fig.6b.

3 Fitting the measured angular correlations

The final e^+e^- angle correlation distribution is described by an exponentially falling distribution modeled after the IPC simulation, and the signal distribution modeled from the simulation of a boson decaying to e^+e^- pairs.

The fit was performed with RooFit [11]. Describing the e^+e^- angular correlation distribution with the following probability density function (PDF):

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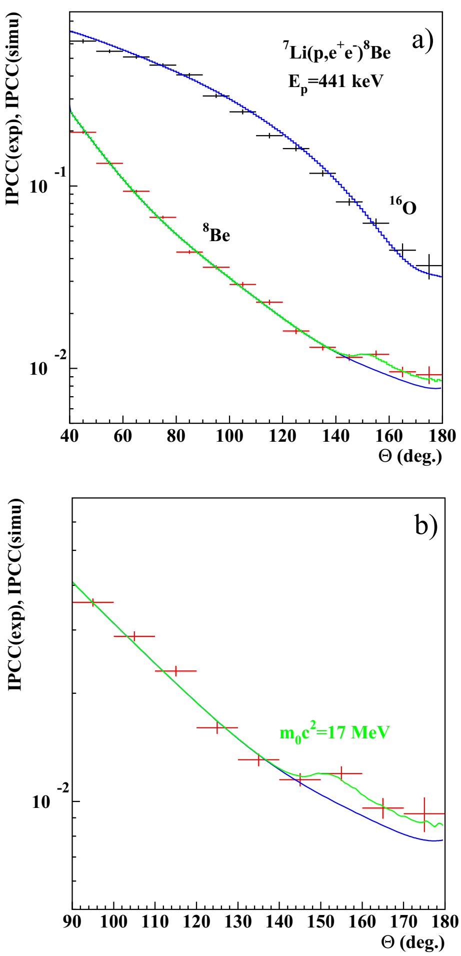

Figure 6. *Measured angular correlation of the e^+e^- pairs originated from the decay of the 17.6 MeV resonance compared with the simulated angular correlations [8] assuming M1+1.4%E1 mixed transitions (full (blue) curve).*

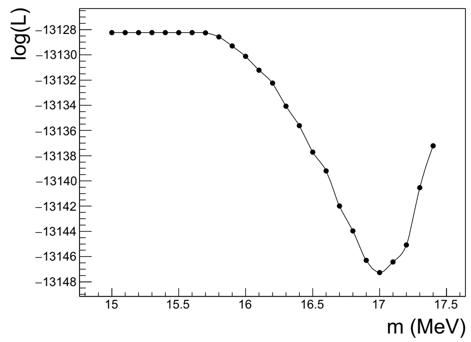

Figure 7. Fit results as a function of the hypothetical new particle's mass.

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

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

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 is shown in Figure 7, and has a clear minimum close to 17 MeV/c^2 simulated particle mass.

Letting the particle mass lose in the fit the best fitted mass is calculated as $m = 17.0 \pm 0.2 \; MeV/c^2$. The result of this fit is shown in Figure 8. The branching ratio of the e^+e^- decay of such a boson to the γ decay of the 17.64 MeV level of ^{8}Be is found to be 4.0×10^{-6} for the best fit.

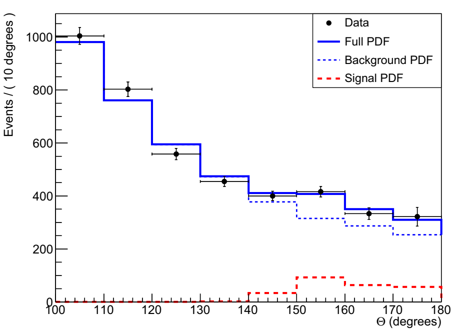

Figure 8. Fit of the e^+e^- correlation angle, letting the fit find the best value of m, N_{Sig} and N_{Bkgd} at the same time.

4 Repeating the experiment for the 18.15 MeV transition

Using the new setup described above we repeated our previus experiment showing the presence of the X boson as well. The 18.15 MeV 1^+ state in ^{8}Be was populated by the ^{7}Li(p,γ)^{8}Be reaction at bombarding proton energy of E_p=1100 keV. The typical beam current was 1.0 μA, and 700 μg/cm^2 thick Li_2O target evaporated on 10 μm thick Al backing was used. The target thickness was monitored continously during the experiment by detecting the 18.15 MeV γ-ray originated from the target. A typical γ-spectrum measured at E_p= 1100 keV is shown in Fig.9. The 18.15 MeV ($1^+ \rightarrow 0^+$ gs.) photopeak and its single and double escape peaks are clearly visible. The broad peak at 15.15 MeV correaponds to the 15.15MeV ($1^+ \rightarrow 2^+$ 3.03MeV) transition.

