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2008 J. Phys. G: Nucl. Part. Phys. 35 125107

(http://iopscience.iop.org/0954-3899/35/12/125107)

J. Phys. G: Nucl. Part. Phys. **35** (2008) 125107 (11pp) doi:10.1088/0954-3899/35/12/125107

Low energy tracking and particles identification in the MUNU Time Projection Chamber at 1 bar: possible application in low energy solar neutrino spectroscopy

Z Daraktchieva[1], C Amsler[2], M Avenier[3], C Broggini[4], J Busto[1], C Cerna[4], F Juget[1], D-H Koang[3], D Lebrun[3], O Link[2], G Puglierin[4], A Stutz[3], A Tadsen[4], J-L Vuilleumier[1], J-M Vuilleumier[1] and V Zacek[5]
(The MUNU Collaboration)

[1] Institut de physique, A-L Breguet 1, CH-2000 Neuchâtel, Switzerland
[2] Physik-Institut, Winterthurerstr 190, CH-8057 Zurich, Switzerland
[3] Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3-UJF-INPG, 53 rue des Martyrs, F38026 Grenoble, France
[4] INFN, Via Marzolo 8, I-35131 Padova, Italy
[5] Universite de Montreal, C P 6128, Montreal, PQ H3C 3J, Canada

E-mail: Zornitza.Daraktchieva@unine.ch

Received 9 May 2008
Published 14 October 2008
Online at stacks.iop.org/JPhysG/35/125107

Abstract
In this paper we present the results from the measurements made with the MUNU Time Projection Chamber (TPC) at 1 bar pressure of CF_4 in the energy region below 1 MeV. Electron events down to 80 keV are successfully measured. The electron energy and direction are reconstructed for every contained single electron above 200 keV. As a test the ^{137}Cs photopeak is reconstructed by measuring both the energy and direction of the Compton electrons in the TPC.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Time Projection Chambers (TPCs) have been used as tracking devices since the invention by David Nygren in the late 1970s [1]. In the recent years TPCs have been the main detector component in a large number of particle physics experiments due to their excellent particle recognition. In the low energy region gas TPCs are successfully used to study the neutrino properties [2] and to search for dark matter [3].

A gas TPC could be used to detect *pp* and Be^7 neutrinos and carry out solar neutrino spectroscopy. The neutrinos are detected via elastic scattering off electrons $\nu_e + e^- \rightarrow \nu_e + e^-$. The contribution of ν_μ and ν_τ neutrinos can be neglected because their cross section with electrons is about 1/7 of ν_e cross section. The initial electron direction can be determined from the tangent to the start of the electron track. This is possible if the tracks are long enough and if the spatial resolution is sufficient to distinguish between the beginning of the track from the end where the ionization is increased. This implies, for a given energy, that the gas pressure is below a given value. A reasonable goal is a threshold around 100 keV on the electron [4]. The neutrino energy can be reconstructed from the electron energy and direction thereafter.

MUNU, a TPC installed at the Bugey reactor to study antineutrino electron scattering $\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$, was used to demonstrate the feasibility of such a scheme. The results of these measurements are presented here. Particle identification properties of gas TPCs, which should lead to a good event selection and a low background rate, will also be addressed.

2. Experiment

MUNU used a commercial nuclear reactor in Bugey (France) with a thermal power of 2.75 GW as a $\overline{\nu}_e$ source. The detector was located in a laboratory underneath the core of the reactor, at an angle of 45°, and a distance of 18 m. The neutrino flux in the lab is 10^{13} ν cm $^{-2}$ s $^{-1}$. The neutrinos are mostly produced in the beta decay of fission fragments of the four fuel isotopes ^{235}U (54% on average), ^{239}Pu (33%), ^{241}Pu (6%) and ^{238}U (7%). The energy ranges up to 8 MeV. Above 1.8 MeV the neutrino spectrum is known within 5% precision from the study of the beta decay of fission fragments. Below 1.8 MeV it is known within 10–20% precision from calculations only. More details on the spectrum are given in [5].

