Low energy investigations and applications with the spherical TPC

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Abstract. The Spherical Proportional Counter, recently developed, allows to instrument large target masses with good energy resolution and low energy threshold. Ultra low energy results are shown here, leading to an energy threshold as low as 25 eV and a single electron detection sensitivity. The bench mark result is the observation of a well resolved peak at 270 eV due to carbon fluorescence, which is a unique performance for such large massive detector. This very promising feature can fulfill the demands of many challenging projects from dark matter detection to low energy neutrino searches. Details of this study are given in reference [1].

1. Introduction

The development of massive detectors, having a low energy threshold and low noise, remains generally a daunting challenge for present-day and future low-background experiments. The search for WIMP (Weakly Interacting Massive Particles) dark matter is under intense development and relies on the detection of low energy (keV scale) recoils produced by the elastic interaction of WIMP's with the nuclei of the detector [2-5]. The need to go to very low energies may become even more crucial, if the WIMP's turn out to be very light [6], since then, the energy transfer to the nucleus is expected to be smaller. New generation of directional detection of dark matter is under development to perhaps allow for an unambiguous observation even in the presence of backgrounds by observing directional anisotropy of the recoils [7-10].

The question of detecting and exploiting neutrinos from both terrestrial and extra terrestrial sources has become central to physics and astrophysics. Coherent neutrino-nucleus scattering is a famous but as yet untested prediction of the Standard Model [11,12]. The process is mediated by neutral currents (NC), and hence is flavor-blind. Despite having relatively high rates, neutrino-nucleus scattering is difficult to observe because its only signature is a small nuclear recoil of energy ~ keV (for MeV neutrinos). The nucleon energy (T_N) depends on the neutrino energy (E_ν) and the scattering angle (θ).

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In the laboratory frame (forward scattering) and for sufficiently small energies, the recoil energy of the nucleon can be approximated as follows [13]:

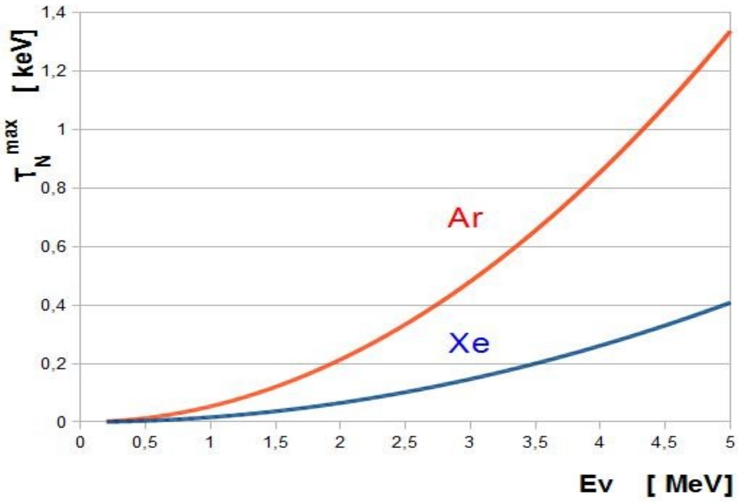

Figure 1. The maximum recoil energy T_N^{max} as a function of the neutrino energy Eν for Ar and Xe respectively (from top to bottom)

$$T_N \approx \frac{2\left(E_\nu cos\theta\right)^2}{m_N} \qquad (1)$$

The maximum recoil energy T_N^{max} as a function of the neutrino energy (Eν) for Ar and Xe as a target nucleus is shown in Figure 1. For a typical neutrino energy of 2 MeV (expected at nuclear reactors) the maximum recoil energy is ~ 66 eV for Xe and ~ 215 eV for Ar. Because the neutrino is light, the nuclear recoil energy is extremely small leading to a signal below threshold for conventional solid or liquid state detectors. Thus, the challenge is to achieve a very low energy threshold (typically below 100 eV).

Several other cases that require a low energy threshold like Supernova neutrinos, the OAK Ridge neutron spallation source, reactor neutrinos, geoneutrinos are discussed in [1]. Ultra low-noise germanium detectors with sub-keV energy capability have been recently developed and are operating at underground laboratories [14,15]. The small excess observed around 1 keV needs to be clarified and verified by detectors having a lower energy threshold.

