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XIX RECONTRE DE MORIOND

Fourth Moriond Workshop on Massive Neutrinos in Particle- and Astro-Physics

SUMMARY TALK

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The theoretical arguments for neutrino mass are reviewed, and the present :atus of searches for neutrino mass in neutrino oscillations, direct measure- :nts and other experiments are summarized.

§ I. Introduction

We have heard many interesting talks at this Moriond Workshop on Massive Neutrinos in Particle- and Astro-Physics, and I will try my best to summarize the main themes. Please keep in mind that, of necessity, the views expressed are purely personal ones.

Let me begin by characterizing the excellent introductory talks of Vanucci[1], Kayser[2], and Steigman[3] with a few words from "Notre Père":

"Que ta volonté soit faite
"Sia fatta la tua voluntá   VANNUCCI
"Thy will be done

sur la terre
come in terra   KAYSER
on Earth

comme au ciel."
cosi in cielo."   STEIGMAN
as it is in Heaven."

As for me, should I omit something of importance, then please:

"forgive us our trespasses, as we forgive them that trespass against us."

Now to the physics! I shall first discuss the present-day theoretical prejudice about the mass of neutrinos, and the experimental methods for detecting it. Then I shall review the limits on masses and mixing angles as presented during the Workshop, and the plans for new experiments. Finally I shall summarize the present status of the field, as I see it.

(a) Theoretical Prejudice

In Grand Unified Theories (GUTS) of strong, electromagnetic, and weak interactions, it is natural for neutrinos to have mass! Zero is a special number, and there is no obvious reason why neutrinos should be different from other fermions, all of which do have mass. However, we must beware that the GUTS do not give us any firm predictions about the likely values of neutrino masses, as they did in the case of the proton lifetime. Indeed, as Kayser[2] has warned us, what predictions there are point toward much smaller masses, in the range $(10^{-6}-1)$ev, than are contemplated in most experiments today! Nevertheless it is important to pursue the question to the limits of present experimental sensitivity.

For all fermions f, we can construct a mass term by coupling the left-handed and right-handed chirality projections in the usual way:

$$M_D = M_D \bar{f}_L f_R \quad + \text{h.c} \tag{1}$$

Such terms conserve total lepton number and require that both fields f_L and f_R exist in the theory being considered. For neutrinos, and for certain other neutral fermions, we can construct a second type of mass term in which the left-handed field f_L coupled to its own charge-conjugate field f_{LC}, which is right-handed ($f_{LC} \equiv f_{CR}$):

$$\mathcal{M}_M \equiv \mathcal{M}_M \bar{f}_L f_{CR} + \text{h.c} \tag{2}$$

This term does not conserve lepton number (and for charged fermions it would not conserve charge), but it has the advantage that it can be constructed even when the right-handed field f_R does not occur in the theory. It has become customary to call the total lepton number conserving mass term of eq. (1) the Dirac mass term, and the lepton number violating term of eq. (2) the Majorana mass term.

In the simplest version of the Weinberg-Salam electro-weak theory, and in the simplest GUT (SU(5)), the right-handed neutrino does not occur. This suggests that if the neutrinos that take part in ordinary weak interactions (e.g. β-decay, μ-capture, τ-decay) do have mass, it must be of the Majorana variety. Morever, this suggestion carries through into those GUTS which do have room for right-handed neutrinos; the mass of the right-handed neutrino is assumed to be very large in the Gell-Mann-Ramond-Slansky[4)] mechanism, and the effective low-energy theory still contains only left-handed neutrino fields. Thus, in addition to the prejudice that neutrinos are massive (or massious[5)]) particles, GUTS also lend support to the notion that neutrino mass is, at least in part, of the Majorana variety.

Neutrino mass matrices which are either dominated by Majorana mass terms, or contain a significant component of such terms, have as their eigenstates, the so-called Majorana neutrinos. Strictly speaking, Majorana neutrinos are eigenstates of CPT, but it is often a good approximation to treat them as CP eigenstates; for some practical applications one can even work with eigenstates of charge conjugation.

Most of the experimental methods for detecting neutrino mass do not distinguish between the Dirac and Majorana varieties, but there is one phenomenon which does, namely no-neutrino double beta decay. This phenomenon is sensitive only to Majorana mass terms and provides no information about Dirac terms. We now turn to a discussion of these methods.

(b) Searching for Neutrino Mass (sur la terre).

Neutrino flavor oscillations will occur if the neutrino flavor eigenstates produced by weak interactions are actually linear combinations of mass eigenstates with different masses. As each flavor eigenstate evolves in time, these mass differences induce changes of phase between the mass eigenstates of which the original flavor eigenstate is composed, and in turn the changes of phase introduce into the neutrino state-vector components of flavor eigenstates which were not present when the particle was born. Detection of these additional flavors (appearance experiments), or of a depletion in the original flavor (disappearance experiments) would demonstrate qualitatively that there exists at least one neutrino with non-zero mass.

The simplest and most common way of analysing oscillation experiments is a two-state model in which the lepton flavors ℓ and ℓ' are assumed to be orthogonal combinations of the mass-eigenstates ν_1 and ν_2. The probability for the appearance of the second flavor ℓ' in a beam which is initially pure ℓ flavor is given by the familiar and oft-quoted formula:

$$P(\nu_\ell \to \nu_{\ell'}) = \sin^2 2\theta \sin^2 (\pi R/L) \tag{3}$$

and the probability for the disappearance experiment is

$$P(\nu_\ell \to \nu_\ell) = 1 - P(\nu_\ell \to \nu_{\ell'}) \tag{4}$$

In these formulae, the oscillation length expressed in kilometres is given by

$$L = 2.5 \ [E(\mathrm{Gev})/\Delta m^2(\mathrm{ev}^2)] \ \mathrm{km} \tag{5}$$

where $\Delta m^2 = m_1^2 - m_2^2$ is the squared-mass difference between ν_1 and ν_2.

When the distance R between neutrino source and detector is very large compared with L, then the oscillatory function $\sin^2(\pi R/L)$ goes through many cycles, and we detect its average value of ½. This situation gives us great sensitivity to very small mixing angle factors, $\sin^2 2\theta$, and it usually arises when Δm^2 is relatively large. When R is small compared with L, we can achieve great sensitivity to very small squared-mass differences Δm^2 as long as $\sin^2 2\theta$ is reasonably large (say $\gtrsim 0.2$). Thus, neutrino oscillations provide us with a very effective means for exploring those regions of the Δm^2 - $\sin^2 2\theta$ parameter space in which one parameter is extremely small while the other is quite large; in fact, oscillations are probably the best means for exploring mass differences down to the $10^{-10}\mathrm{ev}^2$ level.

