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NEUTRINO OSCILLATION SEARCHES AT THE AGS *

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A feasibility study of the time evolution of a long-lived ν beam has been performed. The proton momentum (1.5 GeV/c) was chosen to concentrate the ν flux at very low energy where all background reactions are kinematically suppressed. Sensitivity to oscillations at large proper times $\tau \approx \ell/p$ (where ℓ is the flight length and p is the momentum of the neutrino) is greatly enhanced by the resulting low neutrino momentum. Possible transformations $\nu + \nu$ (searched for via $\nu n + e^+p$ reactions) were not observed in an exposure of 2×10^{18} protons on target. Ten possible $\nu n + \mu^+p$ events were observed. An upper limit of 3eV, comparable to previous limits, can be placed on the mass difference between the two neutrino eigenstates. The accelerator backgrounds are low and the neutrino fluxes copious so that an experiment to approach a mass difference limit of 4eV is currently possible. Future experiments with longer distances and larger masses could reach 0.1eV at the AGS, comparable to the best limits proposed in other accelerator and reactor experiments.

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Proposals to search for neutrino evolution at Brookhaven were submitted in January of 1977. Since then the many problems associated with extracting and transmitting an intense, high repetition rate, low energy proton beam were solved in several short preliminary tests. An extended run of two weeks duration allowed beam optimization and commissioning and evaluation of a new target and focusing horn. The last two days of this run had beam conditions sufficiently clean and stable to take physics data.

We first discuss the physics motivation and possible current and future experiments. We then summarize the principal accomplishments of the test periods.

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Physics Motivation

In contrast to cosmological searches, where neutrinos travel over astronomical distances,¹ all experiments performed at proton accelerators detect neutrinos after a flight path which is as short as possible to maximize a small event rate. A possible disagreement between the two kinds of experiments has inspired many hypotheses. Among them is the possibility that the initially produced neutrino state undergoes a time evolution. The existence of such a phenomenon presumes a non-zero neutrino mass. The current experimental upper limits,² $m_\nu^e \leq 35$ eV and $m_\nu^\mu < 570$ KeV, are by no means restrictive. Furthermore, to undergo transformation neutrinos must violate leptonic number conservation. Again, the experimental limits do not prohibit neutrino evolution. The best test to date has been the absence of the decay $\mu^+ \rightarrow e^+ + \gamma$, for which the published upper limit for the branching ratio² is 3.6×10^{-9} . This can be compared to the predictions of several models^{3,4} for neutrino evolution which accommodate values from 10^{-13} to 10^{-24} . Thus, lepton number conservation might be violated at a substantial level and still be consistent with the non-observation of $\mu \rightarrow e \gamma$. The same models, which unify quarks and leptons in a common multiplet, have mixing angles in the lepton sector $\sim \theta_{\text{Cabbibo}}$. This leads to mass differences between the neutrino eigenstates of ~ 0.1 eV.

A simple model of neutrino evolution has been suggested by B. Pontecorvo.⁴ In analogy with the $K_L^0 - K_S^0$ system, periodic oscillations occur between ν_μ and ν_e states. More complicated models of neutrino evolution allow decays⁵ or strong neutrino elastic scattering⁶ in addition to oscillation. If new, yet undiscovered, types of neutrinos exist, the theory may include terms with oscillations into each of the neutrino types.⁷ If one interprets the negative results¹ of the solar neutrino experiments in terms of neutrino oscillations, mixing between three types of neutrinos (and three now exist!) is sufficient to explain⁸ the signal which is at least a factor of three below the predicted level.

In the model of Pontecorvo, if muon and electron numbers are not precisely conserved and if either neutrino has a small mass, then a beam of pure ν_μ 's will,

after a period of time t , contain a fraction of ν_e 's,

$$|\nu_e(t)|^2 = 1/2 \tan^2 \xi (1 - \cos((E_1 - E_2) t)). \quad (1)$$

The angle ξ measures the degree of muon and electron number violations; it is related⁵ to other processes that do not conserve lepton number, such as $\mu \rightarrow e \gamma$. However, oscillation experiments are potentially more sensitive to lepton number violation: they measure an interference amplitude whereas decay experiments measure an intensity. The frequency of oscillation is related to the difference of the squares of the masses m_1 and m_2 of the two neutrino eigenstates,

$$(E_1 - E_2) t \approx \frac{m_1^2 - m_2^2}{2} \frac{\ell}{p}$$

The parameter ℓ/p is a measure of the evolution time τ in the rest frame of a neutrino of mass m_ν : $\tau = \frac{m_\nu}{c} \frac{\ell}{p}$, where ℓ is the distance the neutrino has traveled and p is the neutrino momentum.

