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ON A DISCRIMINATING LIQUID-XENON DETECTOR
FOR SUSY DARK-MATTER OBSERVATION^a

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We briefly review the arguments for SUSY dark matter and the problems of detecting neutralinos. This may be the easiest way to detect supersymmetry. We then describe the studies of liquid xenon as a detection medium, including various discrimination techniques as part of the ICARUS project. Finally we describe the ZEPLIN project to carry out a definitive search for SUSY dark matter.

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1 Dark Matter--SUSY or Not?

The history of the evidence for dark matter in the Universe was recently reviewed at a University of California Los Angeles (UCLA) symposium.¹ Remarkably, even in the 1920s some evidence had been found and of course in the 1930s,² F. Zwicky provided perhaps the first definitive evidence for dark or non-luminous matter in Galaxies.²

While no one knows the exact cause of dark matter, there is a reasonable likelihood that new elementary particles play some role in this phenomenon. Of all of the current ideas in this regard, many feel supersymmetry is the most "natural." Our viewpoint is to take the SUSY model seriously and to see what level of detection and discrimination is required to observe such particles. While even the SUSY model is not fully predictive, it would appear to be better than other even more ad hoc models. The project described here grew out of the ICARUS project to construct a massive "electronic bubble changer" using liquid argon.³ The first stage of this project, the construction of a 600-ton detector for Hall C at the Gran Sasso, is now approved.

In the early 1990s as the ICARUS technique was being perfected, we considered the possibility of detecting very small recoil energies in the detector. Figure 1 shows a conceptual method to extract a signal from a WIMP collision, which was presented at the 1991 dark-matter detector meeting at Oxford.⁴ We considered the pulse shape and relative scintillation-light output to be important factors needed to discriminate against various radioactive backgrounds. I gave a follow-up talk at a meeting at Waseda University in 1992.⁵

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STUDIES Xe SCINTILLATING LIGHT AT WASEDA U

DOKE et al.
WASEDA U

(A)

POSSIBLE MASSIVE WIMP DETECTOR

(0.1 TON DETECTOR)

Fig. 1. An early conceptual idea for using xenon for WIMP detection (1991).

2 Rates for SUSY Dark-Matter Detector

There are many estimates for the cross section of SUSY-WIMPs with various targets. In this report, we follow the recent work of Nath and Arnowitt.⁶ (Also see the references cited therein.) We believe this illustrates the difficulty, as well as the promise, for the search for SUSY-WIMPs. Figure 2 is taken from a recent work that shows the limits on the rate of interactions (per kg/d) as a function of the approximate neutralino mass (the gluino mass is expected to be approximately the same) for values of $\mu \lesssim 0$. Without getting into the details of the assumptions in this calculation, we note that the range of rates goes from a few kg/d to 10^{-5} kg/d. Although the results are for Ge and Pb, we expect similar results for liquid Xe. These results, if taken at face value, suggest that the detection of SUSY-WIMPs could be very difficult, requiring large detectors of certainly 100 kg and possibly tons of detector. In this case, the rejection of background is even more important.

3 The ICARUS Liquid-Xenon Studies

In 1992, a subset of the ICARUS group started the study of liquid Xe for the purpose of WIMP detection. The first report of this work was given in 1992 at Waseda University and published in the proceedings of the conference.⁷ Figure 3(A) shows the initial experimental setup.⁷ Table 1 presents a schematic view of the reason liquid Xe is potentially an excellent WIMP detector. The scope traces in Fig. 3(B) provide the essential discrimination method. The ratio of primary to secondary scintillation light is very sensitive to the initial ionization of the source; the γ , β , and α particles are clearly separated. In addition, the pulse shapes provide discriminations against background. More recently, this group has constructed a larger detector (Fig. 4(A)) and carried out very detailed tests of the discrimination methods (Figs. 4(B,C)).

A successful test of the detection of a recoil Xe nucleus using neutron scattering has been recently carried out, and it shows clear evidence that SUSY-WIMPs will give a strong, unique signal on a discriminating liquid-Xe detector.⁷ The 2-kg detector shown in Fig. 4(A) will be taken to the Mt. Blanc Laboratory in the Spring of 1996 to test backgrounds further and to perform a first search for SUSY-WIMPs using this technique.

4 The Proposed ZEPLIN Project to Definitively Search for SUSY Dark Matter^a

To allow lower limits to be reached, it is essential to develop methods of discriminating the desired nuclear recoil events from γ - and β -decay backgrounds. At the same time, it is desirable to develop techniques capable of being substantially scaled up in target mass. The need for targets in the 100-1000-kg region would arise in particular in searches for the 5% "annual modulation" of any true dark-matter signal (due to the Earth's motion combined with the solar motion through the Galaxy). Large-mass targets would also be needed for heavier WIMP masses (> 100 GeV), because of the correspondingly smaller flux of such particles.

Liquid Xe satisfies all of the above requirements for a dark matter detector because:

1. It is available in sufficiently large quantities with high purity.

^aThis section is adapted from a recent report⁸ by the ZEPLIN group.

(A)

(B)

Fig. 2. (A) Maximum and minimum curves of event rates for CaF_2 (dash-dotted), Ge (dashed), and Pb (solid) as functions of gluino mass when $\mu > 0$ and all other parameters ($m_0, A, \tan \beta \leq 20$) run over the allowed ranges ($m_t = 168$ GeV, where m_t is the physical mass). The $b \rightarrow s\gamma$ constraint is not imposed. (B) Same as (A) for $\mu < 0$. (From Ref. 4.)

Fig. 3. (A) Geometry of liquid-xenon test chamber, and (B) Observed primary and secondary scintillation signals showing $S1/S2 \gg 1$ for α events and $\ll 1$ for γ events.

