NEUTRINO OSCILLATION POSSIBILITIES WITH THE AGS NARROW BAND NEUTRINO BEAM

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Summary

Limits on neutrino oscillation parameters, Δm^2 and $\sin^2 2\alpha$, that may be possible to achieve over the next few years with the AGS narrow band neutrino beam at Brookhaven National Laboratory, are presented. The $\nu_\mu \to \nu_e$ oscillation and ν_μ disappearance modes are considered. Limits are derived under various assumptions of beam intensity, detector size, and position. The following limits may be possible to achieve:
$\Delta m^2 \simeq 3 \times 10^{-3} eV^2$, $\sin^2 2\alpha \simeq 10^{-4}$ for $\nu_\mu \to \nu_e$ transition, and $\Delta m^2 \simeq 0.03$, $\sin^2 2\alpha \simeq 0.006$ for ν_μ disappearance.

Introduction

The idea of neutrinos oscillating between states of different flavor is due to Pontecorvo.[1] The necessary conditions for such oscillations to take place are: 1) the mass difference of the mass eigenstates be nonzero, and 2) the individual lepton numbers are not conserved. Consider for simplicity only two neutrino flavors, ν_α and ν_β, corresponding to mass eigenstates, ν_1 abd ν_2. Then, the probability that a neutrino ν_α has oscillated into a neutrino ν_β at a distance L (in meters) from the source is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\alpha \cdot \sin^2(1.27 \frac{\Delta m^2 \cdot L}{E_\nu})$$

where α is the mixing angle, $\Delta m^2 = |m_1{}^2 - m_2{}^2|$ the difference of the squares of the masses in eV^2, and E_ν the neutrino energy in MeV. The above equation shows that sensitivity to small Δm^2 involves small neutrino energy E_ν, and large distance L, whereas sensitivity to small $\sin^2 2\alpha$ increases with statistics, the ultimate limit being set by the systematics of the neutrino beam and detector.

Neutrino oscillation experiments[2], in general, fall into two classes. 1) Appearance or exclusive experiments ($\nu_\alpha \to \nu_\beta$). One starts with a pure beam of ν_α type neutrinos and looks for the appearance of ν_β type neutrinos at some distance away. 2) Disappearance or inclusive experiments ($\nu_\alpha \to \nu_x$). Here one starts with a beam of ν_α type neutrinos and looks for flux reduction due to transition to other possible flavors.

In this paper, we present results of calculations of limits on neutrino oscillation parameters that might be possible to establish experimentally with the AGS narrow band neutrino beam. Two experiments are considered.[3]

1) $\nu_\mu \to \nu_e$ transition. This experiment requires one detector at some distance L from the ν_μ source. The ratio N_e/N_μ of electron to muon neutrinos interacting in the detector is measured. The background consists of ν_e from K^+ three-body decays as well as from misidentification in the detector. At L $\simeq$ 1 km, this background is estimated to be $\leq 10^{-3}$. The energy spectrum of ν_e from the $\nu_\mu \to \nu_e$ transition will be identical to the ν_μ energy spectrum. Hence, the use of a narrow band ν_μ beam would be ideal, since it enhances this characteristic signature of the oscillation.

2) ν_μ disappearance ($\nu_\mu \to \nu_x$). It requires two detectors at distances L_1, L_2 from the ν_μ source. The ratio N_2/N_1 of muon neutrinos interacting at the two detectors is measured. In the presence of neutrino oscillations this ratio, adjusted for solid angle, should be significantly different from 1 and should oscillate with neutrino energy. Understanding the relative fluxes at the two detectors is crucial in this experiment. The systematics of the flux normalization sets the ultimate limit on $\sin^2 2\alpha$ whereas the Δm^2 limit is determined by the distance L_2 and the minimum available neutrino energy. For L_2 = 1 km, the flux normalization systematics have been calculated to be about 0.5 - 0.8%.

Table 1. The three running scenarios. Each scenario assumes 50 weeks of running time (see text).

