Bounds on neutrino oscillation parameters from quasielastic scattering in the Serpukhov neutrino beams

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Bounds are calculated for the oscillation parameters of muon neutrinos, $\nu_\mu \to \nu_{x'}$ from data on quasi-elastic scattering in the neutrino beams of the Institute of High-Energy Physics, Serpukhov. The experiment was carried out jointly by the Institute of High-Energy Physics and the Institute of Theoretical and Experimental Physics. At square-mass differences $\Delta m^2 \gtrsim 15\ \text{eV}^2$ the mixing ratio is $\sin^2 2\theta \lesssim 9 \times 10^{-2}$ at a 90% confidence level.

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1. Neutrino mixing, manifested by neutrino oscillations,[1] is at the center of attention in experiments with neutrino beams.

The most extensive results have been obtained in experiments with muon neutrinos on accelerators, where conversions into neutrinos of another type, $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ and $\nu_\mu(\bar{\nu}_\mu) \to \nu_\tau(\bar{\nu}_\tau)$, have been sought. This approach is the simplest, since the admixture of electron neutrinos in beams of muon neutrinos is on the order of 1%, while the possible admixture of tau neutrinos is even smaller. These experi-

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ments have yielded some bounds on the mixing angles ($\sin^2 2\theta \lesssim 10^{-2}$ at large Δm^2) and on the square-mass difference ($\Delta m^2 \lesssim 1$ eV^2 and $\Delta m^2 \lesssim 3$ eV^2 at the maximum mixing angle, $\sin^2 2\theta \simeq 1$, for $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$, respectively).[2]

There is an alternative and more complex experimental approach: to ask which fraction $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu)$ of the original neutrinos remains after the beam passes from the source to the detector. This approach requires either a good quantitative understanding of the initial neutrino spectrum and of the interaction cross section of the process being analyzed or the use of two neutron detectors with identical characteristics at different distances from the source. This "inclusive" version of the experiment may tell us how many of the neutrinos of the original type become "sterile," i.e., noninteracting neutrinos: $\nu_\mu \to \nu_x$. One process which might be involved is $\nu_L \to \bar{\nu}_L$.

Recent experiments with muon neutrinos in cosmic rays[3] and with electron antineutrinos from a reactor[4] have yielded some new bounds on the mixing angles and the square-mass differences: $\Delta m^2 \leqslant 6 \times 10^{-3}$ eV^2 at the maximum mixing angle and $\sin^2 2\theta \leqslant 0.65$ at large mass differences for muon neutrinos and $\Delta m^2 \leqslant 0.016$ eV^2 at $\sin^2 2\theta = 1$ and $\sin^2 2\Theta \leqslant 0.17$ at $\Delta m^2 > 5$ eV^2 for electron antineutrinos.

Some new accelerator experiments of both the exclusive and inclusive types are being carried out or are in the planning stage.[2,5]

In this letter we report bounds on the oscillator parameters for muon neutrinos extracted from a determination of $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu)$, from an analysis of the results of a joint study by the Institute of High-Energy Physics and the Institute of Theoretical and Experimental Physics of the quasielastic scattering of muon neutrinos and antineutrinos by nucleons in the neutrino beams of the Serpukhov accelerator.[6]

2. Our analysis is based on two circumstances.

First, the original energy spectra of the muon neutrinos and antineutrinos (the absolute flux densities in various energy intervals) were determined experimentally[7] from measurements of the muon flux densities in the shielding iron and from information on the emission of mesons in an interaction of 70-GeV protons with a target in the neutrino channel. From these flux densities we found the total cross sections for quasielastic scattering in the corresponding energy intervals.[6]

Second, the total cross sections for quasielastic scattering in the same energy intervals can be calculated from the known form factors for the process; these form factors are determined without appealing to the particular form of the neutrino spectrum.

