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Presented at  
New Directions in Neutrino Physics Workshop  
Fermilab, Batavia, IL, Sept. 14-16, 1988

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# Neutrino Physics at Brookhaven National Laboratory

## S. Aronson and M.J. Murtagh, BNL

### ABSTRACT

The history of neutrino physics at BNL is briefly reviewed and the opportunities for new experiments in the context of the AGS Booster are discussed. A recently proposed long-baseline oscillation experiment to extend the search for  $\nu_\mu$  disappearance oscillations is presented as an example of a neutrino experiment which requires the Booster.

## INTRODUCTION

Brookhaven National Laboratory has been very active in neutrino physics for a long time. Initially there was the definitive 2-neutrino experiment at the AGS in the sixties.<sup>1</sup> In the seventies the present neutrino beam line was completed and most of the subsequent experiments used the conventional horn-focussed wide-band neutrino beam. The AGS neutrino beam is a fast extracted beam(2.5 $\mu$ sec) composed of 12 beam buckets each 25 nsecs wide and separated by 220 nsecs. Recently this beam has run with a 1.4 sec rep rate and  $\sim 1.5 \times 10^{13}$  protons on target(POT) per pulse. With the conventional wide-band horn the neutrino spectrum peaks around 1 GeV and extends up to  $\sim 20$  GeV with 10% of the flux above 4 GeV (Fig. 1). Among the more interesting AGS results from this period were the discovery of charmed baryons, associated work on strange particle production and exclusive final states in the 7' bubble chamber<sup>2</sup> and the observation of  $\nu_\mu p$  and  $\bar{\nu}_\mu p$  elastic scattering by groups from BNL, Harvard, Penn<sup>3</sup> and Columbia, Illinois, Rockefeller<sup>4</sup>. This latter group also measured neutral current  $\nu_\mu p \pi^0$  production.<sup>5</sup> (One should also note in this era the BNL, Columbia collaboration which studied neutrino electron elastic scattering, same and opposite sign dilepton production and hadronic charm decays in the Fermilab 15' bubble chamber with a heavy Neon-Hydrogen fill.<sup>6</sup>)

In the early 1980's the E734 experiment began and continued running until 1986. This experiment was proposed by a USA-Japan collaboration with members from BNL, Brown, KEK, Osaka, Penn and Stony Brook. The E734 proposal was for the measurement of the elastic scattering of neutrinos and antineutrinos on electrons and protons. The primary objective was to determine the weak mixing angle ( $\sin^2 \theta_W$ ) from the ratio of cross sections in the theoretically simple leptonic systems ( $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$ ) and in the relatively simple hadronic systems ( $\bar{\nu}_\mu p \rightarrow \bar{\nu}_\mu p$ ). The experiment collected data for  $3.9 \times 10^{19}$  POT for neutrino running and  $5.1 \times 10^{19}$  POT for antineutrino running. A total of  $160 \pm 17 \nu_\mu e$  and  $97 \pm 13 \bar{\nu}_\mu e$  elastic scattering events were observed. The resulting cross sections<sup>7</sup> determined from these events were

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) = (1.80 \pm 0.20 \pm 0.25) \times 10^{-42} E_{\nu_\mu} (cm^2/GeV)$$

$$\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e) = (1.17 \pm 0.16 \pm 0.13) \times 10^{-42} E_{\bar{\nu}_\mu} (cm^2/GeV)$$

while the measured cross section ratio was

$$R = 1.53_{-0.25}^{+0.30} (stat)_{-0.17}^{+0.18} (sys)$$

The value of the weak mixing angle determined from R was

$$\sin^2 \theta_W = 0.195 \pm 0.018 \pm 0.013$$

The neutrino proton elastic scattering data sets used in the E734 analysis are more than 5 times larger than those of any previous experiments. A total of 951  $\nu_\mu p$  and 776  $\bar{\nu}_\mu p$  events were used in the final analysis. The value of the weak mixing angle determined from the ratio of the  $\nu_\mu p$  and  $\bar{\nu}_\mu p$  elastic scattering cross sections was<sup>8</sup>