The energy resolution of the peaks reflects both the widths of the resonance (Γ=168 keV) and the energy loss in the target. The branching ratio of the γ-transition from the 18.15 MeV 1^+ state to the ground state and to the 2^+ is 30% and 70%, respectively [7]. The population of the ground state from this state is much less favored, then from the 17.6 MeV state.

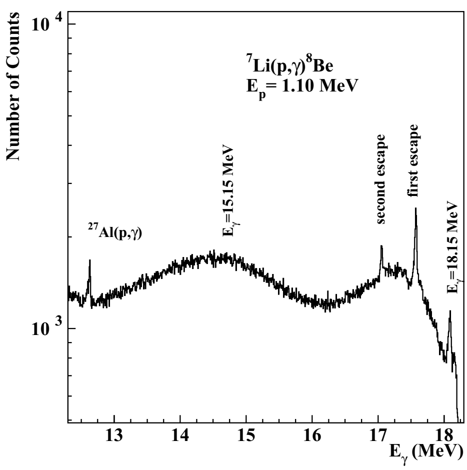

Figure 9. *A typical γ-ray spectrum (left panel) and total energy spectra of e^+e^- pairs (right panel) measured at E_p= 1100 keV.*

Figure 10 shows the e^+e^- sum energy spectrum.

Energy calibration was performed for the electron and positron energies correcting for the different energy losses in the wall of the chamber, and in the ΔE and DSSD detectors.

The 6.05 MeV ^{16}O transition was much stronger in this case, as the cross setction of the ^{19}F(p, α)^{16}O reaction is much larger at this bombarding energy than at 441 keV. We have used an energy threshold of 4 MeV for both the e^+ and e^- energies to reduce the intensity of the 6.05 MeV transition.

Another contaminant line marked by ^{27}Al is coming from the ^{27}Al(p,γ)^{28}Si reaction induced on the backing of the target.

As the branching ratio for the decay of the 18.15 MeV state was very much unfavored, for calculating the angular correlations we set a wide gate from 13 MeV to 20 MeV, covereing both the ground state transition and the transition going to the first excited state. The result is shown in Fig. 11.

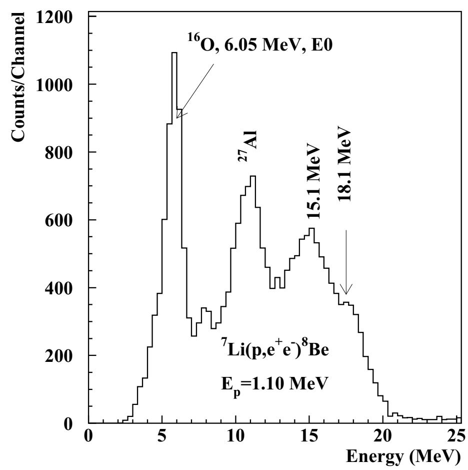

Figure 10. *Total energy spectra of e^+e^- pairs measured at E_p= 1030 keV.*

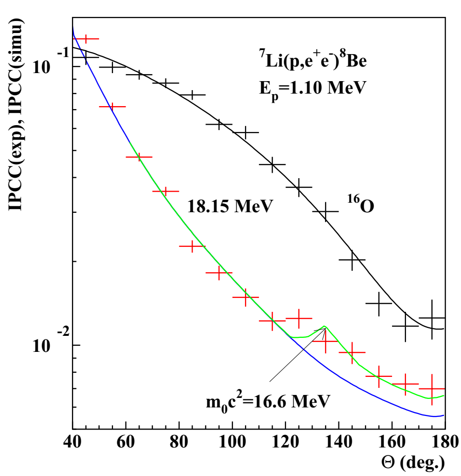

Figure 11. *Measured angular correlation of the e^+e^- pairs originated from the decay of the 18.15 MeV resonance compared with the simulated angular correlations [8] assuming M1+1.4%E1 mixed transitions (full (blue) curve).*

5 Conclusion

We have measured the e^+e^- angular correlations for the M1 transitions depopulating the 17.64 MeV and 18.15 MeV states in ^{8}Be, and observed peak-like deviations from the predicted IPC in both cases.

The peaks were located at 155° and 135° for the 17.64 MeV and 18.15 MeV transitions, respectively. The deviation between the experimental and theoretical angular correlations are significant and can be described by assuming the creation and subsequent decay of a m_0c^2=17.0 MeV boson.

To the best of our knowledge, no nuclear physics related description of such deviations can be made. The branching ratio of the e^+e^- decay of such a boson to the γ decay is less for the 17.6 MeV transition (4.0×10^{-6}), then for the 18.15 MeV one (6.8×10^{-6}), which agrees nicely with the prediction of Feng et al. [4].