Recoil Nuclei

- Heavily ionizing particle
- High recombination, hence
- Mainly scintillation light is produced

Radioactivity

- Minimum ionizing particle
- Low recombination, hence
- Both charge and light are produced

In liquid Xe

- Both charge and light are visible
- This provides an efficient way for signal-to-background rejection

Moreover, in Xe

- No long-lived natural isotopes are present
- Xe^{127} has longest decay time (≈ 36 d)

Table 1: Signature and Background in Liquid Xenon.

Fig. 4. (A) A 2-kg detector that has been constructed for tests at Mt. Blanc and a possible WIMP search. (B) Variations of the secondary scintillation intensity as a function of V_{sc} for photons; (C) same as B but for α particles

2. It scintillates via two mechanisms, which are stimulated to different extents by nuclear-recoil and background electron-recoil events.
3. Its natural form consists of isotopes with and without nuclear spin, so it is suitable as a detector for both spin-independent and -dependent interactions.

The larger nuclear mass of Xe also makes it a better match to heavier WIMPs but, at the same time, the larger nuclear radius introduces a significant form-factor correction unless the energy threshold is low (1–10 keV). Efficient light collection is, therefore, of prime importance in a liquid-Xe detector. Figure 5 shows a schematic of the proposed ZEPLIN detector.⁸ The proposed location for this detector, as shown in Fig. 6, would be in England.

There are two distinct approaches to discriminating nuclear-recoil events in liquid Xe:

1. Analyzing the total scintillation pulse shape or, at low energy, the individual photon arrival times, which will differ significantly for nuclear- and electron-recoil events.
2. Applying an electric field to prevent recombination and measuring (A) the primary scintillation and (B) the ionization component by drifting and producing "secondary scintillation."

To verify this large discrimination factor, we plan the construction of a prototype detector that will contain ~ 3-kg liquid Xe. This detector will be constructed out of several ZEPLIN modules. It will be tested using portable Cf or Am/Be neutron sources, which also emit gammas. The neutron and gamma events will be seen as two distinct populations of events, with energy spectra corresponding to Monte Carlo predictions. This prototype detector will also enable the light collection efficiency to be assessed and appropriate improvements made for a larger scale design and/or improved energy threshold.

All of the above tests will be carried out in the laboratory. However, it is important to appreciate that, if placed underground, even this prototype detector could immediately achieve substantial reductions in dark matter limits. In a typical salt mine (*e.g.*, either the WIPP site in New Mexico or the Boulby Mine site in the UK), the gamma background needs to be reduced by a factor of 10^4 – 10^5 by low activity shielding. The UK site already has a pure-water shielding tank in place (see Fig. 6); for a New Mexico site, a purpose-built shield of Pb and Cu would be used. This project will, thus, achieve three important goals:

1. Demonstrate the primary and secondary (proportional) scintillation technique as a method of discriminating low-energy nuclear recoil from background;
2. Set new dark-matter limits by underground testing in an existing site;
3. Assess design improvements and possibilities for scale-up to a larger size detector suitable for both WIMPs and neutrinos.

Fig. 5. Conceptual design for ZEPLIN system, showing inner proportional zone and outer shielding zone (total length, 40 cm), with PMT or VLPC options for collecting proportional scintillation light. If photomultipliers can subsequently be replaced by (non-radioactive) photodiodes, the outer zone becomes an additional target with pulse shape discrimination.

Fig. 6. Artist rendering of Boulby Mine (low-background) Laboratory.

5 Objectives of the Planned Experiment

The construction of a prototype liquid-Xe detector, with target mass in the range of 1–3 kg is planned; the typical geometry is shown schematically in Fig. 5. The target region is that enclosed between the anode and cathode. An event in this region produces primary scintillation, observed in this prototype system by a UV-sensitive photomultiplier. A passive volume of liquid Xe provides shielding of the photomultiplier activity from the target region. Monte Carlo estimates indicate that this should be ~ 5 -cm thick to achieve an acceptable low-energy background rate.

In addition to the primary scintillation, the event also produces ionization. The electrons from this are drifted by an electric field towards the anode wires. These produce a proportional scintillation pulse, a fraction of the light from this being observed by an array of wavelength-shifting fibres coupled to visible-light photon counters. The overall efficiency of this light-collection process is expected to be $< 1\%$, but this is compensated for by the signal amplification via the proportional scintillation process. Note that the wavelength-shifting fibre and VLPC arrays have already been constructed and operated successfully at UCLA.

This test chamber will fulfill three objectives:

1. Irradiation with neutrons from a portable source will allow verification that signals are produced by the recoiling xenon atoms, and it will permit measurement of the efficiency of this process.
2. Quantitative measuring of the primary/secondary scintillation ratio as a function of energy and particle type, leading to estimates of the discrimination power of the technique. In particular, a portable Cf or Am/Be neutron source emits both neutrons and gammas, which will be seen (via the S1/S2 ratio) as two classes of events, with a small overlap.
3. Operation of the test chamber can then be from an underground laboratory, with gamma shielding, to set new limits on dark matter interactions (Fig. 5).

Figure 7 shows the limits we hope to reach with the initial 20-kg detector. The ICARUS xenon detector operating at the Mt. Blanc Laboratory could also reach favorable limits if the background can be kept under control and if a long operating period is utilized.

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Fig. 7. Dark matter limits for (A) spin-dependent and (B) spin-independent interactions. Typical existing limits are shown for Ge ionization detectors plus recent (1994) improvements using NaI detectors with pulse shape discrimination [from UK data (Gran Sasso data is similar)]. In each diagram, the lower pair of curves show estimated limits versus running time for this proposal, using primary/secondary scintillation in liquid Xe at 10-keV energy threshold. The (Xe-doped) Ar case shows the advantage of data from both Xe and Ar targets.

6 References

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