$$\sin^2 \theta_W = 0.220 \pm 0.16 (stat)_{-0.031}^{+0.023} (sys)$$

The final goal of these types of measurements is to determine  $\sin^2 \theta_W$  with an error of  $< 5\%$ . At this level one becomes sensitive to radiative corrections to the Standard Model. To the extent that the standard model is incomplete a very precise ( $\sim 1\%$ ) determination of  $\sin^2 \theta_W$  would be very useful for testing extensions to the model. The determination of  $\sin^2 \theta_W$  from deep inelastic scattering<sup>9</sup> is already at the 5% level. However, one has to be concerned about the corrections in this process caused by the presence of a hadron target. A measurement with the required precision from the purely leptonic processes  $\nu_\mu e$ ,  $\bar{\nu}_\mu e$  is clearly desirable. One reason, as is discussed later, for the ending of E734 was the realization that one could not significantly improve the error on  $\sin^2 \theta_W$  using the available detector.

In addition to the elastic cross section results outlined above, E734 produced a number of other interesting results. These included measurements on the electromagnetic properties of muon neutrinos<sup>10</sup>, limits on heavy neutrino decays<sup>11</sup> in the range  $200 \leq M_H(\text{MeV}) \leq 400$  and on second class currents from a study of antineutrino quasi-elastic scattering<sup>12</sup>. Perhaps more interesting for the present discussion is the limit obtained in a search for  $\nu_\mu \rightarrow \nu_e$  oscillations.<sup>13</sup> The E/L for this detector was  $\sim 1/0.1 = 10$ . No evidence for oscillations was found and the limits obtained were  $\sin^2 2\alpha \leq 3.4 \times 10^{-3}$  at 90% CL for large  $\Delta m^2$  and  $\Delta m^2 \sin 2\alpha \leq 0.43(\text{eV})^2$  at 90% CL for small  $\Delta m^2$ . (Fig. 2)

Two other experiments have recently been completed at BNL. They were both dedicated neutrino oscillation experiments and they presented results at this Workshop. The E776 experiment<sup>14</sup> by a Columbia, Illinois, Johns Hopkins collaboration reported on a  $\nu_\mu \rightarrow \nu_e$  oscillation search using a narrow-band beam peaked at 1.25 GeV and a detector

at 1km or  $E/L=1$ . They also have data on hand which was taken with the wide-band beam. The E816 experiment, a BNL, Boston Univ., CERN, Paris collaboration<sup>15</sup>, used the wide-band beam with a detector located just behind the E734 detector,  $E/L \sim 10$ , to search for  $\nu_\mu \rightarrow \nu_e$  oscillations. The experiment was, in a sense, a continuation of a CERN experiment (PS191) in a low energy neutrino beam from the PS in which an anomalous number of electron events was observed.<sup>16</sup> The PS191 detector was moved to BNL and improved for use in E816. The E816 experiment collected  $\sim 5$  times the neutrino data of PS191 and also a significant antineutrino data set and a number of possible systematic sources of error were removed compared to the PS191 experiment.

Neither E776 nor E816 are reporting any significant evidence for  $\nu_\mu \rightarrow \nu_e$  oscillations at this time.

Since the completion of E734, E776 and E816, there have been no new approved neutrino experiments at BNL.

Approximately 18 months ago there was a Neutrino Workshop at BNL.<sup>17</sup> The primary reason for this workshop was to evaluate the present status of, and likely directions for, neutrino physics with special emphasis on its relation to a future program of neutrino physics at the AGS. Of particular interest was the potential offered by the addition of a Booster to the AGS.

A brief discussion of the Booster and its relation to the neutrino program is presented, followed by some comments on the future of neutrino physics at BNL from the perspective both of the BNL Neutrino Workshop and subsequent activities.