						$\nu_\mu \to \nu_e$		$\nu_\mu \to \nu_x$	
Running Scenario	Flux Factor	L_1 (km)	L_2 (km)	W_1 (tons)	W_2 (tons)	$\Delta m^2 \cdot \sin 2\alpha$ (small Δm^2)	$\sin^2 2\alpha$ (large Δm^2)	$\Delta m^2 \cdot \sin 2\alpha$ (small Δm^2)	$\sin^2 2\alpha$ (large Δm^2)
a	1	0.3	1	40	350	2×10^{-2}	7×10^{-4}	1.5×10^{-1}	3×10^{-2}
b	10	0.3	1	40	350	1×10^{-2}	2×10^{-4}	9×10^{-2}	1×10^{-2}
c	20	1	3	350	3500	3×10^{-3}	1.5×10^{-4}	2.5×10^{-2}	6×10^{-3}

Beam and Detector

The basic properties of beam and detector used in this study are assumed to be those of the Columbia-BNL-Illinois-Johns Hopkins collaboration.[3]

The narrow band neutrino beam at BNL is based on a system of two focusing magnetic horns followed by a 60 m decay tunnel. This horn system designed for optimum operation at 10 GeV/c is currently being redesigned for optimum operation at 3 GeV/c. An increase by about a factor of ten in neutrino intensity at 3 GeV/c is expected. The new system is expected to produce a ν_μ dichromatic beam from π and K decays of $\Delta p/p \simeq \pm 15\%$ and angular divergence of $\sigma_\theta \leqslant 4$ mrad.

The detector is assumed to be capable of detecting muons and electrons and measure their energy and direction. Planes of proportional drift chambers, interspersed with slabs of absorber (aluminum or concrete) of about 1/4 of a radiation length in thickness, are considered to be adequate to measure the electron energy and direction. The muon energy will be measured by range and/or magnetic analysis in a toroidal spectrometer following the main detector.

The AGS beam intensity used in the calculations is based on recent performance.[4]

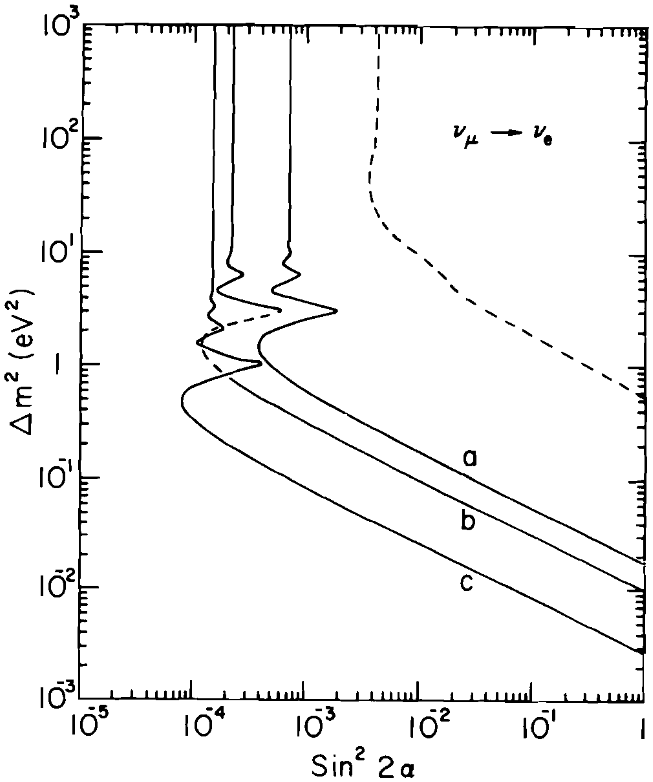

Fig. 1 The 90% confidence level contours for $\nu_\mu \rightarrow \nu_e$ transition. The sensitive region is to the right of the curves. Labels a, b, c correspond to the scenarios of Table 1. The broken curve shows the present experimental limit .

