PROSPECTS FOR EXPERIMENTS ON NEUTRINO MASSES AND MIXING VIA NEUTRINO OSCILLATIONS AT FUTURE ACCELERATORS

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Summary

A study is made of the requirements necessary for improvement in our knowledge of limits in mass and mixing parameters for neutrinos via oscillation phenomena at accelerators. It is concluded that increased neutrino event rate (flux x energy) at modest energy machines (e.g., AGS and LAMPF) is the single most important requirement. This will permit smaller E/L ratios and refinement of systematics.

I. Introduction

The question of neutrino mass and neutrino mixing is a critical one for GUTS. The phenomenon of neutrino oscillations, which requires simultaneously non-degenerate masses among neutrino flavors and lepton number non-conservation, is an important probe for addressing this question.

At present, there is little theoretical guidance as to the mass and mixing parameter scales which should be explored. The range of values which have been examined so far have been set primarily by existing experimental apparatus and available fluxes. In the next few years experiments will be performed which have been developed explicitly for this purpose.

An important question to be raised in a workshop such as this one is: ''Given our present knowledge concerning neutrino oscillations and a knowledge of the technological limits for neutrino fluxes and neutrino detection, what are the attainable limits on neutrino mass and mixing parameters by neutrino oscillation searches?''

To address this problem, we have compiled a list of completed neutrino oscillation experiments (see Section II) and a list of experiments likely to be completed in the next approximately two years (see Section III).

Additionally, there are two fixed target machines discussed at this workshop which would be near the limit of high beam current were they to be constructed. They are LAMPF II and the present A.G.S. with an additional booster ring (''10 x AGS''). They could produce 10 to 40 times the present A.G.S. rate and therefore set a technology scale in which to make speculations. There is also now much data on highly segmented neutrino detectors so this end of the problem is also well covered. Using these as our technological scale we have tried to answer the question posed above (see Sections IV A,B).

We conclude that there will be possible a significant expansion in the mass and mixing angle limits; typically two or more orders of magnitude over what is now known or likely to be known at the end of presently planned or possible experiments.

Perhaps most significant will be the ability to go to mixing angles of $\sim 10^{-5}$ for $\nu_\mu \rightarrow \nu_e$ in a mass difference interval of 1 to several 10's of $(eV)^2$; an interval of currently great interest from astrophysical and cosmological evidence as well as from tritium beta-decay experiments.

Also of significance is the broader range of masses and mixing angles accessed in oscillation experiments. When combined with similar improvements in experimental limits in double-beta decay and peak searches (see contributions of R. Shrock and D. Caldwell to this workshop), we will be able to check for confirmation or consistency in interpretation of effects concerning neutrino mass from widely different processes involving neutrinos.

The phenomenon and formalism of neutrino oscillations has been discussed extensively in many places. Rather than redevelop it here we simply state some conventions and relations which will facilitate our attempt to address the question at hand.

In particular, we consider mixing between only two neutrino types. When considering the limits we reach, the reader should keep in mind that the particular interpretation to be made may depend upon this assumption.

If ν_1 and ν_2 are to be considered as the mass eigenstates, then the weak interaction eigenstates, ν_μ and ν_e, are considered to be mixtures of ν_1 and ν_2 according to

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

where θ is defined as the mixing angle.

The probability for ν_μ transition to an observable ν_e is defined as $P(\nu_\mu \rightarrow \nu_e)$ and is given as

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \frac{L}{E_\nu} \delta m^2)$$

where E (GeV) is the energy of the neutrino, $\delta m^2 = |m_1{}^2 - m_2{}^2|$ in $(\mathrm{eV})^2$ with m_1 and m_2 being the masses involved in states ν_1 and ν_2 and L is the distance between neutrino creation and detection point in kilometers.

(For completeness it should be mentioned that L is not known event by event because we ordinarily do not detect the creation point. Usually an ⟨L⟩ is used averaging over the finite decay volume. This effect can be accounted for explicitly in the above formula; however it is a cumbersome relation and becomes important primariy in ν_i disappearance experiments when the oscillation length becomes commensurate with the decay volume.)

The probability for the ν_μ to be observed as a ν_μ is then

$$P(\nu_\mu \rightarrow X) = 1 - P(\nu_\mu \rightarrow \nu_e)$$

Experiments searching for oscillations then are of two specific types: (a) searches for $\nu_i \rightarrow \nu_j$, appearance experiments or (b) $\nu_i \rightarrow X$, disappearance experiments.

Up to the present, these experiments have been single detector experiments and, except for the well known reactor experiment of Reines et al,[1] have all given negative results which are interpreted as limits.

These limits are taken to be: (1) when δm^2 is small so the term $\sin^2(1.27 \frac{L}{E_\nu} \delta m^2)$ can be set equal to the argument:

$$\delta m^2 \leq \left(\frac{1}{1.27}\right) \left(\frac{E_\nu}{L}\right) \left(P\right)^{1/2}$$

or (2) if δm^2 is large, then $\sin^2\left(\frac{1}{1.27} \frac{L}{E_\nu} \delta m^2\right)$ averages to 1/2 and we have

$$\sin^2(2\theta) \leq 2P$$

A given experiment with a negative result will then produce, on a log-log plot, an excluded region such as that contained to the upper right of curve (a) in Figure 1. The two lines constituting the curve (a) just being given by the two equations above. The straight lines are a good approximation to real experiments if a log-log plot is used.

