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Detection of scintillation light in coincidence with ionizing tracks in a liquid argon time projection chamber

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Abstract

A system to detect light from liquid argon scintillation has been implemented in a small, ICARUS-like, liquid argon time projection chamber. The system, which uses a VUV-sensitive photomultiplier to collect the light, has recorded many ionizing tracks from cosmic-rays in coincidence with scintillation signals. Our measurements demonstrate that

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scintillation light detection can provide an effective method for absolute time measurement of events and eventually a useful trigger signal.

Keywords: Liquid argon; Scintillation light; Time projection chamber

1. Introduction

The liquid argon (LAr) Time Projection Chamber (TPC) has proven to be a very powerful detector for ionizing particles especially suited for the detection of rare events like those coming from neutrino interactions and proton decay [1].

The prototypes developed by the ICARUS Collaboration [2,3] have provided many beautiful images of cosmic-ray muons and showers from which it appears evident that in this detector events can be analysed in an exclusive way. The energy deposited into the active medium can be reconstructed either from the charge collected on the wires or from the measured range of the particles. Identification of particles stopping in the LAr is possible from the energy loss vs. range relation [1].

A problem that has still to be fully solved for the LAr TPC is the reconstruction of the absolute position along the drift coordinate (T_0) for totally contained events. Owing to the finite-electron lifetime in LAr,[1] the lack of information on the T_0 can worsen by a large amount the energy resolution of the detector, especially for those events, like soft electrons (coming for example from solar neutrino interactions) for which the range is badly measured due to multiple scattering. As an effect of the poorer energy resolution, the particle identification capability would also be significantly reduced.

There are several methods that in principle could provide the T_0 information. A first one could consist in reading the signal induced by nearby drifting electrons on a series of electrodes (wires) uniformly distributed in the drift volume; this approach was initially proposed for the former ICARUS 200 ton detector [4] and has recently been abandoned because of the mechanical complications associated with the holdings of such a set of electrodes. A second method is to detect the prompt current induced by the drifting charges on the electrodes surrounding the drift volume; this solution, in principle very simple, has the practical limitation of the noise induced on the readout amplifiers because of the large capacitance of these electrodes and is currently the subject of an intense R&D activity. Finally, a third solution could consist in detecting the LAr scintillation light.

Liquid argon is known to be a very abundant light emitter. Scintillation light is produced by ionizing particles either by direct excitation of an Ar atom followed by excimer formation and de-excitation:

$$Ar^* + Ar \rightarrow Ar_2^* \rightarrow 2Ar + \gamma \text{ (128 nm)} \quad (1)$$

or through ionization, recombination, excimer formation, and, finally, de-excitation [5–9]:

$$Ar^+ + Ar \rightarrow Ar_2^+ + e \rightarrow Ar_2^* \rightarrow 2Ar + \gamma \text{ (128 nm)} \quad (2)$$

De-excitation from the Ar_2^* to the dissociated ground state ($^1\Sigma_g^+$) proceeds from the two states $^1\Sigma_u^+$ and $^3\Sigma_u^+$ giving rise to a fast and a slow component of about 5 ns and 1 μs, respectively, with relative yields of 23% and 77% all around 128 nm [5–9]. As anticipated, the light emission is abundant: about one photon is emitted per 25 eV released in the LAr by the passage of an ionizing particle; this gives about 40 000 photons per MeV released in LAr. In the case of the LAr TPC these figures are somewhat smaller due to the presence of the electric drift field which reduces the electron–ion recombination. At a drift field of 300 V/cm, which is a standard value for our chambers, the reduction is about 35% which leaves about 24 000 photons/MeV [10]. For the application to

[1] We recall that the free electron lifetime is defined as the mean time spent by a free electron in the LAr before being captured by an electronegative impurity. Typical lifetime values that are routinely obtained in our TPC prototypes range from 2 to 3 ms.

