NEUTRINO OSCILLATION AND NEUTRINO MASS EXPERIMENTS

J. M. LoSecco
University of Michigan, Ann Arbor, MI. 48109

ABSTRACT

Astrophysical, geochemical and accelerator techniques of looking for neutrino masses or oscillations are discussed. Astrophysical sources may permit careful time of flight measurements of neutrino masses. Geochemical tests make use of the fact that if the neutrino has a mass the energy of the cosmic neutrino background is many orders of magnitude greater than the thermal energy.

A recently conducted accelerator experiment to search for ν_μ oscillations is discussed. Techniques to perform such searches are described. Preliminary results indicate no unambiguous evidence for neutrino oscillations.

THE USE OF ASTROPHYSICAL NEUTRINO SOURCES TO STUDY NEUTRINO MASSES

If the neutrinos have mass then their velocity, $\beta \neq 1$. For masses small with respect to the neutrino momentum one finds a time of flight deviation

$$\frac{\Delta t}{t} \cong 2\,\frac{\Delta m^2}{p^2}$$

Δm^2 is the mass difference for the two states considered. If one compares the flight time of neutrinos to photons then $\Delta m^2 = M_\nu^2$. For Δm = 10 eV and P = 10 MeV we find

$$\frac{\Delta t}{t} \cong 10^{-12}$$

For galactic sources reasonable distances are ∿ 10 kpc = 10^{12} sec.

An expected galactic neutrino source is stellar collapse. Such a source produces a burst [1] of neutrinos with about 10^{53} ergs of energy and with a mean momentum of about 14 MeV. These neutrinos are a central part of the mechanism of collapse.

We have studied the feasability of observing such bursts in a large, deep underground detector [2] . Neutrino fluxes at the earth of a typical burst would be:

$$N(\bar{\nu}_e) = 1.7 \times 10^{13}/\text{cm}^2/(\text{kpc})^2$$
$$N(\nu_\mu) = 2.1 \times 10^{13}/\text{cm}^2/(\text{kpc})^2$$
$$N(\nu_\tau) \approx N(\nu_\mu)$$
$$N(\nu_e) = 2.8 \times 10^{13}/\text{cm}^2/(\text{kpc})^2$$

A detector under construction, the 8000 ton water IMB detector[3] could observe such bursts through a variety of channels. The most useful is

$$\bar{\nu}_e + P \rightarrow e^+ + n$$

which provides over 80% of the events in water. At 1 kpc the event rate is

$$1.2 \times 10^5 \text{ interactions/burst}$$

and it falls as $1/r^2$. These bursts could be detected by the Cherenkov light produced in water by the final state lepton. Each event in the IMB detector will produce about 4 photoelectrons. Individual events are not detectable.

The time structure of the burst is expected to be narrow ∿ 10 msecs. The energy spectrum times cross section is also expected to be fairly narrow in energy, primarily because of the E^2 cross section behavior and the narrow neutrino spectrum. Detection is possible because of the compact structure of the burst.

Clearly one is faced with a dilemma. For a stronger signal, one would like a close source but the time of flight separation for millisecond bursts is better at long distances. Sources are expected to have a similar distribution to stars in our galaxy, concentrated in the galactic plane and increasing in density toward the center.

Cataclysmic bursts, with the emission of vast amounts of light and mass are thought to be rare. Yet the distribution of collapse remnants[4] implies a frequency of occurance of about one every six years in our galaxy. Estimates range from one a year to one a century.[5]

Given the rarity of such bursts one hopes to optimize the information extracted from one. There are many observables of astrophysical significance, time structure, spectrum, etc. but as far as neutrino masses are concerned there are only a few observables.

The time of flight gives information on masses. A measure of the neutrino flavor content of each mass eigenstate would be important. With the current detector one can try to measure the $\bar{\nu}_e$ content of the mass eigenstates. The two significant processes are $\bar{\nu}_e + p \rightarrow e^+ + n$ and $\nu + e \rightarrow \nu + e$. The latter is highly directional and the former is isotropic. 7% of the light, but 17% of the events, are from νe scattering. So the isotropic component is a measure of the $\bar{\nu}_e$ content of the burst.

Doping the detector with a material with a high ν_e cross section (LiCl) would also help to increase the signal and increase sensitivity to ν_e.

Detection of such bursts may be possible in the near future and one should optimize the information obtained because of the rarity of the event.

GEOCHEMICAL SEARCHES FOR NEUTRINO MASS

If the Q value for the positron decay

$$x \rightarrow y + e^{+} + \nu_e$$

is below the positron mass the reaction will proceed by K capture. If the Q value for the beta process

$$A \rightarrow B + e^{-} + \bar{\nu}_e$$

is below the electron mass then A is effectively stable. Consider the case

$$Q(A\text{-}B) = m_e - \varepsilon$$

and

$$m(\nu_e) \gtrsim \varepsilon$$

The decay A → B will go, at some level, because of the presence of the cosmic neutrino background. The mass gives a cosmic neutrino energy orders of magnitude above the thermal energy. A search for the ratio of B to A in samples can be used to estimate the neutrino mass. At present nuclear energy levels are not known accurately enough to make this study feasible[6] but in principle it could be done.

SEARCH FOR OSCILLATIONS OF A ν_μ BEAM[7]

The sensitivity to neutrino oscillations scales as the square of ℓ/p (ℓ = distance ν travels and $p = \nu$ momentum). It follows that the most sensitive experiment will maximize ℓ/p. Since our 30 ton neutrino detector was fixed 105 to 155 meters from the source at Brookhaven we choose to reduce the momentum.

