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Secondary scintillation yield of xenon with sub-percent levels of CO_2 additive for rare-event detection

The NEXT Collaboration

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ABSTRACT

$Xe–CO_2$ mixtures are important alternatives to pure xenon in Time Projection Chambers (TPC) based on secondary scintillation (electroluminescence) signal amplification with applications in the important field of rare event detection such as directional dark matter, double electron capture and double beta decay detection. The addition of CO_2 to pure xenon at the level of 0.05–0.1% can reduce significantly the scale of electron diffusion from 10 $mm/\sqrt{m}$ to 2.5 $mm/\sqrt{m}$, with high impact on the discrimination

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efficiency of the events through pattern recognition of the topology of primary ionization trails. We have measured the electroluminescence (EL) yield of Xe–CO_2 mixtures, with sub-percent CO_2 concentrations. We demonstrate that the EL production is still high in these mixtures, 70% and 35% relative to that produced in pure xenon, for CO_2 concentrations around 0.05% and 0.1%, respectively. The contribution of the statistical fluctuations in EL production to the energy resolution increases with increasing CO_2 concentration, being smaller than the contribution of the Fano factor for concentrations below 0.1% CO_2.

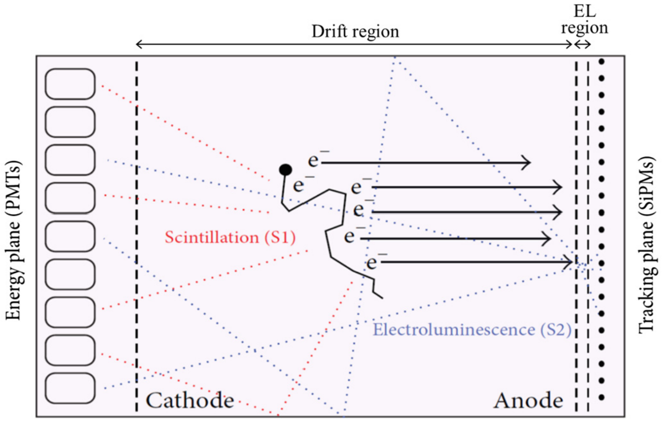

Fig. 1. Schematic of the EL-based TPC developed by the NEXT Collaboration for double-beta decay searches in ^{136}Xe.

1. Introduction

Many experiments aiming for rare event detection such as double beta decay (DBD) and double electron capture (DEC), with or without neutrino emission, as well as directional dark matter (DDM) use high-pressure xenon (HPXe) as the detection/target medium [1–7]. The physics behind these experiments is of paramount importance in contemporary particle physics and cosmology.

When compared to liquid xenon and double phase xenon TPCs [8–14], detection in the gas phase offers some important advantages. While the event detection in liquid TPCs allows for compactness and self-shielding, some features may be essential for the above experiments to succeed. The impact of background depends strongly on the achieved energy resolution, which is much better for event detection in gas than in liquid. Furthermore, event interaction in the gas will allow for discrimination of the rare event topological signature, as demonstrated for DBD and DEC detection [15,16,5], in contrast to the interaction in liquid, where the extremely reduced dimensions of the primary ionization trail rules out any possible trail pattern recognition.

In particular, optical TPCs based on secondary scintillation (electroluminescence) amplification of the primary ionization signal are the most competitive alternatives to those based on charge avalanche amplification. For the latter, the limited charge amplification at high pressure impacts the energy resolution, yielding at present a best value around 3% at 2.5 MeV for a 1 kg-scale prototype based on micromegas [17], to be compared to 0.7% obtained for an electroluminescence (EL) amplification prototype of similar dimensions [18]. In addition, when compared to conventional electronic readout of the charge avalanche, EL optical readout through a photosensor has the advantage of mechanically and electrically decoupling the amplification region, rendering more immunity to electronic noise, radiofrequency pickup and high voltage issues.

Fig. 1 depicts a schematic of a typical optical TPC. Most of the gas volume is occupied by the conversion/drift region where the radiation interaction takes place exciting or ionizing the gas atoms/molecules and leading to the emission of primary scintillation (the t_0 signal of the event) resulting from the gas de-excitation or electron/ion recombination. A low electric field, below the gas excitation threshold, is applied to the drift region to minimize recombination and to guide the primary electrons towards a shallow region with electric field intensity between the gas excitation and ionization thresholds, the scintillation region. Upon crossing this region, each electron gains from the electric field enough kinetic energy to excite the gas atoms/molecules by electron impact, leading to a large scintillation output upon gas de-excitation (electroluminescence). A pixelated photosensor plane enables to determine the x- and y-positions of the primary electrons arriving at the EL region, and the time interval between primary and EL scintillation pulses enables to determine the z-position of where the ionization takes place.

Absolute values of the EL light yield have been measured in uniform electric fields [19–21] and in the modern micropatterned electron multipliers, as GEM, THGEM, MHSP and micromegas [22–24]. The statistical fluctuations in the EL produced in charge avalanches are dominated by the statistical fluctuations in the total number of electrons produced in the avalanche, since all the electrons contribute to EL production. On the other hand, the statistical fluctuations in the EL produced for uniform electric fields below the gas ionization threshold are negligible when compared to those associated with the primary ionization formation [25]. The latter situation is most important when event to background discrimination is also based on the energy deposited in the gas, as is the case of DEC and neutrinoless double beta decay, where the best achievable detector energy resolution is important for efficient background rejection.

The effectiveness of event discrimination based on the topological signature of the ionization trail is related to the low electron drift velocity of xenon and, mainly, to its large electron diffusion. The large electron diffusion is determined by the inefficient electron energy loss in elastic collisions with the xenon atoms, in particular in the range of reduced electric fields of few tens of V/cm/bar used in the drift region. Diffusion hinders the finer details of the ionization trail, especially for large drift distances, and the discrimination based on the topological signature of the events becomes less effective [26].

The aforementioned problem can be mitigated by adding a molecular gas, like CO_2, CH_4 or CF_4, to pure xenon. With the addition of such molecules, new molecular degrees of freedom from vibrational and rotational states are made available for electron energy transfer in inelastic collisions. In this case, the energy distribution of the ionization electron cloud in the drift region tends to build up around the energy of the first vibrational level, typically at ∼0.1 eV, even in the presence of minute concentrations of molecular additives.

Until recently, it was believed that the presence of molecular species in the noble gas would dramatically reduce the EL yield that could be achieved. Experimental studies performed for Ar [27] have shown that the presence of CO_2 and CH_4 in concentrations