NEUTRINO PHYSICS

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I. INTRODUCTION

Experiments are currently under way with neutrino beams from accelerators, from reactors, and from natural sources such as the sun (and, hopefully, other cosmic sources) and those generated by the impact of cosmic rays on the atmosphere. Stars and reactors are sources of electron-neutrinos ν_e (or $\bar{\nu}_e$); the atmosphere and proton synchrotrons are predominantly sources of muon neutrinos ν_μ (or $\bar{\nu}_\mu$). I have assumed that people here are more interested in the accelerator experiments, and I shall concentrate on this aspect. If time permits, I shall mention briefly the work on neutrinos from space and from reactors. In particular, I would emphasize that study of cosmic neutrinos will be enormously difficult but of vital importance to our understanding of the evolution of stars and other objects, and indeed the universe as a whole.

The first phase of high-energy neutrino experiments at accelerators has now been almost completed. A great deal of hard work has given us a considerable body of information about neutrino interactions, not generally of a precise nature, but adequate enough to serve as a basis for planning the more sophisticated experiments of the future. From such a survey, a number of hard lessons have been learned. The next phase of neutrino experiments, before it can start in earnest, will have to await the fulfilment of extensive programmes of machine development and other devices to boost the neutrino fluxes by one to two orders of magnitude, and the building of giant bubble chambers and more elaborate spark chamber detectors. All three laboratories at present committed, namely Argonne, Brookhaven, and CERN, have very similar development programmes, likely to mature in 1969/70.

Neutrinos can interact with matter in two ways: either through the first-order weak process, the classical four-fermion interaction, or through a second-order process involving the induced electromagnetic properties of the neutrino. Either way, assumptions need to be made about the basic properties of neutrinos, and we list these below.

The weak interaction is assumed to be of the current-current type, and involves interaction of the lepton and/or baryon currents. It is useful to consider lepton and baryon currents separately; the latter involve properties of strong interactions, and from both the theoretical and experimental points of view are, therefore, more complex. So, in these seminars I shall consider the following main topics:

i) basic properties of neutrinos;

ii) neutrino interactions - physics problems relating to lepton currents;

iii) neutrino interactions - physics problems relating to weak baryon currents; summary of (ii) and (iii);

iv) technical innovations necessary to investigate these problems at accelerators;

v) related topics, e.g. reactor and extra-terrestrial neutrino experiments.

II. BASIC PROPERTIES OF NEUTRINOS

a) Mass

From the shape of the end-point of the Kurie plot in tritium-β decay[1] one obtains $m_{\nu_e} < 0.2$ keV assuming the two-component theory[2] (and $m_{\nu_e} < 0.7$ keV with less restrictive assumptions).

For ν_μ, the existing values of the mass limit are $m_\nu < 3$ MeV from kinematics of $\pi \rightarrow \mu + \nu_\mu$[3], < 4 MeV from the end-point of the electron spectrum in $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$[4], and < 6 MeV from the reaction $\mu + He^3 \rightarrow H^3 + \nu_\mu$[5]. $\pi \rightarrow \mu$ decay yields the best information, but even here the prospects of reducing the limit by even a small factor look dim. Dennery and Primakoff[6] have suggested going to a low Q-value three-body decay, such as $\Lambda \rightarrow \mu^- + p + \nu_\mu$, and determining the spectrum shape at the end-point, as in tritium decay. But the experimental difficulties are formidable, and one is also at the mercy of largely unknown form factors.

As is well known, according to the two-component theory, the masses of ν_e and ν_μ should be zero in order for them to have unit helicity invariant under a Lorentz transformation. But existing experimental data do not prove that the neutrinos do not have finite masses. In view of the riddle of the μ, ν_μ and e, ν_e duality, accurate measurements of the mass of ν_μ are clearly of great importance.

b) Charge of ν_e and ν_μ

Experimentally, it is established that the difference between the charges of the neutron and the hydrogen atom is $< 10^{-19}$ e [7]. From the neutron-β decay it follows that $q_{\nu_e} < 10^{-19}$ e.

The charge of the muon may be determined by combining information on the energy levels of μ-mesic phosphorus (yielding $m_\mu q_\mu^2$), with that from Larmor precession frequency and the gyromagnetic ratio (yielding m_μ/q_μ). The deviation from the electronic charge is $\Delta e/e < 5 \cdot 10^{-6}$ Since the charge on the pion is known to 1 in 10^{19}, it follows by charge conservation in $\pi \rightarrow \mu + \nu$ that $q_{\nu_\mu} < 5 \cdot 10^{-6}$ e.

c) Spin and helicity

We know that both muon and electron have spin ½. Conservation of angular momentum in weak decay processes shows the component of neutrino spin along the direction of motion must then be ± ½. If the neutrino mass is zero, this implies a spin of ½. According to the two-component theory ($m_\nu = 0$) the helicity $\underline{\sigma} \cdot \hat{\underline{p}}$ must be ± 1 (for $\bar{\nu}$ and ν, respectively). The magnitude of the helicity can be inferred experimentally from the longitudinal polarization of the electron or muon; for ν_e and ν_μ these values are > 0.95 and > 0.80, respectively[5].

The foregoing properties are summarized in Table I.

Table I

Neutrino properties

	ν_e		ν_μ	
	Experimental value	Assumed value	Experimental value	Assumed value
Mass	< 0.2 keV	0	< 3 MeV	0
Charge	$< 10^{-19}$ e	0	$< 5 \cdot 10^{-6}$ e	0
Helicity	> 0.95	1	> 0.8	1
Spin	½(m = 0)	½	½(m = 0)	½
Mean square charge radius	$< 10^{-29}$ cm²	$\sim 10^{-33}$ cm²	$< 10^{-30}$ cm²	$\sim 10^{-33}$ cm²

Table II

Lepton number and Muon number

Lepton number:
- $+1$ e^- μ^- ν_e ν_μ
- -1 e^+ μ^+ $\bar{\nu}_e$ $\bar{\nu}_\mu$
- 0 for all other particles

Muon number:
- $+1$ μ^- ν_μ
- -1 μ^+ $\bar{\nu}_\mu$
- 0 for all other particles

III. PROBLEMS RELATING TO LEPTON CURRENTS

These will be considered under the headings:

a) Conservation laws; lepton and muon number; neutrino flip.
b) Non-locality; the intermediate boson.
c) Neutral currents; charge form factor of neutrino.
d) Lepton-lepton scattering.
e) e-μ universality.
f) V-A interaction, CP violation.

a) Conservation laws

i) Lepton conservation

Conservation of leptons e, ν_e is well established from the absence of neutrinoless double-β decay[8]. If all leptons are absolutely conserved, the additive quantum number + 1 is assigned to ν_μ, ν_e, e^- and μ^-, − 1 to $\bar{\nu}_\mu$, e^+ and μ^+ (and 0 to other particles). Violation of lepton number would follow if the reactions

$$\nu_\mu + p \rightarrow n + \mu^+ \qquad (1)$$

$$\nu_\mu + p \rightarrow n + \pi^{+*)} \qquad (2)$$

were observed.

In the CERN experiment[9], the signs of particles penetrating the magnetized iron plates in the spark chambers were determined. When the magnetic horn current was set so that the beam consisted predominantly of ν_μ with a small $\bar{\nu}_\mu$ contamination the fraction of positive tracks was 0.027 ± 0.006. The proportion of μ^+ from $\bar{\nu}_\mu$ background was expected to be ≈ 0.02. If lepton conservation is violated with amplitude α, it will occur twice (in the decay $\pi \rightarrow \mu + \nu_\mu$ as well as the ν interaction). Hence, $\alpha^2 < 0.01$.

For reaction (2), the CERN heavy liquid bubble chamber experiment[10] yields an upper limit. For $E_{vis} > 1$ GeV, about 7% of the interactions contain among the secondaries only pions or nucleons (as judged by their ionization or interactions in flight). They are attributed to energetic neutrons generated by neutrinos in the material surrounding the chamber, and their number is consistent with that deduced from neutrino events in the chamber producing neutrons which interact in the sensitive volume. These considerations set a rate for reaction (2) of < 0.05 of the neutrino event rate.

ii) Muon number conservation, neutrino flip

Muon number is violated if the reactions

$$\pi \rightarrow \mu + \nu_e \qquad (3)$$

$$K \rightarrow \mu + \nu_e \quad \text{(neutrino flip)} \qquad (4)$$

*) As pointed out by a participant at this school, this reaction also violates angular momentum conservation.

occur in which e-type neutrinos are associated with muons (see Table II). The observed rates of elastic electron production $\nu + n \rightarrow e^- + p$, to elastic muon production $\nu + n \rightarrow \mu^- + p$, is $1.7 \pm 0.5\%$ (spark chamber), and $1.1 \pm 0.5\%$ (bubble chamber). From the decay mode $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ we expect an electron background rate of $\approx 0.7\%$; this estimate depends on the flux of energetic ν's from K decay, and might be systematically underestimated. In any case, the maximum allowed violation (3) is < 1%, and the maximum allowed neutrino flip rate (4) in $K_{\mu 2}$ decay, i.e., $K \rightarrow \mu + \nu_e / K \rightarrow \mu + \nu_\mu$, is 10%. In conclusion then, the existence of two neutrinos, established by the Columbia group[11] is confirmed and muon number is conserved to within 1%; and the neutrino flip hypothesis, at least in its extreme form, is untenable. Bearing in mind the recent history of CP invariance it would clearly be useful to reduce these limits still further.

b) Non-locality and the intermediate boson

i) Local leptonic interactions

It is generally assumed that the pair of leptons (ν, e) or (ν, μ) occurring in the interaction are emitted or absorbed at the same point in space-time[12,13]. Under this assumption, some very general statements can be made, for example, about the high-energy behaviour of neutrino cross-sections (by general statements I mean that specific assumptions, like T invariance, validity of $\Delta I = 1$ rule, V-A coupling, are not needed). For the process

$$\nu + n \rightarrow \mu^- + N \qquad (5)$$

where N is an assembly of strongly interacting particles, the cross-section has the form $d^2\sigma/dq^2\, dM^{*2} = d^2\sigma/d(q^2)\, d(M^{*2}) = A/E_\nu^2 + B/E_\nu + C$, where q is the four-momentum transfer, M^* is the mass of N, and A, B, and C are functions of q^2 and M^*. In the high-energy limit $d^2\sigma/dq^2\, dM^{*2}$ should then tend to an asymptotic value. Clearly, one would need very large numbers of events to make such tests of local action.

ii) Intermediate boson, W

All experiments to date seem to be consistent with the four-fermion point interaction of the original Fermi theory. Such a point interaction leads to embarrassment in high-energy lepton scattering, since perturbation theory then yields cross-sections increasing as $G^2 \bar{p}^2$ ($\bar{p}$ is c.m.s. momentum, and $G = 10^{-5}/Mp^2$ is the weak interaction coupling constant), whereas ordinary wave theory sets an upper limit of $\pi \lambda\!\!\!^{-2}$ for S-wave scattering. The two cross-sections become equal when $\bar{p} \sim 300$ Mp*). To avoid this, and in analogy with the exchange of photons in electromagnetic interactions and pions in strong interactions, it is postulated that the weak interactions are mediated by a charged vector boson $W^\pm$ (see Fig. 1).

