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KINEMATICAL PROBES OF NEUTRINO MASS

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1.0 INTRODUCTION.

The most direct searches for neutrino mass are the experiments which seek a kinematical consequence of this mass in some physical process. These experiments include the study of the β spectrum in tritium β decay as a probe of the mass of ν_e, the measurement of the muon momentum in pion decay as a probe of the mass of ν_μ, the study of the hadronic invariant mass and energy distribution in $\tau \to \nu_\tau$+hadrons as a probe of the mass of ν_τ, and other studies. The present analysis will be concerned with kinematical probes of this kind, and with neutrinoless double beta decay ($\beta\beta_{o\nu}$), a probe of neutrino mass which, like some of the kinematical probes, involves a nuclear decay. We will survey the present situation, argue that interesting physics might be revealed by experiments with somewhat improved sensitivity, and consider some ideas for achieving the heightened sensitivity.

In Sec. 2, we review the present bounds on neutrino mass from both kinematical probes and $\beta\beta_{o\nu}$. In Sec. 3, we discuss the fact that the tritium β decay probes of the mass of ν_e, M_{ν_e}, reveal an anomalous β spectrum whose character is such that the value of $M^2_{\nu_e}$ that fits it best is negative. We describe a neutrino-mass explanation of this anomaly which does not work, and suggest future tests of molecular-chemistry explanations which might work. In Sec. 4, we turn to future neutrino-mass experiments with somewhat improved sensitivity. We explain how current hints of neutrino mass suggest, albeit speculatively, that the neutrino masses might be big enough to be visible in some of these experiments. Other improved experiments, when combined with astrophysical arguments, could serve to significantly restrict some of the possibilities for neutrino masses. We discuss some ideas for more sensitive kinematical probes and for more sensitive $\beta\beta_{o\nu}$ measurements. In Sec. 5, we describe certain new types of experiments, and in Sec. 6, we state our conclusions.

2.0 WHERE WE STAND.

2.1 The M_{ν_e} Bound. In Table 1, we show the bounds on the ν_e mass yielded by the recent tritium β decay experiments. These bounds come from study of the shape of the β spectrum near its upper endpoint. It is seen that the β spectrum has an excess of events near its upper endpoint, rather than having the deficit of events that would correspond to a positive $M^2_{\nu_e}$. We note from Table 1 that in all of the experiments, the value of $M^2_{\nu_e}$ that fits this shape best is negative, in some experiments significantly so. This excess can be seen clearly in the data from the Livermore experiment.[5]

Since the β spectrum has an anomalous shape which is not understood — a shape that corresponds neither to a vanishing value of $M^2_{\nu_e}$ nor to a physical (positive) nonvanishing value — it could be that M_{ν_e} is actually somewhat larger than the bounds quoted in Table 1. However, if it were, say an order of magnitude larger, its effects would have been seen. Thus, the bounds in Table 1 do indicate that current experiments are sensitive to values of M_{ν_e} roughly in the 10 eV range.

2.2 The M_{ν_μ} Bound. Upper bounds on M_{ν_μ}, the mass of ν_μ, have come from studies of the decay $\pi \to \mu\nu_\mu$ using pions at rest or ones in flight, and from studies of the decay $K_L \to \pi\mu\nu_\mu$. The most stringent existing bound is $M_{\nu_\mu} < 0.16$MeV at 90% confidence level.[7] This bound comes from measurement of the muon momentum in the decay $\pi \to \mu\nu_\mu$ of pions at rest, combined with information on the pion and muon masses.

2.3 The M_{ν_τ} Bound. Limits on M_{ν_τ}, the mass of ν_τ, have come from studies of the invariant mass and energy of the hadronic system in $\tau \to \nu_\tau$+hadrons. The bigger the invariant mass is, the less energy is available to make the mass of ν_τ in the final state. The most stringent existing published bound is $M_{\nu_\tau} < 24$ MeV at 95% confidence level.[8]

2.4 The $M_{eff}(\beta\beta_{o\nu})$ Bound. The measurement of the neutrinoless double beta ($\beta\beta_{0\nu}$) decay is at present a more sensitive test of a non-zero neutrino mass than are the kinematic probes. Unlike the latter, $\beta\beta_{o\nu}$ may be one of the best tools to directly explore sub-eV neutrino masses. However one has to pay a price for this extraordinary sensitivity: the mass limits only apply for Majorana neutrinos. Excellent reviews have been given on this subject (see e.g. [9]).In double beta decay two neutrons are simultaneously converted into two protons. The decay becomes observable in those nuclides where single beta decay is either energetically forbidden or at least strongly suppressed. $\beta\beta$–emitters are even-even isotopes. Three decay modes are in general discussed:

$$(\beta\beta 2\nu) : A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 2\overline{\nu}_e \quad (2.1)$$

$$(\beta\beta 0\nu) : A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- \quad (2.2)$$

$$(\beta\beta 0\nu\chi) : A(Z,N) \rightarrow A(Z+2,N-2)+2e^- + \chi \quad (2.3)$$

Although extremely rare, decay (2.1) is allowed as a second order effect in the (S)tandard (M)odel of the electro–weak interaction. Decay channel (2.2) and (2.3) are the much more interesting scenarios because they test physics beyond the SM since lepton number conservation is violated. The right–handed anti–neutrino, emitted in the decay of the first neutron, has to be re-absorbed as a left–handed neutrino in an inverse beta decay of the second neutron. This obviously requires the neutrino to be a massive Majorana particle. The question whether $\beta\beta_{o\nu}$ can happen spontaneously (through an incomplete polarization of the massive neutrino) or is due to the coupling of the neutrino to a massless Majoron χ allows us to draw conclusions on the underlying physics.

In the SM, minimally extended to include Majorana neutrino masses, the amplitude for $\beta\beta_{o\nu}$ is proportional to an effective neutrino mass for double beta decay, $M_{eff}(\beta\beta_{o\nu})$, given by

$$M_{eff}(\beta\beta_{o\nu}) = \sum_m CP(\nu_m) \mid L_{em} \mid^2 M_{\nu_m}. \quad (2.4)$$

Here, the sum runs over all the neutrino mass eigenstates ν_m. The quantity CP(ν_m) is the intrinsic CP parity of ν_m, and M_{ν_m} is its mass. The quantity L_{em} is the element of the leptonic mixing matrix (the leptonic analogue of the quark mixing matrix) coupling ν_m to the electron. In writing Eq. (2.4), we have neglected any CP violation in the leptonic sector. In the SM, the matrix L is unitary, so that $|L_{em}|^2 \leq 1$. Note that owing to the factor $|L_{em}|^2$ and the CP parities in Eq. (2.4), an upper bound on $M_{eff}(\beta\beta_{o\nu})$ does not imply an upper bound on the actual neutrino masses M_{ν_m}. (If CP is violated in leptonic mixing, then the CP(ν_m) in Eq. (2.4) is replaced by a more general phase factor.)

In order to draw conclusions from a measured neutrinoless–decay rate (or a limit of this rate) on the effective Majorana mass of the neutrinos (or a limit on M_{eff}), obviously, one has to unfold the leptonic phase space integral and the nuclear matrix element first. While the calculation of the phase space seems to be well under control, the determination of nuclear matrix elements is a difficult and often controversial task. So far, $\beta\beta_{o\nu}$ has not been seen, and the most stringent existing bound on $M_{eff}(\beta\beta_{o\nu})$ is $|M_{eff}(\beta\beta_{o\nu})| < 0.68$ eV at 90% confidence level.[10] This limit comes from a lower bound of 5.1×10^{24} yr on the half-life for $^{76}Ge \rightarrow ^{76}Se + 2e^-$.

3.0 THE PROBLEM OF NEGATIVE $M^2_{\nu_e}$.

3.1 Neutrino Physics Possibilities. Could the excess of events near the upper endpoint of the tritium β spectrum, relative to the number predicted by the standard formula either for vanishing or positive $M^2_{\nu_e}$, be a consequence of neutrino physics not included in this formula? One possibility we have explored is that the excess results from the existence of a $\bar{\nu}_e$ magnetic dipole moment. If the outgoing $\bar{\nu}_e$ in a tritium β decay has such a moment, then it will interact electromagnetically with the charged particles it leaves behind. At first sight one would not expect this interaction to be significant, since there is a laboratory upper bound of 4×10^{-10} Bohr magnetons on the $\bar{\nu}_e$ magnetic moment,[11] and an astrophysical upper bound of 3×10^{-12} Bohr magnetons.[12] However, the propagator, $1/q^2$, for the photon whose exchange carries the electromagnetic interaction between the $\bar{\nu}_e$ and the charged particles in the final state is large for small q^2. Since one will encounter small values of q^2 near the upper endpoint of the β spectrum, where the momentum carried by the neutrino is small, the dipole moment possibility was examined. Unfortunately, it was found that the large photon propagator is offset by small phase space factors. It was estimated that if the $\bar{\nu}_e$ magnetic moment is 10^{-10} Bohr magnetons, then the interaction between it and the charged final-state particles in tritium β decay modifies the decay amplitude near the upper endpoint of the β spectrum by only one part in 10^{16}! Clearly, a neutrino dipole moment is not the explanation of the observed excess of events.

A second neutrino-physics possibility, which has been considered previously, is that some of the tritium "β decay" events are actually ν_e capture events induced by capture of a ν_e in the cosmic neutrino background. For this mechanism[13] to produce as many excess events as are seen, the local density of background neutrinos would have to be $10^{16} cm^{-3}$.

3.2 Molecular Chemistry Possibility. As is clear from Sec. 2.1, the issue of negative experimental results for the square of the electron antineutrino mass needs further attention. (This problem has also been summarized nicely by Wilkerson [14].) It should be noted that experiments which have yielded significantly negative $M^2_{\nu_e}$ have all involved a T_2 source. Now, the β decay of this molecule creates a $^3HeT^+$ molecular ion. While there is presently no specific, known problem with the 2-electron molecular spectrum, there is a lack of experimental data on the electronic final states of this molecular ion and it is reasonable to seek a possible solution of the negative $M^2_{\nu_e}$ problem by spectroscopic studies of events involving $^3HeT^+$. The branching ratios and energies for all possible final states must be known precisely in order to extract the neutrino mass from the beta decay spectrum. The theoretical calculations pertaining to these states [15] are believed to be very accurate, but the negative-mass-squared results indicate that something is not understood completely. It is thus important to remove as many model-dependent components as possible from the data analysis procedures.

At least one measurement of the vibrational-rotational (infrared) spectrum of the $^3HeT^+$ molecule has been carried out [16]. Transitions were observed from the de-excitation of vibrational states which were excited during the beta-decay process. However, no transitions originating from excited electronic orbitals in the $^3HeT^+$ molecule have been observed. These transitions are in the vacuum ultraviolet range, with wavelengths less than 100 nm, and the development of efficient, high-resolution detectors of photons in this range is still in its infancy. Most of the recent detector development has centered on semiconductor photodiodes [17], although superconducting tunnel junction devices also sound promising [18]. Some detector development would no doubt be necessary before a successful experiment to obtain electronic transition spectra could be performed.

Ideally, the measurement of electronic photon spectra from $^3HeT^+$ should be done in event mode and in coincidence with the emitted beta particles. It would seem that the sites at which the neutrino mass measurements (using T_2) were performed, i.e., LANL [3] or/and LLNL [5], would be good locations to pursue such measurements. However, the source tubes would probably have to be redesigned to permit efficient observation of VUV photons. Further, even with the development of an efficient VUV detector, the counting rate may be too low to use high precision (and low solid-angle acceptance) beta-ray spectrometers—the use of large solid-angle (and lower energy resolution) beta detectors as coincidence triggers would have to be considered. Photon spectra obtained in this way should, nevertheless, be quite useful.

Another problem which may be encountered in such measurements arises from interactions of photons from $^3HeT^+$ with the T_2 source gas. The desired photon spectrum may thusly be contaminated with transitions corresponding to the de-excitation of T_2. Measurements may have to be done at several gas pressures in order to positively identify the transitions of interest.

Several other experimental problems would, no doubt, be encountered in trying to measure $^3HeT^+$ photon energies and intensities. However, if such measurements are not pursued, the tremendous efforts already undertaken to obtain high quality beta spectra for neutrino mass measurements may be partially wasted, merely for lack of understanding of how to properly analyze the data.

