# IMPLICATIONS OF NEUTRINO MASSES AND MIXING IN NUCLEAR AND PARTICLE DECAYS

Robert E. Shrock
Institute for Theoretical Physics
State University of New York at Stony Brook
Stony Brook, Long Island, New York, 11794

We shall divide the discussion of neutrino masses and mixing in nuclear particle decays into two categories: (a) tests for dominantly coupled neutrino masses, and (b) correlated tests for (subdominantly coupled) neutrino masses and mixing. We recall[1] that a neutrino is defined to be dominantly coupled in a decay such as $\pi^+ \to \ell_a^+ \nu_i$ iff a = i, where $\ell_1 = e$ and $\ell_2 = \mu$ .

## (A) Searches for Masses of Dominantly Coupled Neutrinos and Resultant Neutrino Mass Limits.

The old neutrino mass limits quoted in the literature for "m($\nu_e$)", "m($\nu_\mu$)", and "m($\nu_\tau$)" are meaningful only insofar as they are reinterpreted as limits on the corresponding mass eigenstates.[1,2] Specifically, a bound such as the Bergkvist limit,[3] "m($\nu_e$)" < 60 eV (90% CL), really constitutes a weighted limit on each of the mass eigenstates $\nu_i$ in the weak eigenstate $\nu_e$ which are kinematically allowed to occur in tritium decay and which are coupled with strength $|U_{1j}|^2$ sufficiently large to make a significant contribution to the observed spectrum. It is thus certainly a limit on $\nu_1$. If leptonic mixing is hierarchial as quark mixing is known to be (as least for the first three generations), i.e. $|U_{ii}|^2 >> |U_{ij}|^2$, $j \neq i$ , then $\nu_1$ is the only mass eigenstate significantly constrained by a bound on "m($\nu_e$)." Furthermore, a neutrino mass limit cannot be stated in isolation; it always contains some implicit dependence on the relevant lepton mixing angles. Fortunately, this dependence is relatively unimportant for the dominantly coupled decay modes, i.e., $e\bar{\nu}_1$, $\mu\bar{\nu}_2$, and $\tau\bar{\nu}_3$ . Since these modes were the ones responsible for the mass limits given previously, the latter can be reinterpreted without significant complication as proper limits on m($\nu_i$), i = 1, 2, and 3, respectively.

### (1) $\nu_e$

The standard test for "m($\nu_e$)",or more precisely m($\nu_1$), is to measure the Kurie plot for the decay $^3H \to {}^3He + e^- + \nu_e$ near the endpoint at $T_e \approx 18.6$ KeV and search for the early endpoint falloff which would result if m($\nu_1$) ≠ 0. This decay is especially useful for this purpose because of the large nuclear matrix element and small Q value. There have been a number of experiments on tritium $\beta$ decay, all of which obtained null results. Until recently, the upper bound on m($\nu_1$) was set by the work of Bergkvist, who reported "m($\nu_e$)" < 60 eV (90% CL) in 1972.[3] In 1980 an ITEF group, again measuring the same decay, reported that "14 eV < $m_\nu$ < 46 eV" (99% CL).[4] There has not been any nuclear $\beta$ decay experiment completed since this report with sufficient sensitivity to check its veracity. Fortunately, this situation should change in the near future with the installation and running of several new tritium $\beta$ decay experiments. These include, first, a Rockefeller-Lawrence Livermore Laboratory collaboration (O. Fackler, spokesman) which will use a very strong solid $^3H$ source at LLL and intends to be able to detect, after both statistical and systematic errors have been taken into account, a nonzero value of m($\nu_1$) if m($\nu_1$) $\gtrsim$ 4 eV.[5] This experiment will take data in 1983. A similar experiment using solid tritium is being launched by R. Boyd and collaborators at Ohio State University.[6] An additional high-resolution tritium $\beta$ decay experiment is being set up by T. Bowles and R. Robertson (co-spokesmen) at LASL.[7] Finally, among U. S. groups, an experiment by E.Heller et al. using tritium implanted in a semiconductor (Li-drifted Ge) is being developed at the University of California at Berkeley.[8] This method is similar to that used in earlier experimental work by J. Simpson at the University of Guelph, Canada.[9] A magnetic spectrometer apparatus at Chalk River, Canada, is being reactivated by R. Graham and collaborators; this group expects to begin taking data on tritium $\beta$ decay in late 1982.[10] Additional experiments in the development and installation stage include those of K.-E. Bergkvist in Sweden and W. Kundig of the University of Zurich, at SIN.[11] The latter experiment features a projected spectrometer resolution of ∿ 5 eV and will take data in 1983. Thus, by late 1983 or early 1984 the first results should be available from this new generation of tritium β decay experiments, all designed, of course, to have sufficient sensitivity to confirm or refute the central value $m(\nu_1) \approx 35\text{eV}$ obtained by the ITEF group. Moreover, since a $\nu_1$ mass on the order of 20-30 eV has some appeal to astrophysicists,[12] the new generation of experiments should probe the range of values of $m(\nu_1)$ which are perhaps the most likely to yield a positive result. Since the only evidence at present for a nonzero mass for any neutrino is the ITEF claim, the importance of these new experiments is clearly very great.

A different approach to the problem of detecting a nonzero value of $m(\nu_1)$ involves measuring the spectra of photons emitted as part of β transitions that proceed via electron capture.[13] Originally, there were hopes that this type of experiment would yield results competitive with those obtained by $^3H$ β decay experiments; however, these hopes have yet to be realized. At least three groups have made initial efforts in this direction, including a group at CERN[14] (G.Charpak, A. DeRujula, and collaborators), at Princeton[15] (C. Bennett and collaborators) and at KEK[16] (S. Yasumi and collaborators). Only the CERN group has so far reported a result, viz., "$m(\nu_e)$" < 1.3 KeV (90% CL), a factor of 22 worse than the 1972 Bergkvist limit. If this approach is to be competitive with the tritium Kurie plot method, then its proponents must achieve nearly a factor of $10^3$ improvement in their results. It is to be hoped that they will be successful in this endeavor, since the radiative e-capture technique is subject to different backgrounds and systematic errors than the Kurie plot technique and thus has the potential of providing a valuable independent probe of $m(\nu_1)$.