6 Future plans

As a next step of the project, we plan to check the creation of the X-boson in the $0^- \rightarrow 0^+$ 21.01 MeV transition in ^{4}He. The $J^\pi = 1^+$ X boson can be emitted with L=1 angular momentum in the above transition. As the energy of the transition is considerably larger in this case, the created 17 MeV X boson would move with much larger speed, so the expected maximum of the correlation angle is much smaller ($\Theta \approx 105°$). The expected background hovewer, is considerably smaller, since the internal pair cration is forbidden for that transition.

The wide (Γ=0.84 MeV) 0^- state will be excited in the ^{3}H(p,γ)^{4}He reaction. The reaction has a very large and positive Q value (Q=19.814 MeV), so the low energy tail of the state (40% of the strength) can be excited with 1.00 MeV protons wihout creating any background as the threshold energy for the ^{3}H(p,n)^{3}He reaction is: E_{th}= 1.019 MeV. However, at this bombarding energy we excite also the first excited state of ^{4}He (E_x= 20.21 MeV, Γ=0.50 MeV), which has a J^π of 0^+ so we are expecting e^+e^- pairs from its E0-decay to the ground state by internal pair creation.

More recently, Ellwanger and Moretti made another possible explanation of the experimental results through a light pseudoscalar particle [12]. Given the quantum numbers of the ^{8}Be* and ^{8}Be states, the X boson can indeed be a $J^\pi = 0^-$ pseudoscalar particle, if it was emitted with $L = 1$ orbital momentum. We plan to study the $\gamma\gamma$-decay of the 17-MeV particle, as well in ^{4}He, in order to distinguish between the vector boson and the pseudoscalar boson scenarios. According to the Landau-Yang theorem, the decay of a vector boson by double γ emission is forbidden, however the decay of a pseudoscalar one is allowed. The angular correlation of the γ-rays will be measured by using 15 large (3"x3") $LaBr_3$ detectors. If the X boson with a mass of 17 MeV is created in the decay of the 0^- state, and also decays to two γ rays, their angular correlation should peak at an angle of:

$$\cos(\theta) = 1 - \frac{m_x^2}{2E_{\gamma_1}E_{\gamma_2}}\,, \quad (2)$$

where m_x is the mass of the X boson (17 MeV/c^2) and $E_{\gamma 1}$ and $E_{\gamma 2}$ are the energies of the γ-rays. In our case this expression gives $\theta = 105°$ for γ rays with equal energies.

7 Outlook

Current and near future experiments all over the world are looking for the X boson as well. The projected sensitivities of a few relevant experiments will be briefly discussed below.

A recent study has explored the possibility of using BES III and BaBar to probe the 17 MeV X boson [13]. They are already analyzing the data.

The DarkLight experiment use electrons scattering off a gas hydrogen target to produce dark photons, which later decay to e^+e^- pairs [14]. It is sensitive to masses in the range of 10 -100 MeV and coupling constants down to $\epsilon \geq 4x10^{-4}$, covering the majority of the allowed X boson parameter space. Phase I of the experiment is already taking data for the next 18 months, whereas phase II could run within two years after phase I.

The Mu3e experiment will look at the muon decay channel and will be sensitive to masses in the 10 MeV - 80 MeV range [15]. The first phase (2015 – 2016) probed the region $\epsilon \geq 10^{-3}$, while phase II (2018 and beyond) will extend this reach almost down to $\epsilon \geq 10^{-4}$, which will include the whole region of interest for the X boson.

A search for dark photons at LHCb experiment during Run 3 (scheduled for the years 2021 – 2023) has been proposed [16] using the charm meson decay. For dark photon masses below about 100 MeV, the experiment can explore nearly all of the remaining parameter space. In particular, it can probe the entire region relevant for the X gauge boson explaining the ^{8}Be anomaly.

An experiment for a new gauge boson search at the VEPP-3 facility at Novosibirsk was also proposed [17]. The experiment will consist of a positron beam incident on a gas hydrogen target and will look for missing mass spectra. The search will be independent of the X particle decay modes and lifetime. Its region of sensitivity extends down to $\epsilon \geq 2 \times 10^{-4}$, and includes the entire region relevant for X. Once accepted, the experiment will take 3 – 4 years.

The MESA experiment will use an electron beam incident on a gaseous target to produce dark photons of masses between 10 - 40 MeV with electron coupling as low as $\epsilon \geq 3 \times 10^{-4}$. The commissioning is scheduled for 2020.

The Heavy Photon Search experiment (HPS) is using a high-luminosity electron beam incident on a tungsten target to produce dark photons and search for their e^+e^- and $\mu^+\mu^-$ decays [19]. HPS is expected to complete its dataset by 2020.

The PADME experiment will look for new light gauge bosons resonantly produced in collisions of a positron beam with a diamond target. The collaboration aims to complete the detector assembly by the end of 2017. The expected sensitivity after one year of running is $\epsilon \geq 3x10^{-3}$, with plans to get as low as $\epsilon \geq 10^{-4}$ [20].

Acknowledgements

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