## **THE AGS BOOSTER PROJECT**

The Booster is an approved project, now under construction, to enhance the performance of the AGS. It is expected to be completed in 1991. The addition of a Booster ring to the AGS is expected to help in 3 separate areas. Of particular interest to the neutrino program is that it will increase the proton intensity in the AGS by a factor of  $\sim 5$  bringing it from the present intensity to around  $6 \times 10^{13}$ ppp. It will also help in the polarized proton program, increasing the polarized proton intensity in the AGS by a factor of 20 to  $10^{12}$ ppp for spin physics and allowing multi-target operation. Finally, the Booster is

essential for the Heavy Ion program. It will allow the elements from sulphur up to gold to be accelerated in the AGS and eventually to be injected into RHIC.

Figure 3 shows the location of the Booster ring in the AGS complex. Progress so far has been very satisfactory, in that all construction milestones have been met on or before schedule. At present, work is proceeding on all systems. The plan for commissioning the Booster should result in the availability of a full-intensity fast-extracted beam on the neutrino production target by 1993. To match this schedule a large-scale neutrino detector will have a 4-year design/construction/installation/test cycle if it gets underway soon. Based on past experience, once these intensities are achieved, one can expect exposures of  $\sim 10^{20}$  POT in typical neutrino runs of 6-8 weeks. The physics opportunities made available by this new capability are discussed below.

## FUTURE NEUTRINO PHYSICS AT THE AGS

A number of possible future AGS neutrino experiments were discussed at the BNL workshop and to a lesser degree since that time. Of particular note are an improved  $\nu_\mu e$  elastic scattering experiment, to a lesser extent a  $\nu_\mu p$  elastic scattering experiment, and various neutrino oscillation searches. At this meeting a presentation was made on the possibility of a "high" energy muon storage ring to produce an intense ( $\nu_e \cong \nu_\mu$ ) electron-neutrino beam for  $\nu_e$  physics.<sup>18</sup> Of these the only concrete proposal presently active is for a long baseline neutrino oscillation search and it will be discussed later.

It is perhaps worth making a few comments on the other potential experiments mentioned above. In all cases there is theoretical interest in improving the measurements and the major new experimental consideration at BNL is the impact of the improved flux from the Booster. One assumes that in the near future the available proton flux for the neutrino program will increase by a factor of 5. It is expected that the neutrino beam will remain a fast extracted beam with a well defined internal time structure and that the full AGS beam will be available for fast beam running.

The present limitation on the determination of the  $\sin^2 \theta_W$  in E734 from  $\nu_\mu e$  elastic scattering is clearly statistical. The flux increase from the Booster would significantly reduce this problem but the present E734 detector could not handle the increased flux in a straightforward or inexpensive way. Unfortunately even if the statistical limitation could

be overcome the systematic limitations appear less tractable. The primary limitation here comes from the uncertainty in the normalization. The normalization is determined by measuring the quasi-elastic process  $\nu_\mu n \rightarrow \mu^- p$  and determining the flux from the well known quasi-elastic cross section and the number of observed quasi-elastic events. The backgrounds in this case are large ( $\sim 40\%$ ) and come primarily from the single pion final states and to a lesser degree from multipion final states. Since these cross sections are not very well known they produce large and essentially irreducible systematic errors in the normalization. Another non-negligible source of systematic error is nuclear corrections. If  $\sin^2 \theta_W$  is determined from R, the ratio of the elastic scattering cross sections, some of these errors are reduced but in this case there is the added complication of the relative normalization of the neutrino and antineutrino beams.

There is no doubt that with the addition of the Booster at the AGS one could design a detector like E734 which would produce a value of  $\sin^2 \theta_W$  from the ratio of the  $\nu_\mu e$  and  $\bar{\nu}_\mu e$  elastic scattering cross sections which would have a statistical precision of  $< 5\%$  ( $\sim 2000 \nu_\mu e, \bar{\nu}_\mu e$  events) and an improved systematic precision compared to E734. However, there appeared to be little enthusiasm for such an undertaking at the present time. There were a few reasons for this. First the CHARM II experiment which is already running<sup>19</sup> at the CERN SPS will have a statistical precision of  $< 5\%$  and a systematic precision comparable to what is achievable at BNL. In addition there is no strong theoretical motivation to push the measurement further at this time. If improved precision is required then it will likely be achieved by the LCD experiment<sup>20</sup> at Los Alamos. This experiment is designed to measure the ratio of neutrino interactions from  $\pi \rightarrow \mu \nu_\mu$  compared to  $\pi \rightarrow \mu \rightarrow e \nu_e \nu_\mu$  in a large Water Cherenkov detector. Since all the measured quantities come ultimately from  $\pi$ 's produced in the proton beam dump this experiment should not be subject to the same normalization limitations as are the more conventional accelerator experiments such as E734 and CHARM.

