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STUDY OF RARE SIGNALS WITH THE ICARUS DETECTOR*

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ABSTRACT

The ICARUS detector concept of imaging rare events is very well matched to the search for supersymmetric proton decay. We describe very briefly the R&D programs carried out by the ICARUS team over the past 10 years, emphasizing the enormous dynamic range. We discuss the signal and background for the decay, $p - K^+\bar{\nu}_\mu$. We also discuss the search for exotic neutrino processes and the use of the ICARUS method for a liquid-xenon detector to reach very low energy-recoil processes for the detector of SUSY WIMPs.

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1. The Search for Proton Decay

The current generation of detectors has nearly exhausted the lifetime range up to ~ 10^{32} years. The scaling rules for the proton decay search are:

$$\tau_p \propto N_p \text{ (protons in detector)} \quad , \quad S/N >> 1 \quad , \tag{1}$$

$$\tau_p \propto \sqrt{N_p} \quad , \quad S/N \leq 1 \quad , \tag{2}$$

where S is the signal for proton decay and N is the background. In the latter case, a background subtraction is required, which reduces the statistical power of the detector.

In order to explore the τ_p ~ 10^{32} - 10^{34}-yr region, we choose between two options:

1. Construction of very large detectors (M ~ 10^5 tons) that will have $S/N \leq 1$, or
2. Construction of detectors with M ~ 10^4 tons with $S/N >> 1$, with extreme pattern recognition for unique event selection.

In both cases, the background must be known, but in the $S/N >> 1$, we must know N precisely in order to subtract the background. We illustrate this part for the decay, $p - K^+\bar{\nu}_\mu$, given in Table 1.

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Table 1. Current situation in search for $p - K^+\bar{\nu}_\mu$

Mode	Candidates	Gb[a]	Group
K_{μ_2}	11	8.6	KAM I/II 4.92Kt.y.
K_{μ_2}	6	4.7	IMB (90) 3.76Kt.y.
K_{μ_2} K_{π_2}	1	1.8	Frejus 9.98Kt.y.
K_{π_2}	3	15.1	IMB

[a]Region of K_{μ_2} in $(\mu/e)/(\mu/e)_{cal} < 1$

[b]$\tau/B \geq 6 \times 10^{31}$ y 90% C.L.

The ICARUS detector method of detecting particles by ionization and scintillation light in noble gas-liquid has been developed over the past 10 years, starting with small prototype detectors up to the 3-ton liquid-Ar detector that has been operating at CERN for the past five years.[1-3] In addition, we have been operating a 2-kg liquid-Xe detector for the past two years.[4,5]

The features of ICARUS that make it a very sensitive detector for rare processes are given in Table 2.[1-3] One of the most important is the vast dynamic range that, as we shall show, goes down to almost 10 keV.[4,5]

The two types of proton decay that ICARUS is being designed for are shown in Fig. 1, where (A) is for a Pati-Salam model and (B) is for the currently favored, SUSY-GUT model.[1,3] We believe the predictions of the latter, which are illustrated in Table 3 and Fig. 2, should be taken seriously.

Of course there are other tests of SUSY-GUT, as illustrated in Table 4. One very interesting result of the SUSY-GUT concept is the extrapolation to the GUT scale, as shown in Fig. 3.[1] We note that the X mass that would be derived from this extrapolation would give a lifetime for $p \rightarrow \pi^0 e^+$ in excess of 10^{35} years. Thus in our opinion, the only viable options to detect proton decay in the near future are the processes shown in Fig. 1 (A and B). The ICARUS detector is well matched to these decay modes.[3] In Fig. 4, we show the limits for various proton decay modes that can be searched for with the 600-ton ICARUS.[3]

2. ICARUS Sensitivity to SUSY-GUT Predictions

The preferred decay mode of $p - K^+\bar{\nu}_\mu$ is uniquely searched for by ICARUS. Figure 5 shows the spectrum of energy deposition for the K^+ decay and illustrates that the detector efficiency can be ~ 85%.[1] Figures 6 (A) and (B) show two simulated events, indicating how unique the signal will be.[1]

Table 2. Unique features of ICARUS.