At first sight direct determination of the neutrino mass in two- and three-body decays would seem to be the best way of determining whether the neutrino has a mass, and if so how large it is. In practice, however, experimental problems limit the sensitivity of the experiments, or create difficulties of interpretation. The tritium beta decay experiments, for example, have definitely established an upper limit of 55 ev on the mass of the electron-neutrino ν_e[6], and the present question is whether they also establish a lower limit. The claim of the ITEP group that this lower limit is 20 ev[7] has yet to be confirmed; a new round of experiments should be sensitive to a level somewhere in the 1-5 ev range, but there may be questions as to whether any effect observed would be due to the mass of the neutrino, or to the environment in which the daughter nucleus finds itself. As for the ν_μ and ν_τ masses, present techniques of two-body, or quasi-two-body decays have not gone lower than 500 kev for ν_μ and 170 Mev for ν_τ.

Besides the predominantly left-handed, and presumably light neutrinos ν_e, ν_μ, ν_τ, there could exist within the same families other, heavier neutrinos, which might be right-handed. There could also exist entirely new families of fermions with their attendant neutrinos, which might also be heavy. As Gronau[8] emphasized, the theoretical motivation for such neutrinos arises from attempts to understand the mass matrix. In the mechanism of Gell-Mann, Ramond, and Slansky[4] all neutrinos are Majorana particles, and each light left-handed neutrino has a heavy right-handed one associated with it. In other models, the light neutrinos are actually massless because of some discrete symmetry, and the right-handed ones become heavy Dirac particles. Whatever the model, we expect that all of the mass eigenstates become admixed into the flavor eigenstates, and we must try to determine, or set limits on the masses and mixing matrices.

One way of doing this is to search for secondary peaks in two-body decays such as K, $\pi \to \mu\nu$, and another is to look for "kinks" in three-body decay spectra, signifying the kinematic limits for heavy neutrinos. Other methods include searches for decays of heavy neutrinos in conventional beams, in beam dump experiments, and even in the decays of B-mesons and Z°-mesons; some care must be excercized in the interpretation of such experiments because the lifetimes of heavy mesons could be very long (see talks by Kayser[2] and Levy[9]). From these types of experiment we can set extensive limits on the masses and mixing matrices of heavy leptons, as has been discussed by Gronau[8].

The methods for detecting neutrino mass that we have discussed so far are not sensitive to the nature of that mass, to whether it is Dirac or Majorana. One method which is sensitive to this question is the phenomenon of no-neutrino double beta decay:

$$(A,Z) \to (A, Z + 2) + 2e^- \qquad (6)$$

This process can occur as a second-order effect of the usual beta-decay interaction only if:

(i) lepton number is not conserved, and

(ii) the helicity rule associated with (V-A) currents breaks down.

The Majorana mass term satisfies both of these conditions, whereas the Dirac mass term satisfies only the second one; hence no-neutrino double beta decay is sensitive to the Majorana mass term but not to the Dirac one. As we learned from the comprehensive review by Professor Kotani[10] and the experimental report from Dr. Zanotti[11], present experiments (which have not yet detected the no-neutrino decay) on Tellurium isotopes limit the mass to about 5 ev, and those on ^{76}Ge limit the mass to 5 ev or 14 ev, depending upon the theoretical nuclear matrix elements being used:

$$(M\nu_e)_{\text{Majorana}} \begin{array}{ll} \leqq 5 \text{ ev} & (\text{Te}^{128,130}) \\ \leqq 5 \text{ or } 14 \text{ ev} & (\text{Ge}^{76}) \end{array} \tag{7}$$

It should be noted that, even if the no-neutrino decay were observed, we could only set limits on the neutrino mass because small admixtures of right-handed currents in the weak interaction, of order 10^{-4} -10^{-5}, can mimic the effects of neutrino masses of the size given in eq. (7), insofar as the total rates are concerned. Angular correlations are needed to pick out the mass contribution.

Double beta decay is, of course, a low energy phenomenon. An interesting high-energy phenomenon which is also sensitive to the Majorana mass is a process I would like to call the "Grand Prix de Kayser". One takes very energetic positive pions ($E_\pi \sim$ 600 Gev), and looks to see whether the neutrinos produced in their decay will give birth to <u>positive</u> muons when they strike a nucleus, rather than to negative muons. This two-step process has the effect of producing two positive muons and no neutrinos from an initial state that contained no leptons, and so it violates lepton number conservation in exactly the same way as no-neutrino double beta decay.

If one made no attempt to select the neutrinos in the "Grand Prix", then one could set a limit on the parameter $(M_\nu/\langle E_\nu\rangle)$. For energetic pions, the average energy of the neutrino will be high, and hence the limit obtained would not be very severe. However, Kayser[2] argues that if one selects those neutrinos which travel backwards in the pion center-of-mass frame, then the Lorentz transformation into the laboratory frame will flip the neutrino helicity (provided that $M_\nu \neq 0$) and thereby enhance the probability for the neutrino to create a μ^+ at the second stage of the process. This enhancement, Kayser hopes, can greatly tighten the limit on M_ν.

<u>(c) Astrophysical Limits (comme au ciel).</u>

We heard from Steigman[3] that arguments concerning the age of the Universe, its expansion, and the existence of dark matter on various scales indicate that the neutrino mass should fall within the broad range:

$$M_\nu \sim 10 - 100 \text{ ev} \tag{8}$$

Stable neutrinos with masses between a few ev and a few Gev would dominate the Universe, but there are problems, especially for light neutrinos. Such particles could stream freely through the Universe and damp out the perturbations responsible for galaxy and galactic cluster formation. Thus neutrinos with masses in a range somewhere between 25 to 100 ev at the lower end and 2 to 5 Gev at the upper end must be unstable.

These arguments do not distinguish between Dirac and Majorana masses; moreover, some of them appear to be quite controversial. For example, we heard from Lafon[12)] that on the scale of galaxies the roughly constant behaviour of rotation curves does not necessarily imply a halo of dark matter. Lafon has found distributions of visible matter that yield rotation curves consistent with those actually seen; to distinguish between distributions of visible matter and dark haloes, one will have to study the distribution of angular momentum in galaxies.

