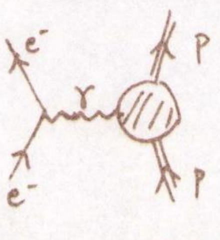
PAPER No 4

THE POSSIBILITY OF NEUTRINO EXPERIMENTS

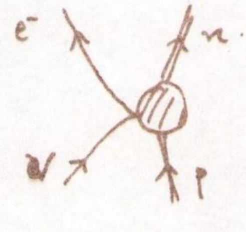
1. GENERAL CONSIDERATIONS

The neutrino is a mysterious particle. It is also likely to be an exciting particle to work with, for even if no basic surprises come in neutrino physics, it provides as clean and, possibly, as important a probe for the study of the structure of other elementary particles as a photon. This type of study, initiated by Hofstadter's experiments, will certainly become one of the main features of high energy physics in the immediate future. (Figure 1)

For this purpose it is essential to use machine, rather than pile, neutrinos, since there are strong theoretical grounds for expecting neutrino cross-sections to rise rapidly with energy, and reach a value of about 10^{-38} cm^2 at about 1 GeV (see below). Another reason for concentrating on accelerator neutrinos (rather than pile neutrinos) is the distinct possibility that the ν in μ-decay may be different from that in β-decay.



$e^- + p \rightarrow p + e^-$ (Hofstadter)
giving e.m. structure of proton.



$\nu + p \rightarrow e^- + n$
giving ν-structure of nucleon

Figure 1.

2. SEMI-QUANTITATIVE CONSIDERATIONS

(i) Thresholds

Typical ν induced processes with threshold energies below 1 GeV are

$$\bar{\nu} + p \longrightarrow n + e^+ \quad (\mu^+)$$

$$\longrightarrow n + e^+ + \pi^0.$$

$$\longrightarrow \Lambda + e^+ + K^0.$$

$$\longrightarrow \Lambda + e^+ (\mu^+)$$

$$\Sigma^0 + e^+ (\mu^+)$$

$$\nu + e \longrightarrow e + \nu$$

The threshold for production processes on electron targets

Process	Threshold (GeV)
$\bar{\nu} + e^- \longrightarrow \mu^- + \bar{\nu}$.	11
$\longrightarrow \pi^- + \pi^0$.	74
$\longrightarrow k^- + \pi^0$	400
$\longrightarrow k^- + k^0$	960

Since even the CERN proton synchrotron ($\sim$ 30 GeV) gives its main neutrino beam in the 1 GeV region, these processes will not be considered further.

(ii) Perturbation Theory

Consider the process

$$\nu + n \longrightarrow p + e^-.$$

Assume a point Fermi interaction, with coupling constant (given by β-decay)

$$G = 10^{-5}/M^2 ,$$

where (in units $\hbar=c=1$) M = 1 nucleon mass,

$$\triangleq \quad 1 \text{ GeV} ;$$

$$1/M \triangleq 2\times10^{-14} \text{ cm}.$$

At the extreme relativistic limit, $(P > M)$,

$$\sigma_{\text{Pert}} \simeq G^2P^2$$
$$\simeq 10^{-38}\left(\frac{P}{M}\right)^2 \quad \text{cm}^2, \qquad (1)$$

where P is c.m momentum, $(P^2 \sim E_{lab})$, (i.e. cross section rising linearly with Lab energy).

(iii) Limitations on Perturbation Estimate

(a) That this perturbation theory estimate must be completely incorrect for high energies and that the cross section cannot rise indefinitely, is easy to see on general grounds. The theory which led to the above estimate assumes a point interaction and therefore only S and P-waves at all energies. By simple unitarity arguments this means that in any case $\sigma_{max} \lesssim 4\pi \lambda\!\!\!^{-2}$

Thus (1) can be valid at most for values $P \lesssim 100\ M \gtrsim 100$ Gev, corresponding to $\sigma \sim 10^{-33}\ cm^2$.

(b) A more stringent restriction comes from the finite size of the proton. That the proton has some effective size is to be expected from relativistic quantum theory, and has been directly confirmed, using photons as probe particles, by the Hofstadter's experiments. As stated above, the measurement of the effective size of the nucleon for neutrino interactions will be one of the main objectives of neutrino experiments. (See Figure 1 . p 1).