Then the high-energy scattering is confined to small forward angles, and the total cross-section reaches an asymptotic value since momentum transfers $q^2 > M_W^2$ are damped out.

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*) I am informed by Professor Veltman that this so-called violation of unitarity disappears of one considers higher-order terms, as in Fig. 5. Then angular momenta $j > 0$ contribute to σ and the total cross-section flattens off because the higher-order processes introduce the necessary degree of non-locality, independently of whether the W exists or not. However, the idea of the boson is a very natural one, i) by analogy with c.m. and strong interaction, ii) in coupling the (e,ν) and (μ,ν) currents to the same boson field, and accounting for e-μ universality.

To find the W boson was the principal goal of the CERN experiment, and at one stage it was even thought to be "in the bag"*). However, it is now agreed that there is no present evidence for its existence, and one can only set lower limits on the mass[10,14]. Since this topic is of crucial importance, it is worth while discussing the experiments in some detail.

In high-energy neutrino experiments the boson would be produced (if at all) through the process as shown in Fig. 2. Since the coupling involved $(G^{1/2}\alpha)^2$ is greater than for the elastic process, (G^2) (Fig. 1), the cross-section can become quite large at high neutrino energy ($\sim 10^{-37}$ cm²/nucleon). The W decays in 10^{-18} sec (rate α M_W^3) into leptons, pions, etc. Limits on the mass have been set by comparing the observations with the rate expected[15] for different M_W integrated over the neutrino spectrum, making use of the production kinematics[16] and assuming branching ratios for the different decay modes:

(i) In the CERN spark chamber experiment events which might be attributed to $\nu \to \mu^- + W^+ \to \mu^- + \mu^+ + \nu$ were examined. Several criteria were applied to select such events, e.g. one should have a pair of penetrating non-interacting particles of opposite electric charge for which the magnetic deflection and range are consistent with the muon mass. A total of 33 such events were observed in a sample of 5000 total. It was observed that the positive members of the pairs had a range spectrum peaked to low values, quite different from that expected for the μ^+ from W decay. Most of the 33 events were therefore background which was removed by imposing a range cut-off. If B denotes the partial decay rate of W into leptons $(e,\nu$ or $\mu,\nu)$, then for B = 0.5 and M_W = 1.9 GeV, 6 - 7 events with μ^+ range exceeding the cut-off were expected, and none observed**).

(ii) In the bubble chamber the positron decay $W^+ \to e^+ + \nu$ could be readily observed. No event definitely attributable to such a process has been seen in a total of 700. For B = 0.5, $\approx$ two events are expected if M_W = 1.9 GeV. The mass limit thus obtained is therefore slightly inferior to that above from the spark chamber. Evidence for the non-leptonic decay of $W^+ \to \pi$'s, $K\bar{K}$, etc., has also been sought in the bubble chamber events. The invariant mass distribution of π's, etc., in events of $E_\nu > 6$ GeV and mesonic charge +1 has been plotted. Four events have invariant mass > 1.2 GeV. Now, in Fig. 2, the relative energies of W^+ and μ^- in their common centre of momentum system is small because the reaction occurs near threshold. Hence, the momenta of μ^- and W^+ in the laboratory system are roughly proportional to their masses. Since $M_W >> m_\mu$, this means that the μ^- spectrum in boson events should be peaked to low energy. In only one of the four events is $p_{\mu^-} < 2$ GeV/c, whereas with M_W = 1.9 GeV and B = 0 (i.e. all non-leptonic decay of W), 4.5 boson events with $p_{\mu^-} < 2$ GeV/c would be expected.

Combining the spark chamber and bubble chamber results, the CERN group concludes that, to a confidence level of 99%,

$$\underline{\underline{M_W \geq (1.7 + 0.4\ B)\ \text{GeV}}} \quad ,$$

where 0 < B < 1 is the leptonic branching ratio $W \to \ell + \nu / W$ total. For such values of M_W, one expects B to be fairly small, of the order of 10%[17].

*) I am indebted to Prof. O. Piccioni for this colourful expression.

**) The calculated rates[15] depend somewhat on assumptions about the magnetic moment of W, but not sufficiently to affect the conclusions.

It should be noted that the above limit was deduced on the assumption that W production is elastic (Fig. 2). If "inelastic" production is important, the mass limit derived from leptonic decay rates will be increased.

The conclusions from the most recent Columbia spark chamber results[18] are essentially the same as those from CERN. So, it can now be conclusively stated that $M_W \geq 1.7$ GeV.

If one plots the boson production rate as a function of mass and neutrino energy for the CERN neutrino spectrum (see Fig. 3), it will be seen that (a) the maximum event rate occurs at $E_\nu \sim 4\ M_W$, (b) this rate falls off exponentially with M_W. Thus, if the value of $M_W = 3$ GeV, it would be extremely difficult to detect such a particle by these means with presently existing proton synchrotrons. If $M_W \gg M_p$, the production threshold $(E_\nu)_{thresh} \sim M_W^2/2M_p$, so that at a proton energy of 70 GeV the lower limit on mass which could be set in a neutrino experiment comparable to that at CERN would be $M_W \sim 5$ GeV. Other methods[19] of producing the W boson have been proposed (e.g. in strong interactions) and one hopes that these will be more successful than the neutrino experiments.

c) Neutral currents, charge form factor of neutrino

Elastic (non-charge-exchange) scattering of neutrinos could occur by two processes:

i) Neutral currents

If a neutral counterpart to the charged boson existed elastic scattering could occur through the reaction as shown in Fig. 4.

No such terms are observed in decay processes involving strange particles, e.g. $K \to \pi + \nu + \bar{\nu}$, and one can conclude that the amplitude is $< 10^{-3}$ of that for charge-exchange scattering. The CERN neutrino experiments set poorer limits for neutral current coupling in non-strange weak interactions at high q^2. In the bubble chamber analysis the number of events which could be ascribed to $\nu + p \to \nu + p$ were compared to those representing the "normal" elastic process $\nu + n \to \mu^- + p$. In order to exclude neutron background it was necessary to consider events in both categories, of proton kinetic energy > 250 MeV, i.e. $q^2 > 0.5$ GeV^2. The ratio $\nu p \to \nu p / \nu n \to p\mu^- < 2\%$ was observed. Thus, $\sigma_{\nu p \to \nu p} < 10^{-40}$ cm^2.

ii) Charge form factor

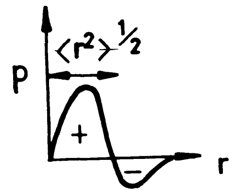
A neutrino may, $\approx 10^{-5}$ of the time, be considered virtually dissociated into charged particles and thus undergo electromagnetic scattering, for example see Fig. 5. The magnitude of this contact electromagnetic interaction is found essentially by replacing the weak charge G by $G\alpha$, where $\alpha^{-1} = 137$.

The current describing the interaction of neutrino with the electromagnetic field in general contains four form factors (charge and magnetic moment distribution). In the V-A theory ($m_\nu = 0$), only one form factor is required (magnetic and electric dipole moments vanish), which can be interpreted in terms of a charge radius

$$F(q^2) = -\frac{e}{6}\, q^2 \langle r^2 \rangle ; \quad [F(0) = 0] \quad . \qquad (6)$$

From the experimental result above, one obtains

$$\langle r^2 \rangle \leq 5 \cdot 10^{-31} \text{ cm}^2 ,$$



The moment of charge $M = e \langle r^2 \rangle$ has been computed[20] for the diagram of Fig. 5, for a W with zero anomalous magnetic moment:

$$M \approx \frac{3eG}{8\sqrt{2}\,\pi^2} \cdot \left[\tfrac{5}{3} \ln 137 - 2 - \tfrac{8}{3} \ln \frac{M_W}{m_\ell} \right] . \qquad (7)$$

If M_W is large, the value of M does not differ too greatly for $m_\ell = m_\mu$ and $m_\ell = m_e$. For example, for $M_W = 5$ GeV, $\langle r^2 \rangle = 0.5 \cdot 10^{-33}$ cm^2 for ν_μ, and $2.2 \cdot 10^{-33}$ cm^2 for ν_e. Notice that the present experimental upper limit for ν_μ is well above this.

To summarize, the cross-section for $\nu + p \rightarrow \nu + p$ is down by a factor of the order $\alpha^2 \approx 10^{-4}$ on the cross-section for $\nu + n \rightarrow \mu^- + p$. Observation of such processes will therefore be very difficult, but of the greatest importance, in connection with the existence and mass of the W boson and its electromagnetic properties.

d) Lepton-lepton scattering (Fig. 6, a and b)

For neutrinos the cross-section for scattering by electrons for a point interaction is

$$\sigma = \frac{G^2}{\pi} \cdot (\text{c.m.s. energy})^2 = \frac{G^2}{\pi} (2mE_\nu + m^2) \text{ cm}^2 \qquad (8)$$

where m = electron mass, E_ν = laboratory neutrino energy, and $G = 10^{-5}/M_p^2$ is the Fermi coupling constant. The conditions under which this formula holds are:

i) $E_\nu > (E_\nu)_{\text{threshold}} = \dfrac{m_\ell^2 - m^2}{2m}$, m_ℓ = mass of charged lepton

$= 0$ for ν_e

$= 10$ GeV for ν_μ .

ii) $E_\nu \ll M_W^2/2m = 6250$ GeV for $M_W = 2.5$ GeV. Thus, for neutrinos from accelerators the maximum $q^2 \ll M_W^2$ and any deviation from a point interaction due to the intermediate boson is negligible.

For antineutrinos the cross-section above is reduced by a factor three. The cross-section is proportional to target mass, and hence, at a given E_ν, is reduced by a factor $\sim 10^3$ compared with that for a nucleon target. This fact, together with the high threshold energy, will make the reaction of Fig. 6b exceedingly difficult to detect. The corresponding reaction (Fig. 6a) with ν_e would also give exceedingly low event rates, especially since the ν_e flux from a proton accelerator is only a few per cent of that of ν_μ. Lee and Sirlin[21] have pointed out that, in the case of ν_e, there is an interference term arising through the electromagnetic scattering which would allow a determination of the ν_e charge radius.

