CERN NEUTRINO EXPERIMENT : CONCLUSIONS

J.S. Bell, J. Løvseth, and M. Veltman

GERN - Geneva

Paper presented at the International Conference
on Elementary Particles, Sienna
30 September - 5 October 1963

7509/TH.382
30 October 1963

This report has been assembled by the authors named. However, the conclusions are of course those of the neutrino group as a whole. They have been extracted from the preceding reports and some theoretical remarks added.

As regards the two-neutrino question (Section 1), neutrino flip (Section 2), and neutral currents (Section 4), the conclusions of the Brookhaven 1) group have been confirmed and strengthened. The evidence on lepton conservation (Section 3), and the indications on weak form factors (Section 5), energy dependence of cross-section (Section 6), and lepton pair production (Section 7), are essentially new.

1. $\nu_\mu \neq \nu_e$

If there were only one neutrino, coupled equally to electrons and muons, these particles should appear about equally often in otherwise similar events. It suffices to consider the "elastic" events 2) 3) in which as well as the lepton candidate there are only nucleon recoils. In the neutrino run the bubble chamber had 60 such events with almost certain negative muons. There were no electron candidates :

68 μ^- against 0 e^-

In the spark chamber, for identification reasons, only electrons of more than 500 MeV were looked for: there were 13 ± 5= Of the 1200 muon events about 1150 can be supposed (on the basis of the distribution observed in the bubble chamber) to have muon energies greater than 500 MeV :

1150 μ against 13 ± 5 e

Clearly, one neutrino, coupled equally to μ and e, is not enough.

The few electrons observed are compatible with the expected ν_e contamination in the beam from K_{e3} decays, which are estimated to contribute a relative counting rate of very roughly 1 %.

$\downarrow$

$K^+ \rightarrow \pi^0 + e^+ + \nu$

2. NEUTRINO FLIP

It has been suggested 4) that the roles of the two neutrinos might be reversed in the decays of strange particles. The neutrinos from $K_{\mu 2}$ decay should then produce electrons in strangeness conserving reactions.

According to the assumed spectrum and "standard theory" (Section 5), which accounts reasonably well for the "elastic" events, about 3 % of these events are due to $K_{\mu 2}$ neutrinos. In the 68 bubble chamber events one would then expect, with neutrino flip, about 5 electrons, against none seen. In the 1200 spark chamber events, about 100 electrons (nearly all above 500 MeV) would be expected, against 13 ± 5 seen.

A second way of arguing is the following. The $K_{\mu 2}$ neutrinos are relatively more important in the high-energy part of the spectrum 5). Above 4 GeV they should be dominant by at least an order of magnitude. Now in the neutrino run the bubble chamber had 18 muon events with visible energy greater than 4 GeV, against 1 electron event. Experimentally, it is conceivable that nearly all of those 18 muon events were strangeness non-conserving (e.g., had charged K mesons which were mistaken for π's), But theoretically it is very unlikely (because of the notorious weakness of strangeness changing leptonic decays) that the strangeness changing processes should be much more probably (or even comparably so) than the strangeness conserving. If we presume most of the 18 events to conserve strangeness, they are evidence against neutrino flip,

Both of the above arguments depend on theoretical notions. Suppose these notions are not violently wrong. Then the neutrino flip hypothesis, in its pure form, is ruled out.

The "strange neutrino" hypothesis 6) is harder to dismiss.

3. LEPTON CONSERVATION

This implies that the charged lepton in the final state (assumed to be the only lepton) should be negative for an incident neutrino and positive for an incident antineutrino.

In the "antineutrino" run the beam was substantially contaminated by neutrinos, but for the "neutrino" run the antineutrino contamination is thought to have been $\lesssim$ 10 %. We refer to the "neutrino" run in what follows.

In the bubble chamber there were 8 possible μ^+'s; relative to 136 μ^-'s this is about 6 %, Of the particles passing through the spark chamber magnet only (8 ± 4) % were positive, and some of them were identified as pions or protons.

There is nothing here against lepton conservation? it is clearly the normal thing. However, a violation of a few per cent could not be ruled out. if for example, ν_μ were a Majorana particle with $(1+\gamma_5)$ coupling and mass m, the expected fraction of wrong sign muons would be of order

$$(m / \text{neutrino energy})$$

We could tolerate here a value for m of more than 100 MeV. The upper limit from other sources is about 3 MeV 7).

NEUTRAL LEPTON CURRENTS

In low-energy physics there is no evidence against the existence of strangeness conserving couplings involving neutral lepton pairs, e.g.,

$$(\bar{\nu}\,\nu)(\bar{p}p) .$$

Such an interaction would give rise to the reaction

$$\nu + p \rightarrow \nu + p$$

and related inelastic reactions which might be seen in high-energy experiments.