- Detect particles by ionization
  (water Č detetors observe only fast particles (3 ≈ 1)
  Sensitive to all charged particles in event
- Detect range and ionization to make a particle ID
  (water Č attempt ID by Č ring, etc.)
- Clear study of the vertex of events to help resolve
  ν interaction vs *p* decay
- Large dynamic range (~ 10s keVs → 100 GeV)

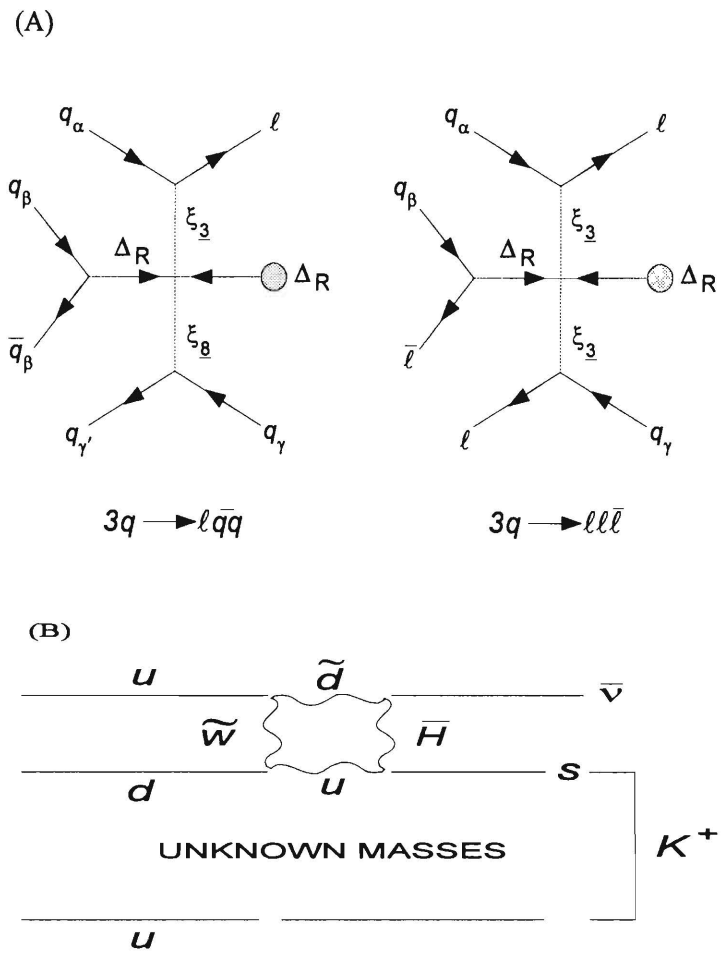


Fig. 1. (A) Feynman diagrams for proton decay into $\ell q\bar{q}$ and $\ell\ell\bar{\ell}$ in the Pati-Salam model, and (B) SUSY-GUT p - $K^+\bar{\nu}_\mu$ decay research.

Table 3. Why should we pay attention to SUSY- GUT predictions? (- Experimentalists)

(Is SUSY science or religion?)

- If a theory has some measured predictions, it should be testable. (SUSY/SUSY-GUTs have "testable" predictions)
- If a new technique is available (e.g., electron drift over large distances in liquid Ar), it should be used.
- Current data are remarkably near expectations for SUSY-GUT
  - $\Omega h^2 \sim 1$
  - $\sin^2\theta_W$ very near $\sin^2\theta_W$ (observed)
  - α extrapolation to GUT scale