One concludes that the observation of lepton-lepton scattering using neutrinos from existing accelerators will require beam intensities $10^4 - 10^5$ greater than those now existing, and will not therefore be possible.

e) e - μ universality

Near $q^2 = 0$, the equality within 1% of the couplings of the (e,ν_e) and (μ,ν_μ) currents is demonstrated, (i) by the value of the $\pi \to e + \nu/\pi \to \mu + \nu$ branching ratio, and (ii) by the equality of the coupling constant in the decay $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ and the vector coupling in nuclear β decay. In other words, all the leptons seem to carry the same unit of weak charge irrespective of muon number.

This universality of the weak coupling of leptons has been investigated at $q^2 > 0$ in the CERN neutrino experiment. The q^2 distribution of events attributed to $\nu_e + n \to e^- + p$ can be found from the spark chamber data since the electron energy and angle can be estimated to within $\sim$ 30%. For the reaction $\nu_\mu + n \to \mu^- + p$, the best data comes from the bubble chamber experiment. Figure 7 shows the electron data (30 events) and muon data (90 events). All one can say is that the two q^2 distributions are consistent with each other within the large statistical errors.

f) V-A interactions, CP violation

According to the V-A theory of the structure of lepton currents, the leptons are longitudinally polarized to a degree v/c, and this maximum degree of parity violation is confirmed to high (1%) accuracy in low q^2 decay processes. Possible deviations from this rule at high q^2 (i.e. in neutrino interactions) require a measurement of the polarization of the charged lepton; for a $\bar{\nu}_\mu$ beam the decay angular distribution of the stopping μ^+ analyses the polarization. The experimental problem is largely one of statistics, in that the high q^2 ($\sim$ 1 GeV^2) events are rare, and the muon must be brought to rest in the detector (without depolarization). Such a measurement could be done in a high-field heavy liquid bubble chamber, but, to measure the polarization within 10% at least 10^3 useful events, out of a total bank of 10^5 antineutrino events, would be required. This number should be compared with a total of 200 $\bar{\nu}$ events which would have been obtained in the CERN chamber if all running time to date had been devoted to antineutrinos. An improvement factor of $10^2 - 10^3$ times would be needed to make such an experiment feasible. The spark chamber technique would perhaps be more suitable in that the sensitive mass and stopping power for muons could be much greater.

The violation of CP invariance would result in polarization of the muon transverse to the production plane. For the elastic reaction $\nu + n \to \mu^- + p$ the proton would be also transversely polarized, and this could be detected by left-right asymmetry in the subsequent scattering of the proton by a carbon analyser[22]. With certain models of CP violation the degree of transverse polarization for $q^2 \approx 0.5 - 1$ GeV^2 could be as high as 20 - 30%[23]. The foregoing remarks on the statistical problems of measuring longitudinal polarization apply equally here.

The foregoing topics on lepton physics are summarized at the end of the next section.

IV. NEUTRINO INTERACTIONS - PHYSICS PROBLEMS RELATING TO WEAK BARYON CURRENTS

The study of weak baryon currents with the aid of a neutrino beam is analogous to that of electromagnetic baryon currents with the aid of beams of electrons or photons. In each case one can measure the transition rate at low q^2 (e.g. $n \to N^*$) as well as the transition form factor at high q^2 (i.e. the departure of the cross-section from that expected for a point electric or weak charge, respectively). The spatial extent of the charge in each case depends on the strong interactions of the baryons and is, at least in principle, predictable from the unitary symmetry models.

There are, however, essential differences between neutrino and electron scattering experiments. First, the neutrino beams are not monoenergetic nor are they so intense as electron beams, and the cross-sections are much smaller. On the other hand, the neutrinos can probe both the vector and axial vector parts of the weak current in processes where the baryon hypercharge can either be conserved or changed by one unit ($\Delta S = 0$ or ± 1); electron experiments are limited to strangeness conserving transitions and the (iso) vector (and scalar) electromagnetic current. According to the CVC hypothesis, the isotopic vector electromagnetic current and the vector part of the weak current of the baryons should have the same structure. This means that, in the neutrino experiments, one can assume the vector part as known from the electron experiments, leaving just the axial vector bit to determine - a big help.

I shall consider the following topics:

a) Elastic process on nucleons - $\Delta S = 0$ and $\Delta S = 1$, $\Delta Q/\Delta S$ rule, etc.
b) Inelastic processes - single pion production.
c) Strange particle production and multipion events.
d) CVC and PCAC hypotheses.

a) Elastic process

The simplest first order weak processes involving the nucleon target are the so-called elastic reactions:

$$\nu_\mu + n \to p + \mu^- \qquad (9)$$

$$\bar{\nu}_\mu + p \to n + \mu^+ \qquad (10)$$

$$\bar{\nu}_\mu + p \to \Sigma^0,\ \Lambda + \mu^+ \qquad (11)$$

$$\bar{\nu}_\mu + n \to \Sigma^- + \mu^+ \qquad (12)$$

as well as the corresponding reactions with ν_e, $\bar{\nu}_e$. These are the transitions between members of the baryon octet ($\frac{1}{2}^+$). They are the inverse of the β decay of the nucleons and hyperons. Reactions (9) and (10) conserve strangeness ($\Delta S = 0$), (11) and (12) are of $\Delta Q = -1, \Delta S = -1$. The coupling involved for the ($\Delta S = 1$) processes is known to be an order of magnitude weaker than for the $\Delta S = 0$ reactions. [Phenomenologically, we can ascribe a unit of weak charge to the octet and split this into two parts; a fraction $\cos\Theta$ is carried by each of the nucleons and $\sin\Theta$ by each of the hyperons [Cabibbo[23]]. The cross-sections for (11) and (12), as compared with (9) and (10), are then reduced by a factor of the order of $\tan^2\Theta \approx 0.06$.]

The process (9) has been studied in detail in the CERN bubble chamber experiment. The reactions actually occurred in heavy liquid (CF_3Br), where the neutrons are members of complex nuclei. Then secondary interactions of the collision products are extremely important, and the principle difficulty has been to extract from the non-pionic neutrino events those which are genuine examples of the elastic process. For example, it can be shown that nearly half of the non-pionic events, in fact, result from the process $\nu + n,p \rightarrow n,p + \pi + \mu^-$, in which the pion is absorbed in the nucleus. The following tests were made:

(i) Kinematic test. For the reaction $\nu + n \rightarrow N^* + \mu^-$, let M* represent the mass of the strongly interacting particles N* (a nucleon or nucleon isobar); then, if the target nucleon, mass M, is considered at rest in the laboratory, we have

$$M^{*2} = M^2 - q^2 + 2M(E_\nu - E_\mu)$$

where both q^2 and E_ν can be computed from a knowledge of the muon momentum and the neutrino beam direction, assuming also that the target is at rest. For a genuine elastic event, the values of M* should group around the nucleon mass. In fact, the distribution for all non-pionic events is skewed to values of M* > M, showing that there is contamination.

(ii) Assuming that one-π production goes through the ($\frac{3}{2}$,$\frac{3}{2}$) isobaric state, and that the form factors involved are the same as the electromagnetic isovector nucleon form factor, it is possible to do a Monte Carlo calculation to find the number of cases where the pion is absorbed. This number accounts for about half the non-pionic events.

(iii) A Monte Carlo calculation of the nucleon cascade generated by the recoil nucleon in the truly elastic events shows that, for the values of q^2 usually considered ($\lesssim 1$ GeV^2), not more than one proton of K.E. > 30 MeV will emerge from the nucleus in the vast majority (~ 90%) of cases. Thus, the zero proton or single proton non-pionic events contain most of the elastic events; the multiproton events result predominantly from one-pion production followed by pion absorption. There are equal numbers of events in the two categories. Although it is clear that one cannot get a really clean sample of elastic events, the zero or one-proton events are probably representative.

Having chosen the elastic sample, one can use it to determine form factors in the transition (9). Assuming G symmetry and T invariance, and neglecting pseudoscalar terms and effects of the intermediate boson (very small even if M_W = 2 GeV), we can express the cross-section $d\sigma(E\nu)/dq^2$ in terms of two vector form factors, F_1 and F_2, and an axial vector form factor F_A. If we use the CVC hypothesis $F_1 = F_2 = F_V = (1 + q^2/M_V^2)^{-2}$ where F_V is the electromagnetic isovector form factor of the nucleon. Electron scattering experiments yield M_V = 0.84 GeV. [I have used here the quadratic form of F_V; nowadays the form $F_V = (1 + q^2/M_V^2)^{-1}$ is gaining popularity, with M_V' = 0.6 GeV; both forms fit the data about equally well.] If we assume the same parametric form for F_A, we are then left with one constant, M_A, to determine. The fit to the experimental data was made by a maximum likelihood technique. Account was taken of the modifications introduced by Fermi motion of the nucleon and the exclusion principle. [To make the result independent of assumptions about the neutrino spectrum the q^2 distribution expected for a given value of M_A,

$$\frac{dN}{dq^2} = \int \Phi(E_\nu) \cdot \frac{d\sigma(E_\nu, M_A)}{dq^2} \cdot dE_\nu \quad ,$$

was evaluated by using for the neutrino flux in the energy interval $E_\nu \rightarrow E_\nu + \Delta E_\nu$,

$$\Phi(E_\nu) = \frac{\Delta N}{\Delta E_\nu} \Big/ \sigma(E_\nu, M_A) \quad .$$

Here, ΔN is the <u>observed</u> number of events in the interval ΔE_ν, $\sigma(E_\nu, M_A)$ is the total cross-section at energy E_ν for the chosen value of M_A.]

The result finally obtained[24] from 50 non-pionic zero and one-proton events was

$$\frac{M_A}{M_V} = 0.95 \pm 0.25 \quad ,$$

where the error is statistical. There is undoubtedly a systematic error in this figure due to uncertainty about the purity of the sample of the same order as the statistical error.

Finally, using this value for F_A, one can calculate the cross-section $\sigma(E_\nu)$ and <u>deduce</u> the neutrino spectrum from the observed event rate. It agrees well with the horn spectrum computed from the π- and K-production data by Van der Meer, except at the lowest point (E_ν < 400 MeV), see Fig. 8.

Of course, more accurate estimates (of both F_V and F_A) could be obtained if one had data from <u>both</u> ν and $\bar{\nu}$ elastic reactions (9) and (10). But it is generally agreed that the most important thing is to improve both the selection of the elastic events and the accuracy of measurement by using free or quasi-free nucleons as targets (i.e. hydrogen, deuterium, or propane and deuterized propane as the chamber filling).

