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On the Possibility of Studying ν_e and $\bar{\nu}_e$
Interactions at a Kaon Factory

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ON THE POSSIBILITY OF STUDYING ν_e AND $\bar{\nu}_e$ INTERACTIONS AT A KAON FACTORY

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ABSTRACT

The possibility of observing ν_e - and $\bar{\nu}_e$ -induced reactions at a high-flux "Kaon Factory" is discussed. A recently suggested neutrino beam derived from K_L^0 decays is the enriched source of ν_e and $\bar{\nu}_e$. Some specific measurements which are feasible are described.

INTRODUCTION

Experimental measurements of interactions of ν_e and $\bar{\nu}_e$ are scarce. Reactors provide an intense flux of ν_e ,

$$F(\bar{\nu}_e/\text{cm}^2\text{-s}) \approx 1.5 \times 10^{12} P/L^2,$$

where P is the reactor thermal power in MW and L is the distance from the reactor core in meters.¹⁾ Unfortunately, the antineutrino energy spectrum only extends up to 8 MeV. This implies that the cross sections are very small and the experiments are very difficult. In addition, there are uncertainties in the antineutrino spectrum and in the significant final state interactions due to the low energies. Nevertheless, measurements of the total cross section for $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$,²⁾ $\bar{\nu}_e p \rightarrow e^+ n$,³⁾ $\bar{\nu}_e d \rightarrow n n e^+$, and $\bar{\nu}_e d \rightarrow n p \bar{\nu}_e$ ⁴⁾ have been performed.

The LAMPF beam stop is a source of ν_e 's with a flux of $\sim 3 \times 10^7$ $\nu_e/\text{s-cm}^2$, and a spectrum which peaks at 35 MeV and extends up to 53 MeV. A measurement of the total cross section for $\nu_e d \rightarrow p p e^-$, accurate to 35%, has been performed⁵⁾ and an experiment to measure ν_e -e elastic scattering is being mounted.⁶⁾

Finally, 200- ν_e and 60- $\bar{\nu}_e$ charged current events have been observed in the heavy liquid bubble chamber Gargamelle exposed to the CERN PS neutrino beam.⁷⁾ There is a several-percent electron neutrino "contamination" of a ν_μ beam from μ^+ decay and from K^+_{e3} decay. The total inclusive cross sections were measured to a precision of 30% and agree with the corresponding ν_μ and $\bar{\nu}_\mu$ cross sections.

The meager amount of information available on ν_e and $\bar{\nu}_e$ interactions despite many years of effort makes it desirable to investigate whether some other source of these neutrinos is not feasible.

THE BEAM

Recently a neutrino beam enriched with ν_e and $\bar{\nu}_e$ has been suggested.⁶⁾ The motivation for this suggestion is the possibility of studying neutrino oscillations at the Brookhaven AGS. It is the point of this note that if such a beam were constructed at a Kaon Factory, systematic studies of charged- and neutral-current interactions of these neutrinos would be possible for the first time. The basic idea of the beam is as follows:

High-energy neutrino beams are derived from the weak decays of long-lived charged particles, primarily $\pi^\pm$ and, to a lesser extent, $K^\pm$ and $\mu^\pm$. These beams have only a small admixture of ν_e or $\bar{\nu}_e$ due to the small branching ratios of charged pions and kaons into these neutrinos. Table I lists the principle decay modes for $\mu^\pm$, $\pi^\pm$, $K^\pm$, and K_L^0 . The only long-lived particles which have large branching ratios into ν_e are $\mu^\pm$ and K_L^0 (BR = 38.8%). Muons have extremely long lifetimes which make them unsuitable for the source of a neutrino beam. The beam should then be enriched in neutral kaons and should be as free as possible of charged π 's and K 's. Thus, the production target is followed by a sweeping magnet to bend all charged particles out of the beam line before they decay. Massive shielding follows the decay region to absorb all strongly interacting and charged particles which result from neutral particle decays. A magnetic field in the decay region would remove charged pions which result from K_L^0 decay before they can, in turn, decay. This may, in fact, not be necessary. A schematic diagram of the neutrino facility is shown in Fig. 1.