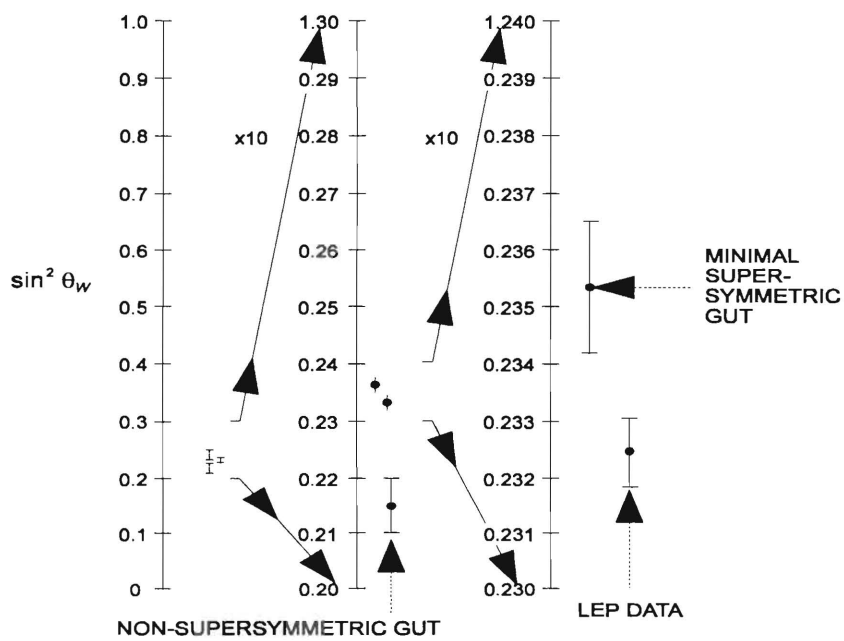


Fig. 2. Gee-whizz plot showing how well GUT predictions of $\sin^2\theta_W$ agree with the experiment data (from Ref. 6).

Table 4. Testable predictions of supersymmetric theories.

1.	Discover SUSY particles at LHC (FNAL): $\tilde{q}$, $\tilde{\ell}$, $\tilde{W}$, ...
2.	Observe proton decay: $p - K^{+}\bar{\nu}_{\mu}$
3.	Detect SUSY dark matter: $\tilde{z}$ (neutralino)

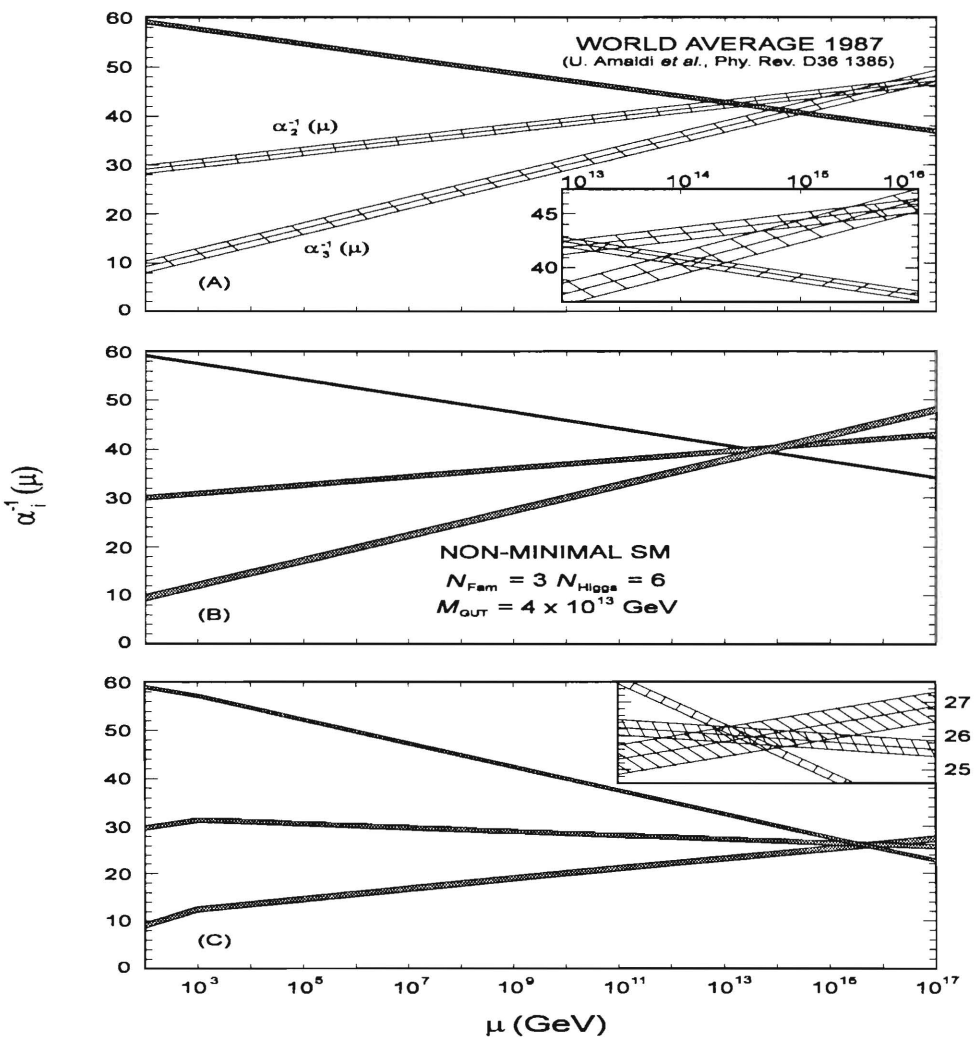


Fig. 3. Extrapolation to the GUT scale.

