ON HIGH ENERGY NEUTRINO PHYSICS

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I will report on investigations in the field of high and intermediate energy neutrino physics carried on at the Joint Institute for Nuclear Research in 1958-60. The full texts of the papers on which I will comment can be found in the pamphlet entitled " On High Energy Neutrino Physics " (Dubna 1960).

Various possibilities of neutrino experiments using accelerators or cosmic rays are discussed in this report. The analyses show that it is possible to carry on neutrino experiments with existing accelerators and underground, with cosmic ray neutrinos. In fact, Pontecorvo has shown that in some neutrino physics problems the medium energy accelerators, which produce π mesons, have an advantage.

One of the fundamental questions in high energy neutrino physics is the following:

> Up to what energy do neutrino cross sections increase quadratically with increasing energy as predicted by lowest order in the four-fermion theory?

From the point of view of the four-fermion formalism this cross section is correct up to 300 BeV in the c.m. system. At these energies weak interaction effects become equal to electrodynamic effects.

Unfortunately such energies will not be accessible to experiment in the near future. Therefore, the answer to this question can be found only indirectly. One of these indirect ways is connected with higher order effects in the perturbation theory of weak interactions, which allow arbitrarily large intermediate momenta. These effects have been theoretically analyzed (Pontecorvo, Asanov, Valuev, Ioffe) under the assumption that intermediate momenta are cut-off so that $k_{\max} < 10^3 M_n$. This cut-off is chosen to give maximum effect which is not in contradiction with experimental data (such as the absence of $\mu^+ e^- \to e^+ \mu^-$ and $\mu \to e + \gamma$).

This (experimentally dictated) cut-off is at a momentum smaller than that at which non-applicability of perturbation theory could be suspected. The decay $\mu \to e + \gamma$ gives the more stringent restriction on the cut-off. In accordance with the experimental upper limit; $\dfrac{W(e+\gamma)}{W(e+\nu+\bar{\nu})} < 1.2 \times 10^{-6}$ the critical momentum must be chosen, $k_{\max} < 50$ BeV.

One natural cut-off mechanism would be an intermediate vector boson. Another possibility is that the neutrino associated with the μ-meson is different from the neutrino associated with the electron. In this event the absence of $\mu \to e + \gamma$ sets no upper limit on the cut-off.

The papers to be quoted deal with the following four questions:

1. Existence of an intermediate meson.
2. The question of two kinds of neutrinos.
3. The existence of interactions of the types (a) and (b) below.
4. Value of critical weak interaction momentum:
   a. for neutrino-baryon interactions;
   b. for neutrino-lepton interactions.

At the present time it is reasonable to suppose that neutrino-nucleon interactions are cut-off by the same form-factor as electromagnetic interactions. We can therefore expect neutrino-nucleon cross sections in the laboratory system to increase with increasing energy up to a few BeV. Beyond this energy, cross sections may be constant or even decrease.

Direct detection of neutrino-nucleon effects in accelerators were considered by Fakirov and myself (1958) as well as by Schwartz. Estimates show that, due to the large pion lifetime, geometrical factors make it unfavorable to place the neutrino detectors at a large distance from the accelerator. Taking shielding requirements into account the best accelerator-detector distance is 40-50 m under Dubna conditions.

Neutrino fluxes from linear and parallel beams of decaying π mesons (ideal magnetic focusing) are considered by Polubarinov (1959). Under the conditions considered by Polubarinov the maximum in neutrino flux density appears at a distance of 100 m from the accelerator target. Beyond this point the neutrino flux density decreases with distance. Calculations of the neutrino fluxes in a 10 BeV proton accelerator are presented in Barashenkov's and Hsien Ding-Chang's papers.