An estimate of the neutrino fluxes that would result from such a beam can be obtained from calculations performed for the fluxes of the CERN PS neutrino beam.⁷⁾ These results are shown in Fig. 2 for a fiducial area of $\sim 3\text{M}^2$ and corresponds to 1.1×10^{10} protons on target. The neutrino beam consists of a decay path of $\sim 57\text{M}$ and a shield with a length of 19M . Gargamelle was located $\sim 90\text{M}$ from the production target. K^0 production peaks at $\sim 4\text{--}5\text{ GeV}/c$ and a 60M decay path corresponds to $\sim 1/3$ of the K^0 's decaying. Since there is no focussing device possible, the neutrino flux decreases as the square of the distance from the production target. Thus, a shorter decay path would result in a somewhat higher neutrino flux (by, at most, a factor of two). However, if the same beam line is also to be used to produce neutrinos from $\pi^\pm$ decay, the decay path cannot be appreciably shortened.

Assuming an incident beam of $100\text{ }\mu\text{A}$ of $\sim 25\text{ GeV}$ protons and a fiducial area of $2.5\text{ M} \times 2.5\text{ M}$ (corresponding to a 15-ton detector), we obtain the neutrino fluxes shown in Fig. 3. The total ν_e flux is $\sim 7.5 \times 10^8/\text{s}$ for $E_\nu > 1\text{ GeV}$. The $\bar{\nu}_e$ flux is the same. The total neutrino flux is $\sim 2.5 \times 10^9/\text{s}$. For comparison, the present AGS ν_μ flux above 1 GeV is $\sim 3 \times 10^{10}/\text{s}$ in the same area, assuming 7×10^{12} protons/s⁹⁾ on target. Thus, the total neutrino flux is $\sim 1/10$ of the AGS flux with the "interesting" part of the flux (ν_e and $\bar{\nu}_e$) constituting 60% of the beam. Some of this flux disadvantage could be recovered by using larger detectors: Detectors at the AGS have been ~ 30 tons.

POSSIBLE MEASUREMENTS

The measurements which have been undertaken in this energy range at the AGS and the CERN PS are:

- a) neutrino-proton elastic scattering,
- b) neutrino-electron elastic scattering,
- c) neutral-current and charged-current single pion production,
- d) threshold dilepton production, and
- e) neutrino oscillation searches.

Most of the data has been accumulated with incident ν_μ 's. Reactions induced by $\bar{\nu}_\mu$'s are harder to study due to the lower incident flux and the smaller cross sections for these reactions.

Neutrino-proton elastic scattering is the simplest hadronic neutral current interaction. The quality of data which has been obtained so far does not permit an accurate determination of $\sin^2\theta_w$. The data do shed light on the space-time structure of the interaction. An experiment measuring elastic scattering with the beam proposed here would detect events initiated by ν_μ , $\bar{\nu}_\mu$, ν_e , and $\bar{\nu}_e$ simultaneously; there is no way to separate the four components. The BNL experiment¹¹⁾ detected 217 $\nu_\mu p \rightarrow \nu_\mu p$ events with $0.4 < q^2 < 0.9 \text{ (GeV/c)}^2$ in a detector with a fiducial mass of 11 tons. The detection efficiency was $< 50\%$ due to the large ratio of total mass to fiducial mass (1/3) and the large cell size ($0.2 \times 2.7 \times 0.2 \text{ M}^3$). A detector which is twice as massive with a finer-grained fiducial volume should be about six times more efficient in detecting elastic scattering events. Exposing such a detector to this neutrino beam would result in an event rate roughly one-half of the BNL ν_μ event rate. Thus, the detection of 200 events within the same q^2 range as the BNL experiment should be feasible. One would expect 70 events each due to ν_e and $\bar{\nu}_\mu$ and 30 events each due to $\bar{\nu}_e$ and ν_μ . The finer-grained detector should allow the detection of events with lower q^2 to be detected making the experiment more sensitive to scalar and pseudoscalar contributions of the weak neutral current.¹²⁾ Extending the region to $q^2 = 0.3 \text{ (GeV/c)}^2$ (0.2 GeV/c^2) would imply 300 (400) events detected. This experiment would be sensitive to differences in neutral current couplings between electron-type neutrinos and hadrons, and muon-type neutrinos and hadrons. There is, at present, no such test of ν_e - ν_μ universality.

