MARKOV : No, I do not agree with you. According to the " pillow-effect " discussed here you can receive an important contribution from 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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$Z \rightarrow (Z-1) + e^+ + \nu_e \qquad (1)$$

Lee and Yang [4)], refering to the possible existence of an intermediate heavy charged boson, discussed all relevant problems which may find an answer when these experiments are approached systematically. Three theoretical papers came out almost simultaneously: by Cabibbo and Gatto [5)], Yamaguchi [6)], and Lee and Yang [4)]. These three papers have in common the calculation of cross sections for high-energy neutrinos, in the pessimistic case, that is if the heavy boson does not exist.

I want to discuss the feasibility of neutrino experiments from this probably very pessimistic point of view. As far as these calculations are concerned, the cross section is supposed first to increase, mainly according to the available phase space, i.e. approximately as the c.m. energy, and then to level-off due to the influence of form factors. The calculations have been made in terms of a " point interaction " with cut-offs extracted from the Hofstadter nuclear form factors

$$F_1(k^2) \simeq F_2(k^2) \approx \frac{1}{\left(1+\frac{1}{12}q^2\alpha^2\right)^2} \qquad (2)$$

where q is the invariant four-momentum transfer and $\alpha = 0.8\times10^{-13}$ cm. To make these calculations, which imply a bold extrapolation from threshold behavior to high energies, several explicit assumptions are made. They are suggested by the Feynman-Gell-Mann and Marshak-Sudarshan *V-A* theory and correspond to symmetry requirements introduced into the single spacetime point Lagrangian. We may say that they are imposed for the following reasons. *Firstly*, to relate in an explicit manner the matrix elements of the two reactions

$$\left.\begin{aligned} \nu+n &\rightarrow p+e^- + \text{pions} \\ \bar{\nu}+p &\rightarrow n+e^+ + \text{pions} \end{aligned}\right\} \qquad (3)$$

that is, to link the current operators

$$J_\lambda \text{ and } J'_\lambda$$

which convert a neutron into a proton, and vice versa also where strong interactions are present. (It is known that this symmetry is experimentally present at low energies.) *Secondly*, to relate a reaction such as

$$\left.\begin{aligned} \nu+n &\rightarrow e^- + p \\ \bar{\nu}+p &\rightarrow e^+ + n \end{aligned}\right\} \qquad (4)$$

to the electron-nucleon scattering experiments. This implies a proportionality between the electromagnetic current and the isotopic vector part of J_λ. With this or an equivalent assumption, the differential cross sections for the reactions (4) can be written as follows:

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{g_v^2}{\pi}\,\frac{E_v^2}{\left(1+\frac{2E_v}{M}\sin^2(\theta/_2)\right)^3}\Sigma(\theta, E_v) \qquad (5)$$

where E_v is the neutrino lab energy and θ the ν-e angle. $\Sigma(\theta, E_v)$ is the expression depending upon form factors, and g_v the vector coupling interaction constant.

The total cross section in the low-energy limit vanishes as E_v^2 and at high energies tends to a constant limit for $q^2 > 1/\alpha^2$.

Actually, instead of only one cut-off, one may consider three cut-offs: two, F_1 and F_2, for the vector part to be practically identified with the Hofstadter form factors, and one F_3 for the axial part of the interaction. If the corresponding cut-offs are $\alpha_1 = \alpha_2 = \alpha_V$ and $\alpha_3 = \alpha_A$

$$\sigma_{\text{total}} = \frac{g_V^2}{6\pi}\alpha_V^2\left\{1+\frac{(\mu_p-\mu_n)^2}{8}\,\frac{\alpha_2^2}{M^2}\right\}+\frac{g_A^2\alpha_V^2}{6\pi} \qquad (6)$$

$$\text{for } E_v > 1/\alpha$$

Fig. 1 shows the results of these well-known calculations for $\alpha_1 = \alpha_2 = \alpha_3 = 0.8\times10^{-13}$. One only has to remember that the difference between σ_ν and $\sigma_{\bar{\nu}}$ is due to the interference terms among the contributions proportional to F_3 and to $F_1+(\mu_p-\mu_n)F_2$. Fig. 1 shows that the maximum value of σ_{tot} for which we may reasonably hope for reaction (4) is of the order of 10^{-38} cm^2. Adding all possible other reactions such as

