Neutrino Oscillation Experiment In DUMAND II employing a Neutrino Beam from the Fermilab 150 GeV Injector

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abstract

It is proposed that a unique neutrino oscillation experiment can be performed employing a new neutrino beam produced by the proposed 150 GeV main injector at Fermilab. DUMAND II, planned for full operation by summer 1993, could observe of the order of 2200 events in a 6 months run. Both contained events (300 NC and CC) and throughgoing muons (1900) would be observed. The contained events give a beam normalization check, while the muon rate would be sensitive to muon neutrino disappearance. The L/E range is unchallenged (6000km/20GeV), and is sensitive to δm^2 down to about 0.001 eV^2. This encompasses possible oscillations from ν_μ to ν_τ, as suggested from recent underground experiments, and from flipped SU(5) models. Such oscillations would result in easily detected deficits of muons (50% of expected flux). It may be possible to discriminate between oscillation to ν_τ versus oscillation to ν_e via the ratio of throughgoing muons to contained events, versus energy.

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Introduction

The idea of using neutrino beams from accelerators to search for neutrino oscillations is not at all new, having been around for 20 years or so, but has recently received renewed interest. One major source of this interest is due to the reported deficit of low energy neutrinos in underground experiments designed to study proton decay. The deficit occurs most prominently in the ratio of μ/e events in the published Kamiokande data[1] in the range of 200 – 700 MeV. This was interpreted in Ref. 2 as possibly due to muon neutrinos oscillating to tau neutrinos, with essentially full mixing and a δm^2 in the range of 0.03 – 0.4 eV^2. The suggestion is bolstered by deficits in both the IMB data and Frejus data (see references in Ref 2) which, while not statistically significant in themselves, do all show less muon events than expected. On the other hand, all these data involve the comparison of the μ/e ratio observed to that calculated, which leaves the concern that the dicrepancy might be simply a problem in calculating the neutrino fluxes and interaction rates.

Further interest in this range of oscillations comes from theory, however, in the flipped SU(5) model of Nanopoulos et al.[3], which yields masses in exactly this range. One need hardly take more space pointing out the physics value of such measurements.

It is quite difficult to probe the range around δm^2 of 0.001– 0.1 eV^2. In terms of distance divided by energy, the oscillations depend upon $\sin^2(1.27(\delta m/eV)^2(L/km)/(E/GeV))$, and the value of L/E suggested by the Kamiokande data is > 24 km/GeV. One sees that on–site accelerator experiments are not practical, while long distance experiments have been limited by inadequate flux. As we shall see, the proposed injector can give a remarkably good signal in DUMAND at a distance of about 6000 km. With an effective beam energy peaking around 30 GeV, the $L/E \cong 200$ km/GeV to DUMAND gets into a new region of sensitivity, down to a $\delta m^2 = 0.001$ eV^2. This goes ten times further than the exploration possible with IMB or other relatively nearby detectors.

One may ask why this range cannot be explored with cosmic ray neutrino fluxes. The answer is that the underground and underwater experiments measuring muon flux versus zenith angle have difficulty exploring this range because of the problem of contamination of the event sample near the horizon by scattered or misfit downgoing muons. A second limitation is simply due to statistics (the total world collection of underground upcoming muons from cosmic ray neutrinos is about 1000 events at present, from the entire lower hemisphere). DUMAND can in fact (uniquely) explore the near horizontal region in zenith angle [4], but the cosmic ray neutrino induced muon flux in the near horizontal direction is dominated by 100 GeV neutrinos, whereas with the accelerator beam we can explore a region with about 1/10 the mean of the cosmic ray neutrino energy. Moreover, as usual, having a beam of known energy spectrum, direction, and timing gives a much cleaner measurement than using the cosmic rays.

And, if an effect should be observed, it can be easily followed up by modifying beam conditions in order to resolve the oscillation parameters.