§ II. The Experimental Situation

Let me now review the experimental data presented at this Workshop. I shall begin with neutrino oscillations, direct measurements, and the solar neutrino problem, and then move on to a discussion of limits on masses and mixing angles for heavy neutrinos.

(a) Neutrino Oscillation Limits.

In order to summarize the limits on oscillations, I shall make use of the $\Delta M^2 - \sin^2 2\theta$ plot and look for any trends indicated by the data. Thus I shall not pay too much attention to the wiggles that occur in the data from individual experiments, but concentrate instead upon the limits of small $\sin^2 2\theta$ obtained when ΔM^2 can be large, and upon the limits of small ΔM^2 obtained when $\sin^2 2\theta$ is itself quite large. As indicated in fig. (1), the narrow allowed region along the ΔM^2-axis is called "La Manche", and that along the $\sin^2 2\theta$-axis is called "Le Doigt."

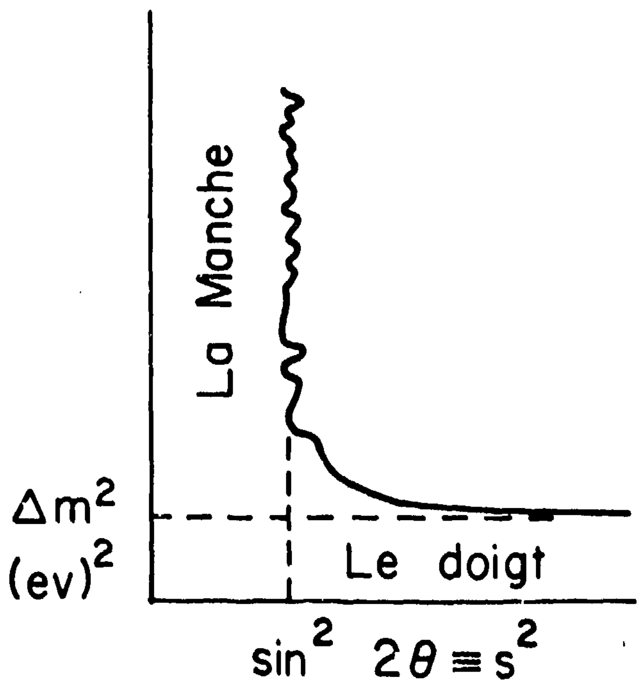

Figure (1) Neutrino Oscillation Limits in the $\Delta m^2 - \sin^2 2\theta$ Plane.

The tendency of much of the data is to push us more and more into the region of La Manche - low $\sin^2 2\theta$ (henceforth called s^2) and possibly large ΔM^2. In

TABLE I, I have assembled the limits presented by various experiments to the Workshop, and one can see that, while the limits on ΔM^2 obtained from accelerator experiments tend to remain in the range of 0.2 → 1 ev^2, the limit on s^2 gets down to 5×10^{-2} in both the CDHS and Fermilab ν_μ disappearence experiments, and in the CHARM $\nu_\mu \rightarrow \nu_e$ appearence experiment. At Brookhaven, the limit on s^2 for $\nu_\mu \rightarrow \nu_e$ has been pushed down to the level of 5×10^{-3}, but at a cost of a much larger mass difference, $\Delta M^2 \simeq 10$ ev^2.

Reactor experiments on $\bar{\nu}_e$ disappearence are not so sensitive to small s^2, but they do yield much tighter limits on ΔM^2. The Goesgen reactor experiment has

TABLE I: Neutrino Oscillation Limits

	$\nu_\mu \rightarrow \nu_x$		$\nu_\mu \rightarrow \nu_e$		$\bar{\nu}_e \rightarrow \bar{\nu}_x$		Notes
	Δm^2	s^2	Δm^2	s^2	Δm^2	s^2	
CHARM[13)]	0.3	0.2	0.2	0.05			
CDHS[14)]	0.25	0.05					"Best fit" $\Delta^2 = 0.32$ $1^2 = 0.2$
BNL[15)]			10	0.005			
FNAL[16)]	1	0.05					Room for osc. in large Δ^2
Goesgen[17)]					10^{-2}	0.15	small s^2
		(A change in τ_n could raise to 0.2)					$\Delta^2 = 500$, $s^2=0.06$
Le Bugey[18)]					0.1	0.10	High statistics Hint at $\Delta^2 = 0.6, s^2 \sim 0.1$
Beam Dump[19)] Oh Brave New World!	G. Conforto						$\nu_e \rightarrow \nu_\tau$ with $\Delta = 360 \pm 40$ $s^2 = 0.32 \, ^{+018}_{-0.08}$

pushed ΔM^2 down to 10^{-2} ev^2 for $s^2 \gtrsim 0.2$, while Le Bugey has achieved a level of 10^{-1} ev^2 in a relatively short period of running. Le Bugey, a large power reactor near Lyons, is a promising newcomer to the field: it has very high power (2750 MW), and offers an excellent location for a detector just 13.6 m below the core! A second position to the right of the first and 18.7 m from the core is also being used. One looks forward to a significant improvement in statistics and sensitivity with this experiment[18].

Almost all of these experiments report hints that there may be an oscillation in the data. In the case of ν_μ- disappearence, for example, CDHS gives a "best fit" to the data with $\Delta^2 = 0.32 \mathrm{ev}^2$ and $s^2 = 0.2$. while the Fermilab experiment could accommodate an oscillation with large mass difference and small mixing angle, namely $\Delta^2 = 500\ \mathrm{ev}^2$, $s^2 = 0.06$. Similarly Le Bugey has a hint of an oscillation in $\bar{\nu}_e$- disappearence with parameters $\Delta^2 = 0.6 \mathrm{ev}^2$ and $s^2 \lesssim 0.1$. In none of these experiments, however, do the experimentalists make any strong claims for the existence of oscillations because of uncertainties in their knowledge of such items as normalizations, backgrounds, and theoretically calculated spectra. There is, in another type of experiment, one exception to this cautious attitude.

Gianni Conforto[19] has analysed a series of Beam Dump Experiments carried out by the BEBC, CDHS, and CHARM detectors at CERN between 1977 and 1982, and by the FMOWW group at Fermilab in 1981-82, and he believes that there is clear evidence for neutrino oscillations. He argues that: (i) the ratio of "prompt" electron-type neutrinos to "prompt" muon-type neutrinos is definitely smaller than unity in certain groups of experiments; and (ii) that the ratio shows a definite dependence on the distance between dump and detector. From a statistical analysis of the data, he concludes that the probability that no oscillation is taking place is about 2×10^{-4}, while the probability for an oscillation is approximately 35%.

