



## A WIMP detector with two-phase xenon

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### Abstract

We describe an important new technique to search for WIMPs. This technique employs a method of background discrimination using double phase xenon as detector target. We describe the construction of a two-phase, 1-kg xenon detector. The detector will be installed at the underground laboratory in the Mt. Blanc tunnel, which provides a low background rate. A comparison between the sensitivity curve of our detector and the theoretical events limit from SUSY calculations is presented. © 2000 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

We have constructed a two-phase (gas and liquid) xenon (Xe) detector to search for WIMP (weakly interacting massive particle) dark matter. Neutralinos, predicted by supersymmetric theories, are the most probable candidates for WIMPs [1]. For numerical work, we used  $\rho_{\text{WIMP}} = 0.3 \text{ GeV/cm}^3$ ,  $M_{\text{WIMP}} = 10 \text{ GeV} \sim 1000 \text{ GeV}$  for the local density of WIMPs, and  $\bar{v}_{\text{WIMP}} = 270 \text{ km/s}$  (corresponding to

the rotation velocity at the Sun's distance from the Galactic centre,  $v_0 = 220 \text{ km/s}$ ) [1] for the mean velocity. The recoil energy is several tens of keV through the elastic scattering of the Xe nucleus, and the theoretical prediction [2,3] for WIMP–Xe-nucleus elastic scattering interactions gives a value of between  $10^{-5}$  and 1 event/kg/day.

### 2. The advantages of using xenon in the WIMPs detector

The Xe nucleus as detector target provides a high event rate because of its high density ( $\rho_{\text{LXe}} = 2.953 \text{ g/cm}^3$ ) and high atomic number ( $Z = 54$ ,  $A = 131.29$ ). Xenon has high scintillation ( $\lambda \approx 170 \text{ nm}$ ) and ionization yields because of its low ioniza-

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tion potential (12.13 eV) [4]. In pure Xe, both scintillation and ionization are measurable. In addition, there is no long-lived radioactive Xe isotope. By centrifugation,  $^{85}\text{Kr}$  and other contamination can be eliminated to a very low level, so the Xe target can be virtually background free.

High density allows the detector to be scaled up with relatively small volume; hence, the surface area will be smaller resulting in a lower external background rate. This is because the event rate is proportional to the mass of Xe, while the background coming from cosmic rays is proportional to the Xe surface area. The high mass of the Xe nucleus provides both a good kinematic match for WIMPs in the energy range between 10 GeV and 1000 GeV and a high event rate since the coherent cross section is proportional to  $A^2$  [1].

The scintillation is produced by the formation of excimer states, which are bound states of ion–atom systems, and many studies and applications of excimer states are available [5,6]. Proportional scintillation will take place if electrons drift under very high electric field ( $\approx 10^5$  to  $10^6$  V/cm) in liquid Xe. While in the gas phase, the electroluminescence will take place at a much lower field ( $\approx$  few kV/cm).

Xenon can be highly purified to the order of  $\sim 0.1$  ppb electron negative impurities [7]. At this purity, both free electron and hard UV scintillation photons can travel much further (respectively, a few meters and  $\approx 1$  m) [8]. This long drift make it possible to design a detector with a very low energy threshold and high background rejection using proportional scintillation in the liquid phase or electroluminescence in the gas phase.

The most important property of Xe as a WIMP detector is its outstanding background discrimination [5], which will be discussed in detail in the next section. Common to all WIMP dark-matter searches, are selection of a low-background underground laboratory, detector shielding, and Compton and muon vetoing efforts. What must be dealt with is the gamma-ray background that comes from the detector materials immediately surrounding the Xe target. The ability to differentiate this background from WIMPs is key, and we recommend using a Xe two-phase technique. A large-scale design can be easily realized and the UCLA–Torino–UK collaboration has proposed ZEPLIN II, a 30-kg two-phase

Xe detector. More details on the ZEPLIN II proposal will appear at a later date [9,10].