$$\bar{\nu}+p \rightarrow e^+ + \text{nucleons} + n(\pi)$$

$$\nu+p \rightarrow e^+ + \Lambda + n(\pi) \text{ etc.}$$

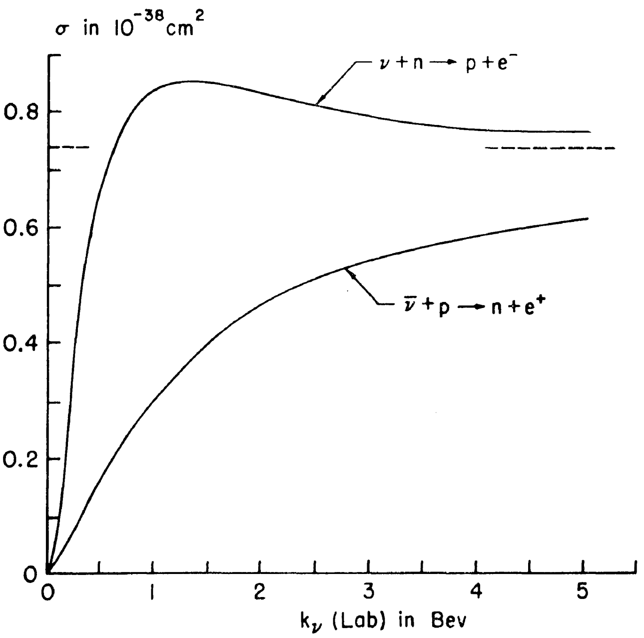

Fig. 1 The $\nu+n\rightarrow p+e^-$ and $\bar{\nu}+p\rightarrow n+e^+$ cross section as a function of k_ν.

one may increase this estimate by a factor $\lesssim 3$. This corresponds to an astronomical mean free path and justifies some of the diffidence that surrounds the idea of this kind of experiment. I want to spread some optimism. I have essentially two reasons for wanting to do this. *Firstly:* the high intensities quickly reached by the new A.G. accelerators at CERN ($\gtrsim 2\times10^{11}$ circulating protons per pulse every three seconds) and at Brookhaven. *Secondly:* the very impressive problem of background and shielding is, in my opinion, much less difficult than generally believed. To begin—a crude but not bad procedure—is the following: one considers a target inside a straight section of the machine, ignoring at first the influence of the magnetic field. One ignores this influence and assumes a target hit by a 25 GeV proton, one can estimate in several ways the flux of charged pions of both signs and of all energies emitted per unit solid angle around 0° with respect to the incident proton direction. Essentially they refer to the angular distribution of the emitted pions and to the target efficiency for producing pions, i.e. the total fraction of energy lost by the proton in the target. To assume an angular distribution corresponding to the isotropy in c.m. would be erroneous and depressing; we know that the distribution is not isotropic. Thus, for instance, it is better to make use (as Steinberger did [7]) of the measured average momentum transfer which has been found to be 500 MeV/c in the 16 GeV π^--p collisions in H_2 bubble chambers [7]. This momentum transfer is supposed to be the same as in p-p collisions. One can similarly use the information provided by the emulsion group at CERN, or finally one can make use, as I did, of the photon spectrum originated by π^0's. This photon spectrum obviously, (if charge independence is correct), provides genuine and direct information on the pions emitted by any target when the magnetic field is neglected. Several persons (Citron and Hine, Salvini, Stermayer, etc.) have pointed out this fact quite a while ago. Then the correct procedure is that which is now being carried out by Krienen, Salmeron and Steinberger: with a computer program they are calculating the orbits of pions, at several energies and of both signs, for several target positions in several straight sections. This is quite laborious and they take into account both horizontal and vertical focusing. The results are not yet complete.

Much cruder procedures have been previously followed by Faissner, Hyams, Love and myself to get a preliminary orientation. Fortunately, I have been told by Salmeron that most probably the final results of the refined calculations in progress will not differ from the crude estimate I made by more than a factor of two [9].

(1) Taking into account the behavior of the cross section with energy, one is at present interested in neutrinos with energies ≈ 0.5 BeV or higher.

(2) Taking kinematics into account the energy E_π of a pion producing a neutrino whose energy is E_ν, must be

$$E_\pi \gtrsim 2.34 E_\nu$$

The lab. energy of a neutrino emitted by a pion of energy γm_π is given by

$$E_\nu = \gamma p^*(1+\beta_\pi \cos\theta^*)$$

where

$$p^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.78 \text{ MeV/c}$$

is the c.m. momentum.

So $\quad E_\nu(\max) \cong \dfrac{E_\pi}{2.5} \quad$ and $E_\nu(\min) \approx 0$.

In the lab frame the angle is

$$\tan\,\theta_\nu = \frac{\sin\theta_\nu^*}{\gamma(\cos\theta^* + \beta)}$$

and the neutrino energy drops rapidly when the lab angle increases. Actually

$$E_\nu = \frac{p^*}{\gamma}\,\frac{1}{(1-\beta\cos\theta)}.$$

Thus the high-energy neutrinos will all make very small angles with the direction of the parent π.

(3) Taking into account some results of the surveys on beams mentioned by Cocconi, at least with the Al targets used so far, the pion spectrum does not change too much at least within the angular range of $\sim\pm 5°$.

