Fermi National Accelerator Laboratory

FERMILAB-Pub-95/366
Revised

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May 1996

Submitted to *Nuclear Instruments & Methods*

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

COULD BENT CRYSTALS BE USED TO CONSTRUCT LONG BASELINE NEUTRINO BEAMS?

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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. However long crystals of germanium or tungsten would be required in most cases. The necessary bend angles would result in substantial dechanneling. While such arrangements are thinkable they are far in the future.

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 kilo-ton 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.

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.

The remainder of this article reviews the rudiments of accelerator neutrino beams, detectors for long baseline beams, plans for neutrino beams, and the possibility of applying channeling to primary beams used to generate neutrinos.

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 of the pion 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 (see 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 is less important than a large flux. The linear rise in the neutrino cross section with energy is offset by the need to accelerate protons for a longer time to get to higher energy. That requirement results in a longer accelerator ramp. In the end, the physics topic will dictate 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 equipment. 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 tunnel curving in the vertical plane is difficult to construct. In a short distance it is well below the surface of the earth. 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 and other particles produced in the target. Characteristically this is a massive, complex system that must completely contain the radioactivity produced by the intense beam. Only muons (and neutrinos) escape the 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.

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[3] 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:

$$N = 2700 \cdot M \cdot \left(\frac{600}{L}\right)^2 \qquad (1)$$

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

Detectors for Long Baseline Neutrino Physics

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 mass 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.

Existing detectors include a number of large operating cosmic ray and proton decay complexes scattered around the globe[4]. 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 kilo-tons. 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 kilo-tons but additional modules could be installed later.

Soudan is a 1.1 kilo-ton detector located in Minnesota 730 Km from Fermilab at a depth of 2090 m water equivalent[5]. 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 near the beam direction 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 kilo-tons. 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 kilo-tons.

Long Baseline Beams, Planned and Possible

Serious proposals for long baseline neutrino beams have been discussed for 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 kilo-ton fiducial volume for accelerator neutrinos there will be a 1.7 kilo-ton 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(0.1 kilo-ton) and a new 10 kilo-ton far detector at the Soudan mine in

Minnesota. The dip angle for the Fermilab-Soudan chord is 64 mrad. As a result of the dip, the near detector on the Fermilab site is nearly 300 feet below ground. The 120 proton GeV 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 in Minnesota. 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 4.

The long baseline program at CERN is still evolving. A number of neutrino sources have been examined[6]. 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, although at the expense of cycle time compared to the Fermilab Main Injector. 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 kilo-ton. The most interesting neutrino detector proposed so far for Gran Sasso is the 0.6 kilo-ton ICARUS module. To be competitive with Soudan five to ten modules will be needed.

Clearly, if a neutrino beam is pointing toward a multi kilo-ton detector a thousand kilometers away, many-thousand event samples can be obtained. As noted in equation (2), counting rates drop as $1/L^2$ so that going to the other side of the globe, ten thousand kilometers away, requires million ton detectors. Such detectors are already being put into operation. The next problem is to point a neutrino beam in the direction of the detector.

Channeling

Bent crystal channeling might be able to contribute to solving two of the major problems associated with long baseline neutrino beams[7,8]. 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[9] 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[10,11,12]. The highest energy so far achieved is 900 GeV at Fermilab[13].

There are several serious 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.

So far the crystal septa used for particle beam deflection have been on the order of 1 mm thick and 1 cm wide. The 1 mm thickness is well matched to the requirements of beam extraction. Crystals up to 15 cm long have been used at Serpukhov[14]. Beams have been deflected as much as 130 mrad at Serpukhov. Silicon crystals have been used in most cases for bent crystal channeling. Very high quality silicon crystals are available as large crystals. Semiconductor crystals can also act as particle detectors for alignment purposes. Tests suggest[15] there should be little significant degradation in channeling properties due to radiation damage up to fluences of $4 \cdot 10^{20}/\mathrm{cm}^2$.