Accelerator neutrino experiments⁹ at 30 GeV have looked for $\nu_\mu \rightarrow \nu_e$ transitions with a sensitivity in the range

$$0.015 < \ell/p < 0.05 \text{ m/MeV.}$$

The high energy neutrino experiments¹⁰ at Fermilab operate in the region

$$0.01 < \ell/p < 0.1 \text{ m/MeV.}$$

Reactor neutrino experiments have been performed¹¹ or have been proposed¹² (at Hanford and Grenoble) using low energies and short drift lengths with

$$0.7 < \ell/p < 3.0 \text{ m/MeV.}$$

An observed $\bar{\nu}_e$ rate is compared with the absolute flux expected from the reactor. Any deviation is interpreted as a missing neutrino flux due to transformations of the $\bar{\nu}_e$. An absolute flux calibration and a knowledge of the spatial distribution of the neutrino source are necessary, yielding a measurement with systematics that are very different from those in accelerator experiments. Also, reactor experiments

are performed with $\bar{\nu}_e$'s, not ν_μ 's. It is possible that muon number conservation is an approximate symmetry but electron number conservation is exact. In this case, ν_μ might exhibit oscillations (although not into ν_e) but $\bar{\nu}_e$ would not. Figure 1 shows the regions of L - p space ultimately accessible to various neutrino facilities.

The null results of previous searches suggest that if oscillations occur, they have a long wavelength. (Short wavelengths would have produced rapid oscillations that would be easy to observe.) Expanding Eq. 1 in the long wavelength approximation yields

$$|\nu_e(L)|^2 \propto (L/p)^2$$

The quadratic dependence on L/p demonstrates that substantial gains in sensitivity are possible by increasing the time in the neutrino rest frame between the production and the detection of the neutrino. This can be accomplished by performing neutrino experiments at large distances from the source which was first suggested by M. Schwartz. Mann and Primakoff¹³ have discussed the feasibility of detecting neutrinos at a distance of ~ 1000 km from their production at Fermilab. A similar experiment using the Fermilab accelerator has been proposed by a group from Washington State.¹⁴ To the extent that the ν_μ flux falls off as $1/L^2$, the sensitivity to detecting $\nu_\mu \rightarrow \nu_e$ is independent of the distance in this particular long wavelength approximation.

Characteristics of Proposed Experiment

In contrast with these experiments, the current experiment (BNL Experiment 704/706) greatly reduces the neutrino energy (to ~ 100 MeV) allowing greater sensitivity with an existing neutrino detector. The low energy has the added advantage that the large ν_μ flux is inactive since its energy is insufficient to produce μ 's or π 's above a kinematic cut. On the other hand, ν_e 's in the beam (say from ν_μ oscillations) can scatter without a kinematic inhibition through the reaction

$\nu_e n \rightarrow p e$, since the investment of 105 MeV to form a muon is unnecessary.

The mere existence of neutrino-induced events with energies above that kinematically allowed for $\nu_\mu n \rightarrow p \mu^-$ would be evidence for ν_e generation and hence of neutrino transformation.

To limit the maximum ν_μ energy to the order of the muon's rest mass, the kinetic energy of the proton beam must not exceed about 800 MeV (proton momentum = 1.5 GeV/c). This proton energy is below that necessary for kaon production (2.3 GeV/c), eliminating the ν_e contamination from K_{e3} decays that has limited searches at higher energies.

A proton beam energy of 800 MeV coincides with the energy for maximum single pion production (the Δ peak) and is the standard energy at pion factories. However performing the experiment at BNL offers a distinct advantage: the neutrino decay region, shield, and detector already exist. To maximize proton flux at low energy, the AGS is operated at high repetition rate.

Figure 2 compares the sensitivity of this experiment with the Gargamelle limit⁹, which is comparable to or better than that from the current reactor experiments.¹¹ This proposal (Phase I), a study with the existing BNL neutrino detector, is characterized by $L/p = 150 \text{ m}/150 \text{ MeV} = 1 \text{ m/MeV}$ vs. $75 \text{ m}/1500 \text{ MeV} = 0.05 \text{ m/MeV}$ in the Gargamelle experiment. It achieves at least a factor of 4 more sensitivity for all mixing angles ξ to the neutrino mass difference, with ~ 0.5 eV being a typical limit. A definitive experiment (Phase II) with 10 times the target mass located ~ 1 km from the target, could reach neutrino masses ~ 0.05 eV over the full range of angles ξ . The proposed reactor experiments, on the other hand, are only competitive for $\xi > 0.4$ due to the insensitivity of detecting a small absolute loss of $\bar{\nu}_e$'s or a small deviation from a $1/r^2$ falloff.