Now consider the hyperon channels (11) and (12). These reactions are allowed by the $\Delta Q/\Delta S = +1$ rule, for which there is ample evidence from decay processes. On the other hand, there is, as far as I know, no very convincing evidence that $\Delta Q/\Delta S = -1$ processes ever occur; in any case, the rate is down by a factor of at least 100 compared with that of $\Delta Q/\Delta S = +1$. It is possible to check possible violations of the $\Delta Q/\Delta S = +1$ rule with neutrino beams (for example, look for the process $\nu + n \rightarrow \Sigma^+ + \mu^-$), but it is doubtful if it will be possible to obtain better limits than already exist (for example, confusion may arise from cases of associated production in which the meson is undetected). So, the principle interest of channels (11) and (12) is to compare the cross-section relative to the $\Delta S = 0$ elastic process (10) at high q^2 [there have been recently some SU_3 predictions indicating that the cross-section (11) for Λ production may be quite high at high E_ν[25]].

b) Inelastic processes - single-pion events

Single-pion production in a neutrino-nucleon collision may proceed through a variety of diagrams, but it is expected that resonance production through the N* $(\frac{3}{2},\frac{3}{2})$ isobar (mass 1.24 GeV) should dominate, just as it does in electro and photo production. (See Fig. 9).

The simplest way to demonstrate that such a process takes place is to plot the M* distribution in single-pion events from the CERN heavy-liquid bubble chamber data. However, at low neutrino energy, any non-resonant contributions will in any case yield a value of M* near the isobar mass, simply because the available phase space is limited. If one considers only events of $E_\nu > 1.5$ GeV, the phase-space curve is flatter, and the enhancement around M* = 1.24 GeV is significant, see Fig. 10.

According to the $\Delta I = I$ rule, one would expect a ratio of final states $p\pi^+ : p\pi^0 : n\pi^+ = 9 : 2 : 1$ if the $(\frac{3}{2},\frac{3}{2})$ resonance is dominant. The actual π^+/π^0 ratio is 1.9 ± 0.4, which is, in fact, compatible with the value of 5.0 expected if one makes allowance for charge-exchange interactions in the nucleus. Using the known cross-sections for these processes, one obtains for the expected charge ratios 63 π^+, 26 π^0, 2 π^-, to be compared with the observed values of 59 π^+, 28 π^0, 4 π^-.

The conclusion of the CERN group[10)] was that single-pion production was dominated (i.e. > 50%) by the diagram of Fig. 9. However, the actual evaluation of the cross-section is bedevilled by uncertainties in the effect of pion absorption to an even greater extent than in the elastic case. Making a cut-off at M* $\leq$ 1.4 GeV, the cross-section after corrections was estimated to be $d\sigma/dq^2 = (0.5 \pm 0.2) \times 10^{-38}$ cm²/nucleon/GeV² in the range $0 < q^2 < 0.2$ GeV², $1 < E_\nu < 3$ GeV. This result is very rough but in fair agreement with the value of 0.7×10^{-38} cm²/nucleon/GeV² predicted by Berman and Veltman[26)]. These authors used the CVC hypothesis and photo-production analysis to estimate the vector contribution, and the one-pion exchange (Goldberger-Treiman relation) to get the axial vector part. The latter can also be estimated from considerations of SU_6 symmetry[27)] which yields a slightly smaller value [in the $q^2 = 0$ limit, exact SU_6 symmetry would make the vector part vanish since in the old language of β decay we have a pure axial (Gamow-Teller) transition $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$]. As far as the total cross-section is concerned, the observed value is roughly a factor two less than that expected, assuming the form factors are the same as for the n-p transition, see Fig. 11. It seems, however, more likely that this is due to the experimental uncertainties rather than "soft" form factors[*)].

c) Strange particle production, multipion events

One of the earliest and most striking results of the CERN neutrino experiment was the observation of the very large cross-sections for the inelastic process at high neutrino energy. Figure 12 shows the recent data. Although there is some uncertainty in the high-energy neutrino flux, it can be seen that the cross-section rises dramatically, and in the region of 10 GeV is more than one order of magnitude greater than the asymptotic elastic cross-section ($\approx 0.4 \times 10^{-38}$ cm²/nucleon). One is concerned here with complex multipion events occurring in heavy nuclei, and therefore there is no possibility of carrying out kinematic analysis to isolate specific reaction channels.

*) More recent evaluation of the CERN data brings it into better agreement with theory.

The rate of production of strange particles at high neutrino energies is of interest. For $E_\nu > 4$ GeV, strange particles occur in about $^1/_4$ of all inelastic events. Of the total of ten events, four are definite cases of associated production ($K + \bar{K}$ or K + hyperon). The remaining cases are consistent with the associated production process, but only one strange particle is identified - the partner being an energetic non-decaying K^+, or a neutral (K^0 or Λ^0) which leaves the chamber. Allowing for detection efficiency, the total number of cases of associated production must have been ≈ 15. In order to compare the rate r = (number of events with strange particles)/(number of inelastic events) with other radiations, it is best to consider it as a function of the energy liberated at the baryon vertex (see Fig. 13). If we denote M* as the mass of the assembly of hadrons in the final state, then the total energy carried into the vertex is

$$E' = \frac{M^{*2} - M^2 - m^2}{2M} \quad ,$$

where M is the nucleon mass, and m can be set as zero for incident pions or photons. So, the procedure is to compare the value of r(E′) for neutrinos (a), pions (b), and photons (c) (see Fig. 14). In this figure the neutrino rates are uncorrected for detection efficiency, and the true rates will be $\sim 50\%$ higher. It can be seen that the ratio "r" in ν events is much greater (by a factor four) than in events produced by pions (axial vector coupling), but of the same order as for the photoproduction process[28)] (vector coupling). In the CEA experiments with γ-ray beams, it was established that production of $K + Y_0^*$ or $K + Y_1^*$ was dominant. The neutrino results are not really numerous or precise enough to investigate this point. The pion data suggest that the axial coupling is rather weak, and in the future it would be of great interest to check this in ν experiments under clean conditions.

d) CVC and PCAC hypotheses

Much of the detailed analysis described above relies heavily on the extended conserved vector current hypothesis, according to which the vector part of the weak interaction is equated with the isovector part of the e.m. interaction, of the baryon.

As we have indicated previously, a test of CVC at high q^2 could be made by comparing ν and $\bar{\nu}$ elastic cross-sections in order to evaluate the axial and vector parts separately. A more ingenious test has been proposed by Adler[29)]. He points out that in an inelastic reaction the matrix element is proportional to the divergence of the weak current $\partial J^A/\partial x_\mu + \partial J^V/\partial x_\mu$ if the charged lepton is emitted at a zero or small angle to the neutrino direction (the so-called "parallel configuration"). Thus, if CVC holds, only axial terms will be present in this case and there will be no parity violation effects (absence of vector triple product terms $p_\mu \wedge p_{\pi 1} \wedge p_{\pi 2}$ in the two-pion ν events for the parallel configuration).

If CVC is valid, then tests can also be made of the partially conserved axial vector current hypothesis. [PCAC has been discussed by Veltman; I would just remind you that the axial weak current of the baryon, unlike the vector, is renormalized by the strong interactions since $G_A \sim 1.2\ G_V$, but there have been speculations that the conservation might become rigorous in the limit $q^2 \gg m_\pi^2$ [30)].] Adler shows that, in the parallel configuration, the energy, angular and polarization distributions in the reaction $\nu_\mu + n \rightarrow N^* + \mu^-$ will, according to PCAC, be identical with those in the reaction $\pi + n \rightarrow N^*$, for the same invariant mass of N*.

The principal difficulty of these tests lies in the very low probability that the muon be emitted under a small angle to the neutrino. Veltman has shown that, even for quite small angles (p_T of muon $\sim m_\pi$), the vector contribution becomes comparable with the axial vector, so such tests could only be made with very large numbers of events.

V. TECHNICAL INNOVATIONS

a) Summary of requirements

It will perhaps be useful to summarize the experimental requirements in connection with the problems listed in Sections III and IV.

Experiments dealing with the study of lepton currents seem to be limited chiefly by statistics of numbers of events, or considerations of beam energy and background contamination. Systematic errors in interpretation of the data have so far played a minor role. Many of the problems considered [for example, lepton-lepton scattering, electromagnetic form factor of the neutrino] involve cross-sections of order 10^{-3} of those for the elastic reaction on nucleons. With the spark chamber technique and more massive detectors, studies of muon polarization at the level of a few per cent will certainly be possible from the point of view of event rate.

On the other hand, the state of the present experimental information on weak baryon currents seems to be limited just as much by systematic errors in interpretation of the data as by statistics. The systematic errors arise chiefly from the use of complex nuclei (freon) to study neutrino-nucleon collisions. The situation would be greatly improved by observing reactions on free or quasi-free nucleons (hydrogen or deuterium, or propane or heavy propane fillings). For a given bubble chamber volume the mass of free nucleons in propane or hydrogen is one order of magnitude less than the mass of bound nucleons in freon; this factor must be compensated by a greater volume of detector and/or improved flux.

b) Improvement programme

The existing neutrino facility at CERN consists of:

i) internal circulating beam of PS;
ii) fast extraction system which ejects the internal beam on to the target;
iii) the target and magnetic horn;
iv) shielding to filter out unwanted radiations, like muons and neutrons;
v) the detectors.

i) Internal PS intensity

The intensity of the circulating beam in the CERN PS has been improving continuously over the years and is now at a level of $\sim 1 \cdot 10^{12}$ protons per pulse. The space-charge limit is believed to be in the region of $2 \cdot 10^{12}$ ppp, so that a further large increase seems unlikely. By installing new power supplies it would be possible to increase the repetition rate by a factor ~ 2.7. A further factor of ~ 5 could be secured by installing a new linac injector

(200 MeV), and so increasing the space-charge limit. Taken together, these factors would amount to $1.5 \times 2.7 \times 5 = 20$, as the number by which the extracted intensity could be increased, as compared with the situation in the ν runs in 1963/64, when the intensity was $6 \cdot 10^{11}$ ppp every 3 secs. Such improvements would take ~ 4 years.

ii) Extraction system

The existing system works with $\sim 90\%$ efficiency and thus no improvement factor is to be gained. The beam is spilled out over a period ~ 2 μsec.

iii) Target and focusing system

Magnetic focusing devices have been employed to increase the degree of collimation of the secondary π's and K's from the target, thus enhancing the neutrino flux. Two systems have been used.

a) Brookhaven plasma lens[18]; this consists of a plasma discharge of several 100,000 amp. in the direction of the beam axis, resulting in magnetic lines of force which are circles about the axis. The performance has not been very satisfactory owing to failure of electrodes and the fact that the maximum current is rather low.

b) The Van der Meer horn[31]; this consists of two coaxial conical conductors made of Al sheet (2 mm thick) down which a pulse of current flows. The magnetic field is a circular "1/r" field between the conductors. It is easy to show that for a point source placed at the horn apex all secondaries of a particular momentum p will emerge from the horn parallel to the axis, regardless, within limits, of the angle of emission Θ, if the horn angle is $\alpha = \sqrt{2/\pi K}$, where $K = {}^{10}/_{6}\ p/i$; p is in GeV/c and i in megamps (see Fig. 15). This relation is true provided $\alpha < \Theta < \Theta_{max}$, where Θ_{max} is determined by the outer radius of the horn. Particles of momentum greater or less than p are diverging or converging when they leave the conductors. Similarly, the focusing is less effective if one uses a target of finite length instead of a point source. I may mention that the natural frequency of the Van der Meer horn is 10 kc/sec, and that the discharge is crowbarred after $^1/_4$ cycle. The conductors rise 30°C in temperature after the discharge, and are cooled with distilled water. Cooling and mechanical considerations limit the peak current to 0.3 megamp. A copper target, 20 cm long and 0.4 cm diameter is used. Such a device produces an enhancement factor varying considerably with neutrino momentum, but of the order of 3-4 times. This is still some way from an "ideal" focusing device which would point all the π's and K's, regardless of momentum or angle, at the centre of the detector - such an ideal device would yield a clear factor of 10 improvement over an unfocused beam.

