12

FERMILAB
JUL 24 1997
LIBRARY

UCLA-APH-0096-3-97

Fermilab Library
0 1160 0052415 4

PROGRESS AND PROSPECTS IN THE DIRECT SEARCH FOR SUPERSYMMETRIC DARK MATTER PARTICLES[a]

UCLA-APH0096-3/97

David B. Cline

Department of Physics and Astronomy, Box 951547
University of California Los Angeles
Los Angeles, CA 90095-1547, USA

ABSTRACT

We briefly review the latest evidence for non-baryonic dark matter. We also review the most recent estimates for SUSY dark-matter particle interaction with matter. We then provide a critique of the current search for the dark matter and describe one very promising method using backgound discrimination in liquid xenon.

INTRODUCTION

The latest evidence for dark matter in the Universe has been reviewed recently at two University of California Los Angeles (UCLA) symposiums.[1] 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.[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 chamber" 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.

EVIDENCE FOR NON-BARYONIC DARK MATTER

The evidence for non-baryonic dark matter is getting even stronger than it has been. Perhaps the best evidence comes from three different measurements of the gravitational potential in Galactic clusters using

1. Dynamic methods (galaxy motion),
2. Hot X-rays (hot gas in the gravitational potential well),
3. Weak gravitational lensing (sensitive to all gravitating matter).

---

[a]Invited talk at the International Conference on Orbis Scientiae 1997 (Miami Beach, FL, Jan. 1997) and to be published in *Twenty-Five Coral Gables Conferences and their Impact on High Energy Physics* by Plenum Pub. Co.

These three methods now give convincing evidence for dominant non-baryonic dark matter in these clusters.

There is also strong evidence for dark matter in dwarf galaxies, which appear to totally dominate the total matter on all scales. Finally, it is now agreed that $\Omega > 0.4$, which is definitely larger than the limits for $\Omega_B < 0.1$ from recent nucleosynthesis studies (see Fig. 1).

METHODS AND RATES TO DETECT SUSY WIMPS

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[4] (and the references cited therein). Without getting into the details of the assumptions in this calculation, we note that the range of rates goes from a few events/kg·d to 10^{-5} events/kg·d (see Figs. 2 and 3). 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. Table 1 gives the schematic for WIMP detectors. Figures 4–6 show some detection methods that will be discussed below.

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. 7). There are extensive studies in the use of this process for Excimer lasers, as well as for many other applications.[10–12]

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 (Figs. 8–10). A 2-kg detector will be installed at the Mt. Blanc Underground Laboratory (UL) to perform a first search for SUSY WIMPs using this tchnique.

In Figs. 5–7, we show the schematic of several other methods of searching for WIMPs and some current results.

The 2-kg ICARUS–WIMPs detector has now been installed at the CNR Torino Mt. Blanc UL and first tests are underway (see Fig. 10). Our goal is to search for WIMPs to the level of 10^{-1} events/kg·d during the next year or so.[13]

CURRENT STATUS OF THE SEARCH FOR SUSY WIMPS

In the early days of the direct search for WIMPs, the motivation was the detection of a massive dirac neutrino, which is now excluded by the data (see Fig. 2). In this search, the expected rate was so large (~ 1000 events/kg·day) that the detector background was not extremely important. In the search for SUSY WIMPs, as was discussed earlier (Fig. 3), we expect much lower rates and either very massive detectors are needed (for the background limited search, which goes like $\sqrt{N}$) or powerful discrimination. The best current limits come from the study of the pulse-shape distribution in NaI or liquid Xe. One NaI detector (the UK group) is shown in Fig. 5, where the current best limits (from the Rome group) are also shown.

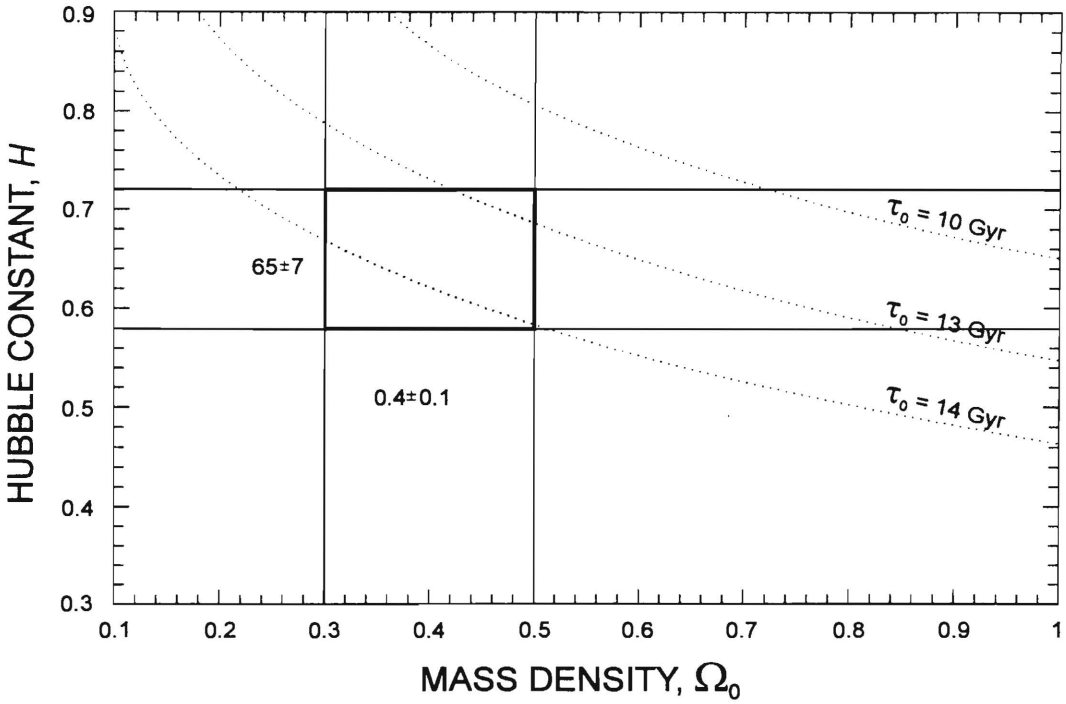


Figure 1. Recent estimates of the mass density as a function of Hubble's constant, and τ_0 is the age of the Universe.

