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Xenon as a detector for dark matter search

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Abstract

We will discuss the detailed properties of xenon and its utilization for detecting weakly interacting massive particles (WIMPs). Xenon scintillation and proportional scintillation are the key factors in the problem of background rejection. We will also consider the possibility of doping liquid Xe with triethylamine (TEA), to lower the energy threshold and to improve background rejection efficiency. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

It is generally believed that more than 90% of the mass in our universe is dark matter (DM), which neither radiates nor absorbs electromagnetic waves. The observed evidence [1] shows that there are about 0.3 GeV/cm^3 DM around our solar system. If the DM is in fact weekly interacting massive particles (WIMP), then it should be detectable by Earth-based detectors. Because of the motion of the solar system relative to the centre of our Galaxy, the WIMPs will transfer energy to the detector nuclei via elastic scattering when the WIMPs pass through the detector. When xenon (Xe) is used as the detector media, the mean energy transfer is about 50 keV, and the event rate is in the range of 1×10^{-5} to 0.1 events/(day kg) [2]. It is a challenging task to detect such low energy and low rate events, because of the high radioactive background events near and from the detector. Currently, many experiments, involving different techniques, are being conducted.

Liquid xenon (LXe) was chosen as the detector media primarily because it has high scintillation yield and because of its high density and high atomic number. Since both the scintillation and ionization can be measured simultaneously, it is easy to differentiate the WIMP signal from those emanating from the background.

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In fact the signal due to Xe nuclei recoil by WIMP elastic scattering behaves like a heavy ionization signal inside LXe, while the signals from radioactive background are minimum ionising signals. Therefore, for the signals from WIMPs and background, the scintillation/ionization ratios of the total recoil energy are different [3].

The high density of Xe makes it easy to built a large-mass detector with a small structure and, thereby, reduces the cost of the dectector shieldings. The high atomic number is especially good for matching the high mass WIMPs kinematicly. The longest lifetime of the radioactive xenon isotope, Xe^{127}, is about 36 days, and using enriched xenon [4], which is Kr-free, makes it possible to construct a detector with extremely low background from the detector itself.

Within the Zeplin II [5] project, the UK RAL group is working on the initial phase of the detector. This phase will only measure Xe scintillation and will use techniques that are similar to those employed by the DAMA group [4]. Discrimination scintillation pulse shape will be considered in this test, because the decay profile of the scintillation by Xe recoil is different from that of the background signal [6].

Because the mean recoil energy is only around 50 keV, the ionization yield is too small for readout by charge amplifiers. Proportional scintillation, which is scintillation caused by electrons drifting under very high electric field around thin wires in LXe, makes it possible to measure the ionization component from the low-energy gamma background [3]. Extensive studies have been conducted with a 2 kg detector by the ICARUS group [3,7].

During the past two years, we have been studying the double-phase Xe detector that is installed at CERN. The electroluminescence in gaseous Xe gives much higher light output and better stability for the ionization measurement. The number of luminescence photons produced by one electron under uniform electric field is well approximated by $N_{\mathrm{ph}} = 70 \times [(E/P) - 1.0] \times \mathrm{d}P$ [8]. Where P, E, and d are, respectively, gas pressure, electric field strength, and drift distance. By drifting the ionization electrons from the liquid to the gas phase, the ionization component can be measured by means of luminescence photons. As in the liquid-only case, the ionization components can be measured by means of proportional scintillation photons. Fig. 1 shows the correlation plot of primary versus secondary scintillation. It is shown clearly that the background rejection (left) obtained by the double phase (liquid and gas) detector is much better than that obtained by the single phase detector (right). A 99.8% rejection was obtained by the liquid-only phase; the double phase is still under investigation.

Another possibility, which is also being studied at CERN, is to use double-phase Xe doped with triethylamine (TEA)[(C2H5)3N] as the DM detector. The TEA acts as the internal photocathode to convert the Xe primary scintillation photons into free electrons, which will then be transported to the gas phase. Electroluminescence will take place when electrons are moving under very high electric field in gaseous Xe. When uniform electric fields are provided in the drift region of the LXe, the shape of the electron cloud can be maintained so that it gives a unique signal-to-background discrimination.

2. The detector design

We will concentrate on the two-phase TEA-doped Xe detector. Because it collects primary light much better, it has a very low energy threshold; it may also have a much better background

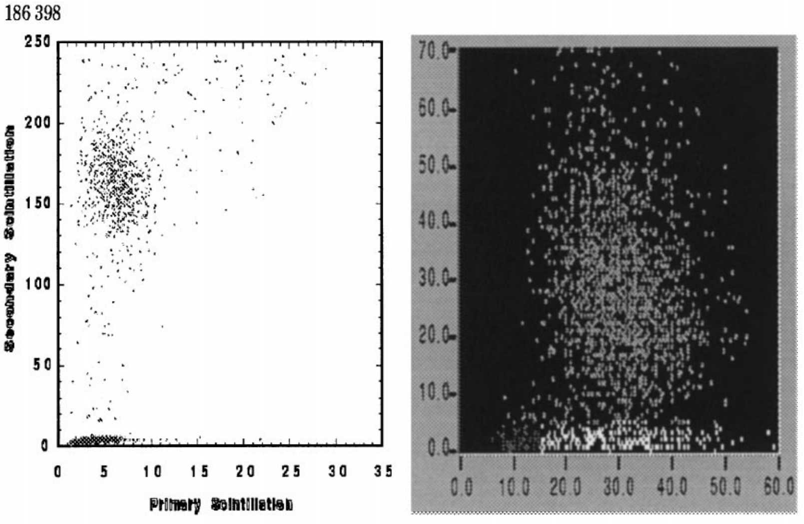

Fig. 1. Primary vs. secondary scintillation in double phase (left) and liquid-only phase detector (right).

