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Progress Report

for

TASK A

**A Research Program in Neutrino Physics,
Cosmic Rays and Elementary Particles**

February 1, 1992 – January 31, 1995

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**Research Program in Neutrino Physics,
Cosmic Rays and Elementary Particles**

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1 Summary of Task A

Physics interests of the group are focussed primarily on tests of conservation laws and studies of fundamental interactions between particles. There is also a significant interest in astrophysics and cosmic rays. Task A consists of three experimental programs; a Double-Beta Decay study (currently at the Hoover Dam), a Reactor Neutrino program (until this year at Savannah River), and the IMB Proton Decay experiment in a Cleveland salt mine.

- Double-Beta Decay:

Energy spectra measured in a time projection chamber for the double beta decay of ^{82}Se and ^{100}Mo both show a distinct anomaly at the high-energy end. Eliminating cosmic radiation by moving the apparatus underground did not diminish the effect. Since a deviation from the standard two-neutrino spectral shape could be an indication of new physics, it is important to remove all suspicion of background. To this end, we have begun a measurement with ^{150}Nd , a double beta isotope with a significantly higher endpoint energy, to see if the anomaly shifts up accordingly. If it does, it is very likely a real effect. Meanwhile, we are investigating the feasibility of a new and potentially very sensitive technique for searching for neutrinoless double beta decay.

- The Reactor Neutrino program:

We have been working on two experiments at the reactor facility in South Carolina. The first is an experiment to look for the oscillation of electron antineutrinos into other flavors. This detector is a massive (100 ton) device constructed so as to be able to move from one location to another. Oscillations would manifest themselves as a departure from the expected inverse square decrease of the signal with distance from the reactor core. We have taken data at two distances from the reactor core. Data taking at the third position was abruptly cut short when the reactor was permanently shut down. A paper is in preparation.

The second reactor neutrino experiment has been recently constructed. It will make an accurate measurement of the interaction probability of electron neutrinos with deuterons. The measurement will look at both the charged current interaction and the neutral current interaction. The detector is complete and studies of operating parameters, calibration and

background measurements have been completed. We currently plan to transport the detector to the Bugey reactor in France where it will run for about two years.

- The IMB Proton Decay Experiment:

The IMB detector is an 8,000 ton water Čerenkov detector, located deep underground in a salt mine near Cleveland, Ohio. It is being used in our ongoing search for proton decay, to investigate neutrino properties and interactions, and to study neutrino and other aspects of particle astrophysics. We are also pursuing new uses of this unique facility including a neutrino oscillation search employing a new beam from FermiLab, a 8B Solar Neutrino search, and reactor neutrino measurements. The detector is currently shut down due to a disruptive leak in our liner system. We hope to be repaired and running in an improved mode in about six months. Data analysis is proceeding. Several papers have been submitted for publication or are in their final stages of preparation.

2 Double Beta Decay

M.K. Moe, M. Nelson, and M. Vient

2.1 Introduction

Although the neutrino is one of the fundamental components of the standard model, the behavior of this enigmatic lepton remains poorly understood forty-five years after its discovery as a free particle. Central to the question of neutrino properties is the Dirac or Majorana nature of the particle, whether it has any right-handed interaction, and whether it has mass. In particular, the question of neutrino mass is one of the burning issues of contemporary physics, as we wrestle with the solar neutrino problem and the mystery of dark matter.

Nuclear double beta decay is sensitive to some, and possibly all of these neutrino properties.[1] The two-neutrino decay mode ($\beta\beta_{2\nu}$) proceeds in the absence of any exotic behavior beyond the massless, lepton-conserving particle assumed in the standard model. However the alternative neutrinoless mode of double beta decay ($\beta\beta_{0\nu}$) is possible only if neutrinos are massive Majorana particles. The phase space available to $\beta\beta_{0\nu}$ being greater than for $\beta\beta_{2\nu}$ by some six orders of magnitude in some isotopes, makes a search for $\beta\beta_{0\nu}$ a very sensitive test for neutrino mass, right handed currents, and lepton nonconservation characteristic of Majorana neutrinos.

2.2 History of the Irvine project

2.2.1 The cloud chamber experiment

The double beta decay research program at Irvine began in the early 1970's with the recognition that the best $\beta\beta$ experiments performed until that time had been limited by background from the uranium-series nuclide ^{214}Bi . These experiments[2] were insensitive to the flag provided by the alpha particle from the decay of the ^{214}Po daughter 164 μs later. Our idea was to exploit the long post-trigger sensitivity of a Wilson cloud chamber to reveal the track of the polonium alpha as a means of rejecting false $\beta\beta$ events resulting from ^{214}Bi .

An excellent cloud chamber was obtained from Arnold Clark who had built several for a free quark search at LLL. The chamber was modified for the $\beta\beta$ project and fitted with a source containing enriched ^{82}Se . The device proved very effective at showing alpha particles sticking out of the false $\beta\beta$ vertices from ^{214}Bi . (The first electron in the fake event is the beta particle, and the second is the internal conversion electron from the excited daughter atom.) Other two-electron events without an alpha particle were interpreted as candidates for $\beta\beta_{2\nu}$. The performance of the cloud chamber was limited, however, by excessive dead time and cumbersome data analysis. The tentative half life determined for $\beta\beta_{2\nu}$ of 1.0×10^{19} years was accompanied by caveats about poor statistics.

Nevertheless, the 10^{19} year number was pleasing to nuclear theorists who had predicted numbers in this range.[3] The experimental $\beta\beta_{2\nu}$ half life serves as a check on the theory because the half life follows directly from the $\beta\beta_{2\nu}$ matrix elements. The theory can then be used to calculate the $\beta\beta_{0\nu}$ matrix elements from which limits on neutrino mass can be determined from limits on the $\beta\beta_{0\nu}$ half life. Geochemical experiments, however, disagreed with the tentative cloud chamber number, and gave measured half lives for ^{82}Se of around 1.3×10^{20} years.[4]

2.2.2 The TPC

The cloud chamber results were published[5] in 1980 just as we learned of a new technology that looked very promising for improving on the slow event rate with which we had been struggling. The time projection chamber (TPC) being assembled at LBL for the PEP experiment at SLAC inspired the design of a smaller and simpler TPC at Irvine for sole purpose of seeing double beta decay.[6] Compared to the cloud chamber the TPC was an experimentalist's dream come true. The efficiency was high with minimal dead time, and the digital output created opportunities for much more thorough analysis of signal and background processes.

The TPC was designed to measure a $\beta\beta$ half life in the neighborhood of 10^{19} years. It soon became apparent that the half life was considerably longer than this, and the accompanying decay rate was very slow indeed. Shielding against external radioactivity was improved, but every change required months of running to accumulate the counts needed to learn if the improvement was adequate. Finally in 1986, after a series of modifications, the competing activity

was reduced to the extent that a paper could be published stating that the $\beta\beta_{2\nu}$ half life of ^{82}Se was greater than 10^{20} years.[7] The longer half life was consistent with the geochemical experiments, and the theorists were forced to reevaluate their approach to calculating nuclear matrix elements.

2.2.3 First observation of double beta decay

The following year a statistical fit of the data to the theoretical $\beta\beta_{2\nu}$ electron sum energy spectrum, the singles spectrum, and the opening angle distribution, showed that 78% of the two-electron events observed in the TPC were from real double beta decay. The half-life limit was replaced with a positive result of $(1.1^{+0.8}_{-0.3}) \times 10^{20}$ years in a 1987 paper entitled "Direct Evidence for Two-Neutrino Double Beta Decay in ^{82}Se ".[8]

This was the first time the extremely rare process of double beta decay had been observed in the laboratory. No evidence for $\beta\beta_{0\nu}$ was seen, but it was encouraging to have a check on the matrix elements and to find that the $\beta\beta$ phenomenon actually does exist. Experiments elsewhere using ^{76}Ge were searching for $\beta\beta_{0\nu}$ with greater sensitivity.[9]

2.2.4 A spectral anomaly

As additional data accumulated during the following months it became evident that the energy spectrum was showing an anomaly at the high end. Just below the endpoint where the probability of counts was negligibly small, a little bump was forming. A bit higher in energy and the bump would have been evidence for the $\beta\beta_{0\nu}$ spike at the endpoint, so the energy calibration was carefully rechecked with the 1 MeV conversion line from ^{207}Bi . (Electron energies in the TPC are deduced from the curvature of the track helices in the magnetic field.) The calibration checked out correctly.

The bump was clearly not $\beta\beta_{0\nu}$. It was more characteristic of a three-body decay such as that associated with a Majoron arising from the triplet Higgs boson as proposed by Gelmini and Roncadelli.[10] Background from known causes was very low at this energy since few natural radioactive species contribute, but one potential background source that was difficult to rule out was the cosmic rays. Since the anomalous spectral shape could be evidence of new physics, it was important to find out whether it would persist in the absence of cosmic radiation.

A search for nearby underground sites led to a tunnel at the Hoover Dam. Lying beneath 400 feet of rock, this little-used valve house is an ideal laboratory for the TPC. The project manager at the dam generously provides us with free magnet power, cooling water, telephone hook-up, even crane operators when necessary. Cosmic-ray muons are down more than two orders of magnitude from our former location at U.C. Irvine.

We have recently completed a year-long run at the dam with ^{100}Mo as the $\beta\beta$ source. (The ^{100}Mo was purchased from the Soviet Union since significant amounts of $\beta\beta$ isotopes are no longer available on loan from Oak Ridge.) Molybdenum was chosen for its theoretically faster decay rate since the accumulation of counts for the selenium spectrum had been painfully slow. The interesting anomalous counts in ^{82}Se had been only four or five per year. We found that the molybdenum does indeed decay faster than selenium, and we measured a half life for $\beta\beta_{2\gamma}$ that is only about 1/10 as long as for ^{82}Se . The faster rate was as predicted by new theoretical calculations and illustrates the progress in theoretical technique since the geochemical ^{82}Se half life was confirmed by the TPC several years ago. The ^{100}Mo result was published recently in *Journal of Physics*. [11]

Interestingly, with the cosmic rays largely eliminated, the anomalous bump is as strong as ever. Unfortunately the $\beta\beta$ Q-values for ^{82}Se and ^{100}Mo are nearly identical at 3.0 MeV, so the fact that the bump is observed at the same energy for both isotopes is consistent both with double beta decay and with background. Our next test will be to operate the TPC with an isotope of higher Q-value and see if the bump energy moves up accordingly. Such a move would constitute strong evidence that the anomaly is truly associated with double beta decay.

The logical choice for the higher Q isotope is ^{150}Nd at 3.4 MeV. The only one higher is ^{48}Ca , but strong cancellations in the matrix elements make it a poor choice for fast decay. We made an agreement with Prof. A. A. Pomansky of the Institute for Nuclear Research in Moscow that we would arrange to purify his ~ 100 grams of ^{150}Nd in the U.S. if we could keep a portion for our experiment. The radioactive europium contamination was removed with great skill by the rare-earth experts at Ames Laboratory at Iowa State University, and we kept 19 grams of the purified material, returning the balance to Pomansky. Measurements before and after by Ron Brodzinsky with the low-background facilities at Pacific Northwest Laboratories indicated that the purification had

been successful.

On July 1, 1991 the ^{150}Nd source was placed in the TPC at Hoover Dam. As of this writing, two weeks of neodymium data have been analyzed, enough to show that the neodymium is pleasingly free of significant radio-impurities. One anomalous event has already appeared, and its energy at 2.9 MeV is higher than any of the ^{100}Mo events. Because of imperfect energy resolution, however, five or ten more events will be required to show a significant energy shift.

2.3 Future plans

The road ahead is forked. If the ^{150}Nd indicates that the anomalous high-energy behavior in the sum spectrum is real, then we will want to focus our attention on the new phenomenon. A high-statistics spectrum with improved energy resolution will be a top priority. A stronger magnetic field, additional source mass, and possibly additional TPC's would be in order. If the spectral bump turns out to be some form of background, we will terminate the TPC experiment in the next 18 to 24 months in favor of a technique with greater sensitivity to $\beta\beta_{0\nu}$. Such a technique has been described in "A New Approach to the Detection of Neutrinoless Double Beta Decay" accepted for publication in Physical Review C (copy attached).

Until the nature of the high-energy anomaly becomes clear we will continue preparing for both scenarios. The new $\beta\beta_{0\nu}$ technique is still speculative and will require some prototype experimentation. It involves the fluorescence detection of the barium ion born in the double beta decay of ^{136}Xe . Some preliminary tests are being carried out in collaboration with Prof. V. A. Apkarian at Irvine to determine feasibility of the method. If successful it would constitute a breakthrough in $\beta\beta_{0\nu}$ sensitivity that would go well beyond the large enriched ^{76}Ge experiments now being assembled in other laboratories.

For budgetary purposes we have assumed the TPC experiment will continue for another three years, with some xenon experimentation on the side. The early xenon work will be done largely in collaboration with Prof. Apkarian and others who have the necessary equipment. Major equipment outlays are not anticipated prior to demonstration of suitable spectroscopy for the barium ion.

In summary, the double beta decay group at UC Irvine has produced the first laboratory observation of two-neutrino double beta decay, and is now finding evidence of anomalous behavior in the shape of the energy spectrum. If the

phenomenon survives tests now underway it could lead to greater understanding of the behavior of the neutrino. If the anomaly fails to survive further scrutiny, the group is prepared to investigate a new technique that it has proposed for significantly increasing experimental sensitivity to neutrinoless double beta decay, lepton nonconservation, and massive Majorana neutrinos.

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A. A New Approach to the Detection of Neutrinoless Double Beta Decay

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A distinctive feature of the double beta decay signature that has been neglected in direct counting experiments is the appearance of the daughter atom. The newly created nucleus, usually being stable, is not easily detected. The atomic physics of the daughter, however, may be considerably more accommodating, especially in the case of ionized ^{136}Ba arising from the double beta decay of ^{136}Xe . The barium ion isolated in the xenon matrix may be detectable by its laser fluorescence. Coincident detection of the ion and the beta particles could well render background nonexistent.

Neutrinoless double beta decay ($\beta\beta_{0\nu}$) is possible if the distinction between neutrino and antineutrino is simply a manifestation of two different helicity states of the same particle (the Majorana neutrino), and if a very small mixing of the two states is driven by a non-zero neutrino mass.^[1] Massive Majorana neutrinos and a number of other possible consequences of $\beta\beta_{0\nu}$ are at variance with the standard model, and the question of their existence has motivated numerous experimental searches^[2] for the $\beta\beta_{0\nu}$ phenomenon.

Several different isotopes have been studied, the best published $\beta\beta_{0\nu}$ result being for ^{76}Ge by the UCSB-LBL group^[3] who report a lower half-life limit of 2.4×10^{24} years, and a corresponding upper limit on the effective Majorana mass for the electron neutrino of ~ 1 eV. Yet one would like to probe still smaller mass regions. Grand unified theories favoring a finite neutrino mass give a very wide range for its predicted magnitude. Indeed, in view of proposed non-adiabatic MSW solutions to the solar neutrino problem,^[4,5] and various cosmological arguments, it may be that neutrino masses are far too small to ever result in observable neutrinoless double beta decay. At present the question remains open, and the $\beta\beta_{0\nu}$ searches continue. A reduction of two orders of magnitude in detectable mass is not beyond imagination.

The dependence of the minimum detectable effective neutrino mass <

$m_\nu >_{\min}$ on the source mass and run time for ^{76}Ge $\beta\beta_{0\nu}$ experiments^[2(b)] is shown for various combinations of background and isotopic enrichment in Figure 1. The advantage of *enriched* germanium is clear. Two new experiments,^[6,7] the larger being ~ 10 kg, are being assembled with germanium enriched to 85% isotope 76, compared to the 7.8% natural abundance used by UCSB-LBL. These experiments should be able to reach a few tenths of an electron volt. With enrichment, energy resolution, and run time then approaching their practical limits, the only remaining parameters available for improved sensitivity in ^{76}Ge are background b (keV kg y^{-1}), and source mass M (kg). The dependence of $< m_\nu >_{\min}$ on these parameters is weak, being proportional to $(b/M)^{1/4}$. An order of magnitude improvement in sensitivity to neutrino mass would require a 10,000 fold decrease in b/M . To accomplish this decrease entirely with larger sources is economically out of the question, so very substantial improvements in background are necessary to make meaningful strides toward smaller neutrino masses.

There are other $\beta\beta$ isotopes with more favorable matrix elements and phase space,^[8-10] and corresponding lines as much as an order of magnitude lower in the figure. As a practical matter, affordable, low-background, high-efficiency, large-scale experiments have not been easy to design for these favored isotopes.^[11]

Among the candidates for double beta decay, ^{136}Xe may have the greatest potential for very large-mass experiments.^[12] The isotope is relatively inexpensive to enrich from its natural abundance of 8.9% to the order of 60% by gas centrifugation; it is a noble gas that can serve simultaneously as source and detector; its $\beta\beta_{0\nu}$ matrix-element, phase-space product is similar to that of ^{76}Ge ; and it has a higher transition energy (2479 keV vs. 2041 keV for ^{76}Ge). Several experiments have been performed with ^{136}Xe in time projection chambers (TPC's), proportional counters, ionization chambers, and scintillation detectors.^[13-16] Some of these experiments have made good progress against background, but all have had to contend with it at some unwanted level.

A feature of double beta decay previously unexploited in direct counting experiments^[17] is the sudden production of two additional protons in the nucleus, which leaves the daughter atom shy two electrons. Decay of ^{136}Xe makes $^{136}\text{Ba}^{++}$. As in single beta decay, often one or more atomic electrons will also be ejected.^[18] The daughter atom, therefore, will be born in a double or higher state of ionization. If the xenon detector is normally kept free of ions by a drift field,

the appearance of a barium ion together with a 2.5 MeV energy pulse could be sufficiently unique that demanding their coincident detection would eliminate background completely.

The detector proposed is a liquid xenon TPC to be operated in a deep-underground laboratory. The range of ~ 2 MeV beta particles in the liquid is a few millimeters, so the position of the barium ion would be localized to that order by detection of the beta particle ionization and a scintillation trigger. The mobility of positive ions in liquid xenon is relatively low, so the barium ion would not move far from its origin in the time required to target it for laser excitation.

Single isolated Ba^+ ions have been successfully detected by their laser fluorescence in the classic experiment of Dehmelt and co-workers.^[19] Irradiation of this favorite ion in the blue-green at 493 nm results in red fluorescence at 650 nm. Following xenon decay, the third and higher ionization states of barium have sufficient potential to pull electrons from neighboring xenon atoms. Once the ion becomes Ba^{++} its subsequent behavior is less obvious. The ionization potentials listed in Table I suggest that xenon will not surrender further electrons, and Ba^{++} will remain stable. In this case the ion's emission and absorption wavelengths would be in the vacuum ultraviolet which, together with the lack of a metastable state, would make detection by laser fluorescence difficult. However, in liquid xenon the gap to the conduction band is slightly below the second ionization potential for barium,^[20] and the Ba^{++} ion is likely to take on an electron to become Ba^+ . Xenon being highly polarizable, would also be expected to attach to the ion to ultimately form $(\text{BaXe})^+$.

The spectroscopy of matrix-isolated $(\text{BaXe})^+$ does not appear in the literature. The behavior of this ion is crucial to the proposed detection scheme, and a small experiment is being set up to investigate its spectroscopy in liquid xenon.^[21]

If a strong fluorescence can be identified, there remain questions of background to be considered. For example, one might ask whether in a large xenon experiment a feeble $\beta\beta_{0\nu}$ spike at the 2479 keV Q-value might blend into the high-energy tail of the much stronger $\beta\beta_{2\nu}$ spectrum. The high end of the theoretical $\beta\beta_{2\nu}$ electron sum spectrum for ^{136}Xe is shown in Fig. 2a.^[22] The spillage of a resolution-smeared version of this spectrum into a $\beta\beta_{0\nu}$ window is shown as a function of full-width-half-maximum (FWHM) resolution in Fig. 2b. (The majoron^[1] is assumed to be nonexistent.)

A large liquid xenon TPC should be able to achieve 4% FWHM at 2479

keV without difficulty. Such resolution has already been seen routinely near 1000 keV, and is expected to improve with the square root of the energy.^[23] A 4% window centered at Q allows only 2.3×10^{-7} of the $\beta\beta_{2\nu}$ events to spill in. The $\beta\beta_{2\nu}$ spectrum thus limits the $\beta\beta_{0\nu}$ half life to the $\beta\beta_{2\nu}$ half life divided by 2.3×10^{-7} (and then multiplied by 0.76 to account for the fraction of the $\beta\beta_{0\nu}$ signal that falls within the FWHM.) To take full advantage of this limit one would need enough xenon and run time to produce at least one $\beta\beta_{2\nu}$ count in the $\beta\beta_{0\nu}$ window. At the theoretical ^{136}Xe $\beta\beta_{2\nu}$ half life of 4.64×10^{21} years,^[9] the required source-mass run-time product Mt is ~ 5000 kg y. For example, one might run for 5 years with 1000 kg of ^{136}Xe (a 78 cm fiducial cube of liquid, isotopically enriched to 60%). At $\sim \$16,000/\text{kg}$ ^[24] for enriched ^{136}Xe it is clear that cost is a more serious limitation than interference from $\beta\beta_{2\nu}$.

There are, to be sure, ways other than double beta decay to create a blob of ionization accompanied by a barium ion. One is $\text{Xe}(\alpha, n)\text{Ba}$ reactions. For the stable isotopes of xenon the thresholds are between 5.3 and 10.6 MeV — often below the energies of naturally occurring alpha particles of up to 10.5 MeV in the uranium and thorium series. However the cross sections are strongly suppressed by a coulomb barrier of 17.5 MeV. There are not enough energetic alpha particles in detector grade xenon to be a problem. Higher energy alpha particles from spallation by cosmic-ray muons would be vetoed by the muon pulse.

Another source of barium ions accompanied by ionization electrons is the single beta decay of radioisotopes of cesium. The common fission product, 30-year ^{137}Cs (which can also arise from $^{136}\text{Xe}(n, \gamma)^{137}\text{Xe}$ followed by beta decay of ^{137}Xe), has a Q -value of 1.2 MeV — too low to be of concern. Cs isotopes with Q -values greater than 2.1 MeV are all fission products with mass numbers 136 and above.^[25] Of these, three have half lives greater than 65 seconds: ^{136}Cs , ^{138}Cs , and ^{139}Cs . Isotopes with shorter half lives will not have time to migrate into the fiducial volume unless they are born from fission within the xenon itself, in which case the fission event would veto the beta decay.

Scaling from existing experiments^[26] indicates that uranium in the xenon could easily be held to $< 10^{-10}$ g/g. In a laboratory such as the Gran Sasso where the thermal neutron flux^[27] is $\sim 10^{-6}/(\text{cm}^2 \text{ sec})$, fission by thermal neutrons on uranium in the xenon is completely negligible. The < 25 spontaneous fissions per year from 10^{-10} g/g of ^{238}U in 1000 kg of xenon would yield < 2 atoms each of ^{138}Cs and ^{139}Cs , and a negligible amount of ^{136}Cs .^[28] The resulting number of beta particles in a 4% window at 2479 keV is well below one per year.