The present determination of  $\sin^2 \theta_W$  from  $\nu_\mu p$  and  $\bar{\nu}_\mu p$  elastic scattering is already systematically limited. The limitations here are not only the normalization but also nuclear corrections in the signal channels and neutrino and antineutrino backgrounds. It should be noted that E734 was far from optimised for  $\nu_\mu p$  elastic scattering. There is no question that a much better measurement could be made with a dedicated  $\nu_\mu p$  detector. Clearly

in this case the increased flux from the Booster would be a definite asset. For example one could make a high intensity narrow band beam to add kinematic constraints to the analysis or build a detector with very light target elements to reduce the nuclear effects. The principal drawback in this case was the lack of any strong theoretical motivation to improve the measurement. If such a need arose there is no question the AGS with the Booster would be the ideal environment for this experiment.

The only experimental topic which generated much enthusiasm was the search for neutrino oscillations. As has been clearly shown at this workshop there is no evidence of  $\nu_\mu \rightarrow \nu_e$  oscillations (Fig. 1) either in accelerator experiments with  $E/L \lesssim 10$ , or in reactor searches for  $\bar{\nu}_e$  disappearance. The parameter space for  $\nu_\mu \rightarrow \nu_\tau$  searches is much less explored. In addition there is a strong theoretical prejudice<sup>21</sup> that  $\nu_\mu \rightarrow \nu_\tau$  is more likely to be a productive area to explore at accelerators. If the present conflict between theory and experiment with regard to the emission of solar neutrinos is correctly understood by the MSW theory<sup>22</sup> of matter oscillations, then at least one neutrino is massive and oscillations exist. Furthermore, if the oscillation responsible for the solar neutrino depletion is  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  and there is a reasonable mass hierarchy among neutrinos  $\nu_\mu \rightarrow \nu_\tau$  oscillations might occur with parameters accessible to accelerator experiments.

A proposal to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations in a long baseline experiment at BNL has been submitted and is under active consideration by the laboratory at this time. A brief description of the proposal follows.

## A LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT

The only currently active neutrino proposal at Brookhaven is one for a long baseline neutrino oscillation experiment which was submitted recently by a Brookhaven, Columbia University, University of Illinois and Johns Hopkins University collaboration.<sup>23</sup> The primary objective of the proposal is to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations via a  $\nu_\mu$  disappearance experiment. Since the AGS wide band beam peaks near 1 GeV and only 10% of the flux is above 4 GeV it is very unlikely that one would observe  $\nu_\mu \rightarrow \nu_\tau$  oscillations via an appearance experiment at the AGS. While the P848 detector is optimised for muon detection it should be efficient for detecting electrons with momenta greater than 1.5 GeV/c. Even

with this high detection threshold it will be possible to improve the range of a  $\nu_\mu \rightarrow \nu_e$  oscillation search significantly compared to earlier experiments.

The proposal is for a two detector wide band neutrino beam experiment with a near detector of 400 metric tons(mt) at 1km and a far detector of 1450 mt at 10 km. There are a number of reasons for the choice of location for the front detector. First, there is no evidence for oscillations in the parameter space covered by a detector at 1 km in a 1 GeV/c beam so a detector at 1 km can be assumed to see the originally produced beam. Also, the neutrino rate near the source with the addition of the Booster is very high (e.g. in the E734 detector it would be  $\gtrsim 6$  events/pulse) so the electronics for a close in detector ( $\lesssim 0.1$  km) would be quite complicated and it would not be trivial to have both detectors identical. Perhaps the most important reason for choosing 1 km is that by this distance the wide band beam appears as a  $1/r^2$  beam and this simplifies the extrapolation of the expected rate from the near to the far detector. Since this extrapolation produces the dominant systematic error in the final analysis it is very important that it be controlled as well as possible.

