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APPENDIX B1-A

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PHYSICS STUDIES WITH ICARUS AND A HYBRID IONIZATION AND SCINTILLATION FIBER DETECTOR†

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ABSTRACT

We discuss the physics possibilities for the ICARUS detector currently being tested at CERN. The physics potential goes from a massive proton decay detector to the study of solar neutrinos. In addition, the detection of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\tau$ will be possible with such a detector. One major topic involves the possibility of a complete determination of the MSW solar neutrino parameters with the ICARUS. The possibility of detecting WIMPS with a scintillating fiber liquid Argon (Ar) detector or fiber Xenon (Xe) detector doped with Ar is also described. Some comments on the measurement of the ^{42}Ar level from an experiment at the Gran Sasso will be made.

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† Invited talk at the ICLRD Conference, Tokyo, Japan, 1992.

1. PHYSICS GOALS OF ICARUS

The development of a sensitive 3D readout, liquid Ar detector has a large variety of physics goals. Table 1 lists some of these goals.

1.a. Overview of ICARUS Type Detectors

The successful test of the 3 ton ICARUS prototype at CERN is a great accomplishment. It also leads to a number of new possibilities for elementary particle research. In this report we will concentrate on the physics goals of ICARUS from solar neutrinos to proton decay to the possible detection of the ν_τ (directly at the LHC or from $\nu_\mu \rightarrow \nu_\tau$ oscillations). We will then discuss the possibility of constructing a novel WIMP detector using a combination of ionization and scintillating light with a fiber readout system.

1.b. Search for ^{42}Ar in a Gran Sasso Experiment

One of the most interesting problems of the use of liquid Ar is the level of radioactive background from ^{42}Ar. This has never been measured but R. Davis has set limits on this impurity.

1.c. Solar Neutrino Experiment with ICARUS

The prospects for detection of neutrino oscillation and hence a finite neutrino mass using solar neutrinos remains high.Current experiments suggest the existence of neutrino oscillations but do not prove it. These experiments typically measure a single scattering reaction such as $\nu_e + e^- \rightarrow \nu_e + e^-$ and thus must compare their results with calculations of the Solar neutrino flux. In contrast, a new generation of Solar neutrino telescope is being constructed and that can be used to measure two reactions simultaneously. This avoids the necessity to use the Solar neutrino flux calculation. In the ICARUS detector the reactions that are measured are

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^- \qquad (1)$$

and

$$\nu_e + \mathrm{Ar} \rightarrow e^- + K^* \rightarrow e^- + K + \gamma \qquad (2)$$

The ICARUS detector program has two phases:

(1) measurement of the response of a model detector at CERN
(2) measurement of background for the Solar Neutrino detection at the Gran Sasso Laboratory.

In this note we show how a 1000 Ton ICARUS detector can be used to conclusively prove the existence of neutrino oscillations (whether vacuum or MSW induced) and to measure the critical parameters of the neutrino oscillations

$$\sin^2 2\theta \text{ and } (m_1^2 - m_2^2)$$

We apply numerical methods to solve the equation of motion with two neutrino flavors. Electron density in the Sun is approximated with an exponential function of distance from the core of the Sun. We calculated the surviving probability of ν_e at the surface of the Sun using fourth order Runge-Kuta method. This value is used to generate the ν_e spectrum. A Monte Carlo program is written to simulate the recoil electron. At 5MeV cutoff energy all the elastic scattering events are confined to less than 20°. This is very important in the event selection since solar neutrino should point toward the Sun.

Three pair of parameters are used to exemplify the wide range of solutions to the solar neutrino puzzle. In Figs. 1 through 3 we show the spectrum for $^8B\nu_e$ as well as the recoil electron. In each case we also show the event rate for absorption and elastic scattering (Fig. 4a-c). In Case I, where high energy neutrinos are converted, we see a drastic change in absorption rate. This is because the absorption channel is sensitive only to neutrinos above the 5.85MeV threshold. In Fig. 4d we show the ratio of absorption event and elastic scattering event for each of these cases. In Table 2 we show the event rate for SSM prediction and three cases we studied with a 1000 Ton ICARUS detector. In Cases I and II we see that the ratios are drastically different from SSM prediction. It is obvious that different solutions can be distinguished if both interaction modes are used.

1.d. Search for Proton Decay with a Massive ICARUS

The search for proton decay with dedicated detectors started in the early 80's. The current generation of detectors has nearly exhausted the lifetime range up to $\sim 10^{32}$ years. The scaling rules for the proton decay search are

$$\tau_p \propto N_p \text{ [protons in detector]} \qquad S/N >> 1 \tag{1a}$$

$$\tau_p \propto \sqrt{N_p} \qquad S/N \lesssim 1 \tag{1b}$$

where S is the signal for proton decay and N is the background. In the latter case, (1b), a background subtraction is required and this reduces the statistical power of the detector.

In order to explore the $\tau_p \sim 10^{32} - 10^{34}$ years region, we choose between two options

(1) construct very large detectors ($M \sim 10^5$ Tons) that will have $S/N \lesssim 1$ or

(2) construct detectors with $M \sim 10^4$ Tons with $S/N >> 1$.

In the first category are new water detectors such as Super Kamiokande (Kam II) and in the second are massive ***electronic-bubble-chamber-like*** detectors such as ICARUS, which uses electron drift imaging techniques.

Several complete searches have been carried out for proton decay. Some recent results are given in Reference 1. Two key decay modes are

$$p \rightarrow \pi^0 e^+ \qquad (\mathrm{I}) \tag{2a}$$

and

$$p \rightarrow K^+ \bar{\nu} \qquad (\mathrm{II}) \tag{2b}$$

In some ways these two modes *tone* the scale for the entire search for proton decay.

Decay mode (I) is expected to go through normal GUT type processes. Decay mode (II) is expected to go through processes where the GUT-Higgs boson is the key intermediate state. Future searches for proton decay can be judged, in some sense, by how well they are able to search for these two modes.

Table 3 gives the current limit on some decays of type II[6,9]. The lifetime limit for $p \rightarrow \pi^0 e^+$ is in the vicinity of 5×10^{32} years as determined from the IMB and Kam II detectors[8,9]. The fact that τ_p, for $p \rightarrow K^+ \bar{\nu}$, goes like $\sqrt{N_p}$ is stated by Table 3.

It is well known that the SU(5) model of Grand Unification disagrees with several precise measurements and the current limits on the proton lifetime. However, for sometime it has also been known that the extrapolation of the three running constants to the GUT scale do not cross in one place (see Fig. 5). One simple remedy for this situation is to invoke a supersymmetric version of SU(5), i.e. SUSY GUTS. Taking this approach has two interesting ramifications

(1) the SUSY particle scale may be beyond the TeV mass range, i.e. squarks, etc., may exist

(2) the decay mode $p \rightarrow K^+ \bar{\nu}$ is favored through Higgs mediated processes, as shown in Fig. 6[11], however, the lifetime is likely to be between $10^{32} - 10^{34}$ years. (See Table 4 for a supergravity model.)

Thus, SUSY-GUTS presents the next challenge to the proton decay searches.

In order to continue the search for proton decay into new lifetime regions and exotic decay modes, new detector techniques are needed. One such technique is being developed by the ICARUS group. This technique uses liquid Argon and electron-drift imaging of the tracks. If successful, this technique can produce spectacular events that may have no important backgrounds. The UCLA ICARUS group has been simulating the decay mode $p \rightarrow K^+ \bar{\nu}$. Fig. 7 shows a simulated event, indicating the quality of the images. In addition, dE/dx information can be used to further define the events.

It would appear that there is no significant background that can fake $p \rightarrow K^+\bar{\nu}$ in ICARUS. The current status of this experiment is that a 3 Ton prototype detector has been constructed and is starting to operate at CERN. The next stage is to construct a $\sim$ 1000 Ton detector for Hall C at the Gran Sasso. The ultimate ICARUS detectors could be $\sim 10^4$ Tons at the Gran Sasso and could extend the lifetime for $p \rightarrow K^+\bar{\nu}$ to 10^{34} years.