The essential features of the MUNU detector have been presented previously [6, 7]. Briefly, the detector consists of a 1 m^3 TPC housed in an acrylic vessel (90 cm diameter and 162 cm long) filled with 3.8 kg of pure CF_4 gas (1.06×10^{21} electrons per cm^3 at STP). The gas was selected because of its high electron density, good drifting properties, low Z (which reduces multiple scattering) and its absence of free protons. Most previous data were taken at a pressure of 3 bars and a threshold of 300 keV. The data reported in this paper have been taken at a pressure of 1 bar with an energy threshold of 100 keV for the recoiling electrons, to gain insight on the behaviour of the TPC at low energy. As shown in figure 1 at one end of the TPC, a cathode is mounted and was held at a negative high voltage. It defines the drift field along with field shaping rings outside the acrylic vessel and a grid at the other end. The cathode was held at a potential of −17 kV for the 1 bar measurements, while the grid was at −1.28 kV. This led to a drift velocity of 2.14 cm μs^{-1}. An anode plane with 20 μm diameter wires and a pitch of 4.95 mm, separated by 100 μm potential wires, is placed behind the grid to amplify the ionization charge. The integrated anode signal gives the total energy deposit. A pick-up plane with perpendicular x and y strips (pitch 3.5 mm) provides the spatial information in the x–y plane perpendicular to the TPC axis (z-axis). The spatial information along the z-axis is reconstructed from the time evolution of the signal. The acrylic vessel TPC is immersed in a steel tank (2 m diameter and 3.8 m long) filled with 10 m^3 of an organic liquid scintillator (NE-235). The liquid scintillator is viewed by 48 photomultipliers and serves as an anti-Compton detector and a veto for the cosmic muons. The liquid scintillator and steel vessel both serve as a low activity active shielding. In addition, there is 8 cm thick borated polyethylene and 15 cm thick lead shielding to absorb the external neutrons and γ rays.

3. Energy calibration of the TPC at 1 bar

For the energy calibration of the TPC at 1 bar pressure of CF_4, ^{54}Mn and ^{137}Cs γ radioactive sources were used with gamma energies of 834 keV and 662 keV, respectively. These sources were introduced into the anti-Compton detector through an acrylic pipe at an axial distance as

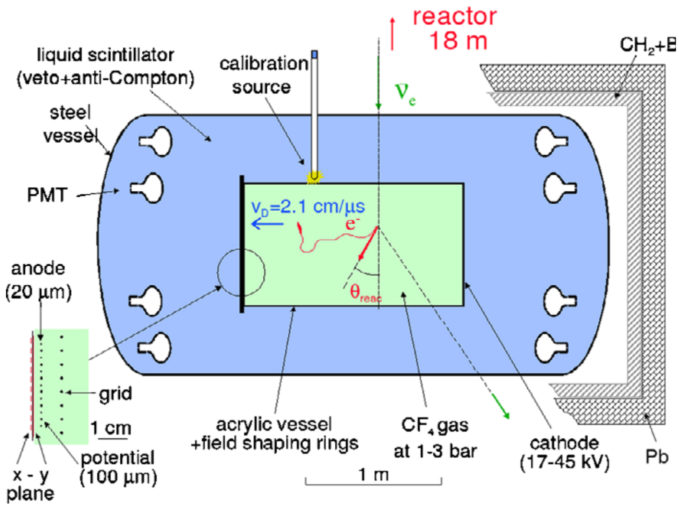

Figure 1. The MUNU detector.

low as 26.4 cm from the centre of the detector (1 cm from the TPC side wall) on the anode side. Most detected photons undergo only one Compton scattering in the active volume of the TPC before leaving it. The calculated energy of the Compton edge is found to be 638 keV and 478 keV for ^{54}Mn and ^{137}Cs, respectively. However, the Compton edge in the TPC is smeared with the resolution of the detector which complicates the direct calibration. We performed Monte Carlo simulations with the GEANT 3 code. The Compton electron spectrum was calculated in the TPC for various resolutions of the detector. The Gaussian width of the detector response was obtained by comparing with the measured spectrum [8]. Figure 2 shows the measured spectrum for ^{137}Cs along with the best simulation with $\sigma/E = 6.8\%$.

4. Energy resolution of the TPC at 1 bar

The energy resolution of a gas TPC depends on one hand on the electrical property of the gas itself (ionization of the gas, attachment and multiplication) and on the other hand on the quality of the detector (homogeneity of the gain on the anode plane and charge attenuation). At 1 bar pressure the effective attachment of CF_4 is found to be 85% [9]. This means that 15% of the primary ionization electrons will survive and reach the multiplication phase of the avalanche. This factor is about four times better than that at 3 bars (4%). The energy resolution of the TPC was measured as described above with ^{137}Cs and ^{54}Mn radioactive sources and was found to be 6.8% (1σ) and 6.1% (1σ) at 478 keV and 638 keV, respectively. It scales with energy following an empirical $E^{0.57}$ law. Thus the resolution varies from 10% at 200 keV to 5% at 1 MeV, being about two times better than the resolution at 3 bar [7].

5. Particle identification

Low background is essential in a solar neutrino experiment. The detector must be made from highly pure materials. In addition, the detector must use an event signature as selective as possible. Particle identification is crucial in this context.