The heaviest stable xenon isotope being 136 means there is no path to ^{138}Cs , or ^{139}Cs via $^A\text{Xe}(n,\gamma)^{A+1}\text{Xe}$ followed by beta decay. Similarly, ^{136}Cs is inaccessible through (n,γ) because there is no stable ^{135}Xe . Although cesium from (α,p) , (α,pn) , etc., on xenon is strongly suppressed by the coulomb barrier, spallation alpha particles often do have enough energy to drive these reactions, and the half lives of the cesium isotopes are too long for a veto by the initiating muon. However, with spallation cross sections for deep-underground muons on the order of 10^{-29} cm² per nucleon,^[29] and a muon flux of ~ 1 (m² hour)⁻¹ at 3600 mwe (e.g. Gran Sasso), high-energy alpha particles are too rare to make significant cesium. Similarly, spallation protons are too few to make troublesome amounts of cesium from (p,n) , (p,γ) , etc., on xenon, and stopping muons are insufficient to cause significant (μ^+, γ) .

Although cesium does not appear to be a background threat, the isotope ^{137}Cs could be purposely introduced to study the efficiency for barium ion detection. The 2.6 minute metastable state in ^{137}Ba would give one a chance to detect the ion and see its presence confirmed by the 0.66 MeV gamma ray or corresponding conversion electron.

Detection of the barium ion in coincidence with the 2.5 MeV energy pulse from the double beta decay of ^{136}Xe may be a potentially powerful method of eliminating background in the search for the $\beta\beta_{0\nu}$ mode. The utility of the technique depends on the presently unknown spectroscopy of the barium ion in liquid xenon. A test experiment is being assembled. If successful, the method will allow one to relax the requirement for ultra-high energy resolution, and concentrate on building a detector of very large mass. A background-free 1000 kg of ^{136}Xe could probe to an effective Majorana mass for the electron neutrino of ~ 0.01 eV in five years of running.

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TABLE I. First and second ionization potentials^a of Ba and Xe (volts).

	I	II
Ba	5.21	10.00
Xe	12.77	21.2

^aReference 30

FIG. 1. The minimum detectable neutrino mass vs. detector mass and run time for ^{76}Ge experiments with various levels of background and isotopic enrichment. The latest UCSB-LBL result (circle) is shown for comparison. Probing the smallest neutrino masses requires a very large detector mass and very low (preferably zero) background.

FIG. 2. (a) The high-energy tail of the theoretical $\beta\beta_{2\nu}$ electron sum spectrum for ^{136}Xe , normalized to unity for the whole spectrum from energy = 0 to the Q-value at 2479 keV. Calculation courtesy T. Kotani.

FIG. 2. (b) The fraction of a resolution-broadened $\beta\beta_{2\nu}$ spectrum falling in an experimental FWHM window centered on the expected position of the $\beta\beta_{0\nu}$ spike. For large xenon $\beta\beta_{0\nu}$ experiments, "background" from $\beta\beta_{2\nu}$ must be considered.

3 The Reactor Neutrino Program

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3.1 History

The decision to conduct neutrino research using the huge flux of neutrinos expected from the production reactors under construction at the Savannah River Site (SRS) was made even before the first reactor was operational. The hope was to verify the neutrino's existence and to study its properties. Since that time (1953), neutrino research has been an active and fruitful program at SRS. The initial experiments were performed by a group from The Los Alamos National Laboratory. This group evolved into the Case Institute of Technology group and still later into our present group at the University of California, Irvine (UCI).

Some of the major accomplishments of the group include:

- verification of the neutrino's existence[1,2]
- limits on the neutrino magnetic moment[3,4,5]
- first observation of the neutrino-electron elastic scattering process[5]
- first observation of the neutrino-deuteron interactions[6,7]
- limits on neutrino oscillation parameters[8,9]

The above results have been crucial to the understanding of the weak interaction, and we anticipate a continuing program of neutrino physics at reactors.

Our current program consists of two experiments:

- neutral-current experiment
- mobile neutrino-oscillation experiment.

These are described in detail in the following sections.

3.2 Neutral-Current Experiment

3.2.1 Purpose of the experiment

The neutrino-deuteron interaction at low energy is unique in being able to probe the axial-vector contribution to the neutral current. In addition to being independent of the Weinberg angle, it does not suffer from ambiguities arising from the presence of vector interactions, nor from momentum-transfer-dependent form factors, to which high-energy experiments are subject.

There are three different reactions of interest to this experiment. The central reaction is the Neutral Current reaction on the Deuteron, or NCD reaction,

$$\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n. \quad (1)$$

In this reaction, the neutrino interacts with the deuteron via the massive, electrically neutral vector boson, Z^0 .

The second is the Charged Current reaction on the Proton, or CCP reaction,

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (2)$$

In this reaction, the antineutrino interacts with the proton via the massive, charged vector boson, $W^\pm$. The third is the Charged Current reaction on the Deuteron, or CCD reaction,

$$\bar{\nu}_e + d \rightarrow e^+ + n + n. \quad (3)$$

There are two main goals of this experiment:

- The measurement of the cross section of the NCD reaction with greater precision than has been previously achieved. This will be measured by using only the single neutron in the final state as a signature.
- The search for neutrino oscillations at large Δm^2 and small $\sin^2 2\theta$. This will be achieved by adding a small admixture of protons to the heavy water in the detector and measuring the CCP reaction rate. A comparison of this rate with the NCD reaction rate is a sensitive indicator of neutrino oscillations.

The CCD reaction is a background since it also produces neutrons in the final state. Although it produces two neutrons, there is a good probability that

only one will be observed, and so it will mimic the NCD and CCP reactions. This will be described in more detail in a later section.

This experiment is an upgraded version of an earlier experiment conducted by our group. The results of differential shielding tests conducted at that time indicated that a substantial improvement in the signal-to-noise ratio could be achieved with more shielding against cosmic ray neutrons. With improved shielding and electronics, we have reduced the background due to cosmic rays by a factor of five. At this stage, we have also been able to reduce the overall systematic uncertainty in the measurement of the neutral current cross section from 7% to 5%.

3.2.2 Background

3.2.2.1 History Measurement of the reaction

$$\bar{\nu}_e + d \rightarrow p + n + \bar{\nu}_e \quad (4)$$

was first proposed by King and Ahrens [10], and Gaponov and Tyutin [11]. It is a rather unique reaction to study for several reasons:

- It provides a probe of the hadronic neutral current in a nucleus whose wave function is well known.
- The low energy-threshold of the reaction and the large M^1 transition matrix element [12] make for a favorable cross section.
- It provides a different method for looking for neutrino oscillation.

The first attempt to see the disintegration of the deuteron by antineutrinos was by C. Cowan and F. Reines [13] in 1957 at Savannah River. They looked for the disintegration via charged currents,

$$\bar{\nu}_e + d \rightarrow n + p + e^+, \quad (5)$$

in a target which was a mixture of light-water and heavy-water, containing CdCl_2 , and surrounded by liquid scintillator. The signature of an event was the capture of both product neutrons on the Cadmium, which produced gammas seen by the scintillator. An upper limit on this reaction was given as $\sigma < 4 \times 10^{-45} \text{cm}^2$.

Successful observation of this reaction was made by T.L. Jenkins, F.E. Kinard, and F. Reines [14] in 1969 at Savannah River. Their target was now

a deuterated decalin scintillator containing Gadolinium, surrounded by a large tank of mineral oil scintillator. Their signature was a prompt pulse produced by the positron in coincidence with a delayed pulse from the capture of the two neutrons on the Gadolinium. The cross section was measured to be $\sigma = (3.0 \pm 1.5) \times 10^{-45} \text{cm}^2$.

The first attempt to see the neutral current reaction was made in 1969 by J.H. Munsee and F. Reines [15]. The target was the same deuterated decalin used for the observation of the charged-current reaction. The signature was a prompt pulse from the proton and neutron and a delayed pulse from the capture of the neutron. An upper limit of $\sigma_{\text{NC}} < (1.7 \pm 1.4) \times 10^{-42} \text{cm}^2$ was placed on the cross section.

The first successful measurement of the reaction 4 was made by Pasierb, Gurr, Lathrop, Reines, and Sobel [16] in 1979 at Savannah River. This experiment measured the cross section as $\sigma_{\text{NCD}} = (3.8 \pm 0.9) \times 10^{-45} \text{cm}^2$. The charged current cross section was also measured and found to be $\sigma_{\text{CCD}} = (1.5 \pm 0.4) \times 10^{-45} \text{cm}^2$.

The current experimental setup is much the same as that used in the 1979 experiment: 10 ^3He neutron counters immersed in a tank of pure heavy water with heavy shielding and active cosmic ray veto. Improvements have been made to this setup, and it will be shown that the background rate due to cosmic ray induced neutrons is significantly reduced in the current configuration.

3.2.2.2 A "model independent" analysis If we consider a generalized neutral-hadronic-current matrix element containing only vector and axial-vector currents and neglect quarks heavier than u and d [17], we can write it as

$$\begin{aligned} \mathcal{M} = & - \left(\frac{G}{\sqrt{2}} \right) \bar{\nu} \gamma_\lambda (1 + \gamma_5) \nu \\ & \times \left\{ \frac{1}{2} [\bar{u} \gamma^\lambda (\alpha + \beta \gamma_5) u - \bar{d} \gamma^\lambda (\alpha + \beta \gamma_5) d] \right. \\ & \left. + \frac{1}{2} [\bar{u} \gamma^\lambda (\gamma + \delta \gamma_5) u + \bar{d} \gamma^\lambda (\gamma + \delta \gamma_5) d] \right\}. \end{aligned} \quad (6)$$

The coupling constants — α, β, γ , and δ — are the isovector-vector, isovector-axial vector, isoscalar-vector, and isoscalar-axial vector components of the interaction. In the Weinberg-Salam model, these components turn out to have the

Table 1: The neutral-hadronic-current coupling constants.

Solution	α	β	γ	δ
A	$0.45 \pm .14$	$0.92 \pm .14$	$-0.35 \pm .15$	$0.12 \pm .15$
WS ($x_W = 0.25$)	0.5	1	-0.17	0

following values:

$$\alpha = 1 - 2 \sin^2 \theta_W, \quad (7)$$

$$\beta = 1, \quad (8)$$

$$\gamma = -\frac{2}{3} \sin^2 \theta_W, \quad (9)$$

$$\delta = 0. \quad (10)$$

Table 1 shows a solution for the constants obtained from neutrino-hadron interactions along with the prediction of the Weinberg-Salam model for a value of $\sin^2 \theta_W = 0.25$. In 1979, Pasierb [18] determined a unique value of $1.00 \pm .15$ for β^2 with the previous version of the neutral current experiment.

3.2.2.3 The reaction cross section In terms of these coupling constants, the cross section for the disintegration of the deuteron to a proton and a neutron via electron-antineutrino interaction can be written in the following form [19]:

$$\sigma(E) = A\beta^2(E^2 Z_1 - 2EZ_2 + Z_3) \quad (11)$$

where

$$A = \frac{8G^2 \sqrt{E_d} (\gamma a_s - 1)^2}{\pi^2 (1 - \gamma r_t)}, \quad (12)$$

$$E_d = \text{deuteron binding energy}, \quad (13)$$

$$\gamma = (mE_d)^{1/2}, \quad (14)$$

$$m = \text{reduced mass}, \quad (15)$$

$$a_s = \text{singlet scattering length}, \quad (16)$$

$$r_t = \text{triplet range}, \quad (17)$$

$$Z_1 = \frac{\sqrt{E - E_d}}{E(bE_d - 1)} + \frac{(bE_d + 1)}{\sqrt{E_d}(bE_d - 1)^2} \tan^{-1} \left[\left(\frac{E - E_d}{E_d} \right)^{1/2} \right]$$

$$-\frac{2\sqrt{b}}{(bE_d - 1)^2} \tan^{-1}[(E - E_d)b^{1/2}], \quad (18)$$

$$Z_2 = \frac{2}{\sqrt{b}(1 - bE_d)} \tan^{-1}[(E - E_d)b^{1/2}] - \frac{2\sqrt{E_d}}{(1 - bE_d)} \tan^{-1}\left[\left(\frac{E - E_d}{E_d}\right)^{1/2}\right], \quad (19)$$

$$Z_3 = 2\left[\frac{\sqrt{E - E_d}}{b} - \frac{1}{b^{3/2}} \tan^{-1}[(E - E_d)b^{1/2}]\right], \quad (20)$$

$$b = ma_s^2. \quad (21)$$

There are also terms in α , but only the term in β^2 will contribute appreciably to the cross section at reactor neutrino energies. Terms in α are suppressed by factors of E/m which are on the order of $1/1000$. Therefore, as we have stated earlier, *the neutrino-deuteron interaction at low energy is unique in being able to probe the axial-vector contribution to the neutral current*. In addition to being independent of the Weinberg angle, it does not suffer from ambiguities arising from the presence of vector interactions, nor from momentum-transfer-dependent form factors, to which high-energy experiments are subject.

In order to calculate the cross section, the deuteron is assumed to be a 3S isosinglet state. The only final state which contributes is the 1S isotriplet np state. The matrix element can be evaluated by the effective-range formulation which is well known from evaluation of the photo-disintegration of the deuteron. The effective range calculation depends on the singlet n-p effective range and scattering lengths, as well as the binding energy of the deuteron.

The expression for the cross section averaged over the antineutrino spectrum is given by Equation (11) integrated over the normalized antineutrino spectrum, $N(E)$:

$$\bar{\sigma} = \frac{\int_{E_d}^{\infty} \sigma(E) N(E) dE}{\int_{E_d}^{\infty} N(E) dE} \quad (22)$$

The cross section as calculated by this method varies from $6.55 \times 10^{-45} \text{cm}^2$ [20], to $7.4 \times 10^{-45} \text{cm}^2$ [21].

3.2.2.4 Measurement of oscillation This experiment is also capable of observing neutrino oscillation since it will measure both the NCD reaction and the CCP reaction. The cross section for the disintegration of the deuteron via

neutral currents is the same for all generations of neutrinos. This is not the case, however, for the disintegration via charged currents nor for the inverse-beta-decay process.

In the inverse-beta-decay reaction, a charged lepton must be produced in the final state. At the energies of reactor antineutrinos, there is not enough available energy to produce a charged lepton with mass higher than that of the positron. This implies that, in the event of oscillation, a deficit of charged current events will be seen. This leads us to define a ratio R , where

$$R = \frac{\frac{CCP_{exp}}{NCD_{exp}}}{\frac{CCP_{th}}{NCD_{th}}}, \quad (23)$$

a ratio of ratios of experimentally determined reaction rates to theoretically expected reaction rates.

Neutrino oscillation can be characterized by the parameters $\sin^2 2\theta$ and Δm^2 . The precision with which we can determine R determines the limits we can impose on the values of $\sin^2 2\theta$ and Δm^2 . Because we are taking a ratio of rates, much of the systematic uncertainty due to detection efficiency and the reactor spectrum drops out. The precision is currently limited, therefore, by the uncertainty in the theoretical calculation of the ratio, which is at the 5% level. With this precision, we will be able to set a limit of $\sin^2 2\theta \leq 0.1$ for $\Delta m^2 \geq 0.2 \text{ (eV)}^2$ at the 95% confidence level.

3.2.2.5 Precision in determining R The ratio of CCP to NCD reaction rates will be experimentally determined from the single-neutron signals in the following manner:

$$\begin{aligned} \frac{CCP_{exp}}{NCD_{exp}} &= \frac{(S_{CCP})/(\eta_{CCP} f_{H_2O})}{(S_{NCD})/\eta_{NCD}} \\ &= \frac{(S'_N - S'_{NCD} - S'_B - S'_{CCD1})/(\eta_{CCP} f_{H_2O})}{(S_N - S_B - S_{CCD1})/\eta_{NCD}} \end{aligned} \quad (24)$$

where

$$S_N = \text{Neutron Signal}, \quad (25)$$

$$S_B = \text{Neutron Background Signal}, \quad (26)$$

$$f_{H_2O} = \text{Fraction of Light Water Included}, \quad (27)$$

$$\eta_{\text{NCD}} = \text{Efficiency of Detecting NCD Neutrons,} \quad (28)$$

$$\eta_{\text{CCP}} = \text{Efficiency of Detecting CCP Neutrons,} \quad (29)$$

$$\begin{aligned} S_{\text{CCD1}} &= \text{Neutron Signal due to CCD Reactions,} \\ &= 2\eta_{\text{CCD}}(1 - \eta_{\text{CCD}})\text{Rate}_{\text{CCD}}. \end{aligned} \quad (30)$$

The primed quantities in Equation (24) correspond to signals modified by the presence of the fraction of H_2O . For instance,

$$S'_{\text{NCD}} = S_{\text{NCD}}(1 - f_{\text{H}_2\text{O}})\frac{\eta'_{\text{NCD}}}{\eta_{\text{NCD}}}, \quad (31)$$

where η'_{NCD} is the modified efficiency to detect NCD neutrons.

As mentioned earlier, the CCD reaction is a significant background to both the NCD and CCP reactions. There are two ways in which this background can be determined. The single-neutron signal due to the CCD reaction can be estimated from the rate of double neutron events in the following manner:

$$S_{\text{CCD1}} = S_{\text{CCD2}} \frac{2\eta_{\text{CCD}}(1 - \eta_{\text{CCD}})}{\eta_{\text{CCD}}^2}. \quad (32)$$

The conversion factor in the above equation is the ratio of the probability of detecting one neutron to the probability of detecting two neutrons from a CCD reaction. Another way of determining this signal is by extrapolating it from the single-neutron signal from the CCP reaction,

$$S_{\text{CCD1}} = S_{\text{CCP}} \cdot F \cdot \frac{\eta_{\text{CCD}}}{\eta_{\text{CCP}}}, \quad (33)$$

where

$$F = \frac{\bar{\sigma}_{\text{CCD}}}{\bar{\sigma}_{\text{CCP}}} \quad (34)$$

is the ratio of cross sections for the two reactions.

The uncertainty in the first method is found to be

$$\frac{\sigma_{S_{\text{CCD1}}}}{S_{\text{CCD1}}} = 2 \frac{S_{\text{CCD2}}}{S_{\text{CCD1}}} \cdot \frac{\sigma_{\text{CCD1}}}{\eta_{\text{CCD}}^2} \quad (35)$$

by the usual means. The efficiency, η_{CCD} , is 0.33 and the uncertainty in the efficiency, which will be described in a later section, is $\sim 5\%$, giving a 25% uncertainty in S_{CCD1} .

In the second method, the major uncertainty is in the ratio F , which is estimated to have a 5% theoretical uncertainty. The uncertainty in the ratio of efficiencies, $\eta_{\text{CCD}}/\eta_{\text{CCP}}$, is small, because they are correlated. The uncertainty in the calculation of the ratio is estimated to be 0.5%. Therefore, the uncertainty in S_{CCD1} from this method is 5%.

Since the single-neutron signal from the CCD reaction is only 20% of that from the NCD reaction, the difference in the uncertainty of the NCD reaction rate is small for the two methods described above. The first method gives an uncertainty of 5.6%, while the second only reduces this to 5.0%.

The uncertainty in the ratio, R_{exp} , was determined by a monte carlo technique, in which each quantity with an uncertainty was varied and the ratio calculated many times. This gave a distribution in the ratio R_{exp} , which can be used to determine the probability of observing a given ratio.

Figure 1 shows the calculated distribution, normalized to the mean value, given a signal-to-noise ratio of 1:1.5, an uncertainty of 5% in the neutron detection efficiency, 10% in the reactor-associated background signal, and infinite run time. As explained above, the uncertainty in the ratios of various neutron detection efficiencies was only 0.5%. Since only ratios of efficiencies appear in the ratio R_{exp} , we are able to do better than the 5% uncertainty of a given detection efficiency. The standard deviation of the distribution shown is 2% using either method of calculating the CCD single-neutron signal.

Given that the experiment will be moved to a power-production reactor, the reactor cycle will be roughly 11 months on, 1 month off. This cycle does not give as much off time as would be liked to reduce the statistical uncertainty in the cosmic ray background. Unfortunately, it will require running the experiment for more than one year. With only one month of background collection per year, the statistical uncertainty in the background rate will be 3% after one year, and 2% after two years. The statistical uncertainty in the reactor-on rate will be less than 1% after one year. Under these conditions, the standard deviation of R_{exp} will be 7% after one year, and 5.5% after two years.

The reactor-associated neutron background is mainly due to neutrons born in the CCP reaction in the mineral-oil scintillator surrounding the target detector. We are currently working on reducing the uncertainty in this background by using source measurements made in the scintillator and monte carlo studies. If this uncertainty can be reduced from 10% to 1%, the standard deviation of R_{exp} can be reduced from 2% to 1%, for infinite run time, and after two years,

Figure 1: Probability Distribution of R_{exp} .

we can achieve a standard deviation of 5.0%.

3.2.2.6 The reported 17 keV neutrino state Recently, Simpson and Hime[22] have reported evidence of a small admixture of a massive antineutrino state to the electron antineutrino in the beta spectra of certain radioactive isotopes. The new state appears to have a mass of 17 keV, and a mixing ($\sin^2 \theta$) of 1%. In terms of flavor oscillation parameters, this would correspond to $\Delta m^2 = 2.9 \times 10^8 \text{ (eV)}^2$ and $\sin^2 2\theta = 0.04$.

Experiments done at accelerators are sensitive to oscillations with this high value of Δm^2 , but are only able to look for oscillations of the type $\nu_\mu \leftrightarrow \nu_e$ and have excluded this oscillation for the parameters given above. They are not currently able to exclude oscillations of the type $\nu_e \leftrightarrow \nu_\tau$, however. Mobile oscillation experiments done at nuclear reactors are sensitive to all oscillations of the type $\nu_e \leftrightarrow \nu_x$, but are not very sensitive to this high value of Δm^2 . This neutral current experiment, on the other hand, is sensitive both to high values of Δm^2 and to the oscillation $\nu_e \leftrightarrow \nu_\tau$, making it a good choice for direct observation of this oscillation.

If the overall uncertainty in the ratio R , defined above, can be brought down to the 1% level, we would be able to push our limit in $\sin^2 2\theta$ down to 0.04, and be able to exclude or confirm the massive state at the 95% confidence level. Since the experimental precision we have is approaching this level, a much better theoretical calculation is needed. In principle, a better calculation can be done by including effects such as nucleon recoil and second-order Feynman diagrams in the neutral current cross section, which are currently neglected.

3.2.3 Status

3.2.3.1 Detector setup All work which involved the installation of the heavier shielding and photomultiplier tubes has been completed. The site is located 11 meters from the center of the reactor core, between two massive concrete pillars and beneath a massive concrete ceiling which provide a good deal of cosmic ray shielding. The space between these pillars is closed off, both front and rear, by massive lead doors which ride on steel rails and can be opened and closed hydraulically. The pillars and doors define the detector and shielding space. Diagrams of the detector and shielding configuration are shown in Figures 2 and 3.

Figure 2: Top view of detector and shielding configuration.

Figure 3: Side view of detector and shielding configuration.

Water tanks for extra neutron shielding are located on the lead doors and on the floor in front of the lead doors. The floor tanks are small tanks which are designed to prevent neutrons from sneaking in underneath the large water tanks which ride on the doors themselves.