In a single detector experiment then the observed ratio of the number of electrons (N_e) to the number of muons (N_μ) can be interpreted as the probability, $P = P(\nu_\mu \rightarrow \nu_e) = N_e/N_\mu$ and the appropriate limits set. Improvements upon this are sometimes made by attempting to calculate the fluxes and making a subtraction; however, such calculations are notoriously difficult to make with precision. A superior way to set limits is by use of two detectors separated by a distance. Changes in ratios then become useful and are freer from systematic errors.

II. Present Status.

In Table III, we have listed all of the experiments known to us[2] which have completed results. These are listed under A1, B1, C1, D1, F1 of the table according to reaction type. For our purpose, to find a guide to the future rather than show each experiment and reaction on a plot, we feel it is more to the point to plot only the envelope of all completed experiments in the channel dominantly studied and closely related to other experiments by C, CP, CPT ($\nu_\mu \rightarrow \nu_e$, Figure 1) or relatively unstudied ($\nu_\mu \rightarrow X$, Figure 2). Curve (a) in both figures show our knowledge so far. The reactor experiments are also shown for reference.

III. Near term future.

Also listed in Sections A2, B2, C2, D2, E2 of Table III are those experiments approved and likely to run in the next few years. Again, as a guide, we plot only the envelope of these experiments -- these are the curves (b) shown in Figures 1 and 2. More (factor 10 in $\delta m^2 \sin 2\theta$) sensitive reactor experiments could be done if larger detectors were to be built but none are planned to our knowledge. The possibilities for deep mine measurements by measuring upward versus downward neutrino fluxes are also shown (see contribution in Non-acelerator Section of this workshop).

Sections A3 - E3 list some longer term experiments which have been proposed and are under various stages of consideration. The parameter space which they cover is inluded in the new[3] areas possible as discussed in the following section.

IV. Longer term prospects.

In Sections II and III we have summarized what has been done and what experiments are currently under construction; in both sections the primary mode of description was, largely for conciseness, the simple statement of the attainable limits, $\delta m^2 \sin 2\theta$ (valid at small δm^2 or more correctly, large oscillation length) and $\sin^2 2\theta$ (valid at large δm^2). To discuss longer term prospects it is essential to examine in more detail the fundamental physical and technological limits to such experiments.

As we discuss further below, an increase in neutrino event (signature of flavor type) rate by a significant factor (say $\gtrsim 10$) is the essential ingredient. The usual method of achieving such an increase is through a combined increase of flux and energy.

To put this into a concrete perspective it is useful to discuss event rates in comparative terms for two exisitng machines -- ''LAMPF'' and ''AGS'' -- which are currently involved in neutrino oscillation experiments and two hypothetical machines -- ''LAMPF II'' and ''AGS plus Booster (= 10 x AGS)'' -- which have been discussed at this Workshop. We omit from this discussion the higher energy machines, such as the FNAL 400 GeV fixed target accelerator, which have contributed much of our present knowledge of neutrino mixing. They have a role in the near term future (see II and III above) but will probably play only a limited role in the longer future. Should the direct observation of ν_τ be made, then a particular contribution could be made by a high energy machine on mixing angles. However, because of the high energy and the dependence of the small mass limit on the factor E /L being small, the distances to make competitive contributions in this variable are probably inconveniently large.

Table I lists some of the quantities directly relevant to comparisons among machines. From the Table it is then possible to make a figure of merit to which the number of neutrino events in any detector will be proportional. Because the neutrino cross sections rise with E (however, the quasi-elastic and elastic neutral current cross sections level off at E_ν = 850 MeV; see Table II) the neutrino energy is included in the figure of merit,[a)]

$$Q = \phi(\text{bare targ.}) \times (\text{PROT.FLUX}) \times (\bar{E}_\nu \times (\text{HORN FACTOR})$$

and using the numbers of Table 1:

$$Q(\text{LAMPF NOW}) = (2.5\times10^{-10})(3.75\times10^{15})(0.150\text{GeV})(1) = 1.4\times10^{5}$$

$$Q(\text{AGS NOW}) = (8\times10^{-8})(7\times10^{12})(1.2\text{GeV})(10) = 6.7\times10^{6}$$

$$Q(\text{LAMPF II}) = (3\times10^{-8})(\frac{1\times10^{-15}}{4})(0.75)(10) = 5.6\times10^{7} \qquad \text{b)}$$

$$Q(10\times\text{AGS}) = 8\times10^{-8})(7\times10^{13})(1.2\text{GeV})(10) = 6.7\times10^{7}$$

$$Q(\text{LAMPF}):Q(\text{AGS}):Q(\text{LAMPF II}):Q(10\times\text{AGS}) = 1:48:400:480 \qquad \text{b)}$$

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a) It should be noted that no account is taken at this point for composition; for example, LAMPF is relatively richer in ν_e.

b) In principle, if a 120 Hz horn were possible and full beam devoted to neutrino physics a factor 4 increase is possible in Q(LAMPF II).

Of course, the details of individual experiments will bring in other factors which change the weights somewhat (e.g., ability to go to small E /L provided high flux is maintained) but as is argued below <u>significant increase in neutrino event rate is the crucial factor in prospects for improving our knowledge of ν-mixing</u>.

From this comparison, it is apparent that for purposes of increased neutrino event rate ''LAMPF II'' and ''10 x AGS'' are sufficiently close that we can use either one in subsequent calculations of sample experiments. For purposes of definiteness (e.g., the relative fluxes of neutrino flavors have been measured at the A.G.S.) we will use the ''10 x AGS'' figures.