The choice of 10 km for the far detector is driven by the expected event rate. The goal in the proposal is to have  $\sim 10,000$  good quasi-elastic candidates in the final analysis. The expected event rate is obtained by extrapolating from the observed rates in the recently completed E734 and E776 experiments. There is good agreement between the rates determined from these experiments; the conclusion is that in an 1100 mt fiducial volume there would be  $\sim 11,000$  identified quasi-elastic candidates for  $2 \times 10^{20}$  POT. Here an identified quasi-elastic candidate is a single muon which originates in the fiducial volume, has an angle within 30 degrees of the nominal beam direction and either ranges out in the detector or is momentum analyzed in the toroidal spectrometer at the rear of the detector. Since 1983 the AGS has routinely delivered  $10^{19}$  POT in 3 calendar weeks for neutrino running. If one assumes a factor of 5 increase from the Booster then  $2 \times 10^{20}$  POT represents only a couple of modest AGS runs once the Booster is fully operational.

The two detectors are intended to be as close to identical as is possible. They will each consist of a main detector made of modules of Iarocci tubes<sup>24</sup> and absorber followed by a toroidal spectrometer(Fig. 4). Each module(Fig. 5) will have a plane of Iarocci tubes with x and y capacitive readout followed by 2 planes of Iron absorber each 5/8" thick.

The absorber will most likely be iron shot. The thickness of absorber was chosen so that a 350 MeV/c muon will have at least 10 hits in the detector. The Iarocci tubes are each 0.9cm  $\times$  0.9cm; the expected spatial resolution from the strips will be  $\sim$  3mm and the angular resolution for tracks that travel at least 5 modules will be  $\sim$  10 mrad. The muon spectrometer will consist of iron toroids and Iarocci chambers. The total iron thickness will be 53" so that the muon momentum resolution of penetrating tracks will be  $\Delta p/p \sim$  18%. The iron toroids are segmented to give an energy resolution for stopping tracks of  $<$  10%.

The near detector will have 100 modules with a transverse size of 17.7'  $\times$  17.7' while the far detector will have 200 modules with a transverse size of 23.6'  $\times$  23.6'. In all other respects the detectors are essentially identical.

If the experiment receives  $2 \times 10^{20}$  POT then there should be approximately 10,000 (250,000) reconstructed quasi-elastic events in the far (near) detector. With these statistics systematic errors from the relative fluxes at the two detectors and from the acceptances of the detectors should be the primary limitations on the experiment. The acceptance error should be very small since the detectors are essentially identical and only simple geometric calculations will be required. Since the beam will have a  $1/r^2$  behavior at both detectors which are at large distances from the beam source, it is expected that the systematic error from this source will be  $<$  2% but it will still be the dominant error in the final analysis.

In its simplest form the experiment counts stopping or momentum analysed muons in both detectors and compares the ratio to that expected from the relative fiducial masses of the detectors and the  $1/r^2$  flux ratio between the detectors. However, if any discrepancy between the measured rates is due to oscillations then it ought to have a well-defined energy dependence. The event energy for each neutrino quasi-elastic interaction can be reconstructed from the measured muon angle and momentum. The actual sample of quasi-elastic candidates collected is estimated to contain only 68% true quasi-elastics, with 31% single pion events and 1% deep-inelastic events. The net effect of reconstructing single pion events as quasi-elastics is to make a slight shift ( $\sim$  300MeV) in the reconstructed incident neutrino energy. While this tends to smear out the theoretical dips due to oscillations in the ratio of events, it does not significantly reduce the sensitivity of the experiment. For example in Fig. 6 is shown the expected ratio of observed quasi-elastic events as a function of energy for oscillation parameters  $\Delta m^2 = 0.03$  and  $\sin^2 2\alpha = 1$ , which are at the

extreme of the expected sensitivity. In generating this figure not only have the expected backgrounds been included but also energy resolution and the expected systematic errors.