(4) For intensity reasons, the useful pions are those between $\sim$2 and $\sim$5 BeV. These pions, if negative, suffer a fairly high dispersion in the magnetic field. If they are positive for the same exit angle θ from the target, the asymptotic divergences are of the order of one or two degrees. The target can then be roughly considered as the origin of lines sources (the decay paths) uniformly distributed in a cone of about 15° total angle, in which the 2-5 BeV pions provide most of the neutrinos. In this matter, at an optimum distance from the target which turns out to be 40-70 m, and which is determined by the density of the screening material (heavy concrete): one finds a neutrino flux $\Phi_\nu = 0.7$ neutrino per interacting proton per steradian[10]. Assuming a circulating proton beam of 2×10^{11} (as it is at present), and a target efficiency of about 50%, at a distance of about 60 m (30-40 m of path, 20-30 m of screening), one finds a neutrino flux[10]

$$\Phi_\nu(60\,\mathrm{m}) \approx \frac{10^{11}}{36\times 10^5} \approx 3\times 10^3/\mathrm{cm}^2-\mathrm{pulse}.$$

With an average $\sigma_{\mathrm{tot}} \approx 3\times 10^{-38}$ one finally finds that the number of neutrino interactions in a detector is $\eta \approx 2$ interactions per-ton-per-day. This number is quite small, as expected; an external beam can improve the situation but not too much. Apart from the extraction efficiency, and interaction efficiency, the fraction of positive pions contributing to the neutrino flux will not change radically. More anti-neutrinos are supplied by negative pions but they have an unfavorable σ_{tot}.

However, with the available bubble chambers of Lagarrigue and Rahm containing 1 ton of liquid freon, some fundamental questions can have a quick answer: for instance, the birth inside the chamber of a single high-energy ($\gtrsim$0.5 BeV) positive electron will establish the identity of ν_e and ν_μ. Further, detectors of 5-10 tons seem possible at present. Several proposals have been made and analyzed in some detail by Faissner and Hyams. Of course, they will not provide as complete a picture as the bubble chamber, but some essential information will be available as to the distinction between high-energy μ and e, and the counting rate will be one order of magnitude higher.

The development of the spark-chamber has very seriously been considered. What I learned from Cronin was quite encouraging. Schneider of the CERN group is now interested in the problem.

There remains the question of the background. As I said at the beginning, it does not seem too serious, but it has already been seen that there are some limitations, and some 10-ton detectors cheerfully considered at the beginning (for instance, those based on thousands of Geiger counters or on the Conversi hodoscopes) may already be ruled out if they are not accompanied by some clever device able to make a sharp selection in time.

The background around the Proton Synchrotron at CERN has been investigated by sandwiches of counters viewed by fast scopes (Faissner, Hyams, Love) with the kind assistance of Hahn and his small freon chamber, by Krienen, Salmeron and Steinberger. It was found that a shield of 15-20 m of heavy concrete in the forward hemisphere, as well as 2-3 m of concrete on the sides and equivalent shielding on top, will be sufficient to reduce the number of confusing events (mostly due to residual fast neutrons) to about 1% of the expected real events. Counters, and particularly the bubble chambers, showed that there exists a residual heavy background associated with very small pulses or recoiling tracks. Probably they are due to slow neutron captures. However, this background is not dangerous for the bubble chamber or for an equivalent visual technique, although it might be quite serious for a more or less conventional counter or hodoscope array, if a time resolution will not improve the discrimination.

Finally, it might be pointed out that (i) in a ~5 ton ~5 m detector, the distribution of the events can be used to discriminate the residual forward background from neutrino interactions; and (ii) layers of magnetized iron can be used (for instance, in spark-chambers) to provide an intense magnetic field distributed along the detector. This seems particularly promising if associated with a spark-chamber device.

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5. Cabibbo, N. and Gatto, R. Nuovo Cimento **15**, p. 304 (1960).
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7. Steinberger, J. CERN Internal Report (PS/int/6015).
8. During and after the discussion which followed my report, I learned that many others had put forward the idea of experiments with high energy neutrino beams. Particularly M. A. Markov "Hyperonen and K-mesonen" Verlag der Wissensc-haften, Berlin (1960); Fakirov, D. "On Spacial Distribution of the Neutrino Beam Generated by High Energy Nucleon Collisions". Faculté des Sciences de Sofia **53**, livre 2 (1958/59), and others. At this point the only thing that I may say with certainty is that I did not have this idea.
9. To those who heard about Steinberger's early calculations, I may say that the two figures are not inconsistent. My figure is a factor 10 lower than that given in the Steinberger report, because in that report the influence of the magnetic field was not considered.
10. In these calculations, if $N_\pi(p, \theta)$ is the distribution in momenta and angle of the out-going charged pions (and neutral, if charge independence holds) from the primary proton beam, the corresponding energy spectrum of the neutrinos at a distance L from the target, is

$$N_\pi(p, \theta, L) = p^* \int n_\pi(p, \theta) \left\{ 1 - \exp\left(-\frac{Lm}{ep} \right) \right\} \frac{dp}{p}$$

where $L = \tau c$. The previous expression differs from the corresponding expression for the γ's produced by the π^0 only by the value of p^* and the term which vanishes. The correlation of the two is then used to express the energy flux of neutrinos in terms of the energy flux of quanta. Due to the assumed flat behavior of the cross section for neutrinos energies $E_\gamma \gtrsim 0.5$ BeV, this is very sensible and is equivalent to introducing a number of "equivalent neutrinos" as is customary to do for "equivalent quanta". The effective calculations have been done numerically starting from the experimentally measured photon spectrum.