the T_0 measurement, where few tens of photoelectrons are sufficient to give a suitable signal, these numbers are large enough to allow, with few percent photocathode coverage of the internal walls of the TPC, the T_0 determination down to few MeV events like those from solar neutrinos. Unfortunately, the wavelength of the light produced by LAr is in the far vacuum ultraviolet (VUV) region and its direct detection requires fragile and costly photomultipliers with MgF_2 windows; moreover, at these wavelengths, the Rayleigh scattering cross-section becomes very large so that very small temperature and pressure non-uniformities can severely reduce the light attenuation length [11,12]. However, the large time constant of the slow emission component has suggested that wavelength-shifting is possible via collisional processes [13]. Among the various collision partners already successfully tested by other authors a convenient choice for our purposes is represented by xenon [14,15], which can be purified using the same filters that we use for LAr [16]. Dissolved in small concentrations ($\leqslant 100$ ppm) into the LAr, xenon provides a shift of the slow component from 128 to 173 nm, in a region where quartz windows are transparent.

In the rest of this paper we shall report the results of a first attempt, to our knowledge, to measure the LAr scintillation light in coincidence with cosmic-ray tracks in a LAr TPC, both in pure LAr and in xenon-doped LAr.

2. Experimental set-up

In order to test the possibility of using the LAr scintillation light as a T_0 signal, we instrumented a small LAr TPC with a VUV-sensitive photomultiplier (PMT). A schematic view of the experimental set-up is shown in Fig. 1.

We used a small LAr TPC built in our laboratories in Pavia. Since the operating principles of the LAr TPC have already been reported in the literature [4], here we shall give only a short description of the detector; more technical details can be found in Ref. [17].

The drift volume is cylindrical with horizontal axis and having dimensions $\ell = 40.5$ cm, $\varnothing = 20$ cm. It is delimited (from left to right in Fig. 1) by the cathode (a stainless-steel disc of thickness 3 mm, $\varnothing = 23$ cm), a set of 26 circular field shaping rings (race tracks) with internal diameter $\varnothing = 20$ cm, external diameter $\varnothing = 23$ cm, thickness 2 mm, spaced by 1.5 cm and, finally, a circular grid. The readout chamber is located behind the grid and consists of two planes made of parallel wires. The first plane (induction plane) is at 3 mm from the grid and is made of 32 sense wires, 20 cm long, running vertically, spaced by 3 mm and interleaved with 32 screen wires. The second plane (collection plane) is structurally identical to the induction plane with wires running horizontally and located 3 mm behind the induction plane. All wires are stainless-steel (AISI 316L) of 100 μm diameter. The sensitive volume is defined by the drift length and by the intersection area of the two wire planes; in this case it is $10 \times 10 \times 40.5$ cm^3.

The proper potential needed to ensure a constant electric field inside the drift volume is distributed from the cathode, which is directly connected to the power supply, to the race tracks by means of a resistive divider chain immersed in LAr. Voltage on the grid and on the wire planes was set by means of separate, independent power supplies. Typical operating conditions were:

- drift field = 300 V/cm;
- induction-grid field = 600 V/cm;
- collection–induction field = 1800 V/cm.

The readout electronic chain is similar to the one already used by us in other prototypes. Signals from the wires are amplified by low-noise charge integrator preamplifiers (10 mV/fC) immersed in LAr. Amplified signals are then digitized by means of 10 MHz 8-bit Flash Analog-to-Digital Converters (FADCs).

The TPC is contained inside an UHV-tight stainless-steel cylinder ($\ell = 60$ cm, $\varnothing = 25$ cm) equipped with a LAr purity monitor [18] and the other instrumentation used to control the operating conditions of the detector (temperature and pressure sensors, LAr level indicator).

The chamber was cooled by immersion in an external LAr bath at atmospheric pressure. Filling of the main container was performed through an Oxisorb/Hydrosorb filter of the same type already