4.0 NEAR-TERM FUTURE EXPERIMENTS WITH IMPROVED SENSITIVITY.

4.1 Motivation to improve sensitivity (Dirac and/or Majorana). In considering neutrino-mass experiments with somewhat improved sensitivity, it is very interesting to note that present hints of neutrino mass suggest, albeit speculatively, that there may be neutrino masses within the range to which these experiments would be sensitive. Let us briefly review the present hints, see what neutrino-mass range they point to, and then ask what experiments would be sensitive to mass in this range.

The first existing hint of neutrino mass is the solar neutrino deficit. The solar neutrino data, while difficult to explain without invoking neutrino mass,[19] are elegantly explained by the M(ikheyev), S(mirnov), W(olfenstein) effect,[20] which does invoke neutrino mass. The MSW effect converts a ν_e produced in the solar core into another kind of neutrino, ν_x, which is invisible (or at least largely invisible) to the present terrestrial solar neutrino detectors. Neglecting the possibility of so-far-unknown sterile neutrinos, ν_x is a ν_μ, ν_τ, or some combination of these neutrinos. The $\nu_e \rightarrow \nu_x$ conversion occurs while the ν_e produced in the solar core is traveling outward through solar material. The MSW explanation of the solar neutrino data requires that the mass of ν_x, M_{ν_x}, be related to that of ν_e, M_{ν_e}, by

$$M_{\nu_x}^2 - M_{\nu_e}^2 \sim 10^{-5} eV^2. \qquad (4.1)$$

Let us recall enough of the physics of the MSW effect to understand why.

Neglecting mixing, the total energy of a ν_e of momentum p_ν in the sun is

$$E_{\nu_e} = \sqrt{p_\nu^2 + M_{\nu_e}^2} + \sqrt{2} G_F N_e. \qquad (4.2)$$

The second term in this expression, in which G_F is the Fermi coupling constant and N_e is the density of electrons at the location of the ν_e, is an interaction potential energy resulting from the charged-current interaction between the ν_e and the electrons. Now, the ν_x, which does not have a ν_e component, does not have a charged-current interaction with electrons. Consequently, the total energy of a ν_x of momentum p_ν in the sun is simply

$$E_{\nu_x} = \sqrt{p_\nu^2 + M_{\nu_x}^2} \simeq \sqrt{p_\nu^2 + M_{\nu_e}^2} + \left(M_{\nu_x}^2 - M_{\nu_e}^2\right)/2E_\nu. \qquad (4.3)$$

Here, in the second step we have assumed that M_{ν_x} and M_{ν_e} are both tiny compared to p_ν, and denoted $(p_\nu^2 + M_{\nu_e}^2)^{1/2}$, which is an excellent approximation to the neutrino energy, by E_ν.

The MSW $\nu_e \rightarrow \nu_x$ conversion requires that, somewhere in the sun, the energy levels E_{ν_e} and E_{ν_x} given by Eqs. (4.2) and (4.3) cross. Thus, this conversion demands that

$$\sqrt{2} G_F N_e = \frac{M_{\nu_x}^2 - M_{\nu_e}^2}{2E_\nu}. \qquad (4.4)$$

Now, we can understand the observation that the solar neutrino flux is below the predicted amount, but not zero, by supposing that the level- crossing condition (4.4) is satisfied for, say, neutrino energies E_ν above $\sim$ 0.7MeV (hence for the ^7Be and ^8B neutrinos), but not for energies below this point (hence, not for the pp neutrinos). Noting that the electron density rises from zero at the outer edge of the sun to a maximum of $\sim 10^{26}/cc$ at the center of the sun, we find that Eq. (4.4) will hold somewhere in the sun for $E_\nu \gtrsim$ 0.7MeV, but not for $E_\nu \lesssim$ 0.7MeV, if $M_{\nu_x}^2 - M_{\nu_e}^2$ obeys condition (4.1). This is the origin of that condition.

Detailed calculations of the MSW effect show that it can explain existing solar neutrino data if $M_{\nu_x}^2 - M_{\nu_e}^2$ satisfies condition (4.1), and $\sin^2 2\theta \simeq 5 \times 10^{-3}$ or 0.6,[21] where θ is the $\nu_e - \nu_x$ mixing angle. Of these two solutions, the one with small θ is favored because it distorts the detectable solar neutrino spectrum in the manner that is suggested by the observations. The pp electron neutrinos do not undergo conversion, and are detected on earth. Both the ^7Be and ^8B neutrinos undergo MSW conversion to the undetectable ν_x particles, but in the case of the ^8B neutrinos, this conversion is not fully efficient because the region in the sun where the level-crossing condition (4.4) is satisfied is too thin. Thus, the ^8B flux is not suppressed as much as the ^7Be flux.

The second hint of neutrino mass is the anomalously low value of the ν_μ/ν_e ratio in the flux of neutrinos generated in the earth's atmosphere by cosmic ray interactions. This flux of atmospheric neutrinos is detected by underground detectors, each of which observes not only neutrinos generated in the atmosphere directly above it, but also neutrinos produced in much more distant parts of the atmosphere, such as those on the side of the earth opposite to the detector.

The anomalously low atmospheric ν_μ/ν_e ratio has been interpreted in terms of vacuum neutrino oscillations. The present data are consistent both with $\nu_\mu \rightarrow \nu_\tau$ and with $\nu_\mu \rightarrow \nu_e$ oscillation.[22,23] To see what neutrino mass difference must be involved, we note that the probability that a neutrino of one flavor, ν_f, will be converted by neutrino oscillation into one of another flavor, $\nu_{f'}$, is proportional to

$$\sin^2\left\{1.27\left(\frac{\delta M^2}{1eV^2}\right)\frac{(L/1km)}{(E_\nu/1GeV)}\right\}. \qquad (4.5)$$

Here, δM^2 is the difference between the squared masses of the two mass eigenstates of which ν_f and $\nu_{f'}$ are composed, and we are assuming that mixing between the $\nu_f - \nu_{f'}$ system and the third, remaining flavor may be neglected. The quantity L is the distance traveled by the neutrino, and E_ν is its energy.

From (4.5), we see that for $\nu_f \rightarrow \nu_{f'}$ oscillation to be appreciable, $(\delta M^2/1eV^2) * (L/1km)/(E_\nu/1GeV)$ must not be small compared to unity. Now, for neutrinos created in the atmosphere directly above a detector, $L \sim$ 20km, while for those created in the atmosphere on the side of the earth opposite to the detector, $L \sim 10^4$km. Thus, if E_ν is typically 1GeV for the detected neutrinos, then if oscillation is to be appreciable at least for those neutrinos for which $L > 10^3$km, we must have $\delta M^2 \gtrsim 10^{-3} eV^2$.

Recent data[23] show that for neutrinos with a mean energy of 6GeV, the ν_μ/ν_e ratio is anomalously small for upward-going neutrinos (which have travelled a large distance L to reach the detector), but not for downward-going neutrinos (which have only travelled $\sim$ 20km from the atmosphere directly above the detector). From (4.5) these data imply that $\delta M^2 \lesssim 10^{-1} eV^2$, or even the downward-going neutrinos would show an anomaly. Thus, we see that $10^{-3} eV^2 \sim \delta M^2 \lesssim 10^{-1} eV^2$. The best fit to all the KAMIOKANDE data is obtained for $\delta M^2 \sim 10^{-2} eV^2$, and near maximal mixing of the two flavors involved in the oscillation.[23]

The third hint of neutrino mass is the existence of dark matter in the universe, combined with the belief that this dark matter includes a "hot" component, and the very natural view that this component is quite likely comprised of neutrinos. Let us call the neutrino mass eigenstates of which ν_e, ν_μ, and ν_τ are made ν_1, ν_2, and ν_3, and let $\sum \equiv M_{\nu_1} + M_{\nu_2} + M_{\nu_3}$, where M_{ν_m} is the mass of ν_m. Further, let Ω_H be the fraction of critical mass density contributed to the universe by hot dark matter, and h be the Hubble constant in units of 100 km/sec/Mpc. Then, if the hot dark matter consists of neutrinos,

$$\Omega_H = \frac{(\sum/1eV)}{91h^2}. \tag{4.6}$$

If we take $\Omega_H = 0.2$,[24] and $h = 0.5$, this relation implies that

$$\sum \equiv M_{\nu_1} + M_{\nu_2} + M_{\nu_3} \cong 5\ eV. \tag{4.7}$$

The previous value of h is somewhat uncertain. Interesting new measurements, some of them made with the aid of the Hubble Space Telescope, yield for this parameter 0.80 ± 0.17,[24] 0.73 ± 0.09,[25] 0.52 ± 0.08,[26] and 0.67 ± 0.07.[27] Now, values larger than approximately 0.65, combined with the non-cosmological lower bounds on the age of the universe, would make the current mixed hot- and cold-dark-matter picture[28] of the universe nonviable.[29] Since this picture is an input to our considerations, we assume in this report that

$$0.50 \lesssim h \lesssim 0.65. \tag{4.8}$$

Then, from Eq. (4.6),

$$4.5\ eV \lesssim \sum \lesssim 7.7\ eV. \tag{4.9}$$

Suppose, now, that the explanation of all three of the hints we have discussed—the solar neutrino deficit, the atmospheric neutrino anomaly, and the hot dark matter—is indeed neutrino mass as we have described. To what values of the neutrino masses does this point?

In exploring this question, we shall assume that the only existing neutrinos are the ones we already know: ν_e, ν_μ, and ν_τ, so that there are no as-yet-undiscovered sterile neutrinos. In addition since some observations by reactor experiments[30] presently indicate that much of the mass-mixing phase space allowed by the atmospheric experiments is unlikely for $\nu_\mu \to \nu_e$ transitions we shall suppose, as an example, that it is indeed $\nu_\mu \to \nu_\tau$ which is occuring. In that case, the atmospheric neutrino data then suggest the $\nu_\mu - \nu_\tau$ mixing is nearly maximal,[23] which implies that the mixing between ν_e and the $\nu_\mu - \nu_\tau$ system is small. Neglecting the latter mixing, each of ν_μ and ν_τ is a roughly 50–50 mixture of two neutrino mass eigenstates, which we shall call $\widetilde{\nu}_2$ and $\widetilde{\nu}_3$. The data are best fit with $|M^2_{\widetilde{\nu}_3} - M^2_{\widetilde{\nu}_2}| \sim 10^{-2} eV^2$, as we have said.

In this scenario, the small-mixing MSW mechanism can still operate more or less as we have described, despite the large mixing between ν_μ and ν_τ.[31] The MSW effect may then be pictured as resulting from the circumstance that, in the absence of mixing between ν_e and the $\nu_\mu - \nu_\tau$ system, the total energy of ν_e crosses, somewhere in the sun, that of $\widetilde{\nu}_2$ or $\widetilde{\nu}_3$. Let us say it crosses that of $\widetilde{\nu}_2$. The neutrino ν_x into which the MSW effect converts a ν_e is then $\widetilde{\nu}_2$, a 50–50 $\nu_\mu - \nu_\tau$ mixture. As for the case where all mixing angles are small, so here the level crossing requires that, somewhere in the sun, Eq. (4.4) hold. To explain the apparent fact that some solar electron neutrinos undergo MSW conversion while others do not, we must then have Eq. (4.1), as before. Since the degeneracy between ν_x and ν_e required by Eq. (4.1) is much greater than that between $\widetilde{\nu}_2$ and $\widetilde{\nu}_3$, it is clear that only one of the latter two neutrinos can be involved in the MSW effect. (When the mixing between ν_e and the $\nu_\mu - \nu_\tau$ system is not neglected, the true mass eigenstates of the three-neutrino system are $\nu_1 \sim \nu_e$, and two states, ν_2 and ν_3, which are not too different from $\widetilde{\nu}_2$ and $\widetilde{\nu}_3$.)

