AU9212347

UM-P-92/41 .

MASSIVE NEUTRINOS

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(To be Published in The Australian and New Zealand Physicist)

ABSTRACT

Neutrinos have intrigued physicists for over 60 years, yet we still have not determined if they possess a mass. Spontaneous oscillations between the various types of neutrinos, in analogy with the observed "flavour" oscillations between quarks, would be irrefutable evidence for non-zero neutrino mass. A group of experimental physicists from Australia has joined a new experiment to search for neutrino oscillations and this article reviews the importance of searching for such phenomena.

INTRODUCTION

Neutrinos are without doubt the most mysterious of the known "Elementary Particles", a position they can claim to have held every since they were postulated by Pauli over 60 years ago. In order to save the basic conservation laws, of energy, momentum and angular momentum, Pauli proposed that a light neutral particle of spin 1/2 (that he dubbed the "neutron") should be produced in β decay. Then Chadwick discovered the particle we now call the neutron, so Fermi coined the present name, meaning "little neutral one". The neutrino was a key ingredient in Fermi's famous theory of β decay.

Massive spin 1/2 fermions are described by the Dirac equation but, sixty years after Pauli's proposal, we still cannot exclude the simplest possibility that the three known neutrinos are massless and are described by the much simpler Weyl equation. However if neutrinos do have mass it open up a whole range of interesting phenonema.

It took nearly thirty years before the neutrino was directly observed, in 1959 by Reines and Cowan at the Savannah River reactor. The mean free path for the absorption of the low energy antineutrinos produced in reactors corresponds to about 100 light-years of water. It can truly be said that they interact only weakly with matter!

Today, thanks to the Large Electron Positron collider (LEP) at CERN, we know that there are only three types, or "flavours", of light neutrino, associated with the three types of known leptons (electrons, muons and tauons).

But even the evidence for the tau-neutrino remains indirect. And other mysteries abound:

- What are their masses? At the present levels of experimental precision neutrinos have no detected masses. However no fundamental principle requires them to be massless. We know that the electron neutrino (ν_e) is much less massive than an electron, less than 17 eV as compared to 511 keV. The limits for other neutrinos are poorer; the muon neutrino (ν_μ) could have as much as 50% of the electron mass, the tau neutrino (ν_τ) could be 70 times more massive than an electron.

- The existence of one or more massive neutrinos would have immense implications for cosmology and our understanding of the evolution of the Universe. It could solve the "missing mass problem" by accounting for the dark matter needed to explain the rotational properties of galatic halos and to close the Universe.
- If neutrinos are found to be massive they may be Dirac particles, with distinct antiparticles, or Majorana particles which are their own antiparticles. The distinction between Dirac and Majorana neutrinos is summarised in Figure 1. With massless neutrinos the distinction disappears.
- The flux of solar neutrinos measured at the earth in several experiments is considerably lower than that predicted.
- In recent years several experiments have observed an effect which could be interpreted as the emission of a neutrino with a mass of 17 keV in β decay, although the evidence is contraversial.

Two excellent books, both titled "The Physics of Massive Neutrinos", appeared a few years ago [1,2]. Both are highly recommended to readers wanting to learn more than will appear in this brief summary.

FERMIONS IN THE STANDARD MODEL

Table 1 shows the twelve known Fermions. Evidence for the top quark, like the tau neutrino, is compelling but indirect. Together with their antiparticles, and the Gauge Bosons (photons, W , Z and gravitons) which transmit the forces between particles, they constitute the known members of the "Particle Zoo". The Fermions are commonly grouped into three families with a striking symmetry.

Table 1: The Known Fermions

Family	Quarks	Charge	Leptons	Charge
1	u	+2/3	ν_e	0
	d	-1/3	e^-	-1
2	c	+2/3	ν_μ	0
	s	-1/3	μ^-	-1
3	t	+2/3	ν_τ	0
	b	-1/3	τ^-	-1

The first family accounts almost entirely for the world that we observe around us. Fermions in the other two families, although equally common soon after the Big Bang, are observed today only fleetingly in high energy interactions of cosmic rays and at accelerators. We almost certainly live in a sea of relic cosmic neutrinos of all types, a remnant of the Big

Bang similar to the Cosmic Microwave Background Radiation but much harder to detect than photons. The neutrinos decoupled from matter earlier and their present temperature is about 2 K.

