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Study of Xe-doping to LAr scintillator

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Abstract. Liquid argon (LAr) is an inorganic scintillator widely used in experimental physics. In this paper, the experimental study of Xe-doping as a volume-distributed wavelength shifter in LAr is described. The efficiency of light collection and the pulse shapes has been measured for the concentrations of Xe in Ar from few ppm to 24^{+16}_{-9} ppm. The stability of the data has been measured for the 24^{+16}_{-9} ppm concentration during 31 hours.

1. Introduction

A liquid argon (LAr) is widely used in experimental physics as a detection medium for particles and radiation, in particular, for Dark Matter search for [1,2] and neutrino detection [3,4,5]. The one of the main reasons for this is the excellent scintillation properties of the LAr: the high scintillation efficiency and self-transparency of the LAr to the scintillation light. The disadvantage of the LAr as a scintillator is a very short wavelength of the scintillation emission, 128 nm. There are no commercially available cryogenic photomultiplier tubes (PMTs) with the large photocathodes for this wavelength. The common solution of this problem is the use of a PMT combined with a wavelength shifter (WLS) [6,13].

The most popular WLS for the LAr scintillator is a tetraphenyl butadiene (TPB). TPB is used for coating by a thin film the detector walls, PMT windows, optically transparent plates in front of PMTs etc. [1,2,3,4,5]. There is also the possibility to use a nanostructured organic luminophore (NOL) films for the purpose of wavelength shifting [7,13]. However, in the film-type WLSs, a natural inefficiency arises from the 4 pi emission of the WLS light. The significant part of the light is lost, thus.

An elegant and attractive idea is to use a volume distributed WLS that provides the more efficient collection of the reemitted light than that with the deposited WLS. Several experimental groups are working with Xe-doping to LAr [8,9]. Scintillation of LAr has fast and slow components (decay of singlet and triplet state, correspondingly) with very different decay times (7 ns and ~1 μs). The ratio between these components depends on the sort of particles. This allows one to perform a pulse shape analysis for selection the events caused by the specific type of particles, for example, the nuclear recoil events in the dark matter search for and neutrino experiments. But xenon doping to LAr affects

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significantly on scintillation kinetics of LAr, and consequently, on the efficiency of pulse shape analysis [8,10,11]. The second point of interests is stability of mixture. The temperature of Ar in liquid state is ~ 85 K. At this temperature, one may expect decreasing of the Xe concentration in LAr in time caused by sorption of Xe on the cold detector walls.

In this paper, we describe our R&D in this direction. This work was inspired by the idea to use the same detector (RED-100 [14]) having the PMTs sensitive to the 175-nm Xe scintillation light filled sequentially by the liquid xenon (LXe) and then by the LAr for the first observation of the effect of elastic coherent neutrino-nucleus scattering by different targets in the experiment COHERENT [15].

2. Test cell and scheme of measurements

For experimental study of WLS characteristics in liquid noble gases (LAr, LXe, LKr) we use a test cell shown in figure 1. The cell temperature is maintained by equilibrium of the heater (10) power and the cooling power of the liquid nitrogen bath (6). The heater is wound on the copper screen circumjacing the cell. The pressure in the buffer volume (9) can be set from the vacuum to several bars depending on the required cooling power. The noble gas is condensed to the cylindrical volume (5) having 22 mm in diameter and 33 mm in height and viewed from the top by the VUV-sensitive (> 115 nm) MgF_2 -windowed PMT (4) (FEU-181 by MELZ, Moscow). The walls of this volume are machined with a zigzag shape in order to reduce the light reflection. There is an alpha source ^{241}Am installed at the bottom of the cell (8). The signal readout was done by two alternative ways: *first*, by a digital oscilloscope (Tektroniks TDS 5034) for the waveform recording, *and second*, by the ORTEC multichannel analyser (MCA) 927 for the quick measurements of the light pulse height. In the series of measurements with LAr + Xe, a fused silica plate was installed in front of the PMT in order to detect only the light reemitted by Xe.