At present the best limits for proton decay come from the large water detectors such as IMB and Kam II. A larger version of Kam II is being proposed for Japan. This detector would have a 22,000 Ton fiducial volume. This would be equivalent to approximately 10 times the size of the current Kam II detector. The major question being asked is whether the proton decay search will be extended by a factor of 10 or by $\sqrt{10}$ (Eqs. 2a or 2b). If the latter is correct, the Kam II detector can extend the search for proton decay to 10^{33} years. This is a very significant advance in the field. A possible comparison of the ICARUS and Kam II detectors is given in Table 3[1].

It appears that SUSY- GUTS is a viable theory and that three major consequences follow

(1) one Higgs boson may have a mass less than M_Z
(2) the SUSY particles may have masses beyond the TeV range and thus might not be detectable even at the SSC
(3) proton decay, mainly $p \rightarrow K^+\bar{\nu}$ is a crucial test of the theory but the lifetime is expected to be $10^{33} - 10^{34}$ years

These points present an enormous challenge to the proton decay searcher.

1.e. Possible Detection of the τ Neutrino (ν_τ)

The spatial resolution obtained in the CERN test is $\sim 60\mu$ and may make it possible to detect τ particles from $\nu_\mu \rightarrow \nu_\tau$ oscillations.

2. DARK MATTER DETECTION – MASSIVE WIMPS

While a search for Cold Dark Matter is underway in several places, there are many uncertainties in the expected flux and types of WIMPs[1]. Recent accelerator constraints imply that higher mass WIMPs are preferred. On the other hand, very low temperature detectors, while progressing, are still far from detector mass of 10 – 100 kilograms that is likely required. In this talk we first discuss the successful development of two new detector technologies: imaging in ultra-pure liquid argon (ICARUS) and the development of scintillating fiber technology.

There are several new developments in the issue of dark matter in the universe that are relevant to the current search

1) recent $\bar{p}p$ collider and LEP results suggest $M_{\rm WIMP} > 20\,\rm GeV$
2) the cross section for WIMP scattering falls rapidly with mass – 0.1 Ton or greater detectors are now required
3) no one knows how much of the dark matter in our galaxy is non baryonic
4) Cold Dark Matter models are in some trouble with the observed large scale structure of the universe For these reasons we believe that an effort should be mounted to search for massive WIMPs with large detectors (> 0.1 Ton). In this report we discuss the possibility of a non ultra low temperature detector using liquid Xenon.

3. THE STATUS OF THE ICARUS DETECTOR DEVELOPMENT

The ICARUS detector was first proposed in 1983 and steady progress has been made over the recent period. Table 1 lists the possible physics goals of detectors that use this technique. The current technical effort is being directed by P. Picchi.

Table 1 lists some of the particle physics goals that can be carried out with detectors that use electron drift in ultrapure liquid argon, Krypton or Xenon. The ICARUS team is listed in reference 2. Recent progress in purification of liquid Argon and previous references are given in Reference 3. Recently there has been a breakthrough in the ICARUS program with the successful operation of the 3 Ton prototype at CERN. The detector has been triggered at 500 KeV (this is why a WIMP search may be possible for the solar neutrino physics simulation. Fig.7 shows a stopping μ in the ICARUS detector at CERN. Pictures of this sort lead to the name *an electronic bubble chamber*. The next step in the ICARUS program is to study the ^{42}Ar level in argon at the Gran Sasso this Fall. (Current attempts to search for ^{42}Ar at the Gran Sasso provide limits below that of the previous experiments of R. Davis.) We believe the initial goals of the ICARUS R & D program have been met and this technology is now available for physics studies as listed in Table 1. Some results have also been reported in liquid Xenon[5,6].

4. THE VLPC FOR SCINTILLATING FIBER TRACKING SYSTEMS

In order to use scintillating fibers for tracking in high energy high luminosity colliders, such as the SSC or LHC, a high quantum efficiency photon detector is required. Such a detector was invented by M. Petroff of Rockwell, Inc. and is being developed by a group that is being led by M. Atac. Much of the research is aimed for use in the SDC detector for the SSC. We now review the recent progress in this field.

The scintillating fiber tracking team in the SDC detector is listed in Reference 7. A UCLA-Rockwell team is carrying out extensive studies at UCLA[8]. The idea of the VLPC is shown in Fig.5[9]. In Fig. 10 we show the experimental arrangement for the UCLA-Rockwell tests. Fig. 11 shows the results of individual photon counting. This is the most efficient photon detector in the world. We believe this technology is now ready to be used in novel particle detectors, as well.

5. A POSSIBLE DARK MATTER DETECTOR USING LIQUID XENON WITH AN EMBEDDED SCINTILLATING FIBER SYSTEM

The basic concept we propose is to attempt to detect individual recoiling Xe atom/nucleus created from the WIMP collision

$$\mathrm{W} + \mathrm{Xe} \rightarrow \mathrm{W} + \mathrm{Xe} \tag{1}$$

for the massive WIMPs. The concept is to use both ionization and scintillation light to identify the Xe recoil. The average energy given to the Xe is

$$\langle E \rangle = 2\,\mathrm{KeV}\,\frac{M_{\mathrm{Xe}}}{1\,\mathrm{GeV}}\left[\frac{M_{\mathrm{W}}}{M_{\mathrm{W}} + M_{\mathrm{Xe}}}\right]^2 \tag{2}$$

For $M_{\mathrm{W}} > M_{\mathrm{Xe}}$ $\langle E \rangle \rightarrow 270\,\mathrm{KeV}$.

Scintillation light from various particles has been recorded in Xe by T. Doke, et al[6]. Fig. 12 shows some of these results. Note that relativistic and non relativistic particles behave differently. We now propose a WIMP detector to record individual Xe recoil from massive WIMP interaction ($M > 250\,\mathrm{GeV}$). **The basic concept is to record ionization (and position) ICARUS style and to detect the Xe scintillation light using a large number of fibers in the liquid Xenon.** Detectors of 0.1 – 1 Ton could result from this approach, allowing a definitive search for massive WIMPs. Fig. 13 shows a schematic view of such a detector. Tests are underway to put scintillating fibers in liquid argon at UCLA. These tests and further studies of ICARUS and the VLPC technology, as well as Monte Carlo simulations, will indicate the feasibility of this idea.

ACKNOWLEDGEMENTS

I wish to thank the ICARUS team for the developments reported in Section 2, especially A. Bettini and P. Picchi, as well as M. Cheng and M. Zhou. The VLPC work was carried out under M. Atac, as well as M. Petroff, J. Park and D. Chrisman. The WIMP detector idea can not be blamed on anyone of these people but has come from interactive discussions. I thank the DOE for support of the UCLA effort in ICARUS and the VLPC work.

TABLE 1.

Physics Potential of Ultra Pure Liquid Drift Detectors Using Ar, Kr or Xe

Energy Range	Physics Study	Type of Detector	Size
0.1 MeV	Massive WIMP Search	Liquid Xe with Ionization and Scintillation Detection	0.1 – 1 Ton
3 – 30 MeV	Double β Decay Solar Neutrino Study (ICARUS) γ Ray Telescope Neutrino Magnetic Moment	Liquid Ar or Xe (Kr too radioactive)	100 – 1000 Ton
100 – 1000 MeV	Atmospheric Neutrino Oscillation WIMPs in the Sun (ICARUS)	Ar	1000 – 10,000 Ton
1 GeV	Proton Decay ($p \rightarrow K^+\bar{\nu}$) (ICARUS)	Ar	1000 – 10,000 Ton
1 – 0.5 GeV	ϕ Factory Detector (Frascati, UCLA)	Ar or Kr (with Scintillation Light)	15 – 200 Ton
5 – 50 GeV	Search for $\nu_\mu \rightarrow \nu_\tau$ or $\nu_e \rightarrow \nu_\tau$	Ar	5 – 50 Ton