1. ν_μ—ν_e PROBLEM

If one has a proton flux of 10^{11} $\sec^{-1}$ at an energy of 10^{11} eV, previous estimates give a neutrino flux, with $E_\nu > 1$ BeV at 50 m from the target, of 10^3 cm^2/sec. Using 1/10 of the primary protons we estimate 1/4 event per day of the type, $\nu + p \to n + e$ using the theory with identical ν_e and ν_μ. Magnetic focusing of the π-meson beam may increase the number of events by a factor of 20. According to Pontecorvo, neutrino experiments are best performed with accelerators of proton energy 1 BeV and lower because the lower neutrino cross sections are more than compensated by the higher intensities.

In his suggestions Pontecorvo concentrates on reactions of the type,

$$\nu_\mu + N \to N' + e$$

$$\nu + e \to e + \nu$$

at small neutrino energies. In particular he considers some advantages of using monochromatic neutrinos produced by the decay of stopped particles.

2. THE INTERMEDIATE MESON

As noted by Pontecorvo and Ryndin and by Lee and Yang, the cross section for vector meson production by neutrinos of one BeV in the Coulomb field of a nucleus may be 10^{-35} cm^2 for $Z = 10$. For a boson with the mass of a nucleon we could expect one event per hour.

The cross section for photo-production with γ-rays of corresponding energy would be about ten times that for production by neutrinos. Barashenkov and Hsien Ding-Chang have estimated photon fluxes in proton accelerators and have found that photo-boson production experiments are indeed feasible.

3. NEUTRINO-LEPTON INTERACTIONS

Unfortunately the cross section for neutrinos interacting with free electrons is smaller than that for the neutrino-nucleon interaction. Besides, it is difficult to detect neutrino-lepton scattering processes in the background of effects,

$$\nu + N \to N + \mu$$

$$\to N + e\,.$$

Instead, Chou Kuang-Chao has suggested searching for lepton pair production in neutrino scattering from a Coulomb field. In the lab system the cross section of the process, $\nu + Z \to Z + e^+ + e^- + \nu$ has the form,

$$\sigma = \frac{8G^2(Ze^2)^2}{3(2\pi)^3} E_\nu^2 \ln \frac{E_\nu}{m_e}.$$

For $Z = 80$ an approximate expression is,

$$\sigma_\nu \simeq 7 \times 10^{-40} E_\nu^2 \quad (E_\nu \text{ in BeV})$$

At sufficiently high energy this may be the dominant kind of weak process. It will be possible also to detect muon pairs and pairs produced in neutrino scattering from Coulomb fields.

4. COSMIC RAY EXPERIMENTS

In the papers by Zheleznykh and myself (1958, 1960) possibilities of experiments with cosmic ray neutrinos are analyzed. We have considered those neutrinos produced in the earth's atmosphere from pion decay. From the known μ spectrum the neutrino energy spectrum is reconstructed. We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation. We consider μ mesons produced in the ground layers under the apparatus. If the measuring apparatus gathers information from an area of 1000 m^2 and the maximum neutrino energy is 3×10^{11} eV, we estimate the number of events as given in Table I.

Rare events of a frequency of less than one per month are also detectable in cosmic rays. Experiments with cosmic rays are also of interest for their own sake because they may give information on possible high energy neutrinos of cosmic origin.

Table I. Comparison of cosmic rays and accelerators

Event	Cosmic rays (Detector area = 1000 m^2. $E_\nu^{max} = 3\times10^{11}$ eV.)	Accelerators (Detector area 1 m^3 of Pb; magnetic focusing. 10^{11} protons per second at $E_p = 10^{10}$ eV.)
Intermediate boson	one per day	one per hour
$\nu+N\rightarrow N'+\mu$	one per month	one per day
ν+nucleus→nucleus+μ+e+ν	"Pillow" $z = 10$ one per month "Pillow" $z = 80$ one in 4 days	one per month

DISCUSSION

YANG: Are there plans for doing these experiments in Russia?

MARKOV: We have discussed this question in Russia and maybe it will be possible.

SCHWARTZ: How will you be able to settle the question of whether there are two kinds of neutrinos in a cosmic ray experiment?

MARKOV: I think that this question may be solved only by an accelerator experiment. But I think that the first step is detection of high energy neutrinos in cosmic rays.