(2) $\nu_\mu$

Upper bounds on "$m(\nu_\mu)$", or more precisely, $m(\nu_2)$, have come historically from three sources (predominantly from the third): (1) measurement of the endpoint of the $e^+$ momentum spectrum in $\mu^+$ decay;[17] (2) measurement of the $\pi\mu$ invariant mass distribution in $K^o_{\mu 3}$ decay;[18] and (3) measurement of $|\vec{p}_\mu|$ in $\pi_{\mu 2}$ decay.[19,20] The most recent and best such limit was obtained by Daum et al. in a precision magnetic spectrometer experiment at SIN on $\pi_{\mu 2}$ decay and was reported as "$m(\nu_\mu)$" < 0.57 MeV (90% CL).[19] This made use of the value of $m_{\pi^+}$ as an input. Subsequently to Ref. 19, a new measurement of $m_{\pi^-}$ was completed; if one combines this with previous measurements to obtain a new world average and then uses that quantity in conjunction with the SIN data from Ref. 19, one obtains the slightly lower limit $m(\nu_2)$ < 0.52 MeV (90% CL).[21] It has been estimated that it might be possible to reduce the limit to "$m(\nu_\mu)$" $\lesssim$ 0.2-0.3 MeV in a future $\pi_{\mu 2}$ experiment.[22]

Examining other possible methods of improving the limit on $m(\nu_2)$, we note that the other two decays listed above involve three-body final states. As is well known, these have the potential advantage that a massive neutrino may have a linear kinematic effect rather than the quadratic effect which it would have in a two-body decay. Specifically, in the latter type of decay, say $\pi^+ \to \mu^+ \nu_2$, the fractional change in the muon momentum due to a nonzero value of $m(\nu_2)$ is

$$\frac{\Delta|\vec{p}_\mu|}{|\vec{p}_\mu|} = -\frac{\left(1 + m_\mu^2/m_{\pi^+}^2\right)}{\left(1 - m_\mu^2/m_{\pi^+}^2\right)^2}\left(\frac{m(\nu_2)^2}{m_{\pi^+}^2}\right) \qquad (1)$$

so that a value of $m(\nu_2) = 0.3$ MeV would cause only a $4 \times 10^{-5}$ fractional change in $|\vec{p}_\mu|$. In contrast, in a three-body decay of the form $P \to p_1 + \mu^+ + \nu_2$, where P and $p_1$ denote the parent and first final state particles, the analogous fractional change in $E_\mu$, for example is

$$\frac{\Delta E_\mu}{E_\mu} = \frac{-2\left(m_{p_1} + m(\nu_2)\right)m(\nu_2)}{\left[m_P^2 + m_\mu^2 - \left(m_{p_1} + m(\nu_2)\right)^2\right]} \qquad (2)$$

In $\mu^+$ decay, $p_1 = \nu_1$ so that the dependence is again quadratic. However, in $K_{\mu 3}$ decay, with $p_1 = \pi$, the effect of a nonzero $m(\nu_2)$ is linear and hence much larger. Using a measurement of the related invariant mass of the $\pi$-$\mu$ system in $K^o_{\mu 3}$ decay, an LBL group obtained the limit "$m(\nu_\mu)$" < 1.5 MeV (90% CL) in 1974. Note that despite the kinematic advantage, this limit was not significantly better than the bound "$m(\nu_\mu)$" < 2.5 MeV obtained earlier from μ decay.[17] Presumably this was due in part to the fact that backgrounds from other K decay modes are not an insignificant problem, in contrast to both $\pi_{\mu 2}$ and $\mu$ decay. Nevertheless, it would be highly desirable to carry out a quantitative study of the $K_{\mu 3}$ decay mode to assess how much the limit of Clark et al. might be improved. The improvement would, of course, have to be substantially better than a factor of three to render the effort worthwhile, given the current limit on $m(\nu_2)$ from the $\pi_{\mu 2}$ experiment of Daum et al.[19] The facilities which could perform such an experiment in the near future are KEK, BNL, and, with perhaps less likelihood (because of LEP priorities), the CERN PS . Possible sites in the far future are LAMPF II and/or the analogous kaon factory planned at TRIUMF.

(3) $\nu_\tau$

Upper bounds on "$m(\nu_\tau)$" ( $m(\nu_3)$) have been established first from analyses of the leptonic decay mode $\tau \rightarrow \nu_\tau e \bar{\nu}_e$ , originally by the SLAC-LBL collaboration[23] and subsequently by the DELCO collaboration,[24] at SPEAR. The DELCO result, which is more stringent, is "$m(\nu_\tau)$" < 250 MeV (95% CL).[24] A second bound comes from an analysis by the SLAC-LBL collaboration of the spectra of $\pi$'s from $\tau \rightarrow \nu_\tau \pi$ decay and is also "$m(\nu_\tau)$" < 250 MeV (95% CL).[25] It would be extremely desirable to push down this upper limit. It has been estimated[26] that a dedicated experimental study of the $\tau \rightarrow \nu_\tau \pi$ decay mode has the potential of yielding a limit in the range of 100-150 MeV. This would involve a substantial data-taking run at a fixed value of $\sqrt{s}$ with a careful study of backgrounds. Among existing facilities, the Mark III experiment (D. Hitlin, spokesman) at SPEAR is in a good position to perform such a measurement. Moreover, this task provides one of many physics arguments for continuation of a strong low and medium energy (i.e. 3-12 GeV) $e^+e^-$ research program in the U.S. Clearly, upgrading the intensity of existing facilities is a very important goal in this program.