To fit the data, which is summarized in the following table, Conforto adopts the admittedly simple hypothesis that ν_μ does not undergo oscillations, while the

TABLE II: Summary of Beam Dump Data

Experiments (n = number of detectors)	Distance	$\langle \nu_e/\nu_\mu \rangle$	χ^2
CERN (77-79) (n = 3)	~ 900 m	0.57 ± 0.09	0.58
CERN (1982) (n = 2)	~ 450 m	0.74 ± 0.10	4.5
Fermilab (81-82) (n = 1)	~ 60 m	1.09 ± 0.09 ± 0.10	-

ν_e oscillates into some unspecified neutrino ν_x. He then finds that the best fit to the data is an oscillation with parameters

$$\Delta^2 = (360 \pm 40)\ \mathrm{ev}^2$$
$$\sin^2 2\theta = 0.32^{+0.18}_{-0.08} \tag{9}$$

The value for $\sin^2 2\theta$ is just within two standard deviations of the Goesgen limit on $\bar{\nu}_e$-disappearence.

Conforto believes that $\nu_e \leftrightarrow \nu_\tau$ oscillations provide the most reasonable interpretation of this data, but he would be glad to examine other hypotheses. He is presently engaged in a more refined analysis.

b) Direct Mass Measurements

On the subject of the direct measurement of neutrino mass, we heard about new experiments on the muon- and tau- neutrinos, and a discussion of the preparations for new efforts to measure the mass of the electron-neutrino in tritium beta decay. Le Coultre[20] described an experiment at SIN in which pions decaying in flight are used to set an upper bound on the ν_μ mass. The energies and decay angle of the parent pion and daughter muon are measured with the aid of an 180° degree magnetic spectrometer, the decay point being determined by time-of-flight. The neutrino momentum, as determined from the vector difference between pion and muon momenta, is then compared with the momentum expected for a zero-mass neutrino and a limit of

$$M_{\nu_\mu} < 0.50 \text{ Mev/c}^2 \qquad (90\% \text{ C.L.}) \tag{10}$$

is extracted from the data with 90% confidence limit.

By far the hardest part of the experiment is the measurement of the decay angle between the pion and muon, and it will require a significant improvement in this measurement in order to improve the above limit by a factor of 2-3. It is interesting to note that, at this time, the limits on $M\nu_\mu$ from decay in flight are very similar to those obtained from decay at rest. Deutsch[21] has suggested that one may be able to push these limits much farther down by looking at the "Concorde Edge" of the Dalitz plot for $\mu^- + Li^6 \rightarrow 2H^3 + \nu_\mu$; this is analogous to studying the end-points of β-spectra.

The previous limit on the tau-neutrino mass of 250 Mev/c^2 has now been reduced to 173 Mev/c^2 in an experiment by the Mark II collaboration[22] at PEP. Whereas the earlier limit was obtained from the decay of the tau-lepton into relatively light systems ($\tau \rightarrow e\, \nu_e\, \nu_\tau$, $\pi\, \nu_\tau$), the new one comes from decay into a heavy system, $\tau \rightarrow 3\, \pi^{\pm}\, \pi^0\, \nu_\tau$. The experiment has been carried out at a PEP beam energy of 14.5 Gev, and a search was made for τ-decays in which the four pions have a total energy of at least 8 Gev. Of the 55 events found to satisfy the cuts, some 14 have an invariant four-pion mass greater than 1.5 Gev. The distribution of these events is compared with the theoretical distribution for $\tau \rightarrow \rho'\, \nu_\tau$, appropriately smeared by the experimental resolution, and the result

$$M_{\nu_\tau} < 173 \text{ Mev/c}^2 \qquad (95\% \text{ C.L.}) \tag{11}$$

is obtained at the 95% confidence level. Under certain conditions this limit can be reduced to 160 Mev/c^2, but it is generally stable against variations of the parameters used in the analysis.

Given the enormous interest in the latest results on $M\nu_e$ obtained by the Moscow group[7] (ITEP-83), it is a great shame that no member of the group has come to the workshop to discuss the details of their tritium β-decay experiment and to respond to questions. The fact that, with greatly improved statistics, background rejection, and resolution, they can set a <u>lower</u> limit of 20 ev on $M\nu_e$ is a result of primary significance, and we are all eager to see whether other experiments will confirm it. In the meantime, questions have been raised about the response function used in the analysis of ITEP-83[23], and it would have been most useful to learn the answers to them. I hope the experts in the field will forgive me if I record my own "gut feeling" that this line of questioning represents the last obstacle to general acceptance of the ITEP-83 result.

Besides the lower limit on $M\nu_e$, there are other very interesting results from the Moscow experiment, in particular the "best fit" of

$$M_{\nu_e} = 33 \pm 1.1 \text{ ev} \tag{12}$$

and the hint, arising from the break in the spectrum at approximately 18,560 ev, that two neutrino mass-eigenstates may be emitted in β-decay. Robertson[24] gave a verbal report of the following two possibilities for the masses and mixing angles:

$$M_1 = 0 \quad ; \quad M_2 = 80 \text{ ev} \qquad 80\% \quad ; \quad 20\% \tag{13a}$$

and

$$M_1 = 22 \quad ; \quad M_2 = 114 \text{ ev} \qquad 95\% \quad ; \quad 5\% \tag{13b}$$

The first possibility is not consistent with the Goesgen limit on mixing angles and ΔM^2 ($\sin^2 2\theta < 0.2$ implies that $\sin^2 1\theta < 0.05$), but the second one is consistent, falling as it does within La Manche.

A number of new tritium decay experiments are under construction. Bergkvist[23] has rebuilt the electrostatic-magnetic high-luminosity spectrometer that he used to set the original upper limit of 55 ev on $M\nu_e$, and he has already achieved order of magnitude improvements in the control of the electric and magnetic fields, and in background rejection. He will use a large source of tritium embedded in aluminum, and he hopes to develop a source of better quality than the original one. His game plan is to try and confirm that $M\nu_e$ must be different from zero before attempting a precision measurement of its actual magnitude.

Robertson[24)] described an experiment under way at Los Alamos in which the source of tritium is an atomic beam and the decay electrons are analysed by an improved version of the Tretyakov spectrometer used in the Moscow experiment. Because the tritium comes in the form of free atoms, the final-state effects are well understood and there are no problems associated with source backing. Ultimately the experiment hopes to achieve an unambiguous result at, or below the mass level of 10 ev.