FLAVOUR OSCILLATIONS

The symmetry between the six quarks and the six leptons while pleasing is broken by their different interactions. In the quark sector Weak Interactions involving a charged W cause transitions between the families. Thus a strange Λ baryon, with quark content (sud), β decays to a (non-strange) proton (uud), plus an electron and neutrino.

This interaction is described by a Lagrangian density:

$$L = g\ [u, c, t]\ \gamma_\mu\ (1\ -\ \gamma_5)\ U \begin{vmatrix} d \\ s \\ b \end{vmatrix}_{weak} W_\mu \qquad (1)$$

in which the charge +2/3 quarks (u,c & t) couple via the W-field to charge -1/3 (d,s & b) quarks which are a linear combination of the set which build hadrons. The unitary matrix U transforms the quark flavour to weak eigenstates which participate directly in the interaction. Called the Cabibbo-Kobayashi-Maskawa(CKM) matrix, U has non-zero off-diagonal elements:

$$\begin{vmatrix} d \\ s \\ b \end{vmatrix}_{weak} = \begin{vmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{vmatrix} \begin{vmatrix} d \\ s \\ b \end{vmatrix}_{mass}$$

Second order Weak Interactions permit a neutral K-meson ($d\bar{s}$) with positive strangeness to transform into its antiparticle, the neutral $\overline{K}$ -meson ($s\bar{d}$) with negative strangeness. These "flavour oscillations" are well known and have been extensively studied for K-mesons and more recently for B-mesons, which contain a b- quark with a light anti-quark.

The Quantum Mechanics associated with flavour oscillations is fascinating and the interested reader is referred to [2] and references therein.

Transformations between the lepton families have never been observed. Many experiments have searched for analogous flavour oscillations in the lepton sector, in particular for neutrino oscillations, the spontaneous transformation of one type of neutrino into another. No evidence for such a transformation has emerged and today we can only set limits on the degree of mixing. The off-diagonal elements of the equivalent CKM matrix for leptons are zero within errors. But interest in their existence remains high and several new searches are being prepared.

To keep the algebra simple the discussion below is restricted to two types of neutrino. If flavour-changing transitions between leptons are allowed and if neutrinos have mass, then the flavour eigenstates and the mass eigenstates should be different, as in the quark sector. They are related via a mixing matrix:

$$\begin{vmatrix} \nu_\mu \\ \nu_\tau \end{vmatrix} = \begin{vmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{vmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \end{vmatrix}$$

If one starts with a beam of one flavour, say ν_μ, then after a distance L the probability that it has become a ν_τ is:

$$P(\nu_\tau, L) = sin^2\ (2\theta\ ) \times sin^2\ (\pi L/L_{osc}) \tag{2}$$

where the characteristic oscillation length is given by:

$$L_{osc} = (4\pi E)/\Delta m^2 \tag{3}$$

and

$$\Delta m^2 = m_1^2 - m_2^2 \tag{4}$$

This equation is in natural units ($\hbar$ =c =1). If we measure L in km, E in GeV and Δm^2 in eV^2 , then:

$$L_{osc} = (2.5E)/\Delta m^2 \tag{5}$$

By conservation of particles, the probabilty that the ν_μ remains a ν_μ is:

$$\mathrm{P}(\nu_\mu, \mathrm{L}) = 1.0 - \mathrm{P}(\nu_\tau, \mathrm{L}).$$

The above formulae hold when the neutrinos are propagating in vacuum. In matter a much more complex situation occurs and resonant oscillations can occur [3,4].

The observation of neutrino oscillations would require neutrinos to massive with L_{osc} giving a measure of the mass difference between eigenstates. Such an observation would have great implications:

- massive neutrinos would be strong candidate for the dark matter sought by cosmologists and astrophysicists.
- it could explain the "solar neutrino problem" discussed above as due to the disappearance of electron neutrinos created in the sun during their passage to earth with the creation of other neutrinos undetectable in present terrestial experiments.