Taken together, the neutrino-mass interpretations of the hot dark matter, the atmospheric neutrino anomaly, and the solar neutrino deficit imply, under our assumptions, the constraints

$$M_{\nu_1} + M_{\nu_2} + M_{\nu_3} \simeq 6\ eV, \qquad (4.10.a)$$

$$|M^2_{\nu_3} - M^2_{\nu_2}| \sim 10^{-2}\ eV^2, \qquad (4.10.b)$$

and

$$M^2_{\nu_2} - M^2_{\nu_1} \sim 10^{-5}\ eV^2 \qquad (4.10.c)$$

Obviously, these constraints require the three neutrino mass eigenstates to be approximately degenerate in mass, with each of them having a mass of approximately $6eV/3$. or 2eV.[32] In summary, in this scenario the neutrino mass spectrum is described by

$$M_{\nu_1} \cong M_{\nu_2} \cong M_{\nu_3} \simeq 2\ eV, \qquad (4.11.a)$$

$$|M^2_{\nu_3} - M^2_{\nu_2}| \sim 10^{-2}\ eV^2, \qquad (4.11.b)$$

and

$$M^2_{\nu_2} - M^2_{\nu_1} \sim 10^{-5}\ eV^2. \qquad (4.11.c)$$

What experiments does this scenario suggest? First, since in this scenario the electron neutrino, $\nu_e \sim \nu_1$, has a mass of 2eV, tritium β decay experiments with somewhat better sensitivity than those whose results are reported in Table 1 would be capable of seeing the ν_e mass! Thus, such experiments are worth considering, even though they may be very difficult. Secondly, since the small mixing between ν_e and the $\nu_\mu - \nu_\tau$ system implies that the mixing matrix elements $|L_{em}|^2$ in Eq. (2.4) are all small except for $|L_{e1}|^2 \simeq 1$, we see from Eq. (2.4) that the effective neutrino mass for double beta decay, $M_{eff}(\beta\beta_{0\nu})$, is given by

$$|M_{eff}(\beta\beta_{0\nu})| \cong M_{\nu_1} \cong 2\ eV. \qquad (4.12)$$

Of course, this assumes that neutrinos are Majorana particles; if they are Dirac particles there will be no $\beta\beta_{0\nu}$.[33] Now, the current upper bound on $M_{eff}(\beta\beta_{0\nu})$, while nominally somewhat below 2eV, is also somewhat uncertain due to its dependence on uncertain nuclear matrix elements (see Table 3 and discussion in Sec. 4.3.3). Thus, an $M_{eff}(\beta\beta_{0\nu})$ of 2eV is not in clear conflict with present $(\beta\beta_{0\nu})$ experiments, but suggests that future experiments which are somewhat more sensitive than the present ones may actually see a signal! Finally, although future solar neutrino and neutrino oscillation experiments are outside the scope of this report, it is obviously highly desirable to carry out solar neutrino experiments which can test the MSW explanation of the solar neutrino fluxes and long-baseline $\nu_\mu \to \nu_\tau$ oscillation experiments with accelerator-generated ν_μ beams which can test the $\nu_\mu \to \nu_\tau$ explanation of the atmospheric neutrino anomaly. It is also interesting to carry out searches, such as those being performed by the Los Alamos LSND and the Rutherford KARMEN experiments, for $\nu_\mu \to \nu_e$ oscillation with $\delta M^2 \geq 1$ eV^2 and small mixing angle. Confirmation of such oscillation would falsify the neutrino mass spectrum of Eq. (4.11).

What if only two of the three hints of neutrino mass we have discussed are actually due to neutrino mass? Let us consider the possibilities in turn.

i) Neutrino mass is responsible for the hot dark matter and the solar neutrino deficit:

In this case, we may, to focus our thinking, assume that neutrino mixing is small, and that

$$M_{\nu_1} \leq M_{\nu_2} \leq M_{\nu_3}, \qquad (4.13)$$

where ν_1, ν_2 and ν_3 are, respectively, the dominant mass eigenstate components of ν_e, ν_μ, and ν_τ. The masses M_{ν_m} must obey the constraint (4.10.a) and, assuming that the solar neutrino deficit is due to MSW conversion of ν_e into ν_μ, the constraint (4.10.c). A possible scenario which is not possible when neutrino mass is assumed to be responsible for all three of the hints we have discussed is then

$$M_{\nu_1} \ll 10^{-3}eV,\ M_{\nu_2} \simeq 3 \times 10^{-3}eV,\ M_{\nu_3} \simeq 6\ eV. \qquad (4.14)$$

Observation of the mass of $\nu_e \sim \nu_1$ in tritium β decay is then out of the question. However, for $M^2_{\nu_3} - M^2_{\nu_1} \simeq (6eV)^2$, as implied by Eq. (4.14), the experimental bound on the neutrino mixing parameter $|L_{e3}|^2$ appearing in Eq. (2.4) for $M_{eff}(\beta\beta_{0\nu})$ is 0.024.[34] If $|L_{e3}|^2$ is not much smaller than this bound, then from Eqs. (4.14) and (2.4)

$$|M_{eff}(\beta\beta_{0\nu})| \simeq |L_{e3}|^2 M_{\nu_3} \simeq 0.1\ eV. \qquad (4.15)$$

Assuming that neutrinos are Majorana particles, neutrinoless double beta decay would then be visible in experiments roughly one order of magnitude more sensitive (in terms of $M_{eff}(\beta\beta_{0\nu})$) than the present ones.[35]

With the neutrino masses as in Eqs. (4.14), the CHORUS and NOMAD searches for $\nu_\mu \to \nu_\tau$ oscillation can see a signal if the $\nu_\mu - \nu_\tau$ mixing angle $\theta_{\mu\tau}$ obeys $\sin^2 2\theta_{\mu\tau} \gtrsim 4 \times 10^{-4}$.[36]

ii) Neutrino mass is responsible for the atmospheric anomaly and the solar neutrino deficit:

The ~eV scale of neutrino mass coming from the hot dark matter constraint (4.10.a) is now gone. Let us assume that the atmospheric neutrino anomaly is due to oscillation of ν_μ into ν_τ, and the solar neutrino deficit to MSW conversion of ν_e into ν_μ. Then, denoting as before the dominant mass eigenstate of ν_e by ν_1, and the mass eigenstates which together are the dominant components of the $\nu_\mu - \nu_\tau$ system by ν_2 and ν_3, we have the constraints (4.10.b) and (4.10.c). It is natural to satisfy these constraints by supposing that

$$M_{\nu_3} \cong \left|M^2_{\nu_3} - M^2_{\nu_2}\right|^{1/2} \quad \sim 10^{-1}\ eV, \qquad (4.16.a)$$

$$M_{\nu_2} \cong \left[M^2_{\nu_2} - M^2_{\nu_1}\right]^{1/2} \quad \sim 3\times 10^{-3}\ eV, \qquad (4.16.b)$$

and

$$M_{\nu_1} \ll 3\times 10^{-3}\ eV. \qquad (4.16.c)$$

All neutrino masses are now too small to have visible effects in forseeable tritium β decay experiments. Turning to $\beta\beta_{0\nu}$, we see from Eq. (2.4) that M_{ν_3} is large enough to produce an $M_{eff}(\beta\beta_{0\nu})$ of order 0.1eV (which may be observable in future experiments as we shall discuss) if the mixing parameter $|L_{e3}|^2$ is near unity. However, the maximal $\nu_\mu - \nu_\tau$ mixing implied by the $\nu_\mu \rightarrow \nu_\tau$ interpretation of the atmospheric anomaly implies that $|L_{e3}|^2$ is probably not bigger than 0.1. Then the contribution of ν_3 to $M_{eff}(\beta\beta_{0\nu})$ is not bigger than $(0.1)\times 10^{-1}eV = 10^{-2}eV$. We do not know of plans or ideas for any experiments sensitive to such a small $M_{eff}(\beta\beta_{0\nu})$ in the near future. (See, however, Sec. 5.3 with regard to the distant future.)

Of course, if this scenario is true, long-baseline searches for $\nu_\mu \longrightarrow \nu_\tau$ oscillation in accelerator ν_μ beams, aimed at confirming the $\nu_\mu \rightarrow \nu_\tau$ interpretation of the atmospheric neutrino anomaly, would prove very interesting.

iii) Neutrino mass is responsible for the hot dark matter and the atmospheric neutrino anomaly:

The hot dark matter constraint (4.10.a) must once again be obeyed. Assuming that the atmospheric anomaly is due to $\nu_\mu \rightarrow \nu_\tau$ oscillation, and denoting as before the dominant mass eigenstate component of ν_e by ν_1 and the dominant components of the $\nu_\mu - \nu_\tau$ system by ν_2 and ν_3, we also have the constraint (4.10.b). Let us assume that

$$M_{\nu_1} \leq Min\{M_{\nu_2}, M_{\nu_3}\}, \qquad (4.17)$$

so that the neutrino mass hierarchy is not inverted. Then, to satisfy the constraints (4.10.a) and (4.10.b), we must have

$$M_{\nu_2} \cong M_{\nu_3} = (2-3)\ eV. \qquad (4.18)$$

In the absence of the constraint (4.10.c) from solar neutrinos, a possible scenario is

$$M_{\nu_1} \ll M_{\nu_2} \cong M_{\nu_3} \simeq 3\ eV. \qquad (4.19)$$

Observation of the mass of $\nu_e \sim \nu_1$ in tritium β decay is then hopeless. Turning to $\beta\beta_{0\nu}$, we note that the contributions of ν_1 and ν_2 to the $M_{eff}(\beta\beta_{0\nu})$ of Eq. (2.4) will be below 0.1eV. However, if neutrinos are Majorana particles, then the bounds[37] on $|L_{e3}|^2$ for the case where $|M^2_{\nu_3} - M^2_{\nu_1}| \simeq (3\ eV)^2$ allow ν_3 to contribute as much as $\sim 0.1\ eV$ to $M_{eff}(\beta\beta_{0\nu})$, so that experiments with sensitivity in this range could see a signal.

In this scenario, there may be $\nu_\mu \longleftrightarrow \nu_e$ oscillation with $\delta M^2 = M^2_{\nu_2} - M^2_{\nu_1} \simeq (3\ eV)^2$. Despite the large $\nu_\mu - \nu_\tau$ mixing, the oscillation would still depend on the distance L travelled by the neutrino as it does in the case where just two neutrinos mix and all neutrino mixing angles are small. The mixing angle $\theta_{e\mu}$ governing the $\nu_\mu \longleftrightarrow \nu_e$ oscillation probability would be below the present bound[38] of $\sin^2 2\theta_{e\mu} \lesssim 4\times 10^{-3}$ for $\delta M^2 \sim (3\ eV)^2$.

In summary, the existing hints of neutrino mass suggest that tritium β decay or $\beta\beta_{0\nu}$ experiments with somewhat greater sensitivity to neutrino mass than the present ones could actually see positive signals. These hints also suggest that certain searches for neutrino oscillation could bear fruit.

The scenarios which the existing hints have suggested have involved neutrino masses which are all in the eV range or below. What if these scenarios are all wrong, and the heaviest of the neutrinos, presumably ν_τ, has a mass in the keV or even MeV range? A ν_τ with mass in the MeV range has interesting cosmological and astrophysical consequences (for a review see [39]). Upper bounds on the allowed total energy density of the universe during nucleosynthesis (at $t \simeq 10^{-2} - 10^2$ sec after the Big Bang) exclude the mass range $0.2\ MeV - 33\ MeV$ for a Dirac ν_τ, and $0.4\ MeV - 30\ MeV$ for a Majorana ν_τ, if the ν_τ lifetime is longer than $O(100\ sec)$ (i.e. if ν_τ does not decay before the end of nucleosynthesis) [40,41,42]. Once combined with the new laboratory upper bounds of less than $30\ MeV$ (the bound of $23.8\ MeV$ from ALEPH, or even the preliminary Beijing bound of $29\ MeV$), this nucleosynthesis argument would push the upper mass bound for these long-lived ν_τ ($\tau > 100\ sec$) to $0.4\ MeV$ (and astrophysical arguments would push the limit much further for Dirac neutrinos, as explained below). Let us remark, however, that these nucleosynthesis bounds apply only if the main annihilation modes of the ν_τ are those of the Standard Model. If the ν_τ are assumed to have additional interactions which increase their annihilation cross sections in the early universe, their relic abundance decreases and the nucleosynthesis bounds are loosened. In most models predicting neutrino masses, neutrinos have extra interactions, and in many of them neutrinos have annihilation cross sections larger than weak.

Another interesting bound coming from the supernova $SN1987A$ excludes a Dirac ν_τ of mass from about $10keV$ to $1MeV$. The reason is that the mainly inert right-handed helicity states of massive Dirac neutrinos can be produced in weak interactions due to their admixture in the left-handed chirality neutrino states. Therefore, right-handed ν_τ with masses in the forbidden range produced in the core of the supernova, would have escaped from the star carrying off too much energy and consequently shortening the observed $\bar{\nu}_e$ pulse [43,44]. Thus, a ν_τ lighter than $1MeV$ must be Majorana, unless it is lighter than $O(10keV)$.

