

Dark decay channel analysis ($n \rightarrow \chi + e^+ e^-$) with the PERKEO II experiment

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Abstract. Discrepancies from beam and bottle type experiments measuring the neutron lifetime are on the 4σ level. In recent publications Fornal and Grinstein proposed that the puzzle could be solved if the neutron would decay on the one percent level via a dark decay mode [1], one possible branch being $n \rightarrow \chi + e^+ e^-$. With data from the PERKEO II experiment we set limits on the branching fraction and exclude a one percent contribution for 96% of the allowed mass range for the dark matter particle. With this publication, we give a detailed description of the experiment and some selected details of the analysis.

1. Introduction

Measurements of the neutron lifetime fall into two categories: the storage and the beta decay method [2]. Whereas the storage method measures the inclusive lifetime, the beta decay method (often called beam method) detects the partial lifetime for decay into a particular channel. The present 4σ discrepancy between the two results led Fornal and Grinstein [1, 3, 4] to propose different decay channels of the neutron involving a dark matter particle with no proton in the final state. These branches would have been missed by the most precise beta decay method experiments which have detected decay protons. Experimental constraints on the dark matter interpretation of the neutron decay anomaly have been set on two decay branches. A recent experiment at Los Alamos National Lab [5] excludes the proposed decay channel $n \rightarrow \chi + \gamma$ as sole explanation of the lifetime discrepancy with 97% C.L. via a direct search for a monoenergetic γ line. Another decay channel, $n \rightarrow \chi + e^+ e^-$, has been searched for by the UCNA collaboration [6]. For this decay channel, the sum of the kinetic energies of the positron and electron $E_{e^+e^-} = E_{e^+} + E_{e^-}$ is restricted to the range of 0 – 644 keV, corresponding to a dark matter mass range of between 937.900 MeV and 938.543 MeV. The UCNA collaboration sets limits on this branching fraction of $< 10^{-4}$ (90% C.L.) in the energy range $100 \text{ keV} < E_{e^+e^-} < 644 \text{ keV}$ which excludes this channel as only explanation for the lifetime discrepancy at the 5σ level [6].

2. PERKEO II

With this publication we present details on the investigation of the channel $n \rightarrow \chi + e^+ e^-$ from data taken by the PERKEO II instrument, which was installed at the

PF1B cold neutron beam position [7, 8] at the Institut Laue-Langevin (ILL). The results of this investigation can be found in [9]; in the present paper we concentrate on the gamma sensitivity of the scintillators and the determination of the statistical sensitivity of the method used in [9].

A drawing of the experimental set-up is shown in Fig. 1, a more detailed description of the PERKEO II spectrometer together with measurements of beta decay correlation coefficients can be found in [10–16]. For the investigation of a dark decay of the neutron into an $e^+ e^-$ -pair, we have reanalyzed the data that was used to extract the beta asymmetry parameter A of Ref. [10]. In that set-up the spectrometer is configured for electron detection only. The electrons are transported from the decay volume towards the detectors by a magnetic field of approximately 1 T. Aside from backscatter events normal beta decay electrons will reach only one detector, while $e^+ e^-$ -pairs will trigger both detectors, if emitted towards opposite detectors.

3. Positron detection

For the electron detection we used two plastic scintillators each read out by four fine mesh photomultiplier tubes (PMTs). The integrated pulse size of this detection system is largely proportional to the incident kinetic energy of a single electron or positron. Since the detector characteristics for positrons were so far unknown, we installed a test set-up using a ^{22}Na source. The main investigation was related to the question whether or not the energy of annihilation gammas would be deposited in the detector. The Bicron 404 scintillator in use is by its composition designed for low gamma acceptance. Furthermore, we have used scintillators with a thickness of 5 mm. In Fig. 2, we show the measured ^{22}Na spectrum. The endpoint of the positron beta spectrum is expected at 546 keV. For the energy calibration we used a ^{207}Bi source. When the detector is triggered, a gate generator

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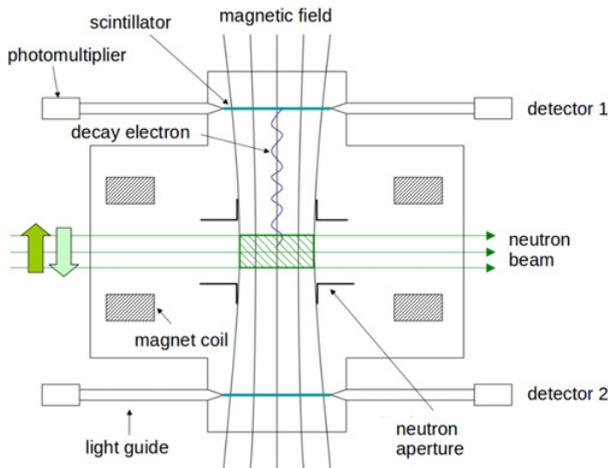


