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Determination of through-going tracks' direction by means of δ-rays in the ICARUS liquid argon time projection chamber

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Abstract

We exploited the crossing muon data, collected in the 50 l liquid argon TPC exposed at the CERN neutrino beam in 1997, to investigate the possibility of identitying the direction of minimum ionizing particle tracks relying only on δ-rays orientation. In this note we show that simple selection criteria allow using δ-rays down to very low energy (few MeV) with high efficiency and no misidentification of their direction. The Monte Carlo prediction – two recognized δ-rays per meter

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of track – is very well matched by the result of the scanning of the experimental data.

1. Introduction

In the ICARUS/ICANOE experiment we plan to study upward-going neutrino-induced muon events [1]. The expected rate is about $5 \times 10^{-5}\,\mathrm{m}^{-2}\,\mathrm{h}^{-1}$ and the momentum ranges from few GeV to few TeV, hence they will cross the detector without stopping. The only way to discriminate them from the overwhelming downward-going sample, whose rate is of the order of $1\,\mathrm{m}^{-2}\,\mathrm{h}^{-1}$, is to rely on the identification of the direction of the δ-rays produced along the track. These δ-rays are practically emitted in the same direction as the parent ionizing particle.

Thanks to the fine grain spatial resolution of the ICARUS Liquid Argon Time Projection Chamber (LAr-TPC), the identification and reconstruction of δ-rays tracks could be performed for kinetic energy, T, down to few MeV. In this energy range, the cosine of the angle, Θ, between the δ-ray and the primary track directions is given by the expression: $\cos\Theta \approx (1 + 2m_e/T)^{-1/2}$, independent from the muon momentum and very close to unity.

Simple analytical calculations, based on the well known T^{-2} behavior of the δ-rays rate [2], suggest that about one δ-rays per meter of track with kinetic energy above 10 MeV should be recognizable. It is nevertheless important to verify on real data the minimum energy allowing full reconstruction of the δ-ray direction and, as a consequence, the effective rate that one can finally expect.

From this rate one can determine the minimum track length that has to be accepted being sure of its direction. This in turn is related to the actual up/down detection efficiency and discrimination power of through-going muons.

2. The LAr TPC

In order to perform a test of the actual reconstruction ability of the δ-rays direction on real muon tracks, we took advantage of the data taken with the ICARUS 50 l LAr-TPC exposed at the CERN neutrino beam during the 1997 physics run. The detector and the experimental set-up has been extensively decribed elsewhere [3]. For sake of clarity, in this note, we just recall few basic parameters.

The LAr-TPC had the shape of a parallelepiped with top and bottom faces ($325 * 325\,\mathrm{mm}^2$) acting as read-out anode and cathode, respectively, while the side faces, 475 mm long, supported the field shaping electrodes.

The read-out electrodes were two stainless steel wire planes with the wires running in orthogonal directions. The plane facing the drift volume worked in *induction* mode while the other was used to *collect* the drifting electrons. The plane separation was 4 mm, the wire pitch 2.54 mm and the wire diameter 100 μm. The total number of wires was 128 for each plane. No screen wires were present in either plane. The wires were soldered on a vetronite frame, which supported also the voltage distributions and the decoupling capacitors.

The cathode and the field shaping electrodes were obtained by metallisation of vetronite boards. The boards were glued on honeycomb structure to ensure rigidity. The field shaping were horizontal strips, 1.27 cm wide, spaced 2.54 cm. A high-voltage divider, made by a series of 14 MΩ resistors interconnecting the strips, supplied the correct voltage to the strips. The drift high voltage was brought to the cathode by a commercial ceramic feed-through.

The LAr-TPC was housed into an ultra-high-vacuum stainless steel vessel, 65 cm in diameter and 170 cm height, for a total volume of 550 l. The active mass of LAr in the drift volume was 200 kg. In order to regulate the heat losses, the whole vessel was partially immersed in a thermal bath of commercial LAr contained in an open air dewar.

The detector was equipped with a standard recirculation–purification system. It allowed a recirculation rate of about 5 l of LAr per hour with the purification filter working in gas phase. The initial filling of the TPC, in liquid phase, took about 2 h.