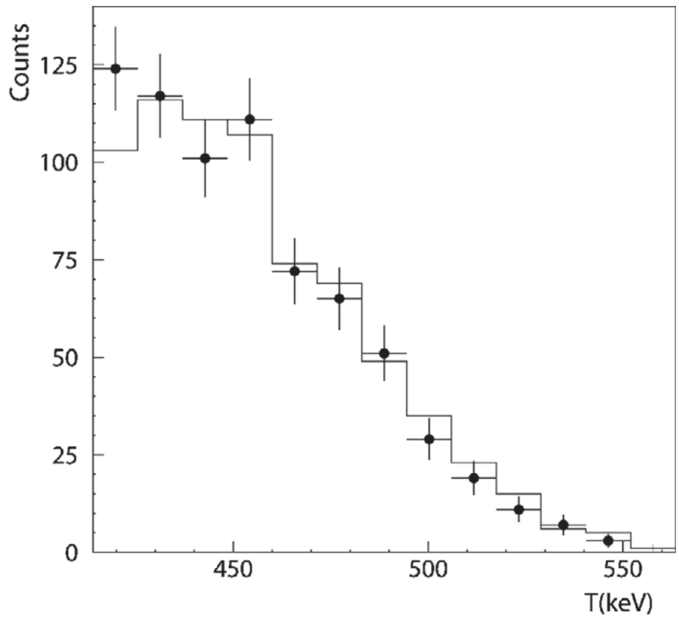

Figure 2. A Compton spectrum of ^{137}Cs in the TPC compared with Monte Carlo simulation (filled circles).

5.1. Compton electrons

A Compton electron from a gamma activity which originates from inside the TPC could mimic an electron from neutrino scattering if the gamma does not re-interact in the active volume of the TPC. In MUNU however the escaping photon will be detected in the veto counter with high efficiency.

The anti-Compton trigger was set at the energy threshold of 100 keV and used multiplicity criteria seeking at least five phototube hits. The suppression efficiency for Compton electrons from γ background is found to be 97%.

5.2. Muons

With an overburden equivalent to 20 metre of water the MUNU detector is exposed to a constant flux of cosmic muons of 32 m^{-2} s^{-1}. The deposited mean energy loss per cm in the CF_4 at 1 bar pressure is 6.4 keV cm^{-1} as estimated from a visual scan [8] of simulated muons. A cosmic muon has to cross more than 1 m of liquid scintillator if it hits the TPC, leaving behind a large prompt signal in the phototube. This signal of the anti-Compton detector is used to veto the muon associated events with almost 99% efficiency.

In figure 3 are displayed the xz, yz and xy projections of a cosmic muon track in the TPC.

5.3. Alpha particles

The alpha particles from natural radioactivity deposit all of their energy in a very short range in CF_4. For example the track length of a 5 MeV α particle, as is shown in figure 4, is 28 mm in 1 bar of CF_4.

(a) (b)

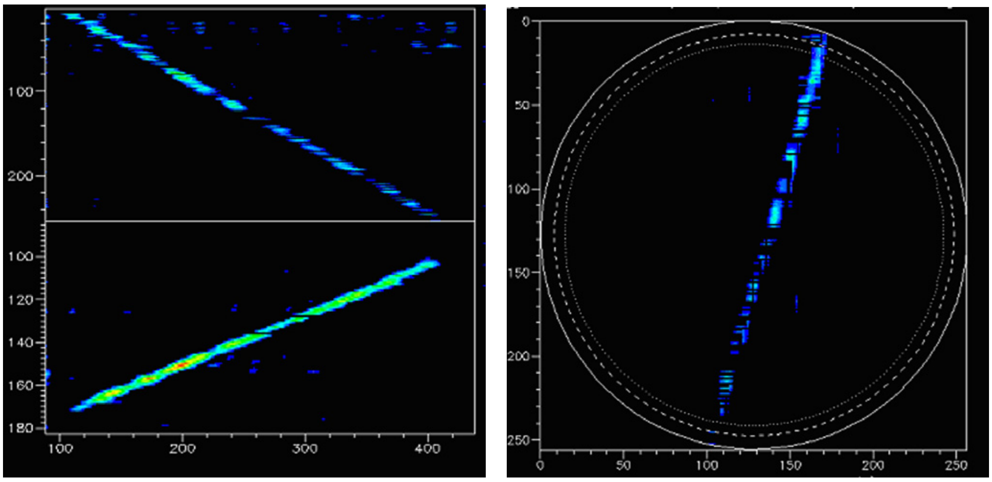

Figure 3. A cosmic muon event in 1 bar of CF_4: (a) *xz* projection (top), *yz* projection (bottom) and (b) *xy* projection. The binning is 3.5 mm for *x* and *y* and 1.7 mm (80 ns for *z*).