Figure 1. Drawing of the PERKEO II spectrometer. A magnetic field of about 1 T transports decay electrons to the detectors. Besides backscatter events normal beta decay electrons will reach only one detector, while e^+e^- -pairs will trigger both detectors, if emitted towards opposite detectors.

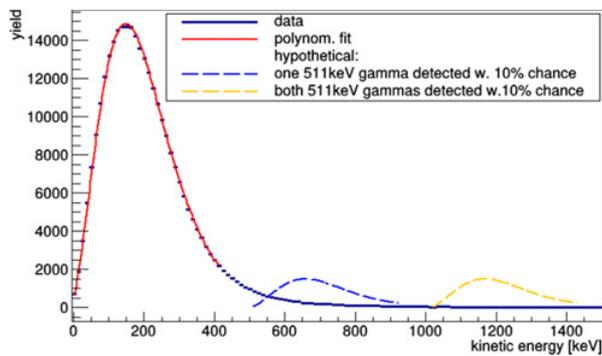


Figure 2. Measurement of a ^{22}Na positron spectrum in a test set-up with a detector similar to the PERKEO II detector. The detection probability of a positron annihilation gamma with its full energy of 511 keV is excluded to be larger than 1%.

is creating a time window for the energy integration of the analog to digital converters (ADCs). The time window is much larger than the expected time between the deposition of the kinetic energy of the positron and the annihilation process. Therefore, a significant probability of full-energy deposition of an annihilation gamma would lead to additional beta spectra shifted by 511 keV or 1022 keV. In Fig. 2 we show hypothetical contributions to the spectrum, if the full energy of one or two annihilation gammas would be detected with a 10% chance. By fitting, we get an upper limit on the full energy detection probability for one gamma of 1%.

This test measurement was performed with a single plastic scintillator without backscatter detector and in a different magnetic field configuration than used during the PERKEO II data taking, resulting in different systematics. Therefore we have investigated low energy contributions by performing GEANT4 [17] simulations. For this purpose we simulated the energy deposition of 511 keV gammas in a plastic scintillator. The overall probability for a 511 keV photon to deposit energy in the scintillator varies between 10% and 20% depending on the starting position. The probability to deposit energy is higher if the annihilation process takes place on the surface of the scintillator. In

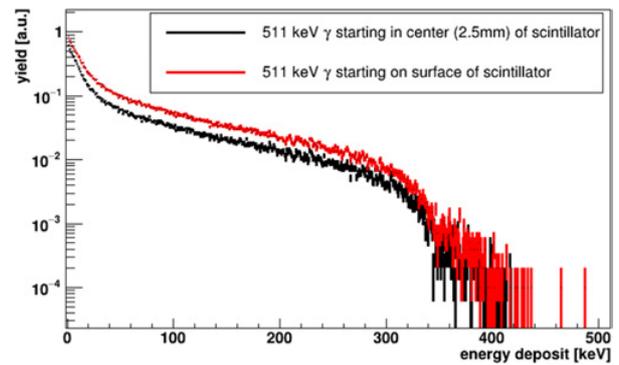


Figure 3. Simulation of the energy deposition of a single 511 keV gamma in a plastic scintillator for a gamma starting in 2.5 mm depth and on the surface of the scintillator. The scintillator is 5 mm thick and its size is $160 \times 440 \text{ mm}^2$. The starting directions of the gammas are evenly distributed. 80% to 90% of the gammas (depending on the starting position) will not interact with the scintillator material.