Crystal types other than Si and Ge are used for channeling but the quality of the crystals (mosaic spreads greater than 100 microradians) and the available size have precluded their use for bending. Tungsten would be a particularly interesting crystal for this purpose. The planar critical channeling angle is several times larger than for silicon resulting in a larger acceptance. The minimum Tsyganov bending radius is a factor of 8 smaller than silicon. Unfortunately large, zone-refined metallic crystals are very hard to make. The largest tungsten crystal we have investigated was 1/8 to 1/4" in diameter and three inches long. Taratin at Dubna and his collaborators are now investigating the possibility of producing and exploiting tungsten crystals for high energy channeling[16].

To understand the possibilities and problems of producing neutrino beams using bent crystal extraction it is helpful to proceed in two steps. First we review a schematic approach developed for estimating the transmission efficiency for bent crystals in external beams. That formula is then modified for extracted beams.

If the beam emittance is substantially greater than the crystal acceptance the transmission efficiency of a bent crystal septum in an external beam can be approximated by[17]:

$$E = E_c\left(\frac{\phi_b^{50}}{\Phi}\right)\left(1-\frac{p}{3R_m}\right)e^{(-sp_0/\lambda_0 p)} \tag{2}$$

In the formula ϕ^{50}_b is the phase space acceptance of the bent crystal (proportional to the thickness times the channeling critical angle), Φ is the 50% phase space emittance of the particle beam for the crystal bending direction, E_c is the surface acceptance of the crystal, R_m is the minimum radius of bend along the crystal 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. To account for the decreased channeling length in a bent crystal[18] the dechanneling length for the straight crystal case is multiplied by $(1-p/3R_m)^2$.

The dechanneling length for a straight crystal is reasonably well established for silicon. 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 (a recent Serpukhov measurement[19] at 70 GeV extrapolates to 8.7 cm). Dechanneling lengths for germanium and tungsten have been extrapolated from measurements of dechanneling lengths for these materials in the 0.1 to 12 MeV regime using an ansatz[20] based on work by Lindhard[21] and Feldman and Appleton[22]. The MeV range measurements typically used beams with an angular distribution smaller than the critical angle so that adjustments must be made to accommodate the angular distributions more characteristic of the GeV range. In addition the transition from non-relativistic to relativistic kinematics must obviously be handled correctly.

Equation (2) is only an approximation. Actual dechanneling is a diffusion process so that a full diffusion treatment for dechanneling would be better. This is particularly true in situations involving large bends extending over a number of dechanneling lengths. A better estimate for the (1 - $p/3R_m$) bending dechanneling term would be a theoretical diffusion function derived by Ellison[23] or Kudo[24]. The Ellison-Kudo bending dechanneling approach does not have the hard cutoff of the approximation in equation 2.

Figure 2 compares the approximation formula to results from a recent experiment at CERN[25]. In this case the formula is applied to a fixed crystal length rather than optimizing the length for each bend as is done for the neutrino calculations below. Illustrations are shown in Figure 2 for the three point bend used in the CERN experiment and a uniform bend (with the same straight section lengths as the three point bend in the CERN experiment). A surface efficiency of $E_c = 0.75$ was used to match the extrapolated CERN transmission efficiency to a zero degree bend. The ordinary dechanneling length used for the calculation was 49.5 cm using the extrapolation above for a (111) plane. The comparison to the CERN data for the three point bender (the actual case) is plausible. The straight line approximation to Ellison-Kudo bending dechanneling over-estimates dechanneling at large angles. As expected the uniform bend gives larger transmission efficiencies since the minimum radius is larger. For this reason a uniform bend is used for the neutrino beam calculations.

For accelerator extraction, a circulating particle that is not channeled often remains in the accelerator and is channeled on a later pass. This multiple pass extraction[26,27,28] leads to an effective higher overall efficiency for the channeling extraction process when the beam divergence is greater than the channeling angle. For accelerator extraction the first two terms in (2) should be replaced by an extraction efficiency, E_e, so that the overall extraction and bending efficiency for the accelerator case is:

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

For maximum transmission efficiency in an external beam, the crystal phase space acceptance should be as close to the beam emittance as possible or even larger. The larger the crystal critical angle, the better. This is less of a factor in an extraction crystal because of the effect of multiple passes. Understanding of multiple pass extraction efficiency is still in a nascent stage. Recent CERN measurements[12] at 120 GeV in an accelerator lattice configuration not specifically optimized for channeling extraction give E_a on the order of 10%. Fermilab has observed extraction at 900 GeV but no efficiency measurements have been reported yet. Simulations by Biryukov for 900 GeV[29] and 7.7 TeV[30] give values of E_a as high as 0.7. For the calculations below E_e is assumed to be 0.5 independent of energy.