(a) (b)

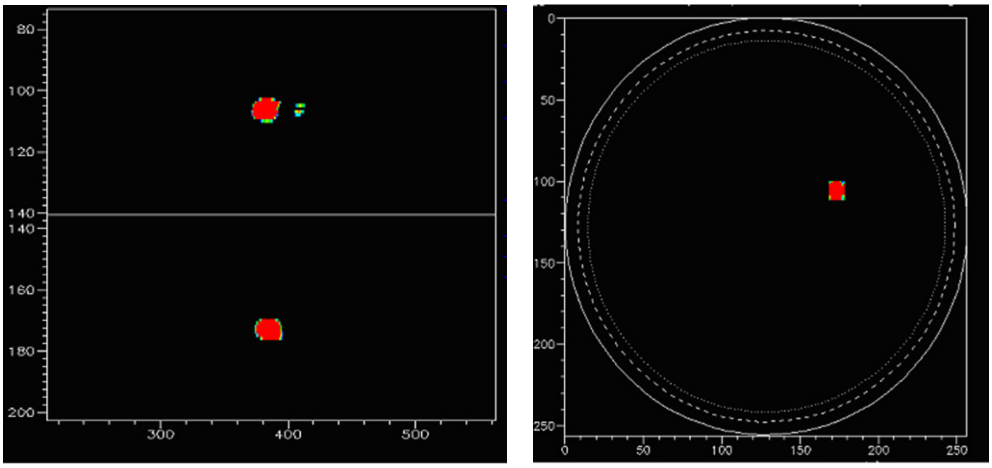

Figure 4. An alpha particle event: (a) *xz* (top), *yz* (bottom) and (b) *xy*.

5.4. e^+e^- pairs

The e^+e^- pairs from cosmics and natural radioactivity can clearly be seen in the TPC and identified. The example in figure 5 shows two tracks in 1 bar of CF_4.

5.5. Rare events

TPC can also detect some rare events, for example protons. A proton can be identified from the high ionization and short straight track as it is shown in figure 6.

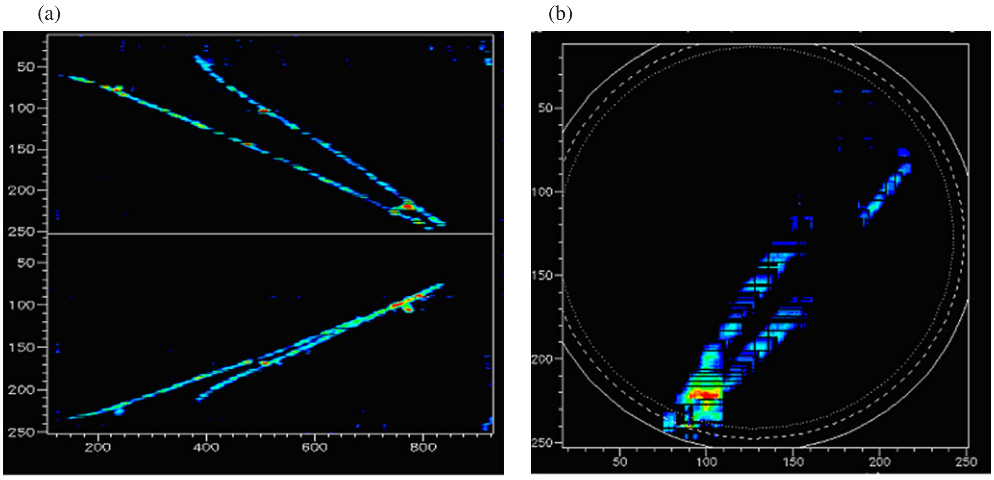

Figure 5. Two e^+e^- pairs: (a) xz (top), yz (bottom) and (b) xy.