3. Experiment

3.1. Preparation of Ar-Xe mixture.

The mixture of Ar-Xe was prepared at the room temperature by filling to a certain pressure the evacuated small pipe with the known volume and then by subsequent opening this pipe to the high pressure cylinder containing Ar. By concentration of Xe in the Ar-Xe mixture we define a molar concentration ($\text{mol}_{\text{Xe}}/\text{mol}_{\text{Ar}}$) at the initial room temperature conditions. In principle, during the gas condensation to the test cell part of the Xe may be frozen on the pipe wall above the test cell. In the

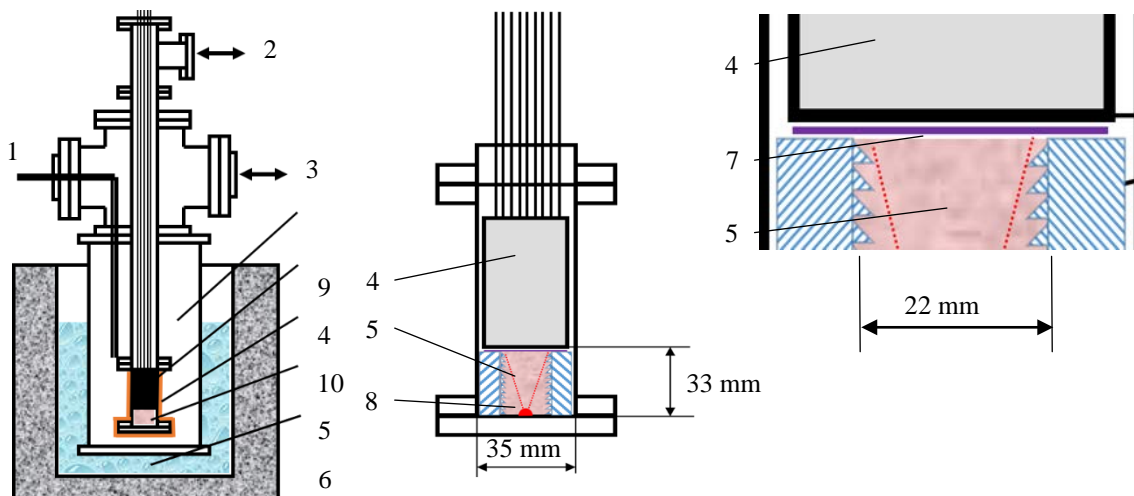


Figure 1. Test cell; 1 – thermocontrol port; 2 – gas inlet/outlet; 3 – vacuum port; 4 – PMT FEU-181; 5 – liquid noble gas sample; 6 – LN_2 bath; 7 – fused silica filter; 8 – ^{241}Am source; 9 – buffer volume; 10 – heater.

design shown in figure 1, the temperature of the wall above the test cell must be higher than that of the cell. Thus, eventually, all the Xe must migrate to the cell volume. However, the real ultimate concentration of Xe in the *liquid* Xe is unknown for us. Note, that we were limited in preparation of the smallest concentration by the accuracy of the pressure measurement in the pipe: the lowest pressure was defined as one division on the mechanical vacuum gauge equal to 0.005 bar. Mixtures with two concentrations Xe in Ar were prepared for tests: 14_{-5}^{+9} ppm and 24_{-9}^{+16} ppm.

3.2. Measurements

3.2.1. Pulse height spectra and waveforms. Measurements were performed with the undoped Ar and with Ar-Xe mixture at two concentrations. The results are shown in figures 2 and 3 for the pulse height and waveform measurements correspondingly. The pulse height spectrum obtained with the undoped Ar is show in figure 2 (a). The peak position is at 86 ± 2 channel (a.u.) of ADC. In spite of the use of the fused silica plate as an optical filter for the 125-nm scintillation light of LAr we, nevertheless, observed the signal. The averaged waveform obtained in this measurement is shown in figure 3, *red* curve. The fact that the shape of the slow component of scintillation (having in our case 455 ± 10 ns exponential decay time at the end of the puls) differs from the classical exponential shape of scintillation in LAr [12] with a decay constant of ~ 1.2 μ s and behaves quite similarly to the typical scintillation shapes for LAr-Xe mixtures (see [8,10,11]) may be explained by the presence of Xe in Ar at a ppb level. Such amount could be in the initial gas from a manufacturer (< 5 ppm of all impurities) or in the gas system. For example, traces of Xe in the Millipore gas getter could remain from the previous Xe tests with the same test cell. Note that the peak on the red line is not a fast component of scintillation. It is an artificial spike caused by the waveforms averaging procedure for small signals: since the statistics of photoelectrons is quite poor in these signals the start point was always assigned to arrival of the first photoelectron in the waveform, i.e. the spike is an average single photoelectron waveform.