SOURCES OF NEUTRINOS

The Sun, natures own fusion reactor, is a powerful neutrino source. Far away here on Earth the flux of ν_e is calculated to be about 6.6 $\times 10^{10}$ cm^{-2} s^{-1}. In his pioneering experiment at the Homestake mine in Dakota, Davis used as detector a tank of dry cleaning fluid containing over 10^{30} Chlorine atoms. Allowing for the efficiency of extraction and other loses, solar neutrinos should have caused 1.22 of those 10^{30} atoms per day to change to a detectable Argon atom. Davis and his team measured less than a half of that rate, 0.46 ± 0.04 atoms of Argon detected per day. Hence the solar neutrino problem was born. Recent experiments, at the Kamiokande mine in Japan and the Soviet-American SAGE experiment in the Caucasas, confirm the Davis result.

Power Reactors provide an intense source of low energy (a few MeV) electron antineutrinos, over 10^{13} cm^{-2} s^{-1}close to the reactor. These can provide event rates as high as 10 per day with a suitably massive detector. Searches for oscillations have studied the decrease of this rate as the detector is moved away from the reactor. It decreases in any case due to the inverse square law. Does it decrease even faster due to the disappearance of neutrinos on account of oscillation? So far there is no evidence to suggest that this is the case.

Big accelerators provide an intense source of high energy (tens of GeV) neutrinos, mostly ν_μ . The event rates in a massive detector can reach several per second. Experimenters look for the appearance of new neutrino types, e.g. a ν_τ in a beam which was initially ν_μ .

A novel source of neutrinos entered the scene in 1987 with the occurence of supernova SN1987A. A burst of neutrino induced interactions were observed in two underground detectors and analysis of the time structure of the arriving neutrinos has provided one of the best limits to date on neutrino masses.

NEW ACCELERATOR EXPERIMENTS

Given the importance of the topic one of the world's largest HEP laboratories, CERN near Geneva, has launched new searches for neutrino oscillations. Two experiments, NOMAD and CHORUS, will commence soon there.

The experimental group from the Research Centre for High Energy Physics at the University of Melbourne was invited to join one of the CERN experiments and the HEP group from the University of Sydney was invited to join the other. We decided to pool our efforts and are undertaking R&D towards constructing part of the NOMAD experiment. We have been joined in this enterprise by physicists from the Australian Nuclear Science and Technology Organisation (Ansto).

Neutrino beams are made by hitting a small target with high energy protons, 450 GeV at CERN, thereby creating many mesons. The decay of these mesons leads to a beam which is mostly ν_μ with a small component of ν_e . Figure 2 shows the spectrum of neutrinos of various types produced at CERN. Magnetic fields are used to focus positive mesons and to defocus negative ones and hence the beam contains many more neutrinos than antineutrinos. Theoretically about one produced neutrino in a million is a ν_τ although these have never been observed.

The two experiments will be mounted, one behind the other, about 900 m from the target. Both aim to detect ν_τ which have appeared in the beam on account of ν_μ (or ν_e) to ν_τ oscillations. Occasionally such a ν_τ will interact in one of the detectors to produce a charged τ lepton. The lifetime of a charged τ is less than a picosecond so, even with a Lorentz boost, it travels hardly any distance before decaying.

CHORUS will use photographic emulsions, with a spatial resolution of a few microns, to seek the short tracks left by such charged τ leptons. Looking directly for such tracks would be much worse than looking for a needle in a haystack and the search will be guided using a large electronic detector behind the emulsion to pick out potential τ production.

NOMAD (figure 3) is a sophisticated electronic detector in a 0.6 T dipole magnetic field which will measure with great precision the decay products of the any neutrino interactions. Kinematic selection criteria will be used to recognise any charged τ leptons through their decay products.

The complimentary nature of the two CERN experiments is a strong point. These are difficult experiments and two very different methods will increase the chances of observing oscillations should they occur.

Finding neutrino oscillations would be an experimental discovery of the first magnitude but we have to face the fact that nature can be unkind and neutrino oscillations may not exist or be beyond the sensitivity of the new experiments. The conclusion would then be to extend the forbidden region of mixing parameters and thus constrain existing theories. Figure 4 shows what NOMAD could achieve while CHORUS has almost identical goals. A gain of about an order of magnitude will be achieved and this can only occur if high statistics are accumulated.

