Fermi National Accelerator Laboratory

FERMILAB-Pub-95/365
Revised

Long Baseline Neutrino Beams

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May 1996

Submitted to *World Scientific* & Contributed to the *Fourth School on Non-Accelerator Particle Astrophysics*, Triest, Italy.

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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ABSTRACT

Several programs are underway to construct long baseline neutrino beams from accelerators for experiments to study neutrino mixing and mass differences. Such programs require an intense proton beam extracted from an accelerator, a deflector to point it in the right direction, a target to make mesons, a meson decay pipe to produce the neutrinos, and a large neutrino detector. Channeling offers a technique to extract and direct such beams but long crystals are required and the bend angles result in substantial dechanneling. While such arrangements are thinkable they are far in the future.

1. Introduction

Tantalizing hints of neutrino oscillations come from several different types of measurements. Solar neutrinos with energies in the MeV range[1] suggest the possibility of neutrino oscillations in the Δm^2 region of 10^{-5} eV^2. The atmospheric muon deficit gives a hint of a problem in the 10^{-2} eV^2 Δm^2 regime[2]. The exploitation of long baseline neutrino beams from accelerators will open a wider window on the question of neutrino mass differences. If some of the other hints develop further, there may still be a spectrum of mass differences. If the other hints disappear, this window will continue to need to be explored.

A long baseline neutrino beam is now in the design stage at Fermilab. It will be generated by the intense 120 GeV proton beam from the new Main Injector that will go into operation in several years. There will be an on-site detector as well as a 10 kton off-site detector at the Soudan mine in Minnesota. A similar program is also under discussion at CERN with an off-site detector at Gran Sasso. A neutrino beam from KEK to Super Kamiokande is also planned.

Neutrino mass difference studies are not the only applications that have been suggested for long baseline neutrino beams. In the eighties, DeRujula, Glashow, Wilson, and Charpak[3] proposed an approach they called "GEOSCAN" to do neutrino tomography of the earth. They suggested sending neutrino beams through the center of the earth. In another scheme they suggested using neutrino beams to explore for oil. Others have even discussed using neutrino beams for communications[4].

Long baseline neutrino beams could be used to good effect. The principal problem in using them is that the neutrino interaction cross section is small so that detectors must be very large and beams must be intense.

Electron accelerators are not satisfactory sources since pion (and neutrino) yields are small. Reactors also provide omni-directional sources of MeV-scale electron neutrinos. Several middle range reactor neutrino beam experiments have been proposed such as Chooz (5 tons of gadolinium loaded liquid scintillator 1 Km from a pair of new French reactors) and a group working at the San Onofre reactor in California[5]. These reactor experiments require new detector facilities and are not discussed further.

2. Accelerator Neutrino Beams

A typical neutrino beam is created by first using a proton beam to produce a large flux of pions (and kaons) and then letting these mesons decay into muons and neutrinos. Since the pion total energy is typically many times its mass the mean life in the laboratory is much longer and adequate distance must be provided for the pion to decay.

A number of elements are required to produce and use a neutrino beam (Figure 1). First there must be a high energy accelerator that can accelerate a large number of protons and extract them on to a production target to produce a high interaction rate. Since target interaction rate is important, parasitic use of the circulating beam in a collider will produce far fewer neutrinos. Energy may be less important. The linear rise in the neutrino cross section with energy is somewhat offset by the need to accelerate protons for a longer time as well as other factors. In the end, the physics topic dictates the beam energy.

Next the proton beam must be extracted from the accelerator. This may require the dedication of a large segment of the accelerator lattice for complex extraction gear. After extraction, the proton beam must be transported to the production target and aimed in the direction the neutrino beam is to go. The beam transport problem can be particularly challenging. A curved tunnel arching in the vertical plane is difficult to construct. In short order it is well below grade. For detectors located on the order of 1000 km away the beam has to be bent down 100 milliradians, comparable to the angles that proton beams are characteristically deflected horizontally. For a detector in the 10,000 km range the deflection angle is on the order of a radian so that one needs about one sixth of an entire accelerator magnet lattice to deflect the beam.

Typically the beam interacts with a one interaction length target. Following that, some focusing device such as a quadrupole system or a current horn gathers the pion flux. Bending magnets may be used to select only one pion polarity and thereby either neutrinos or antineutrinos.