In the formula as the momentum increases for the first parenthetical term the bending efficiency decreases unless the crystal radius of curvature (and length) are increased. This term tends to lengthen the crystal septum. The minimum radius of curvature also depends on the details of the crystal suspension. For large bends a smooth surface with constant radius of curvature seems to be best and is assumed in the calculations. Obviously the crystal should not be over-stressed. For the large radii of curvature in the TeV region this is not a problem. Laminates of thinner crystals could also be used. The exponential term is due to normal dechanneling effects. A shorter septum minimizes normal dechanneling. The septum length is optimized for maximum transmission efficiency.

Estimation of the channeling extraction efficiency is extremely sensitive to dechanneling. Consistent, precision high energy experiments for different materials and orientations in the spirit of the recent CERN experiment using Si(110) would be most welcome. Theorists should be challenged by experiment to make efficiency predictions that accurately track the data, particularly for aggressive bends.

Figure 3 shows E_a for germanium and tungsten crystals for 120 GeV as a function of distance from a neutrino source. The points are the distances for various detectors from Fermilab. Transmission efficiencies of less than 0.1% are untenable for even the largest detectors so that germanium is limited to distances of less than 5000 Km. The range for silicon is even less. To provide some sense of the effect of using different elements Table 1 gives E_a and the septum length for three different crystals at 120, 900, and 7000 GeV for 64 mrad (Soudan for Fermilab) and 540 mrad (DUMAND). Based on the model used here germanium is better than silicon for large deflections . Tungsten is even better. However, as noted earlier, satisfactory large tungsten crystals are difficult to produce and are not currently available.

For Soudan-level deflection angles at the Tevatron the silicon and germanium crystal lengths are probably achievable. For deflections on the order of a radian or for LHC deflections to Gran Sasso total crystal lengths greater than a meter are needed. One way to obtain those lengths would be to use several crystals in series. Several complications are involved. The crystal planes in each successive crystal would have to be aligned to the preceding one to somewhat better than the critical angle. Practically, this alignment would have to be done in an external beam. Note that the angular alignment problem is several-fold since the planes must also be aligned in the direction transverse to the bend. A further problem is the surface transmission loss at each new crystal. One can speculate about the possibility of micro-alignment of individual crystal planes in successive crystals using techniques developed for scanning tunneling microscopes. In practice alignment at this level would be almost impossible. As a result, the overall efficiency would be reduced by a factor of O(0.5) at each successive interface.

Figure 4 shows the neutrino event rates from the Fermilab Main Injector that could be expected at several detectors using a germanium or tungsten crystal. Proton exposures of $2 \cdot 10^{20}$ were assumed. The direct event rate is also shown assuming a normal 120 GeV proton beam could be pointed in the direction of the detector. The detector masses that have been assumed have been noted earlier (10 kilo-tons is used for Soudan). Some of these are quite optimistic. The number of protons from the Fermilab Tevatron at 900 GeV for an equal time period would be $4 \cdot 10^{18}$ or 1/50 of the Main Injector number. As a result, it is barely possible to envision 900 GeV experiments at detectors beyond 5000 Km even with a tungsten crystal.

Interestingly, it is possible to get hundreds of counts at the existing Soudan detector with a 120 GeV proton beam from Fermilab using a germanium crystal. One approach might be to position a crystal pointed in the direction of Soudan downstream of the antiproton production target. A substantial pion decay pipe would still be required.

Conclusions

During the next decade one or more neutrino beams in the 1000 Km range will come into operation. Thousand kilo-ton 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 might offer a method to do this although it suffers from a serious problem of beam attenuation. Even with tungsten crystals which are not currently available in the required sizes the neutrino event rates are discouragingly low at distances of thousands of kilometers. However, a germanium septum pointed toward the Soudan detector with a 120 GeV proton beam from Fermilab may be practical. Other approaches to long baseline neutrino beams may still appear. For example, cooling crystals can substantially increase their dechanneling lengths[31]. We should keep an open mind on the possibilities.