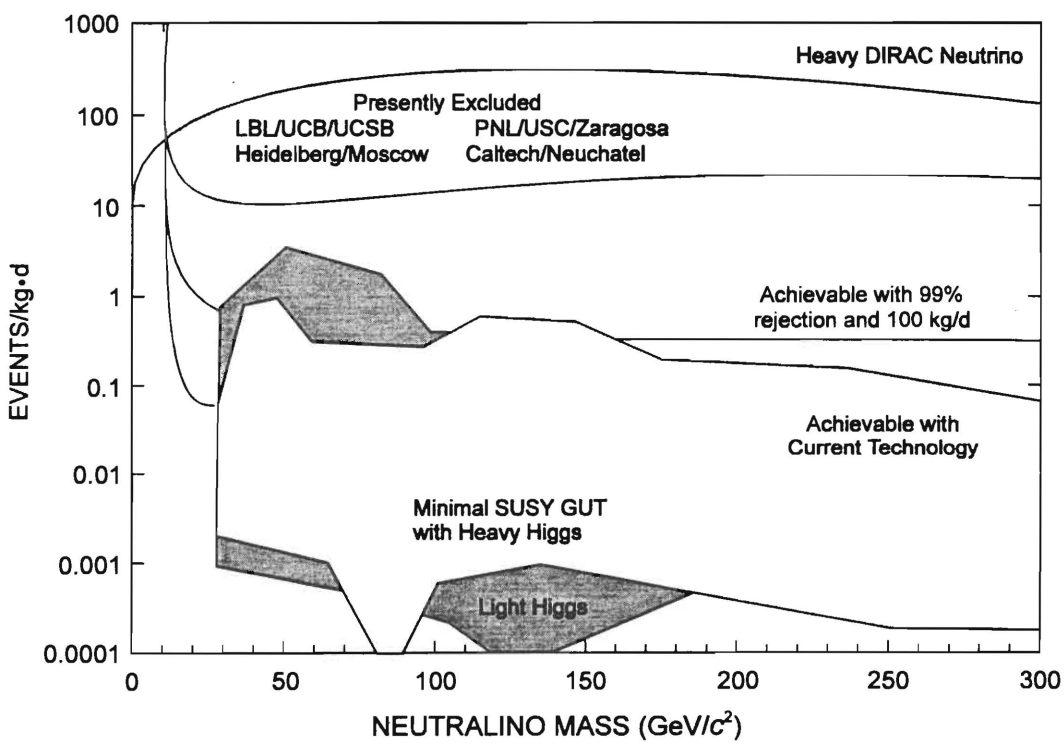


Figure 2. Regions of the event rate as a function of mass that were excluded in 1995 and the expected ranges for SUSY WIMPs.