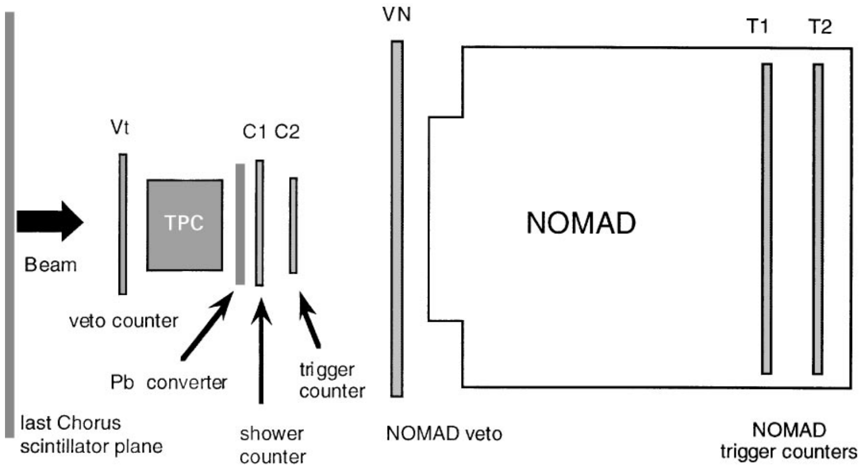

Fig. 1. Experimental set-up (top view) of the 50 l liquid argon TPC exposed at the CERN neutrino beam.

An electron lifetime of several milliseconds was reached after few days from filling.

The front-end electronics was mounted directly on the wire frame in order to reduce the input capacitance of the pre-amplifiers, which were designed to work immersed in liquid argon. The pre-amplifiers were set to work in "quasi-current" mode with a RC constant of 6 μm for those connected to the *induction* plane and 3 μs for those connected to the *collection* plane.

Data were taken in the following running conditions.

- High voltage on cathode set to -10 kV corresponding to a drift field of 200 V/cm.
- *Induction* wire plane set to virtual ground through the pre-amplifiers.
- Voltage on the *collection* wire plane set to $+120$ V; this corresponded to a drift field in the gap between *induction* and *collection* of 300 V/cm, enough to ensure complete transparency to drifting electrons.

An 8-bit FADC, sampling at 400 ns, digitized the waveform from each channel. Being the electron drift velocity 0.91 mm/μs, a full drift length was collected in ≈ 520 μs or 1300 time sampling. To safely contain it, a DAQ buffer of 2 kb per channel was used for a total of 512 kb per event.

The charge deposed by minimum ionizing particles on a single wire induced a signal with a pulse height of 10–12 ADC counts and a FWHM of ≈ 6 μs (15 time samples). The RMS noise level, calculated on a window of 256 time samples, was less than 1.0 ADC count. Hence, a signal-to-noise ratio of at least 10 was always available.

The events were written in raw-data format without zero suppression; they were stored locally on disk and automatically transferred to the main CERN tape facility through the network.

3. Set-up in the CERN neutrino beam

The layout of the experimental set-up is sketched in Fig. 1. The detector together with its cryogenic equipment, argon purification system, vacuum pumps, veto and trigger counters, trigger and read-out electronics, data acquisition system, was installed on a platform at the level of the neutrino beam between CHORUS and NOMAD.

Immediately upstream of the chamber a double plane of scintillators, acting as a veto counter, was installed; downstream of the chamber there was a 6 mm thick lead sheet followed by a plane of scintillators, acting as trigger and pre-shower counter.

Because of the main purpose of the experiement, the LAr-TPC was complemented by the NOMAD detector acting as muon identifier and spectrometer.

The trigger of the LAr-TPC was based on the coincidence between the down-stream scintillators and the NOMAD muon trigger planes. Run number and burst number of the LAr-TPC events were recorded by NOMAD to allow off-line matching of the tracks in the LAr-TPC with the muons reconstructed by NOMAD. The dead time of the TPC data acquisition was measured to be lower than 5%, while the NOMAD dead time was around 15%.

In the case of neutrino runs, the upstream-scintillator planes were used to veto passing through particles, mostly muons produced by neutrino interactions in the CHORUS detector. A small fraction of the data taking time was spent to record these muon events with the main purpose of aligning the LAr-TPC with the NOMAD detector. This was performed using the upstream scintillator planes in coincidence with the other trigger counters.

4. The δ-rays analysis

The latter sample of events (about one thousand) was used to study the possibility to exploit the visible δ-rays to determine the direction of minimum ionizing particle tracks crossing the detector. In fact, δ-rays are emitted with a direction extremely close to that of the parent ionizing particle provided that a threshold of few MeV is applied in their selection. The analysis proceeded through the following steps.

The whole sample of through-going minimum ionizing particle tracks was visually scanned. Only the events containing a muon fully reconstructed in NOMAD and matching a track in the LAr-TPC were retained. This requirement safely predefined the direction of the selected tracks in the LAr-TPC.