TABLE 2

Rates for Events in ICARUS (1000 Ton) for $E_e > 5\,\mathrm{MeV}$ per year

SOLUTION	PARAMETERS	ABSORPTION	ELASTIC	SUM
	No Oscillation	832	918	1740
CASE 1:	$\sin^2 2\theta = 10^{-3}$ $\Delta m^2 = 10^{-4}\,\mathrm{eV}^2$	136	564	700
CASE 2:	$\sin^2 2\theta = 1 \times 10^{-0.5}$ $\Delta m^2 = 5 \times 10^{-5}\,\mathrm{eV}^2$	276	442	718
CASE 3:	$\sin^2 2\theta = 1 \times 10^{-1.5}$ $\Delta m^2 = 1.1 \times 10^{-6}\,\mathrm{eV}^2$	526	546	1072

TABLE 3

Comparison of ICARUS (3K Ton) & Super Kam (30K Ton) Search for SUSY Type Proton Decay – 2 Year Run

Mode:	Assumed τ/B	Signal (ICARUS)	BG (ICARUS)	Signal (S.Kam)	BG (S.Kam)
$p \rightarrow K^+\bar{\nu}$	5×10^{32}	4	~ 0	40	56 ± 30?
$\eta \rightarrow K^0\bar{\nu}$	5×10^{32}	4	~ 0	40	20
$p \rightarrow \pi^+\bar{\nu}$	5×10^{32}	4	~ 0 (if π^+ range measured)	40	280
$p \rightarrow \mu^+\eta$	5×10^{31}	40	~ 0	400	< 16

TABLE 4

Values of m_1 (GeV) of Eq.(4.4) for Kamiokande bound Eq. (2.1a) and IMB bound Eq.(2.1b) for cases (1), (2), and (3) of Sect. 4. ($m_{\tilde{\gamma}} = 10\,\text{GeV}$, $m_{\tilde{\omega}} = 40\,\text{GeV}$, $\alpha_H = 45°$, and $M_H = 1 \times 10^{16}\,\text{GeV}$.) (Ref. 11)

Limits on Photino & Squark Masses from Proton						
	KAMIOKA			IMB		
CASE:	m_1	m_2	m_3	m_1	m_2	m_3
(1)	143	144	3000	142.5	144.5	2050
(2)	138.5	149.5	895	133.5	158	560
(3)	124	220	250	111	–	–

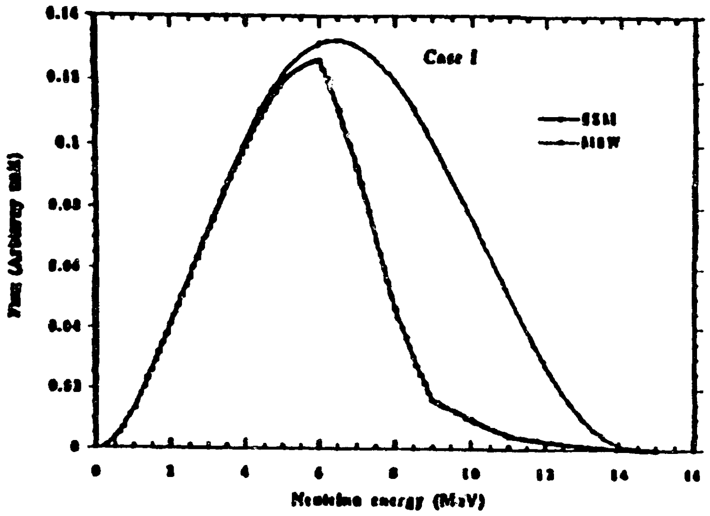


FIG.1a ^{8}B neutrino spectrum from the Sun. $\Delta m^2 = 10^{-4}\,\mathrm{eV}^2$, $\sin^2 2\theta = 10^{-3}$.

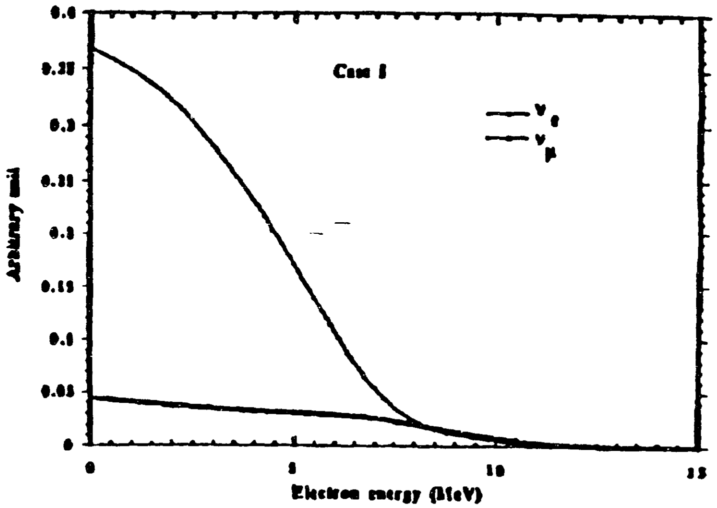


FIG.1b Recoil electron energy spectrum with ν_e scattering at 5 MeV cutoff.

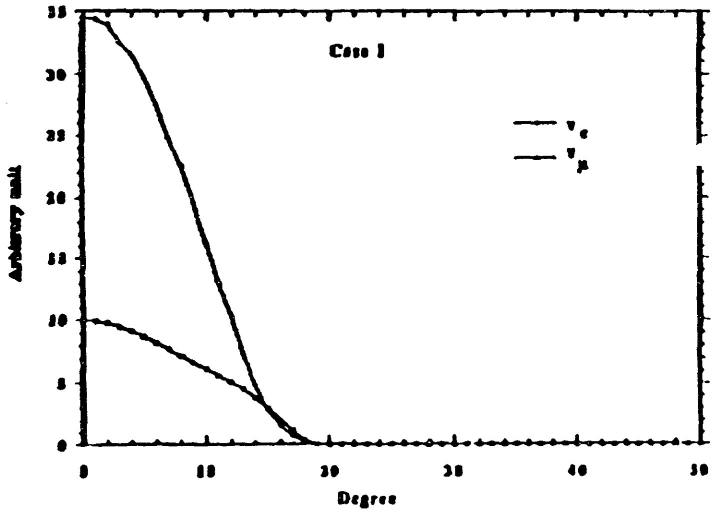


FIG.1c Recoil electron angular spectrum with ν_e scattering at 5 MeV cutoff.

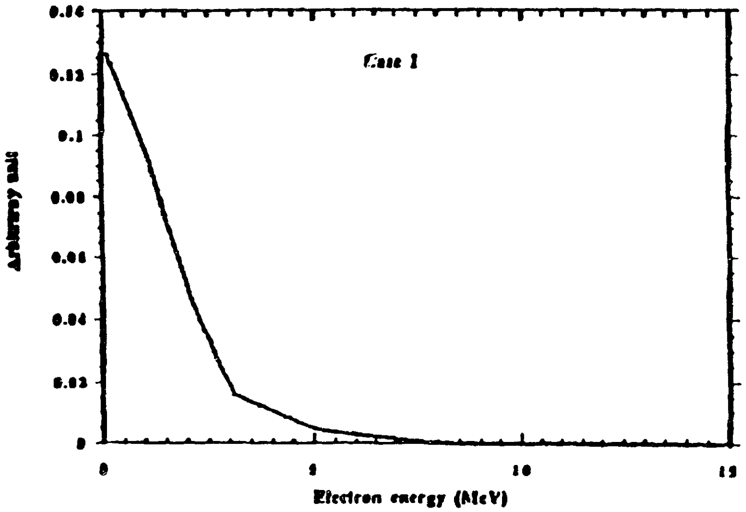


FIG.1d Recoil electron energy spectrum with absorption at 5 MeV cutoff.

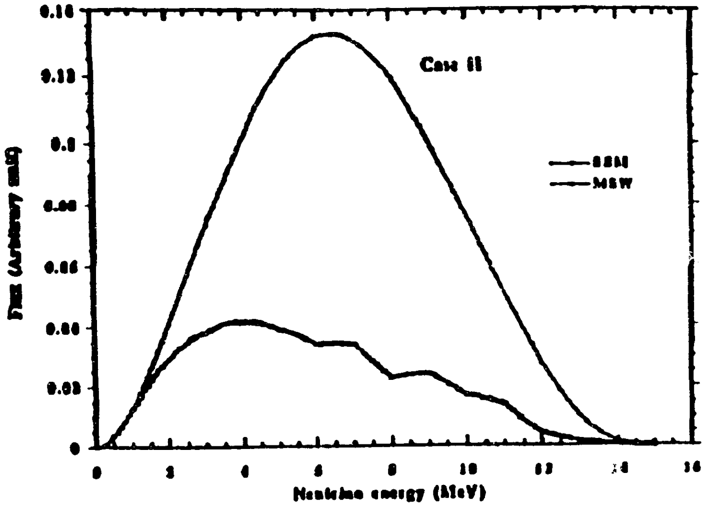


FIG.2a ^{8}B neutrino spectrum from the Sun. $\Delta m^2 = 5\times10^{-5}\,\mathrm{eV}^2$, $\sin^2 2\theta = 1\times10^{-0.5}$.