### 3. UCLA–Torino two-phase Xe WIMP detector with powerful background discrimination

Many experiments using different techniques for WIMP detection are currently under way [11–13]. By measuring scintillation and electroluminescent photons, we will be able to detect low-energy Xe recoil and, at the same time, discriminate low-energy gamma background. For over three years, we have been building and studying the performance of a two-phase, 1-kg Xe detector, which will be installed at the Mt. Blanc Laboratory. This detector comprises a stainless-steel, vertical cylindrical chamber with dimensions of 114 mm outer diameter, 110 mm inner diameter, and 185 mm height. The chamber is vacuum insulated. The active volume has a conical shape, as defined by a hollow Teflon plug. The purpose of Teflon is to maximize the collection of electrons and scintillation photons, thus increasing the efficiency of the detector in signal detection and in background discrimination. Two photomultiplier tubes (PMTs) installed at the top and bottom of the chamber detect the light produced in the liquid Xe by scintillation and in the gas Xe by electroluminescence. A uniform electric field between a number of horizontal, circular stainless-steel electrodes drifts the electrons vertically from the liquid to the gas phase. Fig. 1 shows the design and geometry of this chamber.

In liquid Xe, the nuclear recoil signal is clearly different from the signal coming from the gamma interaction in the detector [5]. In the case of WIMPs interaction, the signal from WIMP–nucleus elastic scattering is similar to that of the neutron–nucleus elastic scattering. Using a neutron beam, we have measured the Xe recoil signals resulting from neutron elastic scattering [14]. The Xe recoil nuclei will produce mainly scintillation and almost no ionization, which is a result that is similar to that of heavy ionizing particles. Heavy ionizing particles produce a high density of electrons that quickly recombine and produce scintillation photons so, even with a high electric field present, very few electrons escape. In the case of gamma rays (minimum ionizing particles),

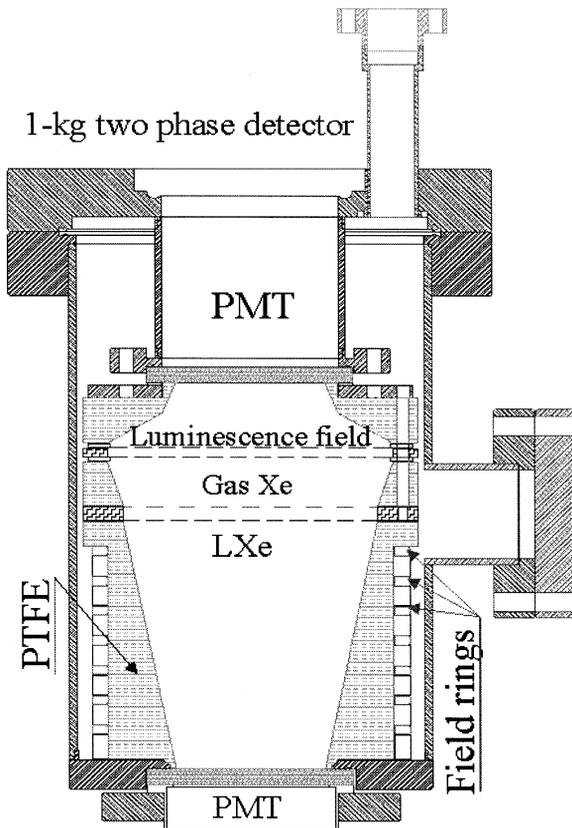


Fig. 1. Two-phase 1-kg Xe WIMP detector.

both scintillation and ionization will be produced. When a normal electric field ( $\approx$  few hundred kV/cm) is present, recombination will be partially prevented so some ionizing electrons will be extracted.

Because of the very high Xe purity, scintillation photons can be collected with high efficiency, and electrons can be drifted to an anode region for further readout. Since very few electrons escape from Xe recoil events due to WIMPs elastic scattering, detection of electrons coming out of these events will be the key for background differentiation. When the drifting electrons pass the interface between liquid and gaseous Xe, most of them can be extracted without loss [15]. The number of electroluminescent photons produced per electron can be well approximated by the equation

$$N_{\text{ph}} = 70 \cdot (E - 1.3P) \cdot d,$$

where the parameters  $E$ ,  $P$ , and  $d$  are, respectively, the applied electric field in kV/cm, the pressure of Xe gas in atm, and the drift distance of the electrons in cm [15].

