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Soudan 2 as a long baseline neutrino detector

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Abstract

In a nine month run with a 150 GeV proton beam and a conventional double horn neutrino beam aimed at the Soudan 2 detector, a search could be made for neutrino oscillations in the mode $\nu_\mu \rightarrow \nu_\tau$. If evidence for oscillations is not found, new limits could be set extending the Δm^2 excluded region from .3 eV^2 to .004 eV^2 at 90% confidence level.

Introduction

Long baseline neutrino oscillation experiment was first suggested in 1977.[1] A sensitive new experiment is considered in this workshop and is motivated by three factors: The possible observation of neutrino oscillations by the Kamioka ν_e/ν_μ ratio,[2] the near completion of the 1 kiloton Soudan 2 nucleon decay detector,[3] and the proposed new injector at Fermilab which could be a source of large neutrino fluxes with relatively low energy.[4]

ν Beam

The present plan for Fermilab neutrino beams from the injector is to use 150 GeV primary energy protons and a double horn similar to the one used by many previous Fermilab wide band beam neutrino experiments. Linda Stutte has run NUADA, the Fermilab neutrino beam generator, for a Soudan 2 sized detector located 810 km from Fermilab. The resulting neutrino flux and event rate are shown as a function of energy in Figures 1 and 2.

Neutrino Oscillations

The probability for a neutrino to oscillate goes as

$$P_{\nu_a \rightarrow \nu_b} = sin^2 2\theta \cdot sin^2(1.27 \cdot \Delta m^2 \cdot \frac{L}{E}) \qquad (1)$$

where L is the distance of flight in kilometers, Δm^2 is in $(eV)^2$ and E in GeV.

If ν_μ's oscillate into ν_τ's, then 82% of them will appear in the Soudan 2 detector as neutral current events. The hadronic showers will be contained in the Soudan 2 detector for at least 50% of the neutrino events. I then assume that Soudan 2 will have 100% separation between neutral current and charged current events. This requires determining the presence or absence of a muon from the main vertex. The granularity of Soudan 2 makes it well suited for such a study. The average event energy will be about 30 GeV, so for most of the y region, this will be true. For very low y, a correction will have to be made for muons which do not come out of the shower. It should be possible to accurately make this correction with the help of a monte carlo.

The assumption is that all of the $\nu_\tau^{\prime}s$ will appear as neutral currents, except the 18%$\tau^- \rightarrow \mu^-$ branching fraction. Thus measurement of the correct ratio, $.31 \pm .01$ is evidence against neutrino oscillations, and measurement of too many neutral current events is evidence for neutrino oscillations. The sensitivity in Δm^2 depends on the distance the beam goes and the

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energy, while the sensitivity to $sin^2(2\theta)$ goes with statistics. For an injector beam with 3×10^{13} protons every 2.9 seconds and 100 hours of beam per week for nine months, Soudan 2 would have 78 analyzable events. The 90% confidence limits we could set in the absence of oscillations are shown in figure 3. Only statistical errors are included.

With an average energy of about 30 GeV, about 5% of ν_τ interactions would be the quasielastic channel $\nu_\tau n \rightarrow \tau^- p$, and in 35% of these, the τ would decay into a single high angle electron or muon. These events would be rather unlikely in the absence of oscillations, and a positive result for ν_τ's in the nc/cc or disappearance part of the experiment should be accompanied by the appropriate number of such events. Our ability to reject hadrons versus electrons at 15GeV should be better than 100 to 1.

Disappearance experiment

There would also be a large number of muons coming in the front of the detector from charged current interactions in the rock. The rate of these muons is

$$n_\mu = 1.0 \times 10^{-12} GeV^{-2} \int_0^\infty dE_\nu E_\nu^2 n(E_\nu) \qquad (2)$$

The two E_ν factors come from the cross section and muon range both proportional to the neutrino energy. In the same running period, with an area of $40m^2$, we would expect 964 muons. Our trigger and reconstruction efficiency should be very high. Only the lowest energy several percent would range out within our detector. With good accelerator timing and angular information, cosmic background will be negligible. Ranging and multiple scattering would give some indication of the energy distribution. However, I have just calculated the neutrino oscillation limits based on the total rate. This is given in figure 3. The accuracy with which one detector can do a ν_μ disappearance experiment depends on the systematic knowledge of the absolute flux. If the flux is known to 5%, the best $sin^2(2\theta)$ limit that could be reached would be .083. The number of neutrino interactions in the detector will help normalize the expected number of upstream μ's.

SSC Beam DUMP

The SSC beam dump is another possible source of neutrinos for long baseline type experiments.[5] The SSC will need two dumps for single turn beam elimination. In principle they could be aimed anywhere. There will be a prompt flux of $\nu's$ from charm decays for the 83 kilometer ring, or 276 microsecond long pulse. Volkova[6] gives the flux of neutrinos per square meter per proton on target from charmed particle decay at a distance from an accelerator:

$$10^{-15}(0.415 log E_p - 1)\frac{10^3 km}{L}^2 E_p \cdot \int_{\frac{E_\nu}{E_p}}^{0.71} (1-x)^{0.4}(\frac{5}{3} - 3x^2 + \frac{4}{3}x^3) x dx dE_\nu \qquad (3)$$

for Λ_c decays and a similar equation from D's. This equation is valid for the "central" region. For the 20 TeV Texas SSC beam with 1.27×10^{14} protons, I calculate the neutrino event rate would be .023 neutrinos interacting in our detector per spill. Using equation 2, we would also have 19 muons from neutrinos interacting in front of the detector. Equation 2 will slightly overestimate the muon flux because muon range is no longer proportional to energy above several TeV. We would see about 1/3 of the muons in one event frame, since we would have about 80 microseconds to see the events. The other 2/3 would be during the deadtime. $\nu_\tau' s$

would be perhaps 1% of the flux, but would not be distinguishable. Based on CDF experience, one might expect about 100-200 dumps per year or a few neutrino events and several thousand muons.