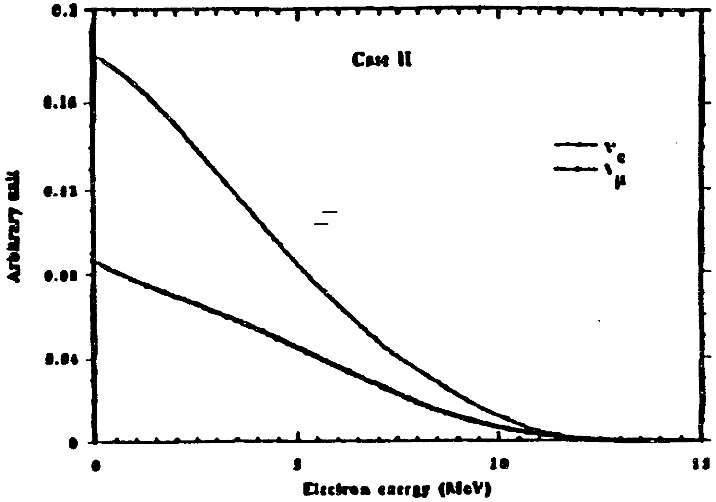


FIG.2b Recoil electron energy spectrum with ν_e scattering at 5 MeV cutoff.

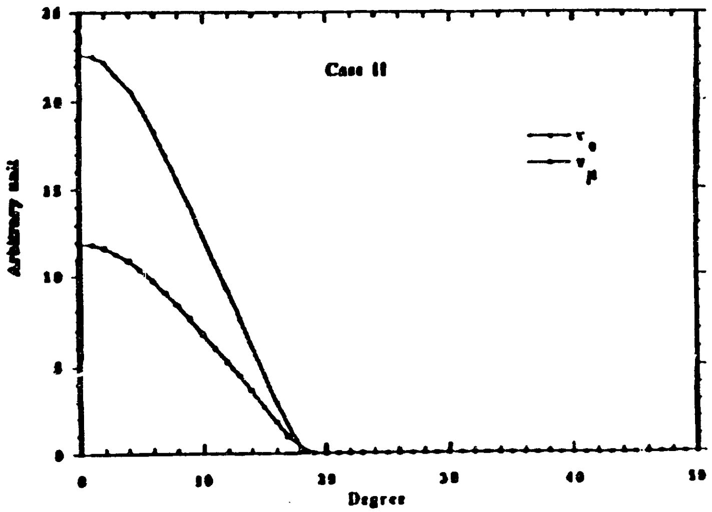


FIG.2c Recoil electron angular spectrum with ν_e scattering at 5 MeV cutoff.

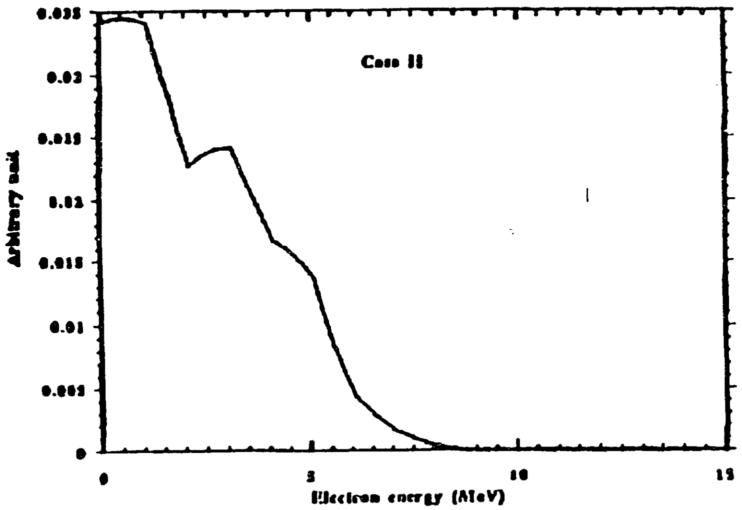


FIG.2d Recoil electron energy spectrum with absorption at 5 MeV cutoff.

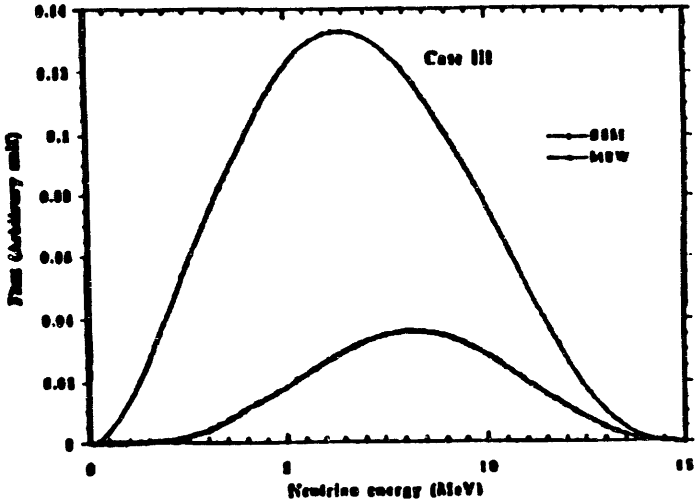


FIG.3a ^{8}B neutrino spectrum from the Sun. $\Delta m^2 = 1.1\times 10^{-6}\,\mathrm{eV}^2$, $\sin^2 2\theta = 1\times 10^{-1.5}$.

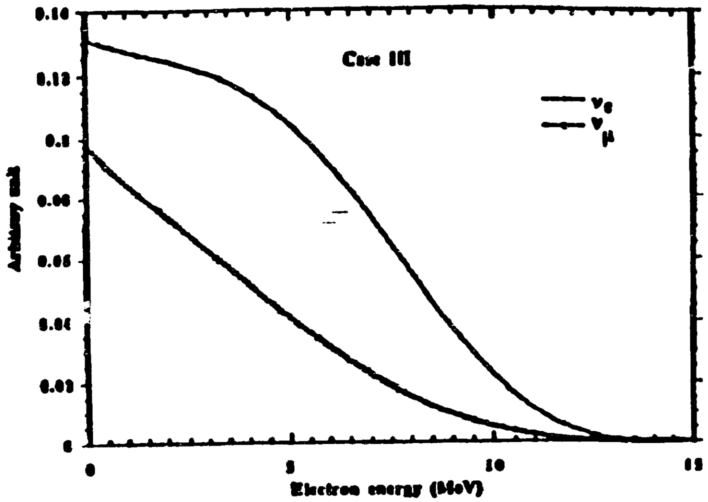


FIG.3b Recoil electron energy spectrum with ν_e scattering at 5 MeV cutoff.

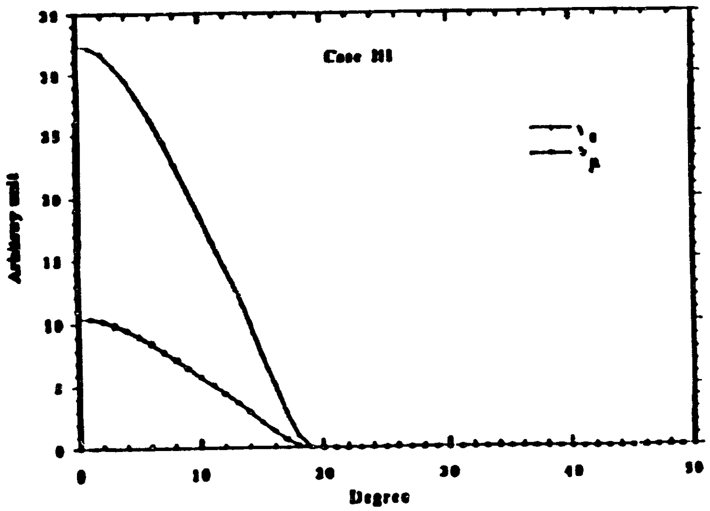


FIG.3c Recoil electron angular spectrum with ν_e scattering at 5 MeV cutoff.