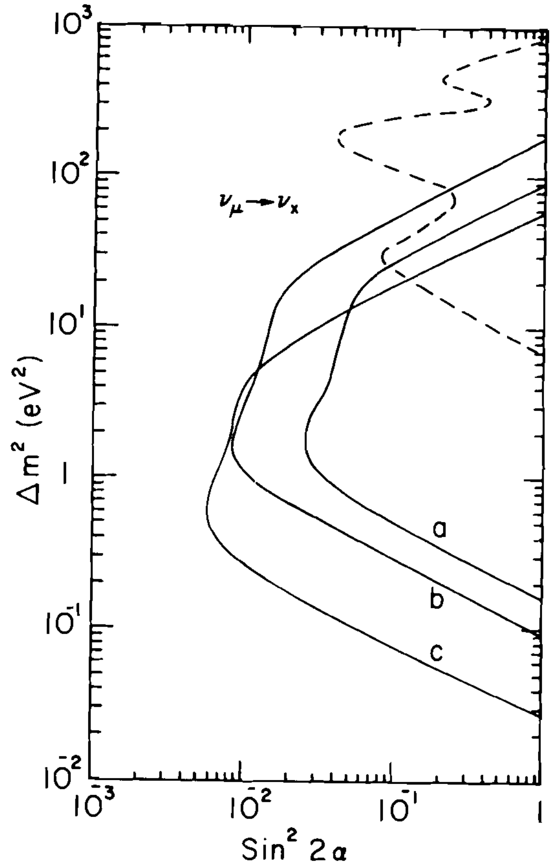

Fig. 2 The 90% confidence level contours for ν_μ disappearance. The sensitive region is to the right of the curves. Labels a, b, c correspond to the scenarios of Table 1. The broken curve shows the present experimental limit .

Assuming 9×10^{12} protons/pulse, a repetition rate of 1.3 sec, 120 running hours/week, and a 10% flux improvement from H^- injection one expects 3×10^{18} protons per week on target. Assuming a target efficiency of 50% one gets 1.5×10^{18} interacting protons per week.

With the above assumptions one can calculate[3] the number of muon neutrinos of energy $E_\nu = 1.28$ GeV ($E_\pi = 3$ GeV) detected at 1 km with a 350 ton detector to be 750 - 1000 per week. In the calculations that follow we assume this number to be 5000 ν_μ's per 10^{19} interacting protons (750 ν_μ's/week).

Calculation of Δm^2, $\sin^2 2\alpha$ Limits

We assume two detectors of masses W_1, W_2 at distances L_1, L_2 respectively, and three different experimental scenarios a , b, c, (Table 1) with various combinations of beam intensity, position, and weight of detectors. Each scenario assumes 30 weeks of running at $E_{\pi,K} = 3$ GeV, 10 weeks at 5 GeV, and 10 weeks at 7 GeV, namely 50 weeks of total running time. The ν_e data from the 3 GeV run are used to calculate the Δm^2, $\sin^2 2\alpha$ limits for the $\nu_\mu \rightarrow \nu_e$ transition, whereas the ν_μ data from 3, 5, and 7 GeV runs are used to calculate limits for the ν_μ disappearance.

Scenario "a" assumes the present AGS intensity with the improved narrow band beam, and two detectors of 40 tons and 350 tons at 0.3 km and 1 km from the neutrino source, respectively. This corresponds to 5000 ν_μ detected at the second detector for 10^{19} interacting protons, as discussed earlier. In scanario b, the AGS intensity is increased by a factor of 10, which might not be impossible to achieve with an upgraded AGS.[4] In scenario c, the distances L_1, L_2 are scaled up by a factor of 3, and the detector sizes by a factor of ten in such a way as to preserve the solid angle. In addition, a factor of two in neutrino flux is gained by doubling the length of the decay tunnel.

The regions of sensitivity in the ($\sin^2 2\alpha$, Δm^2) plane are shown in Figs. 1 and 2, where the 90% confidence level contours are plotted for the $\nu_\mu \to \nu_e$, and ν_μ disappearance experiments respectively. The effects of increasing the statistics and/or the detector distance from the neutrino source are clearly shown. The existing limits[5,2] (broken curves) are also shown for comparison. Since the chance of observing neutrino oscillations clearly depends on the size of the sensitive area in the ($\sin^2 2\alpha$, Δm^2) logarithmic plot, one could consider other scenarios, in which, for example, one trades Δm^2 sensitivity for $\sin^2 2\alpha$. However, it should be kept in mind that sooner or later the systematics of the beam and detector will dominate the errors that determine the $\sin^2 2\alpha$ limit. In the above calculation for example, the ν_μ disappearance $\sin^2 2\alpha$ limit of 0.006 is at the level of the systematics of the relative flux normalization at the two detectors.

In conclusion, we have attempted to estimate the neutrino oscillation parameter limits that one might be able to achieve at BNL by using the AGS narrow band neutrino beam in 50 weeks of running. Several assumptions concerning beam intensity and detector size were made, some presently possible and some perhaps somewhat unrealistic. The effects of beam intensity, detector position, and size are demonstrated. The ultimate limits that one might be able to achieve at BNL seem to be around $\Delta m^2 \simeq 10^{-3}$ eV^2 and $\sin^2 2\alpha \simeq 10^{-4}$.

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