### (B) Correlated Tests for Neutrino Masses and Mixing via Nuclear and Particle Decays

In 1980 a new class of correlated tests for neutrino masses and mixing was pointed out.[1] The basic observation underlying this new class of tests was that, in general, a decay such as $\pi^+ \rightarrow \mu^+ \nu_\mu$ does not just yield a $\mu^+$ and possibly massive $\nu_\mu$, as had previously been assumed[19] in searches for a nonzero $\nu_\mu$ "mass". Rather, if one entertains the possibility of massive neutrinos at all, as, of course, one must in testing for them, then it is not justified to assume that the weak eigenstates $\nu_e, \nu_\mu, \nu_\tau$ , etc. coincide with the mass eigenstates $\nu_1, \nu_2, \nu_3$, etc; instead, the former are linear combinations of the latter, as given by Eq. (3) in the introduction. It follows that a decay such as $\pi^+ \rightarrow \mu^+ \nu_\mu$, which had been used to set the upper bound on "$m(\nu_\mu)$", does not yield just a $\mu^+$ and $\nu_\mu$, but rather consists of the sum of separate decays $\pi^+ \rightarrow \mu^+ \nu_i$ into all the mass eigenstates $\nu_i$ comprising the weak eigenstate $\nu_\mu$ and allowed by phase space to occur in the decay. Thus, the conventional test for "$m(\nu_\mu)$" $\neq 0$ , viz. a shift in the peak in $dN/d|\vec{p}_\mu|$ downward slightly from the "$m(\nu_\mu)$" = 0 value, might very well have missed a positive signal; in the dominantly coupled mode, $\pi^+ \rightarrow \mu^+ \nu_2$, $m(\nu_2)$ might be sufficiently small that there would be no observable shift in the main peak, while a heavy, subdominantly coupled $\nu_i$ might be emitted, in the decay mode $\pi^+ \rightarrow \mu^+ \nu_i$ and might produce a peak substantially below the main one. Since previous experiments had regarded $\nu_\mu$ as a mass eigenstate, they never searched for a multitude of peaks and, indeed, set cuts which would have excluded such peaks from their data even if the latter had been present. It was thus proposed[1] that new experiments be performed with $\pi_{\ell 2}$ and $K_{\ell 2}$ decays to search for possible additional peaks in the charged lepton momentum or energy spectra which would accompany the emission of heavy neutrino(s).

The peak search test is very sensitive because the signal, if it exists at all, is monochromatic and can be distinguished well from various backgrounds, which are continuous. If an additional peak is discovered, one can, of course, immediately determine $m(\nu_i)$ for the corresponding decay mode $M^+ \rightarrow \ell^+ \nu_i$, where $M = \pi$ or K, and, using the assumption of standard V-A couplings, one can determine $|U_{ai}|^2$ , where $a = 1$ or 2 for $\ell = e$ or $\mu$, respectively. Moreover, by carrying out polarization measurements in a second generation experiment, one can test the assumption of V-A couplings, which thus does not have to be made blindly. Alternatively, if no additional peak is observed, to a given accuracy, then one can set a correlated upper bound on $|U_{ai}|^2$ for fixed $m(\nu_i)$. Because of the slow falloff of two-body phase space, there is little phase space suppression of $M^+ \rightarrow \ell^+ \nu_i$ modes until $m(\nu_i)$ approaches the maximum allowed value. Indeed, for $\ell = e$, there is very drastic helicity enhancement of the rate factor for massive neutrino modes relative to that for massless neutrinos.

After the test was proposed, it was applied to existing data on $\pi_{\mu 2}$, $K_{\mu 2}$, and $K_{e2}$ decays to search for any additional peaks within the cuts.[1] (Data on $\pi_{e2}$ decay could not be used for technical reasons; see Ref. 1 ) No such peaks were found, and correlated constraints on $|U_{1i}|^2$ and $|U_{2i}|^2$ were set as functions of $m(\nu_i)$. These upper bounds are shown in Figs. 1 and 2. The most stringent of the limits reached the $10^{-5}$ level for $|U_{2i}|^2$ (from $\pi_{\mu 2}$ emulsion data) and $\sim 3 \times 10^{-6}$ for $|U_{1i}|^2$ (from $K_{e2}$ data). An additional constraint, primarily on $|U_{1i}|^2$, arose from the ratio of branching ratios $B(\pi_{e2})/B(\pi_{\mu 2})$ (see Fig. 1).

The suggested peak search experiments were subsequently carried out with gratifying speed, but before describing the results, we note that the new class of correlated tests for neutrino masses and mixing applies much more generally to any weak decays yielding neutrinos. Thus, for example, a decay such as $\tau \to \nu_\tau \pi$ would also have the possibility of showing a multipeak structure (in the rest frame of the $\tau$; the spectrum would of course be smeared out in actual lab frame data on $\tau$ decays). Such a peak was searched for, and no significant evidence for one was found. Moreover, in nuclear transitions proceedings via e- or $\mu$- capture, the final state is again two-body, so that one could search for anomalous peaks. This search was performed, with negative results. The upper limits on lepton mixing matrix coefficients thereby obtained were not as stringent as those derived from other sources.