In the standard theory,[8] Q^2, which is the distribution in quasielastic scattering, is described by the three form factors $E_V(Q^2)$, $F_M(Q^2)$, and $F_A(Q^2)$:

$$\frac{d\sigma^{\nu,\nu}}{dQ^2} \sim \frac{1}{(s-m^2)}\{[(s-m^2)^2 + \frac{1}{2}t(s-u)](F_V^2 + F_A^2) + M^2 t(F_V^2 - F_A^2)$$

$$+ t(su + 2M^2 t - M^4)F_M^2 + 2Mt^2 F_V F_M \pm t(s-u)(F_V + 2MF_M)F_A\},$$

where $Q^2 = q^2 = -t$; s, t, and u are the usual invariants; and M is the nucleon mass. The upper sign on the last term refers to neutrino scattering, and the lower sign to antineutrino scattering. We ignore the induced pseudoscalar, since it amounts to only a fraction of 1% at these energies.

The form factors F_V and F_M are taken in dipole form from experiments on the scattering of electrons with a vector mass $M_V = 0.84$ GeV/c^2. In the axial form factor, for which we adopt the customary dipole parametrization,

$$F_A(Q^2) = \frac{F_A(0)}{(1 + Q^2/M_A^2)^2} \quad ,$$

where $F_A(Q) = -1.2546 \pm 0.0063$, we are left with only a single unknown parameter: the axial mass M_A.

The value $M_A = 1.00 \pm 0.04$ GeV/c^2 in our experiment[6] was found from a joint analysis of the Q^2 distributions in the processes $\nu_\mu\, n \to \mu^- p$- and $\bar{\nu}_\mu\, p \to \mu^+ n$-. This value agrees within the errors with the average worldwide value for this quantity, which has been determined primarily from data on neutrino scattering at the lower energies. We accordingly took an average, finding $M_A = 0.99 \pm 0.02$ GeV/c^2.

We used this value of the axial mass to calculate the total quasielastic cross sections.

The cross sections found as a result reflect the magnitude of the flux densities of muon neutrinos and antineutrinos at the position of the neutrino detector. In practice, however, it is more convenient to compare the measured and calculated cross sections.

3. By comparing the two values of the total quasielastic cross section in the corresponding energy intervals which were found independently by the different methods, we can determine whether the flux densities of neutrinos (or antineutrinos) causing the interactions in the neutrino detector differ from the original flux densities. Adopting the customary approximation that the attenuation of the neutrinos of the original type is determined primarily by the single conversion $\nu_\mu \to \nu_{x'}$ we write the corresponding probability as[1]

$$P(\nu_\mu \to \nu_\mu = 1 - \sin^2 2\theta \sin^2\left(1{,}27\frac{R}{E_\nu}\Delta m^2\right) \quad .$$

Here R is the average distance from the neutrino source to the detector.

The accompanying table shows the ratios r_{ν_μ} and $r_{\bar{\nu}_\mu}$ of the measured cross sections $\sigma_\nu(\nu_\mu\, n \to \mu^- p)$ and $\sigma_{\bar{\nu}}(\bar{\nu}_\mu\, p \to \mu^+ n)$ to the calculated cross sections σ_ν^0 and $\sigma_{\bar{\nu}}^0$ in the various energy intervals; the central energies of these intervals, E_ν, are listed in the first column.

4. For the analysis we used average data from the neutrino and antineutrino experiments (the fourth column), assuming CP invariance in the neutrino oscillations. We found the values $\Delta m^2 = 4.1 \pm 1.9$ eV^2 at $\sin^2 2\theta = 1$ and, for large mass differences ($\Delta m^2 = 50$ eV^2), $\sin^2 2\theta = 0.02 \pm 0.05$.