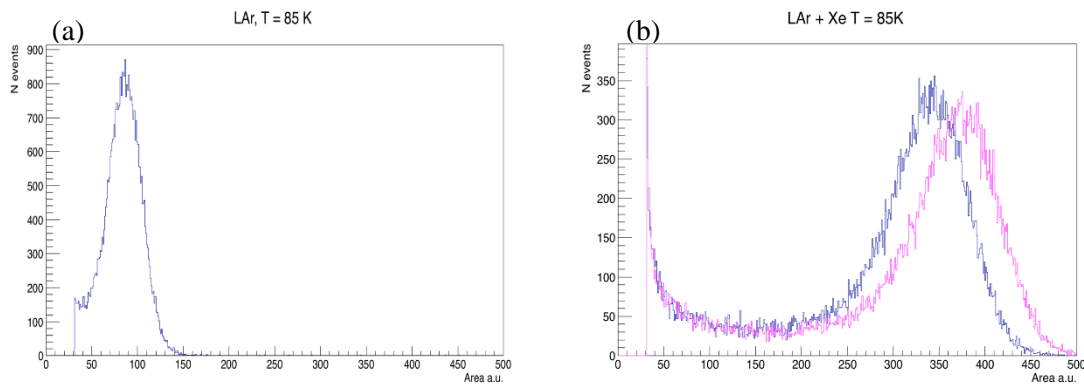


Figure 2. Pulse height spectra measured for the undoped Ar (a) and for Ar-Xe mixtures: blue line corresponds to 14_{-5}^{+9} ppm Xe injection, magenta – 24_{-9}^{+16} ppm Xe injection (b).

The pulse height spectra measured with the Xe doped Ar are show in figure 2 (b). The alpha-peak positions are 341 ± 3 and 375_{-3}^{+4} a.u. for 14_{-5}^{+9} ppm and 24_{-9}^{+16} ppm Xe concentrations correspondingly. The averaged waveforms for these concentrations are shown in figure 3, *blue* and *magenta* curves correspondingly. One can see that the fast component is practically vanished at these concentrations. The artificial spike has also disappeared since the statistics of photoelectrons is high. For the 24_{-9}^{+16} ppm Xe concentration mixture measurements were done also without fused silica plate in front of the PMT (*green* line on the figure 3). The prominent difference between the datasets obtained with and without fused silica plate (serving as a filter for 125-nm): the peak that can be attributed to the fast scintillation component is clearly visible in the last case. The waveform obtained without fused silica plate is similar to that, obtained in [8] with the use of the TPB wavelength shifter placed in front of PMTs, i.e. in the light detection system sensitive as in our case both to the Ar and Xe emission

wavelengths. Since in [8] the concentration of Xe in Ar is by weight (not in mole/mole) our data would corresponds 79 ppm concentration in that paper. One can select the data in [8] measured at 70 ppm concentration which is the closest one to 79 ppm (see figure 4, 4-th row from the top). For that waveform, as in our data, the amplitude of the fast component is significantly higher than the amplitude of the slow component for neutrons.

The obtained results evidently show that practically only the slow component undergone wavelength shifting by Xe. The basic consequence from this fact is that it is impossible to use the detector designed for operation with the liquid Xe, i.e. having fused silica windowed PMTs, for detection of liquid Ar scintillation without losing the capability of fast-to-slow component pulse shape analysis.