[*] Operated by Universities Research Associations, Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy.

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Table 1

E_a(%), the extraction and bending efficiency, and Length (L, cm) for Different Crystals and Energies

Energy (GeV)	Crystal Z	Si 14	Ge 32	W 74
Deflection Angle = 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
Deflection Angle = 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

Figures:

1. Principal elements in a neutrino beam.

2. Comparison of recent CERN transmission efficiency measurements (E) as a function of bend angle for a 450 GeV beam (+) to the approximation formula for a uniform beam (solid curve) and a three point bend (dashed curve).

3. E_a in percent at 120 GeV for a germanium crystal septum (O, dashed line) and a tungsten septum (X, solid line) as a function of the distance S from the neutrino source. The locations of Soudan, DUMAND, Super Kamiokande, and AMANDA at successively larger distances from Fermilab are indicated.

4. Neutrino event rates for a $2 \cdot 10^{20}$ exposure in several different detectors at different distances (S) for a 120 GeV proton beam from Fermilab for a conventional neutrino beam (+) and germanium (O) and tungsten (X) septa.

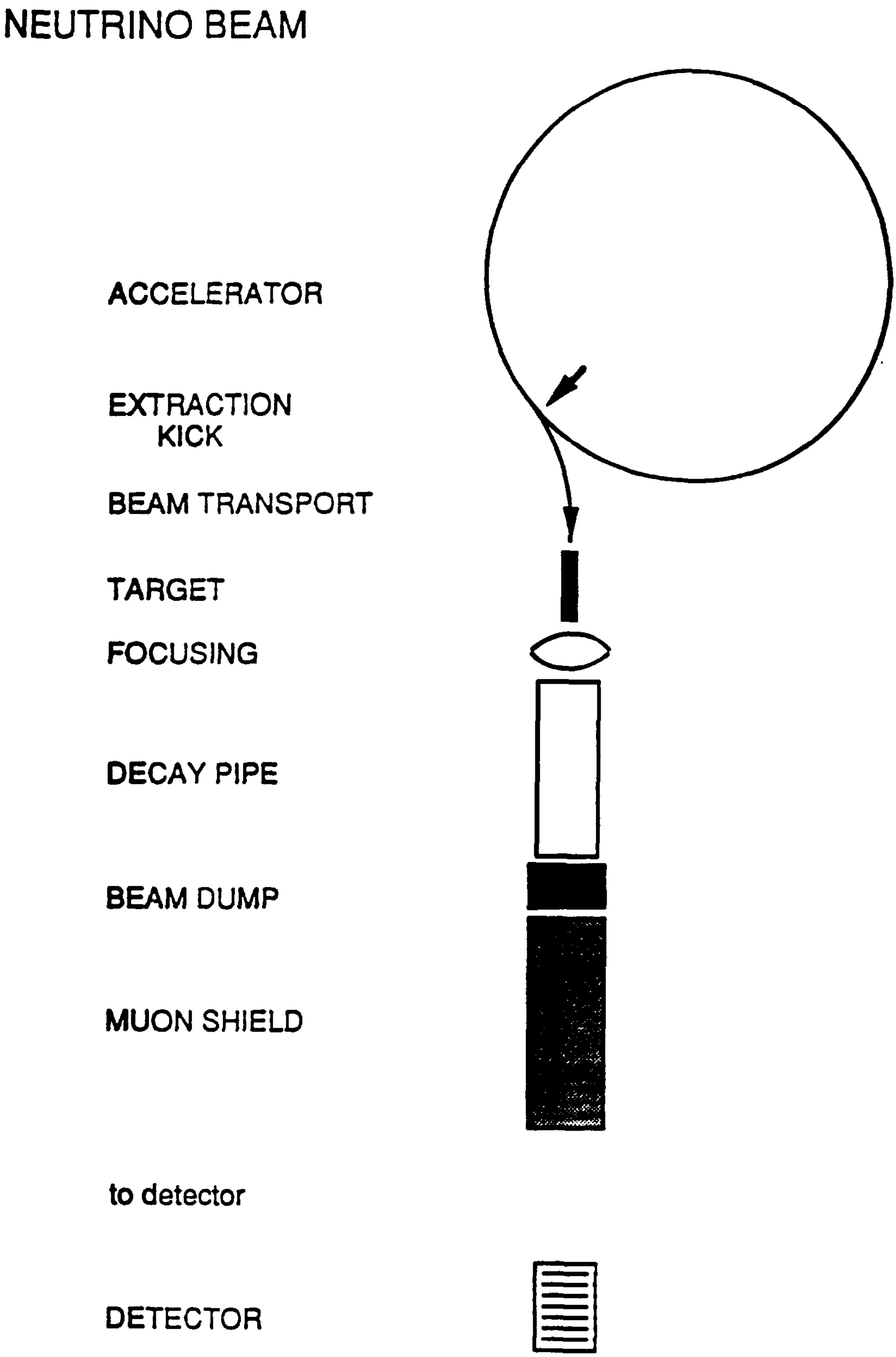
NEUTRINO BEAM
ACCELERATOR
EXTRACTION KICK
BEAM TRANSPORT
TARGET
FOCUSING
DECAY PIPE
BEAM DUMP
MUON SHIELD
to detector
DETECTOR