Now we will report results at low energy obtained by using the novel Spherical Proportional Counter (SPC) which has been recently developed.

2. Detector description

The detector consists of a large spherical copper vessel 1.3 m in diameter and a small metallic ball 16 mm in diameter located at the center of the drift vessel, which is the proportional counter. The ball is maintained in the center of the sphere by a stainless steel rod and is set at high voltage. A second electrode (umbrella-shaped) that is placed 24 mm away from the ball along the rod, is powered with an independent but lower high voltage, serving as electric field corrector. The detector operates in a seal mode: the spherical vessel is first pumped out and then filled with an appropriate gas at a pressure from few tens of mbar up to 5 bar. Electrons originating from ionization of the gas in the volume drift to the region of the central ball where the intense electric field allows gas amplification to occur. The produced signal is amplified through a charge amplifier and a shaper and is read-out by a 14 bit ADC. Detailed description of the detector, its electronics, its operation and its performance could be found in references [16,17,18]. In a previous paper [18] we reported results obtained at higher energy and we pointed out the excellent energy resolution obtained with radon nuclide and its daughters. In this work we will focus our studies to detect very-low energy gamma or *X*-rays emitted by radioactive sources or fluorescence process.

3. Low energy calibration and results

3.1. *Results with radioactive sources and fluorescence X-rays*

For this study (a detailed description can be found in [1]) we are using a gas filling of Argon with 2% admixture of CH_4 at various pressures. The pressure (*P*), the high voltage of the ball (*HV1*), the high voltage of the umbrella field corrector (*HV2*) and the gain (*G*) of the amplifier-shaper in all measurements in the section, are written on each of the following figures.

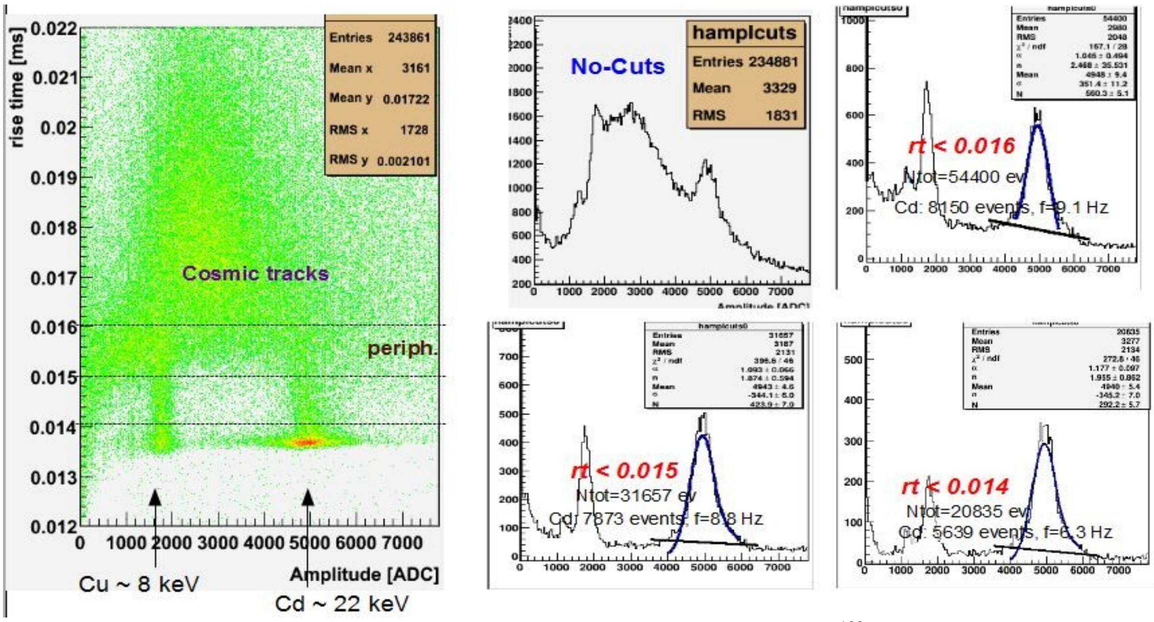

Figure 2. The rise time (rt) versus the amplitude (in ADC) of the ^{109}Cd source and the energy spectrum with the energy lines of 8 and 22 keV respectively, for various cuts in rise time (P = 107 mb, HV1 = 2520 V, HV2 = 1036 V, G = 20).