The direct (or primary) scintillation photons (which appear a few ns after the event) for both Xe recoil and gamma events will be detected by PMTs and the electron will be drifted to the gas phase where electroluminescence takes place. The electrons will also be measured by the same PMTs in terms of luminescent (or secondary) scintillation photons from the electroluminescent process at a later time, depending on the electron drift distance (few tens of  $\mu$ s).

Fig. 2 shows the plot of secondary versus primary scintillations of a 22-keV gamma-ray source in pure liquid Xe. Each dot represents a single event. Since electrons escape from recombination, every gamma event will have both primary and secondary scintillation, so all the dots are clustered above the  $x$ -axis. When mixed gamma-ray and neutron sources are present, as shown in Fig. 3, many dots are clustered near the  $x$ -axis. At a five ADC-count cut at the secondary scintillation, the gamma event contamination according to Fig. 2 is less than 0.2%. As described above, only a few parameters determine the number of electroluminescent photons produced. Therefore, the background discrimination in two-phase Xe is expected to be better than in the single phase, and test results have in fact shown clearly that the separation of gamma and neutron events is better than with the single phase technique (see Fig. 4).

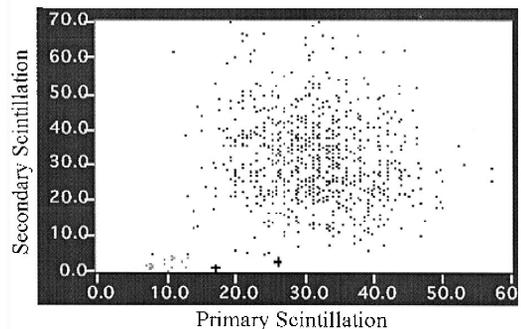


Fig. 2. Secondary vs primary scintillation plot in pure liquid Xe with a 22-keV gamma-ray source. The secondary scintillation photons are produced by proportional process in liquid Xe.

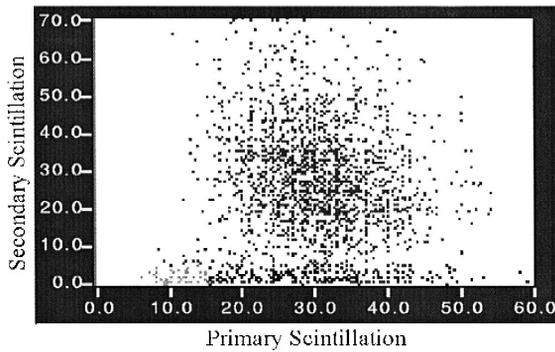


Fig. 3. Secondary vs primary scintillation plot in pure liquid Xe with mixed gamma-ray and neutron sources. The secondary scintillation photons are produced by proportional scintillation process in liquid Xe.

This powerful discriminating technique will be employed in the 30-kg two-phase ZEPLIN II detector (proposed by the UCLA–Torino–UK collaboration, Fig. 5).

Generally, cosmic muons produce  $2 \times 10^{-3}$  to  $2 \times 10^{-2}$  neutrons by way of spallation and capture [16]. The laboratory under Mt. Blanc provides one of the lowest cosmic muon rates ( $10^{-5} \text{ m}^{-2} \text{ s}^{-1}$ ) to be found [16]. From above, the neutron background rate for our detector due to cosmic rays is around  $10^{-3} \text{ d}^{-1}$  and the gamma-ray background is less than 100 Hz, while the surface area of our detector is about  $0.1 \text{ m}^2$ . Using the muon veto counter, the

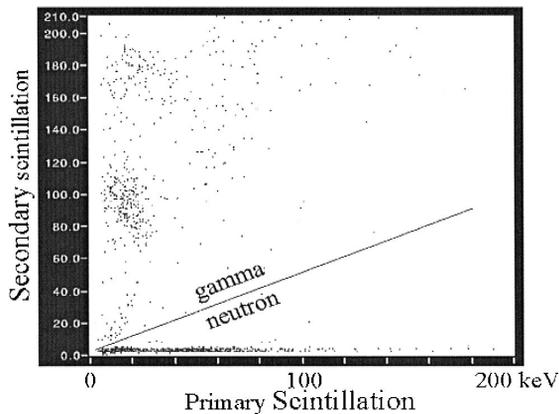


Fig. 4. Secondary vs primary scintillation plot in two-phase Xe with mixed gamma and neutron sources. The secondary scintillation photons are produced by electroluminescent process in gaseous Xe.