Optimum Distance from FNAL

It may be that a double horn beam is built along the present direction of the neutrino beam line for an emulsion experiment.[7] A natural question would be the optimum distance of a detector for a disappearance type experiment. A comparison for various distances is given in figure 8 for a $40m^2$ detector. These plots show statistical errors only. The true $sin^2(2\theta)$ limit comes from the systematic knowledge of the flux in the beam. If the beam is only known to 5%, the practical limit on $sin^2(2\theta)$ is .083. Thus the best location for a detector would be 1000 kilometers. In fact, the problems of pitching down a neutrino beam and then digging a site for the emulsion experiment would probably dictate the distance of the detector. However the nearness of the proposed Sudbury Neutrino Observation detector to the present neutrino beamline should make that direction a very promising one to aim the beam. The limit which could be set by the $240m^2$ Sudbury detector in a ν_μ disappearance experiment is included in Figure 3.

Conclusion

The Soudan experiment together with a run of the wide band beam at the injector could investigate new regions of the mixing parameter and mass difference in a neutrino oscillation experiment. Other experiments at this conference could do similar experiments, including Lena 1, Lena2, Grande, and IMB. The Sudbury experiment which is located near the direction of the present neutrino beam line, could do a good disappearance experiment, but would not be able to distinguish neutral current and charge current events as Soudan 2 could. A long baseline neutrino oscillation experiment should be on the physics agenda of the Fermilab main injector.

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Figure 1. 150 GeV double horn νflux at Soudan 2

Figure 2. Neutrino event energy spectrum. In a nine month run with the injector, we could expect 156 events, and do neutral current/charged current separation on 78 of them.

Figure 3. 90% CL upper limits which could be set by Soudan 2 in the appearance and disappearance experiments, and by Sudbury in a disappearance experiment.

Figure 4. Statistical sensitivity for a 40 m^2 detector at 4 distances. Systematic effects would limit the closer detectors.

Figure 1
Neutrino Flux at Soudan 2

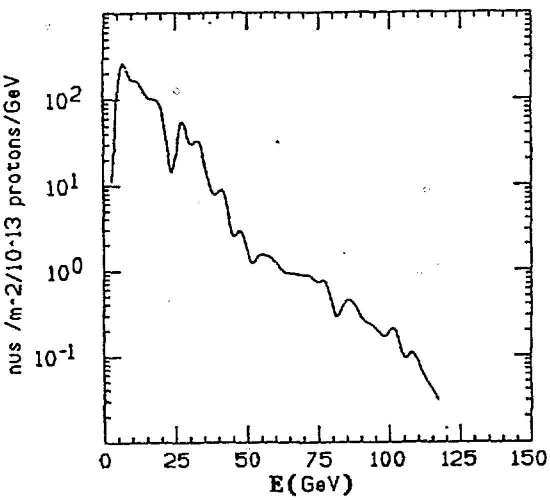

Figure 3
delta m squared limits

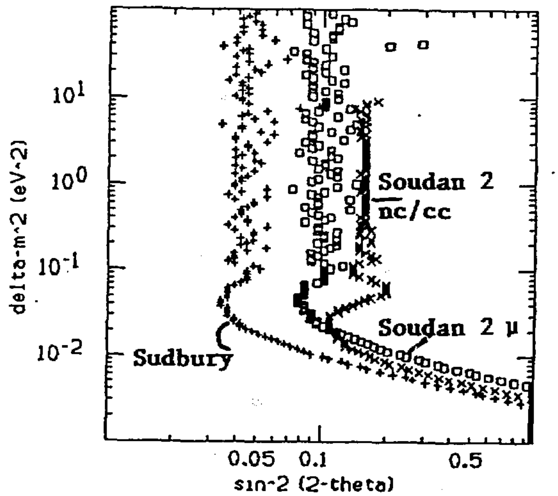

Figure 2
Neutrino Event energy spectrum

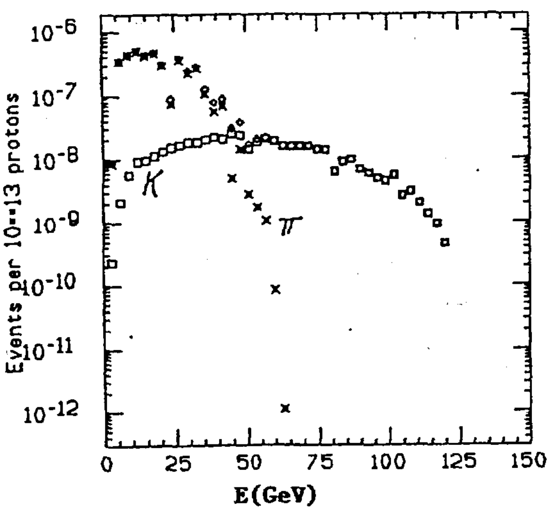

Figure 4
90% CL limits for 10,100,1000,5000 km