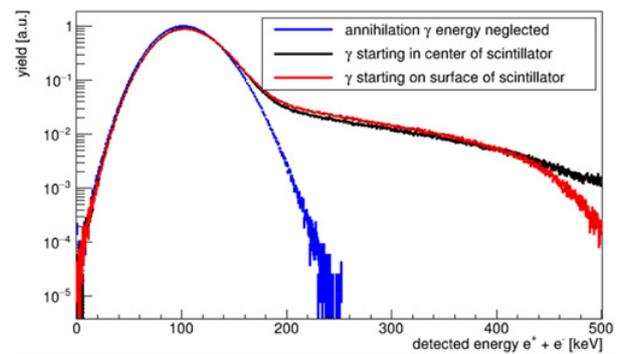


Figure 4. Computation of the effect of the energy deposition of annihilation gammas on a dark matter signal at 100 keV (sum of kinetic energy of electron and positron). Plotted is the total detected energy for two positions. Neglecting the gamma energies (blue line) the dark decay signal is underestimated by about 10%.

this case the gammas emitted towards the detector pass more detector material than gammas starting in the center in 2.5 mm depth. This even compensates for the effect that half of the gammas are lost since they immediately leave the detector. In Fig. 3 we show the resulting distribution of energy deposition for a single 511 keV gamma starting in 2.5 mm depth of the scintillator and a gamma starting on the surface of the scintillator. In general we see that most gammas deposit only a small fraction of their initial energy, the dominant process being Compton scattering.

Finally we investigate the effect on the dark matter signal that we are interested in. More detailed information on the signal cut can be found in the next section. In general we consider the sum of energies that the electron and the positron of a dark decay deposit in our detectors. For the electron this is only kinetic energy. For the positron however, it is kinetic energy plus the energy deposited by the two annihilation gammas. Using the results of the simulations and the fact that the annihilation gammas will be emitted towards opposite directions due to momentum conservation, we compute the effect on the expected signal. In Fig. 4 we show the effect on a signal where the kinetic energies of the e^- and the e^+ sum up to 100 keV.

We show this for the case that all positrons annihilate in the center of the scintillator and for the case that all positrons annihilate at the edge of the scintillator to emphasize the weak spatial dependency. Neglecting the energy deposition of annihilation gammas we would underestimate the dark matter contribution by approximately 10%.

4. Backscattering and dark matter search

About 8% of the electrons hitting on one of the detectors are scattered back and deposit only part of their energy. However, in PERKEO II such electrons will be guided along a magnetic field line and either reflected back by the increasing magnetic field to this detector or transported to the other detector and will, a few nanoseconds later, deposit their remaining energy there. In this way, the total kinetic energy can also be reconstructed for backscattered electrons. Details on the electron backscatter suppression can be found in [18]. The search for the proposed dark matter signal has been done in the following way: by requiring that both detectors have triggered, most of the conventional beta decay events are rejected. For the remaining events, the spectrum of the total energy deposited in the two detectors is calculated. It is composed of conventional beta decay events with electron backscattering, background events that trigger both detectors, and of hypothetical e^+e^- events. Background events contribute with 2% to the spectrum and were measured regularly with the neutron beam closed and subtracted from the data. We do not observe any relevant contribution of cosmic background after background subtraction. This signal would be partly present at energies above the beta spectrum at about 1 MeV. The e^+e^- pairs are monoenergetic and would create a characteristic peak in the backscattering spectrum, in the range from 0 keV to 644 keV depending on the mass of the hypothetical dark matter particle. The expected backscattering spectrum from conventional beta decay, which is the remaining background in the search for the hypothetical e^+e^- peak, has been determined by GEANT4 simulations. A large study on the low energy limitations of electron backscatter simulations with GEANT4 has been performed in [19]. Based on these results, we decided to use the single Coulomb scattering model and derived the model related uncertainty on our analysis. Details on the simulation and on detector systematics like energy resolution, non-linearity and the detector trigger function are presented in [9]. In Fig. 5 we show the experimental spectrum after background subtraction together with a fit using the results of the GEANT4 simulations. For illustration of the signature of the hypothetical e^+e^- peak we show the expected shape of the spectrum for a 1% branching to $\chi + e^+e^-$ for e^+e^- energies of 30 keV, 50 keV, 80 keV, and 400 keV. We scan the spectrum by shifting a hypothetical peak in steps of one channel of the analog to digital converter (ADC), which corresponds to approximately 6 keV, performing a fit at each position. The parameters of the effective trigger function as well as the height of the e^+e^- peak are free parameters of the fit as described in [9].