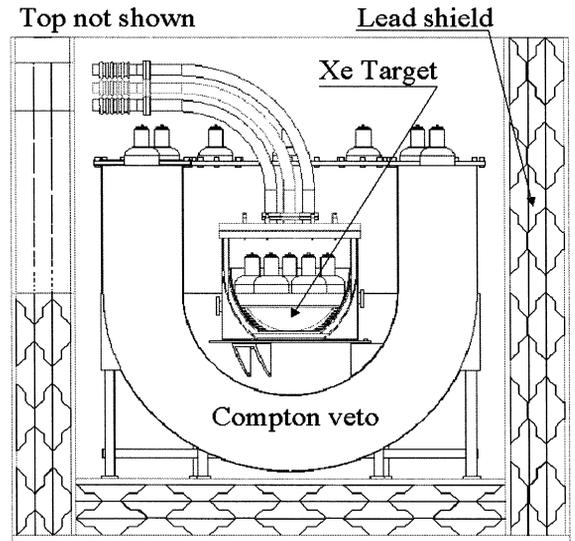


Fig. 5. Conceptual design for the 30-kg ZEPLIN II detector proposed by the UCLA–Torino–UK group [9].

neutron background rate due to the cosmic background can be reduced below  $10^{-5} \text{ d}^{-1}$  for our detector. Fig. 6 shows the sensitivity curve for our two-phase 1-kg Xe detector, as drawn using the equations in Ref. [17], at 10-keV energy threshold. Also shown are the upper and lower limit of theoretical SUSY calculations for WIMP–Xe interaction event [2]. It is essential to lower the detector energy threshold in order to reduce the experimental event limit. Accord-

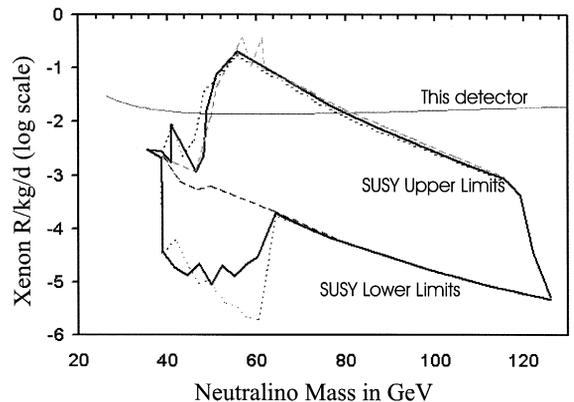


Fig. 6. The upper and lower limits for SUSY calculations compared with the two-phase 1-kg Xe detector.

ingly, the UCLA–Torino ICARUS/WIMP team is running several R&D programs (e.g., searching for new materials) that can further reduce background and decrease the detector threshold energy.

#### 4. Summary

A hint of  $M_w = (59^{+36}_{-19})$  GeV WIMPs has been reported by the DAMA group [18], and an independent detector is needed for further study. A nondiscriminating Xe detector has been successfully operated by the DAMA group [19,20]. With the new improved two-phase Xe technique, we believe that the search for WIMPs will be improved. We will continue to study the two-phase 1-kg Xe WIMP detector performance. The expected WIMPs events rate for our detector is  $10^{-2} \text{ kg}^{-1}\text{d}^{-1}$  with an expected neutron background rate of  $10^{-3} \text{ kg}^{-1}\text{d}^{-1}$  in the Mt. Blanc Laboratory due to the cosmic background. For the next step after this program, the ZEPLIN II experiment will be prepared with upgraded powerful background discrimination techniques.

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