Experiment

The Fermilab NUADA program was employed to estimate the neutrino flux at IMB, in runs made by Linda Stutte. The results are shown in column 2 of Table I, showing the event rate per 2.5 GeV bin, scaled to the 2×10^6 ton contained event volume of DUMAND II. The run assumed a two horn configuration, 400 m decay tunnel and 150 GeV protons. We assume a beam of 3×10^{13} protons per pulse at a rep rate of 20 pulses per minute for 100 useful hours per week, over a 6 months run, and a flux of 70% of the program calculation. The NUADA program calculated interaction rate was also corrected for neutral current events and applies to the total visible energy (from Cherenkov radiating particles). While the assumption of a dedicated 6 month run is surely optimistic, dividing the beam 3 ways over the same period still leaves us with a healthy total of >700 events.

The beam from Fermilab (location 42^o N, 88^o W) would have to be pointed downwards, 29.5^o below the horizon, 1.7^o North of West to intersect the DUMAND site (19^o N, 153^o W). The Neutrinos would arrive, coming upwards at a zenith angle of 119.5^o. This is close to the zenith angle for maximum effective area for DUMAND II (26,000 m^2), for muons of greater than 20 GeV. The distance from Fermilab to DUMAND II along a cord of the earth is 6283 km (59^o along a great circle). The beam spot radius at DUMAND would be about 10 km from π decay and 80 km from K decay, at 20 GeV initial energy. The pointing precision of previous Fermilab beams has been less than 1/10 of the spot size. We thus anticipate no problem in targeting the DUMAND II detector, though care is certainly required.

Fermilab beam monitoring would employ traditional techniques, and could be accomplished to at least ±15%. A more precise monitoring would employ the ratio of throughgoing muons to contained events, as discussed below. Limitations due to systematic errors need study, but we estimate them to be similar to the statistical errors below.

We have not yet employed the Monte Carlo program to study the trigger threshold of DUMAND II for these relatively low energy contained interactions (the DUMAND design was optimized for through going muons). However, we estimate that sufficient light will be generated for high efficiency to be achieved for <50 GeV. Initially the importance of the detection of contained events is mainly as a beam monitor, giving a check that the surveying is correct and that flux calculations at least approximately accurate. A threshold of 50 GeV for contained events would yield, according to Table I, 300 events in a 6 month run, for roughly a 6% beam normalization (statistical). Note that the contained events would include neutral current (NC) and charged current (CC) interactions, including those from τ's, if oscillations are significant.

For fast extraction, the background counting rate in DUMAND II drops by at least 10^3, and if one employs RF structure, perhaps much more. Since we expect a total of 3600 cosmic ray neutrino induced muons per year in DUMAND II from the entire lower hemisphere, the number coming from within 1° of the direction of Fermilab, and within the few millisecond spill time (duty factor of order 10^{-3}), is completely negligible. The background for contained events from the Fermilab beam, for which we do not yet know the angular resolu:ion, will be larger. The background due to cosmic ray neutrino interactions within DUMAND II will be small, but we must look at the background induced by cosmic ray muons.

The use of a common time reference from the Global Positioning System can give us relative times to the nanosecond level.

The physics would come from the measurement of the throughgoing muon rate, which is presented in Table I, in columns 4 and 5. Again, while we need to study the details with the Monte Carlo program, it is clear that since 20 GeV is needed for a muon to traverse DUMAND in the near horizontal direction, we can expect a signal at the level of 1900 events in the proposed run. Oscillations at the level suggested by the Kamioka data would manifest themselves in a 50% deficit in this number, which would be obvious after a run of only one week. The integral fluxes from Table I are plotted in Figure I.

If a deficit is seen in the muon rate, then we must seek to discriminate between the possibilities of oscillation to ν_e or ν_τ. DUMAND II would not have much chance to observe τ production directly, but would count τ events along with the other contained ν events (CC and NC). If the oscillation is to ν_τ, then not only will the the muon flux will be depleted, but the contained event rate will be somewhat depleted due to the reduced ν_τ crossection, especially at the lower energies (eg. 30% at 50 GeV). The other case, of oscillation to ν_e, would not suffer that deficit. Depending upon the value of δm^2, however, matter oscillations could complicate the situation. It remains to do detailed Monte Carlo studies of these different cases to determine the extent of the capability of DUMAND II to resolve the situation.