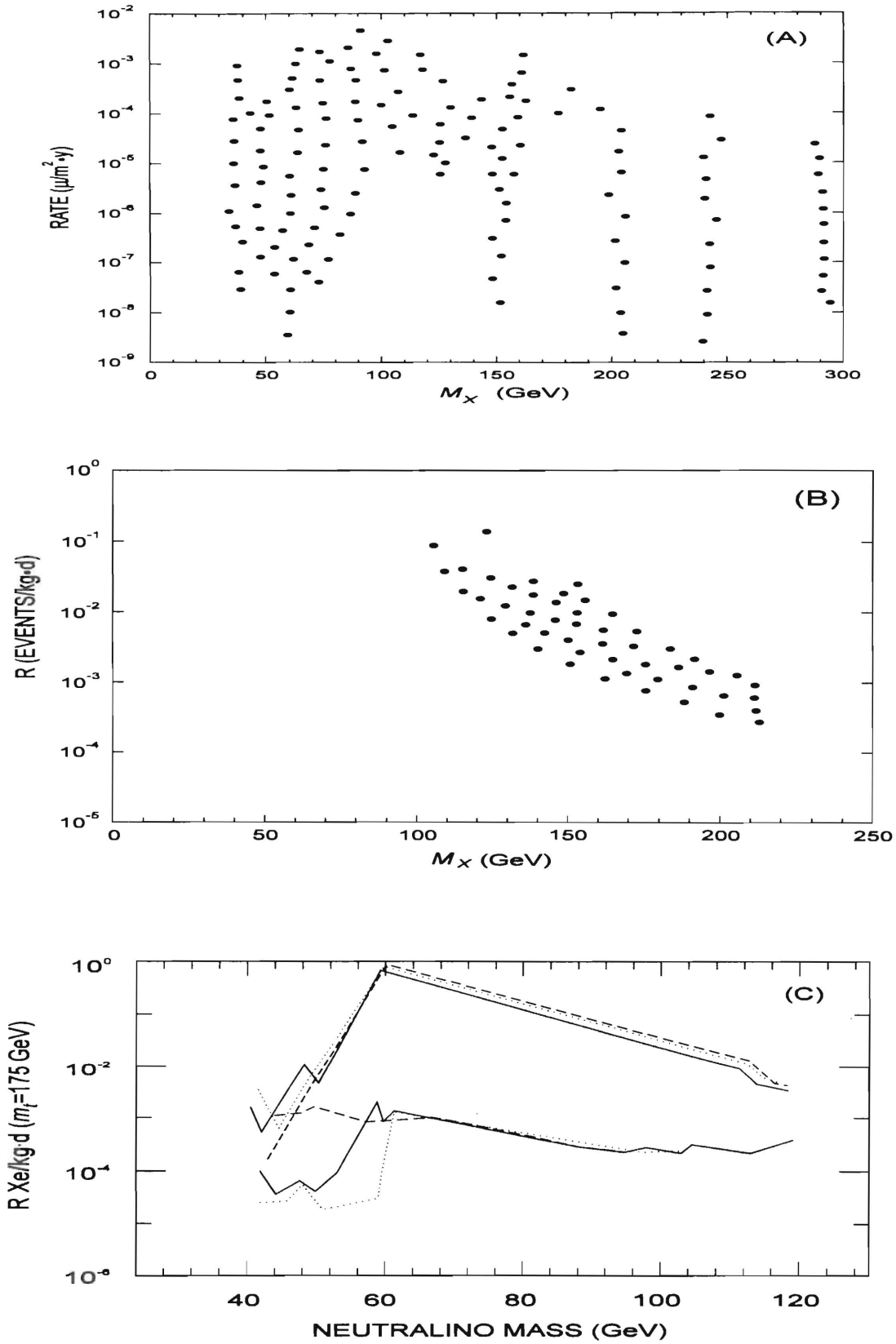


Figure 3. (A) Regions of the SUSY-WIMPs event rate (from Ref. 5); (B) Recent estimates of the events rate for SUSY WIMPs from the Gran Sasso CERN group (from Ref. 6); (C) Very recent estimates of the allowed regions of event rates (from Ref. 4).

TABLE 1. WIMP direct detection schematic.

1. $W + \overset{T}{[\text{atom/nucleus}]} \rightarrow W + \overset{T^*}{[\text{atom}]^*}$	~ elastic scattering with excitation of atom ~10 nm
2. Form factors for recoil [atom/nucleus] $\Delta E \leq 30$ keV measure $n + A \rightarrow n + A^*$	
3. Kinematics	
4. Rate $\leq (1 - 10^{-5})\ \text{kg}^{-1}\ \text{d}^{-1}$	
5. Background - $(10 - 100)\ \text{kg}^{-1}\ \text{d}^{-1}$	
6. Discrimination against background	

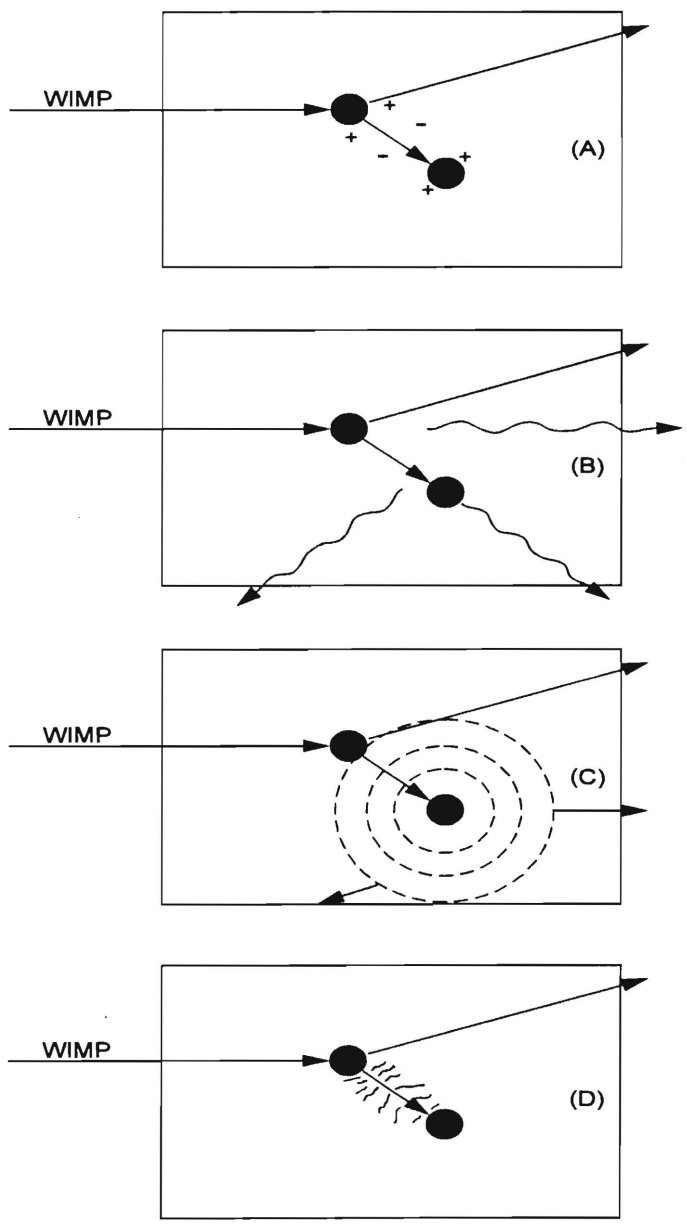


Figure 4. Schematic of WIMP detectors that use (A) semi-conductors, (B) scintillation light, (C) bolometers, and (D) etched mica.