An experiment which is generally expected to produce the first new results in the near future is being performed by a Zurich group at S.I.N.[25)] It makes use of a "secret" source and a Tretyakov-type spectrometer. The resolution function can be calculated with some confidence, and measurements have been made to check the calculations. The group hopes to reach a level of ~ 10 ev for the neutrino mass, which is certainly sufficient to check the ITEP result.

Fackler and Mugge[26)] talked about an experiment at the Lawrence Livermore National Laboratory which makes use of frozen molecular tritium as its source. Fackler discussed the extensive calculations that have been performed in order to elucidate the final state problem, and Mugge described the experimental set-up, including the electrostatic spectrometer. They hope to have preliminary results by late 1984, and expect to determine the neutrino mass to within ± 2 ev as long as $M\nu_e > 4$ ev.

The considerable attention devoted by the Livermore group to the problem of final states serves to underline the importance of understanding the environment of the tritium source when it is embedded in some matrix, or frozen into a molecular state. Because the environment can engender small shifts in the final state energy levels of the decaying nucleus, it can simulate the effects of a non-zero neutrino mass in the Kurie plot. Therefore, without a thorough understanding of the final state energy levels, one cannot decide whether signals for a non-vanishing neutrino mass found in Kurie plots are real or spurious. For experiments with free atoms, the environmental problem is much less severe than it is for atoms bound in molecules or other matrices.

A different method of measuring the neutrino mass is provided by the phenomenon of "Inner Bremstrahlung Electron Capture" (IBEC) or "Radiative EC Beta Decay"[27)]:

$$Z + e_{n\ell j} \rightarrow (Z - 1) + \nu_e + \gamma \tag{14}$$

The end-point of the γ spectrum is sensitive to a non-zero neutrino mass in much the same way as is the Kurie plot, and the effect can be strongly enhanced if the capture takes place from a P-state[27)]. A recent experiment on ^{193}Pt verified the basic theory of the process developed by Glauber and Martin (1956) and by de Rujula (1981), and it set a limit of 500 ev/c^2 on $M\nu_e$. The nucleus ^{163}Ho is regarded as the most promising case for neutrino mass measurements and an experiment described by Ravn is being performed at CERN. Bennett is using this isotope at Princeton, and Raghavan[28)] has suggested ^{158}Tb as another favorable case.

(c) The Solar Neutrino Problem

The solar neutrino problem, which led Pontecorvo to revive his original idea of neutrino oscillations in 1967[29)], is still with us, some seventeen years later! We still cannot say for sure whether the discrepancy between the rate observed in the Davis experiment and the theoretically calculated rate is due to neutrino oscillations, or to a faulty model of the sun, or to some subtle error in the experiment.

To indicate the gravity of the problem, let us recall that there are three major components of the solar neutrino flux:[30)]

(i) pp neutrinos with energies in the range $0 \leq E_\nu \leq 420$ kev and a flux of 6×10^{10} ν_e/cm^2 sec;

(ii) Be^7 neutrinos which are monochromatic with $E_\nu = 861$ kev and have a flux of 4×10^9 ν_e/cm^2 sec; and

(iii) B^8 neutrinos with energies in the range $0 \leq E \leq 14$ Mev and a relatively small flux of 3×10^6 ν_e/cm^2 sec.

The $\nu_e + C\ell^{37} \rightarrow e^- + Ar^{37}$ reaction has a threshold of 814 kev, and so it is sensitive predominantly to the B^8 neutrinos and partially to the Be^7 ones; it has no sensitivity to the major component of the spectrum, namely the pp neutrinos. Averaged over the last three or four years of observation, the experimental rate for the reaction as measured by Davis and his colleagues is[30)]:

$$\langle \text{Exp t}\ell \text{ Rate} \rangle = 2.2 \pm 0.4 \text{ SNU} \tag{15}$$

and the theoretical rate is[30)] either

$$\langle \text{Theor. Rate} \rangle_{\text{Bahcall}} = 7.6\ (\pm\ 40\%)\ \text{SNU} \tag{16a}$$

or

$$\langle \text{Theor. Rate} \rangle_{\text{Münster}} = 4.95\ (\pm\ 40\%)\ \text{SNU} \tag{16b}$$

depending upon whether one uses the Cal Tech value for the parameter S_{34} describing the reaction $He^3 + He^4 \rightarrow Be^7$ (eq. 16a) or the Münster value for it (eq. 16b). The former tends to be the more favored value, but in either case, there is a significant difference between theory and experiment.

According to Schatzman[30)], it is possible to change the solar model in such a way that: (i) it is still consistent with what is understood about Li burning, and with both pressure and gravity modes of solar oscillations; and (ii) the flux of B^8 neutrinos is a factor two smaller than in the standard calculations. However, it would be much harder to reduce this flux by the factor ~4 required by eqs. (15) and the Bahcall rate of eq. (16a). Schatzman also emphasises that the flux of pp neutrinos is proportional to the solar luminosity and subject to no more than a 10% uncertainty; consequently, if the pp neutrinos should not be observed at the theoretically predicted rate, then they must oscillate into flavors which do not undergo charged current nuclear reactions at low energies. It follows that the search for pp neutrinos ' the most important next step in the effort to resolve the solar neutrino neutrino problem. Because of the very long baseline, it could also be the oscillation experiment most sensitive to extremely small mass differences ($\Delta^2 \simeq 10^{-12} ev^2$).

Spiro[31] described a new effort to mount the indium experiment originally proposed by Raghavan. The reaction

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^{**}(7/2) \tag{17}$$

has a threshold of 120 kev, and so it is sensitive to both the pp neutrinos and the ^7Be neutrinos. By measuring the energy of the electron, Spiro hopes to separate these two components of the neutrino spectrum and thereby gain some information about nuclear reactions in the sun.

Unfortunately, the estimated rates are low, being 0.25 events/ton In/day for pp neutrinos and 0.05 events/ton In/day for ^7Be neutrinos. The major background comes from the β-decay of ^{115}In to the ground-state of ^{115}Sn which has a half-life of 5×10^{14} years! Spiro and his colleagues are looking for clever ways to overcome this difficulty, and one technique they are considering is that of superconducting granules. A typical granule is of order 10 microns in diameter and, when it is cooled to a sufficiently low temperature, the energy deposited by a single neutrino is sufficient to restore it to the normal state. The major experimental problem is being able to read out magnetic flux changes in every granule in the detector; Waysand[32] described some ways by which it might be overcome.