A track in the LAr-TPC was considered matched when the NOMAD trace-back passed by at a distance not larger than 5 cm (to take into account multiple scattering in the 2 m thick iron magnet upstream of NOMAD). To avoid ambiguities, no other tracks in the LAr-TPC had to be present within 5 cm from the NOMAD trace-back. A total of 400 events were selected. An example of muon track in the LAr-TPC, passing the above criteria, is visible in Fig. 2.

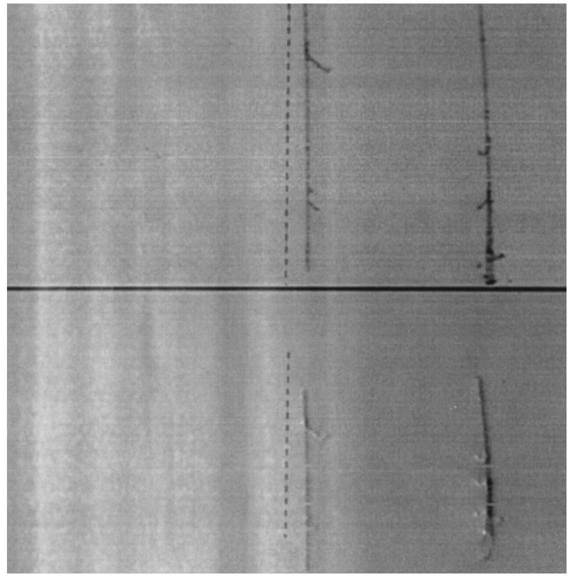

Fig. 2. An example of muon track recorded in the ICARUS 50 l Liquid Argon TPC prototype exposed at the CERN neutrino beam. The horizontal axis is the drift time; the vertical one is the wire numbering (top is the *collection* view, bottom is the *induction* one). The visible area in each view corresponds to $472 \cdot 325\ \mathrm{mm}^2$. The muon enters from the top of the picture on both views. Some δ-rays are clearly visible. The NOMAD trace-back is also drawn (dashed line). The track at the extreme right of the picture is not matched by NOMAD and exhibits a showering electron.

Since the read-out plane of the LAr-TPC was oriented such that the *collection* wires run at an angle 60° with respect to the beam direction, most of the muon tracks spanned the whole *collection* plane (128 wires) and about 75 *induction* wires. With this requirement, the track length in LAr was 375 mm. Shorter tracks hitting only partially the *collection* plane were rejected. This rejection reduced the muon sample of 320 events, corresponding to 120 m of minimum ionizing particle track.

The search and reconstruction of δ-rays were then performed following a series of simple criteria.

- A visible δ-ray was defined as a track starting as double ionization on top of the main muon track in both the *collection* and the *induction* views, and stopping aside of the main track in at atleast one of the two views. This deviation is due to multiple scattering acting mainly near the end of the δ-ray range. The separation of the stopping point from the main track was requested to be at least 6 mm, namely about one FWHM of a typical m.i.p. pulse.

- The δ-ray direction was trivially defined as that going from the starting point (double ionization on top of the main track) to the stopping point (aside from the main track).
- The δ-ray kinetic energy was simply calculated from the reconstructed 3-D range of its track, knowing that the average dE/dx is about 2.1 MeV/cm practically constant over all the range.
- Only δ-rays with at least three wires hit in one view and two on the other, corresponding to a minimum deposited energy of about 2 MeV, were retained. Also full track containment in the LAr-TPC was requested.
- Only δ-rays with kinetic energy below 30 MeV (critical energy in LAr) were considered. Above this value the range in no longer a good estimator of the δ-ray energy because electrons start showering.

The above criteria allowed selecting δ-rays over the total 120 m of tracks, namely about 2 δ-rays per meter, with kinetic energy larger then 2 MeV. Remarkably none was identified with the wrong direction. The δ-rays were distributed as follows: 0 on 132 tracks, 1 on 141 tracks, 2 on 47 tracks; we recall that each muon track was 375 mm long. As expected the δ-rays energy did not depend on the muon momentum, as given by the NOMAD spectrometer.