3.2.3.2 Electronics The design of the data collection electronics has been finalized and set up. The primary goal of the system is, of course, to recognize the neutral current interactions which will be taking place in the D_2O target detector tank. The signature of a neutral current event will be the capture of a neutron in one of the target tank's 3He proportional counters in the absence of activity in any of the surrounding scintillating detectors. Figure 4 shows a typical neutron spectrum of one tube.

The system design uses the six scintillating detectors outside of the new lead shield as active cosmic-ray-veto detectors—that is, when a cosmic ray is detected in any of these detectors, a logical block will be generated for a certain length of time which will prevent any triggering of the system. The inner liquid scintillator tanks have been set up to be an active as well as a passive cosmic ray veto; that is, the system can be triggered and the event recorded, but the trigger may be rejected in later analysis based on events taking place simultaneously in the inner scintillator tanks. The active veto circuit on the inner tanks is designed to catch cosmic ray events which manage to leak through gaps in the outer detectors. It was found that using an active veto on the inner tanks reduced the background trigger rate by roughly a factor of three.

The detector signals are fed to three eight-channel Slow Waveform Digitizers and to two twelve-channel scalars located in a CAMAC crate. The digitizers digitize and store analog pulses as directed by the computer, an IBM-AT which controls data collection. The computer reads the digitizers via a General Purpose Interface Bus which allows the computer to communicate with the CAMAC crate controller module. The crate controller passes the information from the desired modules to the computer.

3.2.3.3 System software The computer program written for the experiment has been debugged and is now collecting reactor-off data. The program was designed to collect data in a background mode so that other applications can be used in the foreground. For example, a data analysis program could be running in the foreground while data is being collected and stored in the background.

Figure 4: Neutron spectrum of a typical ^3He proportional tube.

The program also has two built in analysis features. One is a continuously updating readout of the CAMAC scalars. The other allows event by event scanning of the output of the digitizers. Both of these features are useful for debugging and troubleshooting purposes. Other features may be added in the future.

3.2.3.4 Neutron detection efficiency A monte carlo program has been written using MORSE, which is a three-dimensional neutron and gamma transport code used at Oak Ridge National Laboratory, to simulate the response of the detector. This program is used along with neutron point-source calibrations to calculate with high precision the neutron detection efficiency of the system. This calculation is very important as the efficiency is the most significant source of uncertainty in the experiment.

Measurements were made of the efficiency of the detector using a ^{252}Cf neutron source. Some measurements were carried out using a high-speed multi-channel analyzer attached to the output of the amplifiers of the ^3He proportional counters. Measurements were made at seven positions in the D_2O target tank for comparison with the results of the monte carlo. Because there is uncertainty in the source strength, the absolute efficiency at each point as calculated by the monte carlo did not agree with the measurements, however the ratio of the two was consistent from point to point.

Another measurement of the efficiency was made by looking at the ratios of rates of multiple neutron captures in a 1.25 millisecond window after a system trigger. The ^{252}Cf neutron source was placed at the center of the detector, and a long data-collection run was performed.

This method provides a good measurement of the detector efficiency because it is almost independent of the strength of the neutron source used. If the capture time of the neutrons in the detector is short compared to the time between ^{252}Cf fissions, then in a small enough time window, only neutrons from a single fission event are seen. The expected ratios of multiple neutron detections in the window can be calculated as a function of detector efficiency; the source strength drops out of the ratio.

In our situation, the neutron capture time in the inner detector was calculated to be 275 microseconds, from the average time between neutron pulses in the window. Our source strength at the time of the measurement was calculated to be 824 neutrons per second. Since 3.73 neutrons on the average are emitted

per fission, this corresponds to an average time between fissions of 4.5 milliseconds. This implies that the probability of a second fission occurring within the 1.25 millisecond window is small. Also, since the source rate is still high compared with the neutron rate due to cosmic rays, this background rate has negligible effect on the measurement. Corrections were made for both of these effects for the sake of completeness.

The expected ratios of multiple events were calculated by a monte carlo method in which 10,000 fissions were generated. According to Ref. [23], the number of neutrons produced by ^{252}Cf is Gaussianly distributed with a mean of 3.7 and a standard deviation of 1.21 neutrons per fission. A number of neutrons were generated for each fission according to this gaussian distribution. The number of captures was determined by the efficiency and the probability that captures would occur inside of the 1.25 millisecond window, given the measured mean capture time.

A comparison of the measured ratios to the calculated ratios is shown in Figure 5. The dotted curves represent the calculations of the ratios of the probabilities of various multiplicities. The crosses are the experimentally determined ratios, where the error is due to statistical uncertainties. By minimizing χ^2 , the average efficiency was found to be $(44 \pm 2)\%$. The χ^2 of the average was found to be 3.04 for 3 degrees of freedom.

In order to compare this estimate with the monte carlo, one further correction must be made. The efficiency just determined has folded into it an acceptance factor given by the neutron pulse-height threshold. The threshold used in this run was 150 millivolts, which corresponds to an acceptance of 96%. Therefore, the true efficiency would be $(46 \pm 2)\%$. The MORSE monte carlo gives a value of 48%. This gives us confidence in the accuracy of the monte carlo, and allows us to proceed with the calculation of the efficiency of detecting the neutrons from the antineutrino reactions.

MORSE runs were made to simulate the detector response to the NCD, CCD, and CCP reactions in the D_2O tank. The runs consisted of 50,000 neutrons born uniformly throughout the tank with the appropriate energy distribution.

The outcome of runs for various reactions is shown in Table 2. The efficiency for seeing neutral-current neutrons is calculated to be 33.2% with a statistical uncertainty of 0.8%.

Figure 5: Ratios of neutron multiplicities *vs.* detector efficiency.

Table 2: MORSE runs of antineutrino-induced neutrons.

Reaction	Eff. %
NCD	$33.24 \pm .26$
CCD	$32.19 \pm .26$
CCP	$37.15 \pm .26$

3.2.3.5 Background measurements Over the past year, reactor-off background data has been collected. This is an important measurement, as it shows the effectiveness of the new shielding configuration. A large portion of the 15% uncertainty in the previous version of this experiment was due to the large background of neutrons from cosmic ray interactions in the lead and steel surrounding the detector. The new shielding configuration has effectively cut this background by a factor of five, from roughly 300 day^{-1} down to 60 day^{-1} .

Background measurements have also been made using a NaI crystal. Figure 6 illustrates the effect of the shielding on the gamma background. The region of interest on this graph is above 2.2 MeV since gammas above this energy will be able to photo-disintegrate the deuteron, simulating a neutrino disintegration. This is an upper limit since there is another four inches of lead surrounding the D_2O target detector.

Currently, with all vetos on and the doors closed, we measure a total neutron detection rate of 0.7 per second and have a system trigger rate of 0.0017 per second, or roughly 1 per 10 minutes with a 65% live time. With full software cuts performed on the inner scintillator tanks, we achieve the background rate of 60 events per day.

Figure 7 shows a histogram of data taken in the large inner scintillator tank with a ^{60}Co gamma source inside. This shows the excellent energy resolution of the inner veto detector.

3.2.4 Schedule

We have conducted our reactor neutrino program for several years at the P reactor at the Savannah River Site. In the autumn of 1988, P reactor was shut down by the DoE for extensive upgrading of equipment, procedures, and training. In January of 1991, the DoE decided to close the P reactor permanently, opting to operate only the K and L reactors in the future. These two reactors are unsuitable for use by this experiment because neither has a site as close to the reactor core as does the P reactor (25 m *vs.* 11 m) and these reactors will be operated at about 1000 MW instead of their former full power of 2000 MW.

We have been searching for a new permanent reactor facility in the United States (see Sect. 3.4.2) but at this juncture there does not appear to be a suitable U.S. location for the existing detector.

Since the early 1980's, the Institut de Sciences Nucleaires (ISN) has been

Figure 6: Gamma spectrum taken with NaI crystal inside and outside of the shield.

Figure 7: ^{60}Co source spectrum in inner veto tank #2

involved in reactor neutrino experiments near the Bugey reactors in France. The Bugey power station is a reservation of four reactors, operated by Electricite de France, and located about 35 km from Lyon. J. F. Cavaignac has shown interest in forming a collaboration between his group at ISN and ours. He has invited us to move our experiment to a site adjacent to the space where the ISN group presently is participating in a neutrino-oscillation experiment.

The proposed site is located in the Bugey reactor #5 building. It is 17 m from the reactor #5 core and approximately 90 m from the reactor #4 core. Reactors 4 and 5 operate at 2785 MW when at full power. The site has approximately the same concrete overburden shielding as does P reactor. The gamma background measured near this position is even lower than at the P reactor site. We have not received data describing the neutron background at this site.

ISN proposes to receive our equipment and help install it in the new site. The installation would include the welding of the walls of a new tank #2 at the site because the present tank is too large to fit through standard doorways. Therefore, the walls of the present tank must be cut apart and the components of a new tank delivered to Bugey.

As a collaborator with ISN, we would benefit from the use of a fully equipped laboratory already in existence at Bugey, the availability of ISN itself within an hour's drive from Grenoble, and the ability to connect to the largest IBM mainframe in France at Lyon. This last feature would enable easy communication with the Irvine campus via BITNET and also access to the complete CERN computer library. ISN has several physicists, electronics technicians, and mechanics in their group in case we need technical assistance.

Since, as indicated above, we have been so far unable to locate a suitable site in the United States we are planning on moving the detector to France. The major expenses that we expect are the cost of shipping, travel expenses for our personnel, and the cost of supporting one or more physicists in France. We expect to have the equipment ready to start its journey to France in November or December of this year and to begin the installation at Bugey towards the end of the first quarter of 1992.

3.3 Mobile Neutrino-Oscillation Experiment

3.3.1 Purpose of the experiment

The purpose of this experiment is to search for neutrino oscillations of the form $\bar{\nu}_e \leftrightarrow \nu_x$, i.e. $\bar{\nu}_e$ disappearance, in the range $\Delta m^2 > 0.1 \text{ eV}^2$ with $\sin^2 2\theta > 0.1$. We detect reactor fission neutrinos by observing inverse-beta decay

$$\bar{\nu}_e p \rightarrow n \beta^+$$

on free protons in a liquid scintillator detector. The key idea is to measure and compare the number of inverse-beta reactions and their resulting β^+ energy spectrum at two distances from the reactor. The data may be analyzed by two different techniques:

Relative measurement: The ratio of the rates at the two distances may be compared to the ratio expected from geometry, i.e. essentially $\frac{1}{2}$; a deviation from the expected value indicating neutrino oscillations. The shapes of the β^+ spectra at the two positions may also be compared. If they differ significantly, this also could indicate neutrino oscillations. The primary value of this relative measurement technique is that the results are relatively insensitive to many effects, such as detector efficiencies, since *ratios* of the data taken at the two positions are used.

Absolute measurements: In this technique the data at each position (independently) is compared with the theoretically predicted rate and spectrum for that distance. This technique requires that all quantities, e.g. detection efficiencies, which might affect the data be well understood and quantified. For the additional effort that is involved in performing an absolute measurement one gains a sensitivity to neutrino oscillations with large Δm^2 (i.e. $\geq 10 \text{ eV}^2$).

3.3.2 Status

Since SRS has closed down the reactor that provided the neutrinos for this experiment, the data taking phase of the experiment has come to an end. We obtained excellent data at two distances from the reactor (18m and 24m) but were unable to collect data at the 50m distance. We are now analyzing the data from the two positions. This analysis will be somewhat more extensive

than initially planned because in addition to performing the relative analysis, we have decided to perform absolute measurements at the two positions. This change in objective has been stimulated by our not being able to take data at the third (50m) position and also by the fact that there is currently great interest in neutrino oscillations with large Δm^2 . (The absolute measurements give us information on large Δm^2 oscillations, whereas the ratio of the two positions does not.)

3.3.3 The detector

The detector, illustrated in Fig. 8 is composed of the following major components:

target in which the inverse-beta reactions occur. This completely enclosed tank contains 300 liters of NE313, a xylene-based scintillator loaded with 0.5% gadolinium. This scintillator provides pulse shape information, distinguishing between lightly and heavily ionizing particles (positrons and protons). The gadolinium provides fast, high efficiency neutron detection. The inverse-beta decays of interest all take place in the target. The target is viewed by 21 PMTs.

blanket detector consisting of two volumes which together completely surround the target. The blanket detector contains 1100 liters of a mineral oil based scintillator and is viewed by 60 PMTs (30 on the top and 30 on the bottom). The blanket detector is used both as an active anti and as additional active volume in which to observe gamma-ray interactions.

inner lead shield completely surrounding the blanket detector. This is composed of two inches of very low background lead. It shields against any gamma or charged particle backgrounds that may penetrate through or be created in the outer lead shield.

anticoincidence shield of three-inch plastic scintillator which completely surrounds the inner lead shield. The function of this shield is to veto signals which are coincident with charged cosmic rays which pass through the detector.

outer lead shield consisting of eight inches of lead completely surrounding the anticoincidence shield. This shield reduces the large flux of gamma

Neutrino Oscillation Detector

Figure 8: The mobile detector.

radiation resulting from neutron activated ^{16}N in the water of the heat exchangers above our experiment. When the reactor is on this flux is so large that, without the shield, the gammas impinging on the anticoincidence shield would result in an excessive dead time.

3.3.4 The Pulse Shape Discriminator

In order to reduce the background due to knock-on protons (caused by neutron-proton elastic scatters), it is important to be able to differentiate between a proton and a positron. It is for this reason that a special scintillator, NE313, was chosen for the target.

This scintillator possesses the property that its pulse shape depends rather strongly on the dE/dx of the ionizing particle. The effect causes the rise time of a proton-induced pulse to be significantly longer than that of an electron (or positron) pulse.

Thus if one measures the amount of time that it takes for a pulse to reach say 80% of its maximum height, one can rather clearly differentiate between positrons and protons. The circuit that differentiates these pulses is called the pulse shape discriminator (PSD). The PSD accepts positron-like pulses with an efficiency of 98% while rejecting proton-like pulses at the level of 100:1. Note that the PSD information is not used in the trigger logic, but is applied off line during data analysis.

3.3.5 Other data collection electronics

Output signals from the target and blanket photomultiplier tubes are each ganged into three groups at the detectors. The three signals from each detector are fed via RG-8 cables to an air-conditioned counting house where each is fanned in for processing by fast NIM electronics modules. The individual groups and the summed group signal feed discriminators. Coincidence units require the target and blanket *sum* logic signals to be in coincidence with each of their three associated *group* logic signals.

A *prompt* logic signal is formed when a target signal (seen simultaneously by all three target groups) is not in coincidence with the blanket or cosmic ray detectors. After such a prompt logic pulse is created, subsequent prompt logic pulses are blocked for 30 μs . A *delayed* logic pulse is generated by a discriminator when the sum of the target and blanket detector signals exceeds 4.0 MeV. The

delayed logic pulse is also subject to cosmic ray vetoes. An *event trigger* is generated whenever a delayed pulse is overlapped by a $30\ \mu\text{s}$ gate which was triggered by a prompt pulse. Accidental data is taken simultaneously.

Both event triggers and accidental triggers generate readout of several LeCroy CAMAC modules housed in a single crate. These modules are:

- Two 2249 Analog-to-Digital Converters to process analog signals from the target and blanket detectors. One unit is gated by prompt pulses and the other by delayed pulses.
- An 8837 Transient Recorder digitizes target analog signals in a time window of $\sim 60\ \mu\text{s}$ centered at the time of the delayed pulse.
- A 2264 Slow Waveform Digitizer digitizes analog signals from the target, blanket, and cosmic ray detectors in a time window of $\sim 4\ \text{ms}$ centered at the time of the delayed pulse.
- Two 2228A Time-to-Digital Converters are used. The first processes the PSD timing circuit output over a range of $\sim 100\ \text{ns}$. The second unit has been modified to process signals over a range of $\sim 40\ \mu\text{s}$ and is used to determine the difference in time between the prompt and delayed pulse.
- Two 2551 Scalers are used to record information associated with the various detector discriminator and logic circuit outputs. For each input to this module, there is a duplicate input to an individual NIM-level hardware scaler.

3.3.6 Event signature

When a reactor neutrino initiates an inverse-beta reaction with a free proton in the target, most of the neutrino's energy is given to the positron which quickly stops and annihilates. Each of the $0.5\ \text{MeV}$ annihilation gamma rays has a high probability of depositing its energy in one of the liquid scintillators (target or blanket). Meanwhile the neutron, with kinetic energy of tens of KeV, thermalizes and is then captured by a Gd nucleus with a characteristic time of $10\ \mu\text{s}$. This capture produces $\sim 8\ \text{MeV}$ of gamma rays which are detected in the scintillators with high efficiency. The signature of an inverse-beta reaction in our detector is thus:

- A *prompt pulse*—a scintillation flash in the target having the pulse shape characteristics of a positron.

- A *delayed pulse*—following the prompt pulse within $\sim 15 \mu\text{s}$. The total energy detected in the target plus blanket for this pulse must exceed $\sim 4 \text{ MeV}$.

3.3.7 Major backgrounds

3.3.7.1 Cosmic rays Most cosmic rays are rejected by the anti which completely surrounds the detector. However, some interact outside the anti (e.g. inside the outer lead shield) and produce neutrals which enter the target undetected by the anti. These form the main source of correlated background events in the target. One type occurs when a cosmic ray muon interacts in the outer shield creating a neutron which enters the target and simulates an event by first knocking on a proton and then getting absorbed by a Gd nucleus. The PSD circuit rejects these types of events and, thereby, reduces this background by 50%. Another type of cosmic ray-induced background occurs when a muon creates a bremsstrahlung gamma plus a neutron and they both enter the target producing a "positron-like" prompt pulse and a neutron capture in the target. This background, measured with the reactor off, was $\sim 25 \text{ d}^{-1}$.

3.3.7.2 Reactor associated By subtracting the reactor off PSD spectrum from the reactor on spectrum for each measurement, we have determined that all of the reactor associated background is due to gamma radiation; this can only cause accidental (random) events in the target. We have monitored the accidental background continuously and found the rate to range between 150 and 200 d^{-1} during the experiment.

3.3.8 Data collection

We have collected large samples of data at three detector positions (two different distances from the reactor core):

Position 1A. The detector was initially placed 18 m from the reactor core. 361K events were recorded while the reactor was on; 48K events while off.

Position 2. The detector was then moved to 24 m from the core. 598K events were recorded while the reactor was on; 123K while off.

Position 1B. The detector was returned to its initial position at 18 m, and an additional 226K reactor up and 155K reactor down events were taken. The

primary purpose for returning to the initial position was to investigate the long term stability of the detector.

3.3.8.1 Background data In order to subtract the reactor associated backgrounds, we take data when the reactor is "down" as well as when it is "up." One of the advantages of being at a production reactor is that there are frequent down periods, and we have been able to record data for about as much time with the reactor down as with it up.

To measure the cosmic ray background we record accidental events. These are events in which we receive the same two pulses as in our normal trigger but we reverse their time order and demand their separation to be ~ 2 ms. The net effect is that we are guaranteed that the events measured in this manner truly reflect the accidental, i.e. noncorrelated, ambient background.

3.3.8.2 Calibrations Several types of calibrations were carried out.

Energy calibrations Energy calibrations were performed weekly with sealed ^{137}Cs , ^{60}Co , and ^{228}Th gamma sources inserted in the center of the target and in two locations in the blanket detector. A computer program fit gaussians to each of the source peaks. These peaks were normalized by the corresponding energy deposited in each detector by each source as determined by the CERN Monte Carlo GEANT. Shown in Figures 9 and 10 are the calibration slopes and intercepts as a function of time during the experiment. The data, collected in separate ADCs for each detector, were then converted from counts to MeVs by the prior energy calibration.

Neutron detection efficiency As will be described in Section 3.3.10.1, the expected neutron detection efficiency has been calculated in a two-step process. First the neutron capture efficiency and capture time are found using the MORSE Monte Carlo. This is found to be about 0.64 within a capture time of $15 \mu\text{s}$. Then, the efficiency for absorbing the Gd gammas in the target and blanket detectors is determined with the GEANT code. This second efficiency is about 0.87 when the threshold of the sum of the target and blanket detectors is 4 MeV. In order to have confidence in our Monte Carlo results, we have made measurements of the neutron efficiency by inserting ^{252}Cf and AmBe sources in the center of the target. We ran the detector in the usual data collection mode with the exception that

Figure 9: Slope of the calibration function.

Figure 10: Intercepts of the calibration function.

only a single pulse was required to trigger an event. Several thousand events were collected. The results of the analysis of these runs are still preliminary while we continue to study the effects of cuts on the data. Monte Carlos exactly like those in the paragraph above have been run to simulate having a ^{252}Cf neutron source in the target. When we have completed the analysis of the measured results, we will compare them to the theoretical results.

Light detection response function for the target A set of measurements was made to determine the response of the target volume to a light pulser placed at various positions within it. A subroutine reproducing this response function has been installed in our Monte Carlo (GEANT) and is used in all simulations of events for this experiment.

We have not performed a similar light response measurement in the blanket detector. We are currently attempting to adapt information from the target measurements to simulate the light response of the blanket. If this attempt is not successful, we will perform light response measurements of the blanket detector this fall.

PSD calibration A separate determination of the PSD acceptance was performed for each measurement using the accidental background. Such an event sample is practically free of neutrons and contributes only to the peak in the time distribution where the positron events are located. This allowed us to continuously determine the energy-dependant tail of the positron peak under the neutron peak. In addition, the PSD system was periodically calibrated by placing gamma-ray or neutron sources in the target and observing their PSD spectra. Throughout the experiment the PSD cut was constrained to ensure an acceptance for prompt pulses above the threshold of 98%. A more thorough version of this analysis is under way to determine the energy dependence of acceptance.

3.3.8.3 Detector live time The total time of data collection was determined by counting the output of a 60 Hz pulser with a CAMAC scaler unit. The dead time (due to hardware veto and computer acquisition time) was determined by counting those same time pulses in anticoincidence with the dead-time blocking pulses. The live time was then calculated by subtracting the dead time from the total time.

3.3.9 Determination of event rates and positron spectra

For each position of the detector, the collected events fall into four categories:

1. Normal triggers with the reactor up
2. Normal triggers with the reactor down
3. Accidental triggers with the reactor up
4. Accidental triggers with the reactor down

Each of these samples is separately processed:

1. An event is kept only if the prompt signal has a pulse height falling within a predefined range and its pulse shape consistent with that of a positron.
2. An event is kept only if the delayed signal has a pulse height within a predefined range and it occurs within $\sim 15\mu s$ of the prompt pulse.
3. An event is removed if a significant signal occurs in the anticoincidence counter either within ~ 2 ms preceeding the prompt signal or in coincidence with the delayed signal.

Next, each event sample is converted to a rate (events/hour of live time). These rates are then normalized to the total reactor power recorded during its corresponding live time so. This gives the number of events/hour/MegaWatt.

The accidental event rates are subtracted from the normal event rates to yield corrected rates for reactor up and reactor down. Finally the reactor down rates are subtracted from the reactor up rates to yeild the corrected positron spectrum and total event rate for inverse-beta decays at each detector location.

3.3.9.1 Summary of the cuts The analog outputs of the target and blanket were fanned to two ADCs, one gated by the prompt signal and the other by the delayed signal. In addition, a transient recorder, called the fast waveform digitizer (FWD), digitized target analog signals in a time window of $\sim 60\mu s$ centered at the time of the delayed pulse. Also, a slow waveform digitizer (SWD) processed signals from the target, blanket, and sum of the anti detectors in a time window of ~ 4 ms centered at the time of the delayed pulse. TDCs were employed to measure the neutron time-of-flight.