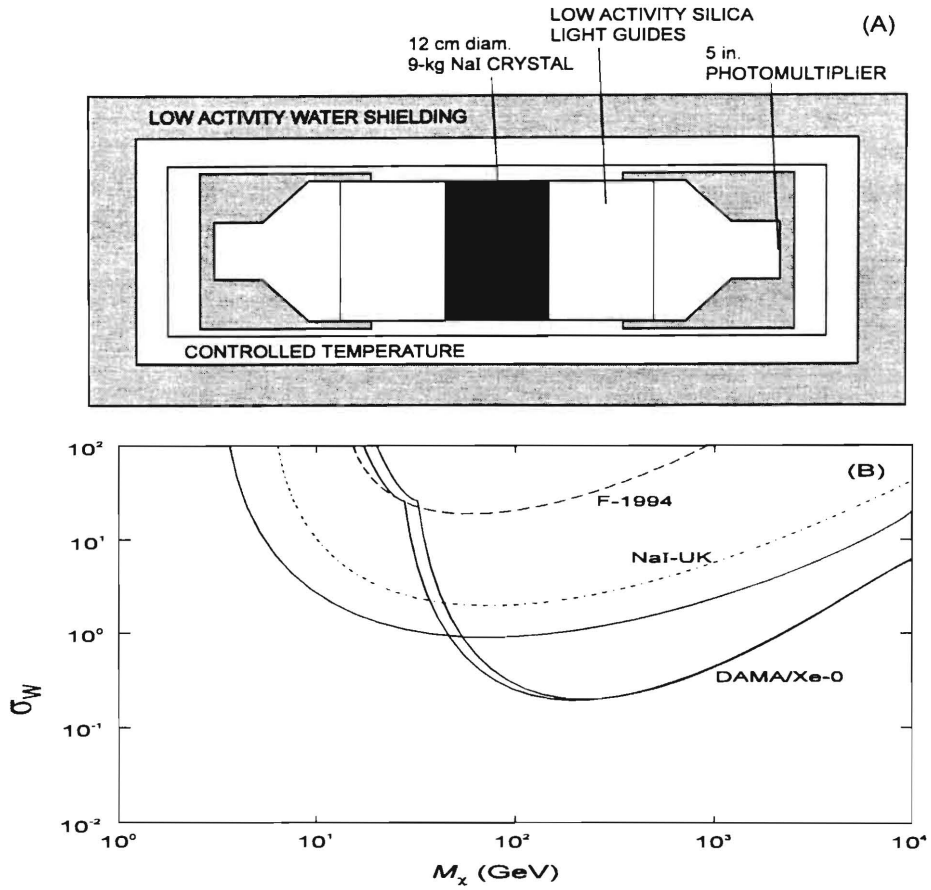


Figure 5. (A) The UK dark-matter-group NaI WIMP detector (from Ref. 7); (B) some recent limits on the WIMP cross section from NaI and Xe detectors (from Ref. 8).

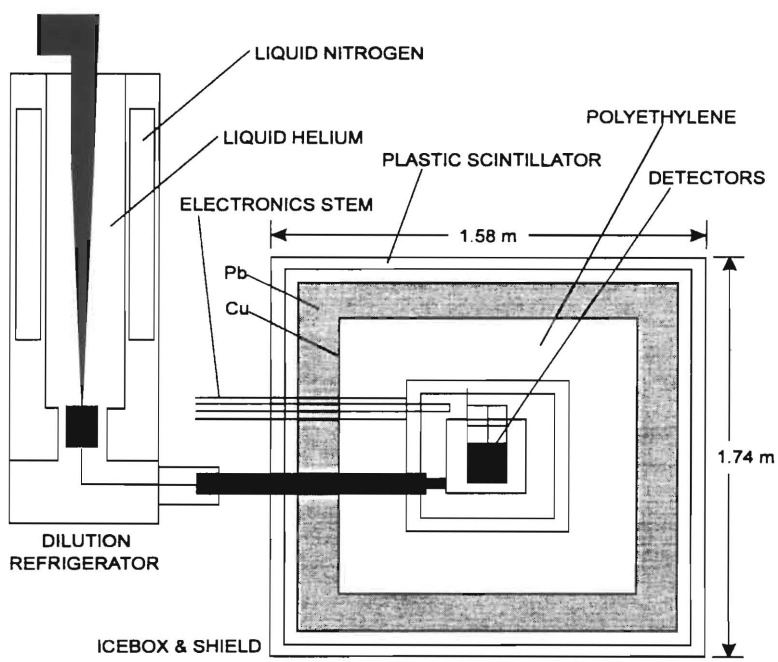


Figure 6. The CDMS detector at SLAC that uses the bolometer method (from Ref. 9).

Table 2. 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)