Calibration of the counter was initially performed using a ^{109}Cd source by irradiating the gaseous volume through a thin 200 μm aluminum window. By applying a pulse shape cut (rejecting long rise time pulses >0.014 ms) we keep 70% of signal in Cd but the effect on the background is spectacular as it is shown in Figure 2. The expected background from cosmic tracks is highly reduced and the energy spectrum with the 22 keV line from the ^{109}Cd source and the 8 keV line, which is an induced fluorescence at the copper vessel, provides a satisfactory energy resolution of 6% and 9% (FWHM) respectively.

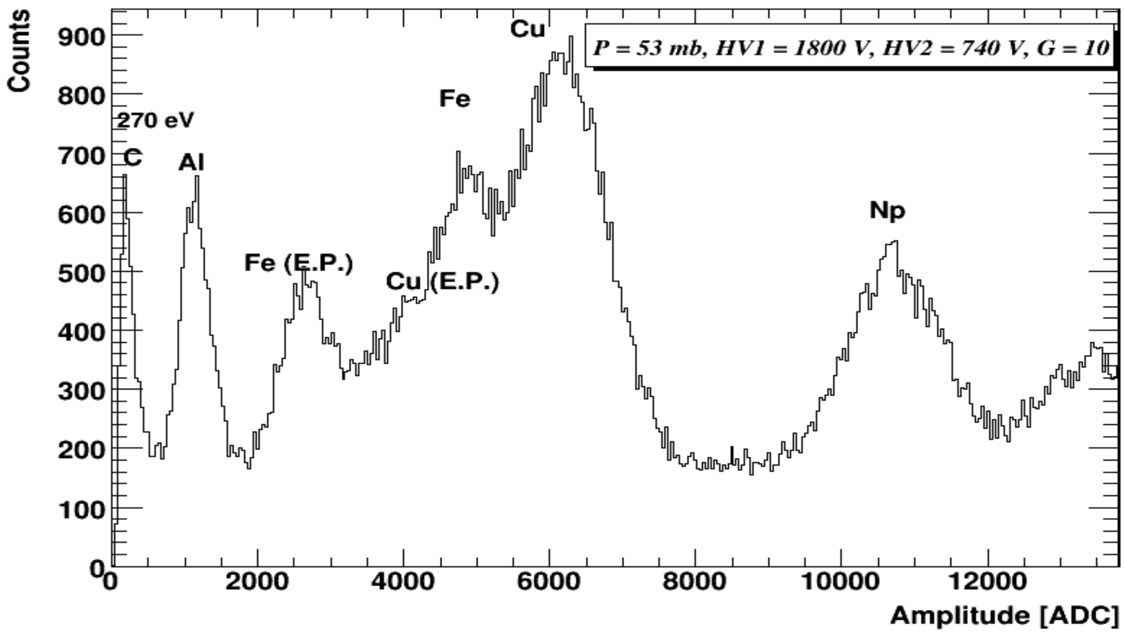

Figure 3. Peaks observed from the ^{241}Am radioactive source through aluminium and polypropylene foil. On the left the Carbon (270 eV) peak is shown, followed by the Aluminium peak (1.45 keV), the escape peak (E.P.) of Iron in Argon (3.3 keV), the escape peak of Copper in Argon (5 keV), the Iron peak (6.4 keV), the Copper peak (8 keV) and the Neptunium peak (13.93 keV) .