All of the information stored for each event by the devices above are used in the final cut procedure. The cuts made on the data off-line are as follows:

1. Reject events with target SWD pulse height (p.h.) < 40 mV (1.0 MeV).
2. Reject events with target or blanket SWD p.h. > 499 mV (~ 10 MeV).
3. Reject events which have more than two peaks in the target during the prompt pulse, as recorded by the FWD.
4. Reject events with neutron capture time $> 15 \mu s$.
5. Reject events with blanket energy > 1.0 MeV in prompt ADC.
6. Reject events with target energy < 1.1 MeV in prompt ADC.
7. Reject "proton-like" events using time-dependant PSD cuts.
8. Reject events with anti pulse in SWD at same time as prompt or delayed pulse.
9. Reject events with the sum of target and blanket SWD pulse heights < 145 mV (4.0 MeV).

Note that cuts 1, 2, and 9 involve information in time with the delayed pulse. The SWD, rather than the delayed ADC, is used to implement these cuts because accidental triggers, i.e., those triggers which are purposely generated to produce a spectrum of accidental events to be subtracted from the normal trigger spectrum, are out of time with the delayed ADC gate. The pulse heights indicated for these cuts represent average values for the experiment and because each affects the neutron efficiency, an effort is under way to perform these cuts as a function of time using the weekly calibration information.

3.3.10 Calculation of the theoretically expected values

We discuss first the expected positron spectrum and event rates assuming that neutrinos do not oscillate. Then we look at the effects of neutrino oscillations on the expected values.

3.3.10.1 Assuming no oscillations The total number of positrons (i.e. the "yield") with energy E_e observed at position j is given by

$$Y_j(E_e) = \frac{N_{targ}}{4\pi^2} \sum_m \sum_n \int [\epsilon_j^{tot}(E_e) \sigma(E'_e) r(E_e, E'_e) S_j(E'_e, m) / L^2] dE'_e \quad (36)$$

where

N_{targ} is the number of protons in the target

$\epsilon^{\text{tot}}(E_e)$ is the total efficiency of the detector averaged over the detector

$\sigma(E_\nu)$ is the inverse beta decay cross section

$r(E_e, E'_e)$ is the detector response function for positrons isotropically distributed in the target

$S_j(E_\nu, m)$ is the number of neutrinos of energy E_ν emitted by reactor segment m while data at position j was being collected

L is the distance between the reactor segment m and detector segment n

and the neutrino and positron energies are related by $E_\nu = E_e + 1.805 \text{ MeV}$.

Inverse beta decay cross section We use the formula for the cross section of inverse beta decay as given by Fayans [27] to evaluate $\sigma(E_\nu)$. The equation includes corrections due to 1) recoil effects, 2) weak magnetism, and 3) radiative processes.

A critical constant in the inverse beta decay cross section formula is the neutron lifetime. Before 1986, the discrepancy among measurements of this constant was as much as 15%. In recent years there has been a vast improvement in techniques and agreement in measurements [28]. The value used in this work, taken from Ref. [28], is $\tau_n = 887.6 \pm 2.7 \text{ sec}$.

The neutrino spectrum The number of neutrinos of energy E_ν emitted by the reactor segment m is represented by $S_j(E_\nu, m)$. It is derived from the product of the spatial distribution of reactor fissions, averaged over the period of time that the detector was at location j , with the corresponding fission antineutrino spectrum of each nuclide (^{235}U , ^{238}U , and ^{239}Pu).

SRS officials supplied power distribution information during the course of the experiment for all the important fissioning isotopes. This information is in the form of 60 horizontal by 20 vertical readouts, i.e. 1200 reactor segments. The number of fissions per second in reactor segment m for isotope i is given by

$$n_i(m, t) = a(m, t) f_i(m, B) W(t) / \sum_p f_p(m, B) E_p \quad (37)$$

where $a(m, t)$ is the relative power contribution of segment m and $W(t)$ is the total reactor power. $f_i(m, B)$ is the relative fission contribution of

isotope i in segment m and depends on the burnup B (MW per day per ton U). E_p is the energy release per fission of isotope p . Integrating Eqn. 37 over the actual measurement times, the average fission rate per isotope per segment $N_i(m)$ was determined.

The neutrino yield per fission isotope i is represented by $S_i(E_\nu)$. We use the spectra deduced from measured beta emissions (Ref. [1] and [2]) of ^{235}U and ^{239}Pu and a calculated neutrino spectrum (Ref. [26]) for the isotope ^{238}U .

The expected neutrino source spectrum $S_j(E_\nu, m)$ is then given by

$$S_j(E_\nu, m) = \sum_i N_i(m) S_i(E_\nu).$$

Figure 11 shows the ratio of the source spectrum of position 2 to position 1a and also of position 1b to position 1a. In each case the spectrum is summed over the reactor segments and corrected for differences in reactor power. This figure indicates that the differences between measurements in the shape of the neutrino spectrum due to the burnup of the isotopes is negligible.

The detector response to positrons The CERN code GEANT was used to determine the response of the detector to positrons isotropically distributed throughout the target scintillator. The resulting quantity, $r(E_e, E'_e)$, was calculated 40 times for positrons born with total energy E'_e ranging from 1.0 MeV to 9.0 MeV in steps of 0.2 MeV. Each calculation followed the energy losses, secondary emissions, and the associated annihilation gammas of 10,000 positrons; the output was stored histograms of deposited positron energy E_e in 0.2 MeV bins.

The total detector efficiency The overall efficiency of the detector is given by

$$\epsilon^{\text{tot}}(E_e) = \epsilon_\beta(E_e) \times \epsilon_n \times \epsilon_\gamma$$

where

$\epsilon_\beta(E_e)$ is the efficiency for detecting a positron of energy E_e . This was determined from GEANT simulations.

Figure 11: Ratio of the source spectra.

ϵ_n is the efficiency for capturing a neutron by a Gd nucleus. The neutron capture time is determined using the Oak Ridge code MORSE with the neutron spectrum associated with inverse beta decay isotropically distributed in the target. With this program, both the neutron capture time and the Gd neutron absorption efficiency are determined.

ϵ_γ is the efficiency for detecting the Gd capture gammas. Once the neutrons are absorbed in the target, GEANT is employed to follow four gammas, with total energy of 8.0 MeV, from their birth at the neutron absorption point, to their eventual absorption or escape. This is done for 50,000 trials with the energies deposited in the target and blanket separately recorded.

3.3.10.2 Assuming that neutrinos oscillate For two-state neutrino oscillations, the probability that a neutrino born in state l with energy E_ν is still in that state after traveling a distance L is given by

$$P(E_\nu, L, \Delta m^2, \theta) = 1 - \frac{1}{2} \sin^2 2\theta \times [1 - \cos(2.53 \Delta m^2 (eV^2) L(m) / E_\nu (MeV))]$$

where $\Delta m^2 = (m_2^2 - m_1^2) c^4$, and m_2 and m_1 are the expectation values of the two mass eigenstates.

To take this effect into account one merely includes this term inside the integral of equation 36.

3.3.11 Comparison of measurements with expected values

Analysis of the data with special attention to the time dependence of cuts made is in progress. In parallel, the theoretical calculations are nearing completion. Afterwards, the results of each measurement will be compared to the theoretical expectations. Finally, the results will be submitted, as part of a complete description of this two-position neutrino-oscillations search, for publication in Physical Review D.

3.3.12 Disposition of the detector

Since we are finished taking data with this detector, we plan to disassemble it within the next few months and ship most of the components back to our campus.

3.4 Plans

We intend to vigorously pursue our reactor neutrino physics program for the foreseeable future. In the coming year we expect to finish the data analysis on the mobile detector experiment and, as stated in Sect. 3.2.4, move the Neutral Current Detector to France. Beyond that, there are several important experiments which we have been considering for sometime, and we believe that given recent advances in electronics and detection media that they are now practical to pursue.

3.4.1 New experiments

Some of the potential new experiments at a reactor facility include:

- Elastic Scattering

Our last result on the reaction:

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \quad (38)$$

was published in 1976[5]. The measured cross-section for this fundamental process has been used to define several parameters of the standard model. In addition, it can be used to search for effects which are beyond the standard model. As an example, the differential electron recoil spectrum can be used to set limits on the magnetic moment of the neutrino. The magnetic moment of the neutrino has generated interest in the last several years as a possible explanation of the solar neutrino problem. The experimental limit comes from our '76 work and is about 2×10^{-10} Bohr magnetons, just at the limit of the range where the solar effect could be explained. Clearly, if only for this application, a new more precise experiment is indicated. Sensitivity to the magnetic moment is enhanced as the energy threshold in the experiment is reduced[29]. We have discussed techniques to achieve lower energy thresholds but a detector design is still incomplete.

- Coherent scattering

Another reaction of interest is the coherent scattering of reactor antineutrinos by nuclei. This experiment was first discussed by T. W. Donnelly and others[30] shortly after the discovery of neutral currents in 1974. An example is the scattering from ${}^7\text{Li}$ nuclei. In this case, the signature would

be the nuclear de-excitation with the emission of a 0.478 MeV gamma ray. The experiment would probe the structure of neutral currents by measuring the isovector axial-vector coupling constant.

- Left-Handed Neutrino search

The electron-antineutrinos produced by the beta decays of nuclear fission fragments are right-handed. If right-handed to left-handed oscillations exist, then one can look for the appearance of left-handed neutrinos. The existing limit comes from an early experiment by Ray Davis at Savannah River in which he used a small version of his solar neutrino apparatus to look for neutrinos. The limit is $\nu_e/\bar{\nu}_e < 0.02$ [31]. Two reactions that we could use in a new search are the neutrino-induced beta decay of ^{11}B and ^{115}In . Scintillators doped with these nuclei have been developed during the past decade mainly because of their potential as solar neutrino detectors. In addition, such a reactor experiment could serve as a feasibility test for making a larger model for solar neutrino counting.

3.4.2 A new reactor neutrino research facility

A major consideration, of course, is with the closing of the P-reactor at SRS, where will be able to perform these experiments?

One attractive possibility is to use the New Production Reactor (NPR) which is proposed for SRS. We have been in contact with the designers of the facility and have requested that they provide us with a special room very close to the reactor core. If they are able to provide us with the type of space and facilities that we have requested, this would be the most ideal reactor neutrino facility in the world. The only negative aspect of a facility in the NPR is that it may be 10 years before it is ready. So where do we go in the meantime?

As discussed earlier the Bugey reactor in France is a viable site, and there are many features of that location that make it quite attractive. On the other hand, we would prefer performing the experiments here in the U.S. if an equally suitable site can be found.

We have had several telephone conversations with upper level management of utilities which operate commercial reactors here in the U.S. Some of the utilities we have contacted are the TVA, San Onofre, Duke Power, Georgia Power Co., and the Southern Company. In most cases, the manager responded negatively to our the proposal that we relocate our experiment to one of their

reactors, stating that a prerequisite would be the completion of an engineering study, paid for by us, proving that our presence would not interfere with any of their systems or reactor safety. The typical cost of such a study is several hundred thousand dollars. The San Onofre management has been somewhat more encouraging and negotiations with them are preceeding. However, due to the many practical considerations (structural engineering, safety, interference with their productivity, etc.) these negotiations are expected to take some time; perhaps a year.

The San Onofre site would be at about 25 meters from the center of the 3300 MW reactor. This distance is large and unsuitable for our already built neutral current experiment, but future generations of experiments can be built to accomodate the reduced flux.

3.4.3 Long-baseline oscillation experiment using the IMB detector

As stated in the IMB section of this report, the IMB detector is 12.9 km from a 3800 megaWatt commercial nuclear power plant (the Perry reactor). This affords us a unique opportunity to perform a long baseline neutrino oscillation experiment ($\bar{\nu}_e$ disappearance) using a very large detector with excellent shielding in a very low background environment; the conditions are ideally suited to the experiment. The expected event rate is about 10 neutrino interactions per day. The results from this experiment would dramatically improve the explored region of Δm^2 versus $\sin^2 2\theta$; we would reach to a Δm^2 of 10^{-4} eV² and a $\sin^2 2\theta$ of about 10^{-1} . This will be an improvement of two orders of magnitude in Δm^2 from previous experiments.

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4 The IMB Detector

4.1 Introduction

The IMB detector was built by the Irvine - Michigan - Brookhaven Collaboration during the period 1980 to 1982, with the major goal of testing the proton decay prediction of minimal SU(5). Secondary goals dealing with other aspects of Particle Physics, Particle-Astrophysics and Cosmic Ray Physics were also motivating factors for the collaboration, and the historic observation of a neutrino burst from SN1987a generated tremendous physics rewards.

Minimal SU(5) predicted that the process $p \rightarrow e^+ \pi^0$, should occur with a partial lifetime $\tau/B = 4.5 \times 10^{29 \pm 1.7}$ years. Our 1983 report (Phys. Rev. Lett. 51, 27 (1983)) concluded that τ/B at the 90% C.L. exceeded 6.5×10^{31} yr effectively ruling out the minimal theory. With subsequent IMB data we have raised our 90% C.L. partial life time to $\geq 5.5 \times 10^{32}$ yr (Phys. Rev. Lett. 42, 2974 (1990)). Our background estimates imply that we can go beyond a few $\times 10^{33}$ yr with the operation of an improved detector.

The portion of this report dealing with proton decay reviews the current theoretical predictions, the status of our data, and our prospects for future measurements. The most exciting recent development is the use of LEP measurements to constrain the value of the unification mass. This gives a prediction from SUSY GUTs of a proton decay lifetime of $\tau/B \sim 10^{33.2 \pm 1.2}$ yr. This suggests the possibility of actually observing proton decay with the further operation of an improved IMB. At the very least, continued operation will further constrain these predictions.

We also discuss:

- The search for Neutrino Oscillations
- Neutrino Astronomy
- Expected data from a future supernova
- Our capabilities for observing Solar Neutrinos
- The status of the laboratory
- Proposed detector upgrades

- A long baseline reactor neutrino oscillation experiment
- A long baseline neutrino oscillation experiment using the FNAL new main injector

4.2 Proton decay:

4.2.1 Is proton decay within our reach?

Proton instability, expected at some level in many extensions of the standard model, still offers a unique probe in searches for the ultimate theory of interactions. The lifetime of the proton depends on the scale of grand unification as determined by the convergence of running coupling constants at a single point at very high energy.

Recent results obtained by LEP experiments have provided much more precise measurements of electroweak and strong coupling constants at the M_Z scale. As can be seen in the paper by U. Amaldi et al.[1], the LEP measurements have allowed for more conclusive extrapolations to high energies in search of the unification scale.

It was found that in a non-supersymmetric Standard Model with only one Higgs doublet, the convergence of coupling constants at a single point is excluded (see Fig. 1a). With additional Higgs doublets unification can be obtained. However, this unification is at a scale conflicting with the experimental limits on the proton lifetime.

In the supersymmetric extension of the Standard Model with a minimal Higgs sector of two doublets, a single convergence point is obtained by fitting both the unification scale M_{GUT} and the SUSY breaking scale M_{SUSY} (Fig. 1b). For the fitted value of $M_{GUT} = 10^{16.0 \pm 0.3}$ GeV, the proton lifetime was estimated to be $10^{33.2 \pm 1.2}$ years, if the decay is dominated by gauge boson exchange. In many SUSY models Higgs exchange interactions further reduces the proton lifetime.

Precise LEP measurements of coupling constants also allowed for more constrained estimates of the proton lifetime in the framework of the Flipped $SU(5) \times U(1)$ supersymmetric GUT derived from string theory [2,3,4]. This theory is attractive because it eliminates the Higgs mediated interactions in a natural way. In other SUSY theories, these lead to proton decays with lifetimes much shorter than the current limits.

The unification mass, M_{GUT} , is shown in Fig. 2 (from ref. [5]) as a function of the strong coupling constant, α_3 , and the electro-weak mixing angle, $\sin^2 \theta_W$. The shaded region represents the current best LEP measurements of α_3 and $\sin^2 \theta_W$. The M_{GUT} values below 2×10^{15} GeV are excluded by the most recent IMB limit [6] on the $p \rightarrow e^+ \pi^0$ decay rate. It is seen that the proton lifetime is

Figure 12: Evolution of the three coupling constants: a) in the minimal Standard Model using M_Z and $\alpha_s(M_Z)$ from DELPHI data, b) in the minimal SUSY model (M_{SUSY} has been fitted by requiring crossing of the couplings in a single point). Figure taken from paper by U. Amaldi et al.

predicted to be near to the current experimental limit. The maximum bound is estimated at 2×10^{34} years [5].

In Flipped $SU(5) \times U(1)$, proton instability arises from gauge boson exchange. The most likely decay modes are $p \rightarrow \bar{\nu}_e \pi^+$ and $n \rightarrow e^+ \pi^-$. Branching rates a factor of two smaller are predicted for $n \rightarrow \bar{\nu}_e \pi^0$ and $p \rightarrow e^+ \pi^0$ modes.

In unification models with dominant baryon violation amplitude generated by the Higgs exchange, the decay rates of $p \rightarrow \nu K^+$ and $n \rightarrow \nu K^0$ could be an order of magnitude greater than any other decay mode [7,8,9]. From the experimental point of view those decay modes require good sensitivity at low visible energy. On the other hand strange particles are very unlikely products of the soft atmospheric neutrino spectrum. Therefore a good energy resolution, which would allow for unique kaon identification, is vital for background reduction.

At present, no event has been found that can be unambiguously ascribed to a baryon number violating nucleon decay. The vast majority of contained events in underground detectors have the rate and characteristics expected from atmospheric ν interactions.

For the past six years, after conventional $SU(5)$ was excluded by IMB-1 results, GUT models have produced a broad range of possible proton lifetimes. The recent precise LEP measurements now confine this range to a region just above and close to the current experimental limits.

4.2.2 Recent results

We have completed the selection and analysis of contained events in the data collected in IMB-3 up to the end of 1988 (see sec. 1.4.2). This sample contains 498 contained events recorded during 376 live days. Out of this sample, 422 events with the number of hit photomultiplier tubes, $NT1 \geq 70$, were used for the preliminary proton decay analysis. They are referred to below as the "DST 1988" sample.

We are now finalizing the DST 1989 sample of 247 contained events covering 227 new live days. If we include the 401 events found in 417 live-days of the IMB-1 phase of the experiment, we now have at our disposal a sample of 1126 contained events. The status of the analysis of data taken after 1989 is described in Sec. 1.4.2

- $p \rightarrow e^+ \pi^0$ decay

Figure 13: Values of M_{GUT} as a function of α_3 and $\sin^2 \theta_W$ in Flipped $SU(5) \times U(1)$. The shaded region represents values of α_3 and $\sin^2 \theta_W$ favored by recent LEP data. Figure taken from paper by J. S. Hagelin.

Our paper [6], published in 1990, was based on the "DST 88" sample covering 376 days of IMB-3 livetime. It set a partial lifetime limit for the proton of 5.5×10^{32} years¹ when 417 days of data from the IMB-1 detector were included. Since then, (up to the end of 1990) we have accumulated data covering an additional 448 days of detector livetime. Preliminary analysis of this sample indicates that there is still no $p \rightarrow e^+ \pi^0$ decay candidate. The combined data set allows us to put a lower bound on the lifetime of 8.4×10^{32} years.

The most recent lifetime limits obtained from other detectors were presented at the 25th ICHEP in Singapore-[11]. No $p \rightarrow e^+ \pi^0$ decay candidates were announced. The Kamiokande collaboration best limit is 2.6×10^{32} years, while the preliminary result from Frejus is 0.7×10^{32} years. With no candidate being seen, the combined limit from the three experiments is then 1.2×10^{33} years. If one compares this result with the proton lifetime of $1.6_{-1.5}^{+2.4} \times 10^{33}$ expected from the unification point derived by Amaldi et al. [1], it is seen that experiments now are probing a lifetime region which is very promising for grand unification.

- $p \rightarrow \nu K^+$ decay

Our recent results on $p \rightarrow \nu K^+$ decay were presented at the 25th ICHEP in Singapore [10]. They are based on the "DST 1988" sample. Kaons resulting from proton disintegration would decay at rest either to $\nu \mu^+$ (63%) or $\pi^0 \pi^+$ (21.2%). The more prevalent $\nu \mu^+$ channel produces a 236 MeV/c muon which fires 56 ± 19 PMTs and is reconstructed with an 11% efficiency². Four candidates with compatible muon energy were found. Without subtracting background, these four events imply a lower limit to the partial proton lifetime of $\tau/B \geq 1.0 \times 10^{31}$ years.

The $K^+ \rightarrow \pi^0 \pi^+$ channel fires 207 ± 49 PMTs, mostly by the light produced by two γ showers from the π^0 decays. The presence of the π^+ is inferred by detection of the delayed μ^+ decay positron signal. Two events were found to be compatible with this decay mode. However, each event had a collapsed Čerenkov ring indicating the presence of a recoil proton as expected from a neutrino interaction. We are thus left with no $K^+ \rightarrow \pi^0 \pi^+$ candidates and restrict the proton partial lifetime to $\tau/B \geq 5.7 \times 10^{31}$

¹All lifetime limits presented here assume 90% confidence level.

²The low efficiency is caused by the $NT1 \geq 70$ cut

years.

Preliminary analysis of 1989 data increases the limit to 8.3×10^{31} years. The current Kamiokande lower bound for $p \rightarrow \nu K^+$ decay mode is 1.0×10^{32} (5 candidates), and the Frejus limit is 0.15×10^{31} with 1 candidate [11].

- Other decay modes.

A preliminary analysis of the "DST88" sample was done to search for other proton decay modes. The first analysis used visible energy and anisotropy to characterize the events. Anisotropy is a normalized vector sum over directions of hit PMTs from the event vertex and essentially measures the visible momentum imbalance of an event. For every decay mode a sample of events was simulated to determine the appropriate energy and anisotropy cuts as well as the efficiency with which the events are saved within the cuts. The data events found within the cuts were then treated as nucleon decay candidates and partial lifetimes were calculated. The quantity of candidates was consistent with the expected neutrino background.

In table 1, we list two preliminary estimates of a 90% confidence limit upper bound on the lifetime. One estimate is calculated assuming all candidates are true nucleon decays. The other estimate includes a subtraction of the simulated atmospheric ν background.

For comparison, we quote also the lifetime limits obtained from previous analyses of IMB data [12,13] as well as the best results reported from other experiments (Kamiokande, Frejus) at the 25th ICHEP in Singapore [11].

For a few decay modes, it was possible to make a more effective candidate selection from the neutrino background by using an invariant mass analysis. In table 2 we present preliminary results based only on the "DST 88" sample for some selected decay modes. The modes have final states with two widely separated visible tracks. The candidates are located among the wide angle 2 prong events that constitute a small fraction (3%) of the data sample. For the selected events, invariant mass and residual momentum are calculated assuming all possible particle hypotheses for each track. The monte carlo simulation of nucleon decays is used to determine the expected ranges of invariant masses and momenta and corresponding efficiencies.