The expected area of sensitivity for this proposal is shown on Fig. 7. As with all disappearance experiments the range in  $\sin^2 2\alpha$  is limited but comparable to other experiments. The expected improvement in  $\Delta m^2$  should be close to an order of magnitude. This  $\Delta m^2$  limit is essentially determined by the distance to the far detector, given adequate statistics. It is possible that some redesign of the beam, e.g. an improved horn design or a longer meson decay region, could increase the flux even more than that projected from the Booster. In this case one might consider moving the detector even further than the presently designed 10km and in this way improve the range in  $\Delta m^2$  even more.

The present detector design is optimised for muon detection above 300MeV. However, as mentioned earlier, it should be possible to clearly identify electrons above 1.5GeV. For the far detector this will yield an  $E/L \sim 0.2 - 0.3$  which is significantly lower than that of recent accelerator experiments, which have  $E/L > 1$ . If one applies the usual assumptions on backgrounds to the electron sample then the expected range of sensitivity for a  $\nu_\mu \rightarrow \nu_e$  oscillation search in the same detector is as shown in Fig. 2. While there is only a modest improvement in the parameters for maximal mixing and for very large  $\Delta m^2$ , there is a very significant improvement in the other regions of  $\Delta m^2, \sin^2 2\alpha$  space.

Proposal P848 which is currently under consideration at Brookhaven offers the possibility of significantly improving the search for neutrino oscillations both in the exclusive search for  $\nu_\mu \rightarrow \nu_e$  and the the search for  $\nu_\mu$  disappearance. In this latter case it could expand the parameter space to be comparable to that for  $\nu_\mu \rightarrow \nu_e$  searches and more importantly cover at least part of the allowed region suggested by some matter oscillation solutions to the solar neutrino problem. In the former case it should in a single experiment not only cover the whole region searched in previous accelerator and reactor experiments but also significantly increase it.

## CONCLUSIONS

A proposed long baseline oscillation search, for which the AGS will be ideal when the intensities promised by the Booster are realized, has been outlined. However, there are many other neutrino physics possibilities, including elastic scattering, where the higher intensities would also be important. In most of the likely directions for future neutrino physics, the combination of the neutrino energy and the increased intensity available with the Booster will make BNL an important participant.

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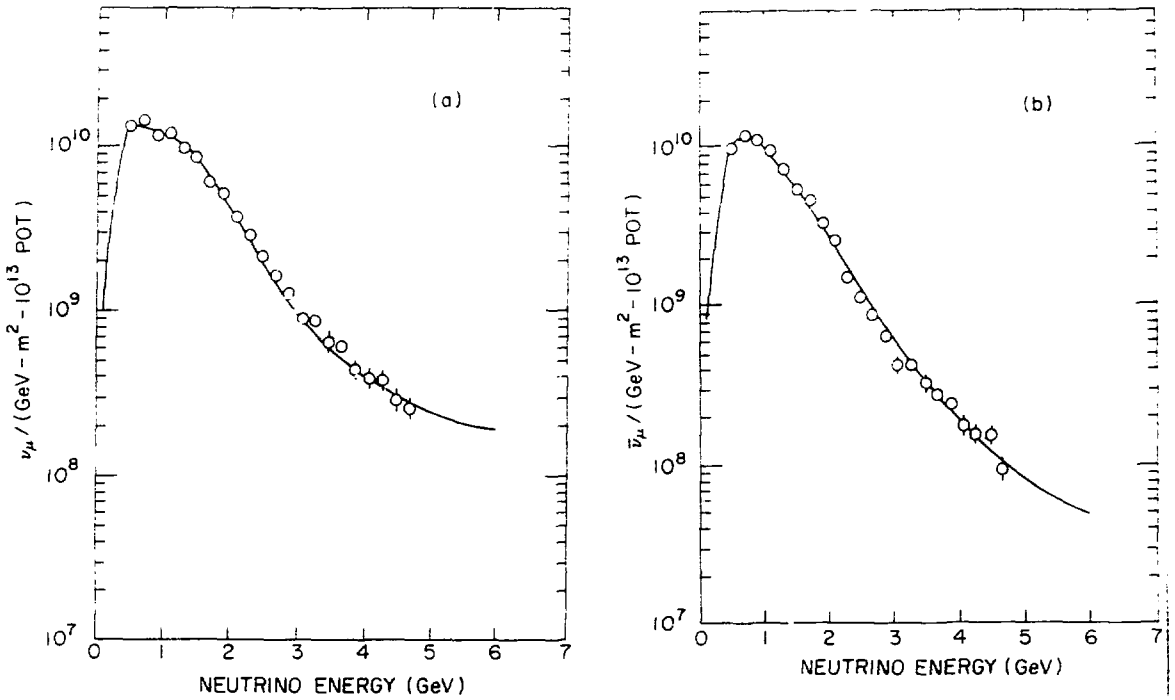


