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Dynamics of the ions in liquid argon detectors and electron signal quenching

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ABSTRACT

A study of the dynamics of the positive charges in liquid argon has been carried out in the context of the future massive time projection chambers proposed for dark matter and neutrino physics. Given their small mobility coefficient in liquid argon, the ions spend a considerably longer time in the active volume with respect to the electrons. The positive charge density can be additionally increased by the injection, in the liquid volume, of the ions produced by the electron multiplying devices located in gas argon. The impact of the ion current on the uniformity of the field has been evaluated as well as the probability of the charge signal quenching due to the electron–ion recombination along the drift. The study results show some potential concerns for massive detectors with drift of many meters operated on surface.

1. Introduction

Liquid argon (LAr) detectors have been widely used during recent years in several fields ranging from neutrino physics [1–3] to direct dark matter searches [4–6], given their particle identification and low energy threshold capabilities in large active volumes [7]. In particular a massive liquid argon time projection chamber (LAr-TPC) is the chosen design for the next generation of underground neutrino observatories recently proposed [8].

Particle interactions in argon produce simultaneous excitation and ionization of the atoms, generating VUV photons and ion/electron pairs. In a typical LAr-TPC, photon sensors are used to detect the scintillation light, while a constant electric field $\vec{E_d}$ drifts the electrons to the anode. The charge readout can be carried out through the collection of the electrons on thin wires placed directly in the liquid [9] or, for double phase liquid–vapor detectors, through their extraction to a gas region placed above the sensitive volume [10]. In this case, a Townsend avalanche can be induced through high electric fields, producing an amplified signal proportional to the number of primary electrons extracted from the liquid phase.

Both single and double phase options are presently investigated for the DUNE experiment [8], with maximum electron drifts of 3.6 m and 12 m, respectively. Other experiments foreseeing drift up to 20 m have been recently proposed [11–14], which require a considerable technological effort to maintain a level of contamination less than 60 ppt of O_2 equivalent [15] (electron half life $>$ 5 ms [16]), in order to reduce the impact of the electron quenching by electronegative impurities contaminating the LAr bulk. A direct charge readout with the wires in a single phase chamber has the advantage of an overall simplified detector design, while the amplification in the gas phase makes it possible to detect smaller charge signals, thus allowing it to reach a lower energy threshold, or to exploit longer drift distances with respect to the single phase design.

The positive and negative charges, produced by the particle interactions in the liquid, drift to the cathode and the anode following the same field lines, although the former have a drift speed which is six orders of magnitude lower than the latter ($v_i \ll v_e$) [17,18]. As a consequence, the positive ions spend more time in the liquid before they get collected on the cathode and neutralized, and the ion charge density is much larger than that of the electrons ($\rho_i \gg \rho_e$). This effect can be particularly relevant for double phase detectors foreseeing large charge amplification factors, where the ions, created in the vapor volume, may drift back to the cathode crossing the gas–liquid interface and further increase the ρ_i in the active volume. The space charge can locally modify the amplitude of the electric field, the drift lines and the velocity of the electrons produced in the liquid, leading to a displacement in the reconstructed position of the ionization signal. Additionally, the positive density ρ_i can be sizable such that the probability of a “secondary electron/ion recombination”, different than the primary electron/parent-ion columnar recombination

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[7], has to be considered between the charge signal produced in the liquid and the ion current. The effect can cause an additional signal loss, with a probability dependent on the electron drift path, that could resemble the charge quenching given by the electronegative impurities in the active volume.

In the present article, we evaluated the impact of the positive charge density, produced by the cosmic rays and by the ^{39}Ar contamination in natural argon, on the electron signal in massive detectors, evidencing, for the first time, an intrinsic limit for the LAr technology given by the maximum drift obtainable with a TPC operated with natural argon, even in case of a low background radiation environment and infinite liquid purity. This aspect can affect the dark matter experiments with a few meters drift only in case of very low drift fields ($\lesssim 100$ V/cm), however the study could be particularly relevant for the new generation of neutrino experiments foreseeing drift paths of many meters, especially for what concerns the supernovae neutrino detection and low energy neutrino research. Particularly, in Section 4 we took into account the design of the protoDUNE detectors, which will be operated on the surface, and the layout of the two single and double phase module types planned for the underground DUNE experiment. More detailed experimental studies and additional cases will be reported elsewhere [19].

2. Dynamics of the ions and impact of the interface gas/liquid

In a double phase detector, the ionization electrons, produced by the particle interaction in the active volume, drift to the gas region where they are extracted and accelerated with the production of a Townsend avalanche. At the same time, given the low diffusion of the ions in gas argon relative to the typical size of the amplification region, a non-negligible fraction of the Ar ions produced by the avalanche can drift back to the liquid interface along the same field lines followed by the extracted electrons. When the distance between the ion and the liquid–vapor interface is greater than several angstroms, the liquid is treated as a continuum, thus an approximated description of the dynamics can be obtained solving a boundary condition problem between different dielectrics with the mirror charge method in a single dimension [20]. Accordingly, a point like charge q in a medium with permittivity ϵ, placed near the interface with another medium with permittivity ϵ', produces a mirror charge $q' = -q \cdot (\epsilon' - \epsilon)/(\epsilon' + \epsilon)$. Taking into account that the relative permittivity is $\epsilon_{LAr} = 1.5$ for liquid argon and $\epsilon_{GAr} = 1$ for argon vapor, the corresponding potential energy for an ion placed at a distance $d > 0$ from the liquid–vapor interface is a function of the inverse of the distance from the surface [21,22]:

$$V_{LAr}(d) = \frac{q^2}{16\pi\epsilon_0\epsilon_{LAr}}\left(\frac{\epsilon_{LAr} - \epsilon_{GAr}}{\epsilon_{LAr} + \epsilon_{GAr}}\right)\frac{1}{d} + c_{LAr} \equiv \frac{A_{LAr}}{d} + c_{LAr}, \qquad (1)$$

$$V_{GAr}(d) = \frac{q^2}{16\pi\epsilon_0\epsilon_{GAr}}\left(\frac{\epsilon_{GAr} - \epsilon_{LAr}}{\epsilon_{LAr} + \epsilon_{GAr}}\right)\frac{1}{d} + c_{GAr} \equiv \frac{A_{GAr}}{d} + c_{GAr}, \qquad (2)$$

and it is depicted in Fig. 1, where the integration constants c_{GAr} and c_{LAr} account for the potential energy of the ion when it is far from the interface (see Eq. (3)).

Classically, the potential is infinite at $d = 0$, thus it has been sometimes assumed that the barrier can preclude the ions from reaching the liquid phase [23], although that is true only if the charge can be approximated as point-like. Considering dimensions of the order of 1 Å, as it is the case for the ionized atomic or molecular states whose formation is typical in noble gases [7], the mirror approximation is no longer valid. As the ion approaches the interface, it induces a displacement of the charge in the liquid that reduces the potential energy. The effective potential should decrease monotonically as the ion plunges into the liquid, following a sigmoidal shape (dashed line, Fig. 1), thus the problem is reduced to a finite classical potential barrier.

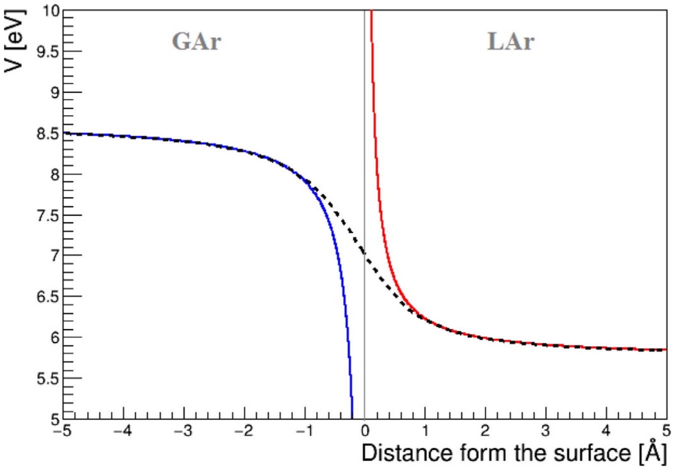

Fig. 1. Potential energy (solid lines) at the liquid (right-red) / vapor (left-blue) interface in the mirror charge approximation and possible effective potential energy (dashed line, see text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

At the same time, the crossing of the liquid–gas interface is energetically favored. Considering the ion as a uniformly charged sphere of radius a, its potential energy far from the surface can be expressed as:

$$V = \frac{3}{5}\frac{q^2}{4\pi\epsilon a}. \qquad (3)$$

Taking into account that a is of the order of ≈ 1 Å, the ≈ 2.9 eV difference between the potential energies at the interface allows the injection of the ions into the liquid,[1] thus the possibility that a large fraction of the positive charge produced in the gas phase enters the liquid cannot be discarded.

For the present study it is irrelevant what kind of charge amplification device is used: we introduce the ion gain G_I defined as the number of positive ions injected into the liquid for each electron extracted. This factor is proportional to the electron amplification G through a constant β ($\beta < 1$) which takes into account the average loss of the positive charge in the gas, given by the ions scattering onto field lines not ending on the liquid surface,[2] as well as the efficiency to pass the liquid–gas interface. If the amplification factor G_I is large enough, the positive charge density ρ_i in the liquid can be widely increased by the secondary ions produced by the avalanche.

3. Drift field distortion and electron–ion recombination

We consider a LAr-TPC with an axial geometry and the l axis perpendicular to the surface of the liquid (Fig. 2–*left*). The drift field $\vec{E_d}$ in the liquid is along l, with the anode at the origin ($l = 0$) and the cathode at a positive distance L. In the following calculation we assume that the detector is wide enough such that the transverse coordinate is not relevant for the discussion and $\vec{E_d}$ is constant in any transverse section of the detector.

In the limit of a null ion current, the drift field is constant and it is equal to the cathode voltage divided by the total drift length L. On the contrary, an ion cloud makes the drift field to change with

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[1] According to the model presented, the difference between the potential energy of the ions at the liquid/gas interface is one order of magnitude larger than that of the electrons (0.21 eV [23]).

[2] The value of β depends on the geometry and the field configuration of the specific charge amplifying device.