Before discussing specific experiments it is useful for purposes of estimation to discuss typical numbers of neutrino event types per ton of CH_2[c)] which might be accumulated in a canonical run of <u>100 days (10^7 seconds)</u> in a standard, <u>wide band horn focused beam</u>:

$$N(\text{reaction type}) = \left(\frac{t}{n}\right) \cdot (\rho) \cdot (\Phi_\nu) \cdot (\text{POT}) \cdot \sigma(\bar{E}_\nu)$$

$\left(\frac{t}{n}\right)$ = fraction of target type t per nucleon N

ρ = number of nucleons per ton ($\sim 5 \times 10^{29}$)

Φ_ν = flux of appropriate neutrino type in cm^2/sec/incident proton

POT = protons on target = proton current x 10^7 sec.

$\sigma(E_\nu)$ = neutrino cross section per target particle at appropriate mean energy.

c) Discussion of suitable detectors follows.

then using the numbers from Tables I and II and E = 1 GeV:

$$N(\nu_\mu n \to \mu^- p) = \left(\frac{6}{14}\right)(5\text{x}10^{29})\left(\frac{8\text{x}10^{-7}}{3}\right)(7\text{x}10^{20})(0.5\text{x}10^{-38}) = 2\text{x}10^5/\text{ton}$$

$$N(\nu_\mu p \to \nu_\mu p) = \left(\frac{p}{n}\right)R_1 N(\nu_\mu n \to \mu^- p) = \left(\frac{8}{6}\right)(0.038)(2\text{x}10^5) = 1\text{x}10^4/\text{TON} \quad \text{d)}$$

$$N(\nu_\mu;\ \text{total charged current}) = E_\nu R_3 N(\nu_\mu n \to \mu^- p) - \left(\frac{1}{0.63}\right)(2\text{x}10^5) = \frac{0.8\text{x}10^5}{\text{TON}}$$

$$N(\nu_\mu;\ \text{total neutral current}) = R_4 N(\nu_\mu n \to \mu^- p) = (0.4)(2\text{x}10^5) = \frac{0.8\text{x}10^5}{\text{TON}}$$

$$N(\nu_\mu e \to \nu_\mu e) = \left(\frac{8}{14}\right)(5\text{x}10^{29})\left(\frac{8\text{x}10^{-7}}{3}\right)(7\text{x}10^{20})(1.4\text{x}10^{-42}) = 75/\text{ton}$$

Typical beam composition in such a wide band beam is $(\Phi_\mu):\Phi(\bar{\nu}_\mu):\Phi(\nu_e):\Phi(\bar{\nu}_e) = 1:1 \times 10^{-3}:5 \times 10^{-3}:2 \times 10^{-4}$. Thus we would expect to see also

$$N(\nu_e n \to e^- p) = 5\text{x}10^{-3} N(\nu_\mu n \to \mu^- p) = 1\text{x}10^3/\text{TON}$$

$$N(\nu_e e \to \nu_e e) = \left\{\frac{\sigma(\nu_e e \to \nu_e e)}{\sigma(\nu_\mu e \to \nu_\mu e)}\right\} \frac{\Phi(\nu_e)}{\Phi(\nu_\mu)} N(\nu_\mu e \to \nu_\mu e) = (10)(5\text{x}10^{-3})(75/\text{TON}) = 4/\text{TON}$$

d) A check on these rates can be made by comparison to the actual rates measured at the A.G.S. in E-734. In that experiment, in 70 fiducial tons at 110 meters with a ~45 meter decay region 140 $\nu_\mu p \to \nu_\mu p$ events are observed for 4.7 x 10^{17} protons on target. Hence (1 x 10^4/TONx(70 tons)x(4.7 x 10^{17}/7 x 10^{20})$(50/110)^2$(45/30) = 145 is predicted in check with what is observed.

Note: To estimate rates for opposite sign (i.e., $\bar{\nu}$-beams) see Table II; however, as a rule of thumb $\Phi(\bar{\nu})/\Phi(\nu) \cong 0.5$ for wide band beams at these energies with the relevant cross sections reduced by the appropriate factor as well. The relative fluxes shift roughly as $\Phi(\bar{\nu}_\mu):\Phi(\nu_\mu):\Phi(\bar{\nu}e):\Phi(\nu_e) = 1:5 \times 10^{-2}:2 \times 10^{-3}:5 \times 10^{-4}$.

A. Oscillation Experiments:

If we take these high rates as being a fair approximation of what is the current technologically practical accelerator, what do they imply as to the attainable limits for neutrino mixing parameters?

To make any quantitative estimate we must also choose a detector; again, we should make a choice at the current, practical technological limit. There is room for debate here, for example colossal mass versus colossal segmentation. A prudent choice which does not compromise limits is in the direction of both size and segmentation such that one preserves ability to measure energy in individual events, selection of exclusive channels, and tracking. This allows the use of the detector not only for oscillation experiments but also for other neutrino experiments benefiting from high rate, such as $d\sigma/dy$ in $\nu_\mu e$ scattering.

To be specific our choice of a detector will be modeled upon that of E-734 at BNL[3] which is a fine-grained, 200 metric ton detector based on liquid scintillator and segmentation involving 4096 photomultipliers and 13,824 proportional drift tubes. An extension to 2.5 times this mass and multiplicity of channels is perfectly feasible.

All calculations below are then based upon a choice of 500 tons and modular construction identical to the E-734 detector. This will permit good electron identification, energy measurements on quasi-elastic events at the $\pm 15\%$ level, elastic neutral current events at a similar level for both $\nu_\mu p \to \nu_\mu p$ and $\nu_\mu e$, and identification of other neutral and charged current events.