Table 1. Nucleon decay lifetimes using visible energy and anisotropy cuts.

mode	lifetime $\times 10^{31}y$	lifetime bkg subtr. $\times 10^{31}y$	lifetime IMB1+2 $\times 10^{31}y$	lifetime other exper [11] $\times 10^{31}y$
$p \rightarrow e^+ K^0 (K_s^0 \rightarrow \pi^0 \pi^0)$	11	11	7	20
$(K_l^0 \rightarrow \pi^0 \pi^0 \pi^0)$	2.3	6.1		
$p \rightarrow e^+ \eta (\eta \rightarrow \text{neutrals})$	9.6	16	10	13
$(\eta \rightarrow \text{charged})$	1.3	2.9		
$p \rightarrow e^+ \rho$	2.2	3.0	1.7	7
$p \rightarrow e^+ \omega (\omega \rightarrow \pi^+ \pi^- \pi^0)$	4	11	2.6	4.5
$(\omega \rightarrow \pi^0 \gamma)$	1.8	1.8		
$p \rightarrow e^+ \gamma$	12	20	46	13
$p \rightarrow \mu^+ \pi^0$	7	16	27	23
$p \rightarrow \mu^+ K^0 (K_l^0 \rightarrow \pi^0 \pi^0 \pi^0)$	3.7	11.	1.9	12
$(K_s^0 \rightarrow \pi^+ \pi^-)$	4.4	7.6		
$(K_s^0 \rightarrow \pi^0 \pi^0)$	0.4	0.4		
$p \rightarrow \mu^+ \eta (\eta \rightarrow \text{neutrals})$	5.5	13	3.4	7
$(\eta \rightarrow \text{charged})$	0.9	1.4		
$p \rightarrow \mu^+ \mu^+ \mu^-$	8.4	17	19	20
$p \rightarrow e^+ e^+ e^-$	19	31	51	50
$n \rightarrow \nu K^0$	0.9	1.4	1.5	8
$n \rightarrow \nu \eta$	2.4	4.1	1.6	5
$n \rightarrow \nu \omega (\omega \rightarrow \pi^+ \pi^- \pi^0)$	1.8	1.8	0.6	4.
$(\omega \rightarrow \pi^0 \gamma)$	0.4	0.5		

Table 2. Nucleon decay lifetimes obtained with the invariant mass analysis

mode	eff	no. of cand	no. of bckgnd	τ $\times 10^{31}y$	τ bkg sub $\times 10^{31}y$	τ IMB1+2 $\times 10^{31}y$	τ other exp $\times 10^{31}y$
$p \rightarrow \mu^+ \gamma$	.62	0	0.2	25	25	38	16
$n \rightarrow e^+ \pi^-$	.15	0	0.4	4.8	4.8	10	13
$n \rightarrow \mu^+ \pi^-$	.25	2	0.7	3.4	4.6	6.3	10
$p \rightarrow \mu^+ \omega$ ($\omega \rightarrow \pi^0 \gamma$)	.46	1	0.6	0.9	1.6	1.0	5
$p \rightarrow \mu^+ \rho$ ($\rho \rightarrow \pi^+ \pi^-$)	.20	3	1.5	2.7	4.1	3	12

The efficiency listed in the table (column 2) corresponds to the recovery of a decay event inside the detector fiducial volume. In cases where there was more than one way for the decay products to manifest themselves, the branching ratio was not included in the efficiency, although it was included in the lifetime calculation.

The lifetimes listed in both tables are conservative because at closer inspection some of the candidate events reveal an additional collapsed track of low energy, not compatible with the proton decay interpretation. The quoted limits are based on only 376 days of the IMB-3 livetime and will soon be improved after addition of the new DST sample covering the remaining 498 days of data. We are also working on the NT1<70 events, which up to this time have not been used for the search for proton decays.

We are now preparing a paper describing a theory non-specific search for nucleon decay into more than 30 different decay modes.

4.2.3 Conclusions and implications for future

Recent developments in the quest for grand unification are encouraging for experimental searches for proton instability. Unification is expected in an energy region which implies a proton lifetime close to the values being currently probed. The upper bound is within an order of magnitude from the limits set by the existing experimental data. Theory, however, does not provide us with any definite

guideline about a preferred decay mode. Depending on the unification model, the dominant decays may lead into a lepton and a pion or into a neutrino and a kaon.

As can be determined from our table of preliminary results, the combined results of IMB-1, -2, and -3, provide the most restrictive bounds on a majority of the proton decay rates. With the addition of new data and a factor of 2.3 increase with respect to the "DST 88" sample, the IMB results will help guide theoretical attempts to unify the forces of nature.

It is also clear that the relatively small coverage of light sensors degrades the quality of our results for those few decay modes where a better Čerenkov image of a massive particle with low velocity would be vital. This applies to all the decays leading to charged pions in the final state. Even if a pion is produced at relatively high energy, as in two-body decay modes, the nuclear interactions inside the oxygen nucleus and during its passage through water decrease its final light output.

Some of the expected decay modes, eg. $p \rightarrow e^+ \pi^0$, are still easily selected from the background. We expect less than 0.1 background events/yr for $p \rightarrow e^+ \pi^0$ decay. In order to probe the broadest possible range of expected proton partial decay rates for the background-free modes, an increase in the fiducial volume (as discussed later) and in the detection livetime is vital.

However for most decay channels, an effective background rejection becomes of major importance. It is seen in the tables presented earlier that very few decay modes have zero candidates (in table 1 those are the modes for which the lifetimes with and without background subtraction are equal). Due to the soft spectrum of atmospheric neutrinos many recoiling protons and produced charged pions remain invisible with the current detector light sensitivity. The observation of the collapsing images of those particles would greatly reduce the number of events considered as candidate proton decays.

Better energy resolution would also improve signal to background ratio. The invariant mass analysis would be more effective in selecting the potential proton decay candidates from the continuous neutrino interaction background. An improved energy resolution would be essential in identifying monoenergetic muons of 236 MeV/c momentum that would unambiguously signal a decay of a kaon resulting from any $p/n \rightarrow \text{lepton} + K^+$ decay. A unique identification of kaons is particularly interesting because they are very unlikely products of the soft atmospheric neutrino interactions. As discussed later, better energy

resolution can be achieved by increasing the number of light sensitive pixels in the detector.

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4.3 Other Physics

4.3.1 The Search for Neutrino Oscillation.

The search for nucleon decay naturally yields a sample of atmospheric neutrino interactions contained in the detector volume. Indeed, the detected neutrinos are the major background to nucleon decay. In addition, the detector records a vast number of entering particles. Of these, a small fraction, about 0.5 /day enter from below the horizon. These are of special interest since they are mainly muons produced in muon neutrino interactions in the rock surrounding the detector. Such neutrinos travel large distances, up to 12000 km between production and interaction.

IMB is the largest existing detector of atmospheric neutrinos. Due to its large target mass and low trigger threshold (~ 10 MeV) it is sensitive to lower neutrino fluxes than other detectors in the same energy range. With an overall efficiency of about 90% it has collected about 500 contained events in IMB-1 and -2 (which had somewhat higher thresholds), and about 1100 in the IMB-3. This is the largest existing sample of atmospheric neutrino interactions.

While the interactions of atmospheric neutrinos are an unavoidable background for the baryon decay search, they are also a source of important physics. They create for example, a unique opportunity for the study of neutrino oscillation. Atmospheric neutrinos are produced in the interactions of primary cosmic rays in the atmosphere. They penetrate the Earth arriving almost isotropically at the detector. On their way to the detector they travel distances from ~ 10 km (when coming directly from above) to ~ 12000 km (when they come from below the detector). Such large oscillation distances are not available with other neutrino beams in this energy range and for these flavors of neutrinos. The large distances together with low mean energy of the neutrinos provide an opportunity to study oscillations with δm^2 as low as a few $\times 10^{-5} \text{eV}^2$.

Oscillation studies with atmospheric neutrinos have several drawbacks however, limiting their sensitivity to large mixing angles. The flux is composed of roughly equal proportions of electron and muon neutrinos and antineutrinos. This composition makes an appearance experiment impractical. Moreover, the energy spectrum is mostly below charged current tau neutrino threshold,

so oscillation to tau neutrinos manifests itself only as a loss of muon neutrinos. Finally, the low energy spectrum creates problems with the interpretation of the data. This energy region, while in principle well understood theoretically, involves mainly quasi-elastic and resonance production processes, in which numerous resonances are either not well established or their form-factors have not been accurately measured. In addition, the interactions in the detector take place mainly within oxygen nuclei, which makes modeling difficult.

Nevertheless, this large sample of contained neutrino interactions constitute a valuable resource, the interpretation of which will give new insight into the neutrino oscillation problem.

Our earlier study of oscillations used data from IMB-1 and has been published [1]. Limits on δm^2 in the range 1.1×10^{-4} and 2.2×10^{-5} were established. The exclusion plots from this early work are shown in Fig. 15. We now have a much larger set of higher quality data to draw upon.

We have used a new sample of 422 events collected during a 376 live-day exposure of IMB-3 (to the end of 1988) in our most recent work. The number of observed events agrees very well with the predicted number of 376.6 considering a 20% uncertainty in the neutrino flux. The agreement between the predicted and observed energy spectra (shown in Fig. 14) for this sample is also good. These results provide no hint of oscillations.

The most accurately predicted feature of the atmospheric neutrinos, ($\pm 5\%$), is the ratio of the muon neutrino to the electron neutrino flux. If oscillations of any kind take place, this ratio could change.

To study this effect one has to be able to identify the leptons produced in the neutrino interactions, namely to be able to differentiate between muon and electron signals. To accomplish this two different methods have been developed:

- Firstly, muons are identified by their decay signal (in a $7.5 \mu\text{s}$ time window). With IMB-1 we observed a $\sim 2\sigma$ deficit of such decays. The same effect appears in the IMB-3 data where we see $39 \pm 2\%$ of contained events with muon decays, while $44.2 \pm 0.8\%$ are expected. Again the observed muon decay fraction is about 2σ below expectation. The spectrum of

events with muon decays is shown in Fig. 14 and compared with the expected spectrum. These agree well with each other.

- Secondly, for a subsample of 284 events (67% of the total) with only one visible track, a method has been developed to resolve "showering" (due to e, π^0, γ) from "non-showering" (due to $\mu, \pi^\pm$) tracks. This method takes advantage of a difference in patterns of illuminated phototubes caused by the difference in the mechanisms of energy deposition by these two classes of particles. The probability of misidentification is estimated to be only 8%. Particle identification provides a better measure of the flavor composition than does muon decay. In the visible energy range $100 \text{ MeV} < E_c < 1500 \text{ MeV}$ in the sample of 236 events only $97 (41 \pm 3(stat) \pm 2(sys)\%)$ have non-showering patterns. This is $3\sigma_{stat}$ below the expected fraction of $51 \pm 1(stat) \pm 5(sys)\%$. A similar deficit was reported by the Kamiokande group, which measured a non-showering fraction to be $43 \pm 4\%$, while they expected 53%. However, if the systematic errors are included our deficit is less than 2σ . In addition, neither IMB nor Kamiokande observe a correlation of this deficit with energy or angle (neutrino path-length) as one might expect from oscillations. Nevertheless, the Kamiokande deficit has been interpreted as a manifestation of muon neutrino oscillation with the most probable δm^2 of 10^{-2} eV^2 and with a mixing as high as $\sin^2(2\theta) \sim 0.69$.

This work has recently been published [2].

The data sample has more than doubled since the above analysis was completed. This new data was collected during a period in which the detector noise was lowered by nearly a factor of three and electronic cross-talk was significantly reduced. These improvements will lead to still more reliable track identification. Furthermore, particle identification will be further improved by the proposed modifications to the detector (see Sect. 4.6). The active veto will eliminate one of the subjective factors of the analysis, the decision as to whether a single down-going track with vertex close to the fiducial edge is entering or contained. The new phototubes, with a better time resolution, more light detecting pixels, and a new electronics will make a track identification even better. The multihit electronics will facilitate almost 100% efficiency in recording muon decays. These improvements will eliminate most of the experimental systematics involved in this oscillation search.

Another source of information for oscillation studies is provided by the neutrinos which interact in the rock surrounding the detector. These interactions produce particles which enter the detector from below. This sample is mainly due to muon tracks with about 5% contamination of charged pions and 4% of electrons produced in the 0.5 m layer of water behind the tube planes in the detector. From the exposure of 3.5 live-years from Feb-1983 till Jan-1991 a sample of 659 entering tracks has been collected. Again, this is the largest sample of its kind. In addition to its use to search for extraterrestrial sources, the sample was tested for indications of oscillations. Since no compelling evidence of extraterrestrial origin of this signal is found, we assume in these studies that the entire signal is due to atmospheric neutrinos. Computer simulations based on a variety of models for atmospheric neutrino fluxes, for the neutrino interactions and for the transport of interaction products through the rock, predict that we should observe between 595 to 646 during the same exposure. No indication of muon neutrino disappearance is seen in this data. From a comparison of the observed and expected rates one can exclude the region of $\delta m^2 - \sin^2(2\theta)$ parameter space shown in Fig. 15.

The sensitivity to mixing angle in this analysis is limited mainly by the 20% systematic uncertainty in the flux. In order to overcome this limitation we studied the ratio of the rate of up-going tracks which stop in the detector and the rate of those which traverse the detector and exit. This ratio is flux independent. Since the median energy of stopping muons is 5 GeV while that of exiting ones is 80 GeV, the ratio is sensitive to oscillations. The measured value of the ratio 0.262 ± 0.025 is in good agreement with the predicted value of 0.20 to 0.26 depending on the model applied. Again, we do not see evidence for oscillation. The excluded region of $\delta m^2 - \sin^2(2\theta)$ parameters is also shown in Fig. 15. As one can see, this results rules out a large range of these parameters, including the most favored value to explain the deficit of muon-like tracks in the contained sample. A paper describing these last two techniques and their results is in preparation.

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Figure 14: Visible energy distribution for contained atmospheric neutrino interactions, measured and expected

Figure 15: 90% CL exclusion areas for $\delta m^2 - \sin^2(2\theta)$ obtained from comparison of observed and expected: (a) rate of up-going tracks, (b) ratio of stopping to exiting up-going tracks.

4.3.2 High Energy Neutrino Astronomy

The idea of detecting neutrinos from extrasolar astronomical sources was developed early on. In the 1960 Berkeley instrumentation conference, Greisen [1] outlined a program to detect neutrinos from supernova remnants, including the suggestion of placing a detector in a salt mine. At the same time, Reines et al.[2] were already building a first generation neutrino telescope in the Morton salt mine near Cleveland Ohio. To date, except for the spectacular neutrino burst from SN1987A, no signal of extra-solar neutrinos has been detected.

The large mass of the IMB detector, and the cosmic ray shielding afforded by its great depth, has provided us with the opportunity to use neutrinos as probes of the universe, a role in which they offer unique advantages:

- Being neutral, neutrinos travel in straight lines from source to detector, undeflected by magnetic fields. Of the other two probes currently available, photons and cosmic rays, photons have the same property, but the charged cosmic rays have arrival directions which are homogenized by the galactic fields.
- The low interaction cross-section of neutrinos, while necessitating huge, IMB (or larger) size detectors, gives the ability to probe areas inaccessible to photon-based astronomy. Neutrino telescopes can "see" through optically thick dust clouds and deep into the cores of stars.
- Neutrinos carry information about the regions where they are produced: the energy producing "engines" of stars, and regions thought to be the birth sites of the observed high energy cosmic rays.

The most promising neutrino sources are expected to be binary systems containing compact objects. In the most popular model, matter from a neutron star's companion forms a flat accretion disk in the plane of the orbit, where high energy protons (accelerated by the intense rotating magnetic field of the neutron star) interact. These systems have been observed to be intense gamma ray sources, usually modulated by the neutron star rotation, or the orbital period of the companion, or the precession period of the accretion disk, or a combination of the three.

To date no evidence for high energy sources has been found. In April 1990 at the Singapore ICHEP [3] we reported the results of an analysis of all IMB

Source	Position		A_{eff} m ²
	RA	Dec.	
Cen X-3	11:19	-60.3	430.4
Cir X-1	15:16	-56.9	418.8
Crab PSR	5:32	+22.0	155.4
Cyg X-3	20:32	+41.0	71.5
Her X-1	16:57	+35.3	100.5
LMC X-4	5:32	-66.4	443.4
Sco X-1	16:19	-15.0	245.8
Vela X-1	9:02	-40.5	322.2

Table 3: List of "promising" high-energy neutrino emitting astrophysical sources within the field-of-view of the IMB detector. The effective area of the detector for each source is also listed.

data to April 1989, which showed no significant deviation from the isotropic atmospheric neutrino background.

In a just completed PhD thesis [4] of Ralph Becker-Szendy of the University of Hawaii, new analysis techniques have been applied to the IMB data through the end of 1990 (640 live days). The following discussion derives mostly from this analysis.

Figure 16 shows the arrival direction, in equatorial coordinates of the 640 events in the up-mu data sample. Figure 17 shows the same data but processed to indicate flux excess over a simulated background. The peak at RA=17:15, Dec=+29.5 has a chance likelihood of $\sim 10^{-4}$ at this point but, the likelihood of such a peak appearing anywhere in such a map (essentially accounting for trials) is $\sim 12\%$. Thus this grouping is not especially significant. The sinusoidal line is the galactic plane. Figure 18 shows the same data, but mapped in galactic coordinates.

This data was also analysed for evidence of a signal from the objects listed in table 3. The positions of these sources are indicated in figures 17 and 18. Two of the sources show excesses: Centaurus X-3 and Hercules X-1. The probability of the observed excess being a fluctuation is (correcting for trials) however $\sim 12\%$ for each source.

Because the results reported in [4] are based on all available data, (except

for 51 live days taken in 1991), we do not expect inclusion of existing new data to alter the results presented here. To make further progress in this area, we need the improvements described in section 4.6: more and faster PMTs, and an active veto region around the detector. The faster PMT's will directly improve our angular resolution, while the veto layer will permit us to work with a data sample less contaminated by stopping and contained events, a background which reduces our effective resolution. Background rejection, for point source searches, improves as the square of angular resolution. Quantitative estimates of the sensitivity of the upgraded detector will be given in our forthcoming proposal for the upgrade.

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Figure 16: Map of upward-going muon arrival directions in equatorial coordinates.

Figure 17: Map of significance of flux excess. The highest peak at 17:15, +29.5, had a 12% chance of occurrence (see text).

Figure 18: Map of significance of flux excess converted to galactic coordinates.

4.3.3 Low Energy Neutrino Astronomy:

4.3.3.1 Supernova Signals - Past and Future Supernova 1987A, at a distance of 50 kpc, was just within the sensitive range of current detectors. The twenty four events recorded at the same time in Kamiokande, IMB and Baksan provided unique data for the worlds of both astrophysics and elementary particle physics, and were the subject of hundreds of journal publications.

- **Expected Signal From a Galactic Supernova Explosion.** The large number and variety of physical and astrophysical results that ensued from the 1987A detection in neutrinos has motivated experimental preparations for the next stellar collapse. An event within our own galaxy, closer by a factor of 2-10 than SN1987A, would produce a spectacular signal in IMB.[2]

Since detecting the supernova, we have made many improvements to the detector. These assure that the signal from the next (galactic) supernova would not only have more recorded neutrino signals, but that the quality and content of the data will be much higher. The upgraded data acquisition electronics will now record bursts of events at rates up to 300 Hz, with $\sim 1\%$ deadtime. A significant reduction in electronic noise, allows the trigger threshold to be decreased to about 10 MeV. This lower threshold increases the sensitivity to all types of neutrino interactions, but especially to elastic scattering on electrons, where on average only half of the neutrino energy is transferred to the electron.

Elastic scattering on electrons is the dominant interaction for muon and tau neutrinos. Detecting these particles from a supernova would provide unique information about their properties. The elastic scattering process, due only to the weak neutral current amplitude, has however, a small cross section. Moreover, its signal must be extracted from the accompanying and much more copious inverse beta decays of the electron antineutrinos. For neutrino energies much higher than the electron mass, the scattered electrons recoil in the forward direction in the laboratory frame. This provides powerful background discrimination. Energies of muon and tau neutrinos are expected to be about twice that of the $\bar{\nu}_e, \nu_e$. A cut on electron energy

would then provide another means of separating the elastic scatterings of different flavors, at least on a statistical basis.

Neutrino masses greater than about 100 eV would cause a measurable delay in the arrival time of the heavier neutrinos with respect to the lower mass particles in the main burst. The sharp peaking away from the supernova would provide a means for separating the signal from the background of atmospheric neutrinos. It is estimated that masses up to 50 keV would produce delayed events discernible from the background.

As the largest instrument, which can measure both energies and angles, IMB would provide unique information about muon and tau neutrino properties. We would record a dozen or so of $\nu_{\mu|\tau}$ interactions depending on the source distance.

- **A Search For The 17 KeV Neutrino.** A galactic supernova would offer a unique opportunity to observe a delayed signal from the controversial 17 keV neutrino. If they are stable or if their lifetime is large compared to the source distance, they would arrive with a delay of a few days. However the cosmological requirement that their energy density be consistent with the observed Universe expansion rate implies that a 17 keV particle should decay with a lifetime, $\tau_0 < 1$ year [5]. If one assumes a two-body decay mode, $\nu_{17} \rightarrow \nu X$, where ν is a weakly interacting neutrino with mass < 50 eV, then it would be delayed with respect to the main burst by $\delta t = \frac{m}{2\gamma}$, where $\gamma = \frac{E}{17\text{keV}}$. It is interesting to note that the delay does not depend on the source distance.

If we assume a shortest detectable time delay of 20 sec (conservative assumption about duration of the thermalization phase), then one gets a minimal measurable lifetime τ_0 of about 10 hours. The maximum cosmological lifetime limit of about 1 year would correspond to a time delay δt of 4 hours for $\gamma = 1000$. For periods this short the background of atmospheric neutrinos is insignificant.

- **Search for Temporal Coincidences During The SN1987A Flareup.**

One feature of the data collected in underground detectors in the few hours prior to the neutrino burst remains puzzling. A correlation in time between background events has been claimed [3,4] in the LSD, BAKSAN and KAMIOKANDE underground detectors. The correlation was found to be significant around the time of the yet to be explained burst of events recorded in LSD about 4.5 hours preceding the neutrino signal.

Moreover it has been suggested by the LSD and BAKSAN collaborations that correlations exist between their data and a selected sample of the IMB high energy, "horizontal" events. In order to check this claim, all the events recorded within 2 hours around the LSD "burst" were refitted. The rate of temporal coincidences was then calculated as a function of zenith angle. No significant rate excess was found [1].

- **Supernova Watch.**

In February of this year new burst detection software was installed on the underground data acquisition computer. The software is designed to recognize likely bursts of contained events, and to automatically alert the experimenters of possibly interesting events. The data could then be downloaded via modem and scanned to confirm that the signal was real and not an instrumental artifact.

The installation of the on-line monitor was feasible due to the significant reduction of electronic noise, made possible by the presence of a full-time physicist at the detector site. Prior to this time, the detector was too noisy with high gain tubes that caused cross-talk, and with malfunctioning tubes that produced bursts of small flashes effectively simulating a supernova burst. The burst software also incorporates sophisticated algorithms to differentiate "PMT flashers" from "real" bursts, and thus greatly reduced the rate of false alarms which plagued our earlier attempts at an on line monitor.

