We discuss the significant properties of liquid xenon for use in a discriminating SUSY-WIMP detector. Since xenon has been used for Excimer lasers, the excitation due to collisions are very well understood. This will help define the signature for the SUSY-WIMP scatter. We discuss a 2-kg ICARUS-WIMP detector now operational at the INFN Mt. Blanc Laboratory and a proposed 20-kg detector by the UCLA-RAL-IC group. We show how these detectors can be used to cover most of the "discovery space" for SUSY-WIMPs.

1 Dark Matter—SUSY or Not?

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

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 chamber" using liquid argon. 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. 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 the Intl. Conf. on Liquid Radiation Detectors, which was held at Waseda University in 1992.
2 Rates for a SUSY Dark-Matter Detector

There are many estimates for the cross section of SUSY-WIMPs with various targets. We believe this illustrates the difficulty, as well as the promise, for the search for SUSY-WIMPs. In this report, we follow the recent work of Nath and Arnowitt (and the references cited therein). Figure 2 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 $\mu \lesssim 0.6$. 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.
Figure 2: (A) Maximum and minimum curves of event rates for Xe as functions of neutralino mass when $\mu < 0$ and all other parameters ($m_{\chi}, A, \tan \beta \leq 20$) run over the allowed ranges ($m_{\chi} = 175 \text{ GeV}$, where $m_{\chi}$ is the physical mass for $\Omega > 0.1$). The $b - s$ constraint is not imposed. (B) Same as (A) but for $\Omega > 0.22$. 
3 The ICARUS Liquid-Xenon Studies

In 1992, a subgroup of the ICARUS team 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. Figure 3A shows the initial experimental setup. Table 1 presents a schematic view of the reason that liquid Xe is potentially an excellent WIMP detector. The scope traces in Fig. 3B provide the essential discrimination method. The ratio of primary to secondary scintillation light is very sensitive to the initial ionization of the source; the $\gamma$, $\beta$, and $\alpha$ particles are clearly separated. In addition, the pulse shapes provide discriminations against background. More recently, this group has constructed a larger detector (Fig. 4A) and carried out very detailed tests of the discrimination methods (Figs. 4B, 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. The 2-kg detector shown in Fig. 4A will be installed at the Mt. Blanc Laboratory to perform a first search for SUSY-WIMPs using this technique.

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

To allow lower limits to be reached, it is essential to develop methods of differentiating the desired nuclear recoil events from $\gamma$- and $\beta$-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.
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.

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*This section is adapted from a recent report by the ZEPLIN group.*
Figure 3: (A) Geometry of liquid-xenon test chamber, and (B) observed primary and secondary scintillation signals showing $S_1/S_2 \gg 1$ for α events and $\ll 1$ for γ events.

**Table 1**: Signature and background in liquid xenon.

**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)
Figure 4: (A) A 2-kg detector that has been constructed for tests at Mt. Blanc and a possible WIMP search, and (B) variations of the secondary scintillation intensity as a function of $V_{\alpha}$, for photons. (C) Same as (B) but for $\alpha$ particles. (From Ref. 8.)
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, for which the proposed location be England (Fig. 6).

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

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."

Figure 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.
Figure 6: Artist rendering of Boulby Mine (low-background) Laboratory.
To verify this large discrimination factor, we plan the construction of a prototype detector that will contain ~20-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 differentiating 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 scaling up to a larger size detector suitable for both WIMPs and neutrinos.

5 Objectives of the Planned Experiment

The construction of a prototype liquid-Xe detector, with target mass in the range of 20 kg is planned; the typical design 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 that result from this ionization are drifted by an electric field towards the anode wires, which produces a proportional scintillation pulse. A fraction of the resulting light is 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, in order to set new limits on dark matter interactions.

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. Figure 8 shows the result of a Monte Carlo simulation of the 20-kg detector, which will have a light collection efficiency that is twice that of the 2-kg detector.

6 Recent Progress in the Test Liquid-Xenon Detector

During the first part of 1996, several advances have been made in the development of the ICARUS-WIMP liquid-Xe detector:

1. A detailed study of the background from low-energy gammas has been conducted.

2. Neutron-induced events in the presence of large backgrounds have been observed directly.

3. A detailed study of the rise-time distribution for Xe events and backgrounds has been made.

The study of the discriminating liquid-Xe detector continues to indicate that this may be one of the best methods to use to detect SUSY-WIMPs. Figure 9 gives some of our recent measurements at CERN, showing that the detector has the capability of performing very powerful background discrimination.
Figure 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 vs 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.

7 Fundamental Processes in Liquid Xenon

In order to discover WIMPs interacting in a medium, the response of the medium must be extremely well understood. Discoveries are not made by removing backgrounds but by identifying a unique signature for the process. Table 2 lists the important signature for a WIMP interaction in liquid xenon. This information builds on more than two decades of study of the excitations in liquid Xe. The UV scintillation light in xenon is produced by the formation of Excimer states, which are bound states of ion-atom systems (see Fig. 10). There are extensive studies in the use of this process for Excimer lasers, as well as for many other applications.7,8,10
Figure 8: Results of a Monte Carlo simulation at UCLA for the proposed 20-kg detector (photon efficiency of WIMPs chamber; (A) shows the efficiency versus Z).
Figure 9: Some recent results on the liquid-xenon detector at CERN: (A) pulse height and time profile for the prompt (primary) and secondary pulses, (B) the rise time of the primary pulse, and (C), the form factor for Xe and NaI for comparison (from Ref. 9).
Table 2: Signal character in liquid xenon.

1. \((^3\Sigma_u^+) \rightarrow 3(^1\Sigma_u^+)\): [Ratio of \(\tau_1\) and \(\tau_2\) signals] \[\frac{\tau_2}{\tau_1}\]

2. \(\lambda_p \sim 175\) nm and \(S/B_g \gg 1\)

3. Homogeneous over full detector (WIMP)

4. \(Q^2\) distributions as expected from WIMP interactions

5. Yearly variation of signal

Figure 10: Emission spectrum of liquid Xe: (1 and 2) pump densities (in Å/cm\(^2\)) and (3) emission spectrum at low excitation density. The resolution of the monochromator is shown in the upper right-hand corner. (From Ref. 10.)
8 Status of the 2-kg Detector at the INFN Mt. Blanc Laboratory

The 2-kg ICARUS-WIMPs detector has now been installed at the INFN Mt. Blanc Laboratory and first tests are underway. Our goal is to search for WIMPs to the level of $10^{-1}$ events/kg·d decay during the next year or so.11

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References

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