To estimate event rates at distances, L(m), from the source other than the 50 meters used for normalization above we scale by $(50/L)^2$ -- for our present purposes this is an adequate approximation for distances greater than L = 100 meters. We make no attempt here at optimization of decay distances since these will not change our conclusions and instead we use the canonical 30 meter decay length from above.

1. $\nu_\mu \to \nu_e$ broad band (Extending the small δm^2 limit). The best result can be obtained using two detectors. The first is fifty tons and located 100 meters from target (L_I). The second is 500 tons and located at the furthest distance where it is still possible to accumulate 10^3 muon quasi-elastic events in 10^7 sec. From our estimate of rates, $(2 \times 10^5/\mathrm{TON})(500)(50/L_{II})^2 = 10^3$ we find L_{II} = 16 kilometers. This yields $L/E \sim 1.6 \times 10^4/1000 = 16$. In Detector I we have for the ratio of number of electron events to quasi-elastic muon events

$$\left(\frac{N_e}{N_\mu}\right)_I = \frac{(5 \times 10^{-3})(2 \times 10^5)(50)\left(\frac{50}{100}\right)^2}{(2 \times 10^5)(50)\left(\frac{50}{100}\right)^2} = \frac{12500}{2.5 \times 10^6}$$

and at the second detector,

$$\left(\frac{N_e}{N}\right)_{II} \approx \frac{5 \times 10^{-3} \times 10^3}{1 \times 10^3} = \frac{5}{1000} \quad .$$

Then dominant error is $\pm\sqrt{5}$ and if we use $(N_e/N_\mu)I$ to correct for N_e/N_μ expected in II were there no oscillations:

$$\left(\frac{N_e}{N_\mu}\right)_{II} - \left(\frac{N_e}{N_\mu}\right)_I \cong 0 \pm \frac{\sqrt{5}}{1 \times 10^3} \cong 0 \pm 2.2 \times 10^{-3}$$

Hence we obtain $P(\nu_\mu \to \nu_e) \sim 2.2 \times 10^{-3}$ so

$$\delta m^2 \sin 2\theta = \left(\frac{1}{1.27}\right)\left(\frac{1}{16}\right)\left(2.2 \times 10^{-3}\right)^{1/2} = 2.3 \times 10^{-3} \mathrm{eV}^2$$

at the small δm^2 limit and

$$\sin^2 2\theta = 2P = 4 \times 10^{-3}$$

at the large δm^2 limit.

Further optimization, longer running, etc. might lead to a further increase of a factor 2 to 3 but not much more; hence we take this as evidence that the small δm^2 limit might be extended to a few times 10^{-4} eV^2 and so indicate in Figure 1. This placement of the second detector does not permit any improvement in the $\sin^2 2\theta$ limit at large δm^2 and for that we turn to a different arrangement.

2. $\underline{\nu_\mu \to \nu_e \text{ narrow band}}$. (Extending the $\sin^2 2\theta$ limit). Here we use a narrow band beam to reduce the effective contamination of the electron signal. In a narrow band beam at these energies and with a detector of the type described, then the expected N_e/N_μ with no oscillations might be $\sim 1\times 10^{-4}$. However, the overall flux is reduced by about a factor of 10.

Again, the best technique is two detectors but with a different distance placement. What distance one chooses depends upon what is the lowest δm^2 for which a very small mixing angle measurement is wanted. For example, if in the region of current interest from tritium beta decay or cosmology (1-50 eV^2) we wish to push to the furthest $\sin^2 2\theta$ limit then a placement of detector I at 100 meters and detector II at about 300 meters is reasonable. With such a choice we would then have (in the canonical 10^7 seconds):

$$\left(\frac{N_e}{N_\mu}\right)_I = \frac{\left(\frac{1}{10}\right)(1\times 10^{-4})\left(\frac{2\times 10^5}{TON}\right)(50)\left(\frac{50}{100}\right)^2}{\left(\frac{1}{10}\right)(2\times 10^5)(50)\left(\frac{50}{100}\right)^2}$$

$$= \frac{25}{2.5\times 10^5}$$

and

$$\left(\frac{N_e}{N_\mu}\right)_{II} = \left(\frac{500\ TON}{50\ TON}\right)\left(\frac{100}{300}\right)^2\left(\frac{N_e}{N}\right) = \frac{28}{2.8\times 10^5}$$

then proceeding as above

$$\left(\frac{N_e}{N_\mu}\right)_{II} - \left(\frac{N_e}{N_\mu}\right)_I \cong 0 \pm \frac{2\sqrt{1.5\times 28}}{2.8\times 10^5} \cong 4\times 10^{-5}$$

or

$$P(\nu_\mu \to \nu_e) \cong 4 \times 10^{-5}$$

yielding limits of

$$\delta m^2 \sin 2\theta = \left(\frac{1}{1.27}\right)\times\left(\frac{1000}{200}\right)\left(4\times 10^{-5}\right)^{1/2}$$

$$= 2.5 \times 10^{-2} eV^2$$

and

$$\sin^2 2\theta = 2(4\times 10^{-5}) = 8 \times 10^{-5}$$

Again, further optimization, increased running time, etc. might reduce these limits by a factor 2 or 3 and so $\sim 2 \times 10^{-5}$ might be achieved — this is a significant improvement by about two orders of magnitude over our present knowledge.

These results are illustrated by curve c in Figure 1. Curve c is the <u>envelope</u> of all experiments utilizing various detector placements which push to the technical limits in different regions of δm^2 and $\sin^2 2\theta$ space.