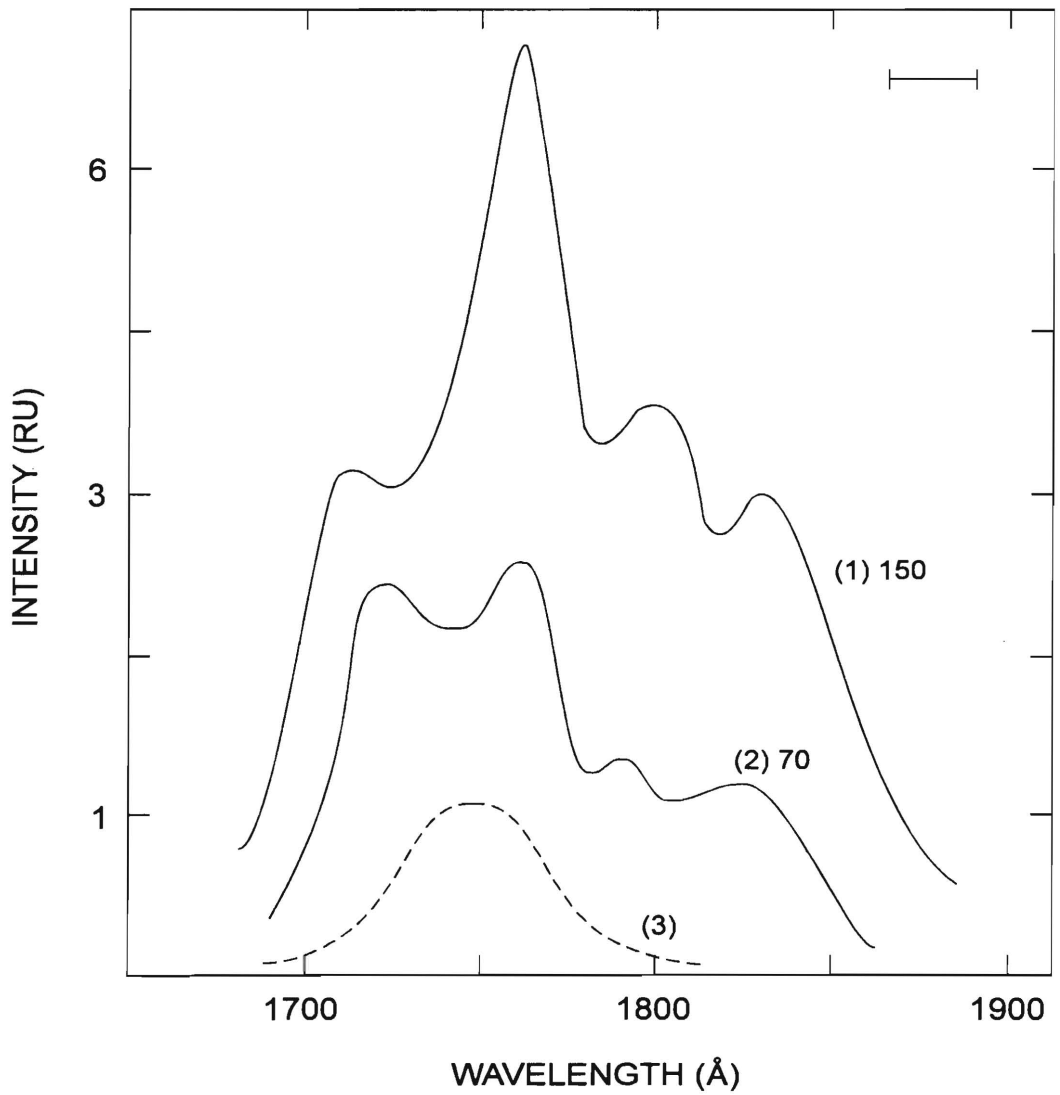


Figure 7. Emission spectrum of liquid Xe: (1 and 2) pump densities in Å/cm^2 and (3) emission spectrum at low excitation density. The resolution of the monochromator is shown in the upper right-hand corner. (From Ref. 10).

