SS-94
2251

THE DESIGN OF A LOW ENERGY NEUTRINO BEAM AT NAL

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ABSTRACT

For form-factor determination a neutrino beam optimized for E_ν = 0.5-2.5 GeV is required. The length of such a beam is estimated to be ~30 meters. A 10-meter uranium shield is proposed. A method is presented that would allow, without inevitable μ background, a 200-GeV proton beam to produce a higher multiplicity of the required energy π's by nuclear cascade. The multiplicity is estimated to be ~5 and this is found to be no more than the repetition rate gain if instead 20-GeV protons are used in a more conventional beam. The latter is recommended.

I. INTRODUCTION

For the study of two-body final states in ν and $\bar{\nu}$ interactions, it is desirable to have the highest possible flux of neutrinos in the energy region 0.5 - 5 GeV. Although such a beam is possible at BNL, a considerably higher intensity is certainly available at NAL.

The NAL machine will have intensity 2 - 5 $\times$ 10^{13} compared with 1 $\times$ 10^{13} at the AGS; the NAL bubble chamber is at least 3 times the volume of any chamber foreseen at BNL, and at the same energy (30 GeV) the repetition rates of the two machines are comparable. Thus even if one used no ingenuity and simply built the BNL beam at NAL, the event rate would be an order of magnitude greater. In physics terms this is of vital importance since it would mean enough inverse hyperon decays (30,000 instead of 3,000) to allow a separation of form factors. An even higher intensity might be possible at NAL if ways can be found to harness the greater energy to produce greater low-energy intensity. In proposing a design to attempt to do this, I will consider beam length, the consequences of magnetizing the shield, an alternative way of avoiding high-energy μ's in the chamber, and finally the advantages of using high-energy protons and the cascade process.

II. BEAM LENGTH

Consider a perfectly focused π beam. All ν's will enter a chamber of radius r provided the total beam length L is given by:

$$L \leq \frac{rp}{p_T},$$

where p_T is the maximum ν transverse momentum (= 0.03 GeV/c) and p is the lowest ν momentum required (0.5 GeV/c). Thus for $r \approx 2$ meters, $L \sim 30$ meters. It is clearly desirable that the shield be a small fraction of the total length; we therefore choose shield ~ 10 meters, decay ~ 20 meters. If the shield is uranium, it will totally stop μ's up to 20 GeV. This sets a conservative machine energy that can be used.

We can now consider tricks that will enable a higher machine energy to be employed.

III. MAGNETIZED SHIELDS

At 20 kG a μ of mean momentum 20 GeV is deflected only 1.6 meters in 10 m of shield. A much higher field would be required to usefully deflect such muons away from the chamber. A superconducting field ~ 60 kG would help but would be ridiculously expensive.

IV. MUON AVOIDANCE

Rather than attempting to deflect the unwanted muons out of the way, it would seem more sensible to start the beam out in the wrong direction and deflect the required particles into the required direction (see Fig. 1). If for instance we aim the proton beam at a point 5 meters to the side of the bubble-chamber axis and then deflect 3-GeV particles towards the bubble chamber, then the angles (θ_π) that other momenta make with the chamber axis are given in Table I.

Monopole systems can be made to accept angles up to ~ 0.6/p where p is in GeV/c; 80% of all particles lie within the same angle. A loss of about 2/3 of the particles will occur when θ_π is of order 0.6/p. The loss will be small when $\theta_\pi < 0.3/p$; 0.3/p is also given in Table 1. It is seen that the proposed system would accept pion momenta between 1 and 5 GeV/c, and thus give a good ν flux between 0.5 and 2.5 GeV, which is the region we wish to cover. Above 3 GeV the ν spectrum from π's would fall very rapidly but would be replaced by ν's from K's up to an energy of ~ 6 GeV.

V. NUCLEAR CASCADE

If the muon avoidance scheme outlined above really works then there is in principle no upper limit to the proton energy E_p employed in the target. A gain with E_p might be expected because pion multiplicity rises as the energy rises, but because the mean pion energy rises faster, so the number of low energy pions actually falls with increase in proton energy. This effect can only be reversed if the unwanted high-energy pions can be made to interact and produce the required lower energy pions in a cascade process.