3. $\underline{\nu_\mu \to X \text{ broad band}}$. An approach to ν_μ disappearance which has considerable analytic power should an effect be observed is to measure the ratio of quasi-elastic events in each detector (N_I/N_{II}) in several energy bins simultaneously. This is reasonably straightforward in the higher flux of a broad band beam and with detectors of the type described here.

The ultimate limit for ν_μ disappearance experiments is in the systematic error associated with knowledge of the beam optics. In a detector set-up identical to that of (a) above, it seems unlikely that this can be improved beyond 1% in which case we would have $P \cong 1 \times 10^{-2}$ leading to

$$\delta m^2 \sin 2\theta \le \left(\frac{1}{1.27}\right)\left(\frac{1}{16}\right)\left(1\times 10^{-2}\right)^{1/2}$$

$$= 5 \times 10^{-3} eV^2$$

and

$$\sin^2 2\theta \le 2 \times 10^{-2}$$

Such a set-up (optimized) would lead to the best mass limit attainable (perhaps ~2 x 10^{-3}eV^2) but gives no improvement over present knowledge of $\sin^2 2\theta$.

To improve upon $\sin^2 2\theta$ a narrow band beam should be utilized in a manner similar to Section IV A1 above; detailed calculations would be required to establish the level of improvement in beam optics which might be expected but a guess of a factor 2 to 5 would lead to an ultimate $4 \times 10^{-3} < \sin^2 2\theta < 10^{-2}$.

An important point in this approach to ν_μ disappearance is that the detector is simultaneously sensitive to neutral current events. For example, using R_4 of Table II there would be about 400 neutral current events (about 80 of which are $\nu_\mu p \rightarrow \nu_\mu p$) in detector II. Under certain conditions these events would be useful for normalization or analysis for specific effects.

Curve c in Figure 2 is the envelope of all such two detector experiments which could be used to map out the parameter space in this reaction. While not as dramatic as in $\nu_\mu \rightarrow \nu_e$ it is nonetheless a significant advance.

Another point should be mentioned, a fundamental limit in $\nu_\mu \rightarrow X$ experiments occurs when the wave length of the oscillation is commensurate with the decay length (de-coherence effect). This reduces sensitivity. With increased flux the decay volume can be reduced and sensitivity restored.

4. Other neutrino mass and mixing experiments. As mentioned in the introduction, $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow X$ are the most convenient examples of oscillations for illustrating the range of parameters to which we can push with present technology. However, the increaed flux will simultaneously lead to other possibilities.

One example, might be $\nu_e(\bar{\nu}_e)$ disappearance. There are two ways in which the fluxes of $\nu_e(\bar{\nu}_e)$ might be enhanced over the conventional broad and narrow band beams. These are by means of a K_L-beams or by muon storage "bottles" or "rings." In the case of K_L-beams approximately equal fluxes of ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ would be available but at reduced overall total flux. Such experiments would not be likely to improve upon reactor limits of $\delta m^2(\bar{\nu}_e \rightarrow x)$. However, they could lead to significant improvement in $\sin^2 2\theta$. In the case of muon storage devices a relatively detailed design and calculation would be needed to estimate possible oscillation parameter limits but large increases in $\nu_e(\bar{\nu}_e)$ fluxes over present accelerators should be possible.

Another example, is in the area of symmetry tests. Should an oscillation effect be discovered in a particular channel or should new theoretical incentives arise then such beams could permit separate tests of CPT, CP, and T. As an illustration we note that

$$P(\nu_\mu \rightarrow \nu_e)=P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) \text{ by CPT invariance}$$

$$P(\nu_\mu \rightarrow \nu_e)=P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \text{ by CP invariance}$$

and

$$P(\nu_\mu \rightarrow \nu_e)=P(\nu_e \rightarrow \nu_\mu) \text{ by T invariance.}$$

The possibility of such fundamental tests should be kept in mind and they deserve a quantitative estimate to establish how well they might be carried out.

In the event of the discovery of a measured oscillation effect, many improvements can be contemplated as long as there is high flux and flexibility in incident proton energy.

B. Non-oscillation experiments. It should be pointed out that with the high flux envisioned and the type of detectors chosen here, there are several other neutrino-related physics experiments which can be done simultaneously.

Several of these are of fundamental importance and have either not been possible to carry out before or have been extremely difficult to do.

Among them are the $d\sigma/dy$ distributions in $\nu_\mu(\bar{\nu}_\mu)$ scattering from electrons and any measurement of $\nu_e(\bar{\nu}_e)$ scattering from electrons and nucleons in a new energy regime.

For example, the higher flux would permit narrow band beams which frees the $d\sigma/dy$ measurement from excessive requirements on

angular resolution at small angles since now the neutrino energy would be reasonaby well known.

As mentioned previously, K_L-beams and muon storage devices allow increased $\nu_e(\bar{\nu}_e)$ and thus permit new studies of interactions of this neutrino flavor.

General References

1. See Ref. 16 for Table III.
2. In compiling this list (and the list of Sec. III) we have referred to the published literature, the Particle Data Group, reviews by H. Chen, F. Boehm, C. Baltay and conversations with experimenters at BNL, CERN, and LAMPF.
3. E-734 is an experiment underway at BNL-AGS to measure a number of weak neutral current parameters primarily in $\nu_\mu e \rightarrow \nu_\mu e$ and $\nu_\mu P \rightarrow \nu_\mu P$. The detector has been constructed and the experiment carried out by a collaboration of physicists from BNL-Brown-Osaka-Pennsylvania-Stony Brook-Tokyo (referred to elsewhere as BNL/USA/JAPAN). Preliminary results and detector performance are presented in Proceedings of Neutrino '82 Int. Conf., Balaton, Hungary (1981) in press.