If a gravitational collapse occurs in the part of the Galaxy which is opaque to visible light, then with adequate numbers of elastic scattering events we

would be able to indicate the supernova direction. This would allow astronomers to orient detectors studying signals in various regions of the electromagnetic spectrum.

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4.3.3.2 Solar neutrinos The solar neutrino problem is one of the more vexing and important issues in particle physics today. It results from the discrepancy between the observed flux of solar neutrinos and the predictions of the combined standard model of particle physics and the standard solar model.

There is to date one solution for this problem, the Mikheyev-Smirnov-Wolfenstein (MSW) effect[1] [2]. This theory invokes finite neutrino mass and neutrino flavor mixing, enhanced by the high matter density in the solar interior. The MSW predictions, if verified, will have profound implications on particle physics. Non-zero neutrino mass, neutrino oscillations, and lepton number violation would be verified. Such a result must be put to the most stringent of tests.

The accurate measurement of the solar neutrino flux is thus an urgent task for particle physics. The results of the Homestake and Kamiokande experiments yield a flux which is less than a half the value predicted by the combined standard models. Preliminary results from the SAGE gallium experiment, sensitive to even lower energy neutrinos from the main solar cycle, seem also to support this interpretation.

These experiments are extremely difficult ones, due to small sizes of the cross sections, the low energies, and the correspondingly high background levels. An independent verification of the Kamiokande result, at a high statistical level, would constitute a valuable contribution.

The IMB detector is situated in a salt mine, in a geological environment with unusually small contamination by heavy radioactive isotopes. It is estimated that a 2.5 meter water layer between the cavity walls and the fiducial volume is needed as a veto region for the radiation originating in the surrounding rock. IMB's fiducial volume of 3.3 kton as compared with 0.68 kton for Kamiokande implies a fivefold enhancement in exposure.

During the past year we have been studying the feasibility of an ^8B neutrino experiment with the IMB detector. Detector noise has been significantly lowered, allowing the detector to trigger at about 10 phototubes within 50 ns (~ 10 MeV). The results thus far are encouraging. None the less, there is still insufficient light collection and too much noise associated with the detector electronics (which were designed to function in the 100 MeV and higher domain).

We plan to continue in this effort and have a good expectation of success once the proposed improvements (Sect.4.6) are implemented.

The key to success in any experiment is the reduction of backgrounds to the level where the signal can be extracted. There are three main sources of background for this work:

1. Cosmic ray induced radioactivity. Radioactive isotopes are produced in the detector by traversing muons. These isotopes subsequently decay with the emission of gammas and betas. One can distinguish two processes:
 - Nuclear spallation. This process involves the fragmentation of an oxygen nucleus by a high energy muon. Several long lived isotopes such as ^{12}B or ^{12}N can be produced. These isotopes have decay products with maximum kinetic energies ranging between 8 and 20 MeV and can imitate a solar neutrino interaction. We estimate the spallation induced background in the detector at about 100 events per day per 3300 tons.
 - Capture of stopping muons or pions by an oxygen nucleus. This results in the creation of a radioactive isotope such as ^{16}N . From the Kamiokande work, we can estimate this rate at about 5 events per day per 3300 tons.

Both of these backgrounds can be efficiently eliminated by associating the event with an earlier, near-by muon track. We estimate that this procedure reduces the detector sensitivity by only $\sim 20\%$.

2. Inherent detector radioactivity. We expect that radioactivity in the water will be the primary source of detector generated background events. A mass spectroscopy study of the IMB supply water reveals concentrations of Uranium and Thorium that are only about 15 percent of those present in the Kamiokande water supply. This gives us great confidence that this background will be manageable.
3. Environmental Radioactivity. Gamma rays from the rock and material surrounding the detector could be a source of background. We have not yet made a detailed study of this problem. We note however that previous measurements in our mine and elsewhere have shown that the salt

environment is unusually clean, containing much less Uranium and Thorium than typical surface or underground sites. In addition, the 2.5 meter thickness of water in between the detector walls and the fiducial volume should absorb most gamma rays, and is in fact a live anticoincidence.

Some of our early efforts at software filtration and data extraction are described in Sect.4.4.2.3. We are at a very early stage in the analysis, but the initial results are encouraging. In Fig. 19 the time interval between a contained event and a preceding muon is plotted versus the number of phototubes lit by the contained event. The large concentration of small events at short time intervals shows evidence for the spallation process.

A better photon sensor coverage seems indispensable in order to make full use of the large IMB volume. This would allow us to reduce the low energy threshold and to improve reconstruction of the electron direction, which is essential for effective background rejection. The improved timing resolution of the current generation of phototubes would reduce the vertex position uncertainty, which determines the size of the fiducial volume. Good vertex localization also decreases the deadtime caused by cuts, which are necessary for spallation background reduction.

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Figure 19: Observation of spallation events in the IMB detector

4.3.4 The Search for Muons from Cygnus X-3

Since 1985, there have been persistent (and controversial) reports of correlations between muon measurements made deep underground, and the direction and orbital period of Cygnus X-3.[1,2] The combined data collected from 1981 to 1989 by Soudan collaboration [3] provide a 2.7σ excess in the phase interval from 0.6 to 0.9 and a 3.2σ excess in a smaller interval 0.70 to 0.75. Nusex collaboration observed a muon excess in the phase interval 0.70 to 0.80 in years 1982 - 1984 and 1987 - 1988 [4]. The chance probability of the excess is estimated to be 0.0007.

Similar results have been published for episodic observations associated with the periodic increase in activity of Cygnus X-3. IMB, for example, observed a 4σ muon excess in the phase interval 0.5 to 0.6 in data collected at the time of October 1983 large radio burst [6]. (This observation was not corroborated by other detectors operating at the time.) Soudan [5] reported a significant signal associated with the increased Cygnus X-3 activity in October 1985.

We also searched for possible correlation with Cygnus X-3 during radio flares in June and July of 1989 [7], as well as an August flare in 1990. No evidence for pulsed emission was found. The 90% c.l. upper limit on the muon flux correlated with Cygnus X-3 was found to be $3 \times 10^{-10} \text{ cm}^{-2} \text{ sec}^{-1}$ during the period 24 May to 23 July 1989 and August 7 to August 28, 1990.

During the recent Cygnus X-3 radio flare (January 1991), the Soudan group again observed a signal correlated with this source.[8] Since IMB was operating during this period, we are analyzing the muon data from that period.

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4.3.5 Dark Matter

The past decade has witnessed an ever strengthening connection between particle physics and astrophysics, the observation of neutrinos from stellar collapse being perhaps the most dramatic example. Particle physicists and astrophysicists are looking to each other in their attempts to resolve outstanding problems in both fields. Continued interest in supersymmetric theories, in which each "regular" particle of the Standard Model has a massive and as yet undetected partner, has provided possible answers to many questions. Such weakly-interacting massive "sparticles" would have been produced during the early universe. Their present energy density may be high enough (depending on the unknown mass of the particles) to solve the dynamical problems of astrophysics while at the same time supplying the missing new particles of supersymmetric unification theories. Due to their large mass and weak coupling to ordinary matter, most WIMPs are inaccessible to accelerator experiments. Many authors have estimated the present abundance of such WIMPs, and find that most interesting varieties would accumulate in massive bodies like the earth or especially the Sun. Trapped by scatterings with the solar plasma, WIMPs would sink to the center of the Sun and eventually pair-annihilate. The rate of annihilations is calculable under the assumption of equilibrium between capture and annihilation. The annihilation products of WIMP annihilations should include the heavy fermions of the Standard Model (τ , c , b , and t), all of which decay weakly giving neutrinos. The neutrino energies in such a scenario are typically 10-20% of the parent WIMP mass, when heavy quark fragmentation and interaction with the solar medium are taken into account. For many interesting WIMP candidates, such as photinos, the flux of these GeV energy neutrinos is comparable to or higher than the ambient atmospheric neutrino flux.

The IMB detector is sensitive to neutrino fluxes from 20 MeV to 10 TeV via three different mechanisms, each with its own bandwidth of sensitivity. Contained events originate from neutrinos in the region $20 \text{ MeV} < E_\nu < 5 \text{ GeV}$. Entering muons produced by neutrinos outside the detector and going upward (downward going neutrino-induced muons are masked by much more numerous cosmic rays) are also collected. Upward-muons which stop inside the detector originate with muon neutrinos between 2 GeV and 50 GeV, while those which traverse the detector and exit are induced by high energy neutrinos of up to 10 TeV. Above about 10 TeV, the Earth becomes optically thick to neutrinos, and

the linear rise of the neutrino cross-section is quenched by the W propagator. Both contained and entering events should point back to their parent neutrino's direction with some degree of accuracy, but the present low level of statistics does not justify tight cuts on the direction. Even so, previously published IMB limits (LoSecco, et.al., Phys. Lett., **B188**,388 (1987)) are within a factor of 2-4 of ruling out photinos as a viable dark matter candidate. Of course, the presence of a signal at or below this level cannot be ruled out either. With a larger data set, the enhanced resolution and particle identification now possible (equal numbers of ν_e and ν_μ should be produced in WIMP annihilations, but the background of ν_μ is about three times higher than ν_e), together with its large mass, IMB is the world's best facility for probing this frontier of particle physics.

4.4 Data Analysis

4.4.1 The Data: A Flood of Gigabytes

It is both amusing and instructive to tally the flood of data the IMB-3 detector has generated. From first turn-on (5/4/86), to the final day of operation (3/27/91), the detector has recorded 21,267 hours, or 886 days of data. The event rate was dominated by downward energetic cosmic ray muons, which triggered the system about 3 times per second. This translates into 2.2×10^8 triggers, and at an average of 2800 bytes per event, a total of 643 gigabytes!

Prior to 3/4/89, storage limitations mandated that only a fraction of this data be kept. After this date, all data were kept, thanks to the huge capacity of 8 millimeter video cassettes. In the pre-8mm tape era, we generally ran in a mode where only events with $NT1^3 < 900$ were kept. This excluded most downward cosmic-ray muons. However, for calibration and other purposes, every 16th event was kept, regardless of the value of $NT1$. Other classes of data were also saved, e.g., events which were classified as upgoing by the on line software.

Beginning 3/5/89, all data were saved (opening new channels of study such as muon astronomy (see Sect.4.3.4)). Thus we have 407 days of livetime, or roughly 290 gigabytes of data for which every event was saved.

This tape library represents a valuable resource which has as yet been only partially tapped for its physics content. Among the topics are proton decay, atmospheric neutrinos and their implications with respect to neutrino oscillations, limits on extraterrestrial neutrinos and dark matter etc., Cosmic Ray studies, and, if the right techniques can be found for noise rejection, solar neutrinos. Our work towards extracting these results is the topic of the remainder of this section.

4.4.2 Analysis of Raw IMB Data

4.4.2.1 Search for Contained Events Each contained event, i.e., one which shows no evidence of being produced by a (charged) particle entering from outside our fiducial volume, is presumed to be a candidate for a proton decay or other interesting physics, and is saved.

³ $NT1$ is the number of PMT hits that are visible in the time window of each event.

The process of isolating the $\sim 1.3^4$ contained events per day out of the raw event rate of ~ 3 per second is accomplished with 3 passes of software filtration, and further purification by physicists/students who look at each surviving event with specially designed graphic software. In order to prevent the loss of events which are close to the edge of the detector's fiducial volume, we initially keep those which reconstruct as much as 50 cm outside. The 50 cm zone corresponds to the size of our vertex reconstruction uncertainty. Events that are in fact outside are rejected at the next analysis stage, as we merge our sample with that of the other analysis group (the "East Coast", our Boston University (BU) collaborators).

The data analysis chain described above is roughly replicated by the BU group. The "East Coast" and "West Coast" (i.e., UCI) analysis chains are completely independent up to this last stage where we look at each other's data samples and combine our results. Since the analysis chains are independent, the overlap of our contained event samples allows us to estimate the event recovery efficiency:

- For $NT1 \geq 70$, the combined efficiency is 90%.
- For $NT1 < 70$, the combined efficiency is 54%.

Analysis of IMB-3 data is proceeding. All data has been processed by our software. The next step, the initial scanning by physicists/students, has been completed for all data through 1990, while the 1991 data is approximately 30% finished. For reference, the detector livetime for each analysis period is presented in table 4.

The next step for the 1990 and 1991 data will be the more critical, re-scanning by physicists and the finalization of the contained event sample (the "DST" or data summary tape). This will be completed (for $NT1 > 70$) by the end of 1991.

• Proton Decay Candidates and Neutrino Interactions

In the search for possible proton decay events, and for neutrino interactions in the detector, the contained event sample is divided into low and high energy regimes. Low energy are those with fewer than 70 tubes (i.e.,

⁴This breaks down as 1.1 events per day for $NT1 \geq 70$ (larger events) and 0.2 per day for $NT1 < 70$ (smaller events).

Time frame	Data Tapes	Live time (days)	$NT1 \geq 70$ status	$NT1 < 70$ status
May 86–Dec 88	2023–3634	376 days	DST completed	DST completed
Jan 89–Dec 89	3635–4000	227 days	DST complete	Scan complete
Jan 90–Dec 90	4001–4216	221 days	Re-scan complete	Scan complete
Jan 91–Mar 91	4217–4277	51 days	Scan in progress	
Totals:	2255 tapes	875 days		

Table 4: Livetimes and contained event analysis progress for IMB-3 data. Analysis steps are (1) software processing, (2) scanning by students or physicists, (3) re-scanning by physicists (4) DST compilation in conjunction with the “East Coast” analysis group, (5) final analysis and publication of results.

$NT1 < 70$). The high energy regime consists of those events with $NT1 \geq 70$.

The scanning and DST compilation for the higher energy events is relatively easy, and the final data sample will be available shortly. The $NT1 \geq 70$ cut means that for this analysis we have a software threshold of, very roughly, 70 MeV⁵

Analysis of the lower energy events (ie, $NT1 < 70$) is progressing. The software processing and initial scanning is completed. The second, more critical (and time consuming) examination of the data has been done only for data through the end of 1988.

In order to accomplish our minimum goals for the proton decay and contained neutrino search, the following activities are required:

- Completion of scanning of 1991 data.
- DST compilation of $NT1 \geq 70$ tube data for 1990 and 1991.
- DST compilation of $NT1 < 70$ tube data for 1989, 1990 and 1991.
- Re-calibration of data for 1989 through 1991 (see section 4.4.3).
- Detailed examination of the selected events.

⁵The energy threshold that the 70 tube cut represents is not a precisely defined quantity in a large Čerenkov detector. The energy depends on the event’s location in the detector, direction with respect to the walls, development (showering vs non-showering), and date (since the high voltage settings of the tubes have undergone adjustments over the years).

It is our expectation that for the $NT1 \geq 70$ tube data, the above tasks will be comfortably accomplished by the end of 1991. Additional time will be required for the $NT1 < 70$ tube events.

4.4.2.2 Search for Upward Going Events The IMB detector sees upward going events more than 95% of which are due to muons with energies up to 1 TeV. The flux is about 0.5 per day, for events with zenith angles in the range of 90 to 180 degrees.

This sample is used to search for neutrino oscillations and for astrophysical sources of high energy neutrinos. Preliminary results of these searches are presented in Sect. 4.3.

The construction of a "West Coast" upward-going event sample was conducted at UCI for the IMB-1, IMB-2 and part of the IMB-3 data sets, and is now being continued at Louisiana State University and University of Hawaii. The graphical scanning of IMB-3 data for upward events has been recently completed at these institutions, providing a data sample of 875 days, in addition to the IMB-1 and 2 combined livetime of 455 days.

4.4.2.3 Solar Neutrinos and Spallation The creation of a data analysis chain for very small events ($NT1 < 30$) is a new UCI project. While it is easy to write software that finds such events, it is much more difficult to do so while rejecting the various backgrounds. These include muons that "clip" a corner of the detector, defective PMT's that emit short flashes of light, cross-talk and other electronics artifacts, and finally, spallation events. (The electronic background will be eliminated when we return the detector to operation. See Section 4.6.)

The approach we are taking to this problem is standard: we have made modifications to the IMB monte-carlo to generate low energy neutrino events. The monte-carlo energies are based on fluxes from Bahcall [1], but with a 7 MeV low energy cut, since events below 7 MeV have a very low probability of triggering the detector. Figure 20 shows $NT1$, the number of tubes, for the simulated events. The monte-carlo events are passed through prototype data filtration software to determine the save efficiencies. Real data is then passed through the same software, to find the efficiency with which uninteresting events are rejected. The filtration algorithms are then tuned to maximize the ratio of the monte-carlo signal to the real data noise.

Figure 20: NT1 (number of tubes) distribution for simulated solar neutrinos with $E_\nu \geq 7$ MeV.

Having had some success in creating filtration software, we are now working on using spallation events as a test signal. We know that there is a 0.1 % chance [2] that a low-energy spallation event will occur in the ~ 1 second after a high energy muon passes through the detector – an occurrence which happens roughly 3 times per second. Our new graduate student, John Breault, is presently writing software to identify these spallation events, with the eventual aim of using them to improve our filtration and event reconstruction algorithms.

Because some spallation events can be indistinguishable from the solar neutrino interactions for which we are searching, we plan to reject them on the basis of their proximity in time and position to their through-going muon parent's trajectory. After each through-muon, a cylindrical "dead zone" coaxial with the muon track will be constructed (in software) to reject possible spallation events. The radius of the cylinder is determined by the accuracy with which we can reconstruct the candidate event's location, and the accuracy with which we can locate the muon track. Currently, our software has a position resolution of 3 meters for solar neutrino monte-carlo events, and 2 meters for the through-going muons. The modifications proposed in Sect. 4.6 should reduce these resolutions.

In order to independently check on the solar neutrino detection and event reconstruction capabilities, a small radio-active source has been built and put in the detector for a test run. The source consists of a nickel can, 12 cm in diameter, with a 0.1 micro-Curie Cf-252 source at its center. The can has small holes to allow water to enter when it is lowered into the detector. The Cf source emits about 500 neutrons per second, which are thermalized by the water, and are captured by the nickel which then emits ~ 9 MeV gammas. We estimate ~ 55 gammas per second from the nickel can. The gammas produce a electromagnetic cascade which will be visible to the detector if enough Čerenkov light is produced.

A total of three hours of with-source livetime was taken and analysed. The source was clearly visible, and its position could be reconstructed with the three meter accuracy expected. We were unable, however, to discern the shape of the 9 MeV line because our NT1 threshold could not be lowered without swamping the data acquisition system with accidental triggers. Using this data, we can estimate our trigger efficiency for 9 MeV gammas to be about 1.4 %, when our threshold is $NT1 \geq 11$. Again, the modifications proposed for the detector (Sect. 4.6) will make this line visible, providing, in addition, a new and lower energy calibration point.

While we have made progress towards the eventual goal of extracting solar

neutrino events from the existing data, it remains to be seen whether we will be able to reject spallation events efficiently without losing too much fiducial volume, and whether we will be able to deconvolve the effects of our trigger threshold and filtration software on the flux values we eventually obtain. Perhaps it is most realistic to view this work as a "dry run" preparing us to efficiently use the data from an upgraded IMB which will be measuring low energy events from the Perry Reactor and from the sun. With the upgraded detector many of these tasks will be much more tractable.

References

- [1] John N. Bahcall, Neutrino Astrophysics, Cambridge University Press, 1989
- [2] Masayuki Nakahata, Search for Boron-8 Solar Neutrinos at Kamiokande-II, PhD thesis, University of Tokyo report UT-ICEPP-88-01 (1988)

4.4.3 Improved Calibration and Energy Determination

The improved quality of the IMB-3 data required changes in the calibration process. For example, the dynamic nature of the population of dead or low gain PMTs must be more carefully included. Since the beginning of 1989 maintenance periods have been concentrated into a few short stretches of down time per year to maximize live time. Because of this the total photo-cathode coverage of the detector has varied by as much as 5% in periods as short as a few months, and, due to the pattern in which repair proceeds, there have occasionally been local variations of photo-cathode coverage as much as 20%. Most PMT problems are associated with failures of resistors in the dynode chain, a problem associated with a bad batch of components. This problem was being corrected as strings are removed and serviced. This and other effects prompted a revision in our calibration and event energy determination procedures.

A number of steps have been taken. The first is a more detailed Monte-Carlo simulation of light transmission which attempts to more realistically simulate the observed light distribution. This is made practical by the dramatically increased computer resources available since the writing of the original IMB-3 Monte-Carlo. This new simulation includes more realistic models of many portions of the detector, including the frequency dependence of the absorption in water and the response of the wave shifter/PMT combination. The primary goal of this code is to reproduce the intensity versus light path length measurement. A secondary goal is to reproduce the light scattering observed in the data with a more realistic model of light scattering. While light scattering is only a secondary factor for the calibration of observed energy, it can play an important role in pattern recognition.

Besides improving the Monte-Carlo simulation of the detector the data collected to calibrate the observed energy has been improved. Calibration of the IMB-3 detector is done by determining the amount of light observed from an average cosmic ray muon. Previously the energy calibration data have been composed of the average number of photo-electrons deposited as a function of path length from a through going central muon. Data was only collected for vertical muons which entered the central portion of the top plane of the detector. In an effort to remove any inhomogeneities in the photo-tube coverage the amount of information being used from through-going muons has been increased. The first major change is that all muons passing through a fiducial volume inside of the

detector are now used for the energy calibration. Further the average number of photo-electrons as a function of distance from the muon track and the angle of incidence of the light to the tube is also collected.

The current method of energy determination which has been used since IMB-1 treats the detector as a calorimeter. The energy of an event is calculated based upon the total number of photo-electrons observed with small correction for light attenuation and photo-tube density. The conversion of photo-electrons to energy is achieved by comparing the average number of photo-electrons observed per meter of track for cosmic ray muons passing through the IMB-3 with the expected number of photo-electrons calculated by a Monte-Carlo simulation of the cosmic ray muon flux. This gives a coefficient to convert total photo-electrons to track length which can then be converted directly to energy. Currently this coefficient is approximately 0.8 observed photo-electrons per MeV. Because of the extreme clarity of the water in IMB-3 this is the preferred method of energy determination for a "perfect" detector, or in other words a detector with uniform PMT coverage. Prior to 1989 the IMB-3 detector in fact had uniform PMT coverage. Unfortunately due to the anisotropic nature of Čerenkov light this method is less accurate for a detector with a non-uniform PMT coverage.

The method of energy determination now being developed is based on the idea of a "guided Monte-Carlo run." In a ring imaging Čerenkov detector all light may be treated as originating from short segments of charged particle track. In Monte-Carlo simulations of our detector short segments of track are used to project light onto the PMTs. For the purposes of energy determination segments of track are used to project light onto the PMTs and the distribution of track segments necessary to explain the observed light distribution is fitted using the maximum likelihood method. As many segments of track as are necessary to fit the observed light distribution are used. At the completion of the fit there is an expected light distribution calculated from the observed light distribution, plus an estimate of the energy based on the total length of track segments necessary to produce the expected light distribution. The method of energy determination is an improvement because it is unbiased by inhomogeneities in the PMT coverage. It also has the advantage that it not only determines the total energy of an event but also direction of energy flow which makes it ideal for use in an invariant mass analysis of events for proton decay.

In the future the basic method being employed as an energy calibration

will be evaluated as a method of particle identification and also as a way to estimate the number of tracks.