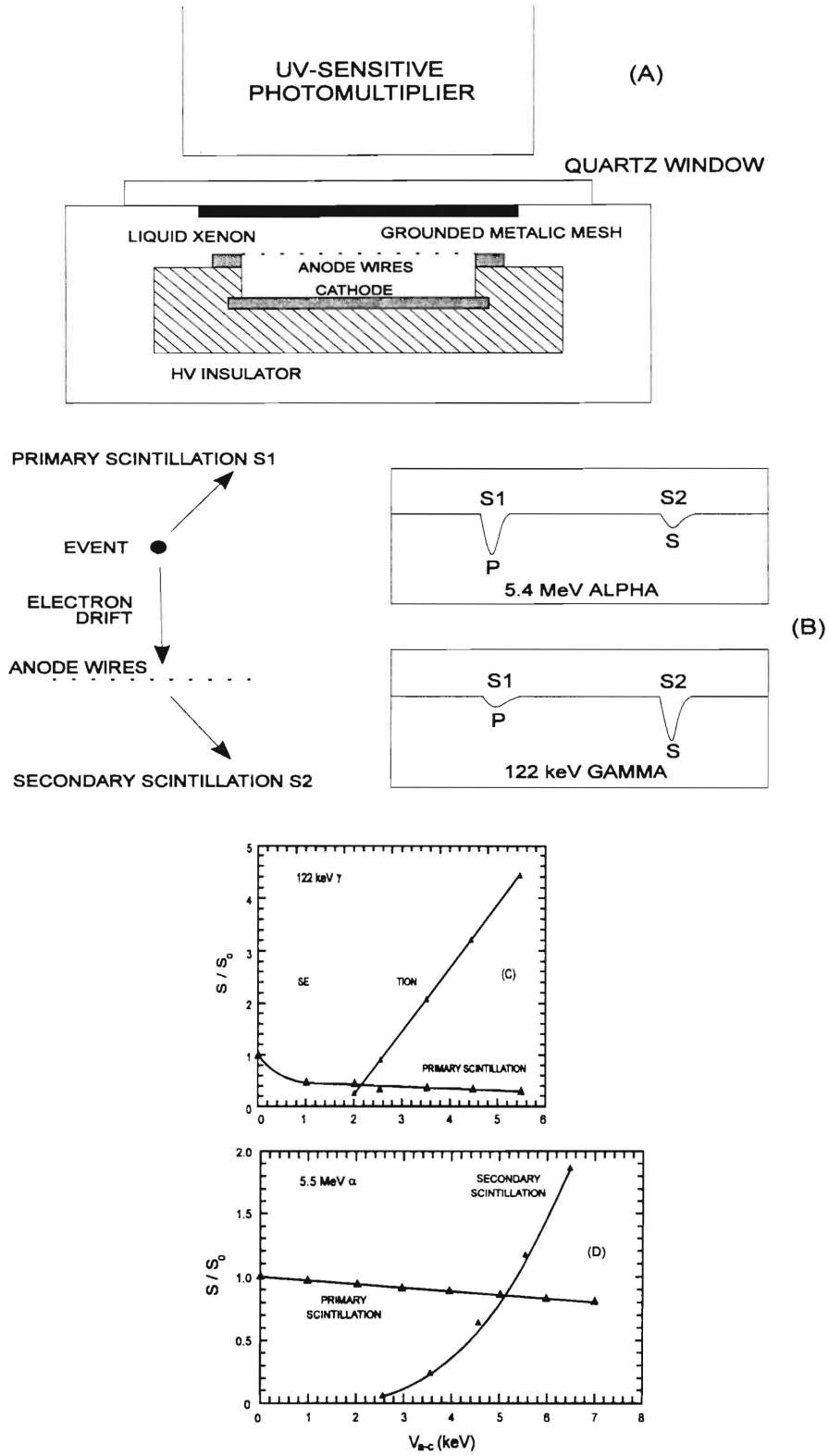


Figure 8. (A) Geometry of liquid-xenon test chamber, (B) observed primary and secondary scintillation signals showing S1/S2 >> 1 for α events and << 1 for γ events, (C) variations of the secondary scintillation intensity as a function of $V_{a\text{-}c}$ for photons and (D) for α particles. (From Refs. 11-13.)

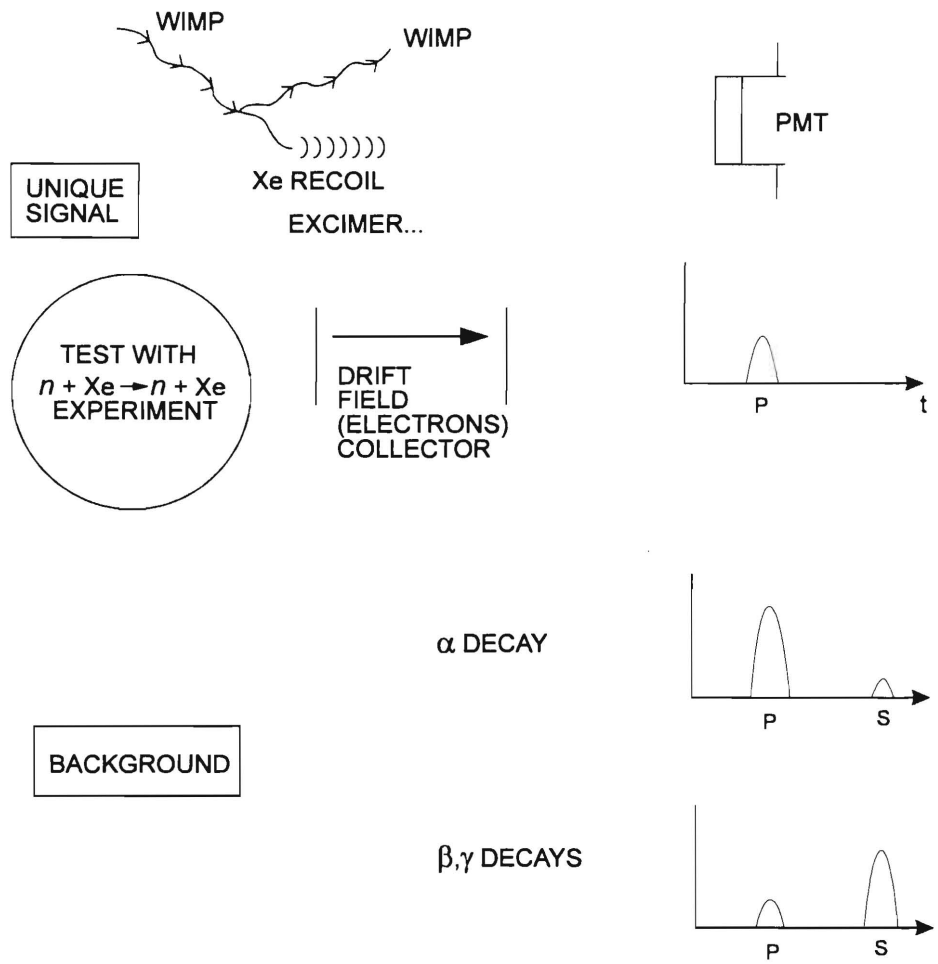


FIGURE 9. Schematic of the background rejection method in liquid Xe (rejection of 10^{-3}).

Discriminating Liquid-Xenon Detector[a]

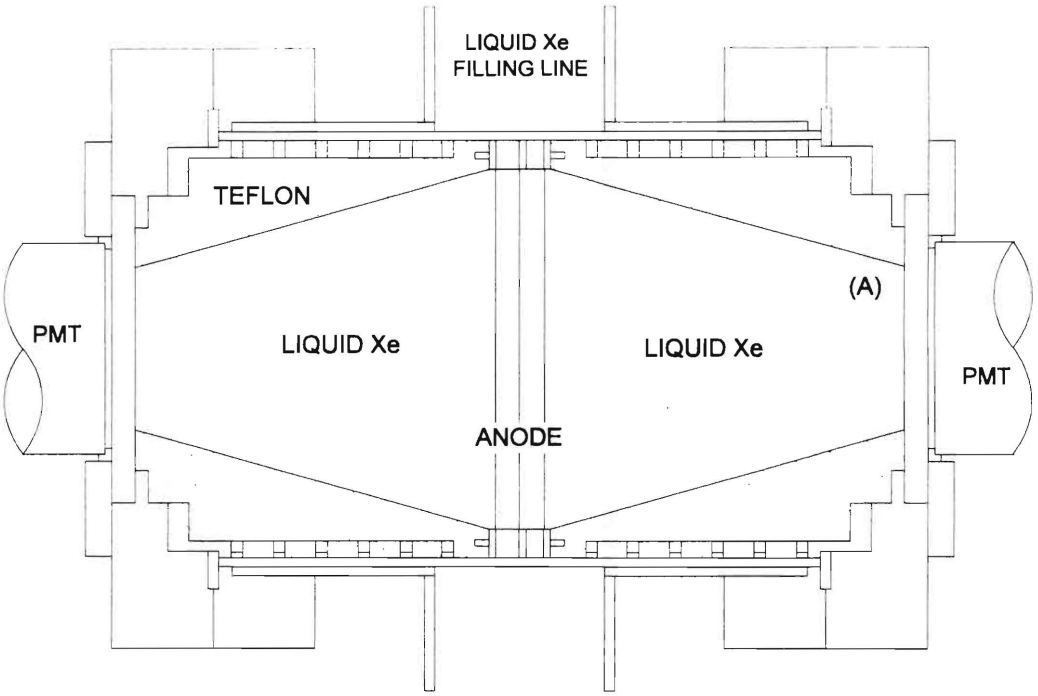
To allow lower limits to be reached, it is essential to develop methods of differentiating the desired nuclear recoil events from γ- and β-decay backgrounds. At the same time, it is desirable to develop techniques capable of being substantially scaled up in target mass. The need for targets in the 100–1000-kg region would arise, particularly 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 (> 50 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.