The next element in the beam is a long decay space for the pion decay. For the planned Fermilab Main Injector neutrino beam the decay path is 800 m long. At the end of the decay path there is a beam dump for the protons that have not interacted. Characteristically this is a massive, complex system that must completely contain the radioactivity produced by the intense proton beam. Only muons (and neutrinos) escape the hadron dump. A long muon shield is required to range out the muon if the neutrino beam is at ground level. The range of a 100 GeV muon is on the order of 100 m.

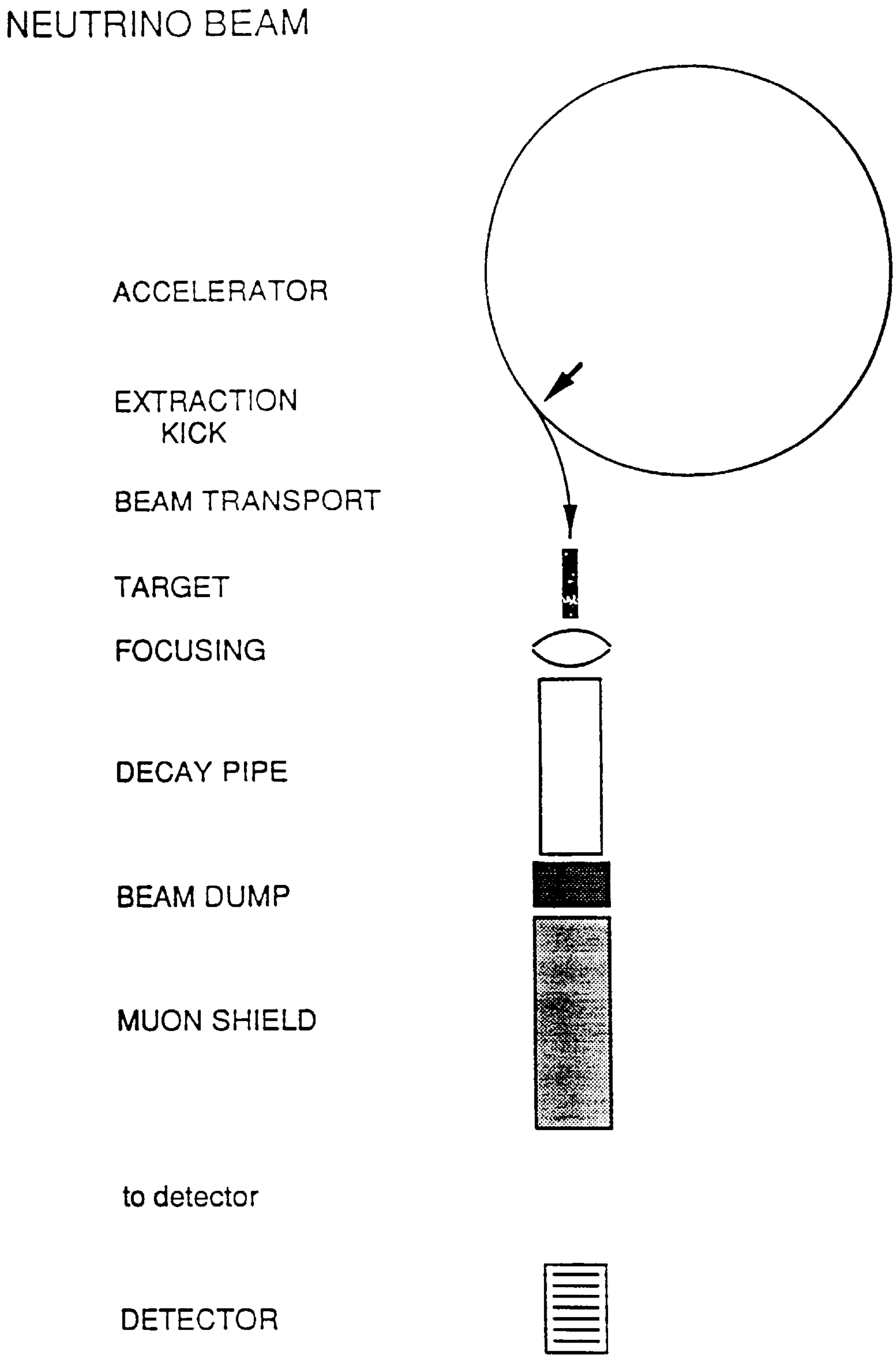

Figure 1 Principal elements in a neutrino beam.