Gamma fluorescence is adequate for producing fluorescence lines in the range above several keVas the Cu line at 8 keV. However, it is very difficult to produce low energy calibration lines below a few keV. In order to create lower energy *X*-rays we have used an ^{241}Am source, which decays by the following process: ^{241}Am $\rightarrow$(^{237}Np)* + ^{4}He + 5.6 MeV. The ^{237}Np nucleus then decays into a lower energy state by emitting a 59.537 keV gamma ray and other L rays , which are used to fluoresce the elements. The source was evaporated to a stainless steel holder and attached to the sensor rod at middle distance; the source then is covered by thin foils with minimal thickness to totally absorb the 5.6 MeV alpha emitted, leaving only gamma rays and fluorescence induced *X*-rays to pass into the gas volume. Covering the source with a 20 μm thick aluminum foil we were able to fluoresce the K *X*-rays ranging from Aluminum whose K electron has a binding energy of 1.56 keV, to Cu whose K electron has a binding energy of 8.98 keV. In order to obtain even lower energy calibration lines we replaced the aluminum foil by a thinner 10 μm one and we attached a 20 μm polypropylene foil. Therefore, the alpha particle that is crossing the aluminum foil, is fully absorbed by the polypropylene foil and induces both aluminum and carbon fluorescence as shown in Figure 3.

High gain combined with low electronic noise can provide energy thresholds clearly below 100 eV. Figure 4 shows the energy spectra at two different gains of the amplifier when no source is used. By applying a cut at the rise time of the signal (which actually provides the depth of the ionized electrons produced in the gas) we can exclude the signal induced by cosmic rays and measure only the Copper energy line of 8 keV (plotted with dashed line in Figure 4). Then, by increasing the gain of the amplifier 20 times (from Gain = 10 to Gain = 200), we keep in the ADC acceptance only the ultra low energy region (plotted with full line in Figure 4). The value of 1000 ADC corresponds to ~ 150 eV and the peak at ~ 50 eV is compatible with single electrons (see section 3.2). Thus, the detection threshold of the Spherical Proportional Counter is as low as 25 eV. The exponential shape of the spectrum has to be confirmed by underground measurements in the LSM laboratory, which are on-going. Preliminary results are shown in Figure 5, where the rise time versus the amplitude is plotted. The 8 keV line from Copper is clearly still present and can be used to calibrate the detector at low energies.

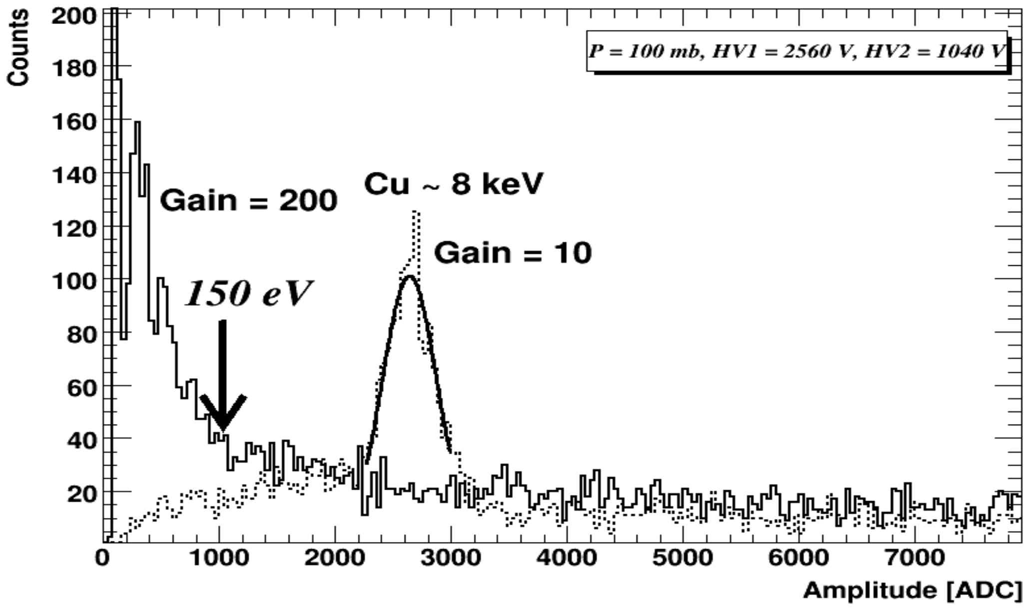

Figure 4. The energy spectrum at Gain = 10 with the Copper peak of 8 keV (dashed line) and at Gain = 200 where the single electron peak at ~ 50 eV is clearly visible (full line).