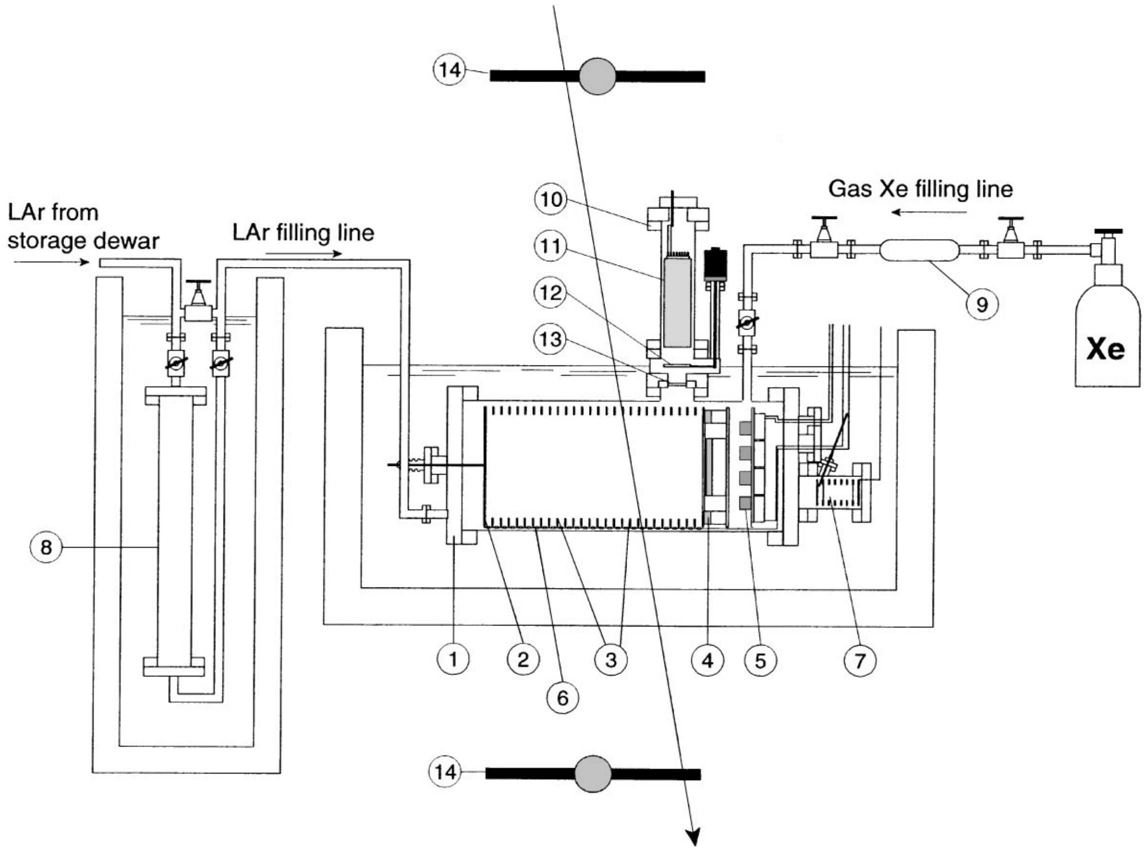

Fig. 1. Schematic view of the experimental set-up: (1) main chamber container; (2) cathode; (3) race tracks; (4) wire chamber; (5) preamplifier boards; (6) HV divider chain; (7) LAr purity monitor; (8) LAr purifier; (9) Xe purifier; (10) PMT container; (11) VUV-sensitive PMT; (12) movable quartz shutter; (13) MgF_2 window; (14) external cosmic-ray scintillator telescope.

used by the ICARUS Collaboration to purify LAr [2,3,19]. Liquid argon purity in the main container was monitored either by using the purity monitor or the track signals from the TPC; electron mean lifetime was always found to exceed 1 ms (corresponding to a concentration of electronegative impurities $\leqslant 0.3$ ppb O_2 equiv.). An independent filling line, with a second small Oxisorb cartridge, was used to introduce purified xenon gas into the main chamber for doping purposes.

In order to detect the scintillation light produced by the passage of ionizing tracks through the LAr, we used a VUV-sensitive PMT of the solar blind type, with CsI photocathode and MgF_2 window (Hamamatsu R2050). Owing to lack of space inside the main chamber container, the PMT was placed externally, in a different vacuum-tight container separated from the main container by a second MgF_2 window. During the detector operation, to avoid frost on the windows and light absorption from air, vacuum was maintained inside the PMT container. In the PMT container was also placed a manually operated movable shutter consisting of a quartz disc. The purpose of the shutter, when placed in front of the PMT window, was to absorb the 128 nm light while leaving the 175 nm component to pass through. Therefore, the shutter was used to test the efficiency of the xenon-doping. Signals from the PMT were sent both to a shaping amplifier (1 μs) and to an electronic logic chain. An amplified signal was sent to one of the mentioned FADC channels and was read out together with the signals from the wire chamber. The signal from the logic chain was occasionally used for internal triggering. The total gain of the PMT + Amplifier + FADC chain has been measured by injecting laser pulses (wavelength = 266 nm) in the main container to be seen by the PMT. The single photoelectron response ($\approx$5 FADC counts/photoelectron) was derived from the amplitude distribution of the signals from the FADC channel.