Finally, there must be some detector to observe the neutrino interactions. Sophisticated mass difference experiments have both a near and a far detector. Charge current events are tagged by very energetic, forward going muons. Neutral current events have hadronic showers that are on the order of one interaction length long. Since neutrino cross sections are low. these detectors must be very large to get useful interaction rates. Bernstein[6] suggests a rule of thumb (modified and updated here to give the total event rate) useful for simple estimates of the number of neutrino events from the Fermilab Main Injector with $2 \cdot 10^{20}$ protons on target:

$$N = 2700 \cdot M \cdot \left(\frac{600}{L}\right)^2$$

where M is the mass of the detector in kilo-tons and L is the distance in km.

Other approaches are available to produce neutrino beams with accelerators. Short-lived particles with neutrino decays do not require long decay paths so that the detector can be placed close to the production target. Charm, bottom and τ particles are suitable candidates. E-872 at Fermilab and CHORUS at CERN plan to exploit this to look for ν_τ production of τs. This same approach could be used to study neutrino processes produced by neutrinos from colliding beam interactions. At present energies the charm production cross sections are in the microbarn regime. At higher energies (eg LHC) the cross section should increase. CERN has recently examined the neutrino production rates from LHC[7]. They are still small in comparison to fixed target beams but could possibly be relevant for τ studies and for short baseline situations.

A second possibility is to produce mesons quasi-parasitically via interactions with collimators, beam dumps, and gas or flying wire targets in colliders. In general the problem is that there will be too few interactions in comparison to a dedicated fixed target run.

Finally, omni-directional fluxes can be produced by stopping pions in a target. This is one of the techniques used to produce neutrino beams at the Los Alamos Meson Facility and the Rutherford-Appleton Laboratory (KARMEN). The energy range of muon anti-neutrinos from stopped pion decays is 36 to 53 MeV.

3. Detectors for Long Baseline Neutrino Physics

The tool kit for a long baseline neutrino experiment requires a proton accelerator with neutrino beam facilities and at least one neutrino detector. Characteristically, sophisticated mass difference experiments have both a near and a far detector.

Detector sensitivity to accelerator neutrinos is a complex function of several factors. If there is a requirement for the interaction vertex to be contained within the detector, the fiducial tonnage is important. For detection of neutral current events this would generally be required. However charged current events originating outside of the detector can also be observed. In that case the detection efficiency is larger but more uncertain. A number of experiments have looked at cosmic ray neutrinos using this approach. Finally, background from cosmic rays can be important. However the background problem in detecting accelerator-generated neutrinos is somewhat mitigated by timing considerations. Neutrino beams can employ fast extraction so that beam pulse length can easily be kept below 10 microseconds per acceleration cycle.

Indeed, absolute knowledge of muon neutrino time of flight raises the possibility of a direct determination of the neutrino mass by measuring the velocity and energy. For example, looking at 1 GeV neutrinos (challenging) from the Fermilab Main Injector with 1 ns timing (extremely optimistic) could set a υ_μ mass limit on the order of 1 MeV. Other experiments on π^+ decays at rest already give lower mass limits than this[8]. However lower energy accelerators such as KEK should consider measuring this.

Existing detectors include a number of large operating cosmic ray and proton decay complexes scattered around the globe[9]. Some of these are very large omni-directional Cerenkov counters (Kamiokande, Lake Baikal, DUMAND, and AMANDA). Others are mixed scintillator-tracking chamber facilities, often with the detector planes oriented horizontally to observe vertical cosmic rays. Such complexes include Soudan in the US (Minnesota) and MACRO in Italy (Gran Sasso). Other detectors are well into planning or construction stages such as ICARUS, a liquid argon chamber at Gran Sasso, NESTOR, a water Cerenkov counter (near Greece in the Mediterranean), and the Sudbury heavy water Cerenkov counter in Canada (SNO).

Kamiokande and Super Kamiokande are two giant water Cerenkov Counters near each other in Japan. They are 250 Km from the 12 GeV KEK proton synchrotron at Tsukuba. Super Kamiokande will have a mass of 50 ktons. A fifty GeV proton synchrotron may be built at KEK in the future.