The mentioned nucleosynthesis constraints are based on the observational upper limit on the abundance of ^4He, because larger densities during nucleosynthesis lead to overproduction of ^4He. A non-relativistic neutrino species can contribute more to the energy density of the universe than a relativistic one. The number of light neutrino species allowed by the abundance of ^4He is $N_\nu \lesssim 3.3$ [45] and, for the ranges rejected, stable ν_τ with weak annihilation cross sections would contribute more than 1.3 relativistic neutrino species. We can understand, therefore, that if ν_τ decays into relativistic particles before the end of nucleosynthesis, these bounds are loosened and become dependent on the nature of the decay products. "Visible" modes ($\nu_\tau \to \nu'\gamma$, $\nu_\tau \to \nu_e^+ e^-$) are ruled out, as the dominant decay mode for MeV tau-neutrinos, through a combination of laboratory bounds, nucleosynthesis bounds and constraints from supernova observations [46,44]. "Invisible" modes are not only allowed but may have very interesting consequences. These modes are $\nu_\tau \to 3\nu$'s and $\nu_\tau \to \nu'\phi$, where ϕ is a light or massless boson, most naturally a Goldstone boson. A ν_τ with mass $< 1MeV$ and short lifetime $\tau < 30$ sec (producing ν_e or ν_μ [41 and 47], but in particular the effect of ν_e decay products is important [41]) would actually decrease the amount of ^4He produced, with respect to a relativistic stable ν_τ. Therefore ν_e, ν_μ and this particular ν_τ would count in nucleosynthesis as *less* than three effective neutrino species, $N_\nu < 3$. This would rescue the Big Bang from a potentially important inconsistency if the observational data would indicate (as sometimes argued) that the abundance of ^4He is actually lower than usually thought at present (what would lead precisely to a limit $N_\nu < 3$). Alternatively, keeping the present bound, $N_\nu < 3.3$, the constraint on additional "new" contributions from exotic particles would be loosened. These possibilities would be eliminated by a laboratory upper bound of around $1MeV$.

There are still other possibilities to be tested or rejected by lowering the upper bound on m_{ν_τ}. A ν_τ with an annihilation cross section faster than weak by a factor of 10 and with a mass of $20MeV - 30MeV$ and lifetime 200 sec - 1000 sec, decaying into ν_e would allow to increase the upper bound on the baryonic density by a factor of 10 [48]. The upper bound on the density of baryons is due to overproduction of ^4He and ^7Li and underproduction of D. Overproduction of ^4He is avoided because the abundance of these ν_τ is so low that the effective number of neutrinos is $N_\nu \simeq 2$, and the other two abundances come out right because the very effective disappearance of free neutrons during nucleosynthesis with large baryon densities, is avoided by the production of neutrons in the interactions of the $\bar{\nu}_e$ produced in the ν_τ decay with protons ($\bar{\nu}_e\, p \to e^+ n$). Thus, this mechanism produces with a large $\eta \equiv n_B/n_\gamma$ the results otherwise obtained for a lower η, and it allows for $\Omega_B h^2 \simeq 0.2$. Notice that for $h \lesssim 0.5$, within the accepted range $0.4 \le h \le 1$, one could have even $\Omega_B = 1$. In this case the nucleosynthesis constraint would not require the existence of non-baryonic dark matter.

Finally, it has been speculated that the residual annihilations of a ν_τ with a mass of 15 MeV to $25MeV$, in the outer core of a supernova could help power the supernova explosion [44] (at present the mechanism of supernova explosion is not well understood), and that a $1MeV - 10MeV$ ν_τ with lifetime 0.1 sec - 100 sec whose decay products include ν_e, could remedy the problems that standard cold dark matter scenarios of structure formation in the universe have to produce acceptably small inhomogeneities on small scales [49].

4.2 Can ~2 eV be Reached in Beta Decay?

Setting aside for the moment the anomaly seen at the endpoint of the tritium spectrum, one can ask, what is the smallest mass detectable in beta decay?

In order to detect the effect of a neutrino mass of m_ν at the endpoint of a beta spectrum of total kinetic energy E_0 , instrumental resolution of order $\frac{m_\nu}{E_0}$ is needed. The spectral fraction per decay that falls in the last m_ν of the beta spectrum is approximately $(\frac{m_\nu}{E_0})^3$.

For spectrometric experiments in which the source and the detector are physically separated, a limit on source thickness is set by the cross section for inelastic interactions of outgoing electrons, such that one must have $\sigma n \leq 1$, where σ is the inelastic cross section (about 5 x 10^{-22} cm^2 for molecular T_2). The dimensions of the source (area A) and the dimensions of the spectrometer (length L) are related through the resolution needed, specifically,

$$\frac{\Delta E}{E} \simeq \frac{\sqrt{A}}{L}.$$

In these conditions, the rate in the last m_ν of the spectrum is of order

$$\frac{dN}{dt} = \left(\frac{\sqrt{A}}{L}\right)^3 \frac{\lambda A}{\sigma},$$

where λ, the mean decay time, is approximately given in seconds (for allowed beta decay) by

$$\lambda = 10^{-33} ft E_0^5,$$

where ft is the beta-decay reduced matrix element (e.g., $\log_{10} ft = 3$ for tritium decay) and E_0 is in eV. Then,

$$\frac{dN}{dt} = 10^{-33} m_\nu^5 ft L^2 \sigma^{-1}$$

when background is absent and detection efficiency is unity. For example, if one sets as a minimum practical limit one event per day and $L = 10$ m, then

$$m_{\nu(ultimate)} = 0.4 \text{ eV}.$$

at 1 standard deviation. A 2-eV limit is then about 3000 times "easier" as a result of the exponent 5. In practice that large factor is eroded quickly by efficiency, background, and the need to explore the rest of the spectrum both for extraction of neutrino mass and for measurements related to systematic uncertainties.

Calorimetric experiments technically evade this limit by virtue of permitting much more intense sources (because energy loss is no longer an issue), but in practice they run into a different limit set by the presence in the data of the entire beta spectrum. The equivalent branching ratio of endpoint data to total is about 3 x $10^{-13} {m_\nu}^3$.

The experiment that most nearly approaches the ideal conditions appears to be the T_2 apparatus of Lobashev et al. [50] A retarding-field spectrometer with magnetic gradients is coupled to a Los Alamos type gaseous molecular tritium source to give very high resolution, large acceptance, and low backgrounds. Initial results are already at the 2.5-eV statistical level [51].

While both the idealized statistical arguments and experimental data indicate that the 2-eV level can be reached, and even slightly surpassed, the anomaly observed at the endpoint must be quantitatively understood before a convincing value for or limit on the rest mass of ν_e can be given.

The structure of the two-electron molecule (T_2) is presumably calculable to arbitrary accuracy given enough effort, but it would clearly be desirable to be able to work with the T atom, or even the T^+ ion, for which the atomic-structure calculations are different and simpler. Space-charge limits preclude a useful T^+ source, but it may not be out of the question to imagine an atomic tritium source of worthwhile density. The Los Alamos source [52] was originally designed to use atomic tritium prepared by dissociation in an RF discharge. The gas was prevented from recombining immediately through the use of a highly polished aluminum source volume (tube), since it had been found that aluminum hindered surface recombination and volume recombination was negligible. The atomic spectrum was never taken, however, because the molecular contamination, even at less than 10%, had to be measured extremely precisely since its endpoint is about 8 eV higher than that of the atomic spectrum. The technology for vacuum ultraviolet absorption molecular spectroscopy using frequency doubled and tripled Nd-YAG pumped dye laser light was still primitive.

Initially a somewhat different approach had been considered, namely the use of the developing technology for preparing dense spin-polarized hydrogen at very low temperatures. The advantage of this method would be the essentially negligible contamination by molecular tritium; the technology was not sufficiently advanced in the 1980s to make this option attractive. Now it is possible to prepare atomic densities in excess of 10^{14} cm^{-3}, within striking distance of the 10^{15} to 10^{16} needed [53]. To establish whether this could form the basis for a successful atomic tritium experiment would require a significant research effort.

4.3 $\beta\beta$ Decay with Improved Sensitivity. Many groups are working in this field using different methods. Because the calculations of $\beta\beta 2\nu$– and $\beta\beta 0\nu$–matrix elements are substantially different, there is no way to test the reliability of neutrino mass limits determined from measured limits of $\beta\beta 0\nu$–decay rates, except to measure this non–standard model decay for several isotopes.

In the absence of any rigorous test, a big experimental effort has been devoted world wide to the measurement of two neutrino double beta decay rates. They can be considered as an indirect probe of our understanding of second order weak decays. It is generally believed that the $\beta\beta 0\nu$–matrix elements are less influenced by the various uncertainties of those calculations than the $\beta\beta 2\nu$ case. If this is in fact true the agreement between calculated and measured $\beta\beta 2\nu$ decay rates can be considered as an upper limit for the uncertainties of the matrix elements of the neutrinoless decay mode.

Almost 40 experiments are studying $\beta\beta$–decay all over the world. The allowed two neutrino $\beta\beta$–decay has now been observed in 9 different isotopes and measured half lives seem to agree reasonably well with the theoretical predictions.

In this Section we would like to outline experiments capable of sensitivities approaching 0.1 eV. Therefore, only the two types of experiments giving the most stringent $M_{eff}(\beta\beta_{o\nu})$ limits today will be discussed. For a more complete description of the field the reader is referred to reference [9]. As will be shown, sub-eV neutrino masses are already within reach of the experiments discussed here.

We shall start with a brief description of the experimental challenges of this field. In fact the problems to be solved are very similar although the ways to solve them might be completely different from experiment to experiment.

Because of the extremely long half lives of $\beta\beta$–decays, often resulting in only a few decays per year, the reduction of background radiation is the major issue in this field of research. Reaching background levels of a few events per year is a nontrivial and time consuming problem if the detector should have kg–size. This goal can be achieved either by reducing the level of background–creating impurities or by detecting their decay with high sensitivity. Two examples for this will be discussed here. In order to eliminate cosmic radiation these experiments are in general performed in underground laboratories.

Within the direct experiments (detecting the electrons emitted in the decay), those using the $\beta\beta$–decaying source simultaneously as detector have at present the highest sensitivity towards a Majorana neutrino mass. In this approach self absorption losses of the electrons in the source can be minimized leading to high detection efficiencies. On the other hand the number of isotopes which can be studied in this way is limited.

The use of large amounts (several kg) of isotopically enriched source material, concentrating the source strength in compact detectors with a low sensitivity towards background radiation, has become customary. ^{76}Ge and ^{136}Xe are the two isotopes studied most successfully so far.

The inclusive geochemical method, detecting the decay product and not the electrons, will not be discussed here. However it can yield stringent limits if the $\beta\beta 2\nu$–half life is sufficiently long, as in the case of ^{128}Te [54].

4.3.1 Calorimetric ^{76}Ge Experiments. Two experiments, done as international collaborations, are currently under way. Both experiments have around 20 kg of isotopically enriched ^{76}Ge at their disposal. In both projects the extremely valuable enriched material was supplied from Russia. It has an isotopical abundance of 86% of ^{76}Ge compared to only 7.8% in natural Ge.

The idea of using high resolution Ge semiconductor detectors as source and detector has been successfully used before with natural Ge. The 11–fold higher concentration of the source strength allowed however a significant step in sensitivity.

This purely calorimetric approach completely relies on the good energy resolution of Ge detectors. The existence of the non–standard model $\beta\beta 0\nu$–decay would lead to a narrow peak at 2.038 MeV well within the energy range of the natural radioactivity. The extremely good energy resolution allows however a precise determination of the peak energy and concentrates hypothetical $\beta\beta 0\nu$ events into a narrow energy interval.

The detection efficiency ϵ for electrons created inside the Ge crystal is limited only through the leakage into the inactive layer of the Ge detector and small bremsstrahlung losses. It is around $\epsilon = 0.9$.

Attempts to use characteristic differences in the charge collection times of strongly localized $\beta\beta$–events and multi site background events, caused by Compton scattering [55], have so far not entered the stage of data taking.

The Heidelberg–Moscow experiment. This experiment, performed as a collaboration between the Max–Planck–Institut für Kernphysik in Heidelberg and the Kurchatov Institute in Moscow, is located in the Gran Sasso underground laboratory in Italy at a depth of 3500 m w.e.. The experiment is taking data since 1991. Three enriched *Ge* detectors of 6.0 kg active mass are in regular operation right now. Large *Ge* crystals, the biggest one having 2.9 kg, are used. They represent a source strength of N=68.7 mol of ^{76}Ge. Two new detectors are in preparation. The total source strength of the experiment will be around 10 kg.