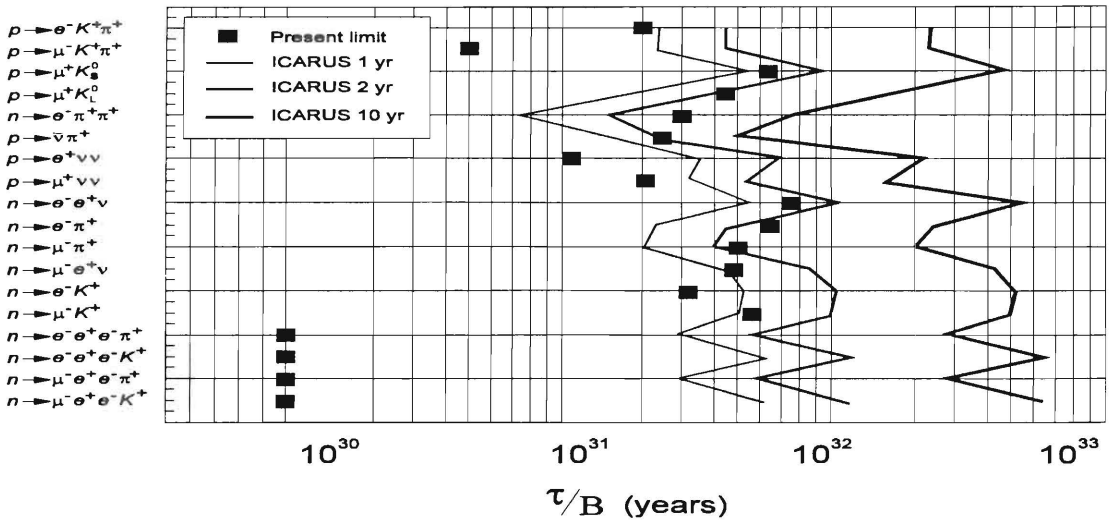


Fig. 4. Present limits for a number of "exotic" proton and neutron decays, together with the 90% ICARUS sensitivity, with the 600-ton module.