Figure 1

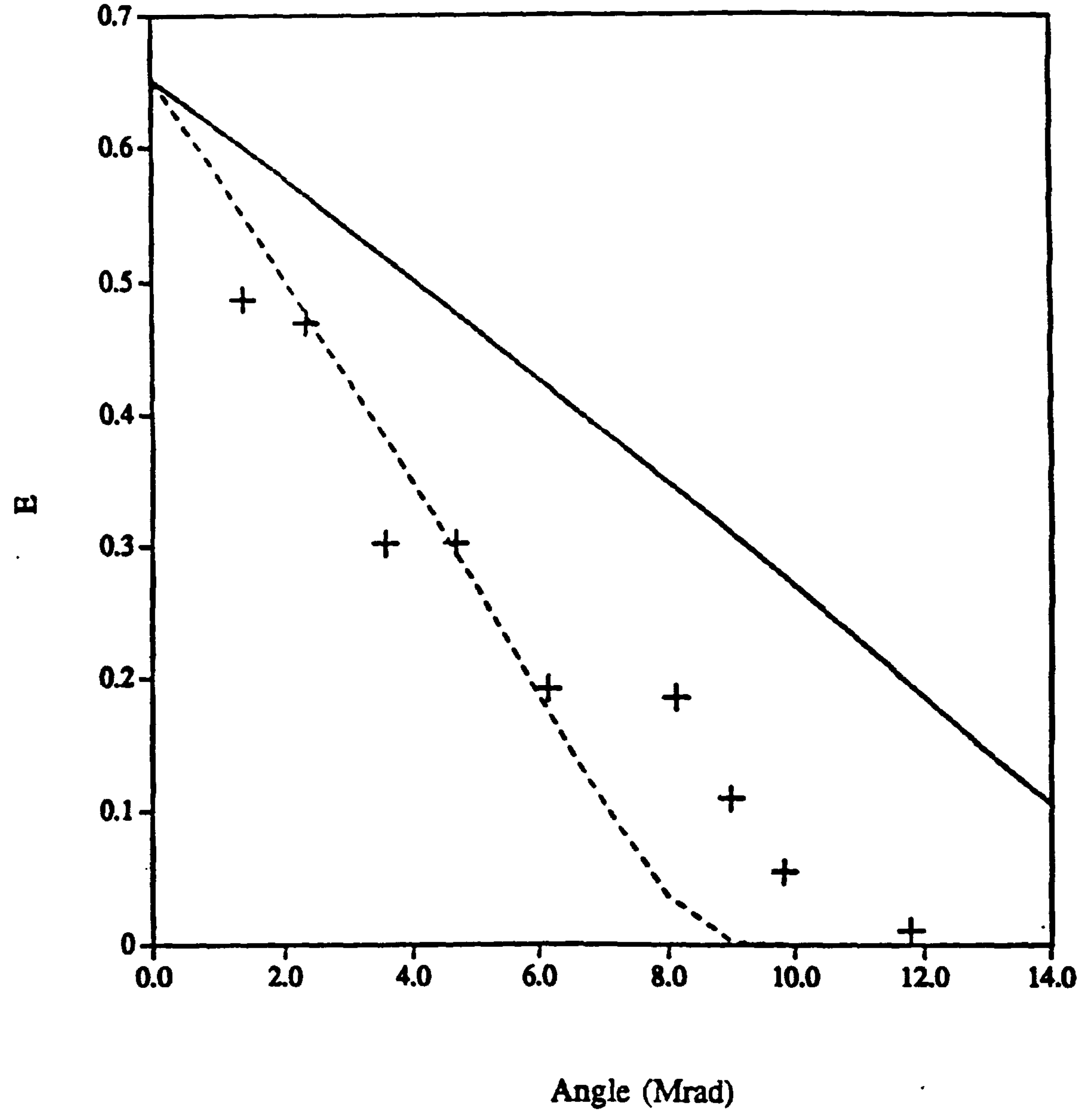

Figure 2

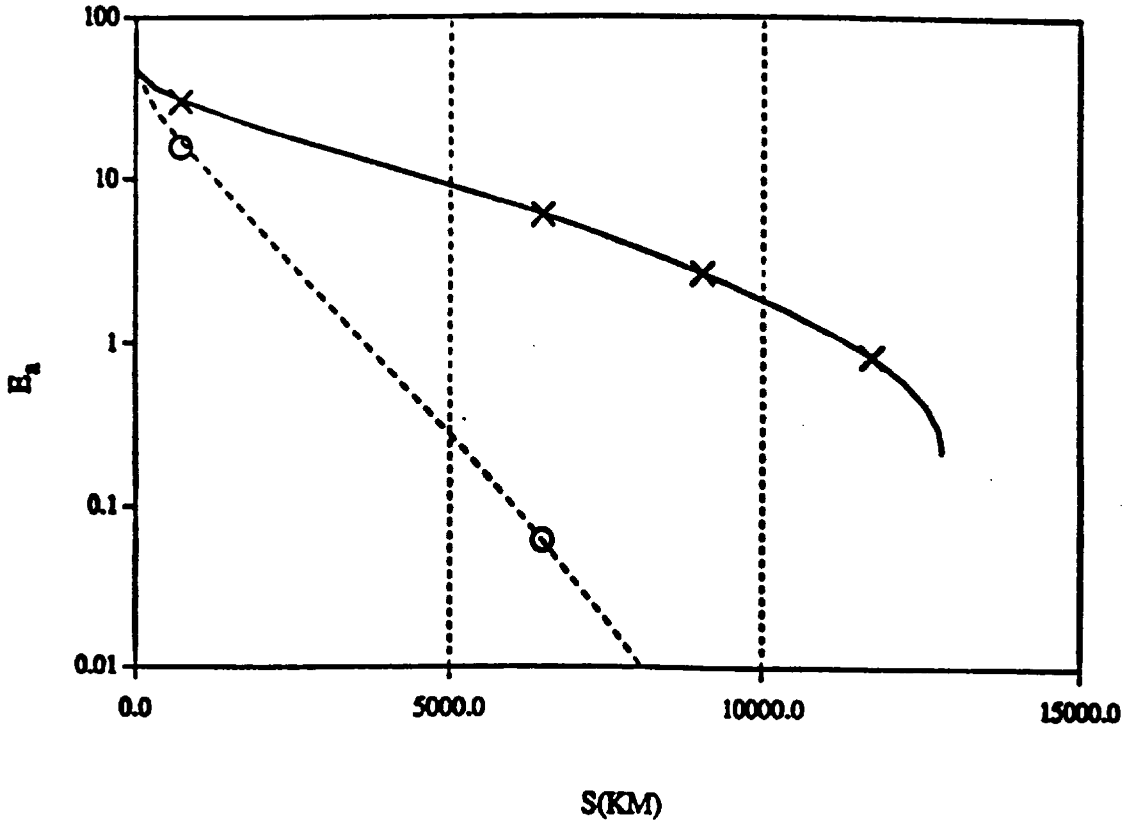