The spark chamber triggering requirements discriminate against the above reaction, as compared with $\nu + n \rightarrow \mu + p$, because of the absence of the long charged muon track. Some associated inelastic reactions would trigger the chamber, and they have been analyzed in this context for the Brookhaven experiment 8). Here we appeal to the bubble chamber "neutrino" run data. There were no events without meson candidates and visible energy exceeding 250 MeV. There were less energetic events of this type, probably due to neutron background. For comparison, the number of events with a single meson candidate which is identified as μ^-, and more than 250 MeV visible in the other tracks, was 31. Thus the ratio of neutral current "elastic" events

$$\nu + p \rightarrow \nu + p$$

to normal "elastic" events

$$\nu + n \rightarrow \mu + p$$

is less than about 3 %. Clearly neutral lepton currents cannot be admitted on a symmetrical basis with the charged.

The above data can be used to give limits on electrical properties of the neutrino, A magnetic moment 9) would have to be less than about 10^{-7} Bohr magnetons. On the $(1+\gamma_5)$ theory with zero neutrino mass a magnetic moment could not arise. A charge form factor, defined by the matrix element of the electric current

$$(\nu\,|J_\mu|\,\nu) = (\bar{\nu}\,\gamma_\mu(1+\gamma_5)\,\nu)\,\frac{e}{6}\,f(q^2)\,q^2$$

would be limited by

$$(f^2_{av})^{\frac{1}{2}} \lesssim 3\cdot 10^{-32}\ \mathrm{cm}^2$$

where f^2 is averaged over the values of q^2 relevant in the experiment. Otherwise expressed

$$(f^2_{av})^{\frac{1}{2}} \lesssim 8\ G$$

where G is the weak coupling constant $(10^{-5}/M_p^2)$. This limit is still much larger than values for f that might be expected theoretically 10),11).

5« ELASTIC EVENTS

One would like to extract from the data some information about the form factors for the "elastic" processes

$$\nu + n \rightarrow p + \mu$$

$$\bar{\nu} + p \rightarrow n + \bar{\mu}$$

Unfortunately, the target used is composed of nuclei rather than nucleons. Thus the reaction products have to travel through nuclear matter. Only very energetic recoils (~500 MeV) are likely to make pions, and therefore one can reject in a first approximation, as candidates for elastic events, those in which pions are seen to emerge from the nucleus. On the other hand, when a pion is actually produced in the primary reaction., it may sometimes be absorbed in the nucleus. Thus there is some error in taking the experimentally "elastic" events, those without visible pions, to be the truly elastic events, This seriously limits the significance of the following analysis.

In spite of the above, we have confronted the results with a "standard theory" which is the following.

1) The primary event is the collision of a free neutrino with a free nucleon, resulting in a free nucleon and a free muon. The collision is then governed in the usual way 12) by two vector form factors

$$F_1(q^2), \quad F_2(q^2)$$

and two axial form factors

$$F_A(q^2), \quad F_P(q^2) .$$

The latter appears bo contribute very little in this experiment, and will not be mentioned further 13)

2) The CVC hypothesis is correct. Then F_1 and F_2 are identical with the nucleon electromagnetic form factors. For these we use the empirical representation

$$F_1 = \frac{1}{\left[1 + \frac{q^2}{M_1^2}\right]^2}$$

$$F_2 = \frac{1}{\left[1 + \frac{q^2}{M_2^2}\right]^2}$$

with $M_1 = M_2 = 0.90$ proton masses = 840 MeV.

We use a similar parametrization for F_A

$$F_A = \left[1 + \frac{q^2}{M_A^2}\right]^{-2}$$

and in the so-called "standard" theory set

$$M_A = M_1 = M_2 .$$

3) There is no intermediate boson.

4) The nucleus is an ideal Fermi gas. We allow then for the exclusion principle and for Fermi motion.

5) Secondary interactions, including the Coulomb interaction of the muon, are ignored.

Some further details on such calculations are given in Ref. 13)

This standard theory predicts counting rates which are too low by about 40 % for the spark chamber and about 30 % for the bubble chamber. These discrepancies may not be significant because of limited statistics in the bubble chamber (68 events) and uncertainties about the spectrum;

the latter are greater for the spark chamber. The standard theory agrees well with the angular distribution of nrnons in the spark chamber [Ref, Fig.] and with their q^2 distribution in the bubble chamber [Ref. 2) , Fig.] The q^2 distribution, where available, is the more valuable because less sensitive to the neutrino spectrum.