Superconducting granules represent an exciting new possibility for detectors of all kinds. Stodolsky and Drukier[33] would like to use them as a "neutral current" detector for all types of neutrino, including solar, reactor, terrestrial, and supernova neutrinos; their basic idea is to make the granules sensitive to the coherent forward scattering of neutrinos arising from the neutral current interactions of the standard model. Gonzalez-Mestres and Perret-Gallix[34] would like to use them to detect monopoles, and to measure their velocities. In addition, it may be possible to apply the superconducting granule technique to detectors at accelerators.

Returning to the solar neutrino problem, we note two other experiments which are being seriously pursued. One is the gallium experiment, based upon neutrino capture in ^{71}Ga giving rise to ^{71}Ge, and the other is the bromine experiment, in which neutrino capture by ^{81}Br gives rise to the noble gas isotope ^{81}Kr. The gallium experiment has a threshold of 236 kev and it is sensitive to both pp and ^{7}Be neutrinos; however, because the detection method is radiochemical in nature, it cannot distinguish directly between these two components of the neutrino spectrum. Like the original chlorine experiment, the bromine experiment is sensitive only to the ^{7}Be and ^{8}B neutrinos, but in a different combination; since ^{81}Kr is metastable, with a half-life of ~200,000 yrs., one cannot use radiochemical detection, and so G. S. Hurst[35)] is planning to make use of Resonance Ionization Spectroscopy, a very sensitive laser detection technique.

(d) Double Beta Decay

Of the two anticipated modes of nuclear double beta decay, one, the two-neutrino mode, is expected to occur as a second-order effect of the effective Hamiltonian for single β-decay, and the other, the no-neutrino mode, will occur only if lepton number and the (V-A) helicity rule are both violated. The expectation in most grand unified theories is that these violations will occur through a Majorana mass term for neutrinos, but right-handed currents (V+A) may also be present. Kotani[10)] has given us a thorough review of the present status of the subject and its relationship to the other phenomena discussed here, and I will try to summarize the situation.

There are several important and presently unresolved problems in double beta decay, some theoretical and some experimental: let me begin with the experimental ones. The earliest definitive evidence for the actual occurrence of the double beta decay phenomenon came from geochemical experiments on ^{130}Te and ^{82}Se. Even though the lifetimes observed in these experiments are consistent with expectations for the two-neutrino mode ($\sim 10^{21 \pm 2}$ yrs), they cannot be used to rule out the existence of the no-neutrino mode because only the daughter nuclei are detected in the geochemical method. Many laboratory experiments to detect the emitted electrons have been attempted, but only one, by Moe and Lowenthal[36)] has claimed any success. Using a cloud chamber and a source of ^{82}Se, they have detected about fifteen candidates which fit the pattern for the two-neutrino mode and correspond to a lifetime of $\sim 10^{19}$ years. Unfortunately, however, this lifetime is an order of magnitude shorter than that measured geochemically: thus the debate rages as to whether the events seen by Moe and Lowenthal are actually due to some very low level background contamination, or whether the geochemical method is inaccurate.

There is also a problem within the geochemical method itself. Many years ago Pontecorvo[37] invented the tellurium ratio argument as a test for which double beta decay mode might be the dominant one. His argument was that, as long as the nuclear matrix elements for the decays of the isotopes ^{128}Te and ^{130}Te can be taken to be approximately equal, the ratio of their lifetimes will be given by the ratio of the appropriate phase spaces; moreover the ratio for the no-neutrino mode is small (of order 10), while that for the two-neutrino mode, with four fermions in the final state instead of two, is much larger (~7000). The first significant measurement of this ratio in 1974 gave a value of ~1600, which is intermediate between the two extremes and which was interpreted by Bryman and Picciotto[38] as implying that the no-neutrino mode occurs through a right-handed current of strength 10^{-4} times that of the left-handed current. Dr. Kotani and his colleagues[39] subsequently re-interpreted the same result as implying a Majorana mass of order 40 ev. Last year, however, the Heidelberg group re-measured the ratio and found it to be much larger[40], which implies an upper limit of only 5.4 ev on the neutrino mass. On grounds of caution alone, one should favor the smaller limit, but it would be helpful to have another measurement.

The most significant theoretical problem is the calculation of the nuclear matrix elements for double beta decay. Primakoff and I originally made a very crude estimate of 0.1, but allowed ourselves an order of magnitude lee-way on either side. More sophisticated calculations by Vergados suggest that they are much closer to unity, while Haxton, Stephenson, and Strottman find values in the range of 2-3. While the former authors calculate lifetimes for the two-neutrino mode that are consistent with the geochemical measurements, the latter obtain much shorter lifetimes. For example the Haxton et al lifetime for ^{82}Se is 6 times shorter than the geochemical value and within a factor of 2 of the laboratory value obtained by Moe and Lowenthal; for ^{130}Te, the Haxton et al lifetime is 150 times shorter than the geochemical one! Recent calculations by Zamick and Auerbach, Huffman, and Klapdor and Grotz all tend to confirm the Haxton et al matrix elements.

Despite these problems, one can still gain some valuable insights from mass limits in double beta decay. As mentioned above, the tellurium ratio argument gives an upper limit of less than 6 ev on the Majorana mass. If we take the latest bound on the no-neutrino decay of ^{76}Ge as given in the talk by Zanotti[11], we find that the Majorana mass must be less than 14 ev if we use the Kotani matrix element, or less than 6 ev if we use the Haxton et al matrix element. In all cases, these upper bounds are smaller than the lower bound of 20 ev obtained by ITEP-83. Therefore, to the extent that we accept these experiments, there appears to be a conflict between the mass limits from no-neutrino double beta decay and those from tritium beta decay.

One way out of this conflict is to say that the Majorana mass term is zero and the neutrino is a pure Dirac particle. This, however, runs counter to the prevailing theoretical prejudice that neutrinos are Majorana particles. Therefore it behooves theorists to find a clever way out of this dilemma.