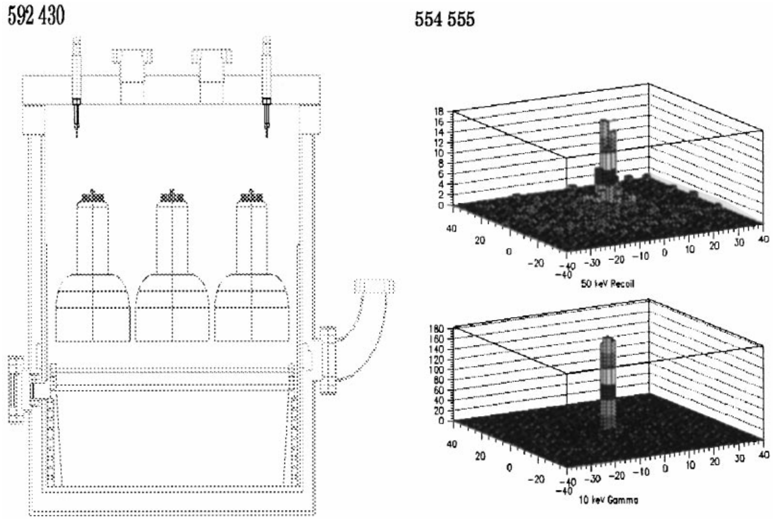

Fig. 2. The proposed Zeplin II detector (left); the projected free electron on the X–Y plane perpendicular to drift (right).

rejection. A cross-sectional view of the proposed Zeplin II detector is shown in Fig. 2 (left). The LXe is confined at the bottom, and the liquid surface is controlled so that it stays between two (focusing and defocusing) plates (to be discussed later). In the gas phase, there are two additional wire planes, which provide strong electric field for electroluminescence, with photon detection devices placed above them. The detector is vacuum insulated with a double layer chamber. This setup is common for both double-phase pure Xe and double-phase TEA-doped Xe.

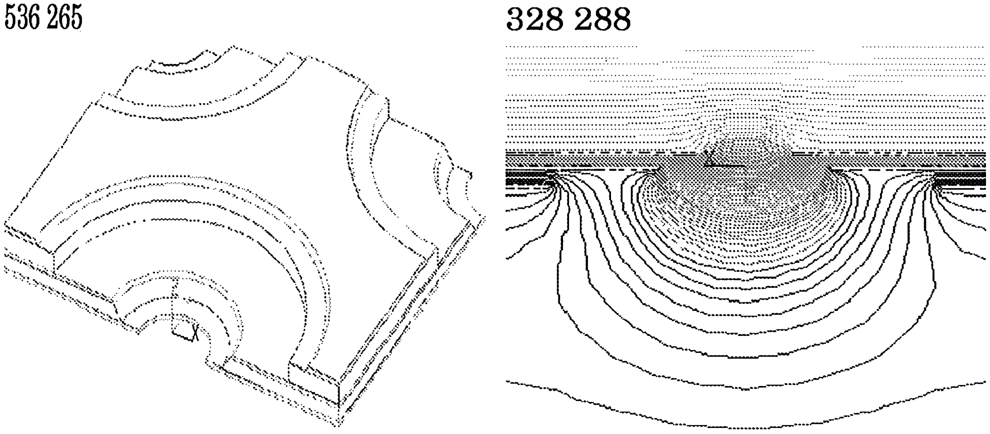

Fig. 3. Structure of the focusing holes (left); proper electric field (right).

The ionising potential of TEA in LXe is about 5.9 eV. The photon absorption wave length for TEA is peaked at about 170 nm, which is excellent for Xe scintillation, and the efficiency of the free electron yield is almost 100% [9]. The absorption length of 40 ppm TEA-doped LXe is about 2 cm.

Xenon recoil nuclei will lose energy via scintillation. A 50 keV Xe recoil nuclei will lose all the energy in a very short distance and, therefore, can be considered to be a point scintillation light source. The scintillation photons will then be converted into free electrons by the TEA internal photocathode, which will then be distributed around the event centre.

The process of energy loss of a radioactive event has significant differences from that of the recoil events [3]. In the case of radioactive background, the total number of free electrons due to ionization under normal electric field in LXe is comparable to the total number of free electrons converted by the internal photocathode from primary scintillation. Conversely, the total number of free electrons due to ionization by recoil nuclei is negligible. The result is that the final electron distribution due to radioactivity has a centre core, but the recoil electrons will be relatively smoothly distributed, as can be seen in Fig. 2 (right). This method enables background rejection on an event by event basis. The main feature of this method is that the primary photon numbers are amplified, resulting in a much better detection efficiency; hence, a low energy threshold can be achieved.

Field-shaping rings are placed along the drift direction with one centimeter spacing; a focusing plate is placed right below the liquid surface, and a defocusing plate is placed a few millimeters above the liquid surface. The focusing plate is an 80 μm thick, three-layer, Kapton-insulated PCB board, shown in Fig. 3 (left). Many small holes (400 μm in diameter) are chemically etched to form the electron focusing structure. When the proper electric potential is provided on the electrodes, these two plates will transport the electron from the liquid to the gas phase. The electric field is shown in Fig. 3 (right). The electron transport was tested in a gas chamber, and the transparency is better than 95%. The electroluminesence in the gas phase provides the amplification of the primary signal with a controllable factor so that the quantum efficiency of the photon detection devices will not play important roles for the overall detection efficiency and energy threshold.

This investigation is on going, and it is clear that the xenon detector gives us hope for a large-scale detector that is suitable for mapping high-mass WIMPs. The Torino-UK-UCLA project is dedicated to the task.

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