Modifications to the horn principle incorporate second (or third) stages of focusing. It seems to be a general rule that each succeeding stage becomes less effective than the previous one and, of course, results in greater absorption in the conductors. Palmer[32] has proposed a system of magnetic "fingers" (Fig. 16). It is possible to arrange the field region so that over a wide range of momentum and angle of emission the transverse momentum p_T is reduced at each stage by a constant amount; if this constant is set equal to the "most popular p_T", the effect is to reduce the width of the angular distribution by a factor ~ 2 at each stage. Although such a system seems to work well with point sources, it has poorer performance for a long target (see Fig. 17). The best device so far proposed is that of Asner at CERN[33] (see Fig. 18).

This employs a long target (45 cm copper) and corrects for this and for over-or under-focusing by means of a converger placed some distance downstream from the horn. This arrangement yields a ν flux twice that from the horn alone, except at 2 GeV, where it is a factor four better.

iv) Shielding

A neutrino beam layout consists of the target, focusing device, decay path (where a fraction of the π's and K's decay in flight into neutrinos), shield, and detector. For proton energies exceeding 10 GeV the shield thickness is determined by the range of muons of the full proton energy, with allowance for straggling. A rough rule is 1 m Fe per GeV proton energy. All existing arrangements use iron shielding, the mass required being of the order of 5000 tons.

The best neutrino flux is obtained by making the length of the decay tunnel about equal to the shield thickness; the optimum flux will clearly be higher the thinner the shield. Use of a plug of dense metal, like tungsten or uranium, would therefore improve the flux. However, such materials cannot be obtained in very large quantities that is, one is limited to $\sim$ 100 tons); hence, incorporating them means cutting down on the width of the decay tunnel (Fig. 19). The factor gained when compared with iron is $\sim$ 1.5. A better factor can be secured more cheaply by keeping an iron shield and wide decay tunnel, and having a second-stage focusing device as described above.

v) Detectors

As I indicated at the outset, all the laboratories undertaking neutrino experiments have plans for large hydrogen and/or propane bubble chambers. The hydrogen chambers have volumes of $\sim$ 30 m^3, the propane chambers 10- 15 m^3. These figures should be compared with the 1.1 m^3 of the recently enlarged CERN HLBC which is the largest existing chamber. For a given neutrino flux, the large chambers will yield event rates on free or quasi-free nucleons more than double the rate on bound nucleons in freon in the existing chamber; momentum measurements will also be more accurate.

Table III lists event rates for typical reactions for various chambers and beams. It will be seen that with new chambers just with the modified horn and increased repetition rate, a few days' running will accumulate several hundred ν and $\bar{\nu}$ elastic events on free nucleons from which fairly precise evaluations of form factors can be expected. Indeed the precision of the measurements of cross-section for various weak transitions should be comparable with that for the corresponding e.m. transitions using photon and electron beams. However, without a new linac the strange particle (Y*, Σ, Λ, etc.) event rate is only $\sim$ one/day which probably prohibits a very precise study of these reactions.

As far as lepton currents are concerned, it is clear that even with the propane chambers and a 40-fold improvement in the neutrino beam, elastic (ν,p), scattering will be very hard to observe. Studies of muon polarization aiming at 1% accuracy, involving $\sim 10^5$ neutrino events, will be possible with long runs in maximum beam with the big propane chambers; but in all probability such experiments are better done with the more massive spark chamber detectors. Several proposals along these lines have been made.

Table III

Beam	Rate/ton n,p per day		Events/day in freon CERN 63/64 (bound nucleons)	New CERN HLBC (free protons) 0.1 ton	20 m³ H,D chamber 1.2 tons	10 m³ (Gargamelle) C_3H_8 or C_3D_8 0.8 ton
× 1.0 63/64 beam	$\nu + n \to \mu^- + p$ $\bar{\nu} + p \to \mu^+ + n$ $\nu + n,p \to \mu^- + p,n + \pi$ $\bar{\nu} + n,p \to \mu^+ + \Sigma,\Lambda$	18 6 20 ~0.2	3 1 3 0.3			
× 3.0 New horn + beam	$\nu + n,p \to \mu^- + p,n + \pi$	60		3 (C_3H_8)	45	30
× 8.0 New horn beam + rep.rate	$\nu + n \to \mu^- + p$ $\bar{\nu} + p \to \mu^+ + n$ $\bar{\nu} + n,p \to \mu^+ + \Sigma,\Lambda$	150 50 1.6		7 (C_3D_8) 2 0.08	100 30 1.2	70 20 0.8
× 40 as above + linac	$\bar{\nu} + n,p \to \mu^+ + \Sigma,\Lambda$ $\nu + p \to \nu + p$	8 ≈ 0.08		0.4	6 ~ 0.06	4 ~ 0.04 on free protons ~ 0.2 on bound "

VI. NEUTRINOS FROM SPACE AND FROM REACTORS

i) Atmospheric neutrinos

A number of cosmic-ray pilot experiments are now under way, or projected, with the object of detecting neutrinos generated by decay of π's and K's produced when the primary cosmic rays impinge on the earth's atmosphere. The cosmic-ray workers are in one sense a step ahead of the accelerator physicists, in that the neutrino fluxes can be calculated quite accurately (within 10%) from the rather extensive data on cosmic-ray muon and pion fluxes. As with accelerators, muons are the chief source of background, and this can best be eliminated by going deep underground. The technique is to go deep enough (~ 8,000 m.w.e.) to cut down the atmospheric muon flux to such a low level that most of the muons traversing the detector are those coming from neutrino interactions in the surrounding rock. Matters are improved if the counter-telescope is set to count nearly horizontal muons ($\Theta \sim 70-90°$), since the decay probability of π's and K's in the atmosphere varies as sec Θ' and the attenuation of atmospheric muons is increased, (see Fig. 20). Integrated over the neutrino spectrum, the muon flux from elastic production (9) is very low - about $10^{-2}/m^2/sr/year$. Pilot experiments are now

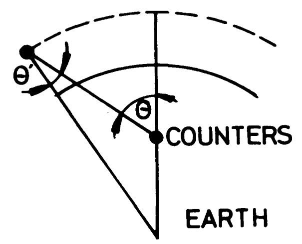


Fig. 20

just starting in gold mines in South Africa and India, and proposed in Utah and the Mont Blanc Tunnel. Some ingenious techniques, which there is not time to describe, are used to produce cheap detectors of large sensitive areas (100's of m^2). [Refer to the papers by the Tata-Japan-Durham group by Keuffel and by Reines in the Proceedings of the CERN Conference on Neutrino Physics (January 1965).] The only numerical result available so far is the observation[34)] that the total neutrino cross-section at high energy ($\sim$ 100 GeV) is $< 10^{-35}$ cm^2/nucleon.

ii) Reactor experiments

As you all know, Reines and Cowan, about 12 years ago, first obtained decisive evidence for interactions of free $\bar{\nu}_e$'s from a reactor ($\bar{\nu}_e + p \rightarrow n + e^+$). These experiments are still going on with the object of getting better values for the cross-sections and neutrino energy spectrum. Recently, it has been found that the spectrum has a very long tail, corresponding to extremely short-lived β-active nucleides with high disintegration energies produced in the fission process.

iii) Solar neutrinos

It is common knowledge that the density of solar neutrinos at the earth's surface is about one/cc. The sun emits $\sim 10^{38}$ ν's/sec, most of them of such low energy that they are very hard to detect. But the sun contains small amounts of Be^7 and B^8, and these can generate high-energy neutrinos by radioactive decay (up to 14 MeV). In one proposed experiment (Davis) the ν's are detected from the argon liberated in the reaction $Cl^{37}(\nu,e)A^{37}$. The chlorine is in the form of a tank of 10^5 gallons of perchlorethylene sunk 4400 m.w.e. underground. About five reactions per day are expected, and this rate should be easily detectable. In another experiment (Reines), the recoil electrons from ν_e - e scatters will be recorded with a large directional Čerenkov counter pointed at the sun.

Supernovae, when they occur, are expected to be much more intense sources of neutrinos than the sun (by a factor 10^{12}). Unfortunately, they are rather distant! If they could ever be detected, at a reasonable rate, one might incidentally get a better estimate of the ν_e mass from the relative travel times of the light and neutrino pulses.

Finally, an interesting point about the statistics obeyed by neutrinos has been made by Weinberg[35)]. If there are enough neutrinos around and they obey Fermi statistics as we expect, then we may be living in a degenerate Fermi sea of neutrinos. Feinberg and others[36)] have shown that such a sea would modify the propagation of primary cosmic rays of energy $> 10^6$ GeV/nucleon through the weak interaction; they conclude that the height of this sea (Fermi energy) is < 100 eV.

REFERENCES

1) D.R. Hamilton, W.P. Alford and L. Gross, Phys.Rev. 92, 1521 (1953).

2) J.J. Sakurai, Phys.Rev.Letters 1, 40 (1958).

3) W.H. Barkas, W. Birnbaum and F.M. Smith, Phys.Rev. 101, 778 (1956).

4) W.F. Dudziak, R. Sagane and J. Vedder, Phys.Rev. 114, 336 (1959).

5) I. Falomkin et al. Proc.Int.Conf. on High-Energy Physics, Dubna (1964).

6) P. Dennery and H. Primakoff, Phys.Letters 6, 67 (1963).

7) A.M. Hillas and T.E. Cranshaw, Nature 184, 892 (1959).

8) For the most recent data, see M. Goldhaber, CERN Conf. on Neutrino Physics (1965).