The way out was implicit in an early remark of Kotani et al[41] that the contributions of different mass-eigenstates to the no-neutrino amplitude could cancel one another. Thus was born the "Pseudo-Dirac" neutrino, which is a coherent linear combination of two Majorana neutrinos with opposite CP eigenvalues and almost degenerate masses -- the analogue, in fact, of the K_1-K_2 system. The opposite CP eigenvalues ensure that the neutrinos interfere destructively in the no-neutrino decay, and the near degeneracy ensures a very small amplitude. Another realization of this idea is to have one light neutrino and one heavy neutrino, again with opposite CP eigenvalues. In the Pseudo-Dirac case the "effective mass" extracted from the measured lifetimes will be the same for all parent isotopes, whereas in the light-heavy scenario it will vary from isotope to isotope because of the propagation of the heavy neutrino through the nucleus[47]. Thus, if the no-neutrino decay mode is eventually discovered, it will be important to measure its rate and extract an effective mass for several parent nuclei.

Two experiments which hope to detect the no-neutrino double beta decay of ^{76}Ge are the "new set-up" in the Mont Blanc Tunnel[11] and the Santa Barbara-LBL experiment[43]. The "new set-up" has a total volume of 169 cc of high purity germanium as compared with 143 cc in the original experiment, and it sits in a much cleaner vessel. In 941 hours of running it has achieved a lifetime limit (1.3×10^{22} years at 68% confidence level) which compares very favorably with the limit (4.7×10^{22} years at 68% c.l.) ahieved by the old detector in 10,068 hours of operation! The old detector is now being used in an attempt to find the $0^+ \to 2^+$ transitions in ^{128}Te and ^{130}Te; for no-neutrino decay these transitions would signal the presence of right-handed currents.

The Santa Barbara-LBL experiment is a much larger one[43], involving eight detectors each of which is comparable in size with the new Mont Blanc detector. Special care has been taken to improve the purity of the germanium and to reduce the activity in the materials from which the detector housing is fabricated. Discrimination against external β-particles, multiple Compton scattering, and cosmic ray neutron induced backgrounds is achieved by surrounding each germanium crystal with ten 15 cm thick Na I detectors. In one year of running, it is hoped to set a limit of 1×10^{24} years on the ground-state to ground state ($0^+ \to 0^+$) transition, and a comparable limit on the $0^+ \to 2^+$ transition; in the absence of right-handed currents, this corresponds to a mass limit of 2 ev with the Kotani matrix element, and 1 ev with the Haxton et al matrix element.

Some other experiments on ^{76}Ge were not discussed at this meeting. They include one by the South Carolina-Battelle group (Avignone et al), and one by a Cal Tech-S.I.N. collaboration (Boehm et al).

(e) Search for Heavy Neutrinos.

As Gronau emphasized in his talk[8], the theoretical motivation for continuing to search for heavy neutral leptons includes the possible existence of a fourth generation, each of whose members would be significantly heavier than their partners in present generations, and the necessity for heavy partners for the known light neutrinos as envisaged in the Gell-Mann-Ramond-Slansky and Yanagida mass mechanisms. Shrock[44] has pioneered the notion of searching for anomalous spikes in two-body decays and kinks in three-body decay spectra, as a means of setting limits on masses and mixing matrix elements, and several experiments of this type were discussed at this workshop.

We heard from Schreckenbach[17] about the search for kinks in the spectra of the $\beta\pm$-decays of ^{64}Cu; the experiment yields limits on $\sin^2\theta$ ($\equiv |U_{eH}|^2$) in the range 10^{-2} to 10^{-3} for a heavy neutrino mass in the range $100 \leq M_H \leq 400$ kev. If the heavy neutrino is a Majorana particle, then the limits on $\sin^2\theta$ obtained by Simpson from double beta decay are about an order of magnitude more stringent.

Olin and Prieels[45] discussed the search for spikes in $\pi \to e\,\nu_H$. From the Triumf experiment, Olin extracts limits on the mixing matrix element $|U_{eH}|^2$ in the range 10^{-5} to 10^{-6} for $20 \leq M_H \leq 120$ Mev. Prieels, in an experiment at SIN, hopes to push these limits down by an order of magnitude. In another Louvain - SIN collaboration, this time on μ-capture in ^{3}He, Prieels and his colleagues hope to push the limits on muon-heavy neutrino mixing matrix elements $|U_{\mu H}|^2$ down to the 10^{-3} to 10^{-4} level for masses in the range $20 \leq M_\mu \leq 100$ Mev. This will help to fill in the gap between the limits obtained at SIN from $\pi \to \mu\nu$ ($|U_{\mu H}|^2 \leq 10^{-4}$ to 10^{-5} for $M_H \leq 20$ Mev) and those found by KEK in $K \to \mu\nu$ ($|U_{\mu H}|^2 \leq 10^{-5}$ to 10^{-6} for $100 \leq M_\mu \leq 200$ Mev).

Eventually we may be able to apply the "spike and kink" approach directly to D-mesons and B-mesons (and even to T-mesons if the top quark ever shows itself) as a way of exploring mass regions beyond a few hundred Mev. But for the moment we can best search for neutral leptons in this mass range through their presumed production as primary or secondary products of high energy neutrino and hadron reactions, followed by their decay into some specific final state. It is impressive how well one can do with this method.

The CHARM detector at CERN has been used in a series of experiments in which various pseudoscalar mesons M ($\equiv \pi$, K, D, ...) are produced in the primary collision of the proton beam and then decay into a heavy neutrino[46]:

$$M \to \nu_H + \ell + X \tag{18}$$

where X represents the vacuum (two-body decay) or some system of hadrons. In its turn, the heavy neutrino is then assumed to decay into an electron-positron pair, for example:

$$\nu_H \to e^- e^+ \nu_e \tag{19}$$

The probability for the occurrence of the sequence in eqs. (18) and (19) is proportional to the product $|U_{\ell H}|^2 \; |U_{eH}|^2$. When $\ell = e$, a limit on $|U_{\ell H}|^2$ can be extracted from the data, and when $\ell = \mu$, a limit on the product $|U_{\mu H}| \cdot |U_{\ell H}|$ is obtained.

In one experiment[46)], the CHARM collaboration makes use of the Wide Band Beam and assumes that the heavy neutrino comes only from the decays of π and K mesons; limits on $|U_{eH}|^2$ and $|U_{eH}| \cdot |U_{\mu H}|$ of the order of 10^{-6} are obtained for heavy neutrinos in the 200-300 Mev range. The beam dump is used in a second experiment and the mass range up to ~1750 Mev is explored through the decays of D- and F-mesons; limits of order 10^{-7} are then found for $|U_{eH}|^2$ and $|U_{eH}| \cdot |U_{\mu H}|$ when the heavy neutrino mass is in the vicinity of 1500 Mev.