The phase space of e^+e^- pairs in the proposed dark decay has been computed in [20]. Under the assumption

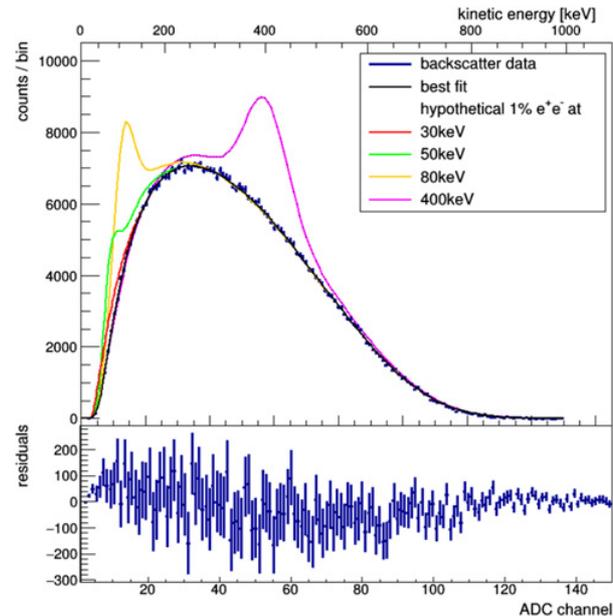


Figure 5. Reanalysis of events of electrons backscattered from the PERKEO II detector system in a measurement of the beta correlation coefficient A and a search for an additional hypothetical dark matter e^+e^- signal. Shown is a fit to the spectrum (with the residuals in the lower graph) and the expected spectra for a hypothetical 1% e^+e^- branch at 30 keV, 50 keV, 80 keV, and 400 keV. The backscatter signal makes up approximately 4% of the total beta decay events.

of a parity conserving dark decay, the probability that the electron and positron are emitted towards opposite detectors is approximately 50%.

5. Statistical sensitivity

As explained in the previous sections, we search for an additional peak in the beta spectrum with a priori unknown energy. For the correct determination of the statistical uncertainty one has to consider the “Look-Elsewhere-Effect” [21]. This effect accounts for the significance of observing a local excess of events, i.e. a dark matter signal somewhere in a possible mass range when we take into account the probability of observing such an excess anywhere in the range. The 5σ tail probability was computed by performing 2.9×10^7 Monte Carlo simulations of the beta spectrum with the same number of events generated as had been measured. This corresponds to the null hypothesis H_0 . Then we fit the simulated data with the test hypothesis H_1 which includes the model for the beta spectrum and an additional dark matter signal. The size of the dark matter contribution is a free parameter of the fit. The dark matter mass is scanned as explained in the previous section. The maximum excitation one observes in 2.9×10^7 Monte Carlo data sets is used as 5σ statistical uncertainty [22]. In Fig. 6 we show one out of the 2.9×10^7 simulations together with the the statistical uncertainties obtained from all simulations. In regions, where the fit to the amplitude of the dark matter signal has a negative outcome, we renormalize the tail probabilities in the positive range and take a 90% / 5σ cut.

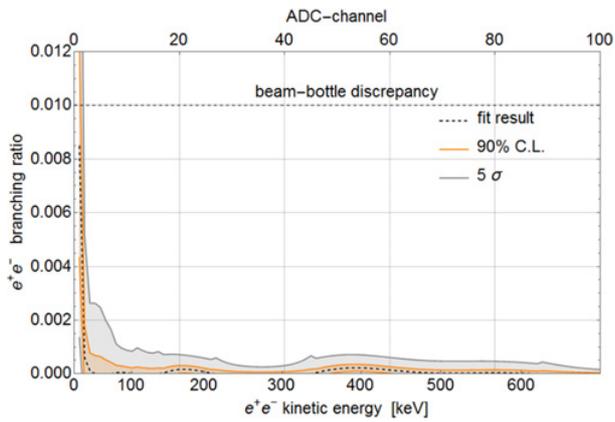


Figure 6. One out of 2.9×10^7 Monte-Carlo simulations used to determine the “Look-Elsewhere-Effect”. The strongest excitation extracted from the 2.9×10^7 simulated data sets is used as 5σ statistical uncertainty.

6. Summary

We analyzed PERKEO II data to set limits on the proposed dark decay branch $n \rightarrow \chi + e^+e^-$. With measurements presented in this publication we show that the detector in use is sensitive to the kinetic energy of positrons. By performing simulations with GEANT4 we could show that the probability to detect annihilation gammas is approximately 10% but that the detected energy is much smaller than 511 keV in most cases and that the spectrum does not show any structure. Furthermore we presented Monte-Carlo simulations used to determine the “Look-Elsewhere-Effect”. The results of analysis will be published in [9].

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