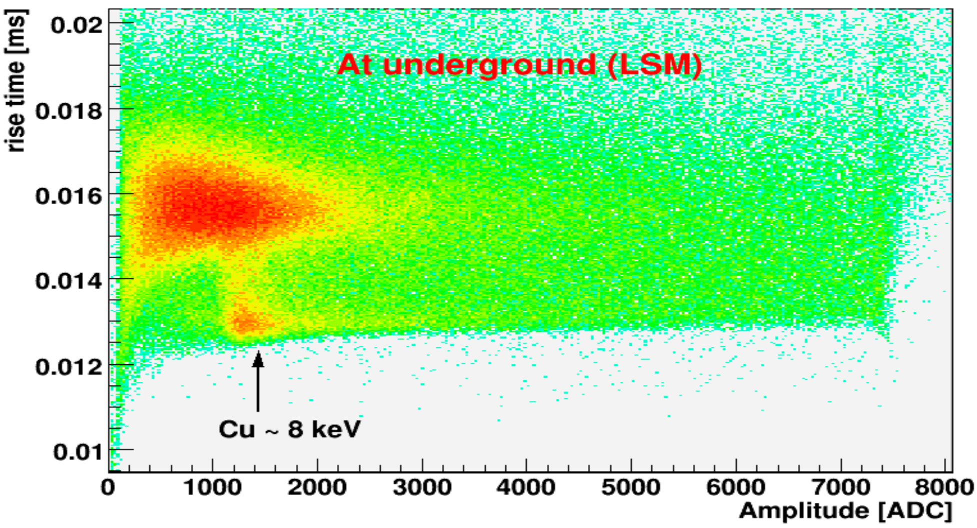

Figure 5. The rise time versus amplitude without source, taken at underground (P = 57 mb, HV1 = 1750 V, HV2 = 713 V at LSM).

3.2. *Results using a UV flash lamp*

A UV window made by MgF_2 crystal was installed in one of the sphere openings. A hydrogen relaxation flash lamp has been used to produce UV photons in the far ultra violet range. The discharge is also producing a fast signal which is observed through a capacitor and after adequate attenuation can be used as a fast trigger. For the present study, all results have been obtained without trigger. Photons are crossing the UV entrance window and hitting copper of the internal vessel producing photoelectrons by photoelectric effect. Electrons are being extracted and drifting through the radial field to the central ball where they are amplified and collected.