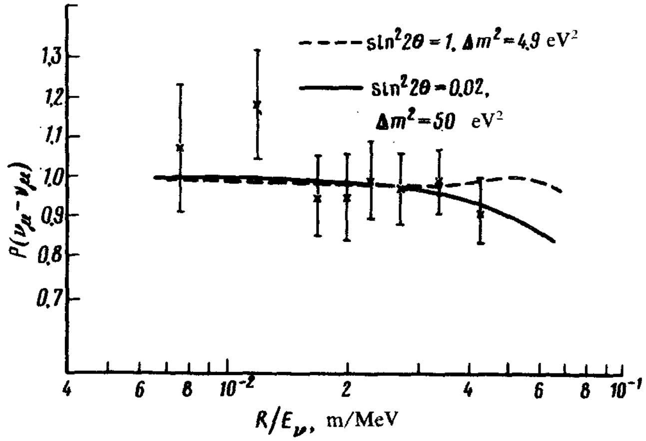

FIG. 1. Experimental probabilities $P(\nu_\mu \to \nu_\mu)$ vs the ratio R/E_ν. Solid and dashed curves—two solutions corresponding to the extreme values of the oscillation parameters.

The results are shown in the accompanying figures. The solid and dashed curves in Fig. 1 show the energy dependence of $P(\nu_\mu \to \nu_\mu)$ for two extreme values of the oscillation parameters: for the maximum mixing angle ($\sin^2 2\theta = 1$, $\Delta m^2 = 4.1$ eV^2), and for large mass differences ($\Delta m^2 = 50$ eV^2, $\sin^2 2\theta = 0.02$), respectively, along with experimental points. The dashed curve in Fig. 2 shows the solution found for the two-dimensional dependence for the parameters Δm^2 and $\sin^2 2\theta$, while the solid curve shows the bounds imposed on these parameters at a confidence level of 90%. Also shown in this figure is the bound found from cosmic-ray neutrinos at the Baksan underground installation.[3]

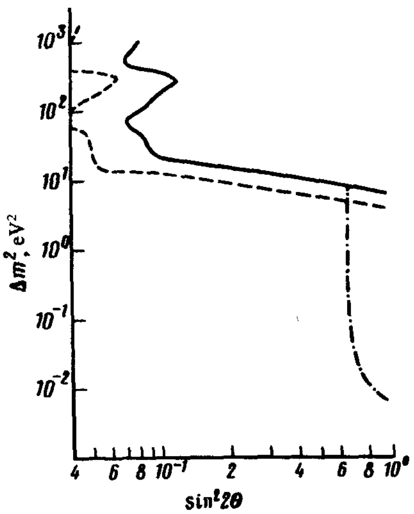

FIG. 2. Bounds imposed on the $\nu_\mu \to \nu_x$ oscillation parameters. Solid curve—Present study; dot-dashed curve—Ref. 3. The dashed curve shows a solution found from an analysis of the data from the present study.

TABLE I.

E_ν (GeV)	$r_{\nu_\mu} = \frac{\sigma_\nu(\nu_\mu n \to \mu^- p)}{\sigma_\nu^0}$	$r_{\bar{\nu}_\mu} = \frac{\sigma_{\bar{\nu}}(\bar{\nu}_\mu p \to \mu^+ n)}{\sigma_{\bar{\nu}}^0}$	$\langle r \rangle_\nu = P(\nu_\mu \to \nu_\mu)$
3.5	0.89 ± 0.11	0.93 ± 0.12	0.91 ± 0.08
4.5	1.05 ± 0.11	0.90 ± 0.13	0.99 ± 0.08
5.5	1.00 ± 0.11	0.93 ± 0.14	0.97 ± 0.09
6.5	0.98 ± 0.12	1.01 ± 0.16	0.99 ± 0.10
7.5	0.94 ± 0.15	0.97 ± 0.17	0.95 ± 0.11
9.5	0.92 ± 0.12	1.04 ± 0.19	0,95 ± 0.10
12.0	1.24 ± 0.18	1.08 ± 0.24	1.18 ± 0.14
20.0	1.05 ± 0.18	1.13 ± 0.35	1.07 ± 0.16

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