In order to understand our results, we compared th experimental δ-rays energy spectrum with the predicted rate valid for kinetic energy much higher than the mean excitation energy ($T \gg 188$ eV for argon) [2]:

$$\frac{d^2N}{dT\,dx} \approx \frac{1}{2} K\rho \frac{Z}{A} \frac{1}{\beta^2} \frac{1}{T^2} F_1 F_2 = \frac{9.67 F_1 F_2}{(\mathrm{T/MeV})^2} \mathrm{m}^{-1}\,\mathrm{MeV}^{-1} \quad (1)$$

To account for the selection requirements two factors, F_1, F_2, were included in Eq. (1). The *containment* factor, F_1, was used to account for the fact that not all the muon track length was available as origin of a δ-ray because a fraction of it was needed to contain the δ-ray. F_1 decreases with increasing δ-ray energy.

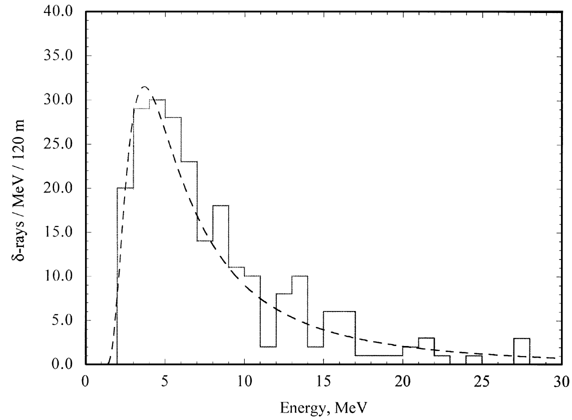

Fig. 3. Energy distribution of the δ-rays: experimental data (solid histogram) are plotted together with the expected rate normalized to 120 m of m.i.p. track (dashed curve).

The fraction of events, whose end-point was separated from the muon track by more than 6 mm in at least one of the two 2-D views, was evaluated by means of the multiple scattering formula. The *separation* factor, F_2, was thus computed as a function of the kinetic energy of the δ-rays. F_2 increases with increasing δ-ray energy.

Fig. 3 shows the energy spectrum of the experimental data of this test superimposed to that predicted with Eq. (1) normalized to 120 m of track. Note that the maximum rate occurs for a kinetic energy of 4 MeV and it drops down rapidly at low-energy side because of the separation requirement.

Fig. 4 shows the integrated δ-rays spectrum as a function of the energy threshold normalized to 1 m of track. Data are plotted together with the predictions. The solid curve gives the rate with no cuts. The dotted line instead takes into account the factors F_1 and F_2: the agreeement with the data is satisfactory.

The dashed line, which included only the factor F_2, has also been plotted because it gives the rate expected in a large LAr-TPC where the δ-rays containment factor, F_1, is close to 100%. About

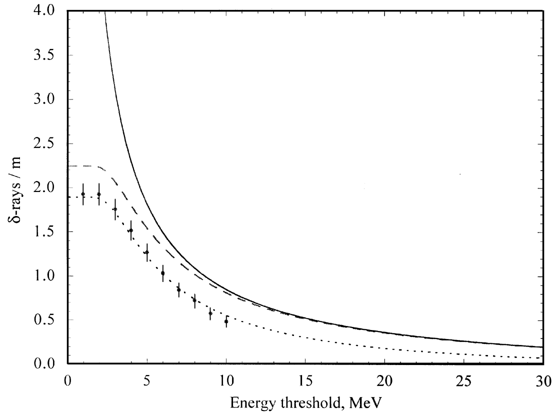

Fig. 4. Experimental cumulative energy distribution of the δ-rays (solid circles). The expectations are also plotted: the solid curve gives the rate with no selection cuts, the dotted line takes into account the factors F_1 and F_2 described in the text, the dashed one includes only F_2.

2.25 reconstructed δ-rays per meter of track are predicted with energy above 2 MeV.

5. Conclusion

We demonstrated experimentally that in the ICARUS LAr-TPC we could make use of the δ-rays kinematics to determine the direction of a minimum ionizing particle track crossing the detector. Slightly more than two δ-rays per meter of track could be fully reconstructed. This implies that the track direction identification ability is very high: an efficiency of 99% is at reach considering only 2 m of track.

In term of up/down rejection power, for the study of upward going neutrino-induced muons, this test is not conclusive due to the limited statistical sample. A larger statistics could be accumulated using all muon tracks visible in the 50 l LAr-TPC events (a factor of ten more should be easily reached). On the other hand, a detailed Monte Carlo simulation, based on the FLUKA99 package, has been performed with high statistics. The simulation, strengthened by the results of the present test, predicts an up/down rejection power better than 10^{-5}. This allows confirming that the ICARUS detector is well suited for the study of through-going muon events. Such a measure will contribute to a better understanding of the atmospheric neutrino deficit in a competitive way with respect to present and planned experiments [1].

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