TABLE 1

Beam Characteristics for Neutrinos and Protons

MACHINE	Ep(MeV)	PROTON BEAM CURRENT	PULSE	PROTONS/SEC
LAMPF NOW	800	600μA	12HZ	3.8×10^{15}
LAMPF II[1]	1600	100μA	120HZ(3μsec)	1×10^{15}[2]
AGS NOW	2800	1μA	1.4 sec (12 buckets)	7×10^{12}
10xAGS (AGS PLUS BOOSTER)	2800	10μA	"	7×10^{13}[3]

NEUTRINO BEAM

MACHINE	$\bar{E}_\nu$ (MeV)	Φ_ν (BARE TARGET)[4] (cm^2/SEC/INCIDENT PROTON)	Φ_ν (HORN)[4,5] (cm^2/SEC/INCIDENT PROTON)
LAMPF NOW	150	2.5×10^{-10}	---
LAMPF II[1]	750	3×10^{-8}	3×10^{-7}
AGS NOW	1200	8×10^{-8}	8×10^{-7}
10xAGS (AGS PLUS BOOSTER)	1200	8×10^{-8}	8×10^{-7}

[1] Preliminary parameters from LAMPF II Report #1 (LA-9433-SR) and private communication H.A. Thiessen.

[2] Under expected operating conditions this beam would be divided among four experimental stations hence 0.25×10^{15} would normally be available for neutrino physics requiring a 15HZ neutrino horn. Were the full 100μA to be used for neutrino physics a 120HZ horn would be required. At present there do not exist horns which can operate at either power level.

[3] Under normal operating conditions suggestion is to deflect 10% to slow beam extraction and other physics programs; 90% would be fast extracted for simultaneous running of neutrino program.

[4] Taken from curves generated by R. Allen, H. Chen, K. Wang UC (Irvine). Internal Report Neutrino #67-E1981. These are useful for relative flux comparison under same conditions; in this case: decay length = 30 meters, detector distance = 50 meters, tunnel and detector radius = 1.5 meters. No target absorption effects were included; when such absorption effects are taken into account fluxes are reduced by about one-third. We have used such a reduction in what follows.

[5] For simplicity we take Φ_ν(HORN) = 10 x Φ_ν(BARE); in detail it can be slightly better or worse at higher or lower E_p.

TABLE II

Some typical Cross Sections and Cross Section Ratios (for purposes of comparison we approximate the cross sections as follows)

$$\sigma^{CC}_{TOT}(\nu_\mu) = 0.79\ E_\nu(\mathrm{GeV})\mathrm{x}10^{-38}\ \mathrm{cm}^2/\mathrm{GeV} \cong 3\sigma^{CC}_{TOT}(\bar{\nu}_\mu)$$

$$\sigma(\nu_\mu n \to \mu^- P) \cong 0.5\mathrm{x}10^{-38}\ \mathrm{cm}^2 \quad , \quad E_\nu \geq 900\ \mathrm{MeV}$$

$$\sigma(\nu_\mu P \to \nu_\mu P) \cong 0.6\mathrm{x}10^{-39}\ \mathrm{cm}^2 \quad , \quad E_\nu \geq 900\ \mathrm{MeV}$$

$$\sigma(\nu_\mu e \to \nu_\mu e) = 1.4\ E_\nu(\mathrm{GeV})\mathrm{x}10^{-42}/\mathrm{GeV} \cong \sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e)$$

$$\sigma(\nu_e e \to \nu_e e) = 1.4\ E_\nu(\mathrm{GeV})\mathrm{x}10^{-41}/\mathrm{GeV} \cong \sigma(\bar{\nu}_e e \to \bar{\nu}_e e)$$

$$R_1 = \frac{\sigma(\nu_\mu P \to \nu_\mu P;\ 0.3 < q^2 < 1)}{\sigma(\nu_\mu n \to \mu^- P;\ \mathrm{all}\ q^2)} = 0.038$$

$$R_2 = \frac{\sigma(\nu_\mu P \to \nu_\mu P;\ 0.3 < q^2 < 1)}{\sigma(\nu_\mu n \to \mu^- P;\ 0.3 < q^2 < 1)} = 0.11; \quad \bar{R}_2 = \frac{\sigma(\bar{\nu}_\mu P \to \bar{\nu}_\mu P)}{\sigma(\nu_\mu P \to \mu^+ n)} = 0.19$$

$$R_3 = \frac{\sigma(\nu_\mu n \to \mu^- P)}{\sigma^{CC}_{TOT}(\nu_\mu)} \cong 0.63/E_\nu \quad , \quad E_\nu \geq /\mathrm{GeV}$$

$$R_4 = \sigma^{NC}_{TOT}(\nu_\mu) \Big/ \sigma(\nu_\mu n \to \mu^- P) \cong 0.4 \quad , \quad E_\nu \geq /\mathrm{GeV}$$

$$R_5 = \sigma^{NC}_{TOT}(\nu_\mu) \Big/ \sigma^{CC}_{TOT}(\nu_\mu) \cong \frac{1}{3}$$

$$R_6 = \frac{\sigma(\bar{\nu}_\mu P \to \mu^+ n)}{\sigma(\nu_\mu n \to \mu^- P)} \cong \frac{1}{2}$$

$$R_7 = \frac{\sigma(\bar{\nu}_\mu P \to \bar{\nu}_\mu P)}{\sigma(\nu_\mu P \to \nu_\mu P)} \cong 0.4$$

