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Drift field limitations to the energy resolution in Time Projection Chambers for ^{136}Xe neutrino-less double beta decay search

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ABSTRACT

The effect of drift electric field in the degradation of the energy resolution of gaseous xenon Time Projection Chambers for the search of neutrino-less double beta decay of ^{136}Xe is calculated with the PENELOPE code. Calculations are presented first for single electron emission with energies from 0.2 to 3 MeV and reduced electric fields in the 0.1–2 V cm^{-1} Torr^{-1} range, showing energy resolution degradations by as much as 12% (FWHM). Calculations are also presented for neutrino-less double beta decay of ^{136}Xe assuming two decay mechanisms, the mass mechanism (MM) and the right-handed current due to the λ parameter (RHC$_\lambda$) mechanism, for reduced drift electric fields in the 0.03–0.8 V cm^{-1} Torr^{-1} range. It is shown that the drift field degrades the energy resolution of the two electrons sum peak (2457.8 keV) by an amount that is significant even for reduced fields as low as 0.1 V cm^{-1} Torr^{-1}. It is concluded that to reach the experimental target of 1% (FWHM) for the energy resolution of TPCs set-ups (like the NEXT collaboration set-up) the drift electric field should be weaker than about 0.1 V cm^{-1} Torr^{-1}.

1. Introduction

Double beta decay is a very slow nuclear process that can occur in two modes: (i) with two anti-neutrino emission and (ii) with no neutrino emission. While the first mode has already been observed for a few cases, there is insufficient experimental evidence regarding the observation of the second mode [1]. The observation of the neutrino-less double beta decay mode would mean violation of the lepton number conservation and that the neutrino is a Majorana particle, i.e. the neutrinos and anti-neutrinos are identical particles. While the first mode is characterized by a continuous beta ray energy spectrum of the two electrons emitted in the decay with total energies from zero up to the Q-value of the decay, the neutrino-less decay mode is characterized by a two electrons sum spectrum with a peak at an energy almost equal to the Q-value. Both processes can be simultaneously present. Therefore, the search for neutrino-less double beta decay should be based on large size and internal counting electron detectors with very good energy resolution ($\approx$1% or better) in an extremely low background environment.

About 10 different nuclides are candidates for such a search and various research groups are carrying out experiments with different set-ups [2]. One of the most interesting candidates is ^{136}Xe, which has the two possible decay modes

$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e + 2\nu$$

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with a Q-value of 2457.83(37) keV [3] but neither of these modes has yet been observed. A few groups are working on experimental set-ups aimed at detecting these ^{136}Xe processes [1], either with liquid Xe or else with high-pressure xenon gas (HPXe) Time Projection Chamber (TPC) detectors [4]. The advantages of HPXe TPC detectors over liquid phase detectors have been discussed by Nygren [5] and lie in their superior potential as far as energy resolution is concerned, one of the most important issues for neutrino-less decay studies.

TPCs, as well as most other gaseous detectors, use an electric field to drift the primary electrons, produced in the gaseous medium by the ionizing beta rays, towards a region (a MWPC, a Micromegas or a secondary scintillation region) where a signal is expected to be produced with an amplitude proportional to the energy T_0 of the absorbed beta ray. However, since beta rays have energies that can reach values over 2 MeV, their tracks are lengthy (up to about 30 cm in Xe at 10 atm) and so the beta rays can gain or lose a significant amount of energy, from the drift electric field, along their tracks. For example (Fig. 1) a beta ray with energy T_0, starting at the z coordinate z_1 and stopping at z_2 will dissipate in the gas an energy of $T' = T_0 + qE(z_1 - z_2)$, where q is the modulus of the electron charge, which is less than T_0 (if the

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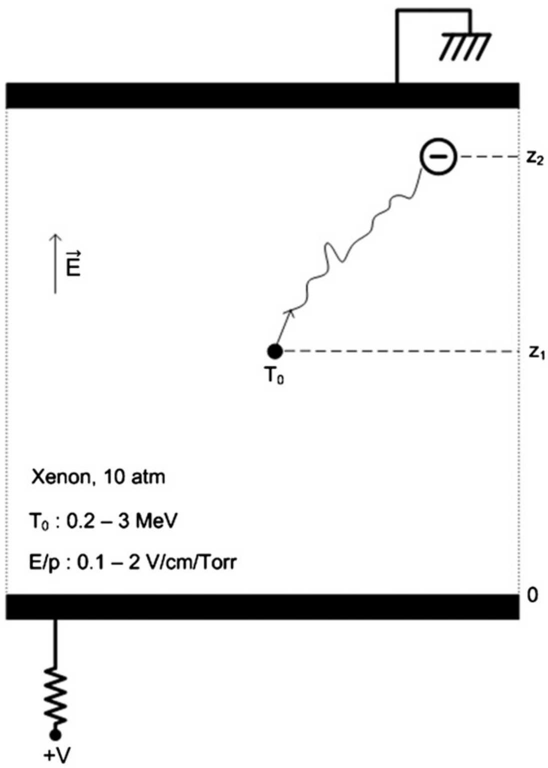

Fig. 1. Schematic representation of the track of a single electron with an initial energy T_0 in a gaseous Xe medium at 10 atm under the influence of a uniform electric field E.

beta ray moved in the opposite direction T' would be larger than T_0). This energy gain, or loss, can be large; for example for a 20 cm electron track in Xe at 10 atm under an electric field below the threshold for secondary scintillation (1 V cm^{-1} Torr^{-1}) it can reach values as high as 150 keV. This effect will introduce fluctuations in the energy dissipated in the gas and so in the number of primary electrons produced [6], degrading the energy resolution. In previous works [7–9], we have carried out the study of the degradation of the energy resolution with the magnitude of the drift electric field but for electron energies up to 200 keV and found the effect to be small. However, as discussed above, for 2–3 MeV electrons it might not be so.