The CERN experiments will need to collect data for 400 days spread over 2 years to obtain their results. In this period over a million "normal" ν_μ interactions will be recorded in each detector. Improvements in our knowledge of the Weak Interactions will be possible through the study of these data.

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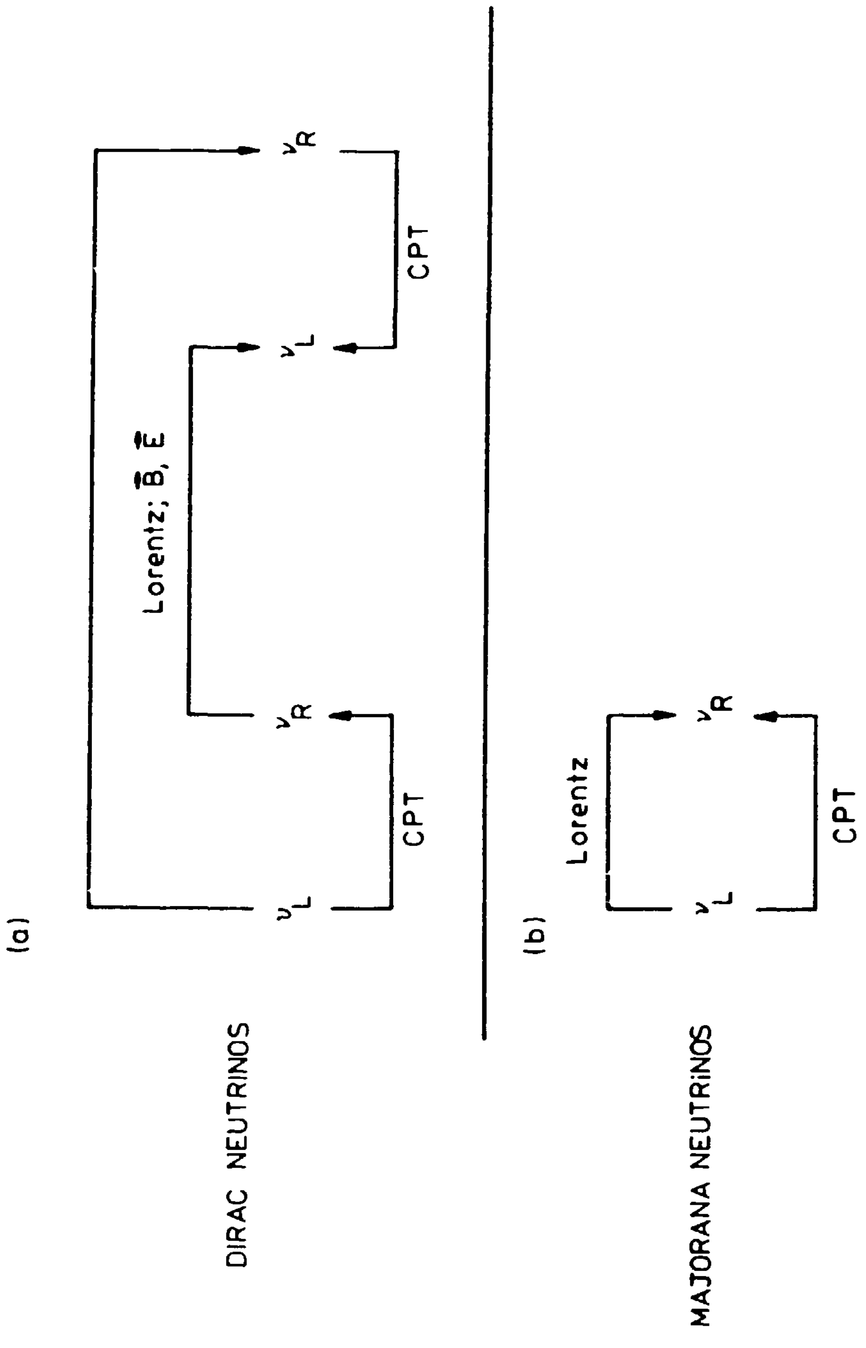

Figure 1: The effect of the combined operations of Charge Conjugation (C), Parity Inversion (P) and Time Reversal (T), and of Lorentz Transformations on: (a) a Dirac-neutrino and (b) a Majorana-neutrino.