TABLE III

(Experiments completed, approved, and planned)*

ABBREVIATION KEY:

N.B. = narrow band beam
B.C. = bubble chamber
ĉ = cerenkov counter
count = electronic detection
LAMPF = Los Alamos Meson Physics Facility
AGS = BNL Alternating gradient synchrotron
FNAL = 400 GeV proton synchrotron
SPS = CERN super proton synchrotron

A. $\boxed{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e}$

(1) Completed

BEAM	GROUP	DETECTOR	LIMITS $(\delta m^2 \sin 2\theta)$ $(\mathrm{eV})^2$	LIMITS $\sin^2(2\theta)$	REF.
$\nu, (\bar{\nu})$	Gargamelle	BC@PS	1.2(1.0)	0.01(0.06)	1,(2)
$\bar{\nu}$	LAMPF-YALE	ĉ@LAMPF	0.91	0.2	3,4
ν	BNL-COL	BC@FNAL	0.6	0.006	5
ν	Gargamelle	BC@SPS	1.7	0.01	6
ν	BEBC	BC@SPS	1.7	0.01	7
$\bar{\nu}$	FNAL/HAW/ UCB	BC@FNAL	2.0	0.01	10

(2) Near Future (≤2 years)

BEAM	GROUP	DETECTOR	$(\delta m^2 \sin 2\theta)$ $(\mathrm{eV})^2$	$\sin^2(2\theta)$	REF.
ν (N.B.)	BNL-USA JAPAN	COUNT.@ AGS	0.6	0.0013	
$\bar{\nu}$	UCI-LAMPF	COUNT.@ LAMPF	0.35 (0.18)	0.02(0.08)	
ν	BEBC	BC@P.S.	0.09	0.03	
$\bar{\nu}$	ANL-OSU et al	COUNT.@ LAMPF (MOVABLE)	0.06	0.008	
ν (N.B.)	BNL-COL** et al	(2)COUNT. @AGS	0.035	0.002	
ν	BNL-USA** JAPAN	(2)COUNT. @AGS	0.06	0.04	

(3) Farther Future (not yet approved)

BEAM	GROUP	DETECTOR	$(\delta m^2 \sin 2\theta)$ $(\mathrm{eV})^2$	$\sin^2(2\theta)$	REF.
ν	LAMPF	(2)COUNT. @LAMPF	0.002	0.004	
ν	CERN et al	(2)COUNT. @SPS (JURA)	0.1	0.014	

*Unless otherwise noted by a (2), all are single detector experiments.

**Only Phase I of this experiment approved at this time.

TABLE III continued

B. $\overset{(-)}{\nu}_{\mu} \rightarrow X$

(1) Completed

BEAM	GROUP	DETECTOR	LIMITS $\delta m^2 \sin 2\theta$	$\sin^2(2\theta)$	REF.
$\nu,\bar{\nu}$	CCFRR	COUNT.@ FNAL (TOTAL CROSS SEC.)	25-250*	0.1	15
$\nu,\bar{\nu}$	B AKSAN	COUNT.- DEEP MINE	0.006	0.8	14

(2) Very Near Future (≤ 1 year)

ν	CCFRR	(2)COUNT @FNAL	$10\text{-}10^3$	∿0.08	
ν	BNL/USA/ JAPAN	COUNT @ AGS	10-100	∿0.15	

(3) Near Future (≤ 2 years)

ν	CDHS	(2)COUNT @PS	0.25	0.13	
ν	CHARM	(2)COUNT @PS	0.3	0.15	
ν (N.B.)	BNL-COL** et al	(2)COUNT @AGS	0.3-40	0.09	
ν	BNL-USA** JAPAN	(2)COUNT @AGS	0.1-40	0.08	

(4) Longer Future (not yet approved)

ν	LAMPF	(2)COUNT @LAMPF	0.02	0.14	
ν	CERN et al	(2)COUNT @SPS (JURA)	0.15	0.02	

* Disappearance experiments have an upper limit set by rate and finite decay region. Some experiments quote range of sensitivity.

** Only Phase I is approved at this time.

C. $\overset{(-)}{\nu}_{e} \rightarrow X$

(1) Completed

BEAM	GROUP	DETECTOR	LIMITS $(\delta m^2 \sin 2\theta)$ $(eV)^2$	$\sin^2(2\theta)$	REF.
ν	LAMPF- YALE	$\hat{C}$@LAMPF	2.5	0.7	3,4
ν	BNL-COL	BC@FNAL	8.0	0.6	5
$\bar{\nu}$ (N.B.)	BEBC	BC@SPS	55	0.3	8
$\bar{\nu}$	BEBC	BC@SPS	10	0.07	7
$\bar{\nu}$	CIT-MUN-SIN	COUNT @GRENOBLE REACTOR	0.15	∿0.15	12
$\bar{\nu}$	CIT-MUN-SIN	COUNT @GOSGEN REACTOR	0.02	∿0.15	13
$\bar{\nu}$	UCI	COUNT @SAVAN. RIVER REACTOR	POSITIVE EFFECT: δm^2-0.95(2.3,3.8) $\sin^2 2\theta$=0.32(0.20,0.25)		16

(2) Near Future

Three more reactor experiments are planned or in progress at different distances. Gosgen II (CIT/MUN/SIN) at 48 meters; Savan. River (UCI) at 15 to 50 meters; Bugey reactor (Annency-ISN) at 15 meters.