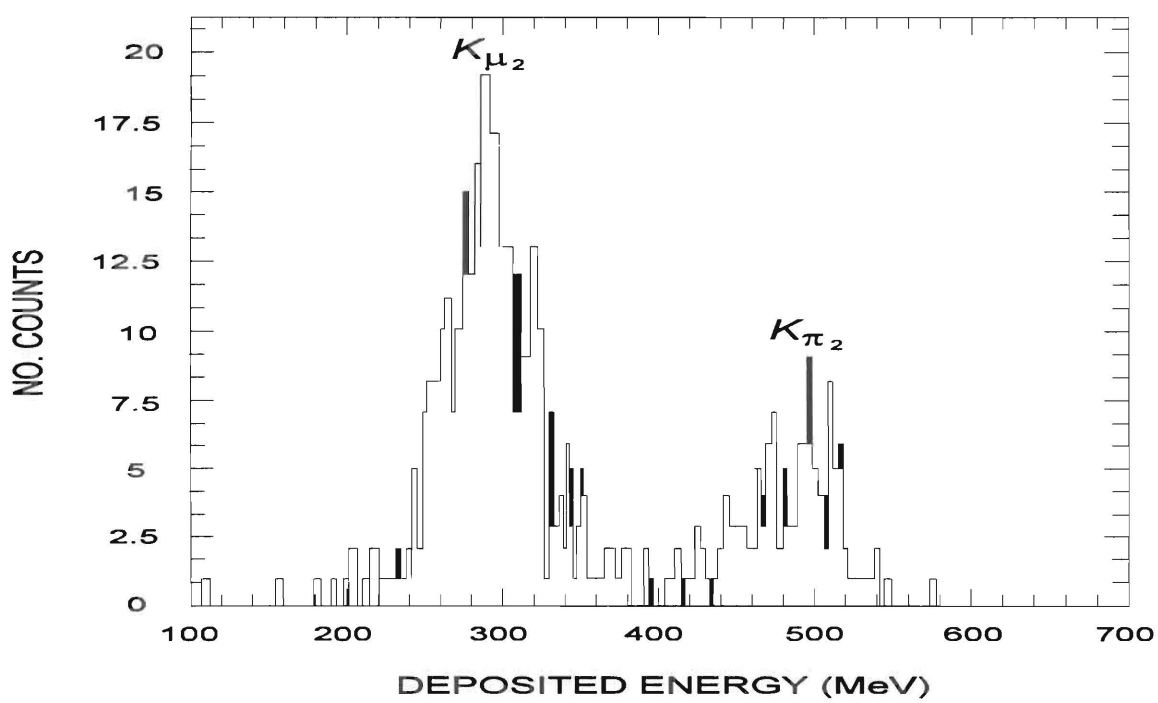
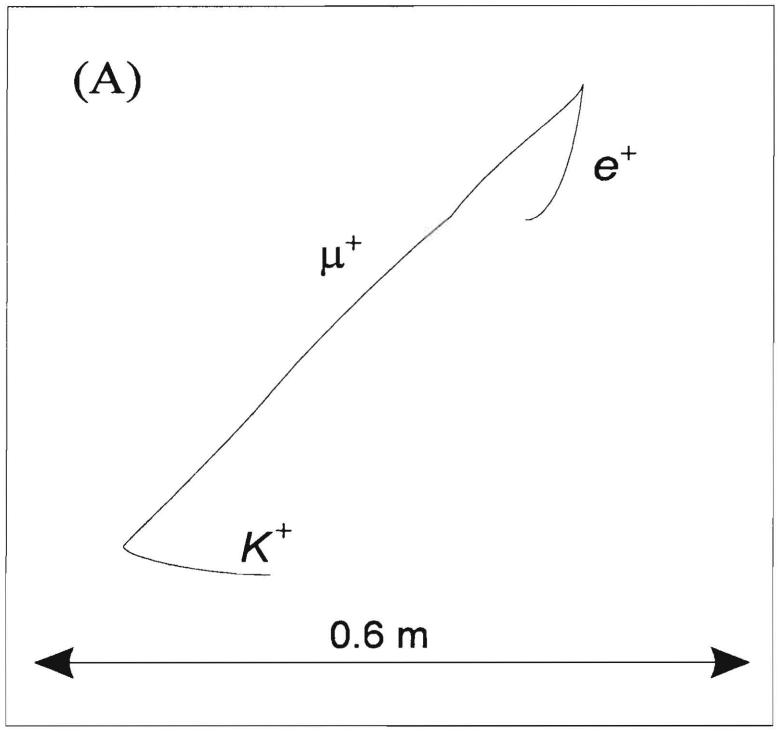


Fig. 5. Spectrum of energy deposition for the k^+ decay. [The two peaks correspond to the decay modes: $k^+ \to \mu^+\nu$ (64%) and $k^+ \to \pi^+\pi^0$ (21%).]



