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Helium–Xenon mixtures to improve the topological signature in high pressure gas xenon TPCs☆

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ABSTRACT

Within the framework of xenon-based double beta decay experiments, we propose the possibility to improve the background rejection of an electroluminescent Time Projection Chamber (EL TPC) by reducing the diffusion of the drifting electrons while keeping nearly intact the energy resolution of a pure xenon EL TPC. Based on state-of-the-art microscopic simulations, a substantial addition of helium, around 10 or 15 %, may reduce drastically the transverse diffusion down to 2.5 mm/$\sqrt{m}$ from the 10.5 mm/$\sqrt{m}$ of pure xenon. The longitudinal diffusion remains around 4 mm/$\sqrt{m}$. Light production studies have been performed as well. They show that the relative variation in energy resolution introduced by such a change does not exceed a few percent, which leaves the energy resolution practically unchanged. The technical caveats of using photomultipliers close to an helium atmosphere are also discussed in detail.

☆ next The NEXT Collabration

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1. Introduction

Double beta decay is a process that has been observed for very few nuclei in its two-neutrino mode. The unambiguous observation of a neutrinoless double beta decay ($0\nu\beta\beta$) would definitely establish neutrinos as Majorana particles, which would ultimately demonstrate the existence of lepton number violating processes [1]. Luckily, one of these nuclei of interest is an isotope of Xenon, ^{136}Xe . Being a noble gas, Xenon can be used in Time Projection Chambers (TPCs) where the target mass is actually the detection volume. The scalability offered by xenon as a detector medium is a key factor in order to probe the entire inverted hierarchy, which would require reaching a maximum sensitivity to the effective Majorana mass of the electron neutrino, $m_{\beta\beta}$, of about 15 meV. In order to reach this sensitivity, ton scale detectors with a background rate less than 1 count/year in the region of interest are a must. The grail of all rare event experiments, which is exacerbated in neutrinoless double beta experiments, is to reach the background free regime.

In this context, one of the specific technologies under development is the electroluminescent (EL) high pressure xenon Time Projection Chamber [2], currently led by the NEXT collaboration [3] that is using a plane of 1 mm^2 SiPMs at 10 mm pitch and 8 mm from the center of the EL region to perform the tracking of the events. Several advantages of this design include good energy resolution, in the sub-percent range at $Q_{\beta\beta}$ (2459 keV), and the ability to perform topological reconstruction of events at this energy.

An ~MeV electron moving through the gas loses its energy at a relatively constant rate until the end of its path where the energy deposition rate increases. As a result, a fully contained ionization trail left by such an electron showcases a 'blob-like' end-point. The topology expected from a double beta event consists then of two electron tracks fully contained in the fiducial volume with a common origin and two 'blobs' at their ends. The main background source around $Q_{\beta\beta}$ stems from the γ-rays emitted from ^{208}Tl and ^{214}Bi events for which one of the end-points of the resulting track is misidentified as a blob. In addition, any characteristic X-rays emitted during the interaction of these gammas must convert relatively close to the main ionization track to avoid being clearly separated from it. While the ionization trail is drifted toward the EL region, the diffusion of the ionization electrons degrades the imaging performance of the TPC. Limiting its impact down to the level of the technical limitation set by the pixel pitch and EL gap thickness will allow for improved background rejection and therefore a reduced background rate.

Hence, the topological resolution is limited by instrumental factors, tracking plane segmentation and the width of the EL region, and physical limitations due to the diffusion of the drifting electron cloud. Diffusion is particularly large in pure xenon (see [4] for further discussion specific to NEXT detectors). After one meter of drift, a point-like ionization deposit becomes a cloud distributed as a Gaussian of 10 mm sigma in the direction perpendicular to the electric field (transverse) and 4 mm in the parallel direction (longitudinal). This situation is far from ideal and can be largely improved by adding molecular electron coolants to the gas [5,6] or by positive-ion detection [7]. As a reference, the thermal diffusion limit which can be found in [8] gives a diffusion factor of $\sim 1.5\ \mathrm{mm}/\sqrt{\mathrm{m}}$ for a field of 250 V/cm, which is very close to the $\sim 2.5\ \mathrm{mm}/\sqrt{\mathrm{m}}$ value obtained for instance in Xe/CO_2 mixtures [6].