The Gran Sasso National Laboratory in Italy lies about 750 Km southeast of CERN approximately in the direction of one of the SPS to LHC injection lines. ICARUS, a large liquid argon digital ionization chamber, is in the pre-approval stage at Gran Sasso. It will have a mass of 0.6 ktons but additional modules could be installed later.

Soudan is a 1.1 kton detector located in Minnesota 730 Km from Fermilab at a depth of 2090 m water equivalent[10]. The Soudan site will be used for MINOS, the planned Fermilab long baseline neutrino experiment. A new neutrino line pointing toward Soudan will be constructed off the Main Injector. A new detector will also be constructed. A short baseline detector will be built on the Fermilab site for comparative oscillations studies.

Several other interesting giant detectors are not in the fields of view of any neutrino beams that have been discussed so far. One is DUMAND. DUMAND is a water Cerenkov counter located in the Pacific near the Hawaiian Islands. In the near term it will consist of three strings of photo-multipliers lowered into the ocean to a depth of 4.8 Km. The detector is intended for TeV-scale cosmic neutrino investigations. The experimenters are now trying to bring the first string into operation. For the estimates below, DUMAND is assumed to have a mass of 10^3 ktons. A similar detector is in an early stage of operation at Lake Baikal.

AMANDA is a fourth large scale Cerenkov counter at the South Pole. It uses polar ice as a Cerenkov medium. One string of phototubes has been placed in operation. The ice in the polar ice cap is surprisingly clear so that optical transmission distances are large. The ice cap above the detector strings is thin by the standards of these detectors so that background could be a problem. For the estimates below, AMANDA is assumed to have a mass of 10^4 ktons.

4. Long Baseline Beams, Planned and Possible

Serious proposals for long baseline neutrino beams have been discussed at KEK in Japan, the CERN complex in Switzerland/ France, and the Fermilab Main Injector in the US. Several other accelerators are also potential sources. DESY in Germany operates a proton storage ring, HERA, that is quite similar to the Fermilab accelerator. No neutrino beams have been considered for the facility. The Serpukhov accelerator in Russia is another candidate facility. Ultimately the 7 TeV LHC at CERN could be used although there are no plans at present to extract the beam. Finally, the proton linac at the Los Alamos Meson Facility should also be mentioned. While the accelerator energy is only 800 MeV, the proton beam current is extremely high.

The KEK long baseline program will have three detectors on the 250 Km line to Super Kamiokande. In addition to Super Kamiokande with a 22 kton fiducial volume for accelerator neutrinos there will be a 1.7 kton detector 0.5 Km from the source and an intermediate detector 25 Km away. A 95° deflection of the accelerator beam is required to point it toward Super Kamiokande. The average energy of the neutrino beam will be 1.4 GeV. Super Kamiokande will record hundreds of events for 10^{20} protons on target and a 0.5 Km pion decay path.

At Fermilab the MINOS program will have two detectors, a near detector on the Fermilab site with a mass of O(.1 kton) and a new 10 kton far detector at the Soudan mine. Figure 2 shows the path of the beam on the Fermilab site and the overall path to Minnesota. The dip angle is 64 mrad. As a result of the dip, the near detector is nearly 300 feet below grade. The 120 GeV proton beam produces a neutrino beam with an average energy of about 10 GeV. The pion decay pipe is 0.8 Km long while the muon shield before the near detector is 0.16 Km. A six months exposure of $2 \cdot 10^{20}$ would produce 18,000 events at the far detector. The projected neutrino event rates for a Fermilab 120 GeV proton beam exposure of $2 \cdot 10^{20}$ to Soudan and several other detectors at different distances are shown in Figure 3.

The long baseline program at CERN is still evolving. A number of neutrino sources have been examined[7]. The most promising possibility is to point a 450 GeV beam from the SPS in the direction of Gran Sasso 732 Km away. Using the SPS, it would be possible to have protons with energies up to 450 GeV giving neutrinos with an average energy of 50 GeV, albeit at the expense of cycle time. The dip angle for Gran Sasso is 58 mrad. For a 450 GeV exposure of 10^{19} protons and a 1 Km pion decay path about a thousand events are expected per kton. The most interesting neutrino detector proposed so far for Gran Sasso is the 0.6 kton ICARUS module. To be competitive with Soudan five to ten modules will be needed.