The *Ge* crystals are mounted in low background cryostats custom made from electrolytical *Cu*. The detectors have a common passive shield to suppress the γ–radiation coming from ^{232}Th and ^{238}U contained in the laboratory walls, reaching up to 2.6 MeV. It is composed of 10 cm ultra pure so called LC2 grade lead followed by 20 cm of less clean Boliden *Pb*. The shield has recently been upgraded with 10 cm of boron loaded polyethylene to suppress neutrons coming from (α, n) reactions in the laboratory wall, or residual μ interactions with the walls. The setup has no cosmic veto system. All construction materials of the cryostats and the shield have been carefully selected for their radiopurity using an existing low background *Ge* detector. Their exposure time to the cosmic radiation above ground has been limited to a minimum, to prevent the production of long lived activation products. The passive shield is mounted in an airtight steel container continuously flushed by high purity nitrogen gas to displace radioactive *Rn* gas contained in the air.

The large body of data accumulated by this experiment during the last three years of operation allowed for the first time to reach a neutrino mass limit below 1 eV. The group has published [56] a half life limit of $T^{0\nu}_{1/2} > 5.1 \cdot 10^{24}$ y (90% c.l.) corresponding to $M_{eff} < 0.7$ eV if the nuclear matrix element of [57] is used. This August 1994 result is based on 8.6 $kg \cdot y$ of measuring time corresponding to an exposure of 98.3 $mol \cdot y$ for ^{76}Ge. Available now and being analyzed are 157 $mol \cdot y$ of measuring time. Earlier tentative indications for an excess of events at the $\beta\beta$–decay energy seem to have disappeared with longer measuring time. Figure 1, which was taken from reference [56], shows the measured spectrum around 2.04 MeV.

The large source strength together with the low background of the detectors allowed the first high statistic measurement of the $\beta\beta2\nu$–decay channel [58]. The half life measured is $T^{2\nu}_{1/2} = (1.43 \pm 0.03^{stat} \pm 0.13^{syst}) \cdot 10^{21}$ y. A stringent limit for the Majoron–neutrino coupling of $\langle g_{\nu\chi} \rangle < 1.8 \cdot 10^{-4}$ [59] has been determined as well.

Taking into account the background of 0.021 $counts/keV \cdot y \cdot mol$ measured in the interval from 2.00 to 2.08 MeV and assuming that the experiment will continue for two more years after the full source strength has been implemented one can estimate the $T^{0\nu}_{1/2}$ range which can be eventually tested. A square root approach, discussed later, yields a half life limit of around $2 \cdot 10^{25}$ y.

The International Germanium Experiment. The IGEX collaboration is formed by groups from Russia, Spain and the US. The experiment has just recently started taking data. The experimental ansatz is quite similar to the project described before. Five enriched *Ge* detectors having an active mass of 5.8 kg are in operation in different underground locations. Two of them having 2 kg each, installed in the Homestake mine in SD at ~ 4000 $m.w.e.$, can be considered to be in their final configuration. The cryostats are made underground of electro-formed *Cu*. The electro-chemical production of *Cu* parts called electro-forming is another cleaning step since elements as *U* and *Th* tend to be depleted in this way. If done underground it prevents the activation of the *Cu*. The detectors are in a passive shield made of selected lead. In addition one detector of 0.65 kg fiducial mass is operated in the Canfranc tunnel in Spain and another one of 0.7 kg in the Baksan underground laboratory in Russia.

To date, the experiment has accumulated 15 $mol \cdot y$ of ^{76}Ge exposure time. The background of 0.014 $counts/keV \cdot y \cdot mol$ around 2.04 MeV is comparable to the level of the experiment described before. The group used 11 $mol \cdot y$ to derive a half life limit of $T^{0\nu}_{1/2} > 1.7 \cdot 10^{24}$ y (90% c.l.) for the neutrinoless decay mode. The experiment sees evidence for the $\beta\beta2\nu$–decay of ^{76}Ge but with a somewhat shorter half life of $T^{2\nu}_{1/2} = (1.12 \pm 0.17) \cdot 10^{21}$ y [60] than that of the Heidelberg–Moscow experiment. The goal of the collaboration is to produce as many *Ge* crystals as possible from their enriched *Ge*. Perhaps they will also end up with around 10 kg in form of *Ge* detectors. In this respect the reachable sensitivity towards neutrino masses will be similar to that of the previously discussed experiment.

4.3.2 The Caltech–Neuchâtel–PSI ^{136}Xe TPC. The investigation of ^{136}Xe is at present the only other method to match the sensitivity level reached with Ge detectors. The fact that Xe can be used as a counting gas has stimulated many experiments to study this topic. The most successful instrument is the Caltech–Neuchâtel–PSI TPC using isotopically enriched (62.5 %) ^{136}Xe gas at 5 bar pressure. The spatial resolution of this instrument allows to distinguish two–electron events from one–electron events and various other backgrounds. This is a powerful tool to reduce backgrounds even below the astonishing levels reached with Ge detectors. The Q-value of the decay is 2.48 MeV slightly higher than that of ^{76}Ge but still within the energy range of the natural radioactivity.

The TPC is operated in the St. Gotthard underground laboratory in Switzerland at a depth of 3000 m.w.e., by a collaboration between Caltech in Pasadena, the University of Neuchâtel and the Paul Scherrer Institut in Villingen [61]. A source strength of N=24.2 mol of ^{136}Xe is used. The TPC itself and all its metallic components are made from selected OFHC Cu. All technical components such as e.g. resistors have been selected by monitoring with a low background Ge detector. The TPC is shielded against the radioactivity of the laboratory by 5 cm of Cu and 20–30 cm of Pb. The shield is continuously flushed with dry nitrogen gas to remove the Rn. The purity of the counting gas itself is maintained on the 0.1 ppm level in electro-negative contaminants by continuously pumping it through a low Rn getter. The setup is equipped with a cosmic ray veto to tag the muons.

Two–electron events are identified through differences in dE/dx at the beginning and end of a track, respectively. The discrimination efficiency for single electrons is 98 %. Multiple scattering in the high pressure gas prevents the identification of the vertex of the decay. The TPC has an energy resolution of 6.6 % at 1.6 MeV. The powerful background rejection capability of this instrument results in the lowest background level among all existing $\beta\beta$–decay experiments of $B = 0.002\ counts/keV \cdot y \cdot mol$. A drawback is the relatively small detection efficiency of $\epsilon = 0.23$ for electron pairs, which is a folding of the probability that both electron tracks are completely contained in the TPC (30 %) and the finite analysis efficiency (76 %).

The first phase of this experiment was completed in 1992. Figure 2 depicts the measured sum energy spectrum of the two–electron events, together with the excluded $\beta\beta 0\nu$–signal.

An exposure time of 18.9 $mol \cdot y$ allowed to exclude a neutrinoless decay half life of $T^{0\nu}_{1/2} \leq 3.4 \cdot 10^{23}\ y$ (90% c.l.) which corresponds to a neutrino mass limit of 2.8 eV. Due to the steep rise of the TPC background at lower energies the $\beta\beta 2\nu$–decay has not been measured yet. A half life limit of $T^{2\nu}_{1/2} > 2.1 \cdot 10^{20}\ y$ has been determined which is the best limit obtained so far for this isotope. The group published also a limit for the Majoron–neutrino coupling of $\langle g_{\nu\chi}\rangle < 2.4 \cdot 10^{-4}$ using the matrix element of ref. [62].

The TPC has recently undergone remodelling [63]. A new anode has been constructed. Resistors were replaced by those having lower background. To avoid soldering the TPC wires are now crimped to an acrylic frame. The XY plane was reconstructed as well.

After installation of these new components about 1000 h of data has been taken by mid August 1994. These data show an encouraging factor 5 reduction in background. Meaningful new results should be available within a few months. The group plans to reach a half life limit of $10^{24}\ y$ in one year of operation. Another important goal is to measure the two neutrino $\beta\beta$–decay. To do this the TPC will be operated at lower pressure to improve the track quality at low energies.

Xe gas depleted in the isotope ^{136}Xe is available and could be used to measure the background. This method, however, relies on the assumption that the background of the enriched source and the depleted sample is identical.

The measurement of the $\beta\beta 2\nu$–channel is interesting because the theoretical predictions show a considerable discrepancy, while reference [57] gives $1.4 - 21.1 \cdot 10^{21}\ y$, ref. [62] predicts $8.2 \cdot 10^{20}\ y$.

4.3.3 Discussion of the Results. If we combine the technical parameters of both detection concepts into a figure of merit S we can directly compare the TPC to the calorimetric Ge experiments.

$$S = \epsilon \cdot \sqrt{\frac{N}{\Delta E \cdot B}} \qquad (4.9)$$

ΔE [keV] is the energy resolution (FWHM) at the $\beta\beta$–decay energy. The sensitivity S is directly connected to the half life limit to be determined from the data if no peak can be found after measuring for the time t [y]. This relation which does not depend on the used isotope, is

$$T^{0\nu}_{1/2} > (3.2 \cdot 10^{23}\ mol^{-1}) \cdot \frac{S}{f} \cdot \sqrt{t} \qquad (4.10)$$

f depends on the chosen confidence level of the limit.

The Caltech–Neuchâtel–PSI TPC has a sensitivity of $S = 1.98\ mol \cdot \sqrt{y}$ whereas the Heidelberg–Moscow experiment has $S = 27.9\ mol \cdot \sqrt{y}$ in its present configuration. From this we see that the superior background of the TPC is more than compensated by its worse energy resolution and efficiency.

A comparison in terms of the neutrino mass limits which can be reached is more difficult because the nuclear matrix element calculations of refs. [57,62] are similar to each other for ^{136}Xe but differ considerably for ^{76}Ge. Table 2 gives a compilation of these sensitivities.

As can be seen from Table 2 the technology available today will allow us to explore neutrino masses around 1 eV. Because these experiments are already using tens of kg of highly enriched, and therefore very expensive isotopes, it is difficult to imagine how to gain another order of magnitude by scaling up these ideas. Some of the new ideas are discussed in the next section. To set the scale we estimate the lifetimes corresponding to 0.1 eV neutrino mass.

How good will detectors have to be to see neutrino masses $M_{eff} \approx 0.1$ eV? The Table 3 contains estimates of the lifetimes that correspond to 0.1 eV in several potentially useful nuclei. The table was constructed by culling calculated rates from the available literature. The "best values" reflect a certain degree of personal bias towards one calculation or another. The uncertainties are obviously difficult to estimate; what they really represent is a conservative assessment of the spread in values from respectable calculations. The possibility that none of the calculations is good in some particular nucleus cannot be completely ruled out. The ranges of uncertainty are usually least reliable where they are smallest (e.g. in ^{136}Xe), most often because only one method of the several in circulation (shell model, QRPA, pseudo-SU(3) ...) has been used. When no uncertainty is given it is because only one believable result was found.

5.0 PROSPECTS FOR FURTHER IMPROVEMENT.

5.1 M_{ν_μ}: Ideas for going below 160 keV. Historically, $M^2_{\nu_\mu}$ has also suffered from having negative experimental values yielded from experiments with stopping pions. However, recently this difficulty has been removed by improved extraction of the pion mass from studies of pionic x-rays. Nonetheless efforts should continue to seek other means to lower the limits especially by in-flight methods.

In this workshop, preliminary studies were carried out. The first involves the use of $K^\circ_{\mu 3}$ decay spectra and the second a novel suggestion using pion decays in a $(g-2)$ apparatus.

Limit on the m_{ν_μ} from $K^\circ\mu 3$ Decay Spectra. Recent upgrades to the BNL-AGS have made it possible to make many high statistics measurements. Here we will consider the statistics and the resolution needed to improve the limit on the muon neutrino mass using decays. The method relies on the shape of the invariant mass distribution of the pion and the muon, $m_{\pi\mu}$, near the end point where the neutrino energy is low in the center of mass [64]. The use of simultaneously detected $K^\circ_L \to \pi^+\pi^-$ events to calibrate the mass scale and understand the resolution of the spectrometer reduces the sensitivity of this method to previously measured particle masses and to the magnetic field in the spectrometer. An additional check on the experimental method can be obtained by measuring the endpoint of $K^\circ_L \to \pi^\pm\mu^\mp\nu_e$ decays in which one does not expect to observe a non-zero neutrino mass at the sensitivity level of this experiment. Finally, by comparing the end point spectra for neutrinos and antineutrinos one can obtain the most stringent limit on a neutrino-antineutrino mass difference, a non-zero value of which would violate CPT invariance. The only other method that limits a neutrino-antineutrino mass difference is the measurement of π^+ and π^- lifetimes, if one attributes the difference in the lifetimes to the dependence of the decay amplitude on neutrino mass [65,66].