Figure 3

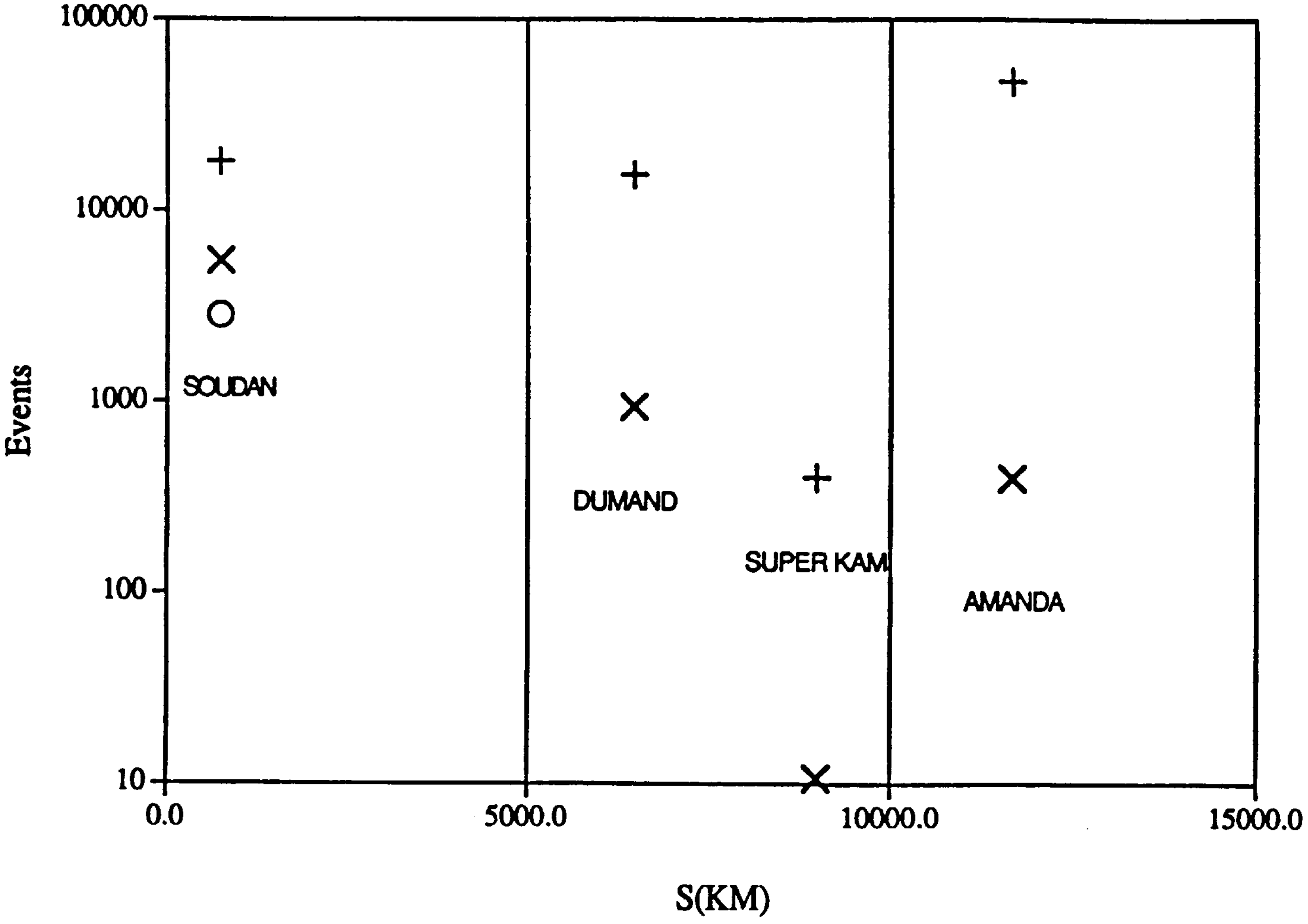
100000
10000
1000
100
10
Events
SOUDAN
DUMAND
SUPER KAM
AMANDA
0.0
5000.0
10000.0
15000.0
S(KM)

Figure 4