The purpose of the present work is to study the effect of the drift electric field on the total energy deposited by the two electrons emitted in a ^{136}Xe 0ν2β decay. For that we use the PENELOPE code which simulates the electrons' tracks in Xe, during slow-down.

2. Simulation method

The PENELOPE software package [10] is a Monte Carlo algorithm based computer code used for the simulation of coupled electron–photon transport from energies of a few hundred eV up to 1 GeV, including the effect of the applied electromagnetic fields. In this type of applications the user defines the detector geometry and absorbing medium and PENELOPE routines keep track of several quantities, including the energy deposited during the absorption and energy degradation process.

This work has been divided into 2 parts. Firstly we assessed the effect of the drift electric field on the energy deposited by single monoenergetic electrons with energies from 0.2 to 3 MeV, isotropically emitted in a gaseous medium of Xe at 10 atm (Fig. 1). The reduced electric drift fields considered in the calculations are in the range 0.1–2 V cm^{-1} Torr^{-1}. We note that in the absence of an electric field the deposited energy is equal to the energy T_0 of the initial electron. Secondly we studied this same effect on the total energy deposited by the 2 electrons emitted in a ^{136}Xe 0ν2β decay for reduced electric fields in the range 0.03–0.8 V cm^{-1} Torr^{-1} (Fig. 2).

As in Ref. [11] two decay mechanisms were taken into account, the mass mechanism (MM) and the right-handed current due to the λ parameter (RHC$_\lambda$). The angle between the two emitted electrons (θ_{12}) and their kinetic energies (T_1 and T_2) were extracted from the respective probability distributions. Mathematical expressions for the probability distributions are given in Ref. [11] (using units such as the mass of the electron, m_0=1 and the speed of light c=1) by

$$\rho_{MM}(T_1,T_2,\cos\theta_{12}) = c_1(T_1+1)p_1(T_2+1)p_2 \times F(T_1,Z)F(T_2,Z)\delta(Q-T_1-T_2)(1-\beta_1\beta_2\cos\theta_{12})$$

$$\rho_{RHC}(T_1,T_2,\cos\theta_{12}) = c_2(T_1+1)p_1(T_2+1)p_2 \times F(T_1,Z)F(T_2,Z)(T_1-T_2)^2\delta(Q-T_1-T_2)(1+\beta_1\beta_2\cos\theta_{12})$$

here the electron momenta are $p_i=\sqrt{T_i(T_i+2)}$, velocities are β_i=$P_i/(T_i+1)$, and the mass difference is Q between the mother and daughter nucleus, which in this case is Q =2457.83(37) keV; c_1 and c_2 are normalization constants. The Fermi function F is given by

$$F(T,Z) = c_3 p^{2s-2} e^{\pi u} |\Gamma(s+iu)|^2$$

where $s=\sqrt{1-(\alpha Z)^2}$, $u=\alpha Z(T+1)/p$, $\alpha=1/137.036$, Γ is the Gamma function and c_3 is a normalization constant. Z is the atomic number of the daughter nucleus, which in this case is Z=56 (^{136}Ba). These curves were normalized to unit area before being used to simulate 0ν2β decays. 10^5 events were generated

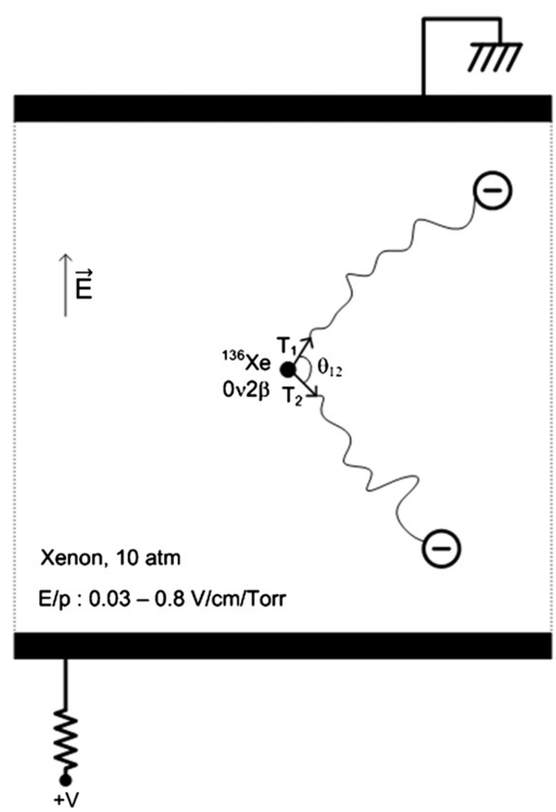

Fig. 2. Schematic representation of the tracks of the two electrons emitted in a ^{136}Xe 0ν2β decay under the influence of a uniform drift electric field E. T_1 and T_2 are the electrons' initial kinetic energies and θ_{12} is the emission angle.