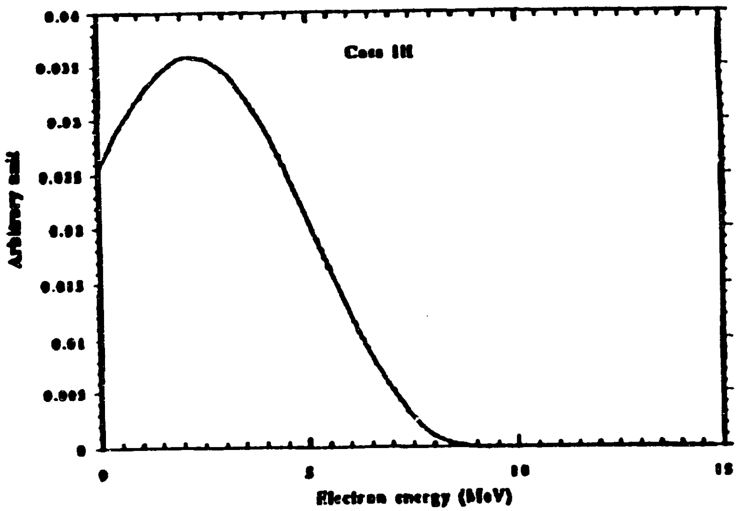


FIG.3d Recoil electron energy spectrum with absorption at 5 MeV cutoff.

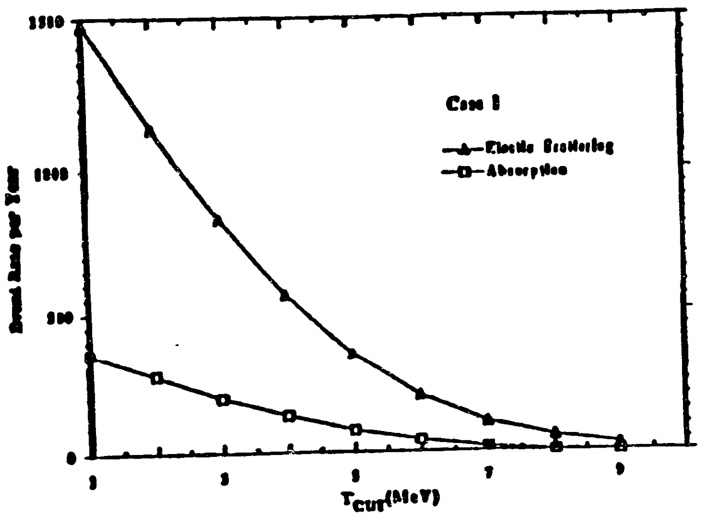


FIG.4a Event rate per year as a function of cutoff energy of recoil electron at $\Delta m^2 = 10^{-4}\,eV^2$, $\sin^2 2\theta = 10^{-3}$.

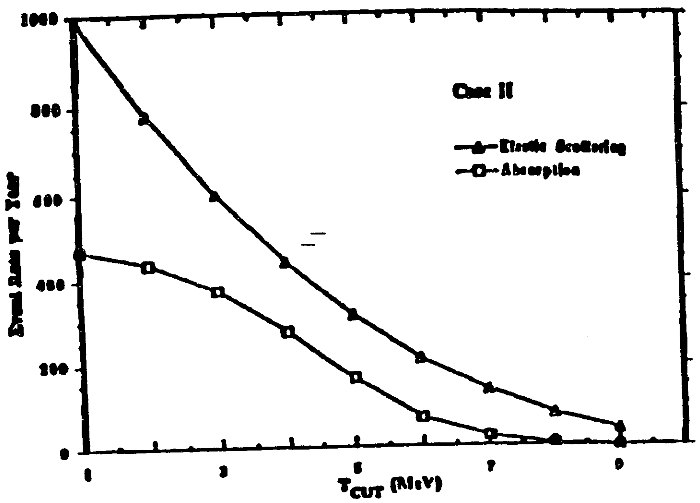


FIG.4b Event rate per year as a function of cutoff energy of recoil electron at $\Delta m^2 = 5 \times 10^{-5}\,eV^2$, $\sin^2 2\theta = 1 \times 10^{-0.5}$.

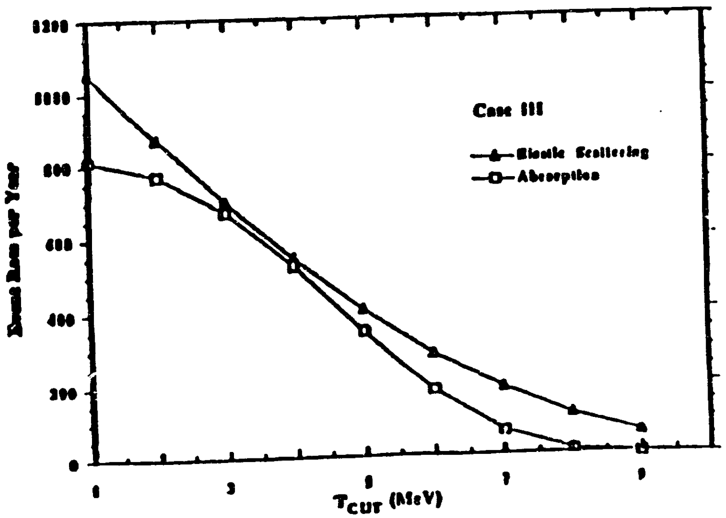


FIG.4c Event rate per year as a function of cutoff energy of recoil electron at $\Delta m^2 = 1.1 \times 10^{-6}\,eV^2$, $\sin^2 2\theta = 1 \times 10^{-1.5}$.

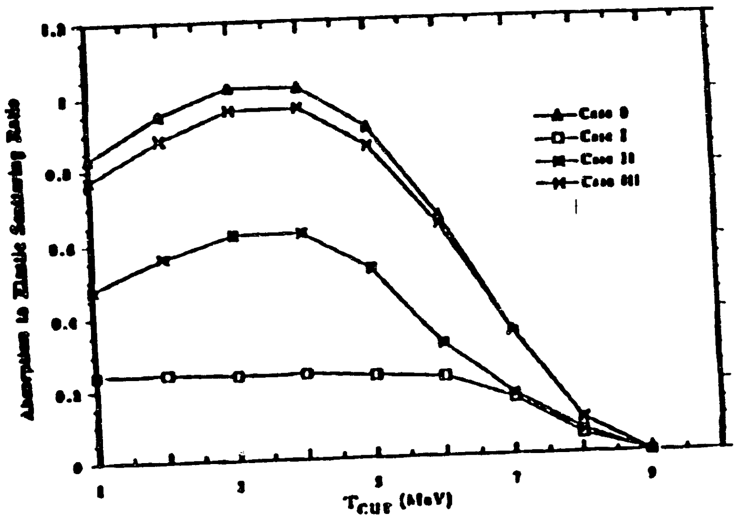


FIG.4d Ratio of absorption and elastic scattering event as a function of cutoff energy. Case 1 is $\Delta m^2 = 10^{-4}\,eV^2$, $\sin^2 2\theta = 10^{-3}$. Case 2 is $\Delta m^2 = 5 \times 10^{-5}\,eV^2$, $\sin^2 2\theta = 1 \times 10^{-0.5}$. Case 3 is $\Delta m^2 = 1.1 \times 10^{-6}\,eV^2$, $\sin^2 2\theta = 1 \times 10^{-1.5}$.