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

[a]This section is adapted from a recent report[12] by the ZEPLIN group.



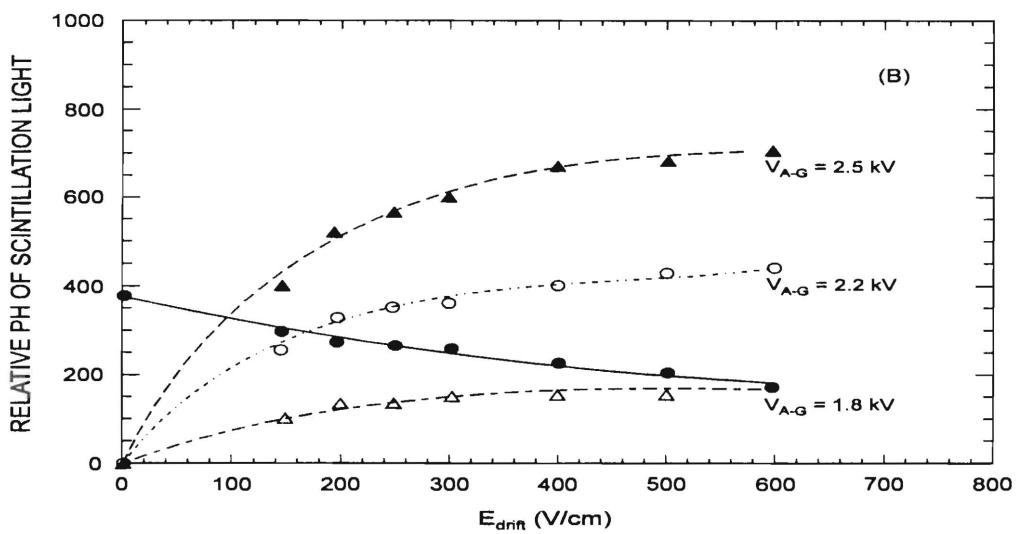


FIGURE 10. (A) A 2-kg detector that has been constructed for tests at Mt. Blanc and a possible WIMP search, and (B) variations of the secondary scintillation intensity as a function of E_{drift} and V_{A-G} for photons.

threshold is low (1 – 10 keV). Efficient light collection is, therefore, of prime importance in a liquid-Xe detector. Figure 11(A) shows a schematic of the proposed 20-kg ZEPLIN detector.

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 (i) the primary scintillation and (ii) the ionization component by drifting and producing "secondary scintillation" (see Figs. 7 – 8). The lowest possible backgrounds [Fig. 11(B)] may be achieved at the Boulby Mine site.