The experimental set-up is completed by a muon telescope consisting of two plastic scintillators placed one above and one below the TPC chamber and which were used to give the primary trigger and the T_0 signal for through-going cosmic muons.

3. Experimental results

Cosmic-ray muon data were taken under four different conditions: pure and xenon-doped (100 ppm) LAr with the quartz shutter on and off. Events were then individually selected by means of an event display and analysis program. To simplify the interpretation of the light yield as a function of the released energy in LAr, in selecting the events, we required the presence of a single vertical through-going muon passing approximately through the horizontal axis of the chamber, with the absence of relevant δ-ray tracks associated with the muon as a further constraint. In these conditions the length of the track in the TPC container is approximately constant ($\approx$25 cm) and the total amount of light emitted by the particle is therefore also approximately constant. The signal on the PMT should therefore depend only on the geometry (solid angle associated with the track) and on the light transport properties.

A typical TCP image of a cosmic-ray event taken from the display program is shown in Fig. 2, where the lowest window represents the signal from the PMT looking at the LAr. Taking into account a 20 μs time off-set, it is worth noticing the coincidence between the signals from the external muon telescope and from the internal PMT. For each one of the selected tracks the relevant quantities extracted are the collected charge, the track position along the drift axis, the signal amplitude on the PMT. We obviously also checked the coincidence between signals from the external muon telescope and from the internal PMT.

The amplitude distribution of the PMT signal as a function of the track position along the axis in pure LAr, hence with the quartz shutter off, is shown in Fig. 3. The distribution is compared with the prediction of a Monte Carlo simulation which takes into account the geometry of our set-up, refractive indexes of all the materials (liquid and gaseous argon, windows, etc.), the transmission and quantum efficiencies of the windows and the PMT. The light yield from minimum-ionizing particles (2 MeV/cm) was taken from published values [5–9] and corrected for the effect of the drift field on the recombination probability [17]; the computed value (22 300 photons/MeV) fits our data almost perfectly (Fig. 3). It is clear from Fig. 3 that our geometry is non-optimized since the angular acceptance for tracks a few centimetres away from the PMT axis becomes rapidly very small. Also the shadowing effect due to the presence of the race-tracks (evidenced as a ripple on the tail of the Monte Carlo and the data distributions) contributes significantly to reducing the detected amount of light from tracks far from the PMT axis.

Comparing the data with the Monte Carlo predictions we can draw two other conclusions:

1. light reflection from internal surfaces of the chamber (mainly electropolished stainless-steel) was practically absent;
2. the light attenuation length was well above our sensitivity limit of the order of 20 cm.

Within our acceptance window the efficiency for light signals was very high (practically 1). Most important for the T_0 application is that the occurrence of multiple signals within a drift time window was practically absent: T_0 reconstruction errors due to uncorrelated signals from the wire chamber and the PMT are therefore very rare. The counting rate from the internal PMT alone ($\approx$0.25 Hz) was compatible with the one computed from the cosmic-ray flux at sea level taking into account the acceptance window (for comparison, the trigger rate of the external muon telescope was about 1 Hz).