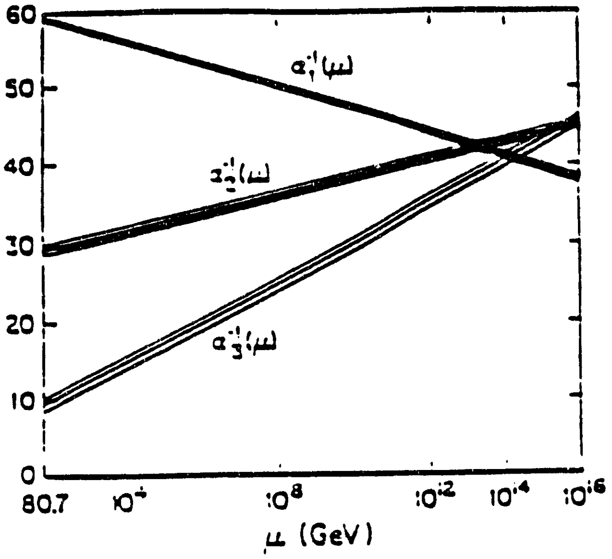


FIG.5 Early attempt to extrapolate the running coupling to the GUT scale.

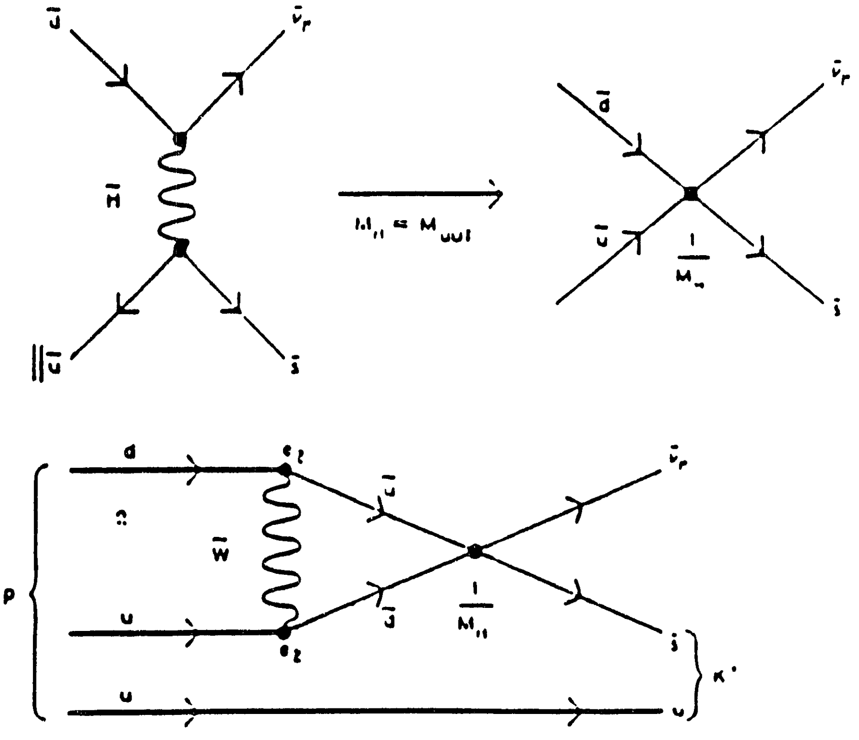


FIG.6 SUSY GUTS proton decay process.

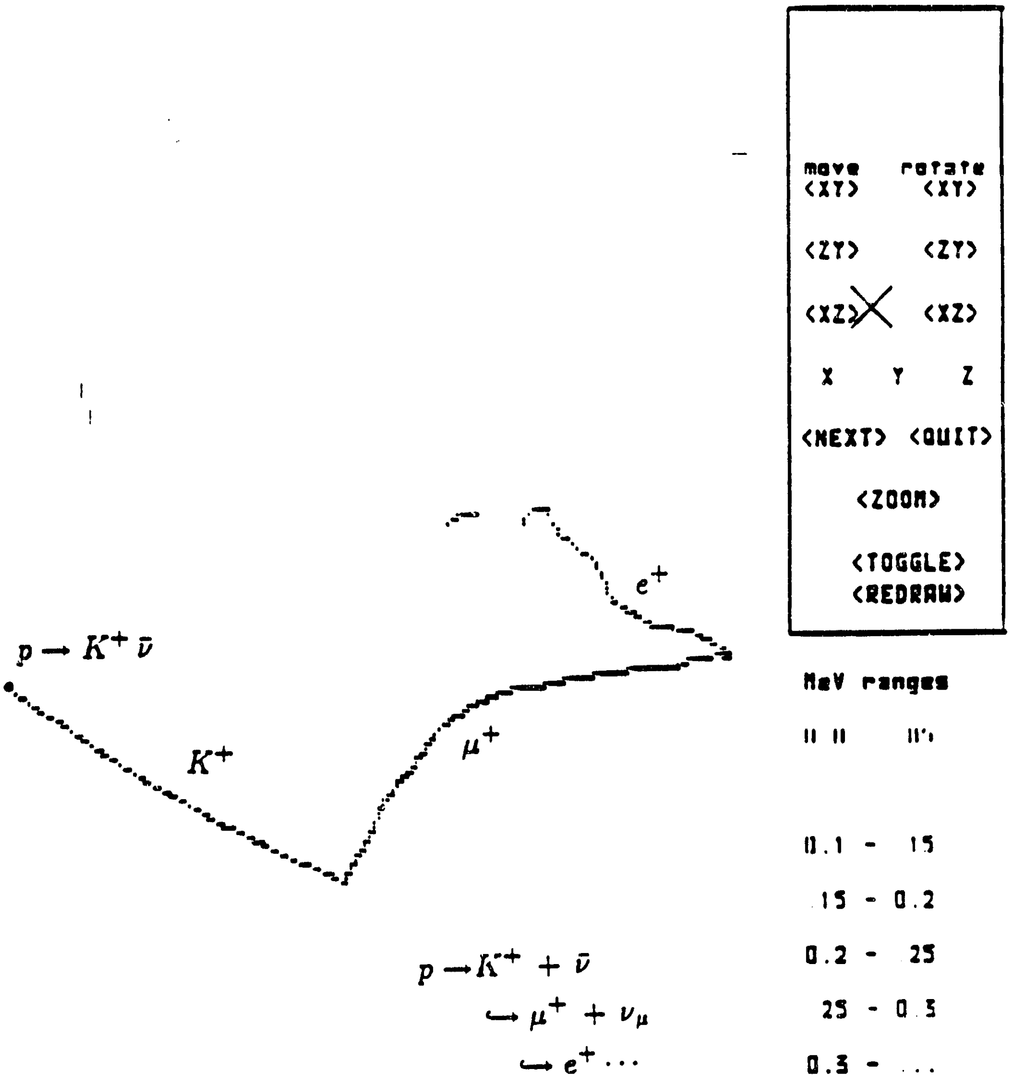


FIG.7 Simulation of $p \rightarrow K^+\nu$ in ICARUS.

FIG.8 Muon stop and subsequently decay into electron seen in the collection plane.