Details of the Low Energy Neutrino Beam and Detector

The neutrino beam for the experiment is produced by targeting the proton beam from the AGS on a carbon target at the normal high energy neutrino target station. If unfocused, the pions that are produced yield at the detector the theoretical neutrino spectrum labeled "no focussing" in Fig. 3. Since the pion production occurs primarily via the Δ resonance which decays almost isotropically (it is produced nearly at rest in the laboratory), substantial gains can be achieved through focussing the pions. If the tracks of all forward going pions are rectified along the beam line, then the "perfect focussing" spectrum of Fig. 3 is obtained. Note a factor of 20 enhancement. Our horn achieves a gain of a factor of 8, producing a calculated neutrino spectrum similar to that shown in Fig. 4. Note the sharp cutoff in flux at ~ 230 MeV. The calculation traces particle tracks through the target and the horn, and accounts for Fermi motion, nuclear absorption, scattering, etc.

The neutrino cross sections calculated for the interactions of both ν_μ and ν_e are displayed in Fig. 5. The target material, liquid scintillator, is predominantly CH in chemical composition. The Pauli exclusion principle has been included in the curves for C^{12} . Note that no interactions from ν_μ 's occur below a threshold energy of ~ 105 MeV. Even at the mean energy of our neutrino beam, 150 MeV, the ν_e cross section (10^{-33} cm²/neutron) is double that for the ν_μ .

The product of the neutrino spectrum of Fig. 4 and the ν_e cross section of Fig. 5 produces the energy spectrum (histogram in Fig. 6). Note the narrow ($\sim 30\%$) width of the distribution. The response of the detector to heavily ionizing protons degrades the ν_e spectrum (the histogram) $\sim 10\%$ to produce the visible energy spectrum drawn as a heavy line. In contrast, the spectrum anticipated for ν_μ 's is depressed by ~ 100 MeV in energy and by $\sim 60\%$ in total rate (due to the suppressed cross section).

The experimental technique employed in this experiment is straightforward: Observe neutrino events with a muon in the final state to directly measure the left hand curve in Fig. 6. Then search for any events with an energy above that kinematically allowed for $\nu n \rightarrow \mu^- p$, ~ 130 MeV. The spectra of Figure 6, which in essence assume 50% oscillation (in the short wavelength approximation, averaged over all E_ν) shows that 95% of the ν_e events with a mean energy of 190 MeV are retained by this cut. If only 5% of the ν_μ 's oscillate to ν_e 's, they will primarily have lower energies and longer proper times. In this conservative case, $\sim 40\%$ of the ν_e events with a mean energy of 140 MeV lie above the energy cut. The left hand curve in Fig. 6 thus monitors the muon neutrino spectrum, provides a flux normalizer, and is the primary ingredient in predicting the shape of the right hand curve.

Discrimination between muons and electrons in the detector is accomplished by the muon decay signature. The top of Fig. 7 shows the pattern of energy deposited in the cellular structure of the detector for both electrons and muons. The bottom of Fig. 7 illustrates the energy deposited in or near the cell where a muon stops. This energy is deposited by the electron from the muon decay ~ 2 μ sec after the primary event. The decay electron deposits ~ 45 MeV in two cells, each of which has a threshold of ~ 3 MeV. The efficiency for detecting a stopped muon has been measured¹⁵ to be $60 \pm 3\%$ using stopping cosmic rays and beam associated muons in our $\nu p \rightarrow \nu p$ experiment. One half of the detector during the feasibility run was capable of recording a second firing in the same cell. Second timing for the entire detector is now implemented.

The ultimate background to oscillation events is produced by electron neutrinos originating from muon decay in flight in the pion decay tunnel. A detailed Monte Carlo calculation estimates this background to be $< 0.3\%$ of the ν_μ events. An inspection of events occurring within a gate equal in length with the beam spill gate, but opened 0.3 sec after protons hit the target, provides an evaluation of the cosmic ray background.