The V-A theory of weak interactions predicts little dependence of the $K_{\ell 3}$ matrix element on the neutrino mass. The boundary of the Dalitz plot does, however, depend on the neutrino mass. In the case of zero neutrino mass the $m_{\pi\mu}$ distribution approaches m_K with the first derivative zero, and in the case of non-zero neutrino mass the same distribution terminates before approaching m_K. The measured quantity, $m_{\pi\mu}$, at the endpoint is simply related to the neutrino energy in the kaon center of mass by the following formula:

$$
\begin{aligned}
E_\nu &= \frac{m_K^2 - m_{\pi\mu}^2 + m_\nu^2}{2m_K} \\
&\approx \frac{(m_K + m_{\pi\mu})}{2m_K}(m_K - m_{\pi\mu}) \\
&\simeq m_K - m_{\pi\mu}\,.
\end{aligned}
\tag{5.1}
$$

Since m_K is effectively measured in the same experiment by using $K_L^\circ \to \pi^+\pi^-$ decays, the neutrino energy measurement is independent of the kaon mass. Furthermore, the dependence on pion mass is only in second order, and therefore the pion mass uncertainty (0.4 keV) contributes only about 0.23 keV to the neutrino energy uncertainty.

The previous best experiment of this type achieved mass limits of 725 keV for the muon neutrino and 500 keV for the electron neutrino at 90% confidence level [64]. The experimenters collected 2130 well identified $K_L^\circ \to \pi^\pm\mu^\mp\nu_\mu$ events with $m_{\pi\mu} > 493.5$MeV (the fraction of the total spectrum in the Dalitz plot that is above this mass without dilution due to resolution smearing is 3.1×10^{-5}). They used the invariant mass spectrum including the non-Gaussian tails of $K_L^\circ \to \pi^+\pi^-$ events to calibrate the absolute mass scale and also to simulate the experimental resolution. The lower limit on the mass window is dictated by the need to suppress background arising from $K_L^\circ \to \pi^+\pi^-$ events in which one of the pions either decays in flight or is misidentified as a muon. Kinematically this background should not populate events with $m_{\pi\mu}$ above 489 MeV. This is seen most simply from the use of the following approximation for two body invariant mass in the laboratory frame:

$$m_{12}^2 \approx m_1^2 + m_2^2 + \frac{p_2}{p_1}m_1^2 + \frac{p_1}{p_2}m_2^2 + p_1 p_2 \theta^2 \tag{5.2}$$

where p_1, p_2 and θ are the laboratory momentum of particle 1, particle 2 and the laboratory angle between particles 1 and 2, respectively. In the extreme case that the momentum of the misidentified muon is much larger than the momentum of the pion the invariant mass will be: $m_{\pi\mu}^2 \approx m_K^2 - (m_\pi^2 - m_\mu^2)$. Errors in momentum measurements cause background events to leak out of this kinematic limit to populate the end point region.

One must collect much higher number of events with $m_{\pi\mu} > 493.5$MeV with better mass resolution and muon identification to improve the muon neutrino mass limit. Experiment E871, a search for $K_L^\circ \to \mu^\pm e^\mp$, at the BNL-AGS offers such a possibility [67,68]. E871 is a two arm magnetic spectrometer optimized for two body charged decays of neutral long lived kaons. Two magnets provide nearly independent measurements of the momentum of each particle. A Cerenkov counter, lead glass, and a fine grained muon range system provides redundant particle identification. The trigger and data aquisition system is built to take data at very high rates to achieve sensitivities of 10^{-12} for two body charged decays of the K_L°.

The estimated mass resolution for E871 is 1.13 MeV for $K_L^\circ \to \pi^+\pi^-$ events. The number of $K_L^\circ \to \pi^\pm\mu^\mp\nu_\mu$ events with $m_{\pi\mu} > 493.5$ MeV necessary as a function of the limit on m_{ν_μ} assuming a Gaussian mass resolution with $\sigma_m = 0.5$, 1.0 and 1.5 MeV have been computed; see Figure 3. Barring systematic error the number of events needed to achieve a sensitivity of 100 keV (a significant improvement on the best 90% confidence level limit of 160 keV from pion decay at rest [7]) is about 3.0×10^5. The number of events needed increases very rapidly as the limit is lowered mainly because the V-A shape approaches the kaon mass with zero slope so that in the case of zero neutrino mass there are no events at the end point. Most possible systematic errors, such as variation in the spectrometer acceptance over the fitted mass range or background contamination, will either change the shape smoothly or cause the overall normalization to shift. A non-zero neutrino mass should cause a relatively abrupt change in the shape only at the endpoint, therefore the systematic errors should not be a major difficulty. This, of course, will have to be studied with actual data. The geometric dimensions of the E871 spectrometer, the appropriate kaon spectrum, and the requested intensity have been used to compute the rate of $K_L^\circ \to \pi^\pm\mu^\mp\nu_\mu$ events with $m_{\pi\mu} > 493.5$MeV to be about 300 per hour. E871 should be able to collect more than enough events in a 4000 hour run for this measurement.

Limit on M_{ν_μ} from $(g-2)$ Apparatus. Kinematic tests of the neutrino mass which rely on nuclear beta decay can provide very sensitive limits for the electron neutrino mass, but need well understood resolution functions for the spectrometer and model-dependent atomic corrections as discussed above. A complementary kinematic test of neutrino masses which does not suffer from these limitations is provided by the decay $\pi \to \mu\nu$. As a simple 2-body decay, it is more accessible to experimental measurements of the neutrino mass than the 3-body purely leptonic muon decay $\mu \to e\nu\nu$. The current lowest bounds on the muon neutrino mass were measured in experiments of this kind: from the pion-stopping experiment of Assamagan et al. [7] mentioned above, and $m_\nu < 500$ keV (90% CL) from the pion in flight experiment of Anderhub et al. [69].

Experiments where the pion is brought to rest rely on a very accurate measurement of the momentum of the daughter muon, from which the neutrino mass is inferred using the relation $p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2/4m_\pi^2$. The other ingredient in the formula is the mass of the pion, which contributes about equally to Δm_ν^2. Uncertainties in the mass of the muon are a much less significant contribution. Two earlier papers from the same group ([70] and [71]), used essentially the same technique, but with a less efficient production mechanism which necessitated wider collimator openings in their spectrometer and thus a poorer momentum resolution. In the first paper, Abela et al., an upper limit of 250 keV (CL=0.9) is calculated by assigning the probability function to zero for $m_\nu^2 < 0$, a necessary step since plugging directly in the values in the formula above and using the pion mass defined in the Review of Particle Properties (e.g. $m_\pi = 139.5675 \pm 0.0004$ MeV [1990]) yields a negative value for m_ν^2. In the second paper by Daum et al., the uncertainties on the muon momentum were reduced, measuring $p_\mu = 29.79206 \pm 0.000684$ MeV, but the problem of a non-physical neutrino mass squared term remained, with $m_\nu^2 = -0.154 \pm 0.044$ MeV$^2/c^4$. If the momentum measurement is correct, there are only 2 other alternatives (barring the interesting suggestion that neutrinos are tachyons): either the π^- mass measurements are wrong or $m_{\pi^-} \neq m_{\pi^+}$. Since the second alternative implies a violation of CPT, it is more likely that the pion mass is the problem, since the Particle Properties value is heavily weighted by one experiment [72] which is based on pion capture (4f→3d transitions in ^{24}Mg) and therefore subject to a vacuum polarization correction of 0.2% for a 0.0002% measurement. Thus, the authors choose to quote their result as a determination of the π^+ mass, a result which is 3σ larger than the previous world average. Since that time, the Jeckelmann pionic X-ray spectrum has been reanalyzed [73], resulting in two solutions for the pion mass, depending on whether the strongest component in the 4f-3d transition is assumed to be one or two K-electrons. With the larger pion mass (2 K-electrons), Assamagan et al. find $m_\nu^2 = -0.022 \pm 0.023 MeV^2$, consistent with zero. Since the smaller pion mass still gives a negative mass-squared term by six standard deviations, and since earlier pion mass experiments (e.g. [74]) which observed pionic X-rays in other materials (e.g. phosphorus and titanium) are consistent with the smaller mass, there is still a model-dependent element in this analysis.

If, instead, the pion decay is observed using high energy pions in flight, the neutrino mass determination becomes almost independent of the value of the pion and muon masses. Measuring the difference in momenta $p_\pi - p_\mu$ for forward going muons gives the neutrino momentum, from which the mass can be extracted: $m_\nu^2 = [\sqrt{p_\mu^2 + m_\mu^2} - \sqrt{p_\pi^2 + m_\pi^2}]^2 - p_\nu^2$. In the Anderhub experiment, 350 Mev pions were momentum analyzed in a 180° spectrometer, passed through a decay region, and the daughter muons were reanalyzed in the same spectrometer to reduce any systematic error in the momentum difference measurement. Time of flight was used to identify the decay muons. It is interesting, but not significant, that the Anderhub experiment also measured a negative $m_\nu^2 = -0.14 \pm 0.20$ MeV$^2/c^4$.

For 350 MeV pions, the effect of a massive 300 keV neutrino is to reduce the forward going daughter muon momentum of 355.7 MeV by ~ 3 keV. Such a precision momentum difference measurement requires superb determination of the decay angle and is ultimately limited by multiple scattering and energy loss along the flight path. Since small angle multiple scattering goes as the square root of the number of radiation lengths of material, and we are measuring the square of m_ν, then to achieve a factor of 10 improvement in m_ν one must be able to reduce the thickness of the chambers by 10^4 while maintaining the same position resolution. This is an extremely difficult, but not necessarily impossible task, and would require new technologies. One possibility is the use of high yield secondary emission foils. The secondary electrons can be electrostatically accelerated across the vacuum chamber, using the magnetic field of the spectrometer to maintain their coherence, then read out by a microchannel plate and image intensifier/CCD chain. These types of detectors have been in use for a long time, usually as beam monitors in accelerators [75]. In order to achieve the required efficiency for very thin foils, it may be necessary to go to NEA (negative electron affinity) foils such as *GaAs* [76]. Although requiring a considerable amount of detector R&D, it now seems possible to repeat the Anderhub experiment with thinner detectors in order to improve the muon neutrino mass limit. Since the uncertainties in the pion mass will still be negligible, even with a factor of ten improvement in precision, this experiment would be worthwhile.

Performing an experiment to measure the pi-mu momentum difference requires an extremely precise and well-understood spectrometer. This has led one of us [77] to consider using the new storage ring being built at Brookhaven for the g-2 experiment for a neutrino mass limit experiment using pions in flight. The ring is 7 meters in radius and will be shimmed to 1 ppm for a median field of 1.47 Tesla. Stationary NMR probes, an NMR trolley which maps the field every day, and absolute NMR calibration probes will ensure that the field is known (and controlled via current feedback coils) to 0.1 ppm. Pions or muons of 3 GeV can be injected into the ring from the AGS. There are several techniques that could work. The most straightforward method would be to measure the pion momentum after the production target, allow the pions to decay in the straight section of the injection line to select for forward-going muons, then measure the muon momentum in the g-2 storage ring using three very thin secondary emission foils. Another interesting possibility is to allow both pions and muons to circulate in the storage ring and measure the time of flight after each turn. Since the period of revolution in a fixed radius, fixed B-field ring is inversely proportional to the energy of the particle, a forward going muon produced in a decay with an associated massive neutrino, having a lower momentum than one produced in conjunction with a massless neutrino, will circle the ring faster. The period in the g-2 storage ring is about 150 ns. Three GeV pions will travel 35 ps/revolution slower than their daughter muons, and muons associated with 300 keV neutrinos will be 1 ps/rev quicker than any of them. This type of measurement is extremely difficult and is only possible because some of the dilated lifetime muons will survive 50 turns or so. In addition, the time of flight measurement must be made in a non-destructive way; the proposed method being the detection of a change in the light output of a laser beam passing through an electrooptic crystal situated a millimeter or so from the particle beam. The polarization of the material is changed by the electric field of the passing particle and is detected by a photodiode through a polarized filter. As with the secondary emission foils, this will require some detector R&D, since the required time resolution (several psec) and sensitivity (single particles at 1mm distance) are close to the current limitations of this method.