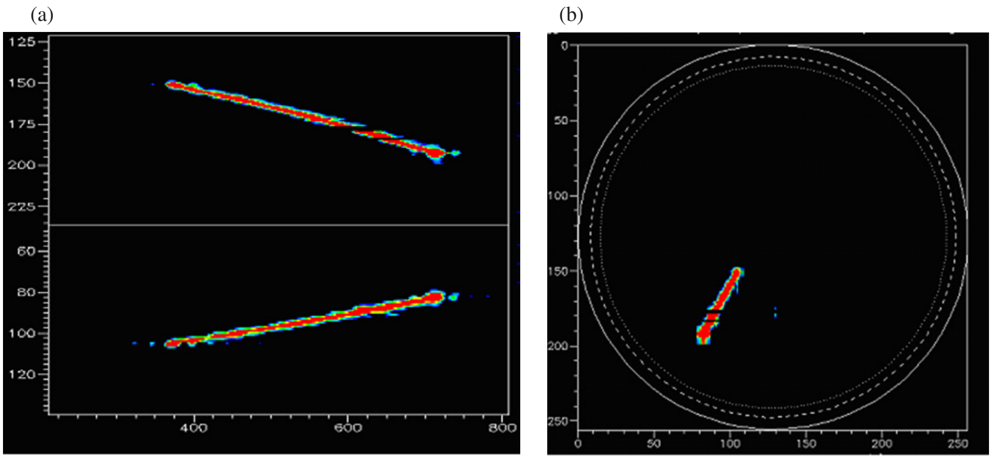

Figure 6. A proton: (a) xz (top), yz (bottom) and (b) xy.

5.6. Contained single electron events

Data were accumulated during 5.2 days live time reactor on as reported in [10]. Electron events down to 70 keV have been measured in the TPC. Examples of low energy single electrons of 80 keV and 540 keV, respectively, are displayed in figures 7(a) and (b). The low ionizing start of the track and the increased energy deposition at the end can be seen in both projections. The counting rate of single electrons (neutrino trigger) above 100 keV is 0.4 s^{-1}: 0.05 s^{-1} from cosmic muons and 0.31 s^{-1} mostly from Compton electrons associated with natural radioactivity. The deadtime, about 50% of the total time, is mostly due to the low energy threshold, leading to a high data readout and transfer time, and to the anti-Compton veto.

Above 150 keV the electron tracks are long enough and can be reconstructed with good precision. Here the neutrino candidates are carefully selected being single electrons fully contained in a 42 cm TPC radius, with no energy deposition above 100 keV in the anti-

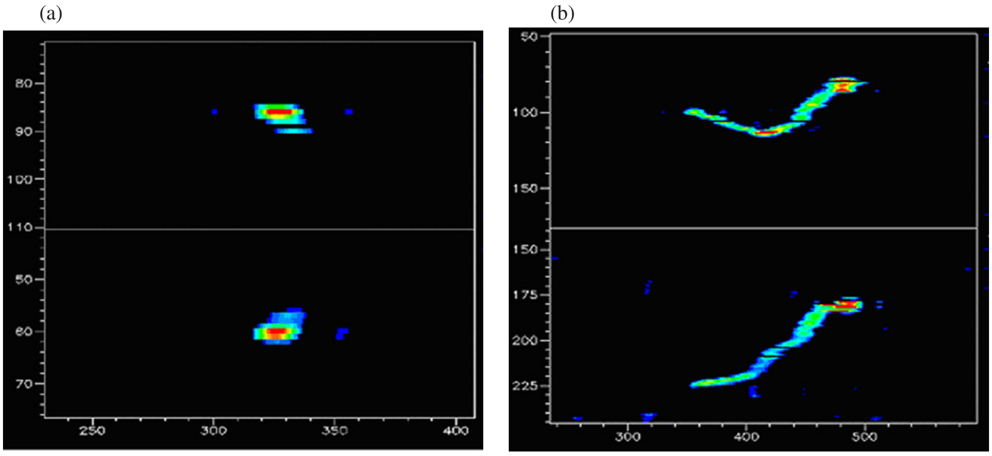

Figure 7. Low energy single electrons of (a) 80 keV (4.5 cm) and (b) 540 keV (35 cm) at 1 bar in the TPC: xz (tops) and yz (bottoms).

Compton detector in the preceding 80 μs corresponding to the longest possible drift time in the TPC. In the data analysis an additional software energy filter of 200 keV is applied in order to suppress some point-like electrons. For single electrons fully contained inside the TPC above 200 keV the rate is 2900 counts per day (cpd) live time, i.e. 760 cpd kg^{-1}. The containment efficiency was computed by GEANT 3 simulations, 10 000 single electrons were generated randomly inside the TPC with a flat energy distribution between 20 keV and 2 MeV. The containment efficiency of the TPC at 1 bar then is found to vary from 85% at 200 keV, 50% at 400 keV to 10% at 800 keV. The energy distribution of measured contained electrons is in good agreement with the results from simulations (figure 8).