Results of Feasibility Run

To date, feasibility studies have achieved the following milestones: 1) the proton beam has been extracted at 1.5 GeV/c at 50% efficiency over 4 turns ($\sim 12 \mu\text{sec}$) of the main ring. The rf structure of the beam (beam spill $\sigma = 30\text{ns}$ with a 263ns period), which was essential in eliminating slow background in the previous experiments at BNL, is preserved in the extraction process. The repetition period is 0.7 sec. 2) Low-current regulated power supplies and several new quadrupoles have been installed to increase the emittance of the transport channel to the target for the low energy beam. A transport efficiency $>92\%$ has been achieved. Currently 5×10^{12} protons/burst reach the target. 3) A new target and a horn, optimized to focus the large angle pions produced at these energies, has been constructed, and the horn power supply has been modified to cycle every 0.7 sec. The performance of the new horn system has been verified by observing particle distributions in the tunnel. 4) The detector of our $\nu_p \rightarrow \nu_e$ experiment has been covered by a four layer veto counter to shield it from cosmic rays which might otherwise be a substantial background in this low counting rate experiment. 5) Second timing capability to detect $\mu \rightarrow e$ decay has been installed in the entire detector (only 1/2 was operational at the time of the feasibility study). 6) The entire system has been operated for six days to assess feasibility of the experiment. 7) The data accumulated during an exposure of 2×10^8 protons on target (50 hours when the beam losses had been minimized) have been analyzed and show a substantial but tractable neutron background and no ν_e background. These data alone set a limit on neutrino oscillations comparable to previous work.

The multiturn fast extraction techniques used at this low momentum are now well documented¹⁶, as is the transport system¹⁷ for 1.5 GeV/c protons. Operation of the beam has been detailed in Reference 18. For the purpose of this discussion, the two most important features are (1) the intensity is 5×10^{12} protons/pulse $\times 1.6$ pulses/sec = 1×10^{13} protons/sec, and (2) the transport is achieved with low losses. Figure 8 is a copy of several traces of the outputs of the radiation monitors along the beam line. After initial, inevitable loss at the extraction point (far left) extending up to the 4° bend, the monitors show no activity. This is in sharp contrast to 28 GeV operation, where (despite a smaller beam by a factor of 4) major losses have generally occurred at Q9 after the second bending magnet (8°).

During the feasibility run, the performance of the horn was evaluated by measuring the flux of secondary particles through ionization chambers at several locations in the decay tunnel: (1) At a wide angle (150mrad) $\sim 10\text{m}$ downstream of the target. (2) In the forward direction (20mrad) looking at the target through a $1" \times 1"$ 4m long aperture in an aluminum collimator $\sim 40\text{m}$ from the target. (3) At 20m from the target with a chamber on a remotely controlled X-Y scanner. The chamber output taken during a typical horizontal traversal is shown in Figure 9a. The central peak ($\sigma = 20\text{cm}$) is primarily due to uninteracted or multiple scattered, forward going protons. The sharp fall off at either end of the scan is due to the shielding of the target by a steel tunnel in which it is housed. A 12" cube of iron, through which only primary protons are transmitted is placed in the tunnel. It separates the proton signal from the total charged particle flux. The notch in the left shoulder of the distribution is the shadow of the cube, showing that 50% of the particles there are protons.

To suppress the dominant, uninteracted proton beam, measurements were made with a thick lead plug in the beam line at the exit of the horn. Its size stopped most of the proton beam at that point, but allowed the focussed pions to pass around it. A typical scan in this configuration is shown in Fig. 9b. The wings of the distribution are essentially unchanged from Fig. 9a (for equal protons on target), but the central peak is strongly suppressed. (Our calculations predict that 1/2 of the particles in Fig. 9b at $X = 0$ are pions.) With the horn current turned on, a comparable traverse is shown in 9c. Note that there is no increase in the signal in the notch; i.e. the protons scattered by the target are unaltered by the horn. In contrast, outside the notch the total particle flux has increased by a factor of ~ 4 , i.e. the pions have increased by a factor of 8. Similar observations, as well as those of the two stationary chambers, are consistent with the expected fluxes of p , π , and μ calculated with the hadron cascade Monte Carlo used to design the horn and predict the neutrino fluxes of Figures 3 and 4.

During the feasibility study, $\sim 2 \times 10^{18}$ protons were deposited on target under clean beam conditions. Figure 10 displays the configuration of the apparatus with a typical event superimposed. Figure 11 shows the distribution of track lengths for a sample of triggers in the beam gate and in the cosmic gate for equal live times. Note that the enhancement of triggers in the beam gate over those in the cosmic gate is only $\sim 10\%$ and is primarily for short tracks, i.e. low energy depositions. An inspection of beam and cosmic gates shows that they are dominated by accidental left-right coincidences in the detector. Although final event selection is the same for beam and for cosmic gates, no events from the cosmic gate survive.