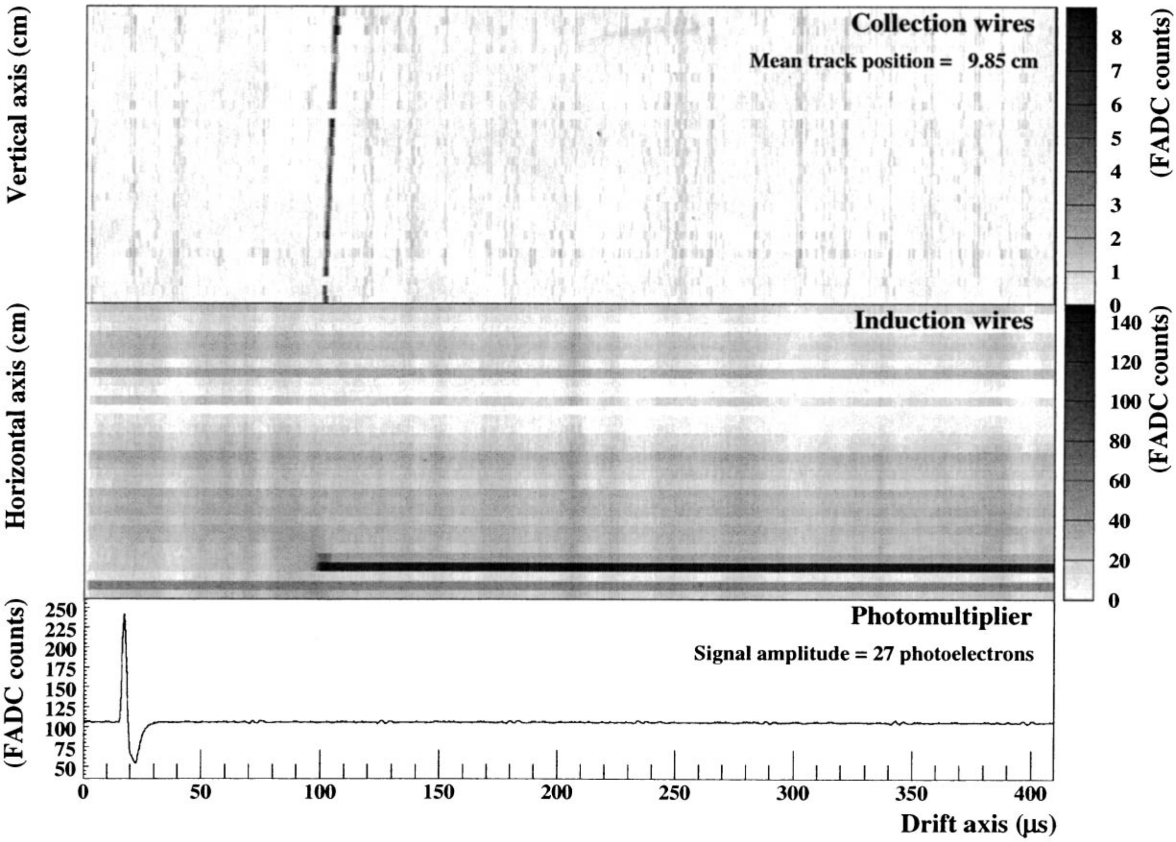

Fig. 2. Display of a muon crossing the detector. The grey level of the pixel codes the pulse height (FADC counts), proportional to the detected charge. In the lowest window is shown the signal from the internal PMT; the origin on the horizontal time axis is given by the primary trigger from the external muon telescope. The zero is slightly off-set (by about 20 μs) in order to have the signal fully contained in the display window.

The amplitude distribution of the PMT signals as a function of the track position along the drift axis was also measured with xenon-doped LAr (see Fig. 4). As expected, with the insertion of the quartz shutter, the light signal in pure LAr disappears, confirming that very little or no light is emitted at wavelengths significantly above 128 nm. On the contrary, with xenon-doping, a signal was seen with the shutter both on and off. This confirms that xenon produces a wavelength-shift of part of the light (slow component) into the optical transmission region of the quartz ($\gtrsim$150 nm). To compare the data in pure LAr with those with xenon-doping, one must take into account the different efficiencies for the 128 and 175 nm light: about a factor of two is lost at 175 nm due to the combined effect of the lower PMT quantum efficiency and the higher transmission efficiencies of the windows.

Visual inspection on an oscilloscope of the signals from the PMT indicated to us that the time structure does not change significantly when going from pure LAr to xenon-doped LAr at 100 ppm. We have not made a measurement of the decay time constant in the two cases, however, by comparing the relative signal amplitudes in pure LAr with the shutter off and in xenon-doped LAr with the quartz shutter on and off, we see that roughly 25% of the light in pure LAr remains at 128 nm while the rest is wavelength-shifted to 175 nm