BERNARDINI: I want to object a little bit to your optimism although I myself am very optimistic. If you want to see these events at a rate of one per day or one every four days, this is extremely interesting and maybe the fundamental problem of whether there are one or two neutrinos will be solved in these early days. But to speak about neutrino physics is not only a question of one event per day or one event every four days. Some new detector should be developed in which you use 10 tons of material and in which you are able to realize an appreciable amount of information. My optimism is concentrated on the possibility of developing such a detector. Because otherwise neutrino physics, like cosmic ray physics, will give only qualitative information. With a high intensity accelerator and this kind of heavy detector this situation would be changed.

MARKOV: I agree with Bernardini, but cosmic ray neutrinos have their own importance. I mentioned only neutrinos resulting from the decay of pions produced in the earth's atmosphere, but maybe there are neutrinos from the galaxy. Maybe the intensity of these neutrinos is different. It is necessary to solve this problem too.

BERNARDINI: I do not know how many thousands of cosmic ray pictures have been scanned, but I would not be so optimistic about the supply of neutrinos from extragalactic bodies. Because after all, apart from the Anderson picture of one event of this kind, I have never heard of a layer in the cloud chamber and one positive electron alone coming out. Now if this neutrino flux were abundant I think these very strange events would have been noticed.

MARKOV : No, I do not agree with you. According to the " pillow-effect " discussed here you can receive an important contribution fiom the portion of the neutrino spectrum near 10^{11} eV. It seems to me that neutrinos with energies $\sim 10^{11}$ eV and greater will not be obtained so soon from accelerators. On the other hand if a galactic neutrino flux with energies greater than 10^{11} eV does exist, then according to the cross section $\sigma \sim E_\nu^2 \ln E$ such a neutrino flux will be detectable if its spectrum falls off no more rapidly than $dE_\nu/(E_\nu)^{3.5}$

LEDERMAN : I would like to point out that something is known about this if you remember the underground experiment, just published by Frauenfelder and Hyams at CERN, in which they just looked at particles going upward. You can use Markov's formula of one event per day and assume they ran something like 10 days with 1/1000 the area. One can then say that the cross section is not much more than 100 times your cross section.

BLUDMAN : Would you explain again the reaction $\nu+e \to \nu+e$ and its bearing on the $\mu \to e+\gamma$ reaction?

MARKOV : I have only quoted Pontecorvo's work in this connection. If this $\nu+e \to \nu+e$ interaction exists, it is possible for electrons to lose energy in the form of two neutrinos and this effect may be important in astrophysics.

PRIMAKOFF : I would like to comment in connection with Bludman's question, that if $\nu+e \to \nu+e$ is possible then $\mu \to e+\gamma$ is allowed in the second order in weak interactions, so there is a connection.

MARKOV : I have thought of this possibility, and I mentioned it in my talk.

FEINBERG : $\mu \to e+\gamma$ will happen anyway to second order in weak interactions through the β decay and μ capture interactions, and it will happen in third order through the μ decay interaction alone. So, probably e-ν scattering is irrevelant to the question of why $\mu \to e+\gamma$ does not happen.

THE PROGRAM OF " NEUTRINO EXPERIMENTS " AT CERN

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The title of this short report indicates clearly that so far very little has been done at CERN in this direction.

Furthermore, I consider it quite probable that the " present-day program " will be substantially modified during the next three or four months before an effective start of the experiments is made.

I could say that our investigations, so far as they have gone, have been very encouraging. As you know, the idea of this kind of experiment was put forward by Pontecorvo and later, independently, by Schwartz [1]. The proposal was made by Pontecorvo at the Kiev Conference and was published a few months later [2, 8].

The more well-known proposal is to use high-energy neutrinos produced in the decay in flight of high-energy pions as a probe to investigate and to extend our knowledge of weak interactions. This knowledge is limited to threshold reactions as, for instance, in the experiment of Reines and Cowan [3].

In his paper Pontecorvo particularly emphasized a test of the identity of the two neutrinos, ν_μ and ν_e emitted in the two reactions