The cross section for an effective radius, r, can be estimated simply, since the forward scattering is as in perturbation theory, but the scattering is now confined to a small forward cone of angle given by the first diffraction minimum,

$$\theta \sim \frac{1}{Pr} .$$

$$\sigma_r \approx G^2\ P^2 .\ \theta^2 \approx \frac{G^2}{r^2} = \frac{10^{-10}}{M^2} \left(\frac{1}{rM}\right)^2 .$$

$$= 10^{-38} \left(\frac{1}{rM}\right)^2 \quad cm^2 ,$$ (constant with energy).

A reasonable order of magnitude estimate is

$$r = \frac{1}{M} \simeq 10^{-14} \quad cm ,$$

so that we arrive at an estimated "elastic" cross section

$$\sigma_{el.} \simeq 10^{-38} \quad cm^2$$

for all energies above a certain minimum. More detailed calculations by Yamaguchi indicate that this maximum is reached at

$$E_{lab} \simeq M \simeq 1.\ GeV.$$

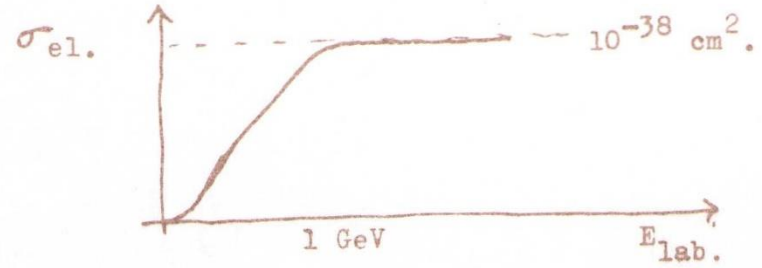


Fig.2.

(c) A still further reduction in the cross section is to be expected if the Fermi interaction itself is non-local by $(1/_B)$. In this case, we must make the replacement $G^2 \longrightarrow \dfrac{g^4}{(p^2+B^2)^2}$ in (1) where the coupling strength, g, and the mass, B, of the intermediary particle mediating weak interactions are connected by

$$\frac{g^2}{B^2} \sim 10^{-5}/M^2 \ .$$

This will give rise to a momentum dependence of $\sigma \sim \frac{1}{p^2}$ for $p \gg B$.

(iv) Inelastic Processes

Perturbation theory gives even more rapid increase with energy for production processes with three or more particles in the final state. However similar (but less precise) considerations suggest that cross-sections will again be the order of magnitude estimated above (10^{-38} cm^2). In any case it is not at all to be expected that the opening of a new channel will give a similar boost each time it occurs to σ_T as shown in Fig.2 for the elastic case. Quite roughly one may expect that at best $\sigma_T \simeq n \times \sigma_{el}$ where n is the number of open channels at a given energy.

3. CONCLUSIONS

These figures indicate that neutrino experiments, although difficult, are not impossible and development along these lines is already being seriously considered at CERN with the existing P.S. machine.

Three important general considerations emerge.

(1) Neutrino experiments require very intense beams (the CERN P.S. giving a lower limit at which such experiments become feasible).

(2) An increase in energy in the range 1 - 10 Gev is not likely to increase σ_T, but will certainly add complexity to the physical processes observed and to their theoretical interpretation.

(3) Any machine giving an intense π beam (which is what is required generally for strange particle physics) automatically gives rise to neutrinos.

Our general conclusion is thus that the idea of neutrino experiments does not indicate the necessity for any special type of machine, but gives an additional and powerful reason for the serious consideration of any technique promising increased intensity of π's. (and consequently μ's, k's. hyperons and ν's) in the 5-10 GeV region.

Such a machine would clearly have to offer an improvement by a large factor on Nimrod, before it could be seriously considered. Failing this a strong case could be made out for high intensity electron machine in the same energy region. This would certainly be of value in 'conventional' strange particle physics, and might be used in the new neutrino field by the study of the process

$$e^- + p \rightarrow n + \nu.$$

$$(\text{or even } e^+ + n \rightarrow p + \nu)$$

(giving the same information as the reverse process considered in some detail above).

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