It is also possible in this second experiment to set very tight limits on $|U_{e\tau}|^2$ through the sequence

$$\begin{aligned} P &\to F + \ldots\ldots \\ &\quad \to \nu_\tau + \tau \\ &\qquad \to e^- e^+ \nu_e \end{aligned} \tag{20}$$

The probability for this sequence is proportional to $|U\tau\tau|^2 |U_{e\tau}|^2 \sim |U_{e\tau}|^2$, and so, if one makes "reasonable" assumptions about the production cross-section and branching ratio for F in eq. (20), one obtains a limit on $|U_{e\tau}|^2$ rather than on $|U_{eH}|^4$ directly from the data. If the production cross-section for F is assumed to be 20% of that for D-mesons, and the branching ratio for $F \to \nu_\tau \, \tau$ is 3%, then the limits on $|U_{e\tau}|^2$ are 10^{-9} for $M_{\nu\tau} \sim 100$ Mev and 10^{-10} for $M_{\nu\tau} \sim 170$ Mev, its new upper bound! When the most recent 1983 run is analysed, it is hoped to improve these remarkable limits by one or two orders of magnitude.

We summarize these results in Table III; for a more detailed picture the reader should turn to the various $|U_{\ell H}|^2$ - mass plots given by the speakers to whom I have made reference. As a point of comparison, we note that the Conforto oscillations[19)] occur at $\sin^2\theta \sim 0.1$, $M \sim 20$ ev.

According to Gronau[8)], new beam dump experiments and the decays of b-quarks produced in e^+e^- collisions should be able to push the mass limits to $\gtrsim 3$ Gev with $|U_{\ell H}|^2 \lesssim 10^{-6}$ -10^{-5}, while high statistics neutrino experiments may extend the excluded mass range to 5 Gev. W and Z decays will eventually push the mass limits out to ~ 50 Gev, and the SSC could even venture as far as 10 Tev! The theoretical "see-saw" reciprocity between heavy and light neutrinos makes the search for high mass leptons as important as the search for light ones.

TABLE III: Summary of $|U_{\ell H}|^2$ - mass limits

$\lvert U_{\ell H}\rvert^2$	limits	Mass Range	Method
$\lvert U_{eH}\rvert^2$	10^{-2} - 10^{-3}	100 - 400 kev	β-decay
$\lvert U_{eH}\rvert^2$	10^{-5} - 10^{-6}	$10 \leq M_H \leq 120$ Mev	$\pi \to e\nu$
$\lvert U_{\mu H}\rvert^2$	10^{-3} - 10^{-4}	$20 \leq M_H \leq 100$ Mev	μ-capture
$\lvert U_{\mu H}\rvert^2$	10^{-4} - 10^{-}	$M_H \leq 20$ Mev	$\pi \to \mu\nu$
$\lvert U_{eH}\rvert^2$ $\lvert U_{eH}\rvert \cdot \lvert U_{\mu H}\rvert$	10^{-6}	200 - 300 Mev	$K \to \nu_H \to ee\nu$
$\lvert U_{eH}\rvert^2$ $\lvert U_{eH}\rvert \cdot \lvert U_{\mu H}\rvert$	$\sim 10^{-7}$	~ 1500 Mev	$D \to \nu_\mu \to ee\nu$
$\lvert U_{e\tau}\rvert^2$	$\sim 10^{-9}$	~ 100 Mev	$F \to \nu_\tau \to ee\nu$
-"-	$\sim 10^{-10}$	~ 170 Mev	-"-

§III. What To Make Of All This?

Que Faire?

What sense can one make of all this information? Let me try to give you a personal view, which may, or may not, coincide with other points of view.

1) Neutrino oscillation limits continue to move into the regions "La Manche" and "Le Doigt" of the Δ^2 - s^2 plane (see fig. 1). My own preference is for La Manche, and so I hope that experimentalists will not give me "Le Doigt" in the next round of experiments. As a word of caution, let me admonish you to "Ricorda Conforto", who believes that oscillations are here to stay.

2) The case for non-zero $\bar{\nu}_e$ mass from tritium β-decay seems to be still "Not Proven". But help is on the way with several new experiments which may have something to tell us next year! Unfortunately molecular and environmental corrections in the source render these experiments not quite as clean as one would like in relation to the qualitative question: does $\bar{\nu}_e$ have a non-vanishing mass? In principle, the experiments are simple, but in practice environmental energy shifts may imitate or mask the effect for which one looks. An attractive exception to this is the atomic experiment described by Robertson[24], in which the

final states are well understood. It may well be, however, that oscillations are a better qualitative demonstration of non-zero mass, especially if the masses are very small (Kayser's Warning!).

3) The solar neutrino problem is still with us, and there is a crying need for more experiments, especially those that will detect the pp neutrinos! The flux of these neutrinos is proportional to the solar luminosity, and any significant deviation from the predicted reaction rate would be a sure sign of oscillations. Thus solar neutrino experiments could make or break the oscillation hypothesis.

4) Double beta decay experiments are getting to a point where limits on the effective Majorana mass begin to be in conflict with the tritium experiment. If the latter is confirmed, it could either mean "the end" for Majorana neutrinos, or an enrichment of the spectrum. One form of enrichment is the pseudo-Dirac hypothesis according to which the electron-type neutrino is an admixture of two almost degenerate Majorana neutrinos with opposite CP eigenvalues. Another is the light-heavy option in which ν_e is still an admixture of Majorana neutrinos with opposite CP, but now one is light and the other heavy; the mass and mixing angle of the heavy neutrino should be located in La Manche region of the oscillation plot.

5) Mixing matrix elements for heavy neutrinos have now reached the general level of $|U_{\ell H}|^2 \leq 10^{-6}$ and are still falling! Future experiments should push this down by one or two orders of magnitude, and extend the range of excluded masses considerably. We may have to wait for W and Z factories, or even the SSC before we see a heavy neutral lepton!

6) We have, at present, no definitive evidence for the existence of neutrino mass, either of the Dirac kind, or the Majorana kind. We must therefore begin to face the ultimate question: could it be that neutrinos are massless Dirac particles which neither oscillate nor behave in any other exotic ways?

FIN

I began my talk on a religious note, so let me end on a poetic one. "We are such stuff as dreams are made of," said William Shakespeare; and for us the dream is a universe filled with neutrinos, a world of powdery snow.

Many thanks to our hosts for giving us such a wonderful week. May they give us many more!

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