9) J.K. Bienlein, A. Böhm, G. von Dardel, H. Faissner, F. Ferrerp, J.M. Gaillard, H.J. Gerger, B. Hahn, V. Kaftanov, F. Krienen, M. Reinharz, R.A. Salmeron, P.Q. Seiler, A. Staude J. Stein and H.J. Steiner, Phys.Letters 13, 80 (1964).

10) M.M. Block, H. Bürmeister, D.C. Cundy, B. Eiben, C. Franzinetti, J. Keren, R. Møllerud, G. Myatt, M. Nikolić, A. Orkin-Lecourtois, M. Paty, D.H. Perkins, C.A. Ramm, K. Schultze, H. Sletten, K. Soop, R. Stump, W. Venus and H. Yoshiki, Phys.Letters 12, 281 (1964).

11) G. Danby, J.M. Gaillard, K. Goulianos, L.M. Lederman, N. Mistry, M. Schwartz and J. Steinberger, Phys.Rev.Letters 9, 36 (1962).

12) A. Pais, Phys.Rev.Letters 9, 117 (1962).

13) T.D. Lee and C.N. Yang, Phys.Rev. 126, 2239 (1962).

14) G. Bernardini, J.K. Bienlein, G. von Dardel, H. Faissner, F. Ferrero, J.M. Gaillard, H.J. Gerber, B. Hahn, V. Kaftanov, F. Krienen, C. Manfredetti, M. Reinharz and R.A. Salmeron, Phys.Letters 13, 86 (1964).

15) A.C.T. Wu, C.P. Yang, K. Fuchel and S. Heller, Phys.Rev.Letters 12, 57 (1964).

16) M. Veltman, Physica 29, 16' (1963).

17) H.S. Mani and J.C. Nearing, Phys.Rev. 135, B 1009 (1964).

18) L.M. Ledermann, CERN Conf. on Neutrino Physics (1965)

19) O. Piccioni, CERN Conf. on Neutrino Physics (1965).

20) J. Bernstein and T.D. Lee, Phys.Rev.Letters 11, 512 (1963).

21) T.D. Lee and A. Sirlin, Preprint (1964).

22) M.M. Block, CERN Conf. on Neutrino Physics (1965).

23) N. Cabibbo, Phys.Rev.Letters 10, 531 (1963);
S.M. Berman and M. Veltman, to be published (1965).

24) E. Myatt, CERN Conf. on Neutrino Physics (1965).

25) N. Cabibbo and F. Chilton, in the press (1965).

26) S.M. Berman and M. Veltman, CERN 9276/Th/455 to be published.

27) N.J. Papastamatiou and D.G. Sutherland, Phys.Letters 14, 246 (1965).

28) H.R. Crouch et al., Phys.Rev.Letters 13, 636 (1964).

29) S.L. Adler, Phys.Rev. 135, B 963 (1964).

30) Y. Nambu, Phys.Rev.Letters 4, 380 (1960);
M.L. Goldberger and S.B. Treiman, Phys.Rev. 110, 1178 (1958);
J. Bernstein, S. Fubini, M. Gell-Mann and W. Thirring, Nuovo Cimento 17, 757 (1960).

31) S. van der Meer, Proc.Int.Conf. on Elementary Particles, Sienna (1963).

32) R. Palmer, CERN Conf. on Neutrino Physics (1965).

33) A. Asner, CERN preprint.

34) M.E.K. Menon, Proc. IUPAP Cosmic Ray Conf. Jaipur (1963).

35) S. Weinberg, Phys.Rev. 128, 1457 (1962).

36) E.L. Feinberg, Proc. IUPAP Cosmic Ray Conf. Jaipur (1963).

FIGURE CAPTIONS

Fig. 1. See text

Fig. 2. Diagram of possible W-boson production process.

Fig. 3. Boson production rate as a function of mass and of neutrino energy for the energy spectrum of the CERN neutrino beam.

Fig. 4. Elastic ν-p scattering via the exchange of a neutral W-boson.

Fig. 5. See text

Fig. 6. Lepton-lepton scattering.

Fig. 7. The q^2 distribution for the 30 events $\nu_e + n \rightarrow e^- + p$ and for the 90 events $\nu_\mu + n \rightarrow \mu^- + p$.

Fig. 8. The neutrino spectrum deduced from the observed event rate compared with the horn spectrum computed from the $\bar{u}$ and K-meson production data by van der Meer.

Fig. 9. Single pion production via the $N^*(3/2, 3/2)$ isobar.

Fig. 10. The M* distribution in single pion events from the CERN heavy liquid bubble chamber data.

Fig. 11. The total cross-section for single pion events as a function of neutrino energy, compared with the prediction of Berman and Veltman.

Fig. 12. The variation of the cross-section for inelastic processes with neutrino energy.

Fig. 13. See text

Fig. 14. The variation with E′ of the ratio r of the number of events with strange particles to the number of inelastic events for associated production by neutrinos, pions and photons.

Fig. 15. Principle of van der Meer horn.

Fig. 16. Schematic representation of system of magnetic "Fingers" proposed by Palmer.

Fig. 17. Neutrino energy spectrum from different experimental systems (see text for details).

Fig. 18. Horn plus converger proposed by Asner.

Fig. 19. Schematic neutrino beam lay-out.

Fig. 20. Illustrated in text.

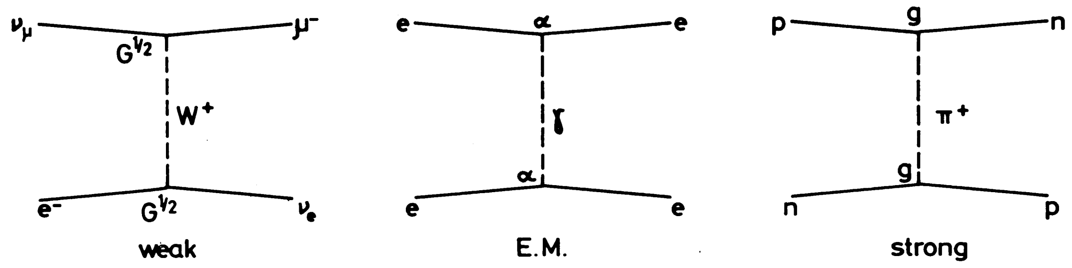


Fig. 1

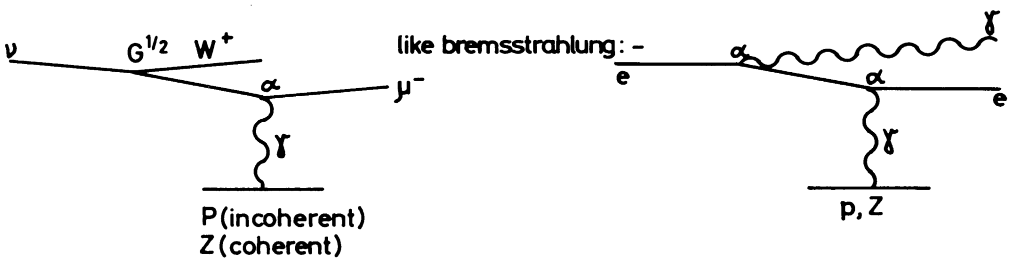


Fig. 2

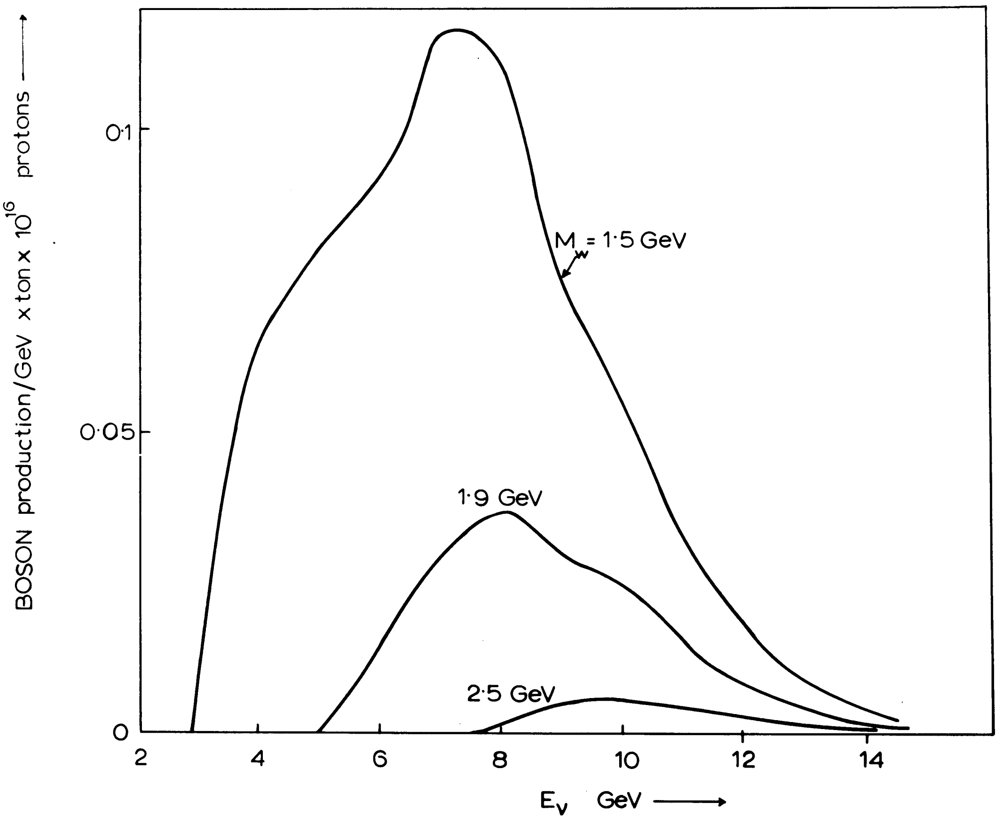
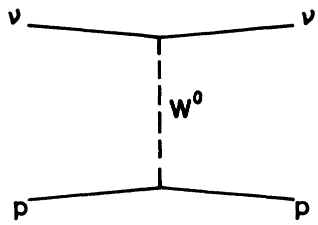


Fig. 3



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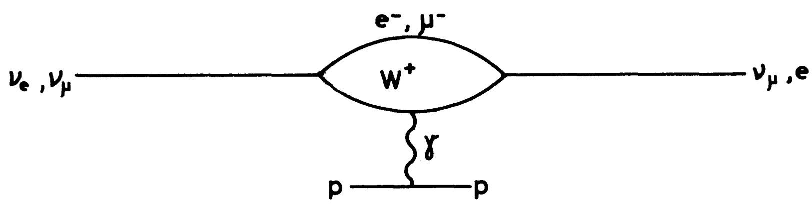