The rates for neutrino-electron elastic scattering are quite low: In a 50-ton detector, one would expect 0.1 event/day for $\bar{\nu}_e$ -e and 0.25 event/day for ν_e -e. These rates are much lower than the ν_e -e rates expected for LAMPF Exp. 225⁵⁾ (1.5/day): Nevertheless, this may be the best way to study ν_e -e scattering.

Studies of neutral-current single-pion production¹⁰⁾ have been limited by systematic errors such as nuclear absorption effects, clean proton and pion identification, and neutron-induced backgrounds. The data are useful in studying the isospin structure of the neutral-current interaction. These studies could be continued with this beam as a further test of μ -e universality.

The observation of dilepton events is thought to provide evidence for charmed particle production. BNL Exp. 734 expects to detect a μe event approximately every two hours: Thus, useable μe event rates should be obtained with this beam again testing ν_e - ν_μ universality.

The neutrino oscillation experiment proposed in Ref. 8, to search for the time evolution of an electron neutrino beam, can of course also be performed with

this beam. The higher neutrino flux implies that the proposed sensitivity (1 (ev)^2 to 20 (ev)^2) could be reached in 1/100th of the proposed running time (10 hours rather than 6 weeks), a smaller detector (2 tons rather than 175 tons) or a combination of the two. On the other hand, data could be taken at larger distances to improve the sensitivity. A particularly attractive feature of such an oscillation experiment is the possibility of studying $P(\nu_e \rightarrow \nu_e)$, $P(\nu_e \rightarrow \nu_\mu)$, $P(\nu_\mu \rightarrow \nu_\mu)$, $P(\nu_\mu \rightarrow \nu_e)$, and various exclusive oscillation channels, simultaneously. This would allow various tests of CP-violation in neutrino oscillations to be performed.

SUMMARY

It appears feasible to construct a neutrino beam at a kaon factory which is composed primarily of ν_e and $\bar{\nu}_e$. With such a beam, it should be possible to compare ν_e - and $\bar{\nu}_\mu$ -induced reactions involving both charged current and neutral currents, so as to test μ -e universality. In addition, interesting neutrino oscillation studies can be performed.

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Fig. 1. Schematic diagram of the neutrino beam.

Fig. 2. Neutrino fluxes at Gargemelle. The fluxes correspond to 1.1×10^{18} protons on target and a fiducial area of $3\text{M} \times 3\text{M}$.

Fig. 3. Neutrino fluxes in the proposed beam in a fiducial area of $2.5\text{M} \times 2.5\text{M}$ and a $100\text{-}\mu\text{A}$ proton beam.

TABLE I
PRINCIPAL DECAY MODES

<u>Particle</u>	<u>Mode</u>	<u>Branching Ratio</u>
μ^+	$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	100%
π^+	$\pi^+ \rightarrow \mu^+ \nu_\mu$	100%
	$e^+ \nu_e$	1×10^{-4}
K^+	$K^+ \rightarrow \mu^+ \nu_\mu$	63.5%
	$\pi^+ \pi^0$	21.2%
	3π	7.3%
	$\mu^+ \nu_\mu \pi^0$	3.2%
	$e^+ \nu_e \pi^0$	4.8%
K^0	$K_L^0 \rightarrow 3\pi$	33.9%
	$\pi^\pm \mu^\mp \nu_\mu$	27.0%
	$\pi^\pm e^\mp \nu_e$	38.8%