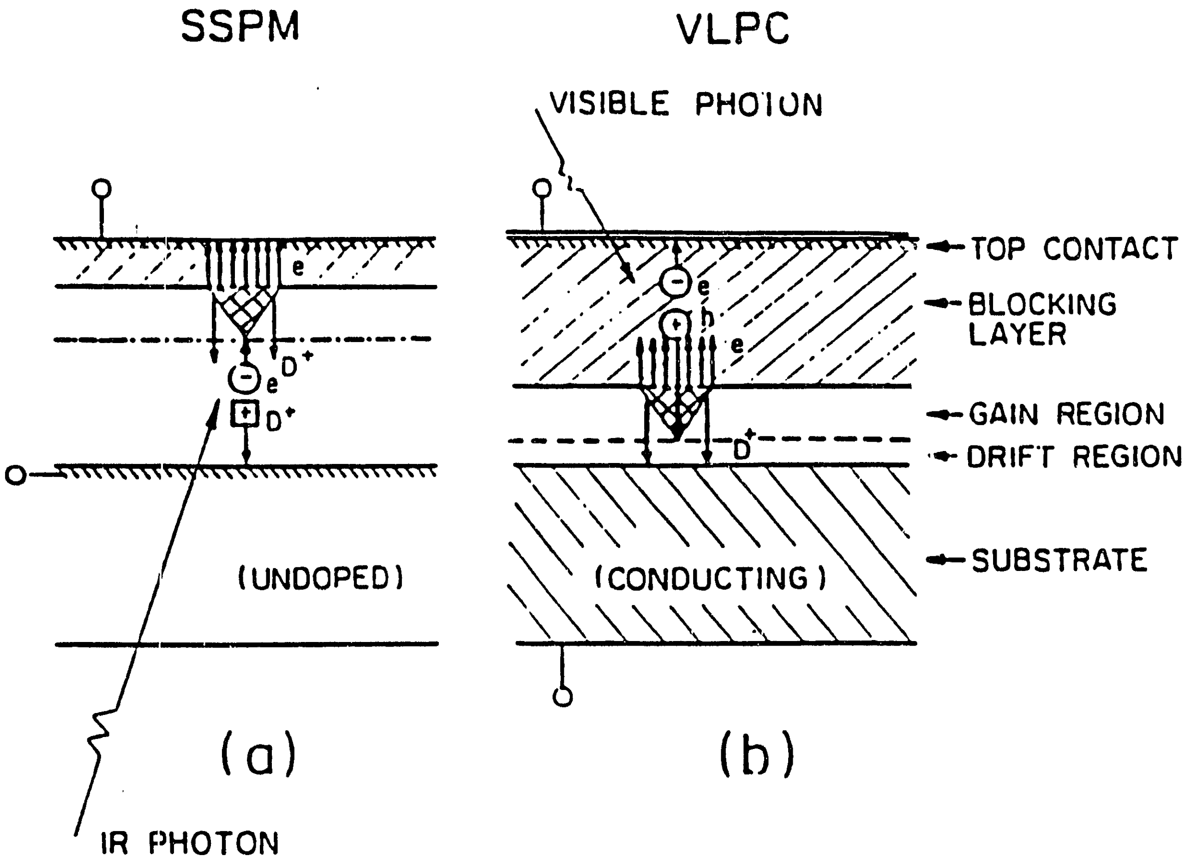


FIG.9 Operation principles of SSPM and VLPC are indicated.

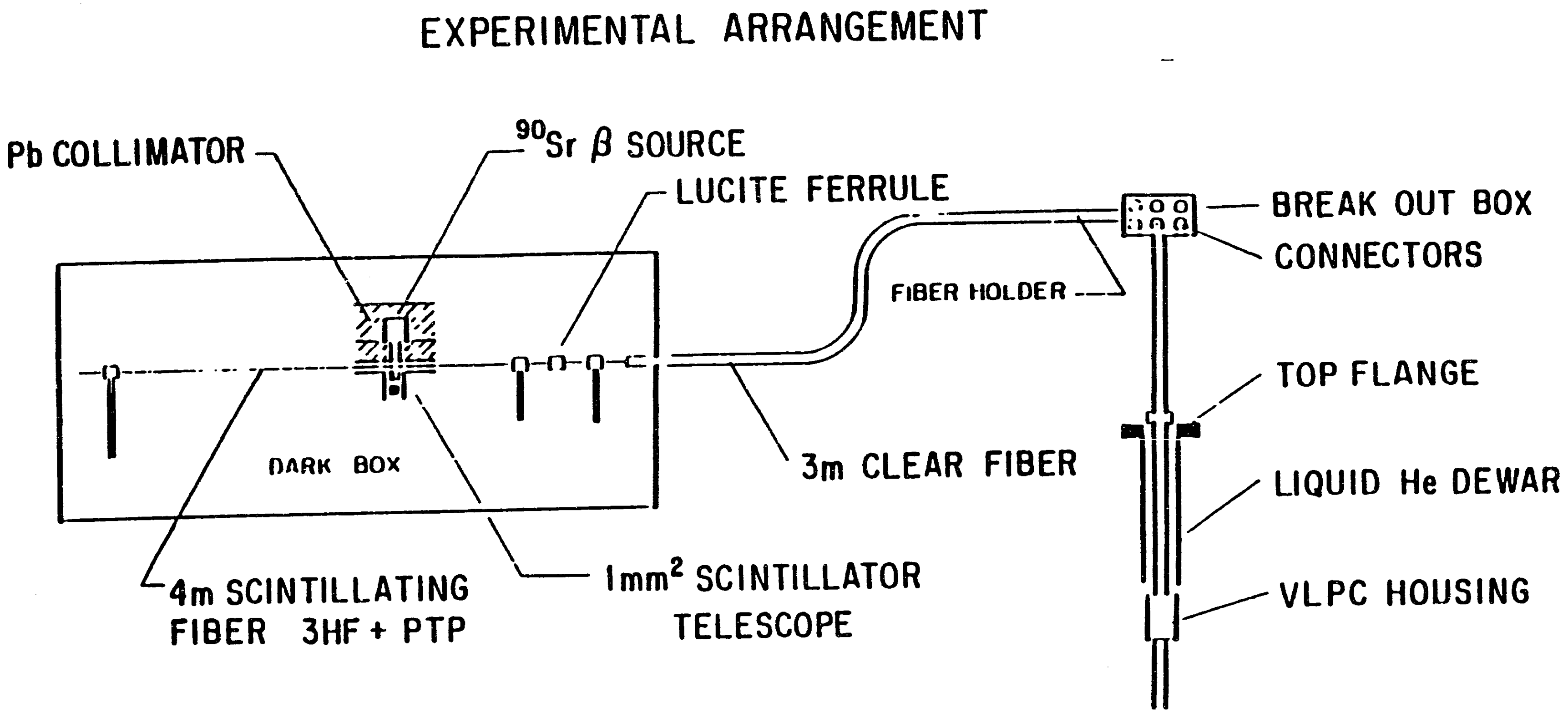


FIG.10 Experimental arrangement for measuring detected photon by a VLPC using a 4 meter length of scintillating fiber of 0.8 mm core (3HF + PTP in polystyrene). The scintillating fiber is spliced to a 3 meter long optical clear fiber that carries the photons to the VLPC.