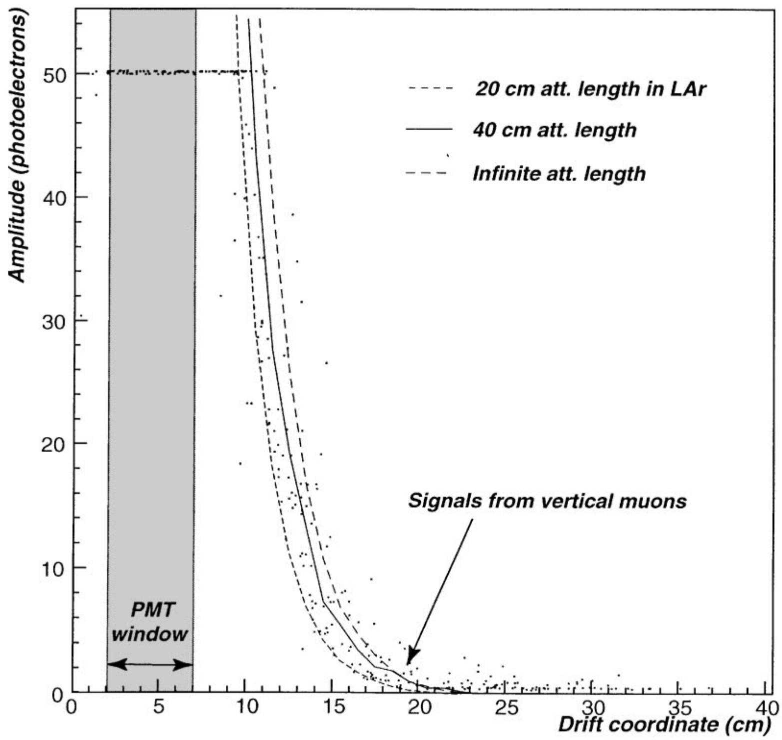

Fig. 3. Amplitude distribution of the PMT signals as a function of the track position along the drift axis in pure LAr. The drift coordinate express the distance from the electrode structure. The FADC saturates at ≈ 50 photoelectrons, i.e. for tracks crossing the detector very near to the PMT axis. Superposed to the data points are the curves obtained with the Monte Carlo simulation described in the text for three different attenuation lengths: 20, 40 cm and infinite attenuation length.

(Fig. 5). This indicates that, at 100 ppm, xenon shifts most of the slow component to 175 nm and that the resulting light is efficiently collected within the integration time of the shaping amplifier (1 μs). This is largely sufficient for our purposes, because a spread of 1 μs in the T_0 corresponds to an incertitude of the order of 1 mm in the global positioning of the event along the drift coordinate.

4. Conclusions

We successfully implemented a system to detect scintillation light in a LAr TPC prototype both in pure and xenon-doped LAr. The results of our measurements demonstrate that the use of a scintillation light signal to provide the absolute drift coordinate does not present any particular conceptual or technical problem. In fact:

- timing of the light signals was found to be always in agreement with that of the external fast triggering system (cosmic-ray telescope);
- light signals were quite distinct with rates compatible with those expected from cosmic-rays crossing the sensitive volume;
- no unexpected negative interference was found when operating a PMT in conjunction with the TPC;
- good agreement was found between our measurements and data on scintillation light properties in pure and xenon-doped LAr (light yield, time structure, wavelength, etc.).

The design of a T_0 system should therefore be straightforward, based on known data on scintillation light in LAr. However, for implementation on very large detectors like those in preparation for the ICARUS experiment, a good knowledge of the