4.4.4 New Event Scanner

About two years ago it was decided that the visualization software which had been used since the beginning of the IMB-3 experiment had become the major bottleneck in the data reduction chain. As a consequence new computer hardware was acquired and became available in mid 1990. The visualization software to exploit this new hardware has been developed and has reduced the amount of hand scanning time by an order of magnitude. This new "scanner" has become a powerful tool for quickly sifting through large amounts of data. Tapes which in the past would be rejected as unusable due to intermittent detector problems are now managed without difficulty since a person can look at events quickly and skip past the affected periods of time. Due to the new scanning software we have been able to use live time from tapes that would be otherwise rejected simply because scanning those tapes would take far too many man hours.

During the development of the new scanning software it also proved worthwhile to develop a more systematic method of storing information about saved events. This was primarily necessitated by having to move data between machines with incompatible file structures. We have developed an extendable data packing scheme that is compatible across various machine architectures.

4.4.5 Data Archival

Effective utilization of data from the current and earlier experiments requires proper archival storage of the data. Rapidly evolving storage technologies, present both an opportunity and difficulties. IMB-3 data, for example, was collected on two tape technologies, giving us an extensive (and space consuming) library of nine-track, 6250 bpi tapes, and a much more compact library of 8mm video cassettes. The least costly solution to the archival problem will be the copying of the older tapes to the 8mm format. A student will be employed part-time during the next year to carry out this task.

We have also considered transferring the raw data from IMB-1 and IMB-2 to the 8mm format. This however is problematic; the data are in an obsolete format which would require considerable time and effort to translate. This, plus

the lower quality of the data from these earlier versions of the detector and the age of the data tapes, suggests that this task would be unproductive.

4.5 The Laboratory

This section describes the detector liner problem which developed in late March 1991, and the physical effects this had on the detector and laboratory. It also outlines the actions taken to date, the work yet to be done to stabilize the detector cavity and laboratory, and to empty the remaining water from the detector. It is anticipated that this process will be completed in early 1992. A supplemental request for funds to cover the costs of these activities has been submitted (July 1991).

4.5.1 Background Information

The IMB detector relies on a double liner system to contain the detector water and to prevent this water from coming in contact with the surrounding material, most of which is salt. For some months it had been apparent that the outer liner, which is not accessible to inspection or repair, was developing leaks and was thus no longer functioning at full efficiency. Our ability to keep the environment surrounding the detector free of this fresh water is limited by our pumping capacity, currently 25 gpm (modulated by a pumping schedule which is tied to Morton Salt personnel being present in the mine).

Since its completion in 1981 the detector has had small leaks, averaging about 0.5 to 1 gpm. The nature of the liner material (high density polyethylene) precludes permanent repair of holes and tears, as heat welding, the only permanent sealing technique, is not feasible under water. Our patching technique has employed a reinforced putty-like rubber compound forming a patch held in place by the mastic of the putty and by the water pressure itself. These patches require periodic attention as evidenced by the slow increase in leak rate with time after their attachment or repair. To service these patches and to inspect the liner for possible problems, a team of divers has been employed for approximately monthly maintenance dives. This has been a standard procedure since the detector became operational.

4.5.2 The Leak

Between the 25th and 26th of March of this year a severe leak developed, increasing the leak rate from approximately 1 gpm to over 40 gpm in a matter of hours. Under normal conditions, the divers would have found and repaired the

problem in a short time. Unfortunately the conditions were not normal: It was the week preceeding Easter Sunday and the mine was to close for a scheduled holiday and maintenance period. This prevented general access to the mine from 3/27 to 4/2. Servicing of one of the two hoists precluded all underground activities during this period except during a 5 hour window on 3/29. Further, the emergency visit of the dive team arranged for 3/27 was canceled when the full complement of divers could not be assembled. (Safety considerations require a full diving team.)

An inspection dive during the window on 3/29 showed that significant damage had already been done to the detector and the liner. The water level in the pool had fallen only an additional 5 inches (since 3/27), an additional 15,000 gal for a total loss of 72,000 gal. However, the pool had been invaded by heavy brine from outside (showing that a much larger amount of water had in fact been lost) and the liner had formed a bubble at the bottom, presumably due to the presence of heavy brine under or between the liners.

4.5.3 Immediate Actions

Our initial concern was for the safety of personnel and the laboratory. We inspected the facility with the help of the mine supervisory personnel. The lab and the catwalk surrounding the pool were deemed safe, but the washout under the utility room which contains the water processing equipment, the electrical sub-station and miscellaneous equipment was problematic, and it was felt that immediate measures were needed to resupport this area. Morton recommended the mining contractor firm of Dynatec, and a temporary support scheme was developed and implemented. MSHA and (Ohio) State Mine Inspectors were by this time on site and concurred with the actions taken. In addition, exploratory holes were drilled in our access tunnel. Some sub-surface cavities were detected and appropriate actions taken to support equipment in the area.

Our next concern was for the experimental equipment, especially the PMTs. With the introduction of brine into the detector, the PMTs, designed to be neutrally buoyant in pure water, began to float, tangling many of the adjacent strings and beams. It was apparent that the safety of the PMTs, and any subsequent inspection and repair of the liner would require their removal. This was a major undertaking requiring nearly 4 weeks of 24 hour shifts and employing personnel from 5 of the collaborating institutions. The PMTs, wave

shifters, beams, etc. are now safely out of the detector, boxed and/or palletized, and temporarily stored in the mine near the lab.

The electronics, computers, and electromechanical equipment are in the process of being serviced to minimize any deterioration.

4.5.4 The Current Situation

Our goal is to pump the detector dry and to determine the extent of the damage to the existing liner system and to the detector cavity. Additionally, we need to further support the utility room and its equipment, and find safer storage for the PMTs, beams, etc. presently stored outside our lab area.

An on-going labor-management dispute (now developed into a full strike) has restricted the time one can work in the mine to about 6 hours per day, and has curtailed Morton's maintenance of vital equipment such as the water pipes in the shaft. This has limited our ability to proceed in some areas at the hoped for speed, but progress has been steady if slow.

The pool's water level is now about 17 feet below its normal full depth of 65 feet. Removal of the water has been slowed by the above mentioned factors, and is now limited by the need to remove the materials behind the bulkhead as we lower the water level.

Salt dissolved by the fresh pool water has resulted in voids in the cavity containing the pool and in other areas of the lab, e.g., under the utility room. These regions must be refilled, with grout or other materials, in some cases such as the utility room immediately, and in the case of the pool cavity as the detector is refilled.

4.5.5 The Plan for Emptying the Detector

A limitation on emptying the pool is the need to support the 65 ft tall by 18 ft wide bulkhead which keeps the backfill materials in the construction ramp out of the pool cavity. The bulkhead is supported by many 4 ft rock bolts drilled into the salt walls of the ramp. These supports have most likely been badly eroded by the fresh water released from the detector. The extent of the erosion and damage must be assessed as the water level is lowered. This in turn requires the removal of several hundred tons of gravel and salt from behind the dam. Equipment to move this material has been researched and specified, and we are in the process of getting bids. It is expected that the equipment will be on site in

early Sept. As these materials are removed from behind the bulkhead, support will be reestablished, making it safe to lower the water further.

A second limitation on the emptying of the pool is the waste water line to the surface. This is a pipe which was installed by Morton in the early sixties and which they no longer use. The pipe was originally designed to transport fresh water into the mine. Its age combined with our pumping of corrosive brine has led to a nearly continuous cycle of leaks and repairs. Major sections of the pipe now need to be replaced and this cost was reflected in the submitted budget.

4.5.6 Other Remedial Actions

Other areas of the lab and its equipment require immediate attention:

- The materials removed from the bulkhead areas will be used to backfill and resupport the utility room.
- The subsidence in the access tunnel must be backfilled before construction equipment can be moved into the lab. This will be done with the use of Morton Salt equipment and also with the material handling equipment purchased for the bulkhead work.
- Equipment temporarily stored in the mine is not in a safe and secure location. In addition, the combustible nature of the materials constitutes a safety hazard according to MSHA and Ohio state inspectors. The PMTs will be stored in the lab and in our access drift (after it is repaired). The beams, wave shifter plates, and other items must be stored in another area of the mine and properly fenced.
- The liner and detector cavity will be inspected during the emptying to determine the extent of the damage. This is necessary to insure that the structure does not collapse, and to estimate the costs of future repair.

4.5.7 Technical Support

It has become apparent over the past year that we have insufficient technical support to maintain the array of electromechanical equipment which is needed to support the laboratory. It has been necessary to use emergency visits by collaborators, and to employ expensive outside vendors to do routine maintenance

previously handled by our in-house, underground staff. Even with this additional source of assistance the amount of deferred maintenance has increased. This is an inefficient use of students, physicists, and equipment, and a costly way to do many of these jobs. To alleviate this situation, we plan to employ an additional technician, bringing the technical staff to a complement of 3 persons.

We are also studying the possibility of having several members of the collaboration OSHA certified to dive in the detector. Such a backup diving team would help to prevent a reoccurrence of the problem encountered last March when we were unable to mount an urgently needed dive team.

4.6 Future Plans

Our plan is to bring the detector back on line as quickly as possible, with extended capabilities for proton decay and other physics. Our ultimate goal is to take advantage of the unique geographical location of the detector and perform one, possibly two long base line neutrino oscillation experiments: the first with reactor neutrinos using the nearby Perry nuclear power plant, and the other with neutrinos from the new main injector at FNAL. Both experiments would greatly benefit from the detector enhancements outlined below, and both require some development using the enhanced detector as a test facility. The improvements will also enable us to begin a more sensitive search for proton decay, and to pursue our other physics goals (e.g. atmospheric neutrino oscillations, solar neutrinos, supernova neutrinos) while the long baseline experiments are being developed.

We must begin to rebuild quickly to prevent the deterioration of the facility and to protect the large investment which has been put into its development. In addition, we must be concerned with the dissipation of the collaboration and the technical staff with its accumulated expertise.

Many of the ideas presented below have been high on our priority list for a long time and need no further study before they can be implemented. Others are relatively new and require development.

4.6.1 Proton Decay/Detector Upgrades

A major goal for the immediate future continues to be the search for proton decay. As discussed in Sec.4.2.1, recent LEP measurements of the electro-weak and strong coupling constants have been used to predict new proton decay lifetimes for various unification schemes. Some of these theories are already ruled out by the current lifetime limits. Others predict limits in the range now being tested by IMB. To test these ideas, it is critical to continue the search. In this section we discuss detector upgrades which will significantly improve our exposure rate (i. e., kton-years per year), improve our sensitivity to low light producing decay fragments, and which will greatly enhance our background discrimination.

- **Anticoincidence**

Our detector has 6800 tons of water inside the tube planes, but we use only 3300 tons as fiducial volume for the proton decay search (and for most other physics). There are several reasons for this cut, but one of the most important involves the determination of whether or not an event is totally contained in the volume. The addition of an anticoincidence layer outside of the tube planes would positively identify an entering or exiting track and allow us to expand our fiducial volume. The gain from this additional information will vary from mode to mode, but we estimate a factor of at least 1.5 in additional fiducial volume.

- **New digitizing electronics**

- Many of the proposed modes of proton decay involve a muon either as one of the primary products or as the result of a secondary decay. (This is also the case in the signatures for the signals or backgrounds for a variety of other signals we study.) Due to limitations in our present recording system, we are only about 65% efficient in observing muon decay. We can increase this efficiency by a factor of about 1.3 (to nearly 100% for μ^+) by replacing our present digitizing electronics with new commercially available versions. This improvement has a compound effect: not only is our efficiency for observing these modes increased, but the potential backgrounds for other modes are reduced.
- A major source of systematic uncertainty in our search for proton decay arises from energy calibration. We currently extrapolate our detector's response to the energy range of interest for proton decay (100 - 1000 MeV) from dE/dx of through-going muons (a few GeV deposited from ≥ 100 GeV muons). The new electronics and increased light collection (described later) will allow us to calibrate more accurately on stopped muons and on muon decay electrons, and for the first time, on radioactive sources. These are much more suitable to our energy range of interest and will assure more accurate calibrations from 10 MeV to 2 GeV.

- **New photomultiplier tubes**

Our light collection area is marginal for some of the low light level decay modes. The addition of 2000 new 8 inch tubes will have several beneficial

effects.

- The timing of the new generation of tubes is significantly better than the tubes we currently employ (2.5 ns FWHM vs. 8 ns FWHM). This factor of >3 improvement will greatly improve our track identification algorithms and improve our vertex localization. The improvement in vertex resolution in conjunction with the surrounding anticoincidence will yield an increased fiducial volume.
- The increase in light collection will lower our threshold, increase the number of pixels in a given track and improve our ability to distinguish showering from non-showering tracks.

• Uninterruptible Power Supply

We presently experience a dead time of about 15% from loss of primary mine power. A motor generator/UPS system which can supply power during these intervals is a very cost effective way of gaining back this lost exposure.

The combination of these factors will allow us to improve our sensitivity to the mode $p \rightarrow \nu K^+$, for example, by about a factor of three, which will make us more sensitive than any other existing detector.

4.6.2 Long Baseline Reactor Neutrino Oscillation Experiment

The IMB detector is 12.9 Km from a 3600 MW commercial nuclear power plant (The Perry Reactor). This happy coincidence affords us a unique opportunity to perform a long baseline neutrino oscillation experiment ($\bar{\nu}_e$ disappearance) and represents an extrapolation of our extensive experience in reactor neutrino physics. We have an existing deep underground laboratory, a very large active water Čerenkov detector with suitable light collection and a low background environment. The conditions are ideally suited to the experiment, and would cost many millions of dollars to reproduce.

Our current plans involve the addition of approximately one kiloton of liquid scintillator in a vessel at the center of the water detector. This scintillator would be loaded with a nuclide such as Cl or Gd which has a high neutron

absorption cross-section and a high energy (~ 8 MeV) deexcitation γ . The scintillator acts as both target and detector of the $\bar{\nu}_e$ (and product neutron) while the water Čerenkov detector acts as a massive, active/passive shield. The expected signal from such a configuration would be about 10 neutrino interactions per day. (Also under consideration is a alternate scenario utilizing a loaded water target in the center of the detector.) The results from this experiment would dramatically improve the explored region of δM^2 versus $\sin^2 2\theta$; we would reach a δM^2 of 10^{-4} eV² and a $\sin^2 2\theta$ of about 10^{-1} . This would be an improvement of two orders of magnitude in δM^2 from previous experiments.

We anticipate development work toward this experiment to proceed while the proton decay search continues. We will directly measure backgrounds in the detector, develop the particular scintillator and neutron capture material best suited to our needs, and develop the vessel needed for the scintillator.

4.6.3 Other Physics

The modifications which are necessary for enhanced sensitivity to proton decay significantly enhance our detector for other physics.

- **Atmospheric Neutrino Composition**

As discussed in Sec.4.3.1, IMB was the first of several (IMB, Kamiokande and FREJUS) detectors to note that the measured ratio of ν_μ to ν_e is less than expected. Kamiokande has interpreted this result as a possible oscillation of the ν_μ 's. Our modifications will improve our discrimination between contained showering and non-showering tracks reducing our systematic error in making this determination. The veto region will eliminate possible selection effects due to entering tracks, the new electronics will improve our muon decay identification, the enhanced light collection will produce better pattern recognition, and the increased fiducial volume and efficiency will nearly double our exposure rate.

- **Solar Neutrinos**

The solar neutrino "problem" has been in the literature since the Homestake detector was turned on in the mid-60's (see Sect.4.3.3.2). The Kamiokande detector has now also observed fewer 8B neutrinos from the

sun than that expected from the standard solar model, this time with a direct counting experiment. This extremely difficult measurement deserves to be tested. The salt mine location is an especially low background environment (our input water, for example, is 2.8×10^{-2} pCi/l, a factor of 6 below the Kamiokande level), well suited for this application. Our enhanced light collection should allow us independently to check this result. The active veto will allow us to track through-going muons with better localization of the possible region of background events due to nuclear excitation.

- **Supernova Neutrinos**

The observation of the neutrinos from SN1987a was an extremely fruitful by-product of the IMB operation. New, more sensitive tests of neutrino properties have been suggested should we observe the many hundreds of events associated with a supernova in our galaxy, the most exciting of which may be the possibility of observing neutrino mass. The enhanced light collection and timing improvement will allow us to lower our detection threshold for these neutrino events and improve our direction reconstruction, the improved electronics will reduce our dead time and the improved control over our main power will give us a 20% greater chance of being operational when an event occurs.

4.6.4 Other Detector Enhancements

Other enhancements to the detector have been actively discussed and we are studying their possible employment. These include:

- **Active tracking**

High resolution tracking planes on the top (and perhaps sides) of the detector would improve the localization of penetrating muons. Iarocci tubes, for example, may be a cost effective way to achieve this goal.

- **Wavelength shifter**

A wavelength shifting material can be dissolved in the water to shift short wavelength light to a longer wavelength before it is absorbed by the water. This could add additional useful light to an event and could be a cost effective way of decreasing our threshold. In addition, the isotropic light emitted in this process would help in localizing the event vertex. There is uncertainty, however, in predicting the ease of extracting the directional Čerenkov light from the isotropic component and further study is necessary, perhaps with an in situ experimental test.

- Neutron capture loading

Many of the physical processes that we study with the detector are accompanied by the release of neutrons. A neutron capturing material (dispersed in this instance through the detector volume) would be very useful in tagging these events; the typically 8 MeV de-excitation energy being easily seen by the enhanced detector.

Most of the physics goals outlined above may be greatly enhanced with such an additive and we will continue to develop this idea both with simulations and experimentally.

4.7 Long Baseline Neutrino Oscillation Experiment Using a Neutrino Beam from the Fermilab Main Injector.

4.7.1 Introduction.

The Main Injector at Fermilab will be able to generate the world's most intense neutrino beam. This unique beam will make feasible a neutrino oscillation experiment with a base line of more than 500 km. The experiment will be sensitive to the range of neutrino masses down to a few $\times 10^{-3}(eV)^2$ and mixing $\sin^2(2\theta) > 0.03$, a domain of the parameter space which is as yet unexplored under well controlled accelerator conditions.

This range of neutrino masses is of particular interest to the IMB Collaboration. We have, for a number of years, studied oscillations in this mass range, employing atmospheric neutrinos. The results of these studies have provided ambiguous results. While the characteristics of muons produced in charged current interactions in the rock below the detector agree well with the expectations, too few muon tracks from interactions in the detector volume have been observed. This deficit of contained muon tracks, reported also by the Kamiokande group, can be interpreted as a manifestation of muon neutrino oscillation to tau neutrino. The mass squared difference and mixing required to explain the observed deficit (see Fig. 21) are in the range of sensitivity of the proposed long baseline neutrino experiment.

Studies of neutrino oscillations based on atmospheric neutrinos are limited not only by poor statistics, but also by other factors intrinsic to the atmospheric neutrino flux. This flux consist of a mixture, in almost equal proportions, of electron and muon neutrinos and antineutrinos. Their average energies are low ($\leq 2GeV$), so their interactions involve many resonances and poorly understood nuclear effects. These uncertainties make the interpretation of the results difficult.

The neutrino beam from the Main Injector, due to its high intensity, will facilitate a high statistics experiment. In a typical exposure one would collect several thousands interactions in the IMB fiducial volume. Moreover, the beam will consist mainly of the muon neutrinos with little contamination of other neutrino species. Such a beam purity makes interpretation of the experiment

Figure 21: Region of oscillation parameters allowed by a deficit of muon tracks observed by the Kamiokande group and regions excluded by accelerator experiments, Frejus and IMB-1 for $\nu_\mu \rightarrow \nu_\tau$ oscillations.

easier, and facilitates both disappearance and appearance searches. In addition, the energy spectrum of the accelerator beam is harder than that of atmospheric neutrinos so nuclear effects are negligible, and tau neutrinos can interact via charged current interactions.

These factors motivated our interest in conducting a long baseline experiment, and prompted our very active involvement in the design of the appropriate neutrino beam at Fermilab.

4.7.2 Capabilities of the IMB Detector.

IMB has several advantages over other existing detectors which could perform a long baseline experiment. It is 570 km from Fermilab, closer than Soudan-2 detector (807 km) or DUMAND (6300 km). This shorter distance gives a higher neutrino flux (by a factor of two with respect to Soudan-2) without greatly reducing the sensitivity to the smallest reachable mass difference (which depends on the square-root of the distance). The active volume of the IMB is 6.7 kton, a factor of six larger than that of Soudan-2. These factors combine to provide a factor of twelve times larger neutrino interaction rate in IMB than in Soudan-2. The smaller distance and the position of the detector east of Fermilab makes it easier and less expensive to construct the neutrino beam. The extraction of the beam from the Main Injector can be coupled with the beam abort at the MI-50 straight section which is pointing almost east. There is also appropriate real estate available in that direction to accommodate the beam line. In addition, the shorter distance means that less excavation is required to direct the beam towards IMB. This lowers the cost of the beam by about 3M\$.

The IMB detector provides a continuous sampling of hadronic and electromagnetic cascades with the trigger threshold around 10 MeV. A substantial difference in the energy deposition by muon and electron tracks in the detector provides a mean of identifying high energy electron tracks by total calorimetry. Muon tracks produced in charged current interactions in the rock and entering the detector can be easily identified. Also, tracks exiting the detector provide an easily distinguishable signature. Positions of interaction vertices in the detector volume can be reconstructed from the patterns of phototubes recording

Cerenkov light and timing to an accuracy of about 1 m.

Association of the events observed in the detector with a beam spill can be achieved by a system of clocks recording the absolute time of each event and that of the beam spill.

4.7.3 Search for Neutrino Oscillations.

The Long Baseline experiment can search for oscillations via both ν_μ disappearance and ν_e appearance. Further, if the experiment demonstrates ν_μ disappearance, the absence of a corresponding signal of ν_e appearance will show that the oscillation channel is $\nu_\mu \rightarrow \nu_\tau$.

Given the distance (570 km) between FNAL and the detector site, and the mean energy (13 GeV) of the neutrinos, the experiment is sensitive to δm^2 to $\sim \text{few} \times 10^{-3} (\text{eV})^2$.

ν_μ Disappearance

The main goal of the Long Baseline experiment is to look for ν_μ disappearance. This can be accomplished in two ways:

1. by measuring the ratio of the number of events whose vertex is contained in the fiducial volume and which have an identified (exiting) muon track to the number of events without such a track;
2. by measuring the ratio of the number of entering tracks to the total number of contained events.

In each of these techniques, the ratio of events with a muon to those without a muon would be formed. Muon neutrino disappearance would lower the number of observed muon events (the numerator), and simultaneously the product neutrino would increase the number of muonless events observed (the denominator). Both effects act in the same way to decrease this ratio.

ν_e Appearance

The identification of contained events with unusually high energy deposition will enable the detector to look for a positive signal of ν_e appearance due

to $\nu_\mu \rightarrow \nu_e$ oscillation.

4.7.3.1 Muon Neutrino Disappearance. The experiment will measure the rate of beam associated neutrino interactions in the detector volume and the rate of tracks entering the detector. Events in the detector volume are due to charged and neutral current neutrino interactions and the rates depend on the flux, energy spectrum and the cross section of each neutrino flavor in the beam. In a large fraction of these events it will be possible to identify a muon track, and so, identify them as due to charged current interactions.