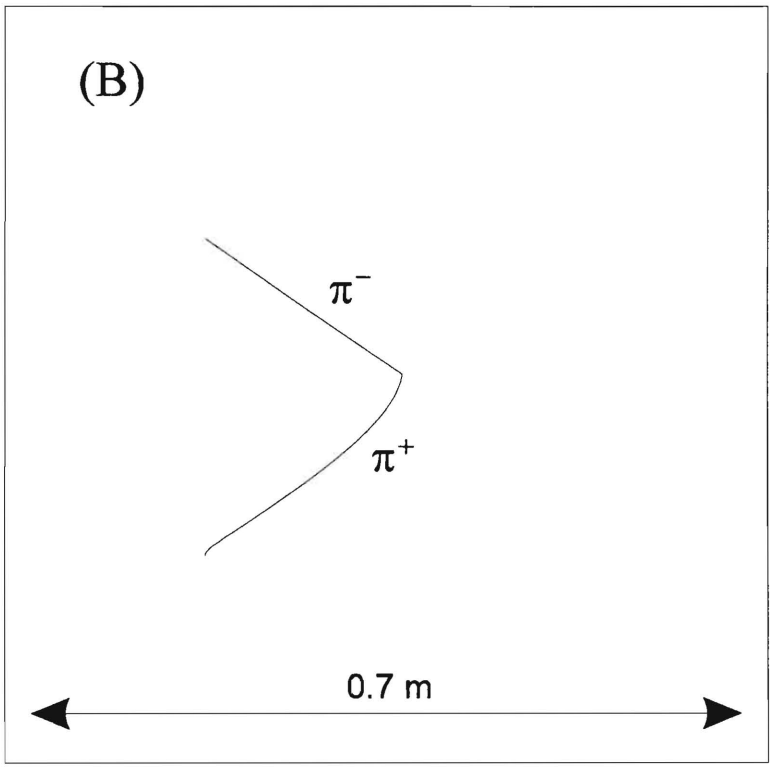


Fig. 6. Simulated $p - K^+\bar{\nu}_\mu$ with k_{μ_2} decay and (B) $n \rightarrow K^0\bar{\nu}_\mu$ in ICARUS.

We have carried out a careful background study to show that $\tau \geq 10^{33}$ years can be achieved with the 5000-ton ICARUS. The reason the background is so small is that the neutrino reaction

$$\nu_\mu + N \rightarrow \nu_i + K^+ + X\,(s = 0) \quad , \tag{3}$$

is forbidden, since it is a flavor-changing weak-neutral-current process. In fact, it may be possible to reach 10^{34} years for this decay with enough operating time! In Table 5, we show the limits (or discovery) that can be reached with the 5000-ton ICARUS.[1]

3. Other Rare Processes with ICARUS

There is a very interesting window of discovery for new sources of 20–30 MeV neutrinos, as shown in Fig. 7. We will not discuss solar neutrinos here, but simply remark that ICARUS can make a unique contribution to this subject as well.[7]

4. Low-Energy Studies with a Liquid-Xenon Detector

In the early 1990s, as the ICARUS technique was being perfected, we considered the possibility of detecting very small recoil energies with the detector.[4,5] 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.[4]

In 1992, a subset of the ICARUS group started the study of liquid Xe for the purpose of WIMP detection.[5] The first report of this work was given in 1992 at Waseda University and was published in the proceedings of the conference.[5] Figure 8(A) shows the initial experimental setup. Table 6 presents a schematic view of the reasons that liquid Xe is potentially an excellent WIMP detector.[4] The scope traces in Fig. 8(B) provide the essential discrimination method.[5] 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.[5] In addition, the pulse shapes provide discriminations against background. More recently, this group has constructed a larger detector [Fig. 9(A)] and carried out very detailed tests of the discrimination methods [Fig. 9(B,C)].[8]

A successful test of the detection of a recoil Xe nucleus using neutron scattering has been carried out recently, 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. 9(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.[8]

Acknowledgements

I wish to thank members of the ICARUS team for their great work on the R&D and detector design presented here. I also wish to thank the ICARUS–WIMP team, including H. Wang and P. Picche.

Table 5. Sensitivity of 5-k ton ICARUS for various proton and neutron decay modes and for a data-taking period of five years.

Decay mode	Sensitivity[a]	No. of events[b]
$p \to e^+\pi^0$	1.2×10^{33}	2.7
$p \to \bar{\nu}\pi^+$	1.2×10^{33}	2.7
$p \to \mu^+\pi^0$	1.5×10^{33}	2.4
$p \to \bar{\nu}K^+$	2.4×10^{33}	5.4
$p \to e^+\pi^+\pi^-$	3.5×10^{32}	0.8
$p \to e^+\rho^0$	2.4×10^{32}	0.5
$p \to e^+e^+e^-$	2.7×10^{33}	6.4
$n \to e^+\pi^-$	1.4×10^{33}	3.1
$n \to \mu^+\pi^-$	1.2×10^{33}	2.9
$n \to \nu\pi^0$	1.4×10^{33}	3.3
$n \to e^-K^+$	2.9×10^{33}	6.6
$n \to e^+\rho^-$	3.0×10^{32}	0.6
$n \to e^+\pi^-\pi^0$	4.1×10^{32}	1.0
$n \to e^+e^-\nu$	3.3×10^{33}	7.8

[a]90% C.L. limit expressed in years and for one module.
[b]corresponds to a nucleon lifetime of 10^{33} years.