The optimum proton beam energy for single pion production is about 800 MeV. Neutrinos from such pion decays have many nice features including a low momentum. A major task was to produce the low energy neutrino beam. This was successfully done.[8]

Experimentally there are many problems. Pion production at 800 MeV tends to be at large angles (120 mrad). To maximize the neutrino flux a horn was designed and built to focus pions at wide angles. Neutrino cross sections at these energies are very low (2×10^{-39} cm^2) but large exposures (7.9×10^{18} protons) are possible at the A.G.S.

The neutrino spectrum runs from 150 MeV < E_ν < 250 MeV. Since in the 30 ton liquid scintillator calorimeter the visible energy is the total energy minus the mass

$$E_{vis} = E_\nu - m_\ell$$

one can distinguish ν_μ from ν_e by total energy deposition. For ν_μ

$$50 \text{ MeV} < E_{vis} < 150 \text{ MeV}$$

for ν_e

$$150 \text{ MeV} < E_{vis} < 250 \text{ MeV}.$$

The character of dE/dx is also very different for the final state μ and e. The muon is minimum ionizing while the electron tends to shower. The detector also has a "second timing" capability. The detector is live for more than 6 μsec following a trigger. A muon decay in this time can be observed (∿ 60% efficiency).

The experimental analysis is not yet complete but many results are available.

The background falls rapidly with energy. There is only about 1/3 the background in the ν_e energy window than in the ν_μ window. The neutrino cross section is strongly suppressed at low q^2 by the Pauli exclusion effect in carbon nucleii. At higher q^2 form factors reduce the cross section. The technique we used to operate the A.G.S. accelerator, multiturn shaving extraction, increased the duty factor and live time a factor of 5 to 6 over that in normal 28 GeV/c neutrino running. A background subtraction is needed in spite of the extensive use of active shielding. Finally, we have found that a realistic detection efficiency for such an experiment can at best be only ∿ 30%.

Our tentative physics results are: The observed ν_μ rate is consistent with the Monte Carlo rate (but a very small signal). Some cosmic ray μ topologies mimic ν_e candidates. These can be studied because of the μ decay signature. There is no unambiguous ν_e signal present.

REFERENCES

1. James R. Wilson et al., Annals of the New York Academy of Sciences, 262, 54 (1975).

2. J. LoSecco, Additional Physics with the IMB Detector, Feb. 1980 Neutrino Bursts of Astrophysical Significance May, 1980 (unpublished internal reports).

3. The IMB nucleon stability experiment is a collaboration of M. Goldhaber (Brookhaven), B. Cortez and G. Foster (Harvard) W. Kropp, J. Learned, F. Reines, J. Schultz, D. Smith, H. Sobel, C. Wuest (Univ. of Cal. Irvine), J. LoSecco, E. Shumard, D. Sinclair, L. Sulak, and J. VanderVelde (Univ. of Michigan), C. Bratton (Cleveland State Univ).

4. J.H. Taylor and R.N. Manchester, App. J. 215, 885 (1977).

5. John N. Bahcall, Rev. Mod. Phys. 50, 881 (1978).

6. M. Goldhaber, private communication.

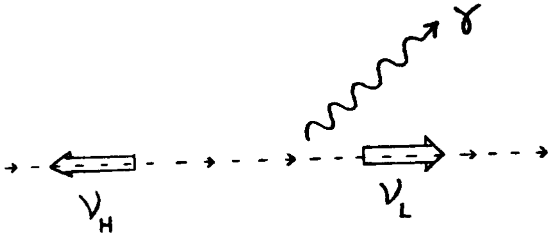
7. This work was performed by B. Cortez, J. LoSecco, L. Sulak, of Harvard University and A. Soukas and W. Weng of Brookhaven.

8. W.T. Weng et al., IEEE Trans. Nuc. Sci. NS-26, 3224 (1979).

CAN WE OBSERVE NEUTRINO DECAY IN THE LABORATORY?

A.R. Erwin
University of Wisconsin-Madison
1150 University Avenue, Madison, WI 53706

How can a neutral, heavy neutrino decay if it is too light to go into known particles and has no electric dipole moment to radiate photons? If it has a magnetic moment, perhaps it can undergo a magnetic dipole transition as sketched here, where a normal left handed neutrino flips to become a sterile right handed neutrino.



$$\nu_H \longrightarrow \nu_L + \gamma$$

For such a process to take place the neutral particle must have a magnetic moment, so what could we expect for its size?

1) Composite sub-quark models of leptons and quarks could readily imply magnetic moments for neutrinos just as quark models account for magnetic moments of n, Λ°, Σ°, and Ξ°. In that case, however, we might expect the magnetic moment of the neutrino to be large, comparable to that of the electron or muon.

$$\mu_\nu \sim \mu_e$$

2) Without any such model one might guess the magnetic moment of a particle with a vanishingly small mass might be extremely large.

$$\mu_\nu \sim e\hbar/2m_\nu \to \infty$$

3) Or, since its charge is zero, the magnetic moment might be zero.

$$\mu_\nu \overset{?}{=} 0.$$

No. Not if we believe we understand electro-weak interactions. There are a half dozen diagrams with charged current loops that must contribute something to a magnetic moment.[1]