Fig 1. AGS wide band a) neutrino b) antineutrino fluxes. The curves are the result of the NUBEAM Monte Carlo calculation and the data points are from E734.<sup>25</sup>

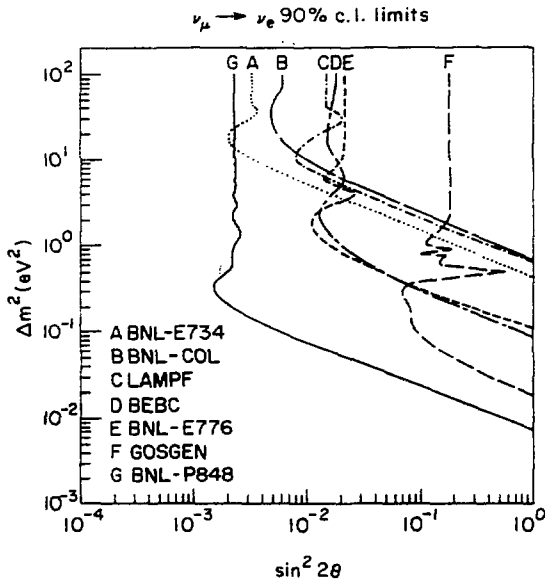


Fig 2. Limits on  $\nu_\mu \rightarrow \nu_e$  oscillations. Curves A-F are for currently existing limits while Curve G is for AGS proposal P848 which is discussed later in the text.

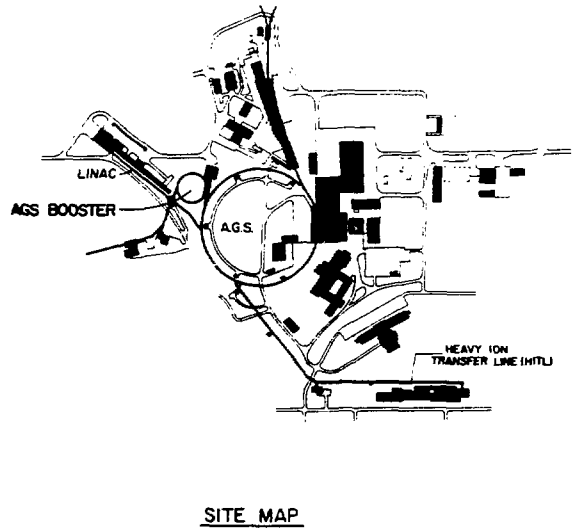


Fig 3. Location of the Booster in the AGS complex.