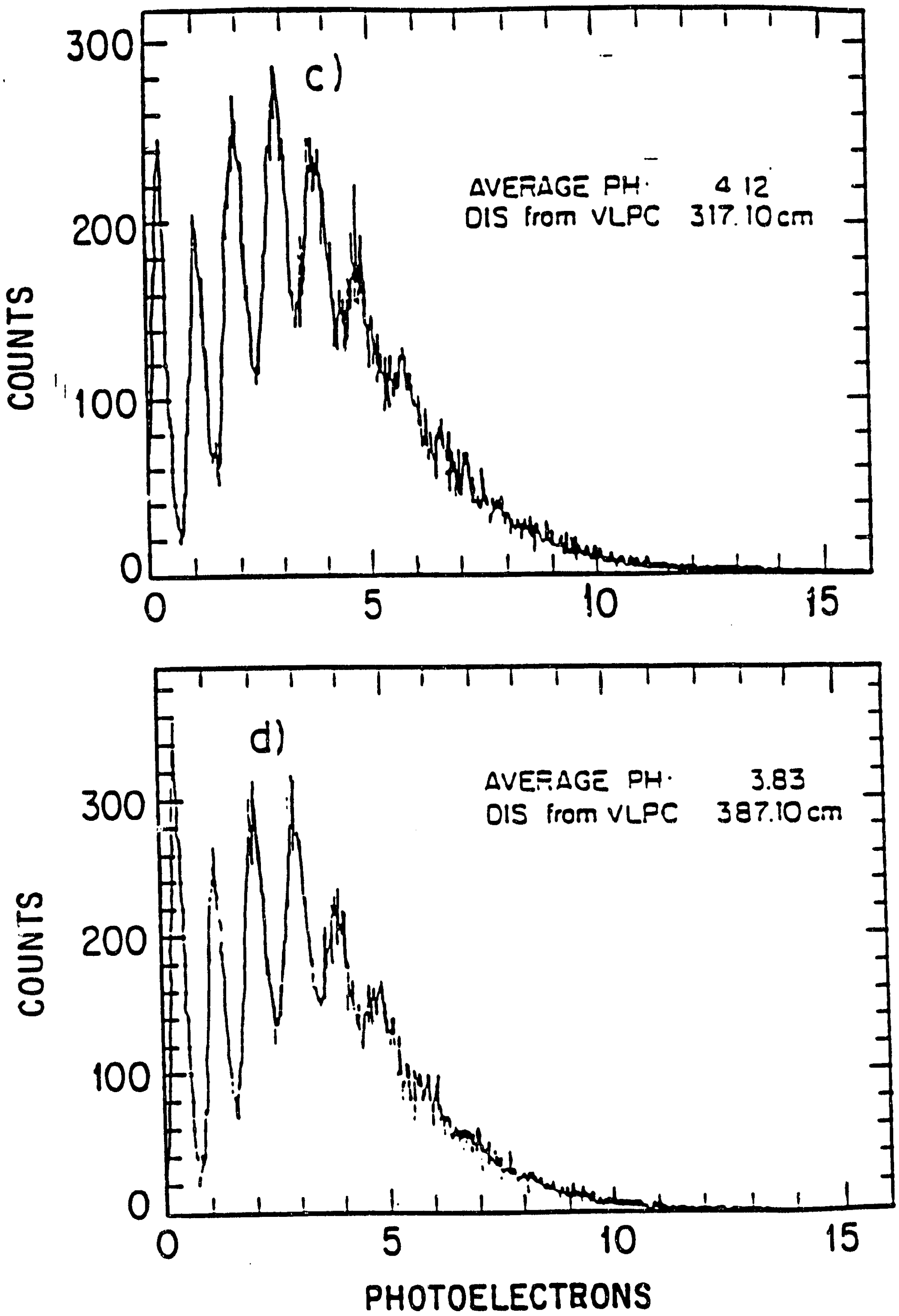
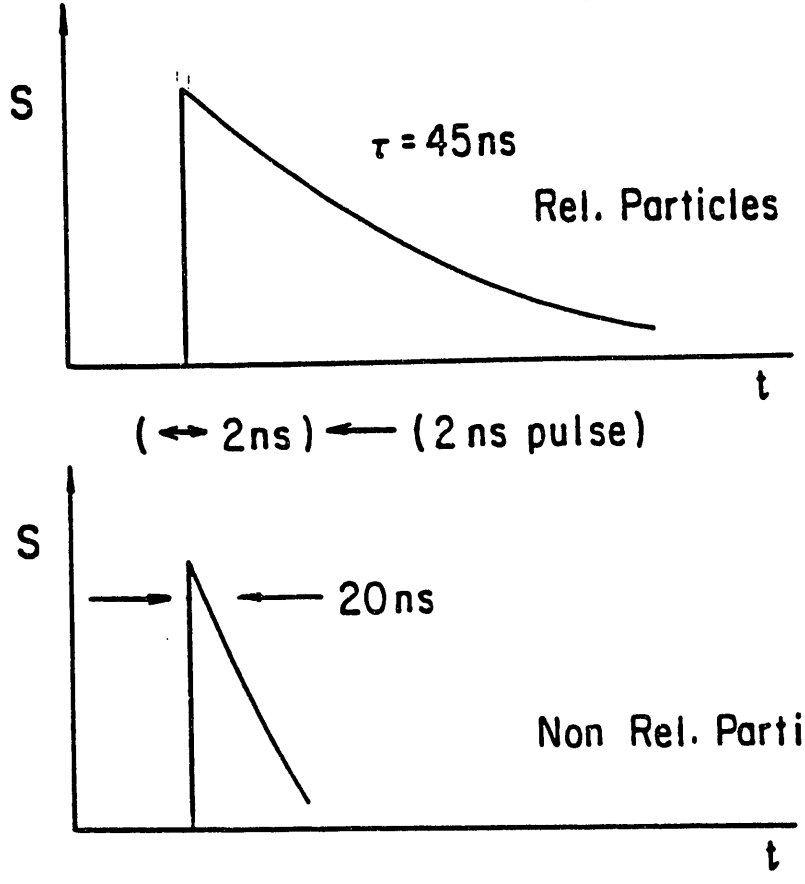


FIG.11 Two samples of pulse height spectra obtained at the indicated sources positions. The weighted average number of detected photoelectrons.

Studies Xe Scintillating Light at Waseda U.

Duke et al.
Waseda U.



Rel. Particles 60% in 1μs

Non Rel. Particles - all light in 0.1μs

FIG.12 Time structure of different type of ionization process in Liquid Xenon.

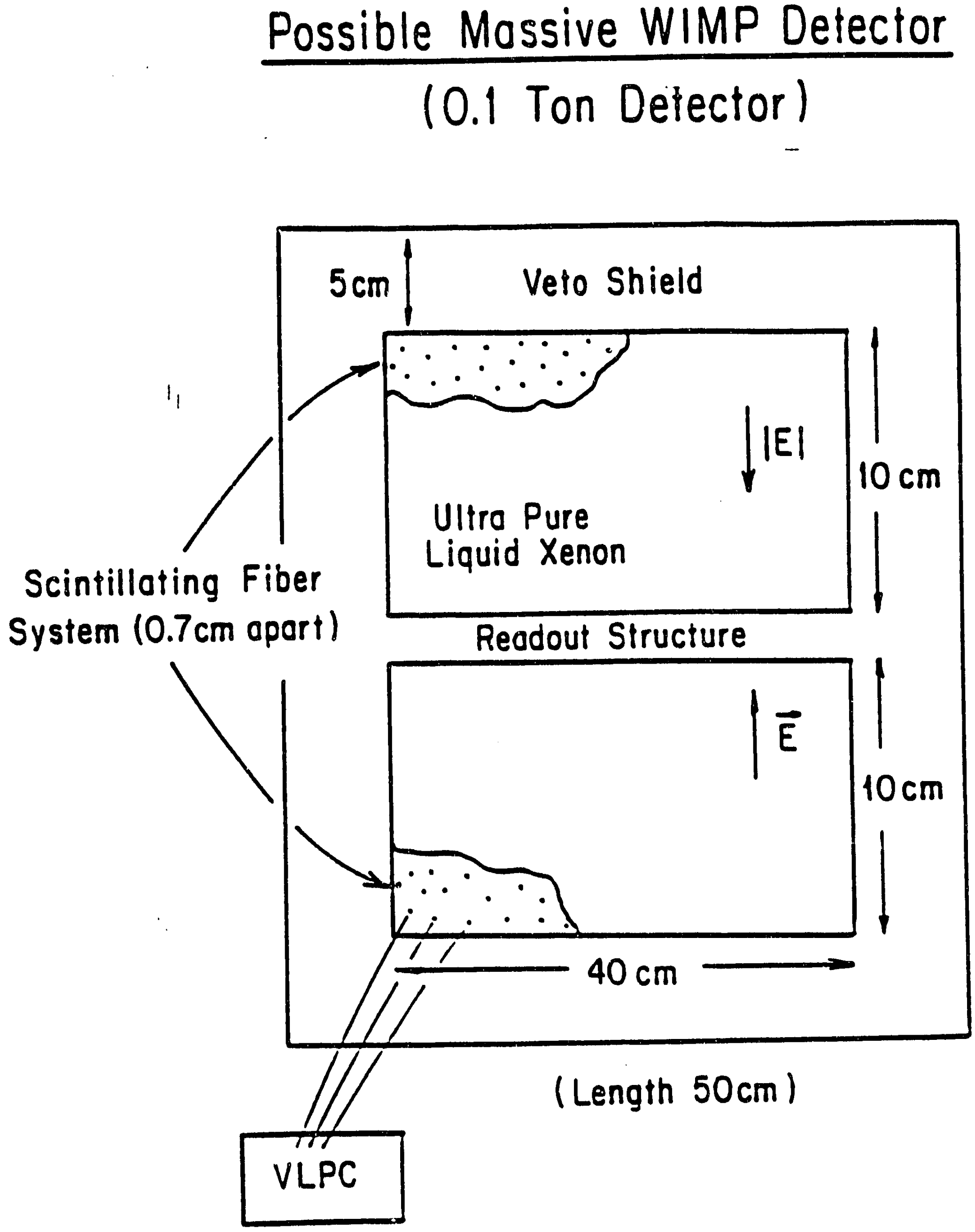


FIG.13 Schematic of a massive WIMP detector using Liquid Xenon.

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