5.2 M_{ν_τ}: What is needed. No explicit work was done by this group on methods to improve limits on M_{ν_τ}; however, we note in passing that studies made for future "B-factories"[78] or "Tau-Charm-factories" with improved detector resolution suggest that levels of $\sim$ 2.5MeV might be reached as a consequence of increased statistics and background subtractions.

5.3 Double Beta Decay: Ideas for approaching 0.1 eV.

The NEMO project The international NEMO collaboration is exploring a new way to reach sub–eV sensitivities in neutrino mass [79]. The experiment [80], which is fully funded, will be done as a collaboration between French, Russian, Ukrainian and US groups in the Frejus underground laboratory in Modane (France) at a depth of 4800 m.w.e.. From the previous discussion it is obvious that the combination of a detector having tracking capabilities and a good detection efficiency for the electrons would be desirable. Because these requirements are difficult to be met if the source and the detector are identical, the NEMO collaboration is preparing a detector using Geiger tubes filled with a He-ethyl alcohol mixture at atmospheric pressure as a tracking device while the electron energy will be measured with plastic scintillators covering the walls of the setup. Because the density of the gas in the sensitive volume is only about 0.2 mg/cm^2, the average energy loss of the electrons in the tracking device will be limited to 14 keV for a 1 MeV electron. The detection efficiency and therefore the calorimetric features of the detector are determined by the fraction of the solid angle covered by the plastic scintillators. The compound efficiency for the detection of two–electron events, estimated through a Monte Carlo simulation, will be $\epsilon = 0.4$. The energy resolution of these scintillators is around 9 % at 3 MeV. Because of the separation of source and detector one is now free to choose a $\beta\beta$–emitter having a Q-value above the energy range of the natural radioactivity. The limited energy resolution results in $\beta\beta 2\nu$–events being scattered into the analysis interval of the $\beta\beta 0\nu$–decay, which is hence an irreducible source of background.

The collaboration prepares 10 kg of isotopically enriched ^{100}Mo (98 % abundance), which has with 3.03 MeV a high Q-value. The source will be put as a thin foil inside the cylindrical tracking detector to limit the energy loss of the electrons in the foil. The requirement of kg quantities for the $\beta\beta$–sources hence results in a relatively large detector (3m in diameter and 3m in height). Figure 4 shows the planned detector and its shielding components.

The design goal of the setup is to be sensitive to $T_{1/2}^{0\nu} = 10^{25}\ y$. Depending on the detector background which can be achieved eventually a sensitivity of a few tenths eV for the Majorana neutrino mass could be reached. The spatial resolution of the instrument as well as the strong segmentation of the calorimetric part of the detector will help to identify backgrounds. A magnetic field (30 Gauss) will allow the measurement of the electron momenta as well as to discriminate against e^+e^- events coming from high energy γ–radiation interacting with the Mo–foil. Delayed particles crossing the tracking device will be tagged to identify e.g. ^{214}Bi whose daughter ^{214}Po is a short-lived α emitter.

Through a measurement of the $\beta\beta 2\nu$–decay in the prototype detector NEMO II the group has already shown that the strict background requirements can be met by such a complicated and big device if the enriched Mo is of sufficient radiopurity [80]. Because the strong point of this project is that ***any*** isotope can be used, the group is investigating whether larger quantities of enriched ^{82}Se, ^{96}Zr, ^{116}Cd or ^{150}Nd can be made with sufficient purity.[81] This project will perhaps allow the next major step in sensitivity.

Other ideas. Thermal detectors offer the possibility of using a wide range of $\beta\beta$–emitters in the detector=source approach. A clever selection of the isotope can yield improved sensitivities.

The Milano group uses a 334 g crystal of natural Tellurium oxide in the Gran Sasso laboratory to study ^{130}Te which has a natural abundance of 34.5 % and a relatively high decay energy of 2.53 MeV. This instrument has an energy resolution of 16 keV at the decay energy coming close to the values of Ge detectors. They have reached a half life limit of $T_{1/2}^{0\nu} > 1.4 \cdot 10^{22}\ y$.

Another project following the conventional calorimetric approach is a collaboration between the $\beta\beta$ groups from Heidelberg and from Kiev preparing $CdWO_4$ scintillators. The idea is to use such scintillators made from isotopically enriched $\beta\beta$–unstable ^{116}Cd. The Q-value of 2.8 MeV (beyond the natural radioactivity) should help to achieve low background. The energy is on the other hand close enough to the prominent γ–line at 2.615 MeV (coming from ^{232}Th) to be contaminated. If the energy resolution is worse than 6.6 % at 1 MeV the $2\cdot\sigma$ intervals around the background peak and the $\beta\beta$–energy will overlap, which sets stringent requirements to the resolution of the detector. Another drawback is the fact that only 32 % of the scintillator mass is contributed by Cd leading to a relatively low abundance of the decaying isotope even if enriched Cd is used. The group is investigating these problems using a 1 kg detector made from natural $CdWO_4$, installed in the Gran Sasso tunnel.

Another potentially promising way to get to the 0.1 eV level as a limit for neutrinoless double beta decay is the use of ^{150}Nd in a cryogenic detector. Until recently this favorable isotope with its 3.4 MeV energy release could be used only as a source, and because multiple scattering of the emerging electrons required that it be used as a thin foil, the amount of ^{150}Nd had to be quite small. As NdF_3 cooled to milliKelvin temperatures, it can be both source and detector, permitting use of as much material as one can afford. Since NdF_3 has a high Debye temperature (θ_d = 390K), its small specific heat provides a large signal and an energy resolution of less than 1 keV at 3.4 MeV in a 10^2 g crystal. This is a factor of at least three improvement in resolution compared to a Ge semiconductor detector.

Another advantage compared to Ge is the energy available. In this energy range backgrounds go down about an order of magnitude per MeV, and Ge has only 2 MeV energy release. Indeed, 3.4 MeV is above any naturally occurring beta or gamma background. It appears possible using ballistic phonons to utilize pulse shape so that alpha backgrounds could also be eliminated. With the good energy resolution and the low radioactivity backgrounds, it is likely that at a deep site during the needed counting time there would be no counts at the endpoint energy unless neutrinoless double beta decay were seen. The lifetime limit would then increase directly with counting time, instead of as the usual square root of that time.

The main issue regarding the feasibility of reaching the 0.1 eV level is the ^{150}Nd matrix element. The QRPA calculation by Staudt, Muto, and Klapdor [57] gives a factor 70 improvement in rate, for all other factors equal, with respect to ^{76}Ge. If that turns out to be true – and the main part of that improvement comes from the larger energy release – then achieving the 0.1 eV level is assured. However, Hirsch, Castaños, and Hess in a recent publication[82] get a very suppressed matrix element because the nucleus is deformed, making it less favorable even than ^{76}Ge.

All of these experiments will probably, on a certain level, be limited by residual background. An elegant way to reach the zero background regime could be to detect the electrons in coincidence with the decay product created at the same location in the detector, to have an additional signature for $\beta\beta$–decays. This requires a detector with spatial resolution. The big problem here is, that the requirements of a large detector containing a reasonable number of source atoms and the identification of single atoms in this "ocean" are hardly compatible. The double beta group in Irvine, which pioneered in the field of the measurement of $\beta\beta 2\nu$–decays in several isotopes, is working on this problem.

All discussed projects are dealing with kg quantities of the investigated isotope. If the source should be increased to several tons the only practical $\beta\beta$–emitter left seems to be Xe. The idea of using Xe gas dissolved in a large liquid scintillator, having very low intrinsic radioactive contaminations, has been proposed [83]. Large low background facilities as the test detector of the BOREXINO project (FV: 2 tons) in the Gran Sasso tunnel could be used. The source strength of this configuration would be 27 mol of ^{136}Xe if natural Xe would be used or 733 mol for the final BOREXINO detector (FV: 60 tons).

Because the solubility of Xe gas in liquid scintillator is limited to ~ 2 % the fraction of source to active detector would be far from ideal. The use of enriched Xe would again allow a much more compact detector.

A serious problem would be the poor energy resolution of the device spilling two neutrino double beta events into the zero neutrino analysis interval. Any estimate of the achievable sensitivity depends hence on the unknown half life of the allowed background decay channel.

An even more avantgardistic idea would be the use of a large (several kton) liquid Xe detector similar to the liquid Ar TPC developed by the ICARUS collaboration. A fiducial volume of 1 kton of natural Xe corresponds to a source strength of $6.7 \cdot 10^5$ mol of ^{136}Xe. In the most optimistic case of no background a neutrinoless half life of 10^{29} y could be tested within one year. This corresponds to a neutrino mass limit of $4 \cdot 10^{-3}$ eV. A similar background and energy resolution as in the previously discussed Xe TPC reduces the sensitivity to 10^{26} y or 0.1 eV. The truth may be somewhere in between these two numbers. The questions whether the high density of the liquid Xe will allow the identification of tracks of MeV electrons and whether long lived radioactive noble gases as e.g. ^{42}Ar, (produced in atmospheric nuclear bomb tests) emitting electrons with energies of up to 3.52 MeV, are a serious problem, remain to be answered.

5.4 Other Topics.

100 keV Neutrinos. If neutrinos have mass then it is of course possible for the different types of neutrinos to mix with each other. Such an admixture would exhibit itself in the kinematics of weak two-body and three-body decays in which the neutrino is one of the final products. The spectra of the accompanying particles in these decays would feature an extra peak (in the case of two-body decays) or a kink (in the case of three-body decays) the location of which will depend on the mass of the admixed neutrino and the strength of which will depend on the mixing angle. A wide variety of experiments has been conducted to search for the admixture of a heavy neutrino with the electron neutrino (ν_e) by looking for such extra peaks or kinks in decays involving the electron neutrino (e.g. [84]). These experiments have established varying upper limits on the strength of the admixture of ν_e to heavy neutrinos with masses ranging from a few keV to several GeV. The least stringent limit for the mixing of ν_e with ν_τ is for 100 < mass of ν_τ < 1000 keV, where the current limit is $\sim 0.5\%$. A collaboration between a Nuclear Physics group from Tennessee Technological University (Hindi, Kozub, Robinson) and a Surface Science group from Montana State University (Avci, Zhu, Lapeyre) is currently conducting an experiment which aims to bring down these limits to $< 0.1\%$.

The basic idea is to measure the spectrum of recoil velocities of ^{37}Cl ions following the electron capture (EC) decay of ^{37}Ar. For an isolated ^{37}Ar atom energy and momentum conservation dictate that the recoil energy be 9.54 eV when ν_e is emitted. If a neutrino with mass m_ν is emitted in a certain fraction of the decays then the recoil energy of that fraction will be shifted down in energy by a fractional amount of $\frac{\Delta E}{E} = \left(\frac{m_{\nu_\mu}}{Q}\right)^2$, where Q is the decay energy (814-E_b) keV, where E_b is the excitation energy of the hole left in the daughter ^{37}Cl atom). Thus the highest mass neutrino that could be emitted in the decay is 814 keV; if a 250 keV neutrino were to be emitted, for example, the change in energy of the recoiling ^{37}Cl would be 9.5%. The lowest neutrino mass to which the method could be sensitive depends on our ability to resolve the peak associated with the emission of the massive neutrino from the dominant peak associated with the emission of the electron-type neutrino in the recoil spectrum. The factors which lead to a broadening in the energy spectrum are dependent on the experimental technique, a brief account of which will be given next. Full details of a preliminary measurement have been published recently [85].

The spectrum of recoil velocities from a monolayer consisting of a mixture of one part ^{36}Ar and $\sim 5 \times 10^{-5}$ parts ^{37}Ar physisorbed on a gold-plated Si wafer cooled to 16 K was obtained under ultra-high vacuum conditions by measuring the time-of-flight of the recoiling ^{37}Cl ions. The time-of-flight spectrum was obtained by starting a time-to-amplitude converter by detecting one of the Auger electrons emitted after the EC decay, and stopping it by detecting the ^{37}Cl ion after it had travelled a distance of ~7 cm. The observed energy distribution was found to have a maximum close to the expected energy of 9.5 eV; the FWHM of ~3 eV is about 50% larger than that expected for isolated ^{37}Ar atoms. The factors contributing to energy broadening for an isolated ^{37}Ar atom are the thermal motion of the ^{37}Ar atom prior to decay (~3% of the recoil energy at 16 K), recoil from Auger electrons emitted by the ^{37}Cl atom after the decay (12.2% for KLL Augers, 3.5% for LMM Augers) and various instrumental effects such as variation in the flight distance over the finite size of the detector and source. A Monte Carlo simulation which takes into account all of these effects gives an energy broadening of about 14% if the coincident Auger electron was required to be a KLL Auger and 20% if any Auger electron was accepted. Several additional experimental observations [85] have led to the belief that the extra broadening observed is due to inelastic charge exchange reactions between the recoiling Cl ions and the neighboring ^{36}Ar atoms and possibly with the Au substrate. Until a full quantitative understanding of the width of the observed peak is obtained, mixing limits from this preliminary measurement cannot be quoted.