Consider the following crude model for a nuclear interaction of an incident particle of energy E_0:

1. multiplicity of secondary pions = $2.7\ E_0^{1/4}$
2. the initial particle emerges with $1/2\ E_0$
3. of the secondary pions half share $1/3\ E_0$ and the other half share $1/6\ E_0$, corresponding to those produced in the forward and backward directions in the center-of-mass.

If the target is about two effective interaction lengths long then, very approximately, we can assume:

1. that all initial protons interact
2. 70% of all secondaries interact
3. 20% of all tertiaries interact
4. there are no further interactions.

If four-tenths of all final pions are π^+, then the final π^+ spectrum from a single 200-GeV initial proton is found to be approximately:

8	π's	0.5 - 1 GeV
6	π's	1 - 2 GeV
2	π's	2 - 4 GeV
1.5	π's	4 - 8 GeV
1	π	8 - 16 GeV
18.5	π's	0.5 - 16 GeV

The multiplicity is seen to be 18.5 instead of a multiplicity of 2 for a 10-GeV proton beam on a short target. The width of the energy distribution is much broader than that from a short target. When the muon avoidance scheme suggested above is used, then only a limited momentum range of secondaries can be used. In the arrangement proposed, this range is 1 - 5 GeV/c and the multiplicity in this range is only about 8 giving a resultant gain over a short target of only a factor of 4.

This analysis should obviously be done by a Monte-Carlo method but this rough guess would indicate:

1. a target length should be selected to maximize a two-interaction cascade.
2. the pions from even two interactions are peaked at a surprisingly low energy (~ 1 GeV) even when a primary of 200 GeV is used. The highest possible primary energy is thus required.
3. a gain in multiplicity of about 4 is obtained relative to that obtained with a 10-GeV beam in a short target. This may be compared with the repetition rate gain achieved by running the NAL machine at 10 GeV, i.e., ~ $\times 4$.

VI. CONCLUSION

I conclude, provisionally, that there is nothing to be gained by the cascade process that cannot be better achieved by lowering the machine energy and thus increasing the repetition rate. Further I would expect that the problems involved with the high-energy μ's produced by 200-GeV protons are likely to be so bad that the cascade process will be expensive, if not impractical. Instead, it appears better to recommend the construction of a more conventional beam using 10 - 20 GeV protons without "muon avoidance." Alternatively, protons could be used from the booster during the time that it is not being used to load the main ring. In this case a storage ring would have to be constructed, but the resulting integrated flux would be 4 times that of the main machine and the use of it would be entirely parasitic. Such a storage ring to hold ~10 booster pulses might cost as little as 3 million dollars and would also find application in strong-interaction physics.[1]

REFERENCE

[1] R. Stiening, A Proposal for the Use of the 10-BeV Booster Accelerator as a Source of Low Energy K^+ Mesons, National Accelerator Laboratory 1968 Summer Study Report B.5-68-21, Vol. II, p. 101.

Table I. Pion Angles.

Proton energy (GeV)	1	2	3	4	5
Angle of π from axis (θ_π)	0.32	0.08	0	0.04	0.06
Cocconi angle 0.3/p	0.3	0.15	0.1	0.075	0.06

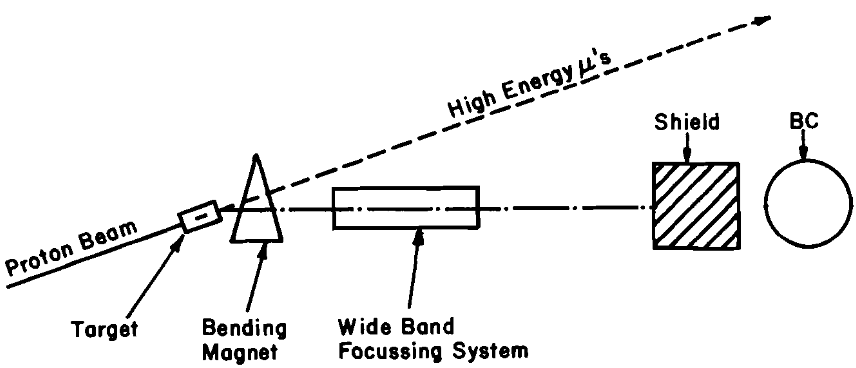

Fig. 1. Removal of high-energy muons from neutrino beam.