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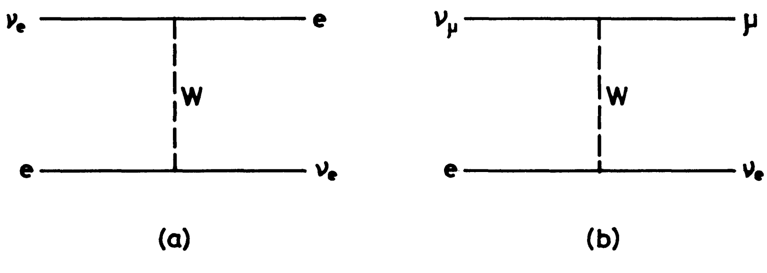
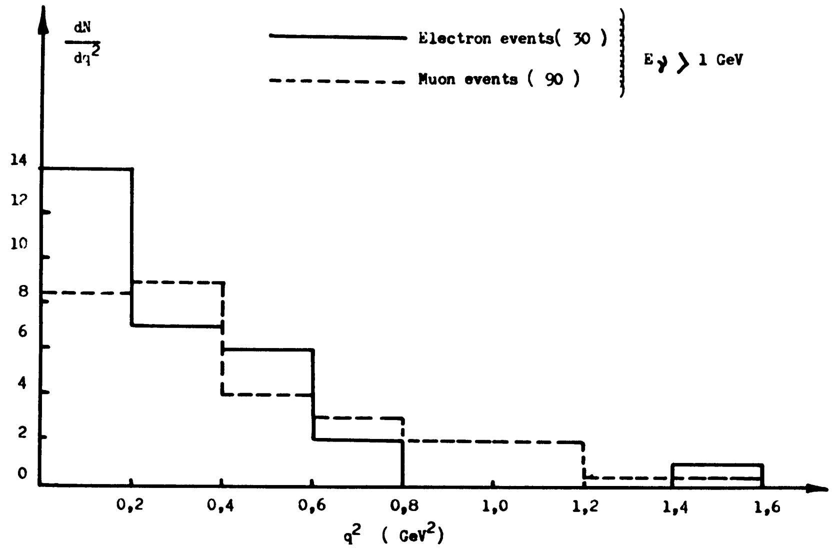
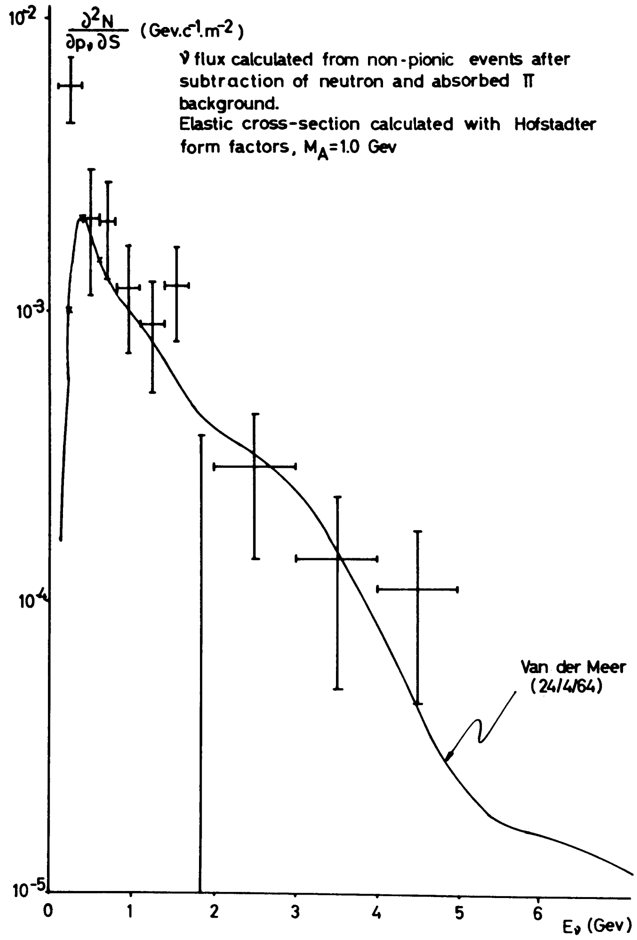


Fig. 6



dN/dq²
Electron events(30)
Muon events (90)
E ν > 1 GeV
14
12
10
8
6
4
2
0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
q² (GeV²)

Fig. 7



∂²N/∂p,∂S (Gev.c⁻¹.m⁻²)
ν flux calculated from non-pionic events after subtraction of neutron and absorbed π background.
Elastic cross-section calculated with Hofstadter form factors, M_A=1.0 Gev
10⁻²
10⁻³
10⁻⁴
10⁻⁵
Van der Meer (24/4/64)
0
1
2
3
4
5
6
E ν (Gev)

Fig. 8

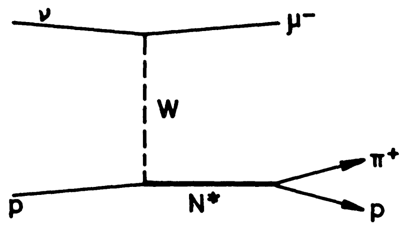


Fig. 9

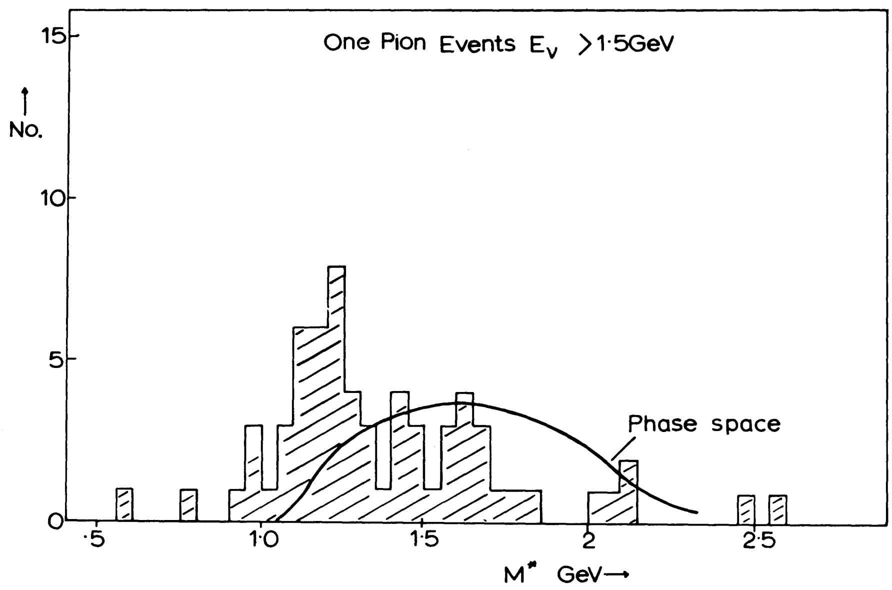


Fig. 10

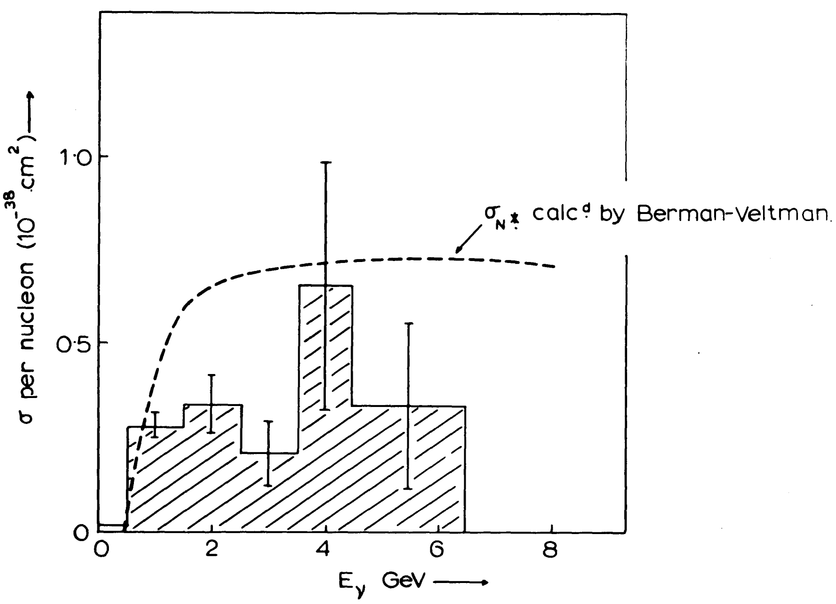


Fig. 11

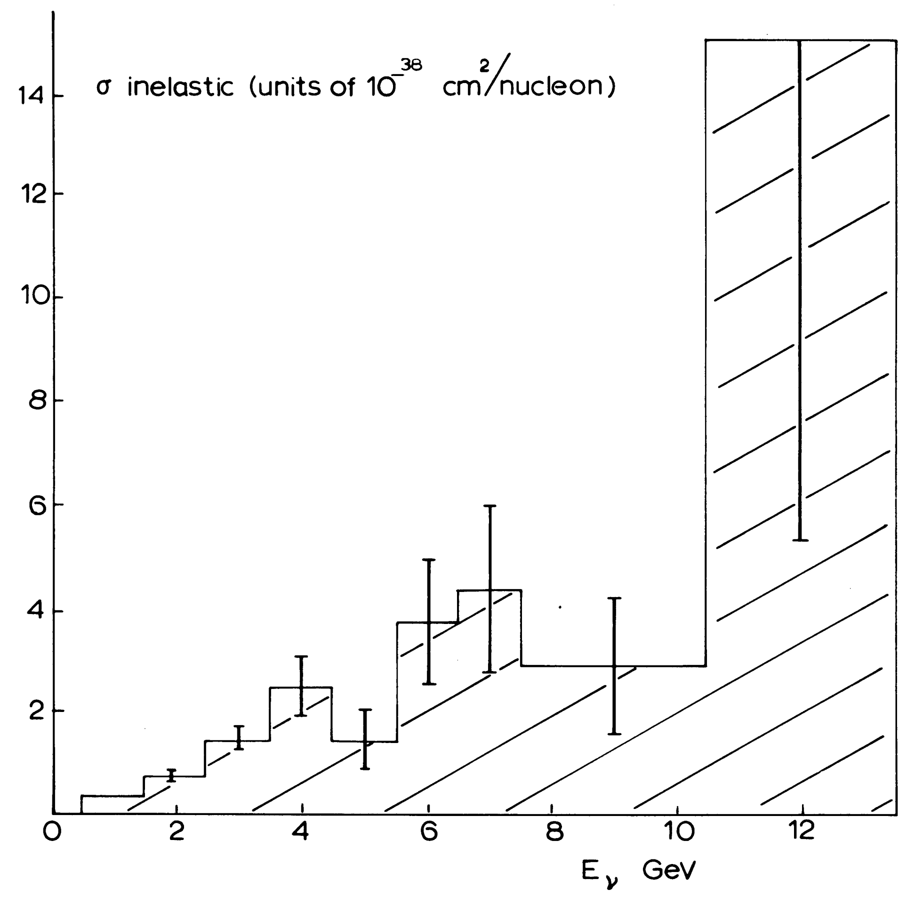

σ inelastic (units of 10⁻³⁸ cm²/nucleon)
14
12
10
8
6
4
2
0
2
4
6
8
10
12
E_ν GeV