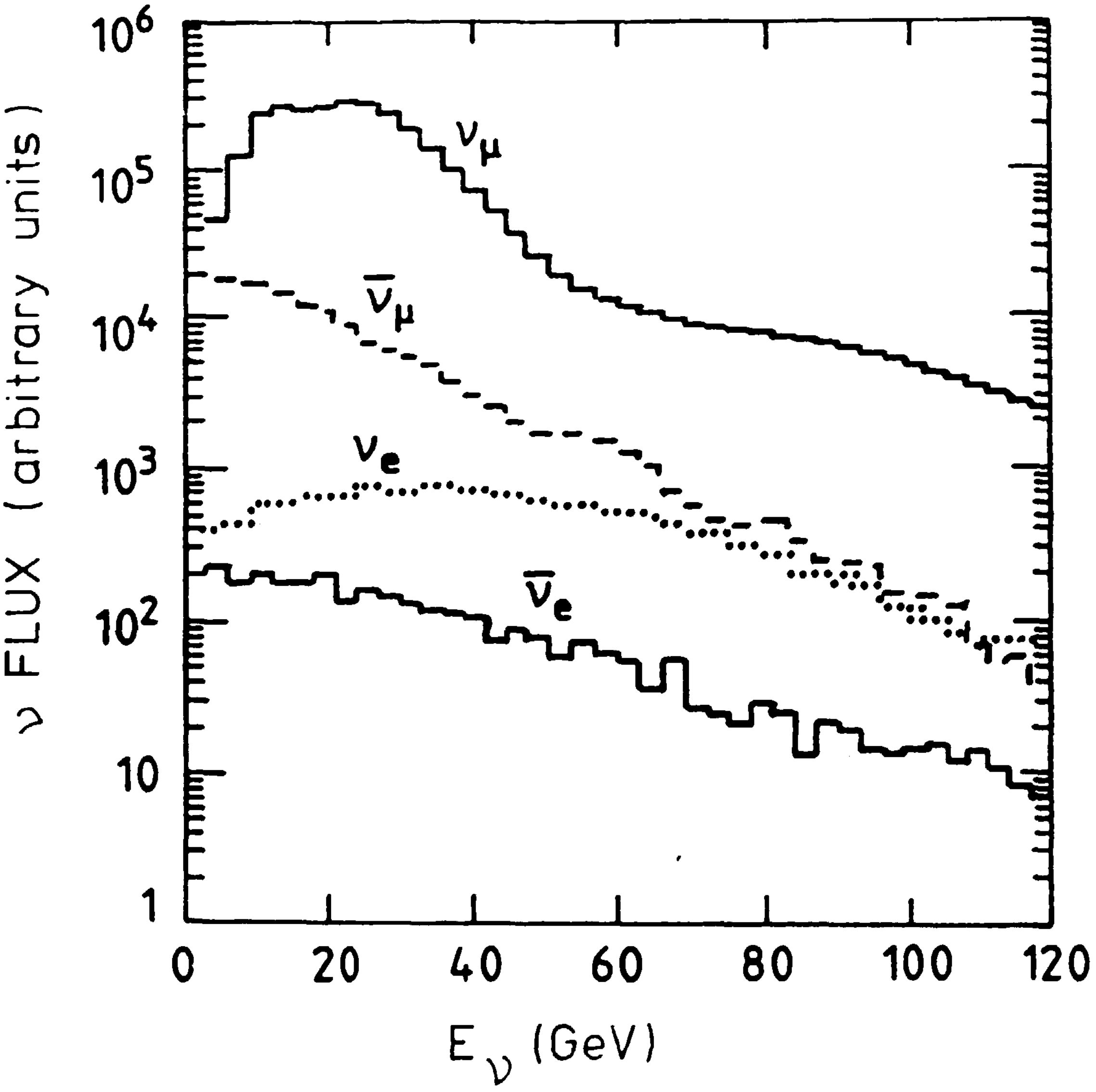

Figure 2: The fluxes of neutrinos expected in the CERN beam, as a function of energy, in arbitrary units. The beam is predominantly ν_μ but has significant numbers of ν_e and of anti-neutrinos.