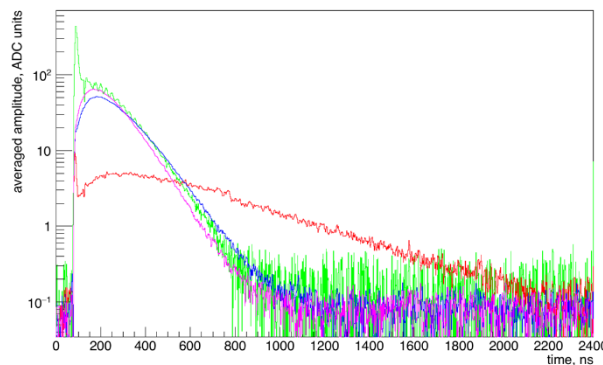


Figure 3. Averaged waveforms for different Xe contaminations. Red line stand for “pure” argon, blue – 14^{+9}_{-5} ppm Xe injection, magenta – 24^{+16}_{-9} ppm Xe injection, green – 24^{+16}_{-9} ppm Xe mixture without fused silica plate in front of the PMT.

3.2.2. Stability. A long term stability of scintillation characteristics of Ar-Xe mixture is very important. In a continuous 31-hours run, the stability of the 24-ppm Ar-Xe mixture characteristics was checked. The temperature of the test cell was maintained at 86 ± 1 K. During the run, 33 datasets by MCA of 10^6 events in each and 8 datasets by digital oscilloscope of 10^4 events in each were recorded. These data were used for monitoring of the peak position and the stability of average waveform. The averaged waveforms for all 8 datasets are shown in figure 4 (a); the evolution of the alpha peak position is shown in figure 4 (b).

One can see that there is no noticeable change in the average waveform during this run. There is the small drift (of $\sim 1.3\%$) of the peak position during the run which we may attribute to the PMT instability. It is important that it is in the opposite direction than one may expect from the effect of decreasing of the Xe concentration.

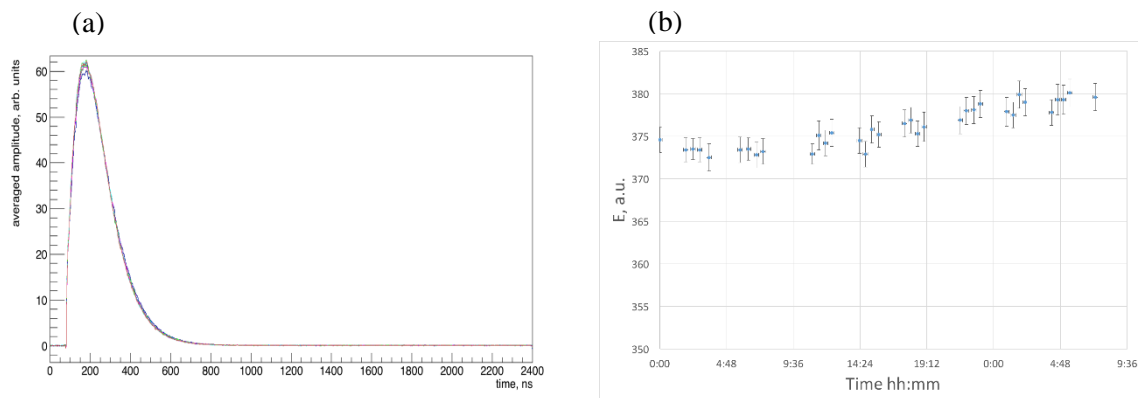


Figure 4. Mixture stability. (a) 8 averaged waveforms for different 8 time intervals. (b) MCA data for alpha peak position during the 31-hour run.

4. Conclusion

In this paper, we describe our study of the Xe-doping as a volume-distributed WLS in LAr. We confirm experimentally for the first time that only the slow component of the LAr scintillation light can be wavelength shifted by Xe. The consequence from this fact is that one cannot use Xe-doping as the only one WLS-technology in LAr detectors designed for operation with LXe without losing capability of slow-to-fast component PSD analysis.

The stability of Ar-Xe mixture was demonstrated during a continuous 31-hours run for the first time. This fact is very important for Xe-doping WLS technique for LAr detectors.

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