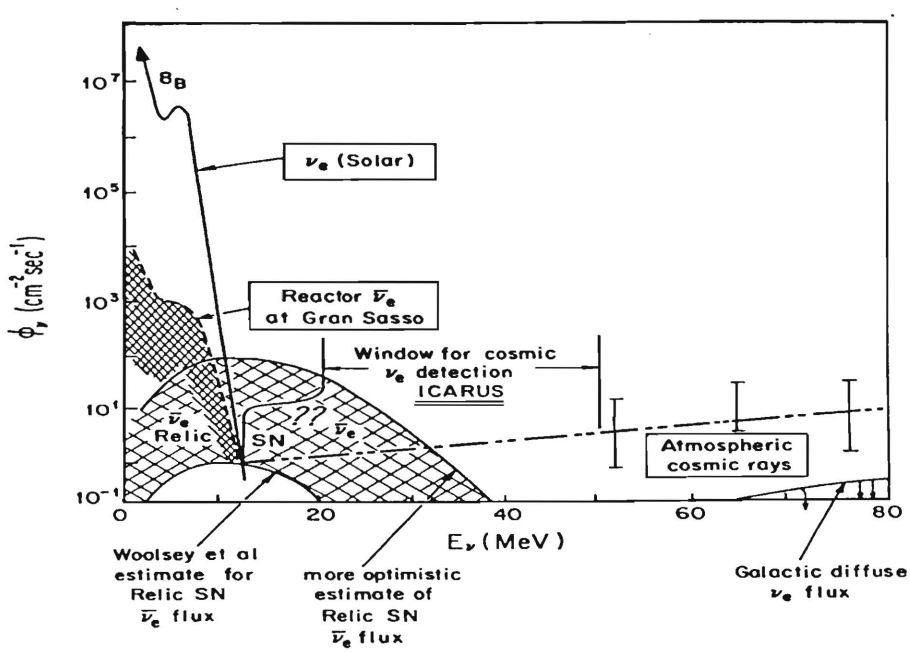


Fig. 7. Window of neutrino sources in which new, possibly cosmological, sources could be detected with ICARUS.

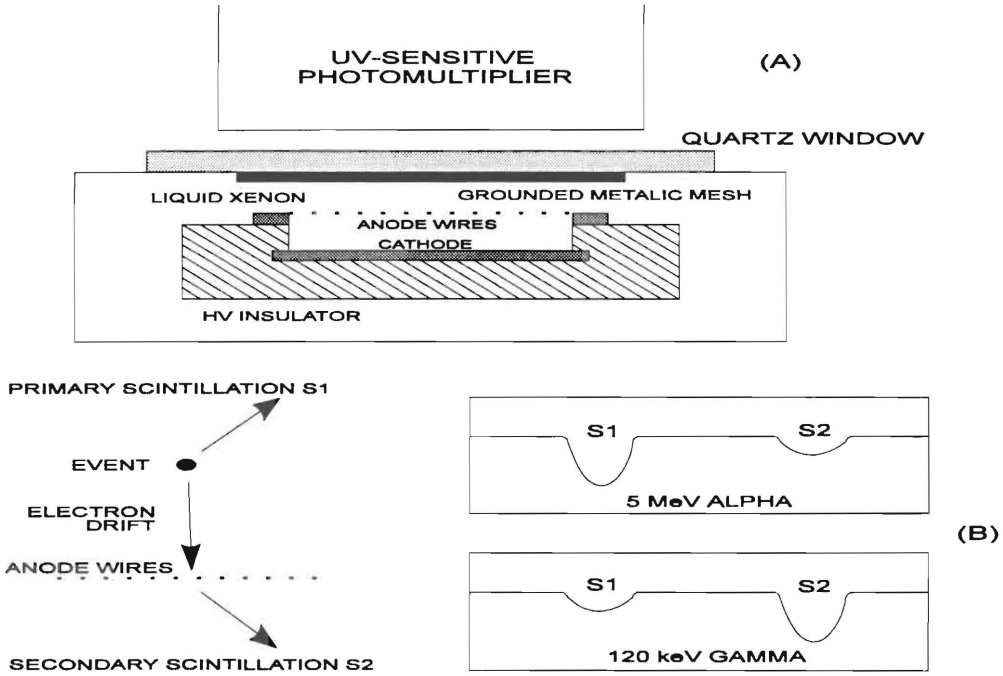


Fig. 8. (A) Geometry of liquid-xenon test chamber, and (B) Observed primary and secondary scintillation signals showing S1/S2 >> 1 for α events and << 1 for γ events.