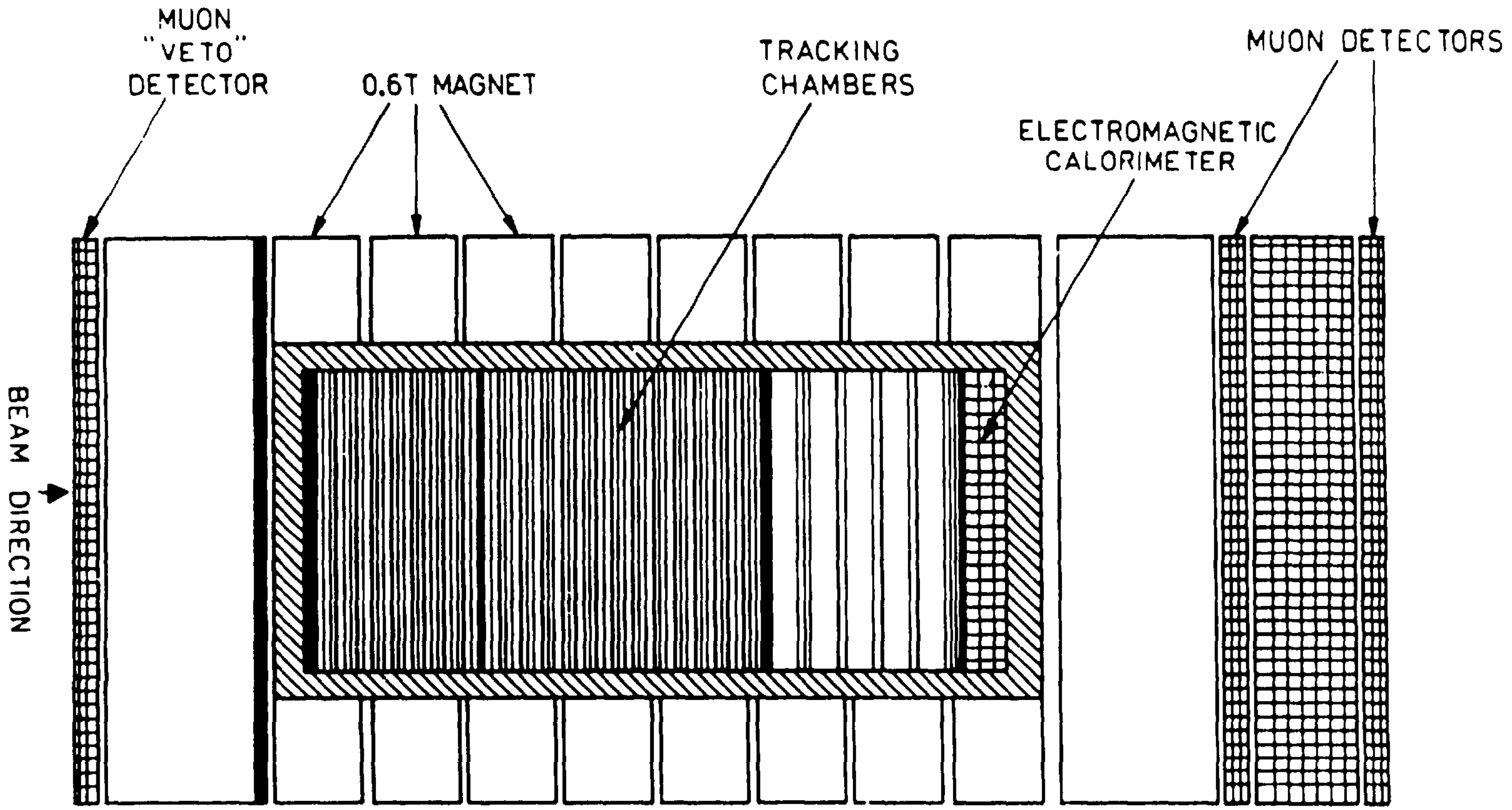

Figure 3: A simplified plan view of the NOMAD detector. The neutrino beam enters from the left.

