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Low energy recoil detection with a spherical proportional counter

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ABSTRACT

We present results for the detection of low energy nuclear recoils in the keV energy region, from measurements performed with the Spherical Proportional Counter (SPC). An ^{241}Am-^{9}Be fast neutron source is used in order to obtain neutron–nucleus elastic scattering events inside the gaseous volume of the detector. The detector performance in the keV energy region was measured by observing the 5.9 keV line of a ^{55}Fe X-ray source, with energy resolution of 10% (σ). The toolkit GEANT4 was used to simulate the irradiation of the detector by an ^{241}Am-^{9}Be source, while SRIM was used to calculate the Ionization Quenching Factor (IQF), the simulation results are compared with the measurements. The potential of the SPC in low energy recoil detection makes the detector a good candidate for a wide range of applications, including Supernova or reactor neutrino detection and Dark Matter (WIMP) searches (via coherent elastic scattering).

1. Introduction

The detection of very low energy nuclear recoils is essential to the field of direct neutrino detection and of direct dark matter searches. During the last years the dark matter hunt is continued with increasing rate. Weakly Interacting Massive Particles (WIMPs) are an eminent candidate for Dark Matter (DM). A common way of search for this type of particles relies on the elastic scattering of WIMPs on the target nuclei. The recoil energy is expected to be in the keV (or less) energy range, for WIMPs with a mass lower than 10 GeV. Another important field of searches concomitant to that of DM searches [1] (being also a background source to them), is the direct detection of low energy neutrinos (1 MeV – 100 MeV). Supernova neutrinos, solar, geoneutrinos and reactor neutrinos all belong to this category. The Standard Model neutrino–nucleon interaction was proposed years ago and it is gaining in popularity lately because of the large cross section it provides through the coherence effect, where all nucleons contribute to the scattering (especially the neutrons), resulting in a cross section increased by the neutron number squared. Again the detection of these neutrinos relies on the observation of the recoiling nuclei in the keV energy range and depending on the neutrino source, observing recoils of a few hundred eV (reactor neutrinos for example [2,3]). These applications require a detector with a very low detection energy threshold ($\sim$ 100 eV). We propose the utilization of the SPC, a spherical gaseous detector recently developed by Giomataris et al. [4], for applications with such requirements. In this work, we present the capability of the SPC in the detection of low energy nuclear recoils (keV — 150 keV energy region), as well as the simulated detector response to low energy recoils, taking into account the effect of the Ionization Quenching Factor (IQF) [5] by using GEANT4 [6] and SRIM [7].

2. The spherical proportional counter

The detector consists of a spherical vessel which is grounded and filled with a gas mixture (up to 5 bar pressure). The anode which consists of a small ball (usually made from a metallic or a resistive material) is placed in the center of the vessel and supported by a grounded metallic rod, through which the high voltage is applied. Thus the electric field is varying with the reverse of the distance squared ($1/r^2$) and it is highly inhomogeneous along the radius. The difference in the intensity of the electric field, from the outer to the inner radii, divides the detector volume into two regions, the drift and the amplification region (Fig. 1). Primary ionization electrons in the drift region, drift towards the anode (the drift time varies from μs to ms depending on the gas mixture and pressure). When these electrons reach a distance of a few mm from the anode, the avalanche starts due to the intense electric field. The pulse shape of the signal depends on the charge spatial density distribution and the distance of the interaction from the anode. The main advantages of this detector, for low energy recoil detection (either neutrino or WIMP

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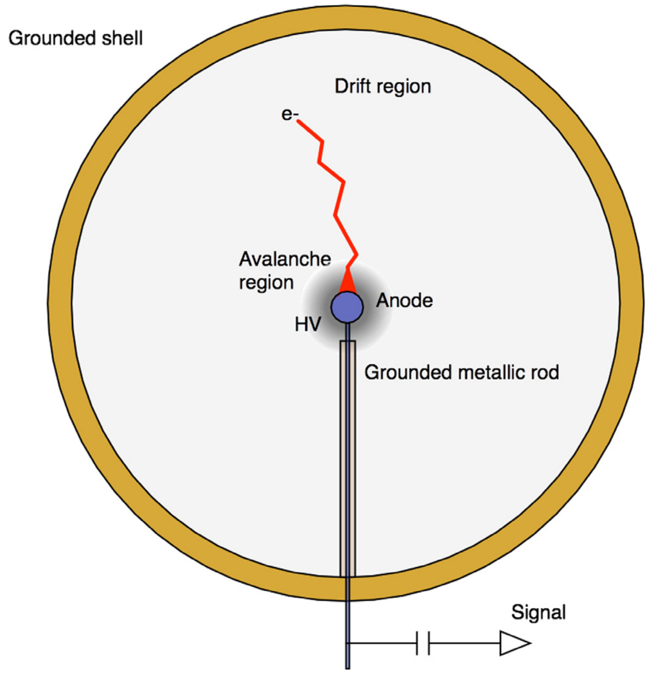

Fig. 1. A schematic of the spherical proportional counter and the detection principle.

induced recoils), are the simple design, the large volumes achievable, the energy resolution in the low energy region (< 10% at 5.9 keV) [8,9] and the low electronic noise provided by the low capacitance due to the spherical geometry [10] (even for large detector sizes). The low energy threshold of the detector is limited only by the mean ionization energy of the gas mixture [8]. The detection range varies from a few eV to tenths of MeV, depending on the amplification field, allowing detection of low energy gammas, electrons, alpha particles and heavy ions. Lastly, the fiducialization capability of the detector [11] allows us to distinguish point like energy depositions (low energy gammas, low energy electrons, heavy ions) from spatially extended depositions (muons) through pulse shape analysis. A complete description of the SPC (principle of detection, characteristics and capabilities) can be found at [4].