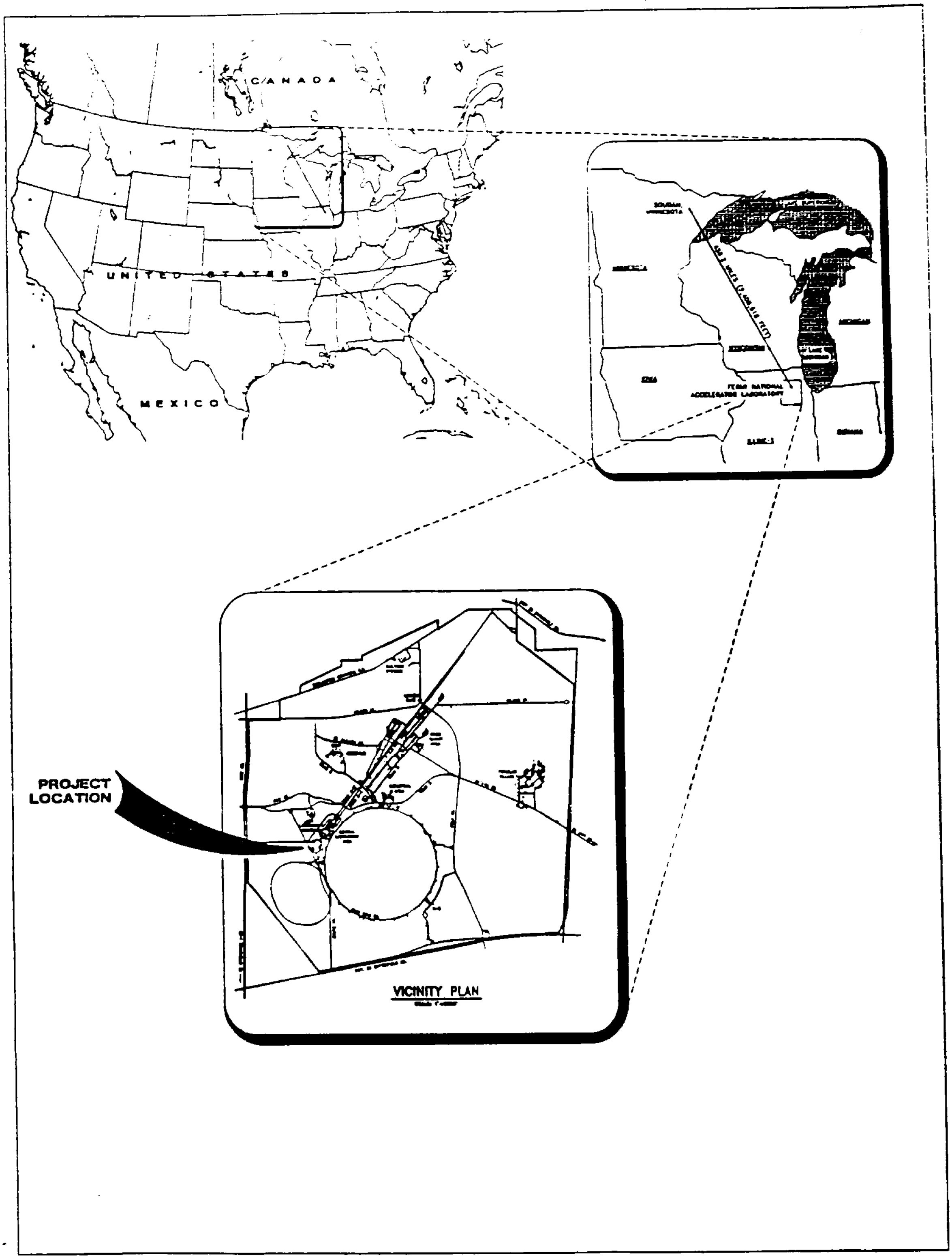

Figure 2 Fermilab neutrino beam to the Soudan detector in Minnesota.

Clearly, if a neutrino beam is pointing toward a multi-kton detector a thousand kilometers away, many thousand event samples can be obtained. Going to the other sideof the globe, ten thousand kilometers away, requires million ton detectors. Such detectors are already being implemented. The next problem is to point a neutrino beam in the direction of the detector.