Table 6. 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

<u>In liquid Xe</u>
- Both charge and light are visible
- This provides an efficient way for signal-to-background rejection

<u>Moreover, in Xe</u>
- No long-lived natural isotopes are present
- Xe^{127} has longest decay time ($\approx$36 d)

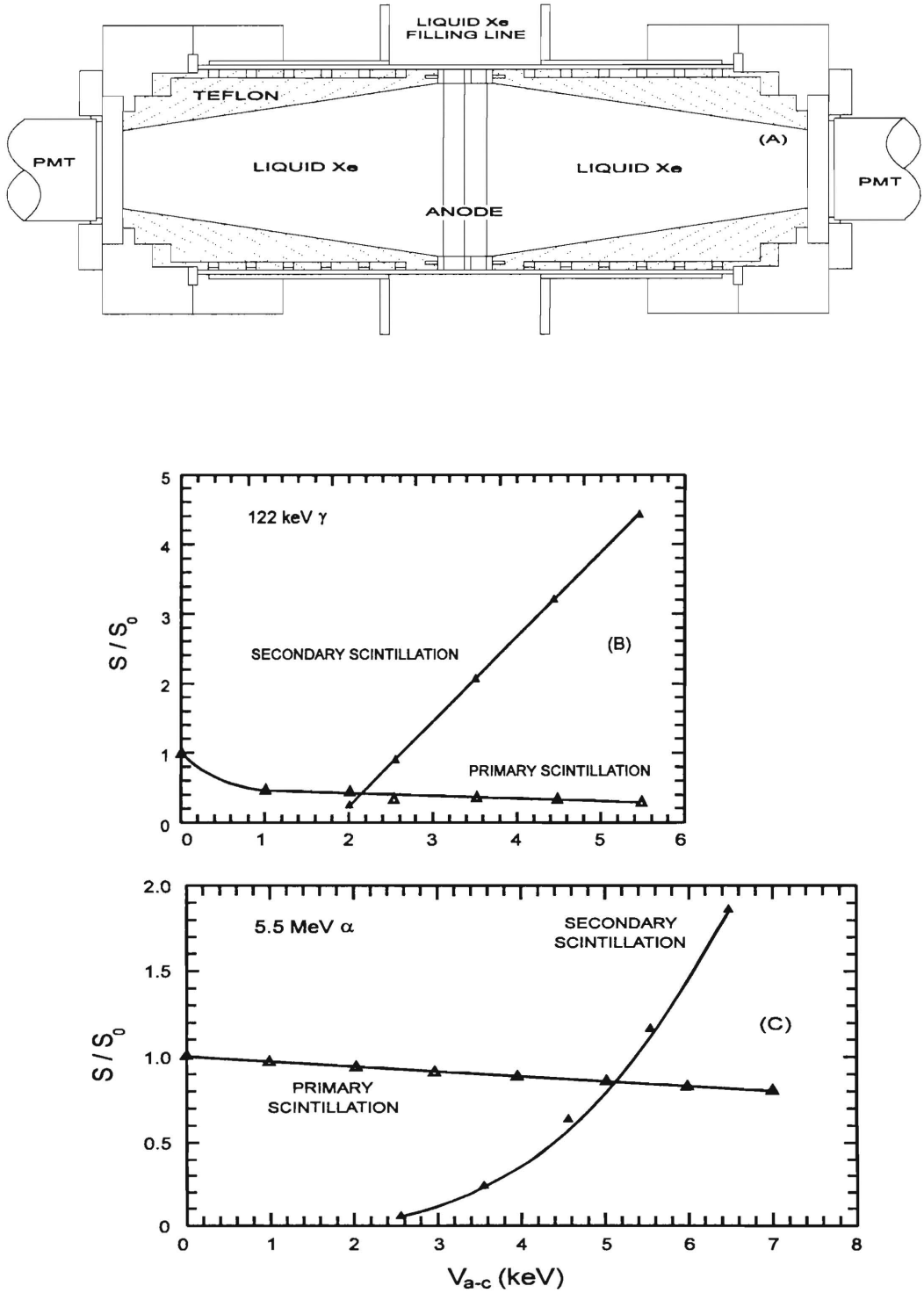


Fig. 9. (A) A 2-kg detector that has been constructed for tests at Mt. Blanc and a possible WIMP search; (B) Variations of the secondary scintillation intensity as a function of $V_{a\text{-}c}$ for photons; and (C) The same as B but for α particles.

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