To remove the background, we have applied requirements similar to those used in our $\nu p \rightarrow \nu p$ experiment to isolate neutrino-induced events:

- 1) Total containment: no deposition above a threshold of ~ 3 MeV is allowed in the first or last slabs, in the top or bottom large veto cells, or within 12" of the edge of a cell. This eliminates entering charged cosmic rays.
- 2) ≥ 2 adjacent cells (4 tubes) fire in coincidence: This rejects accidentals as well as low energy neutron-induced background.
- 3) No energy deposited in cells non-contiguous with the primary track: this eliminates neutron-induced multiple, separated interactions.
- 4) No events with ≥ 7 slabs firing, each with ~ 1 minimum ionization loss. This eliminates vertical cosmic ray muons that pass through the detector.

Satisfying these requirements were 40 candidates. The energy distribution ($\langle E \rangle = 40$ MeV) of these events appears in Fig. 12. The spatial distributions of these events show asymmetries. The distribution along the beam line, Fig. 13, shows that most events occur in the front, low threshold (~ 2 MeV) calorimeter as opposed to the back, high threshold (~ 5 MeV) calorimeter. The distribution of events transverse to the beam (Fig. 14) displays an excess in the top and to the right. These spatial asymmetries are for events with low energy. With a requirement of an energy deposition of ≥ 70 MeV, 10 events with no statistically significant spatial asymmetries remain. (An energy cut of this type was also necessary in our $\nu p \rightarrow \nu p$ experiment to eliminate neutron background.) Two of these events have muon decay signatures. For 60% efficiency in identifying muon decay in 50% of the apparatus, two decay events are consistent with the 10 total events. Although some of the ten could be due to background, we do not have sufficient discrimination with this small sample of data to subtract them. The number of events is consistent with the flux calculation which predicts 5 events for 10^{18} protons on target.

Since none of the events deposited an energy above 130 MeV, the kinematic limit expected for $\nu n \rightarrow \mu^- p$ events, we conclude that no electron candidates exist in the data. If this is the case, the feasibility study yields an upper limit on $(m_1^2 - m_2^2)^{1/2}$

of ~ 3 eV over most mixing angles.

Due to the paucity of events, the above conclusion is only indicative of the capability of the experiment. Since the ν_μ signal appears to be present at the expected level and the background seems to be tractable, in a run of 2×10^{19} protons on target (~ 800 hours) 120 ν_μ events should be collected, ~ 75 of which should include a muon decay signature. As is shown in the Appendix of the proposal for Experiment 704, if a number $N(\nu_e)$ ($N(\nu_\mu)$) of ν_e (ν_μ) events are observed, then in the Pontecorvo model

$$(m_2^2 - m_1^2)^{1/2} \approx 2 \left[\frac{\chi_c}{\sin^2 2\theta} \left(\frac{p}{E} \right) \right]^{1/2} \left(\frac{N(\nu_e)}{N(\nu_\mu)} \right)^{1/4}$$

If no ν_e candidates are observed during this run, the experiment will set an upper limit on $(m_2^2 - m_1^2)^{1/2}$ of ~ 1 eV over a broad range of mixing angles.

Possible machine improvements would be invaluable to this experiment. An extraction magnet with wider aperture could increase the extraction efficiency from 50 to 100%, doubling the number of protons on target. Higher power inflector magnet and focussing horn supplies could increase the repetition rate fivefold to 10/sec.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

[illegible]

7-10

IONIZATION CHAMBER OUTPUT
(arbitrary units)

Fig. 9

RUN 6066
EVENT 1414

CALORIMETERS

Fig. 10

Fig. 11

Fig. 12

DISTRIBUTION OF CANDIDATES
ALONG BEAM LINE

Fig. 13

DISTRIBUTION OF CANDIDATES TRANSVERSE TO BEAM

Fig. 14

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DISCUSSION

M. L. GOOD (Stony Brook). Do I understand correctly that your events are muon events - that is, would you see electron events?

L. SULAK. Our detector has never been used to see electrons. We are not certain how an electron would look, so we cannot rule out that the big showers, for example, can include electrons.

M. L. GOOD. And does the Baltay experiment see electrons?

L. SULAK. We are waiting for their results. They have the ideal detector for detecting electrons.

Y. Y. LEE (BNL). I need to make a comment for the CIR experiment. We agree with Larry's data completely on the number of events, etc. However the only anomaly we see is the weakest part - the number of events. There is no anomaly in the electron/muon or n.c./c.c. ratios. It seems unlikely to be conventional charm or anything else we can think of. So we are puzzled.

M. GOLDBABER (BNL). Do you take hyperon or K meson production into account in your background calculations?

L. SULAK. Yes. However their effect is negligible, namely on the order of 1 - 2 percent.