Entering tracks are due mostly to charged current interactions of the muon neutrinos in the rock surrounding the detector. The rate depends on the flux, energy spectrum and cross section of muon neutrinos. Since the rock has density about 3 times larger than water, this signal consists predominantly of muons with $< 4\%$ contamination of hadrons.

The absolute disappearance of the ν_μ flux can be equally sensed by a decrease of either contained or entering events. It can however be measured only to the accuracy with which the beam is known. The total flux and other characteristics of the neutrino beam can be calculated knowing the physics of interactions of primary protons in the target and the layout of the beam. The precision of such a calculation is $\sim 10\%$. This can be significantly improved by comparing the results of the calculation with the measurements of the beam interactions in a detector with good spacial resolution (such as the short baseline oscillation experiment P803) positioned close to the end of the beamline.

Oscillation of muon neutrinos to any other left-handed neutrino can be sensed with the greatest precision by measuring ratios of signals, one of which is mainly due to charged current muon neutrino interactions. Such ratios are independent of the least known parameter of the beam, its absolute flux.

With the IMB detector it will be possible to measure at least two independent ratios, each of different sensitivity to the oscillation probability:

Method 1: The ratio of the number of contained events with an identified muon track to the number of contained events without such a track;

Method 2: The ratio of the number of entering tracks to the total number of contained events.

Method 1

To measure the first of these ratios we propose the following scheme:

1. vertexes of contained events associated with the beam are reconstructed;
2. only events which took place in three nonoverlapping fiducial volumes, each of the size of 1 kton, are selected (see Fig. 22 a)
3. these events are examined for an evidence of tracks exiting through any of the detector walls.

The measured ratio is of the number of events produced in any particular fiducial volume without exiting tracks to the number with exiting tracks.

For the three 1 kton fiducial volumes ($5 \times 14 \times 14 m^3$) situated contiguously starting from the west wall and continuing east (the direction of the beam from FNAL), the exiting tracks are muons. The contamination of this signal by a hadronic component of the interaction will not exceed 0.5%. Monte Carlo studies based on the beam spectrum expected at the detector show that in this simple way one can identify 65-75 % of muons produced in charged current interactions (see Fig. 22 b).

The sensitivity of the experiment using the above technique to the oscillation probability P for the oscillation $\nu_\mu \rightarrow \nu_\tau$ is given by the approximate formula (derived in appendix A):

$$\delta P \approx 2 \frac{1}{\sqrt{N}} \sqrt{\left(\frac{1.3}{\epsilon} - 1\right)}$$

where the numerical factors correspond to the expected characteristics of the beam, ϵ is a fraction of muons produced in charged current ν_μ interactions which can be identified, and N is a total number of events collected in a fiducial volume. One can see from the formula that the sensitivity of the experiment is the highest if $\epsilon \sim 1$ (like the Soudan-2, which due to the fine granularity, can achieve $\epsilon \sim 0.95 - 0.98$). The loss in sensitivity due to $\epsilon \sim 0.7$ in the IMB detector however is fully compensated by the improvement in statistics. In fact, the

Percent of exiting muons from CC interactions

Figure 22: a: Fiducial volumes for looking for ν_μ disappearance with the Method 1 in the IMB detector. b: corresponding efficiency of muon track identification in such fiducial volumes.

size of each of the three fiducial volumes has been chosen so that each provides the same sensitivity as that of the entire Soudan-2 detector. The variation of ϵ from one fiducial volume to the another provides an independent check of any observed effect. The overall sensitivity to the oscillation probability after a run with 2.4×10^{20} protons on target should reach 3.5% at the 90% CL. The limits on the oscillation parameters $\delta m^2 - \sin^2(2\theta)$ which can be obtained with this method are shown in Fig. 23. To achieve a similar sensitivity by a detector of Soudan size would require at least three times the exposure.

A major concern with any scheme similar to the one described above is the precision with which the parameters involved in predicting the expected ratio are known, namely the ratio of neutral current to charged current interactions and the efficiency of muon identification. Further studies of the accuracy with which these parameters can be extracted from the existing data on low energy neutrino interactions collected in various target materials is required. We can, however, directly address this issue by making the appropriate measurements with a water target replacing emulsion in the P803 detector situated close to the end of the beam line. This problem is common for any long baseline experiment.

A general problem with all of the proposed experiments arises from the lack of a far detector with both large target mass and efficiency for muon identification (ϵ) close to 100%. A solution would be to design a new detector, which would fulfill both requirements. These issues will be discussed at a dedicated workshop at Fermilab in November 1991. The outcome of this workshop may be a decision to construct an entirely new detector specifically designed for the experiment. In this case a site in the Fairport mine near the IMB detector would be ideal, and would allow both detectors to observe the beam. We of course would continue to be active in both experiments.

Method 2

The measurement of the second ratio, of the number of entering tracks to the number of contained events, has been discussed in detail in our proposal to Fermilab and does not require further elaboration. As this method is about a factor of two less sensitive than Method 1, we consider it a complementary control of the measurement described above.

Figure 23: Region of 90 % CL sensitivity to $\delta m^2 - \sin^2(2\theta)$ of the IMB Long Baseline experiment to oscillations $\nu_\mu \rightarrow \nu_\tau$

4.7.3.2 Electron Neutrino Appearance. Since the oscillation process $\nu_\mu \rightarrow \nu_\tau$ will produce different rate of CC interactions than $\nu_\mu \rightarrow \nu_e$ oscillations, correct interpretation of the disappearance experiment requires the elimination of one of these channels. One can use for this purpose the results of our proposed oscillation experiment with the Perry reactor which will be sensitive to oscillation of electron neutrinos in a similar mass range. In addition, the IMB detector provides the means to directly search for electron neutrino appearance in the beam from the Main Injector. Events due to charged current high energy electron neutrino interactions will have much larger visible energy deposition in the detector than those due to muon neutrinos. Thus the observation of more events with very high energy deposition than expected from muon neutrino interactions and from the unavoidable contamination of the beam (about 1% ν_e 's in this energy region) would indicate $\nu_\mu \rightarrow \nu_e$ oscillation. The region of sensitivity to $\delta m^2 - \sin^2(2\theta)$ of this experiment is similar to that of the disappearance experiment. This neutrino mass range is above the range considered in the explanation of the solar neutrino puzzle, however this region has never been tested under well controlled accelerator conditions.

4.7.4 Progress to Date.

The Collaboration submitted a letter of intent in August 1989 and a proposal in October 1990 to Fermilab (P-805) to conduct a long baseline oscillation experiment using a neutrino beam from the Main Injector.

This proposal was based on extensive computer simulation of neutrino interactions for the designed beam and of the detector response to such interactions. Possible backgrounds and some systematic uncertainties due to the beam characteristics have also been carefully studied.

In our studies thus far, the neutrino interactions have been simulated using slightly modified CERN library programs LEPTO and JETSET (known as Lund programs). LEPTO properly simulates deep inelastic neutrino - quark interactions, JETSET provides hadronization of the resulting quark - diquark

system in accordance with the Lund model. If the energy/momentum transfer to the hadronic vertex is too small to apply Lund hadronization model, only lepton parameters are saved in these programs. For better understanding of the physics involved in the experiments, it is essential to develop a more realistic program which would generate the neutrino interactions in the energy range of interest. In addition to the deep inelastic interactions, this program has to account for quasi-elastic and resonance production processes. Our programs for simulation of atmospheric neutrino interactions may be well suited to fill this gap.

Tracking of neutrino interaction products in IMB and in the surrounding rock were simulated using GEANT. The detector response to the Čerenkov light emitted in water was treated using programs developed by IMB. We have also developed programs combining all the convenient features of GEANT with IMB Monte Carlos.

Since the success of the experiment depends strongly on the characteristics of the neutrino beam, we have devoted a major effort to the beam design. To increase neutrino yield per proton on target we proposed to use several solutions which proved themselves at the CERN neutrino beam. A segmented thin pencil-like target improves the escape of secondary products of proton interactions in the target. We calculated the energy deposition of the primary proton beam in target materials applying the FLUKA program, commonly used for this purpose at CERN [1]. It became evident that the materials used thus far at FNAL could not withstand the intensity of the beam from the Main Injector. We proposed a new material, graphite, calculated its resistance to thermal stresses [1] and developed ways of cooling such a target [2]. Also, we contributed significantly to the design of the focusing system, horns, and studied horn survivability to magnetic pressures [3] and other sources of stress. This effort is continuing: a finite element analysis simulation (PATRAN [4]) is being used to reach a final mechanical design for the horns.

The neutrino yield of the beam has been analyzed using an original computer program based on GEANT with a new model for production of secondaries in 120 GeV proton interactions with graphite [5]. This program is the only one available which treats in a correct way particle interactions not only in the tar-

get but also along the beam line, and in particular in the horns. As the result, we have been able to achieve a tenfold improvement of the neutrino yield per incident proton with respect to the wide band beam which existed at FNAL a decade ago.

We have participated regularly in meetings at Fermilab of a Main Injector Neutrino Oscillation group (MINOS) working on the establishment of a neutrino program with the Main Injector and writing a Neutrino Conceptual Design Report [6]. Our contributions to this document were significant and widely appreciated. This document has already positively passed both Technical and Directors Reviews at Fermilab.

4.7.5 Future Plans.

We are planing to continue our effort towards the realization of long baseline experiment. This includes both, a continuation of the work towards construction of the neutrino beam when the Main Injector is completed, and the development of the best method to detect neutrino oscillations at large distances. The last point include further studies of how to best employ the IMB detector, or, if it turns out to be a better solution, how to design and build a new detector at the best site.

To achieve these goals we are planing to work in the following directions:

1. To continue our collaboration with the MINOS group at FNAL on improvements of the design of the neutrino beam. The final goal of this effort is to reach the blue-print level for every element of the beam line. A prototype of the more complex first horn has to be built and tested by cycling of at least 10^6 current pulses. To be able to participate in this process, at least one trip a month to Fermilab of at least one person from UCI is essential. At UCI we have already an access to the necessary computer hardware and software to continue to play an major role in this design process.
2. To continue development of a model for neutrino interactions in the energy region of the beam from the Main Injector. The basic elements of this model are in hand, the model must now be integrated into our programs.

Predictions of the model have then to be compared with available data from the relevant neutrino experiments.

3. To continue studies of how best to employ IMB for the long baseline experiment. Several improvements to the detector, proposed to enhance the search for proton decay and atmospheric neutrino studies (and discussed later in this document), will have a positive impact on the detector capabilities for the oscillation experiment:

- the active veto around the detector walls will facilitate unambiguous identification of entering and exiting tracks which is so essential for the proposed scheme of the experiment;
- the additional phototubes with much improved time resolution will improve a precision of vertex reconstruction;
- new electronics with multihit TDC's and ADC's will facilitate muon decay detection and reconstruction of the muon's range from the decay electron's ring pattern. Additional study is needed to determine if this information will improve identification of events containing muon tracks as being due to charged current muon neutrino interactions. This would extend the detector sensitivity to the oscillation probability.

The impact of these improvements needs to be studied and quantified by detailed simulations.

4. If the decision is reached to build a new far detector for the experiment, we have all the tools required for designing of such a detector. We will have a realistic model to simulate neutrino interactions and wide expertise in GEANT application for particle tracking.
5. We plan to study a promising new and inexpensive tracking device: a resistive plate chamber [7]. Such devices feature time resolutions of the order of 1 ns, and spacial resolutions of a few centimeters, with very good multihit efficiency. They can cover large area at low cost ($< 100\$/m^2$). As such, they seem ideally suited for an active veto over the top of the IMB detector, as well as for a tracking device in any eventual new far detector. There is no expertise in USA in building such devices; only an Italian group in Rome has reported promising results.

References

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Appendix

Let us consider a simple neutrino detector [1] consisting of an active target, an absorber block and a muon counter as shown in Fig. 24. The active target records all neutrino interactions taking place in its volume. In a fraction ϵ of charged current interactions a muon is produced which penetrates the absorber and is recorded by a muon counter. The hadronic component of the interactions is totally absorbed in the absorber. The detector is exposed to a muon neutrino beam, a fraction P of which oscillate to another type of neutrinos (ν_x).

The rate of events counted by the active target is due to charged and neutral current interactions of the remaining muon neutrinos and the neutrinos created due to the oscillations, and is given by a formula:

$$N_{ctn}^{tot} = M^{trg} \Phi \sigma_{\nu_\mu}^{CC} \left\{ (1 - P) + P \frac{\sigma_{\nu_x}^{CC}}{\sigma_{\nu_\mu}^{CC}} + (1 - P) \frac{\sigma_{\nu_\mu}^{NC}}{\sigma_{\nu_\mu}^{CC}} + P \frac{\sigma_{\nu_x}^{NC}}{\sigma_{\nu_\mu}^{CC}} \right\}$$

where M^{trg} is the target mass, Φ is the beam flux and σ 's are appropriate neutrino cross sections. The rate of muons counted by the muon counter depends on the fraction of muon neutrinos which survived the oscillation and on the production of high energy muons in interactions of the new neutrinos. For instance if tau neutrinos are created due to oscillations, in their charged current interactions tau leptons are produced, which decay with the branching ratio B_τ

Figure 24: Layout of a generic neutrino oscillation experiment.

to muons. Since such muons have a different spectrum than those produced by muon neutrinos, a different fraction ($\epsilon_{\nu_r}^\mu$) will reach a muon counter. The rate in the muon counter can be expressed by the formula:

$$N_{ctn}^\mu = M^{trg} \Phi \sigma_{\nu_\mu}^{CC} \epsilon_{\nu_\mu}^\mu \left\{ (1 - P) + P B_x^\mu \frac{\sigma_{\nu_x}^{CC}}{\sigma_{\nu_\mu}^{CC}} \frac{\epsilon_{\nu_x}^\mu}{\epsilon_{\nu_\mu}^\mu} \right\}.$$

For simplicity, let us introduce the following means over the neutrino energy spectrum $\rho(E_\nu)$:

$$\Psi(x) = \int_0^\infty x(E_\nu) \rho(E_\nu) dE_\nu,$$

$$r = \Psi\left(\frac{\sigma_{\nu_\mu}^{NC}}{\sigma_{\nu_\mu}^{CC}}\right),$$

$$\eta = \Psi\left(\frac{\sigma_{\nu_x}^{CC}}{\sigma_{\nu_\mu}^{CC}}\right),$$

$$\epsilon = \Psi(\epsilon_{\nu_\mu}^\mu),$$

$$\epsilon' = \Psi\left(\frac{\epsilon_{\nu_x}^\mu}{\epsilon_{\nu_\mu}^\mu}\right).$$

From the rates measured by the active target and the muon counter we can construct a following ratio, which is independent of the least well known beam characteristics:

$$R = \frac{N_{ctn}^{tot} - N_{ctn}^\mu}{N_{ctn}^\mu} = \left(\frac{1+r}{\epsilon} - 1\right) \left\{ 1 + \frac{r + \eta - B\eta(1+r)\epsilon'}{1+r-\epsilon} P \right\}$$

We have neglected higher than first order dependance on the oscillation probability P in this formula. One can see, that the expected value of this ratio, when there is no oscillations ($P = 0$), is given by:

$$R_{exp} = \left(\frac{1+r}{\epsilon} - 1\right)$$

and that it depends on the muon identification efficiency. This expected ratio is equal to the neutral current to charged current ratio r when muon identification efficiency ϵ is equal to 1. The factor in front of P :

$$\beta = \frac{r + \eta - B\eta(1+r)\epsilon'}{1+r-\epsilon}$$

is a measure of sensitivity of the experiment to the oscillation, and it is the largest when $\epsilon = 1$.

However it is worth noting that with the increase of the muon identification efficiency one is decreasing the statistics of events in the numerator of the ratio and increasing the denominator. The sensitivity of the experiment to the oscillations has to be corrected for this fact in the following way:

$$\delta P = \frac{1}{\beta} \frac{\delta R}{R_{exp}} = \frac{1}{\beta} \frac{1}{\sqrt{N}} \frac{1+r}{\sqrt{\epsilon(1+r-\epsilon)}},$$

giving:

$$\delta P = \frac{1+r}{r+\eta-B\eta(1+r)\epsilon'} \frac{1}{\sqrt{N}} \sqrt{\left(\frac{1+r}{\epsilon} - 1\right)}.$$

where N is a total number of events seen in the active target. Still, this formula shows, that the experiment is the most sensitive to the oscillation when $\epsilon = 1$, but it also shows, that the lost of the efficiency for $\epsilon < 1$ can be compensated by increasing N .

For the oscillation $\nu_\mu \rightarrow \nu_\tau$ and for the neutrino beam from the Main Injector as seen by a far detector on the beam axis one gets: $r = 0.3$, $\eta = 0.4$, $\epsilon' = 0.7$ and $B=0.18$. The constant in the expression for δP in this case has a value of ~ 2 .

It is worth noticing here too, that if one constructs a ratio of any muon rate to the total rate in the active target, one gets:

$$R = \frac{N^\mu}{N_{ctn}^{tot}} = R_{exp} \left\{ 1 + \left(\frac{1-\eta}{1+r} + B\epsilon'\eta - 1 \right) P \right\}.$$

In this case the sensitivity to the oscillation:

$$\beta = \left(\frac{1-\eta}{1+r} + B\epsilon'\eta - 1 \right)$$

does not depend on the muon identification efficiency, and $\beta \sim 0.5$ for the oscillation $\nu_\mu \rightarrow \nu_\tau$. Thus such a ratio is less sensitive to the oscillation than the ratio discussed before. An experiment which would measure a flux of muons

entering the "active target" from an infinite target in front of it, would see a rate of entering tracks given by the formula:

$$N_{entr}^{\mu} = M_{\nu_{\mu}}^{eff} \Phi \sigma_{\nu_{\mu}}^{CC} \left\{ (1 - P) + P B_x^{\mu} \frac{\sigma_{\nu_x}^{CC}}{\sigma_{\nu_{\mu}}^{CC}} \frac{M_{\nu_x}^{eff}}{M_{\nu_{\mu}}^{eff}} \right\}$$

where M^{eff} is the effective target mass in which muons were produced. In spite of the fact, that such an experiment can collect a large number of events, it is not as sensitive to the oscillation as an experiment measuring the "neutral to charged current ratio" even with as poor a muon identification efficiency as $\epsilon \approx 0.7$!

References

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4.8 The Collaboration

We have been operating the IMB experiment now for about a decade and during this time the collaboration has undergone many changes in personnel. With the changes to the detector outlined above, and the development needed for the future, we fully recognize the need for a substantial addition to the collaboration; we believe that the physics outlined above is currently of great interest to the High-Energy Community, and we anticipate no difficulties in finding interested colleagues who will want to participate in this program. The collaboration has already been strengthened with the addition of Dick Steinberg and Chuck Lane from Drexel, Emmanuel Bonvin from Chalk River and Sharam Hatamian from Irvine. These physicists are particularly interested in the reactor oscillation experiment and have expertise in this area and in the development of liquid scintillators. We expect that other groups will be added as we proceed with our detector enhancement plans.

4.9 Schedule and Estimated Cost

Since it is clear that valuable and unique physics can be done with this facility for many years to come, we would like to stabilize the detector cavity by refilling the detector with water immediately. We estimate that this refilling, which would include a new inside liner (resulting in a conservative triple barrier to future leaks), repair of the cavity walls, and general refurbishing of the detector to new more rigorous standards, would cost about \$500k, and would take about six months.

We expect to submit a detailed proposal to DoE within the next few months. This proposal will detail the physics with the improvements outlined above. We estimate the additional costs to be:

Anticoincidence system	\$100k
New digitizing electronics	\$350k
New photomultiplier tubes	\$2000k
Uninterruptible power	\$100k

4.10 Publications

Appended to this report are selected papers from the current years work.

*reprint
removed*

A Travel Reports

Travel and Talks

Fred Reines

Cleveland	Case Western Reserve	April 90
	To receive Michelson-Morley award	
Washington	PDK Collaboration	May 90
Geneva	14th International Conference on Neutrino Physics and Astrophysics	June 90
New York	Colloquium, NYU	Sep. 90
UCLA	Super Nova Watch Conference	Nov. 90
London	Texas-ESO Cern Symposium	Dec. 90
Moscow	A.D. Sakharov Conference	May 91
	Invited paper	

Travel and Talks

Henry W. Sobel

Notre Dame	PDK Collaboration meeting	Aug. 90
Savannah River	Work on Neutral Current experiment	Sept. 90
Cleveland	Work on IMB experiment	Sept. 90
Ann Arbor	Attend International Conference on High Energy Gamma-Ray Astronomy	Oct. 90
Cleveland	Work on IMB experiment	Oct. 90
UCLA	Attend Supernova Workshop	Nov. 90
UCLA	Attend Trends in Astroparticle Physics Confer- ence	Nov. 90
Cleveland	Work on IMB experiment	Dec. 90
Venice	Invited talk - Workshop on Neutrino Telescopes	Feb. 91
Hawaii	PDK Collaboration meeting	March 91
Little Rock	GRANDE Collaboration meeting	March 91
Cleveland	Work on IMB experiment	April 91
Cleveland	Work on IMB experiment	April 91
DoE, Germantown	GRANDE presentation to DoE	May 91
FNAL	Attend PAC meeting re: Long baseline experi- ment	May 91
Cleveland	Work on PDK experiment	May 91
Boston	IMB Collaboration meeting	June 91

Travel and Talks**William R. Kropp**

Notre Dame	IMB Collaboration Meeting	Aug. 90
Cleveland	Salt Mine Lab	Sept. 90
Cleveland	Salt Mine Lab	Oct. 90
Ann Arbor	Int. Conf. on High Energy Gamma-Ray Astronomy	Oct. 90
UCLA	Supernova Workshop	Nov. 90
UCLA	Trends in Astroparticle Physics Conference	Nov. 90
Cleveland	Salt Mine Lab	Dec. 90
Goddard	Workshop on the NASA Cosmic Ray Program for the 1990s and Beyond, NASA Goddard Space Flight Center	Dec. 90
Hawaii	IMB Collaboration Meeting	March 91
Little Rock	GRANDE Meeting	March 91
Cleveland	Salt Mine Lab (2 trips)	April 91
Germantown	GRANDE and IMB Presentations to DoE	April 91
Savannah River	SRS Laboratory	May 91
Cleveland	Salt Mine Lab	May 91
Cleveland	Salt Mine Lab	June 91
Boston	IMB Meeting	June 91

Travel and Talks

LeRoy Price

Savannah River	Work on Neutral Current experiment	Sept. 90
Ann Arbor	High Energy Gamma-Ray Astronomy Conference	Oct. 90
UCLA	Attend Supernova Workshop	Nov. 90
UCLA	Attend Trends in Astroparticle Physics Conference	Nov. 90
Pomona, CA	Southern California Area Modern Physics Institute, Invited talk	Dec. 90
Little Rock	GRANDE collaboration meeting	March 91
Pomona, CA	Calif. State Polytechnic University, Pomona. SPS/AATP Joint Meeting. Invited talk	April 91
Los Angeles	Calif. State University, Dominguez Hills. Invited talk at the $\Sigma\Pi\Sigma$ chapter founding	April 91
Boston	IMB collaboration meeting	June 91

Travel and Talks

Michael K. Moe

Bratislava,	14th Europhysics Conference on Nuclear Physics	Oct. 90
Czechoslovakia	Rare Nuclear Decays and Fundamental Processes (presented invited paper)	
Hoover Dam	Work on experiment	many trips