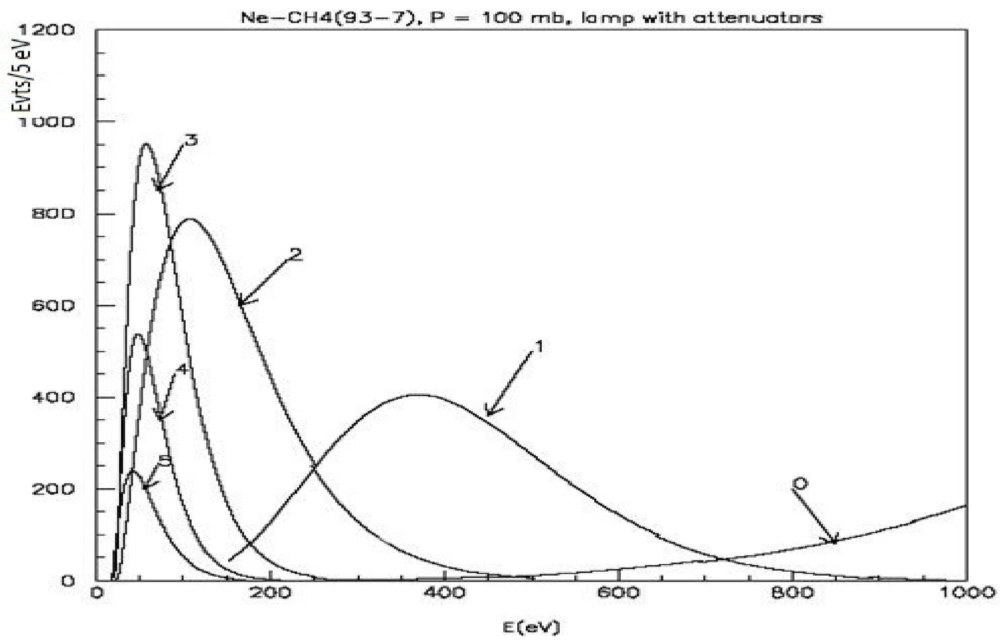

Figure 6. Fitted energy spectrum for several attenuators.

The energy calibration has been done using the 22 keV photon *X* decay of ^{109}Cd source and the 8 keV Cu fluorescence. The UV light flux of the lamp was adjusted by introducing adequate light attenuators down to the single photo-electron extraction on the Copper. The subtraction of the amplitude spectrum of the sample lamp -off from that of lamp -on suppresses the huge background due to cosmic rays. The gas used was a mixture of Ne with 7% CH_4 at a pressure of 100 mbar (the complete study can be found in [1]).

The lamp light was then gradually attenuated by 1,2, up to 5 identical attenuators. Each distribution is well fitted by a Polya function with an offset. With less than 3 attenuators, the number of events is stable, which means for those sample all the flashes are detected with a mean frequency close to 45 Hz. In fact the probability not to detect the flash is very low, 2.5% with 2 attenuators. It is compatible with the probability to get zero in the Poisson distribution with a mean value close to the number of photoelectrons per detected flash given by the fit. With more attenuators the mean frequency of detected flashes is decreasing because the probability of producing zero photoelectrons per flash is increasing exponentially. The mean number of extracted electron per flash decrease exponentially with a reduction factor close to 3 as expected, even with a large number of attenuators, pointing to a negligible inefficiency to detect the single photelectrons. The various distributions for all used attenuators are shown in Figure 5. We observe a decrease of the mean value of each distribution up to about 3 attenuators. After that the mean value is not decreasing any more assuring we are at the single electron level (the number of photoelectrons per detected flash given by the fit decreases asymptotically to one as expected) .

4. Future developments and applications

The spherical proportional counter can be applied for low-background experiments, which require a low energy threshold. An example is the detection of the coherent neutrino-nucleus scattering producing sub keV ion recoils. A spherical detector of radius 4 m and employing Xe gas at a pressure of 10 Atm will detect about 1000 events for a typical supernova explosion at 10 kpc [19]. A world wide network of several such simple, stable and low cost supernova detectors is proposed.

It is also important to study the behavior of this spherical proportional counter using well known terrestrial neutrino sources. One such source is Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory [20] that provides an excellent opportunity to employ and test this new detector [21].

For underground tests another similar detector of 1.3 m in diameter has been installed in the LSM laboratory in Modane (Frejus) under 1700 m of rock (4800 meters water equivalent) providing protection from cosmic rays. Comparisons between measurements in the sub-keV energy region taken with both detectors are carried out in order to understand the background level and optimize the detector in terms of sensitivity and noise background. The development of a new spherical prototype 70 cm in diameter made of low radioactivity materials is in progress and will be installed in the LSM laboratory. By using a mixture of gas containing ^{3}He, it will be possible to measure not only the thermal neutron component [22] but also the fast neutron energy spectrum by taking profit of the 1 to few barn cross section of capture above 100 keV neutron energy. By adding a lead and Polyethylene shields, it will also be possible to measure the residual background at low energy and assess potential sensitivity to dark matter particle search and coherent neutrino-nucleus scattering.

5. Conclusions

A new detector has been developed that combines large mass and low sub-keV energy threshold with the capability of sensing even single electrons. This is a new type of radiation detector based on the radial geometry with spherical proportional amplification read-out. Its moderate cost, simplicity and robustness, make this technology a promising approach to NC based detection of reactor and astronomical neutrinos and opens a new window in dark matter searches.

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