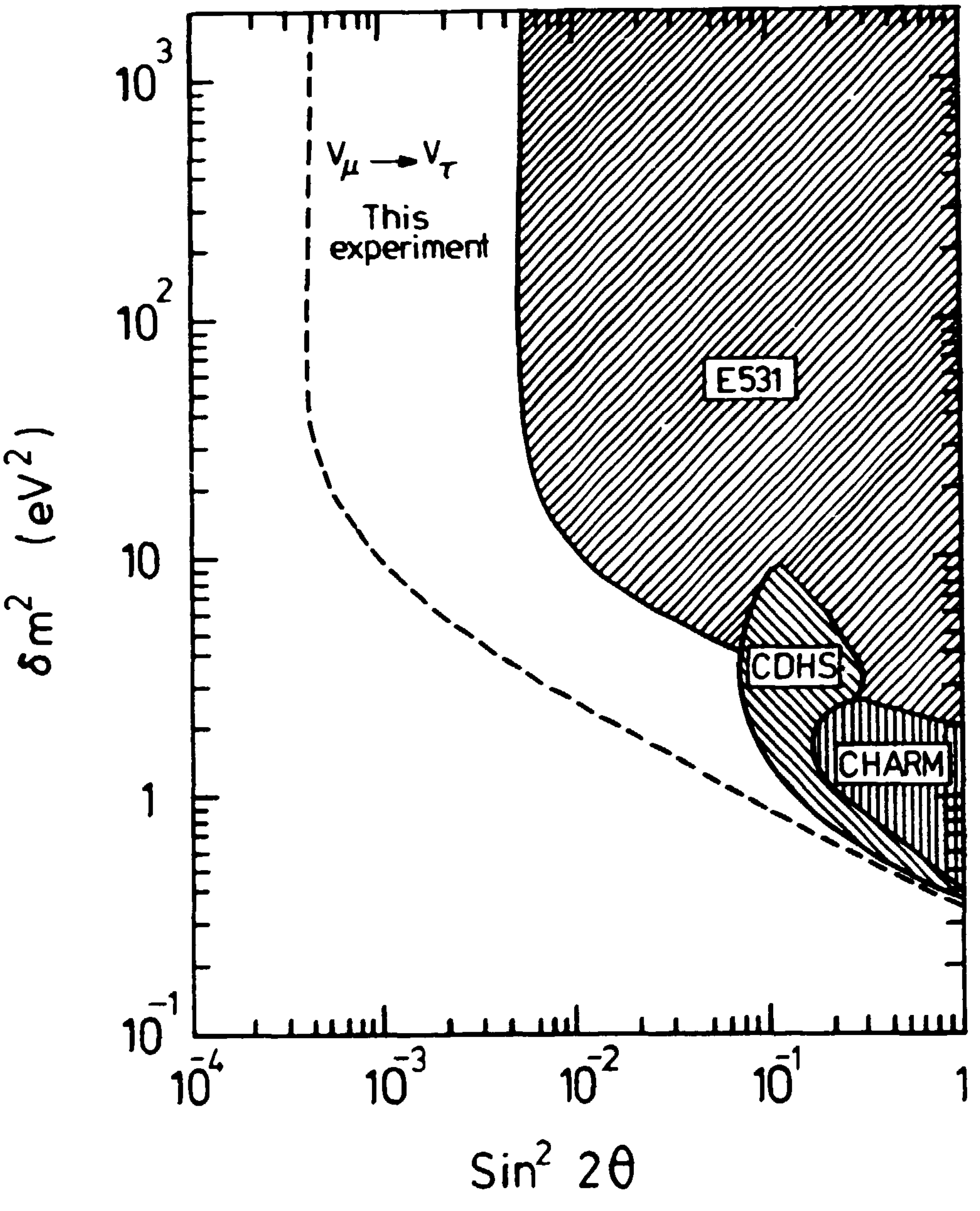

Figure 4: The space of the neutrino mixing parameters for ν_μ to ν_τ oscillations. The shaded regions are excluded by existing experiments, the best being E531, at the Fermilab near Chicago. Also shown is the region in which NOMAD will be sensitive to ν_μ to ν_τ oscillations.