The consequences of the basic observation are more complicated in the case of three-body decays. Nuclear $\beta$ decay, $(Z,A) \to (Z \pm 1, A) + e^\pm + \overset{(-)}{\nu}_e$, really consists of the sum of separate modes $(Z,A) \to (Z \pm 1, A) + e^\pm + \overset{(-)}{\nu}_i$, where again i runs over all the generations of mass eigenstates allowed by phase space, with $i = 1$ being the dominantly coupled mode. Thus, contrary to convential wisdom, the general test for "$m(\nu_e)$" $\neq 0$ in nuclear $\beta$ decay is not an early endpoint falloff in the Kurie plot, but rather a series of kinks in this plot. There might or might not be an early endpoint falloff, depending on the size of $m(\nu_1)$. It is even possible that there could be a kink at an intermediate position, but no early endpoint falloff. When this observation was made, an analysis was performed on the available Kurie plots and a conservative upper limit of $|U_{1i}|^2 < 0.1$ was obtained for $m(\nu_1)$ in the range of $\sim 1 - 5$ MeV. A comparison of the relative $\mathfrak{F}t$ values for certain superallowed Fermi $\beta$ decays also yielded an upper bound on this lepton mixing matrix coefficient. Similarly, other three-body decays such as hyperon semileptonic decays and $K_{\ell 3}$ decays in general have a multimode structure, although these latter two types are unlikely to provide as sensitive probes of neutrino masses as the modes discussed above. For $\mu$ decay, $\mu \to \nu_\mu e \bar{\nu}_e$, the observed decay spectra consists of the sum of the separate modes, $\mu \to \nu_i e \bar{\nu}_j$. Moreover, in this case, the spectra depend on whether the neutrinos are Dirac or Majorana particles, in contrast to the previously mentioned decays.[27] A further correlated constraint on lepton mixing was obtained from an analysis of the momentum spectrum and $\rho$ parameter in $\mu$ decay;[1] this bound is shown in Figs. 1 and 2.

We proceed to discuss the experiments that applied the peak search test proposed in Ref. 1. A group at SIN[28] performed the search in $\pi_{\mu 2}$ decay in 1981 and obtained the 90% CL upper limits on $|U_{2i}|^2$ for a heavy $\nu_i$ shown in Fig. 2. These improve upon the limits established from our analysis of data for $4 \text{ MeV} \lesssim m(\nu_i) \lesssim 12$ MeV and are comparable to the limits which we obtained from $\pi_{\mu 2}$ emulsion data for $12 \text{ MeV} \lesssim m(\nu_i) \lesssim 34$ MeV. The great sensitivity of the peak search test is demonstrated by these bounds, which extend down to the $10^{-5}$ level and apply for a decay mode in which massive neutrinos have so significant helicity enhancement. Two peak search experiments have been carried out by T. Yamazaki and collaborators at KEK on $K_{\mu 2}$ decay.[29,30] The first used an already existing apparatus and determined $|\vec{p}_\mu|$ via a range measurement technique.[29] It achieved a good upper limit on $|U_{2i}|^2$ in the range $160 \text{ MeV} \lesssim m(\nu_i) \lesssim 230$ MeV, as indicated in Fig. 2. The Yamazaki group then proceeded to perform a beautiful, dedicated high-precision magnetic spectrometer experiment in early spring, 1982.[30] The apparatus for this experiment is shown in Fig. 3; note, in particular, the substantial quantity of NaI(Tl) crystals to veto events from the decays $K^+ \to \pi^0 \mu^+ \nu_\mu$ ; $\pi^0 \to \gamma\gamma$ and $K^+ \to \mu^+ \nu_\mu \gamma$. No definite additional peak was observed in the range of muon momenta corresponding to $60 \text{ MeV} \lesssim m(\nu_i) \lesssim 320$ MeV, and an extremely good correlated upper bound was thus set on mixing strength $|U_{2i}|^2$ in this range, extending down to $\sim 10^{-6}$ (see Fig. 2). This group will take data again in the spring of 1983.[31]

Beyond that, there are two possibilities for further work.[31] First, consideration is being given to a TPC type of detector which would have greater efficiency for detecting photons and thereby vetoing background events. It is estimated that such a third-generation $K_{\mu 2}$ peak search experiment might be able to push the 90% CL limit on $|U_{2i}|^2$ down to the $10^{-7}$ level for $m(\nu_i)$ in the range from $\sim$ 200 to $\sim$ 300 MeV, and achieve commensurate improvements for lower masses. Second, there is perhaps some possibility of a peak search in the $K_{e2}$ decay mode. Although a massive neutrino signal would be kinematically enhanced by a factor as large as $\sim 10^5$ relative to a massless neutrino mode, there is the challenge of a very small overall branching ratio with which one must must contend.

A peak search has also been conducted recently by a group at TRIUMF using $\pi_{e2}$ decay.[32] The preliminary upper limits on $|U_{1i}|^2$ from this experiment are shown in Fig. 1. The reason that the bound becomes much weaker for $m(\nu_i) > 80$ MeV is that the background from the dominant decay chain $\pi^+ \to \mu^+ \to e^+$ sets in at a serious level in this lower $e^+$ momentum region, thereby reducing the sensitivity of the experiment to a small peak. Nevertheless, the power of the peak search method is again demonstrated by the extremely small limit of $|U_{1i}|^2 \lesssim 3 \times 10^{-7}$ which was established for 60 MeV $\lesssim m(\nu_i) \lesssim$ 75 MeV.

This, then, is the present state of experiments that have applied the peak search test for heavy neutrinos. As for the future, especially as it pertains to the U.S. experimental particle physics program, we have already mentioned the plans at KEK. In Europe, there is a $\mu$-capture experiment being started by J. Deutsch and collaborators at SIN.[33] Since the final state is two-body, this group will again perform a search for anomalous peaks in the kinetic energy spectra of the recoiling nucleus. This experiment will directly probe the $\nu_i$ mass range below 100 MeV, and will be especially useful in the interval 34 MeV $< m(\nu_i) <$ 60 MeV, where only the previous analysis of old $K_{\mu 2}$ data and $\mu$ decay data sets upper limits on $|U_{2i}|^2$.

In view of this very rapid progress in peak search experiments on $\pi_{\mu 2}$ and $K_{\mu 2}$ decay at SIN, KEK, and TRIUMF, our recommendation for the U.S. program is to encourage similar efforts, but with the caveat that in order to be worthwhile at this point in time, a U. S. experiment must be able to demonstrate a potential for significantly improving on the limits that have already been set by the groups mentioned above. This comment applies, for example, to a possible $K_{\mu 2}$ peak search experiment at BNL or an analogous search with $\pi_{e2}$ decay at LAMPF.