Looking forward, this paper explores the possibility of using a substantial addition of helium to reduce the transverse diffusion while keeping the energy resolution intact. Helium is a particularly interesting alternative to the use of molecular additives, being easier to handle and expectedly free from light quenching effects. Its working principle and main enabling assets are sketched in this communication.

Table 1
Mean fractional energy loss of electrons in collisions against noble gas atoms.

He	$2.74 \cdot 10^{-4}$
Ne	$5.44 \cdot 10^{-5}$
Ar	$2.75 \cdot 10^{-5}$
Kr	$1.31 \cdot 10^{-5}$
Xe	$8.07 \cdot 10^{-6}$

2. Electron cooling and diffusion

The high diffusion of electrons drifting in heavy noble gases is a well known issue. For VUV-quenched gas mixtures, as those commonly used in the operation of gaseous detectors, the presence of molecular additives (CH_4, CO_2, C_4H_{10}, ...) can be used advantageously in order to adjust diffusion. The low energy rotational and vibrational states of these molecules allow the electrons to cool down very effectively leading to very low diffusion. This solution, applied to an EL Xenon TPC, is detailed in [9]. In this section we discuss the diffusion in pure noble gases and explain the mechanisms by which adding helium significantly reduces diffusion in xenon. We also present results of simulations demonstrating that helium-doped xenon is a serious candidate in the prospect of lowering the gas diffusion, maintaining the energy resolution of pure xenon at the same time.

2.1. Transverse diffusion

While drifting in a noble gas TPC, secondary electrons reach statistical equilibrium by balancing the energy gained through the action of the electric field with that lost in collisions with the environmental noble gas atoms. The fact that electron energies (under the typical drift fields in TPCs) are far from the excitation levels of the noble gas atoms implies that electron–atom collisions are elastic, allowing a fairly accurate estimate of the momentum transfer by using a classical kinematic calculation of two body collisions. The momentum transfer efficiency depends, then, on the mass ratio of the two bodies. Assuming isotropic scattering, one can approximate the fractional energy loss averaged over all scattering angles by the formula:

$$\frac{\delta\varepsilon}{\varepsilon} \sim \frac{2mM}{(m+M)^2} \qquad (1)$$

where m is the electron mass and M is the atomic mass of the noble gas. Table 1 lists this value for all noble gases generated using Eq. (1). It must be said that elastic scatterings are not necessarily isotropic, but this assumption is reasonable for helium in the whole context of this paper [10]. As for xenon, this is a valid assumption for electron energies up to about 2.75 eV [11]. As can be seen on the bottom panel of Fig. 1, this condition is well fulfilled.

By contrast to this large increase of the momentum transfer for light gas, one could expect that the total energy loss of the electrons will remain approximately constant as the cross section at very low energies becomes much larger for xenon than for lighter atoms, by virtue of its larger size ('solid sphere' model). However, the existence of the Ramsauer minimum [12] in the xenon cross section that can be seen in Fig. 1 counteracts the increase in atom size, making the overall electron cooling of helium much more effective.

Neon and helium are the two natural options with respect to Table 1. While neon is easier to manipulate, helium is much more promising in terms of performance, as can be expected from its higher cross section at eV energies.

We provide the results of simulations performed with the software Magboltz [14] as shown in Fig. 2. The most relevant parameter to look at is the transverse diffusion, which is the dominating factor in the overall 3D diffusion. Additionally, as we will show, the transverse diffusion component is the one that can be drastically reduced in the presence of additives.