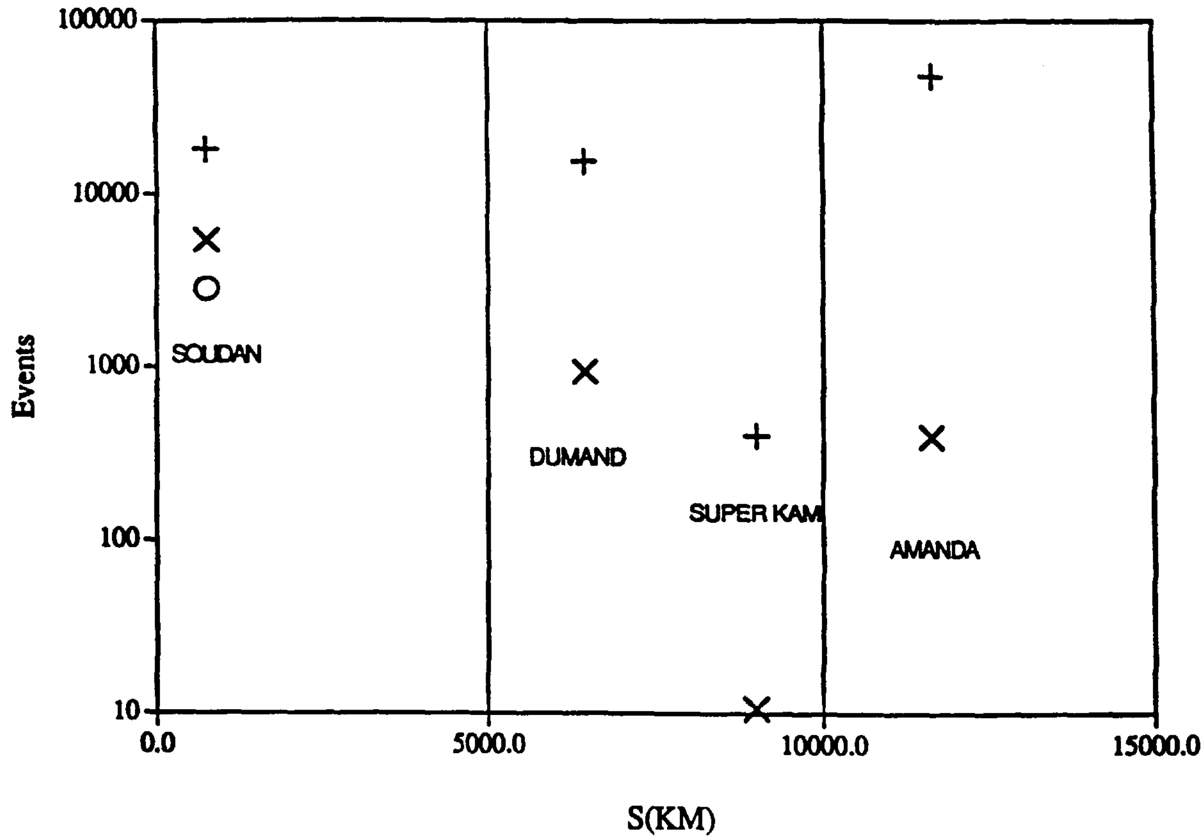

Figure 3 Neutrino event rates for a 120 GeV beam from Fermilab for a conventional beam (+), a germanium septum (O) and a tungsten septum (X).

5. Channeling

When a positively-charged particle moves through a crystal close to a plane or an axis, it is channeled[11]. For an angle smaller than the so-called critical angle the particle glides back and forth between the planes, repelled by the higher positive charge density near the nuclear centers. The critical angle is small, about 5 microradians at 1000 Gev, so that the angular acceptance for channeling is small.

Down to a certain radius of curvature, the Tsyganov radius, a channeled particle in a bent crystal follows the bend. In the extreme relativistic limit the Tsyganov radius is:

$$R_T = pc/(eE_c) \tag{2}$$

where p is the particle momentum, e is the charge of the electron, and E_c is the critical field at which the particle no longer channels. In practical experiments the radius of curvature must be several times larger than the Tsyganov radius to avoid significant de-channeling.