The initial direction of the electron track is obtained from a visual fit to the xz and yz projection of events, as discussed in detail in [10]. From that three angles characterizing the track are determined. These angles are the scattering angle, taken as the angle between the initial track direction and the reactor core-detector axis θ_{reac}, the angle with respect to the detector axis z, θ_{det}, and the angle between the projection on the plane x–y perpendicular to the detector axis and the vertical y axis, φ_{det} (see figure 9). The angular resolution obtained from the visual scan of simulated electron tracks is found to vary from 15° (1σ) at 200 keV to 10° at 600 keV.

An angular cut $\theta_{\mathrm{det}} < 90°$ is applied to discard the background from activities on the read-out plane side of the TPC. This reduces the acceptance, but improves significantly the signal-to-background ratio. For each electron track the neutrino energy E_ν is reconstructed from the scattering angle θ_{reac} and the measured electron recoil energy T_e. The electrons are selected in four kinematical cones, as shown in figure 9. Events with $E_\nu > 0$ are called the forward events with an initial track direction within the forward kinematical cone. The forward cone contains recoil plus background events, while the backward cone, i.e., the one being opposite to the forward cone and the two perpendicular upward and downward cones contain only background events. This is because electrons from neutrino scattering are emitted forward with regard to the reactor core, while the background from activity is isotropic around the detector axis. This method takes advantage of the symmetries of the detector–reactor core system to suppress the systematics from possible nonlinearities in the angle reconstruction.

We normalize the background to the forward cone by dividing by 3 the background in the backward, upward and downward cones. This normalized background (NB) is then directly

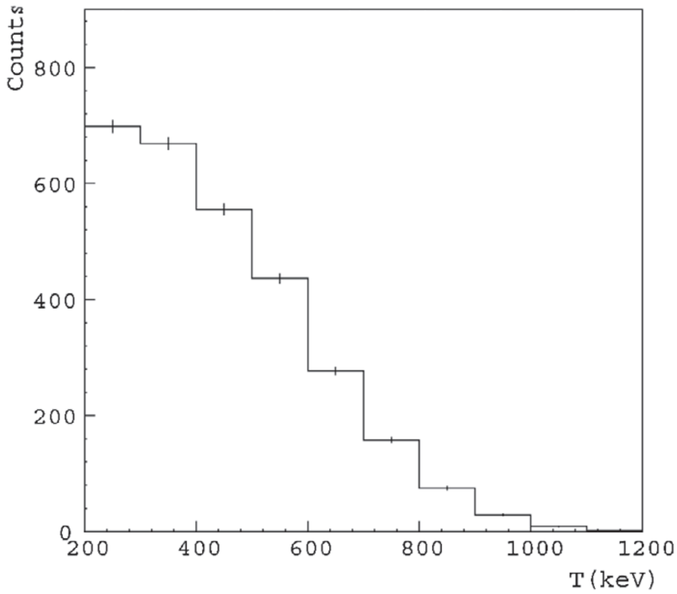

Figure 8. Contained single electron events above 200 keV.

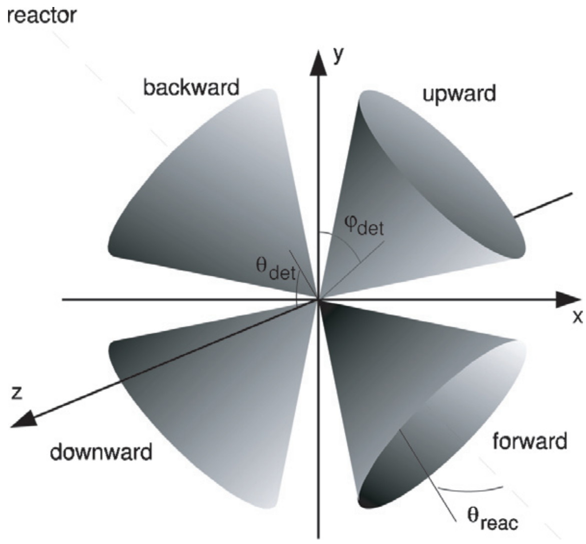

Figure 9. Four kinematical cones.

compared with the event rate in the forward cone. The energy distributions of the forward (124 ± 11) and NB (109 ± 6) electrons are displayed in figure 10. The signal is 15 ± 12 events. The energy distribution is given in figure 11.