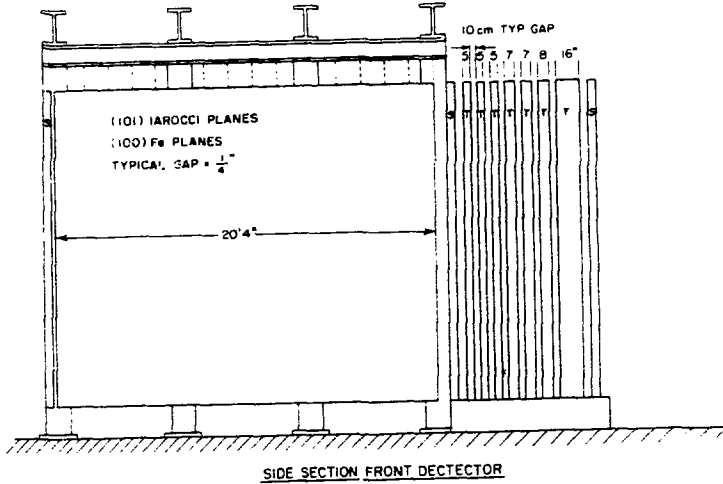


Fig 4. Schematic of the P848 detector.

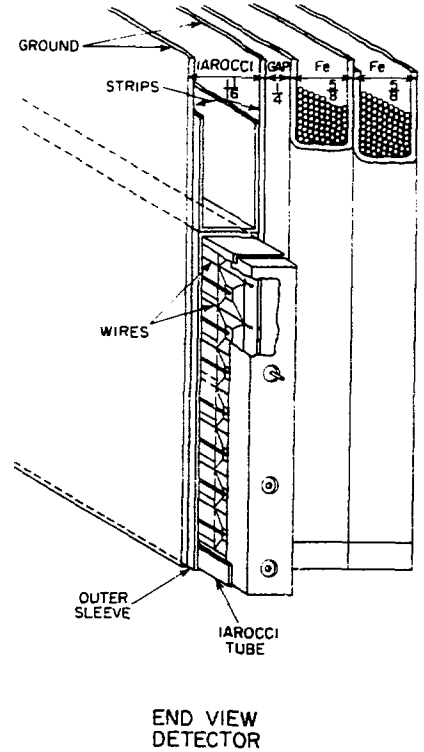


Fig 5. End view of a P848 detector module.

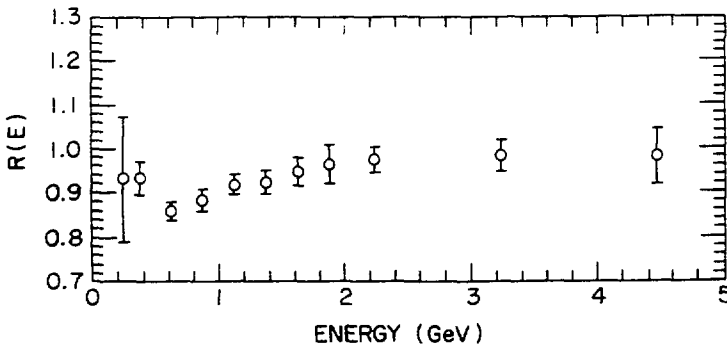


Fig 6. Expected ratio  $R(E)$  of observed quasi-elastic events in the far to near detector for  $\Delta m^2 = 0.03$  and  $\sin^2 2\alpha = 1$ .

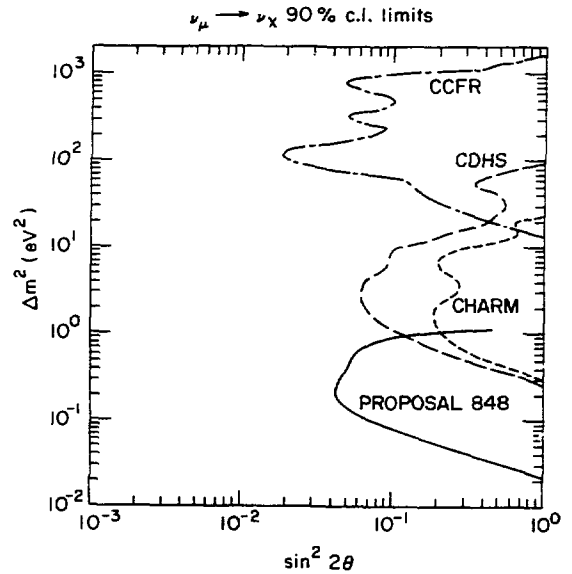


Fig 7. Present oscillation limits for  $\nu_\mu \rightarrow \nu_x$  and the expectations for BNL proposal P848.