Fig. 12

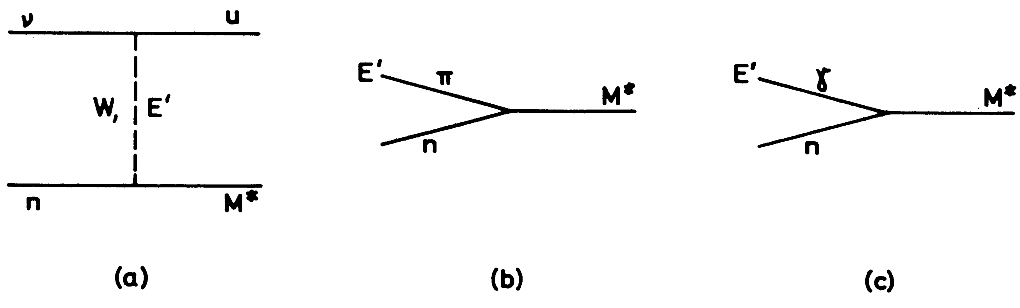

ν
u
W, E'
n
M*
E'
π
M*
n
E'
γ
M*
n
(a)
(b)
(c)

Fig. 13

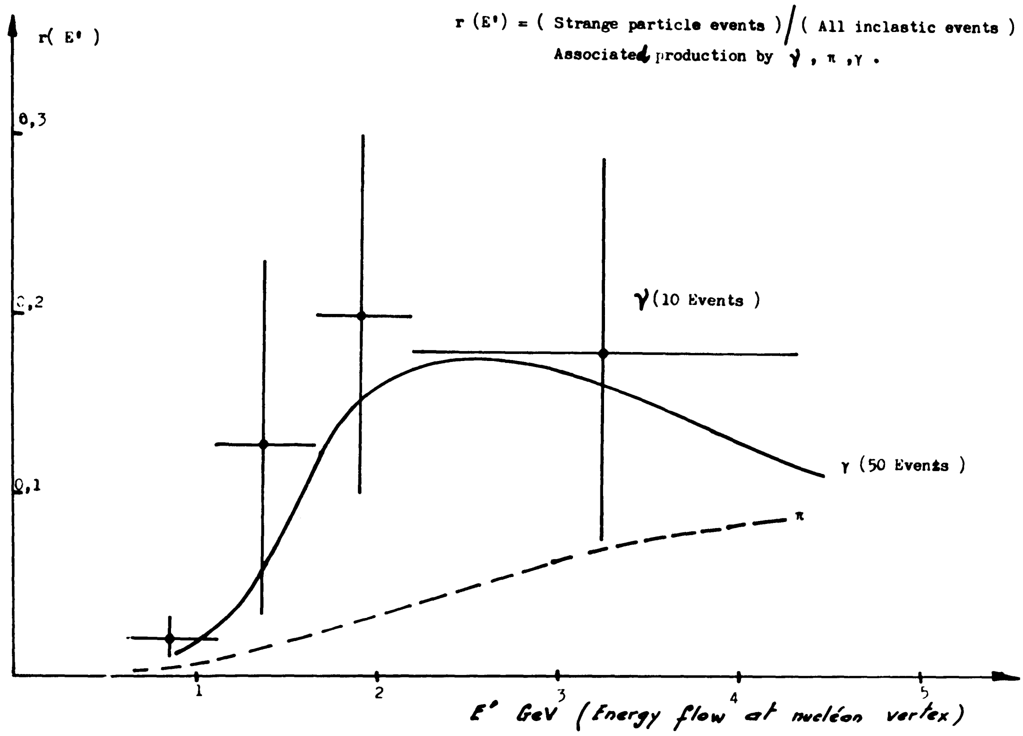
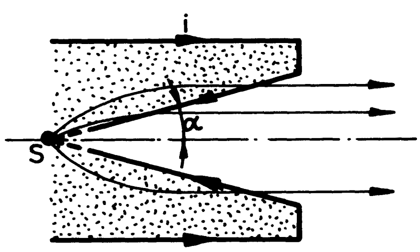


Fig. 14



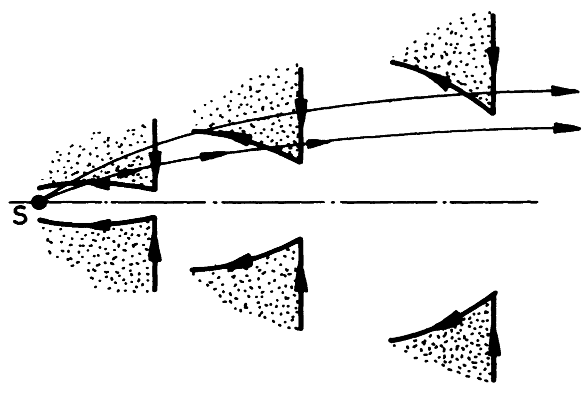


Fig. 15

Fig. 16

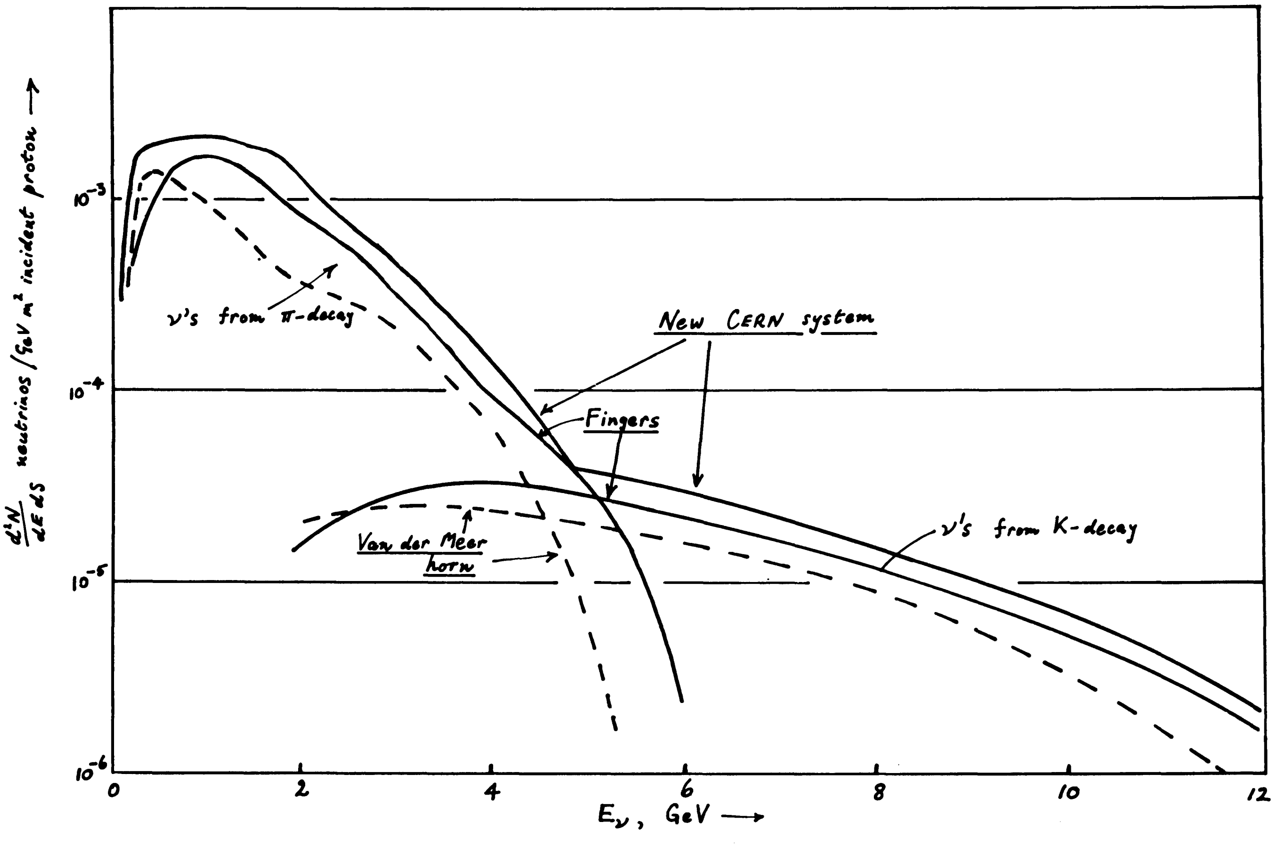


Fig. 17

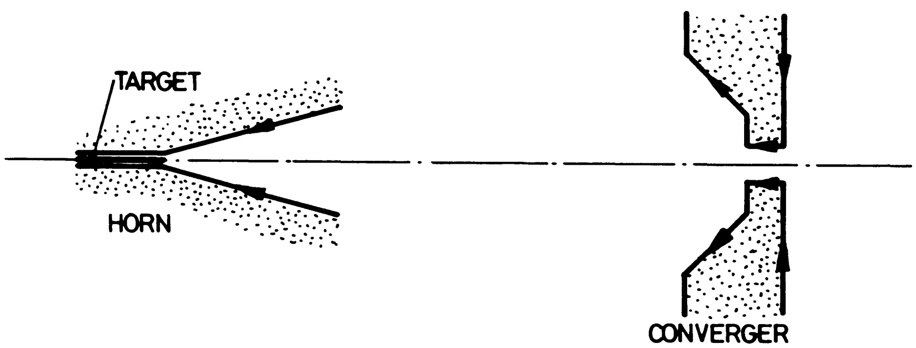


Fig. 18

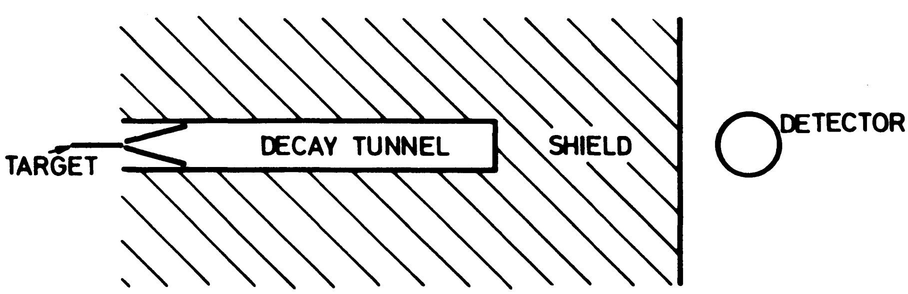


Fig. 19