It should be noted that there are three new experiments on $\mu^+$ decay, including one by H. L. Anderson and collaborators at LAMPF,[34] which will measure all of the spectral parameters $\rho$, $\eta$, $\xi$, and $\delta$ ; and two at TRIUMF, by M. Strovink et al. (a measurement of $\xi$)[35] and by K. Crowe et al. (a measurement of $\eta$).[36] We found in our earlier analysis that the parameter $\rho$ was the most sensitive to the presence of heavy neutrino decay modes;[27,37] the LAMPF experiment will thus be particularly well suited to search for possible massive neutrino effects. Indeed, it intends to measure $\rho$ with an accuracy an order of magnitude greater than previous experiments.

In addition to particle decays, we strongly encourage nuclear experimentalists to search for kinks in Kurie plots in nuclear $\beta$ decays. Such a search could ultimately cover the range of neutrino masses from $\sim$ 50 eV to $\sim$ 5 MeV. The costs for these experiments would be quite modest on the scale of high energy physics.

The peak search and kink search in regular nuclear $\beta$ decay do not directly test whether the neutrino mass is of Dirac (D) or Majorana (M) type. If a positive signal is ever seen, one might set up an experiment involving charged or, probably preferably, neutral current reactions of tagged, massive $\nu_i$'s . By this means, one could possibly distinguish between D and M neutrinos.[38] There would also be differences in $\mu$ decay, but it would not be easy to observe these in the decay spectra.[27] One could also inquire whether the electromagnetic properties of a neutrino afford an experimentally feasible means of distinguishing between D and M types. It is certainly true that these properties are different for the two cases. A chiral Dirac neutrino can have a magnetic moment if it has a nonzero mass; in the standard electroweak theory, appropriately extended to allow such a neutrino, this moment is[39]

$$\mu_{\nu_i} = \frac{3eG_F m_{\nu_i}}{8\pi^2 \sqrt{2}}$$

In a theory with CP violation in the leptonic sector, a massive Dirac neutrino could also have an electric dipole moment (EDM).[40] In contrast, a Majorana neutrino, whether massless or massive, has no magnetic or electric dipole moment because of its defining property of self-conjugacy. Thus, for example, one might envision an experiment in which neutrinos propagate through a region of magnetic field, and one tests for the spin rotation which would be caused by a nonzero $\mu_{\nu_i}$ . If one could establish this effect, then this would show that the neutrino was of Dirac type.

Unfortunately, our analysis indicated that such an experiment is not likely to be feasible.[40,41] The same comment applies, a fortiori, to the analogous experiment to search for an EDM of the neutrino. Thus, it appears that the classic test for Majorana neutrinos and total lepton number violation, viz., neutrinoless double $\beta$ decay, is still the best method.[42] This subject will be discussed by D. Caldwell below.

## REFERENCES

1. R. Shrock, Phys. Lett. 96B, 159(1980); Phys. Rev. D24, 1232, 1275(1981).
2. This paragraph follows R. Shrock, Neutrinos, P.54 in Particle Data Group, Review of Particle Properties, Phys. Lett. 111B, 1 (1982).
3. K.-E. Bergkvist, Nucl. Phys. B39, 317(1972).
4. Lubimov et al., Phys. Lett. 94B, 266(1980); Sov. J. Nucl. Phys. 32, 154(1980).
5. O. Fackler, private communication (1982).
6. R. Boyd, talk at the 1982 International Conference On Neutrino Physics and Astrophysics, "Neutrino - 1982," Balaton.
7. R. Robertson, talk at the Neutrino - 82 Conference, Balaton; T. Bowles, private communication.
8. E. Commins, private communication (1982).
9. J. J. Simpson, Phys. Rev. D23, 649(1981).
10. R. Graham, in Quarterly Progress Report of Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited, Report AECL - 7683, p.14 (1982) and in Chalk River preprint AECL - 7778, PR-P-134(1982).
11. K.-E. Bergkvist, talk given at the Brookhaven Neutrino Oscillation Workshop (January, 1981); T. Bowles, private communication (1982).
12. For a recent review, see M. Turner, in Proceedings of the 1981 International Conference on Neutrino Physics and Astrophysics, "Neutrino -81", Maui, vol. 1, p. 95(1981).
13. A. DeRujula, Nucl. Phys. B188, 414(1981).
14. J. Andersen et al., CERN preprint CERN-EP/82-50.
15. C. Bennett, talk at the Workshop on Low Energy Tests of High Energy Physics, U. C. Santa Barbara (January, 1982).
16. S. Yasumi, in the Proceedings of the 1982 International Conference on Neutrino Physics Astrophysics, "Neutrino - 82", Balaton (1982), to be published .
17. M. Bardon et al., Phys. Rev. Lett. 14, 449(1965).
18. A. R. Clark et al., Phys Rev. D9, 533(1979)
19. M. Daum et al., Phys. Lett. 74B, 126 (1978); Phys. Rev . D20, 2692(1979).
20. For a complete list of limits on "$m(\nu_\mu)$" from $\pi_{\mu 2}$ experiments, see Particle Data Group. Review of Particle Properties, op. cit., Ref.2.
21. D. C. Lu et al., Phys. Rev. Lett. 45, 1066(1980).
22. R. Frosch, private communication (1981).
23. M. Perl et al., Phys. Lett. 70B, 487(1977) In this original paper on $m(\nu_\tau)$, the upper limit obtained was 600 MeV (90% CL).
24. Bacino et al., Phys. Rev. Lett/ 42, 749(1979).
25. C. Blocker, Ph.D. Thesis, LBL Report No. LBL-10801 (1980); C. Blocker et al., Phys. Lett. B. to be published.
26. J. Dorfan, private communication (1981).
27. R. Shrock, Phys. Lett. 112B, 137(1982).
28. R. Abela et al., Phys. Lett. 105B, 263(1981). (Subsequently, a Princeton-Indiana group carried out another $\pi_{\mu 2}$ peak search experiment, but set much weaker bounds on $|U_{2i}|^2$ ($\sim 10^{-2}$) than those which had been obtained by the SIN experiment; see F. Calaprice, et al., Phys Lett. 106B, 175(1981).)
29. Y. Asano et al., Phys. Lett. 104B, 84(1981).
30. R. Hayano et al., University of Tokyo-KEK-University of Tsukuba preprint (1982). A review of this new experiment and other peak search experiments is given by T.Yamazaki, in the Proceedings of the International Conference on Neutrino Physics and Astrophysics, "Neutrino-82", Balaton (1982).
31. T. Yamazaki, in Proceedings of Neutrino-81, Maui, vol. 2, p. 49, and private communication.
32. D. Bryman, talk at the Workshop on Low Energy Tests of High Energy Physics, U.C. Santa Barbara (1982).
33. J. Deutsch, private communication (1982).
34. H. L. Anderson et al, LAMPF Research Proposal.
35. C. Oram et al., TRIUMF Research Proposal.
36. K. M. Crowe et al., TRIUMF Research Proposal.
37. R. Shrock, in Weak Interactions as Probes of Unification, (VPl-1980), AlP Conference Proceedings No.72, eds. G. Collins, L.-N. Chang and J. Ficenec, (New York, AlP 1981), p.368.
38. B. Kayser and R. Shrock, Phys. Lett. 112B, 137(1982).
39. K. Fujikawa and R. Shrock, Phys. Rev. Lett 45, 963 (1980).
40. However, this would vanish at the one-loop level in the standard $SU(2)_L \times U(1)$ theory. In theories with both V-A and V+A couplings, such as a (non)-left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)$ model there could be a $\nu_i^D$ EDM induced at the one-loop level; see R. Shrock, Nucl. Phys. B206, 359 (1982).