Per unit time the forward minus backward rate corresponding to the signal from antineutrino electron interactions is 2.89 ± 2.39 counts per day. This is consistent with the expected number assuming no neutrino magnetic moment, 0.49 ± 0.12 cpd. Due to the

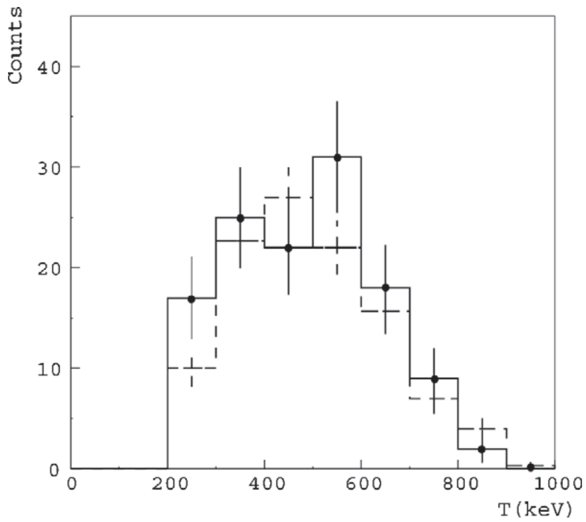

Figure 10. Energy spectrum of forward (solid line with filled circles) and NB (dashed line) electrons.

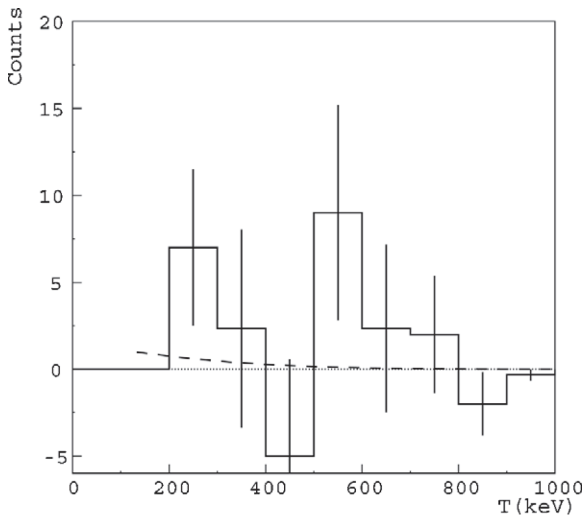

Figure 11. Energy distribution of the forward minus NB electrons (solid line) compared with the expected spectrum, assuming no magnetic moment (dashed line).

limited statistics and uncertainties in the low neutrino energy spectrum this result is not used to study the neutrino magnetic moment. However, it proves that a gas TPC can be used to measure the energy and directions of the recoil electrons at least down to 200 keV.

6. Reconstruction of ^{137}Cs photopeak

To investigate more precisely the reconstruction of the neutrino energy from the electron scattering angle and kinetic energy, the TPC was exposed to gammas from a ^{137}Cs source (662 keV). These measurements were performed at a pressure of 1 bar of CF_4.