D. $\nu_e \rightarrow \nu_\tau$

(1) Completed

ν	BNL-COL	BC @FNAL	8.0	0.6	

E. $\boxed{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\tau}$

(1) Completed

BEAM	GROUP	DETECTOR	LIMITS $\delta m^2 \sin 2\theta$	$\sin^2(2\theta)$	REF.
ν	BNL-COL	BC@FNAL	3.0	0.06	5
ν	Gargamelle	BC@SPS	4.6	0.017	6
$\bar{\nu}$	MICH/FNAL USSR	BC@FNAL	2.2	0.044	9
$\bar{\nu}$	FNAL/HAU/ UCB	BC@FNAL	8.0	0.16	10
ν	FNAL/OSU JAPAN	EMULSION	3.0	0.013	11
ν	BEBC	BC@SPS	6.0	0.05	7

(2) Further Future (not yet approved)

BEAM	GROUP	DETECTOR	$\delta m^2 \sin 2\theta$	$\sin^2(2\theta)$	REF.
ν	CERN et al	(2) COUNT (JURA)	0.15	0.034	

TABLE III
References

1. E. Bellotti et al, N.C.L. 17 (1976) 554
2. J. Blietschau et al, N.P. B133 (1978) 205
3. P. Nemethy et al, P.R. D23 (1981) 262
4. S. Willis et al, P.R.L. 44 (1980) 522 and Errata 45 (1980) 1370
5. N. Baker et al, P.R.L. 47 (1981) 1576
6. N. Aremenise et al, P.L. 1003 (1981) 182
7. O. Erriquez et al, P.L. 102B (1981) 73
8. H. Deden et al, P.L. 98B (1981) 310
9. A. Asratyan et al, P.L. 105B (1981) 301
10. H. Bingham, Private communication and FNAL/ Hawaii/UCB Preprint (1982)
11. N. Ushida, P.R.L. 47 (1981) 1694
12. N. Kwon et al, P.R. D24 (1981) 1097
13. J. Vuillmeumier, P.L. (1982) in press
14. A. Chudakov et al. Proceedings 17th Int. Cosmic Ray Conf. (Paris 7 (1981) 106
15. M. Shaevitz, Proceedings of Int. Neutrino 81; Maui, Hawaii (1981)
16. F. Reines et al. P.R.L. 45 (1980) 1307

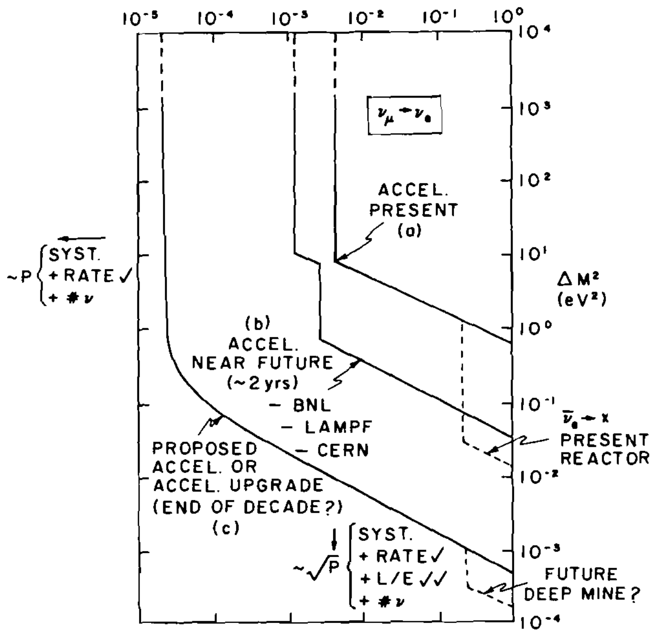

Figure 1

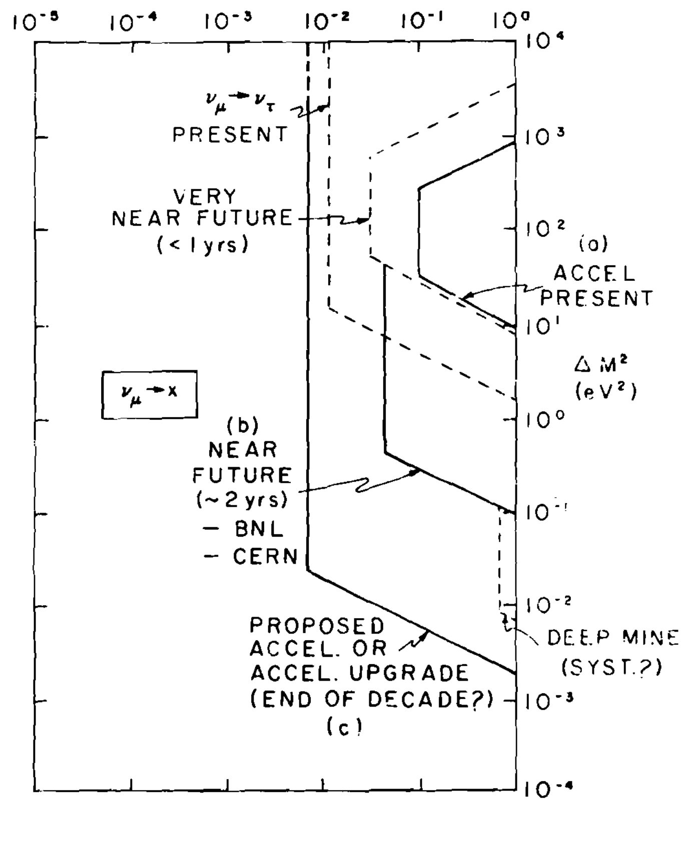

Figure 2