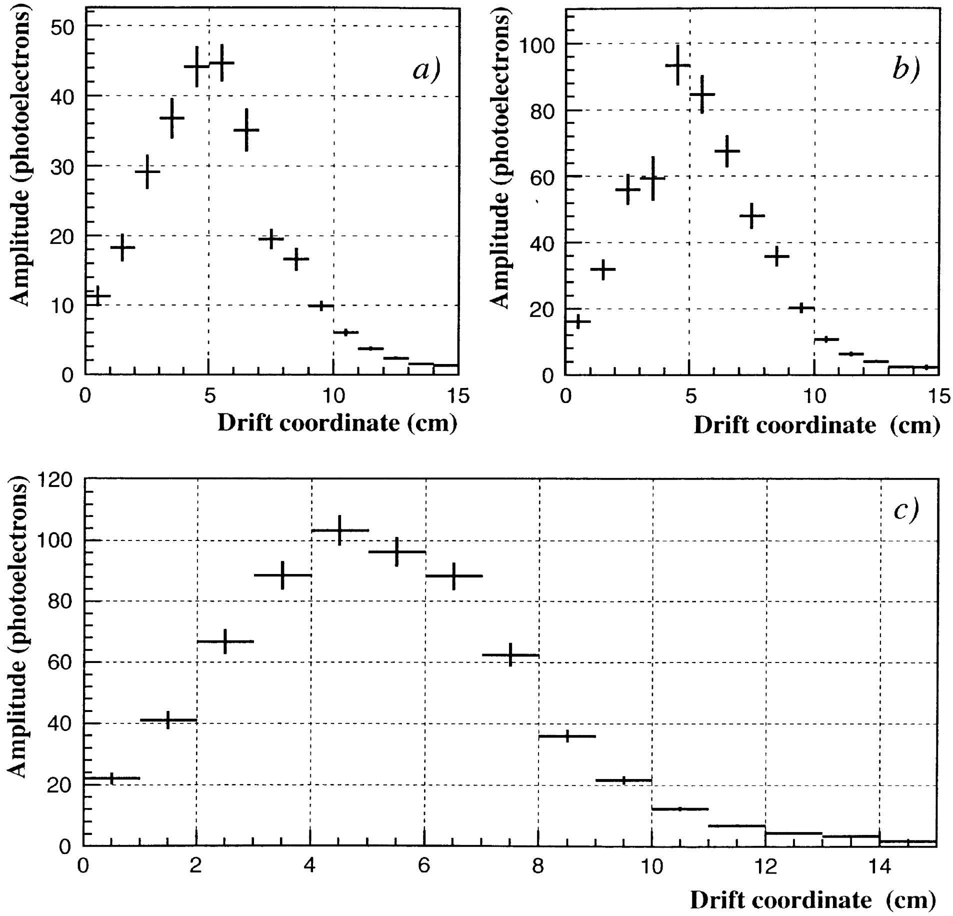

Fig. 4. Amplitude distribution of the PMT signals as a function of the track position along the drift axis in (a) xenon-doped LAr with the quartz shutter on; (b) xenon-doped LAr with the shutter off; (c) pure LAr. To avoid FADC saturation the gain of the amplifier of the PMT signal has been lowered by a factor of about 7 with respect to the one used for the data shown in Fig. 3.

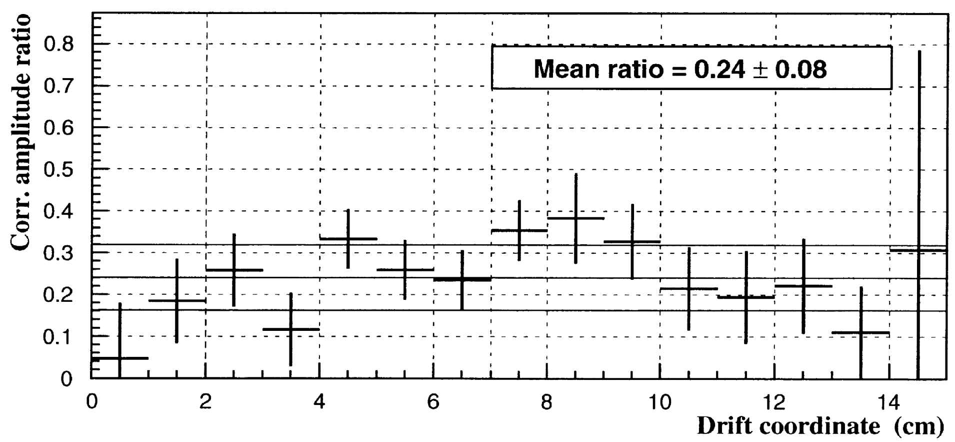

Fig. 5. Fraction of the 128 nm component that remains after doping LAr with xenon obtained by combining the three plots in Fig. 4 taking into account the relative efficiencies at 128 and 175 nm wavelengths.

light attenuation length is mandatory. Direct wavelength-shift by doping the LAr may be necessary if the attenuation length is found to be too short at 128 nm, the intrinsic wavelength emitted in LAr.

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