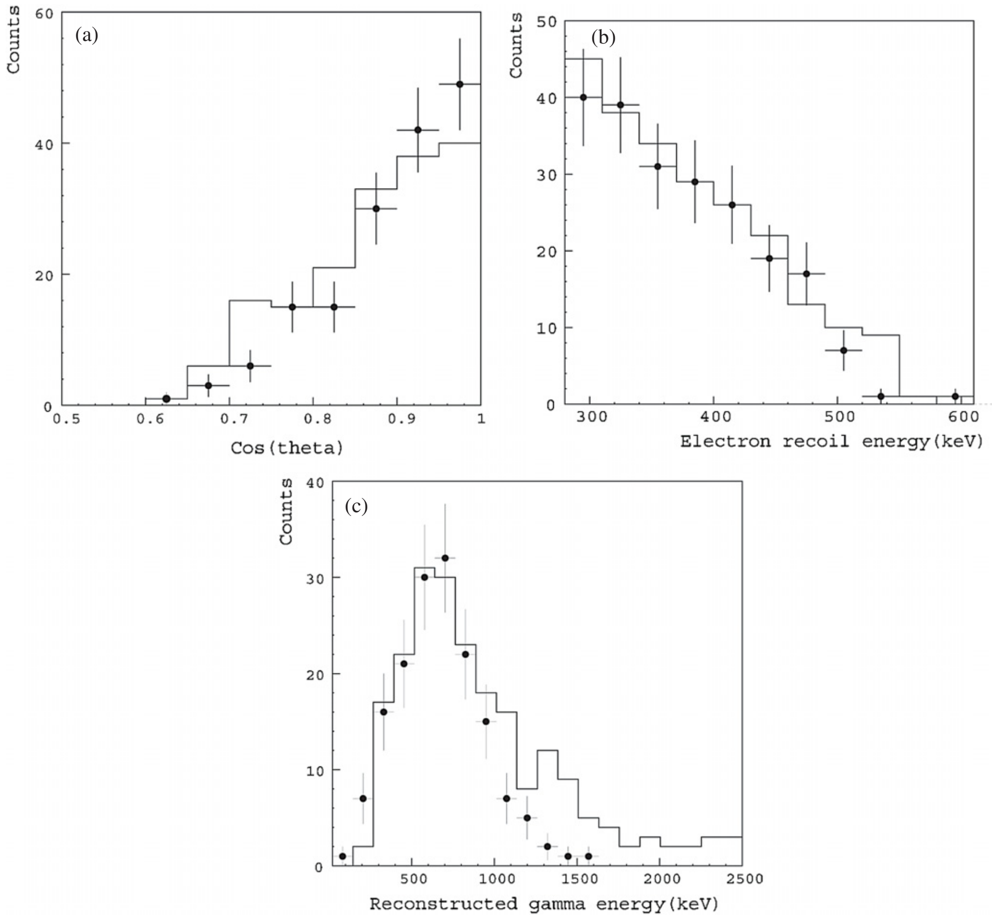

Figure 12. (a) Scattering angle θ_{source}, (b) electron recoil energy T_e and (c) reconstructed gamma energy E_γ (c) for ^{137}Cs, compared with Monte Carlo simulations (filled circles).

The γ-ray from ^{54}Mn at 835 keV at 3 bar pressure of CF_4 was measured by MUNU previously [7].

The Compton scattered photon is measured in the scintillator. The recoil electron track and energy are measured in the TPC. The Compton electrons initial direction is obtained by a visual fit. The angle θ_{source} with respect to the source axis (perpendicular to the detector–reactor axis) is calculated from this fit. The initial photon energy E_γ is reconstructed thereafter from the scattering angle θ_{source} and the electron recoil energy T_e measured in the TPC.

The reconstructed 662 keV photopeak from the ^{137}Cs source at 1 bar of CF_4 together with the cosine of the scattering angle θ_{source} and electron recoil energy from Compton scattering are presented and compared with Monte Carlo simulations in figure 12. The energy resolution from the Compton edge at 1σ is 32.6 keV at 480 keV. The angular resolution of the Compton recoil spectrum above 150 keV is $\sigma_\theta = 11.6^\circ \pm 0.9$. This is in good agreement with the above-mentioned determination from Monte Carlo simulations. The width of the reconstructed energy peak at 1σ is 220 keV at 662 keV.

Monte Carlo simulations have been performed in order to check the feasibility of using a gas TPC to detect neutrinos from the Sun [4]. In more detail the reasonable volume of a

TPC should be about 1000 m^3 with 3.7 ton of CF_4. The counting rate is expecting to be five solar event/day from both *pp* and ^{7}Be neutrinos at a threshold of 100 keV of electron recoil energy. Here the source is not fixed with respect to the detector, as in MUNU, but moves. The strategy to kinematically select good events must therefore be adapted. But it is always possible to compare the rate in a forward cone, which follows the Sun, and outside, with proper normalization, to obtain the signal rate. At a given time a kinematic region measures signal plus background while the other the background only, so that systematics from the nonlinearity of the angle reconstruction or anisotropies in the background cancel.

The simulations have demonstrated that after 2 years of data taking with such a TPC operating at 1 bar pressure, it is possible to reconstruct the energy spectrum of the *pp* and ^{7}Be neutrinos via elastic scattering with electrons. The σ of the reconstructed ^{7}Be peak is found to be 230 keV at 862 keV, which result is in very good agreement with the result of the reconstructed here ^{137}Cs photopeak at 1 bar. It also demonstrates that the MUNU technology could be used in the future for solar neutrino spectroscopy if instead of photons one chooses the low energy neutrinos from the Sun.

7. Conclusion

The measurements made with the MUNU TPC at 1 bar of CF_4 are presented. The background is well understood and separated from the good single electron events. The TPC can work successfully at energies as low as 100 keV. The single electron events down to 80 keV (4.5 cm length) are measured in the TPC. Above 200 keV the electron tracks have been analysed, the direction and energy are reconstructed.

Also, here we presented the reconstructed 662 keV ^{137}Cs full γ energy from Compton scattering for 1 bar of CF_4. All these results are encouraging and demonstrate the possibilities of future low energy solar neutrino spectroscopy with a gas TPC, installed in a very low background environment underground facility.

A very large TPC with ultra low background as required for solar neutrino spectroscopy would also provide an ideal environment for experiments searching for dark matter, provided that the energy thresholds below tens of keV can be attained. The flexibility to use different gases like He, CF_4, Ne, Xe would enhance the possibility of establishing the nature of a dark matter induced signal. Tests with the MUNU TPC at one bar have shown that energy depositions of 40 keV electrons are indeed recognizable. However the amount of quenching in the case of low energetic nuclear recoils has yet to be quantified for the respective filling gases.

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