41. One might also inquire as to whether radiative neutrino decays could be useful as a means of distinguishing between D and M neutrinos. Unfortunately, the situation is even worse here, because for $m(\nu_i) < 2m_e$, where the branching ration $B(\nu_i \to \nu_j\gamma)$ is not negligibly small, the <u>rate</u> $\Gamma(\nu_i \to \nu_j\gamma)$ <u>is</u> almost certainly negligibly small. For example, in the standard $SU(2)_L \times U(1)$ theory, extended to include D or M neutrinos, $\tau(\nu_i \to \nu_j\gamma)$ is typically $\gtrsim 10^{18}$ sec, rendering a feasible experiment essentially hopeless. Indeed, even if the rates were not abysmally small, one could still not tell, from a rate measurement alone, whether the neutrino was of D or M type, since although the D and M rates are different, one would know the values of the mixing angles and possible charged lepton masses, $m_{\ell_a}$ for $a > 3$, that could enter into the decay amplitude, and hence one would not know what the precise rate was predicted to be for either case. There are many papers on this subject, including J. Bernstein, M. Ruderman, and G. Feinberg, Phys. Rev. <u>132</u>, 1227(1963); R. Shrock, Phys. Rev. D<u>9</u>, 743(1973); B. W. Lee and R. Shrock, Phys. Rev. D<u>16</u>, 1444(1977); W. Marciano and A. I. Sanda, Phys. Lett. <u>67</u>B, 303(1977); M. Beg, W. Marciano, and M. Ruderman, Phys. Rev. D<u>17</u>, 1395(1978); J. Schecter and J. Valle, Phys. Rev. D<u>24</u>, 1883 (1981); erratum, ibid., D<u>25</u>, 283(1981); P. Pal and L. Wolfenstein, Phys. Rev. D<u>25</u>, 766(1982); J. Nieves, University of Puerto Rico preprint; B. Kayser, NSF preprint; R. Shrock, op. cit., Ref. 40; A. DeRujula and S. Glashow, Phys. Rev. Lett. <u>45</u>, 942(1980); R. Kimble et al., Phys. Rev. Lett. <u>46</u>, 80(1981).

42. For theoretical reviews, see H. Primakoff and S. P. Rosen, Ann. Rev. Nucl. Part. Sci., <u>31</u>, 145(1981); S. P. Rosen, in the Proceedings of the International Conference on Neutrino Physics and Astrophysics, "Neutrino-81", Maui, vol. II, p.76; and S. P. Rosen and W. Haxton, talks given at the Workshop on Low Energy Tests of High Energy Physics, U. C. Santa Barbara (Jan., 1982). See also, for example, M. Doi et al., Prog. Theor. Phys. <u>66</u>, 1739, 1765 (1981) and errata, to be published.

43. P. Nemethy, letter of intent submitted to Brookhaven National Laboratory (September, 1982), and private communication.

Note added: After this review was written, we learned of a plan by P. Nemethy to carry out a new experiment at BNL to measure $m(\nu_2)$ in $\pi_{\mu 2}$ decay by means of a ring-imaging Cerenkov counter[43]. The ultimate sensitivity of the experiment is stated to be a neutrino mass of 50 KeV. (To reach this ultimate level would require a commensurate improvement with which the charged pion mass is measured, but such an improvement is likely to be achieved in time to be used in the $\pi_{\mu 2}$ analysis.[43]) One may thus look forward hopefully to a dramatic reduction in the upper limit on $m(\nu_2)$ (or, of course, an observation of a nonzero value for this mass ) in the near future.

<u>Figure Captions</u>:

Fig. 1. Upper bounds on $|U_{2i}|^2$ from $\pi_{\mu 2}$ and $K_{\mu 2}$ peak search tests, and from analysis of $\mu$ decay.

Fig. 2. Upper bounds on $|U_{1i}|^2$ from nuclear $\beta$ decay, $\mu$ decay, $B(\pi_{e2})/B(\pi_{\mu 2})$, and $K_{e2}$ peak search tests.

Fig. 3. Apparatus of the KEK $K_{\mu 2}$ experiment of Yamazaki and collaborators (Ref. 30).