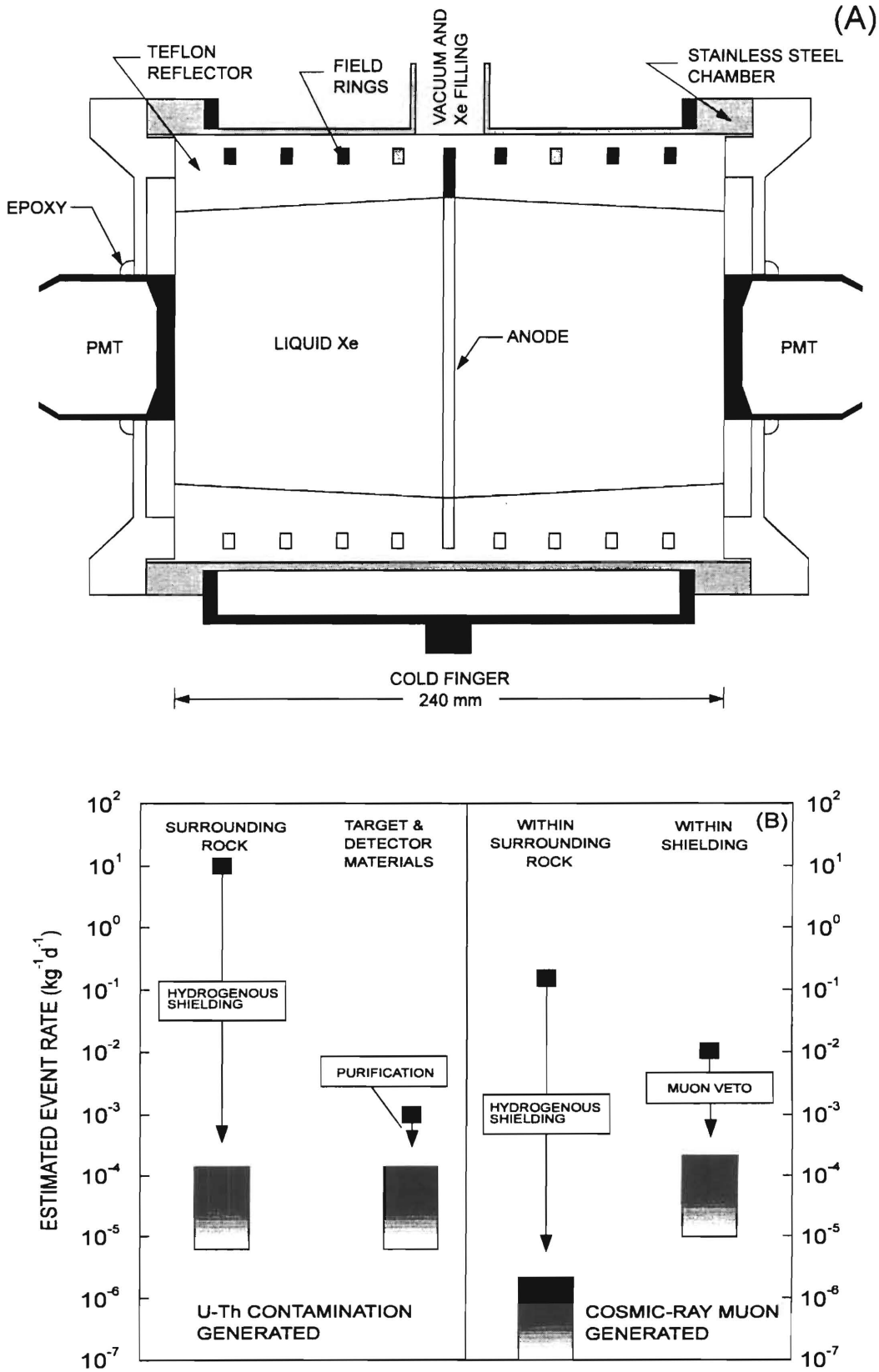


Figure 11. (A) Conceptual design for ZEPLIN system, showing inner proportional zone and outer shielding zone (total length, 40 cm), with PMT for collecting proportional scintillation light;[14] (B) Estimated background at the Boulby dark-matter laboratory in the UK.[15]

In Fig. 12 we show some estimates of how well the search for SUSY WIMPs can go using the Xe detectors discussed here.

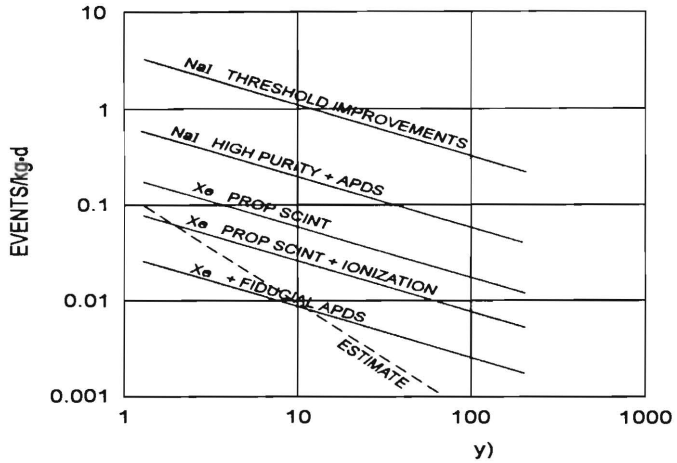


Figure 12. Possible sensitivity that can be reached with the Xe detetor discussed here (adapted from Ref. 15). The dashed lines show the sensitivity if the signal exceeds the background, as we expect for a discriminating liquid Xe detector.

SUMMARY

The search for SUSY WIMPs must now be one of the most important activities in particle physics. Recent estimates of the rate put it into the 10^{-1} - 10^{-5} event/kg·d level, which is an extremely difficult task. We believe the search is well worth the effort needed.

ACKNOWLEDGMENTS

I wish to thank Hanguo Wang for his excellent work on the ICARUS-WIMP detector and the other members of the ICARUS and ICARUS-WIMP groups (P. Picchi), as well as members of the proposed ZEPLIN group (P. Smith in particular); my thanks also to P. Nath and R. Arnowitt for discussions on the theory of SUSY-WIMP detection and for Fig. 3(C).

REFERENCES

1. See the proceedings of "Sources of Dark Matter in the Universe," Santa Monica, 1996, ed. D. Cline, *Nucl. Phys. B* (PS) 51B (1996); and L. H. Aller and V. Trimble, in *Sources of Dark Matter in the Universe*, ed. D. Cline (World Scientific, Singapore, 1994) pgs. 3 and 9.
2. F. Zwicky, *Ap. J.* 86:217 (1937).
3. CERN-UCLA-INFN Group, ICARUS Proposal (1993) unpublished.
4. P. Nath and R. Arnowitt, *Phys. Rev. Lett.* 74:4592 (1995).
5. G. Jungman *et al.*, *Phys. Reports* 267:195 (1996).
6. A. Bottino *et al.*, *Astropart. Phys.* 2:77 (1994).
7. P. Smith *et al.*, *Phys. Lett. B* 379:299 (1996).
8. R. Bernabei *et al.*, *Phys. Lett. B* 389:757 (1996).
9. B. Cabrera, *Nucl. Phys. B* (PS) 51B:297 (1996).
10. N. Basou *et al.*, *JETP Lett.* 12:329-331 (1970).
11. P. Benetti *et al.*, *Nucl. Instrum. Methods A* 327:203-206 (1993).
12. J. Park, M. Atac, D. B. Cline, H. Wang, and P. F. Smith, in *Sources of Dark Matter in the Universe*, ed. D. Cline (World Scientific, Singapore, 1994) p. 288.
13. H. Wang, CERN-UCLA, private communication (1996).
14. D. Cline, *Nucl. Phys. B* (PS) 51B:304-313 (1996).
15. P. Smith *et al*, *Nucl. Phys. B* (PS) 51B:284-293 (1996).