Bent crystal channeling could solve two of the major problems associated with long baseline neutrino beams. One problem is extraction from colliders not equipped for extraction such as HERA and LHC. Another is beam deflection into directions not easily served by existing extracted beam lines. Sun and others[12] looked at the problem of extraction for the SSC and suggested the approach of using a crystal-channeling septum. Such crystal septa using silicon crystals have now been demonstrated at a number of accelerators[13,14,15]. The highest energy so far achieved is 900 GeV at Fermilab[16].

There are several new problems associated with crystal septa, namely low beam transmission and the need for long crystals. The low transmission leads to the need for more accelerator beam time. The low beam transmission is due to dechanneling and the small phase space admittance for particle beams. The limited phase space results from the fact that particles at angles greater than the critical angle do not channel.

Crystals up to 15 cm long have been used at Serpukhov and beams have been deflected as much as 130 mrad. Silicon crystals have generally been used since large, high quality crystals are available. Tests suggest there should be little degradation in bending properties due to radiation damage up to fluences of $4 \cdot 10^{20}/cm^2$ before significant increases in the dechanneling occur.

The transmission of a bent crystal septum used for extraction can be approximated by[11]:

$$E_a = E_e\left(1-\frac{p}{3R_m}\right)e^{(-sp_0/\lambda_0 p)} \tag{3}$$

In the formula E_e is the accelerator extraction efficiency, R_m is the minimum radius of bend in cm, p is the beam momentum in GeV/c, s is the length of the crystal, and λ_0 is the bent crystal dechanneling length at p_0. The dechanneling length is reasonably well established for silicon[17]. In what follows the Si(111) mean dechanneling length is taken as 11 cm at 100 GeV for a beam that is uniform over the channel. This value is extrapolated to other materials. To account for the decreased channeling length in a bent crystal[18] the dechanneling length for the straight crystal case is multiplied by $(1-p/3R_m)^2$. A uniform crystal bend is assumed here.

For accelerator extraction, a circulating particle that is not channeled often remains in the machine and is channeled on a later pass. This multiple turn extraction[19] leads to a higher overall efficiency for channeling extraction. Understanding of multiple term extraction efficiency is still in a nascent stage. Recent CERN measurements[15] at 120 GeV in an accelerator configuration not tailored for crystal extraction give E_e on the order of 10%. Fermilab has observed extraction at 900 GeV but no efficiency measurements have been reported yet. For these calculations E_e is assumed to be 0.5 independent of energy.

To provide some sense of the effect of using different elements Table 1 gives the extraction transmission and septum length for three different crystals at 120, 900, and 7000 GeV for 64 mrad (Soudan for Fermilab) and 540 mrad (DUMAND). Figure 3 shows the neutrino event rates from the Fermilab Main Injector that could be expected at several detectors using a germanium crystal and a tungsten crystal. Proton exposures of $2 \cdot 10^{20}$ for 120 GeV were assumed. The direct event rate is also shown assuming a normal 120 GeV beam could be pointed in the direction of the detector. The detector masses that have been assumed have been noted earlier (10 ktons is assumed for Soudan). Some of these are quite optimistic.

Table 1 Extraction Transmissions (T, %) and Length (L, cm) for Different Crystals and Energies

Energy (GeV)	Crys Z	Si 14	Ge 32	W 74
Def. Ang. = 64 mrad				
120	E_a	8.8%	15.8%	30.3%
	L	9.7	5.4	2.3
900	E_a	9.4%	16.9%	32.0%
	L	73.0	38.4	16.3
7000	E_a	9.5%	17.0%	32.2%
	L	567	298	127
Def. Ang. = 540 mrad				
120	E_a	0.0%	0.06%	6.0%
	L	67.8	32.3	9.85
900	E_a	0.0%	0.07%	6.5%
	L	477	242	73.8
7000	E_a	0.0%	0.07%	6.6%
	L	3710	1880	574

6. Conclusions

During the next decade one or more neutrino beams in the 1000 Km range will come into operation. Thousand kton detectors will operate for neutrino astrophysics. Most of these are at distances on the order of 10,000 Km from a major accelerator. Because of their size, they should be able to record significant numbers of accelerator produced events provided a neutrino beam can be pointed at them. Bent crystal channeling may offer a method to do this although it suffers from a serious problem of beam attenuation. Other techniques may appear. We should keep an open mind on the possibilities.

7. Acknowledgements

Fermilab is operated by Universities Research Associations, Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy.

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