3. Experimental setup and low energy calibration

A SPC placed at the Aristotle University of Thessaloniki, was used for this study. The spherical vessel of the detector is 40 cm in diameter and made from 1.5 cm thick Duran 2.3 glass (coated with a graphite layer for electric conduction). The anode in the center of the cavity is metallic and 2 mm in diameter. The electronics used during these measurements were the CANBERRA 2006 charge sensitive preamplifier (50 μs fall time) and an Amplitude to Digital Converter used to readout the output of the preamplifier and to digitize the pulses, which were then registered to a computer memory. The vessel was filled with Ar:CH_4 (98 : 2) gas mixture at pressure up to 500 mbar. The low energy calibration of the detector was performed using a ^{55}Fe source (5.9 keV), the fluorescence lines of ^{27}Al (1.45 keV) [9] and ^{241}Am (13.95 keV, 17.7 keV) [12]. To test the response of the detectors to neutrinos or WIMPs, nuclear recoils have to be produced, for this reason the detectors were exposed to an ^{241}Am-^{9}Be source with an activity of 5.94×10^4 neutrons per second. The ^{241}Am-^{9}Be source also emits gamma rays, the most important line being the 4.44 MeV line from the deexcitation of the ^{12}C* nucleus produced from the Be(α, n) reaction [13]. The intensity of this line is directly related to the neutron intensity with a ratio $R = S_g/S_n = 0.591 \pm\ 2.6\%$ [14]. The source was placed 15 cm away from the surface of the detector. To prevent gamma ray contamination, it was cased inside a lead castle of 12 cm thickness along the axis (Fig. 2).

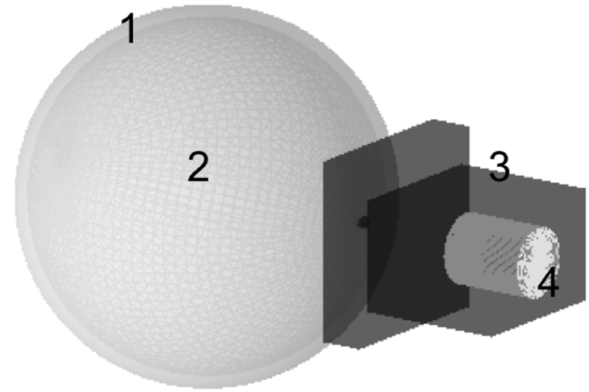

Fig. 2. A schematic of the detector setup: (1) The detector vessel, (2) The gaseous volume, (3) The lead shielding and (4) The source case.

4. Results — pulse shape analysis

To attain the results presented below, the detector was filled with Ar:CH_4 (98 : 2) at 500 mbar and was irradiated by the ^{241}Am-^{9}Be source (for a period of 3600 s); due to cosmic radiation (ie atmospheric muons [15] and neutrons) and natural radioactivity from the surrounding walls (ie ^{40}K, ^{238}U and ^{232}Th daughter isotopes) the background contribution had to be measured (also for a period of 3600 s), in order to be subtracted from the recorded signal. The data acquired during the measurements were analyzed using Pulse Shape Analysis (PSA). The parameters used in the analysis were (a) the pulse height, which is used to estimate the energy deposition of an event, (b) the pulse rise time, which is the time interval between 10% and 90% of pulse height, (c) the Full Width at Half Maximum (FWHM) of the pulse and (d) the number of "peaks" or local maxima in a pulse, which is calculated from the number of zero crossings of the pulse derivative. The pulse rise time and width correspond to the dispersion of the primary electron drift time (time interval between their production and their arrival to the anode under the influence of the electric field). Figs. 3–5 show the results of the analysis without any pulse shape cuts. The data acquisition threshold set corresponds to an ∼ 2 keV energy detection threshold. The atmospheric muon contribution to the energy deposition spectra is visible at Fig. 3 (top diagram) as a "peak" with energy around 20 keV.

Particles with enough energy to cross the whole length of the detector such as atmospheric muons and energetic electrons deposit energy all along their lengthy track (∼ tenths of cm). They can also produce delta rays energetic enough to ionize further at a distance from the primary track, creating ionization clusters with large charge density. This kind of "behavior" is translated to pulses with higher width than punctual energy depositions (Fig. 6(a)), which may contain multiple peaks (due to variations in drift time and in spatial ionization density), as for example the pulse presented in Fig. 6(b).

The muon contribution can be minimized by rejecting events outside specific pulse width and pulse rise time intervals and also rejecting events with multiple peaks. These rejection intervals can be determined by looking at the calibration measurements, as for example the width versus energy deposition and rise time versus energy deposition plots of Figs. 7 and 8 which correspond to the calibration measurements with a 5.9 keV ^{55}Fe X-ray source. Utilizing the information provided by the analysis of the calibration measurements, one can infer that events with width outside the 50 μs and 70 μs interval, pulse rise time outside the 11 μs and 21 μs interval and with multiples peaks should be rejected. A comparison between the pulse height spectra before and after the pulse shape cuts is presented in Fig. 9. Events corresponding to extended energy depositions (compared to the short ranged events of the 5.9 keV electron events of the ^{55}Fe X-ray line) are rejected while retaining more than 85% of the measured X-ray line. The results after performing the pulse shape cuts to ^{241}Am-^{9}Be run data and the background run data are presented in Figs. 10–12.