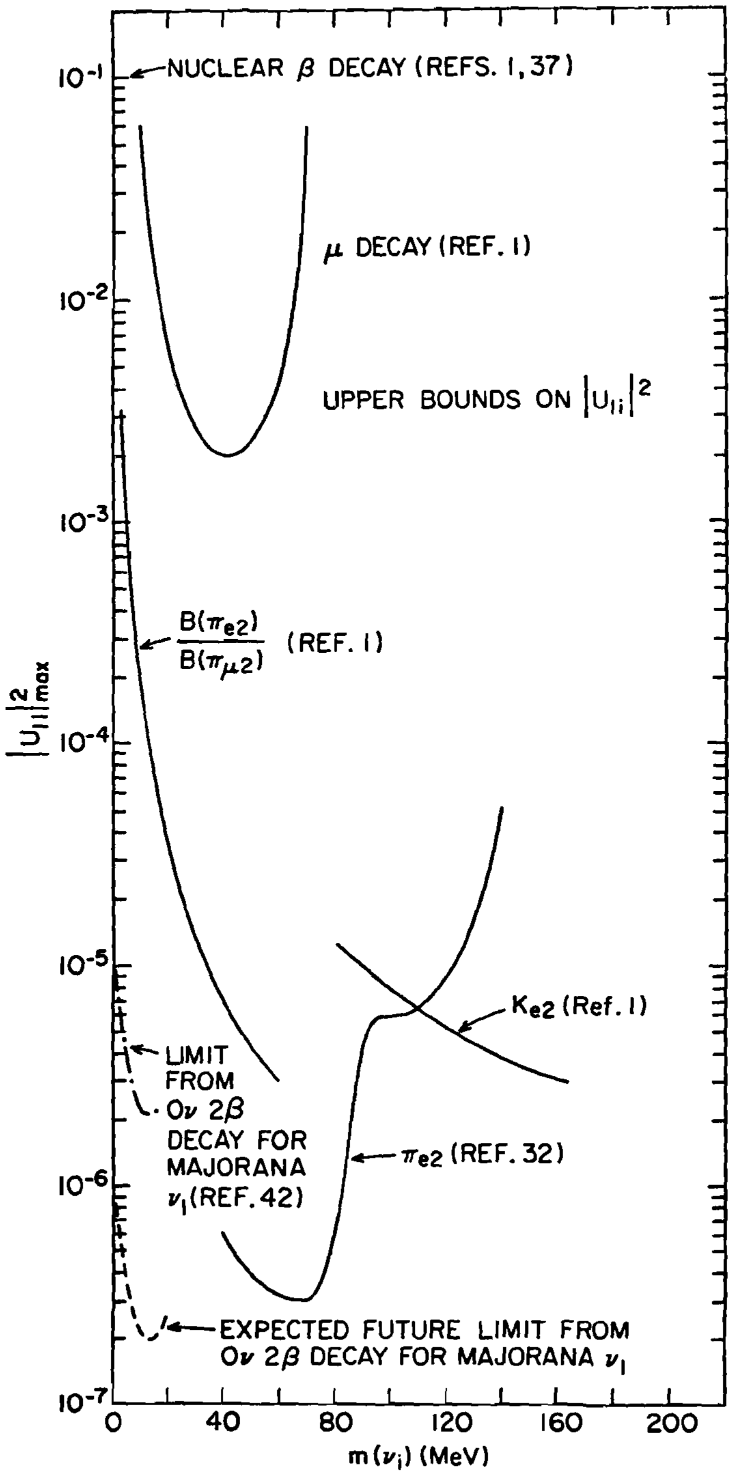
$10^{-1}$
NUCLEAR $\beta$ DECAY (REFS. 1,37)
$\mu$ DECAY (REF. 1)
$10^{-2}$
UPPER BOUNDS ON $|U_{1i}|^2$
$10^{-3}$
$\frac{B(\pi_{e2})}{B(\pi_{\mu 2})}$ (REF. 1)
$|U_{1i}|^2_{max}$
$10^{-4}$
$10^{-5}$
$K_{e2}$ (Ref. 1)
LIMIT FROM $0\nu$ $2\beta$ DECAY FOR MAJORANA $\nu_1$ (REF. 42)
$\pi_{e2}$ (REF. 32)
$10^{-6}$
EXPECTED FUTURE LIMIT FROM $0\nu$ $2\beta$ DECAY FOR MAJORANA $\nu_1$
$10^{-7}$
0
40
80
120
160
200
$m(\nu_i)$ (MeV)