Conclusions

We have taken a quick look at the potential for detecting neutrinos from the proposed Fermilab 150 GeV injector in DUMAND II and find, remarkably, that the muon neutrino signal would be eminently detectable. The experiment would cleanly probe a unique region in δm^2 a factor of >100 below present accelerator based limits, down to about 0.001 eV^2, and could cleanly detect the presence of oscillations causing muon neutrino disappearance.

If signals of oscillation are detected then various measures may be taken to discriminate between oscillation to electron or tau neutrinos, but more work is needed by the DUMAND Collaboration to determine the limits of sensitivity.

It may also be that the potential distance measurement (to about 1 m), via time of flight, may have interest for geodesy. Certainly the calibration of DUMAND II survey and event angle reconstruction would be of great use as well.

The biggest technical problems seem to be the cost of the 30 degree downward bend, and the decay pipe required to send neutrinos towards DUMAND. There may also be environmental concerns about the beam dumping in the ground water, which concerns need exploration.

Followup experiments with DUMAND could be considered in which the beam conditions are varied and/or lower energy sensitivity could be optimized in the detector via increased phototube density. In a more fine grained detector one could discriminate between hadronic and electromagnetic showers in order to pin down the source of oscillation (by carrying out a ν_e appearance experiment).

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References

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Table I

Neutrino Rates in DUMAND II from proposed Fermilab 150 GeV Injector for hypothetical 6 months run. Columns 2 and 3 are for events contained in DUMAND. "Integ rate" means Integral of rate above that energy. Stated energy is in middle of bin. For contained events it represents visible energy. The last two columns show the expected rate of muons with at least that energy at entering surface of the DUMAND array.

Energy GeV	Cont Evt Rate /2.5 GeV	Integ C E Rate	μ Rate /2.5 GeV	Integ μ Rate
1.25	1975.8	12430.1	89.2	4435.1
3.75	1499.6	10454.3	237.4	4345.9
6.25	1261.3	8954.7	337.2	4108.5
8.75	1115.1	7693.4	389.5	3771.3
11.25	982.8	6578.2	406.0	3381.8
13.75	822.8	5595.4	401.3	2975.8
16.25	947.3	4772.6	365.2	2574.5
18.75	537.3	3825.3	322.1	2209.3
21.25	627.1	3288.0	288.3	1887.2
23.75	449.5	2660.9	246.0	1598.9
26.25	268.6	2211.4	222.5	1352.9
28.75	324.7	1942.8	200.9	1130.4
31.25	483.2	1618.1	157.2	929.5
33.75	228.7	1134.8	112.6	772.2
36.25	138.7	906.2	93.7	659.6
38.75	193.5	767.5	74.5	565.9
41.25	113.3	574.0	55.2	491.5
43.75	47.8	460.7	46.6	436.3
46.25	53.2	412.9	42.1	389.6
48.75	32.0	359.7	38.1	347.6
51.25	26.8	327.8	36.2	309.5
53.75	26.4	301.0	34.1	273.3
56.25	30.0	274.6	31.7	239.2
58.75	25.3	244.6	29.0	207.5
61.25	24.9	219.3	26.3	178.5
63.75	24.3	194.4	23.7	152.2
66.25	17.1	170.1	21.7	128.5
68.75	19.6	153.1	19.6	106.8
71.25	21.7	133.4	17.0	87.2
73.75	17.2	111.7	14.5	70.2
76.25	17.0	94.5	12.2	55.7
78.75	10.5	77.6	10.5	43.5
81.25	13.6	67.0	8.9	33.0
83.75	9.6	53.4	7.3	24.1
86.25	11.9	43.8	5.6	16.8
88.75	8.2	31.8	4.2	11.2
91.25	6.8	23.6	3.2	6.9
93.75	6.3	16.7	2.1	3.8
96.25	5.4	10.4	1.2	1.6
98.75	5.0	5.0	0.4	0.4

Figure 1

Integral neutrino event rate in DUMAND II versus energy. Solid line: number of muons with more than that energy at the surface of DUMAND II. Dashed line: contained events versus total visible energy. Numbers are for hypothetical 6 month run with 3×10^{13} PPP, a 20 PPM rep rate, a 400 m decay tunnel, and two horn focussing.