The experimental group is currently working on several improvements and modifications which it is hoped will reduce the broadening of the main peak and increase the sensitivity to admixtures with heavy neutrinos. These improvements are 1) The production of ^{37}Ar from the $^{40}Ca(n,\alpha)^{37}Ar$ reaction instead of from the $^{36}Ar(n,\gamma)$ reaction. This will eliminate the ^{36}Ar from the surface and allow a much higher activity at a much smaller coverage and source area. 2) The use of position sensitive detectors to better define the flight path. 3) The use of a graphite substrate for adsorbing the ^{37}Ar. This should hopefully lower the charge exchange probability with the substrate and reduce the fraction of backscattered Auger electrons. 4) Possibly detect the Cl ions in coincidence with a K x-ray instead of with Augers. Detection of a K x-ray insures that the Cl ends up with a charge state of +1 (in contrast with the Auger filling of the K hole, which leaves the Cl, on average, with a charge state of +3); thus if the Cl were to pick up an electron it would become neutral and hence would not be detected by the system. This would eliminate the problem of inelastic charge exchange.

The above improvements should enable the experiment to set limits of $\leq$ 0.1% on the admixture of heavy neutrinos with the electron neutrino. The measurement will be sensitive to neutrinos with masses in the range 200–800 keV. It would be difficult to push the mass below 200 keV with adsorbed ^{37}Ar atoms because of (the insurmountable) broadening due to the initial zero-point motion of the trapped Ar.

6.0 CONCLUSION

We have considered the potential impact and the feasibility of improved kinematical probes of neutrino mass. Existing hints of neutrino mass lead one to speculate that moderately improved probes of M_{ν_e} via tritium β decay, and of the effective Majorana neutrino mass M_{eff} via neutrinoless double β decay, may actually observe neutrino mass signals. The requisite improvement in the tritium experiments appears possible in principle, but very difficult. In addition, the tendency of current tritium experiments to yield $M^2_{\nu_e} < 0$ must be understood; a possible role for molecular spectroscopic studies which might help is also presented. The required improvement in the $\beta\beta_{0\nu}$ experiments appears to be attainable. Indeed, several different approaches to significantly improving the sensitivity of $\beta\beta_{0\nu}$ searches are being considered or implemented. Turning to M_{ν_μ}, we examined the possibility of improving sensitivity to this quantity through experiments on pion or kaon decay. We did not examine in any detail the prospects for improving the laboratory bounds on M_{ν_τ}, but argued from astrophysics that improved bounds would be quite valuable. Finally, we considered improving the sensitivity to neutrinos which have masses in the 200 keV – 800 keV range, and are admixed in the electron neutrino, via experiments on electron capture.

The present hints of neutrino mass, and the general theoretical prejudice that neutrinos have nonvanishing masses, give to experimental searches for neutrino mass significant and important discovery potential. We conclude that improvements to the kinematical searches are well-motivated and promising.

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Experiment	Sources	$M^2_{\nu_e}$ (eV^2) for Best Fit	M_{ν_e} Bound (eV) at 95% CL
INS, Tokyo	Cd Arach.-T	$-65 \pm 85 \pm 65$	13[1]
Zurich	OTS-T	$-24 \pm 48 \pm 61$	11[2]
Los Alamos	T_2 gas	$-147 \pm 68 \pm 41$	9.3[3]
Mainz	T_2 solid	$-39 \pm 34 \pm 15$	7.2[4]
Livermore	T_2 gas	$-130 \pm 20 \pm 15$	7[5]
INR, Moscow	T_2 gas	-18.5 ± 6	4.5[6]

Table 1: Bounds on M_{ν_e} from tritium β decay experiments.

Experiment	$T^{0\nu}_{1/2}$ *reached* [y] 90% c.l.	M_{eff} [eV] *using*		$T^{0\nu}_{1/2}$ *final* [y] 90% c.l.	M_{eff} [eV] *using*	
		Ref. [29]	Ref. [34]		Ref. [29]	Ref. [34]
H-M ^{76}Ge	$5.1 \cdot 10^{24}$	0.7	2.3	$2 \cdot 10^{25}$	0.4	1.2
IGEX ^{76}Ge	$1.7 \cdot 10^{24}$	1.2	4.0	-	-	-
C-N-P ^{136}Xe	$3.4 \cdot 10^{23}$	2.6	4.3	10^{24}	1.5	2.5

Table 2: Half life and neutrino mass sensitivities of the discussed experiments using different nuclear matrix element calculations. H-M and C-N-P denotes the Heidelberg-Moscow and Caltech-Neuchâtel-PSI experiments, respectively. The mass limits already reached are listed together with the estimates for the final sensitivity. Because the IGEX project is still in a relatively early stage no final sensitivity is given for it.

Isotope	Range			Preferred value
^{48}Ca	?	—	?	3.2×10^{26}
^{76}Ge	1.7×10^{26}	—	2.7×10^{27}	3.0×10^{26}
^{82}Se	5.8×10^{25}	—	1.1×10^{27}	1.0×10^{26}
^{96}Zr	5.3×10^{25}	—	7.8×10^{26}	3.8×10^{26}
^{100}Mo	2.6×10^{25}	—	1.9×10^{26}	1.0×10^{26}
^{116}Cd	?	—	?	5.1×10^{27}
^{150}Nd	5.0×10^{24}	—	1.0×10^{26}	9.0×10^{25}
^{130}Te	1.6×10^{25}	—	1.3×10^{26}	3.3×10^{26}
^{136}Xe	1.0×10^{26}	—	6.3×10^{26}	2.5×10^{26}

Table 3: Lifetimes for $M_{eff} = 0.1$ eV.

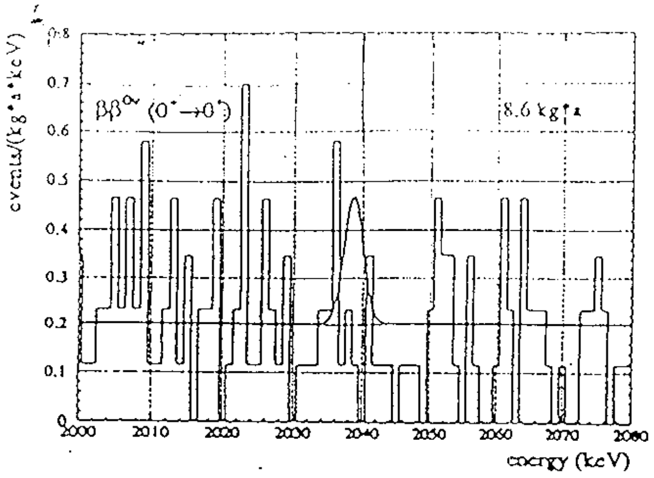

Figure 1: Measured spectrum of the Heidelberg–Moscow experiment around 2.04 MeV after 98.7 $mol \cdot y$ of ^{76}Ge exposure time. The $\beta\beta$–signal excluded with 90 % c.l. is also indicated.

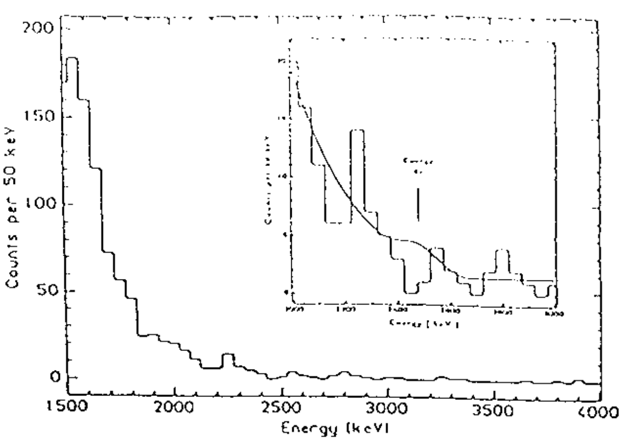

Figure 2: Measured spectrum of the TPC Sum energy spectrum of the two-electron events measured with the Xe TPC, taken from ref. [61]. The exposure time is 18.9 $mol \cdot y$. In the insert the energy range around the $\beta\beta$–decay energy is shown together with the excluded signal.

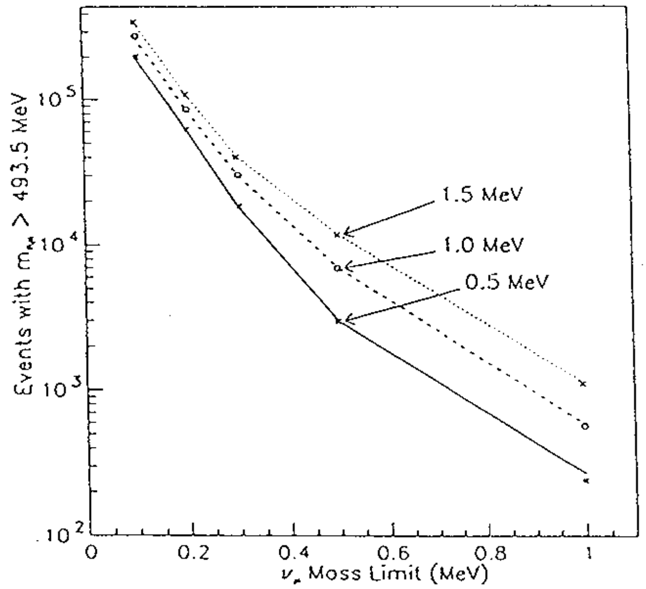

Figure 3: Number of $K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$ events needed with $m_{\pi\mu} > 493.5$ MeV versus the muon neutrino mass sensitivity for various mass resolutions. This was calculated assuming that the data will be binned with a binsize equal to or smaller than the mass sensitivity. A maximum likelihood method using the small event statistics at the endpoint should yield somewhat better sensitivity.

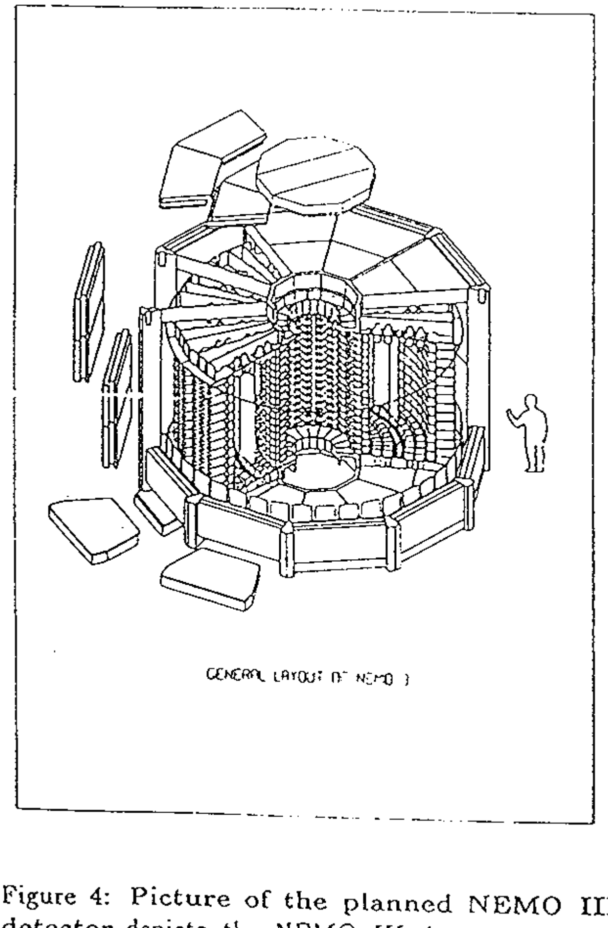

Figure 4: Picture of the planned NEMO III detector depicts the NEMO III detector and its shielding. The $\beta\beta$–source is surrounded by plastic scintillators covering the walls of the gas–filled detector. Electron and positron tracks have to be reconstructed over more than 50 cm.