Fig. 1

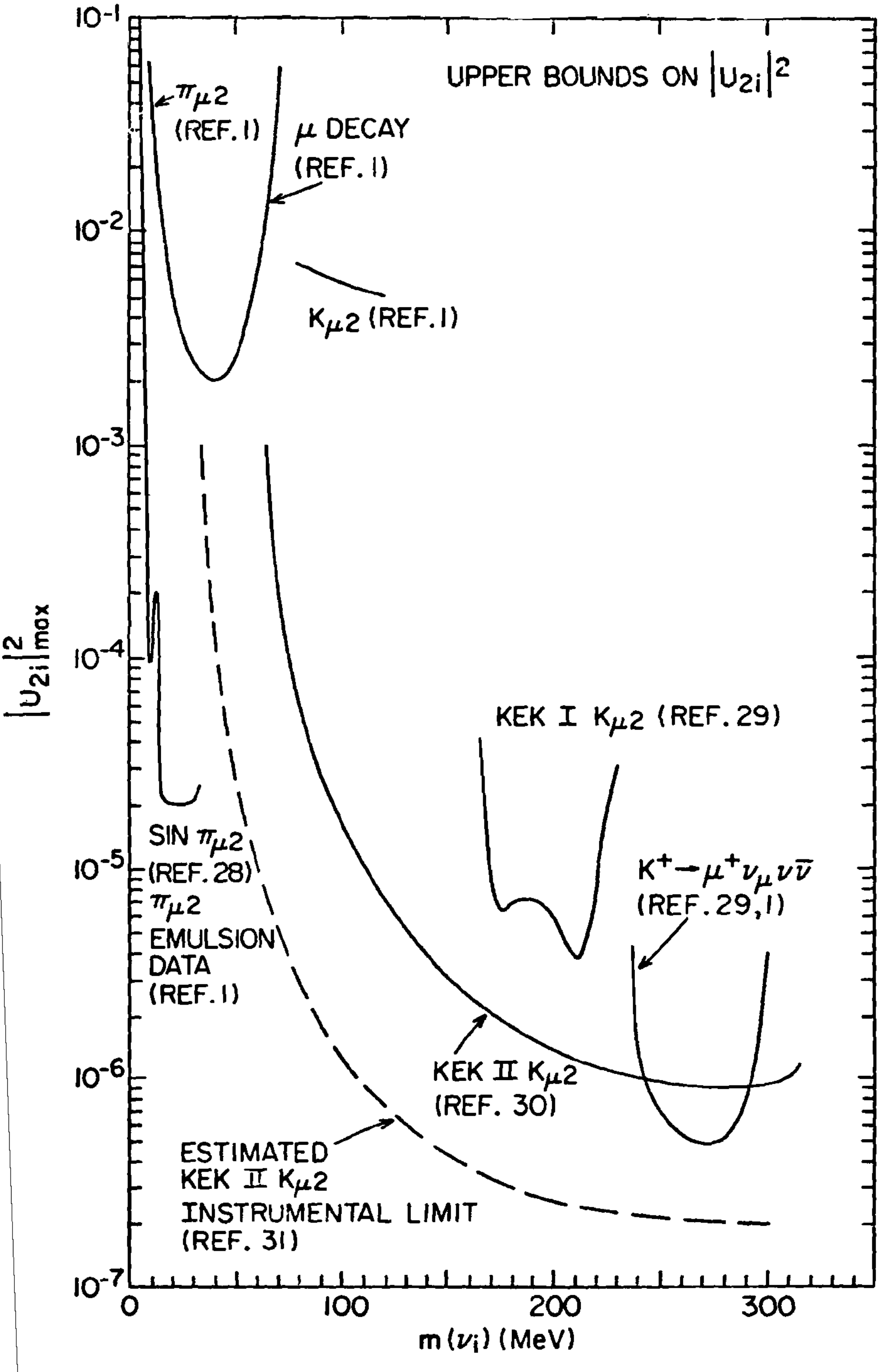
UPPER BOUNDS ON $|U_{2i}|^2$
$\pi\mu 2$ (REF. 1)
$\mu$ DECAY (REF. 1)
$K\mu 2$ (REF. 1)
KEK I $K\mu 2$ (REF. 29)
SIN $\pi\mu 2$ (REF. 28)
$\pi\mu 2$ EMULSION DATA (REF. 1)
$K^+ \to \mu^+ \nu_\mu \nu \bar{\nu}$ (REF. 29, 1)
KEK II $K\mu 2$ (REF. 30)
ESTIMATED KEK II $K\mu 2$ INSTRUMENTAL LIMIT (REF. 31)
$|U_{2i}|^2_{max}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0
100
200
300
$m(\nu_i)$ (MeV)

Fig. 2

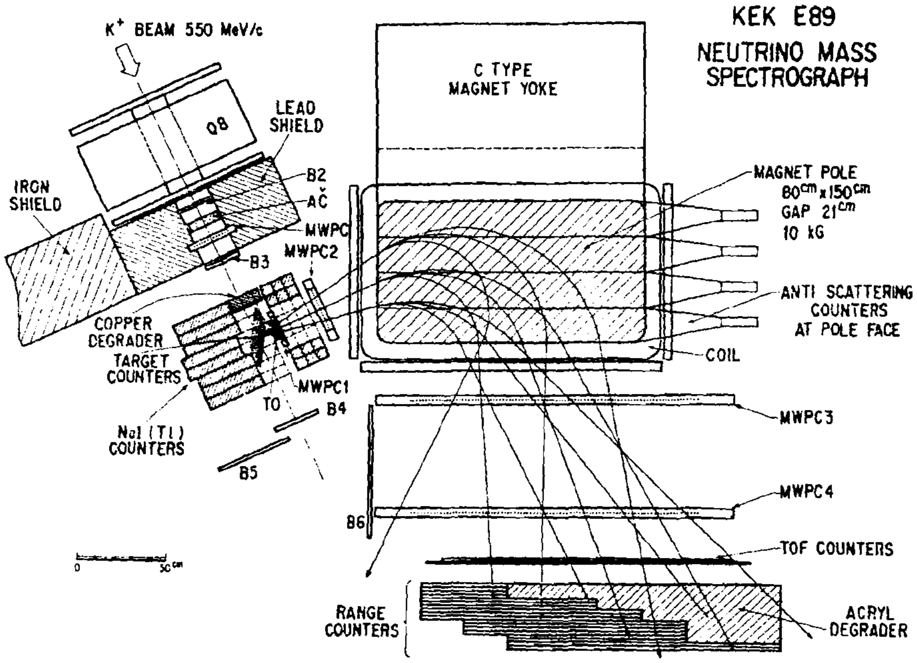
KEK E89
NEUTRINO MASS
SPECTROGRAPH
K+ BEAM 550 MeV/c
Q8
LEAD SHIELD
IRON SHIELD
B2
AČ
MWPC
B3
MWPC2
COPPER DEGRADER
TARGET COUNTERS
NaI (Tl) COUNTERS
MWPC1
TO
B4
B5
0
50cm
C TYPE MAGNET YOKE
MAGNET POLE
80cm x 150cm
GAP 21cm
10 kG
ANTI SCATTERING COUNTERS AT POLE FACE
COIL
MWPC3
MWPC4
B6
TOF COUNTERS
RANGE COUNTERS
ACRYL DEGRADER

Fig. 3