The axial form factor might be expected to fall off less rapidly with q^2 than the vector, because there appears to be no low-lying resonance with appropriate quantum numbers. But if we take an extreme case $M_A = \infty$ (instead of $M_A = M_1 = M_2$) the theoretical counting rate becomes about three times too high, and angular and q^2 distributions become much too broad. So it would appear that F_A does fall off in the q^2 range important here.

If there is an intermediate boson, the factor $(G/\sqrt{2})^2$ in the cross-section is replaced by

$$(g^2/M_W^2+q^2)^2 .$$

This can be regarded as an alternative to P. for cutting down events with large q^2. Making $M_A = \infty$, the agreement with experiment is restored by taking for the boson mass $M_W \approx 800$ MeV If $M_W \approx 1300$ MeV, for example, the implication would be that F_A does fall off but less rapidly than F_1 and F_2 : the best fit is then with $M_A \approx 1300$ MeV also.

This is all we can say about form factors. Because of the difficulties enumerated, there are no firm conclusions. But the tentative results are quite reasonable.

INELASTIC EVENTS

The experimental "inelastic" events are those with visible pions. The over-all rates of "elastic" and "inelastic" events are about equal, but their energy distributions are quite different [Ref. 3), Fig. 9]. The "elastic" events are compatible with the assumption of a cross-section that remains constant beyond a few GeV, at about $0.4\times10^{-38}\,\mathrm{cm}^2$ ^{2} per nucleon. The "inelastic" cross-section appears to increase dramatically with energy (up to about 9 GeV) and is actually somewhat greater than

$$0.2\,E^2\,10^{-38}\,\mathrm{cm}^2 \quad \text{per nucleon}$$

where E is neutrino energy in GeV, Above 4 GeV (13 events) all events fall into this "inelastic" class. It is tentatively supposed that the "inelastic" events are mainly those in which pions are produced in the primary neutrino-nucleon collision. One would not expect strange particles to play a big role and very few are seen.

There are no reliable theories of inelastic processes. However, the assumption of a basic current-current weak interaction, or the exchange of a vector intermediate boson, restricts the energy dependence of the cross-section [14] Neglecting the lepton mass,

$$\frac{d^2\sigma}{dq^2\,dM_F^2} = \frac{A}{E^2} + \frac{B}{E} + C$$

where A, B, and G are functions of q^2 and M_F^2 and E is the neutrino lab. energy; M_F is the mass of the final heavy particle state :

$$M_F^2 - M^2 = 2MT - q^2$$

for a target nucleon at rest, where M is the nucleon mass, T is lab. energy transfer from leptons to heavy particles, and q is four-momentum transfer from the leptons. This formula applies equally to the elastic process, for which A, B, and C contain a delta function $\delta(M_F^2-M^2)$ and combinations of form factors. In that case one sees how, with the effective range of q^2 limited by the form factors, the cross-section becomes constant at high energy. To obtain an increasing cross-section the range of either or both of q and M_F^2 must increase. For the inelastic processes [Ref.3), Figs. 10, 11] both do appear to increase somewhat with energy.

-^ A process which would bo expected to appear is the production of the 33 isobar. Support for the importance of this comes from the π^+ to π^0 ratio observed in the bubble chamber s (4 ± 1.5) to 1 for single pion events. A pure isospin $\frac{3}{2}$ would imply a ratio of 5 to 1. On the basis of a simple model 15), which we have recently improved, isobar production can easily account for an inelastic rate comparable with the elastic. However the cross-section, as in the elastic case, would be expected to become constant at a few GeV. Steeply rising elastic or isobar cross-sections could be obtained by assuming hard cores in the form factors. The events with large q^2 might appear more complicated because of secondary processes. However the values of q^2 should then reach the kinematic limit (2ME); they appear to be well below this.

Other estimates of inelastic cross-sections have been made with one-pion exchange diagrams 10),15),16). These estimates are quite low and even at 10 GeV do not much exceed the elastic cross-section mentioned above. Nguyen Van-Hieu 17) has obtained a rapid asymptotic rise of inelastic cross-section with "Pomeron" exchange. However, he has made no numerical estimate, and has implicitly assumed hard cores ln certain form factors.

It is tempting to invoke the production of intermediate bosons W
to account for the cross-section 18). This could be done by a W mass
near to the nucleon mass, However, it would then be hard to understand the absence of both lepton pair candidates and a multi-pion mass peak in the bubble chamber. Moreover, the muons associated with ¥ production would be expected on average to take about a fraction $(m_\mu / M_W) \approx 10\,\%$ of the total energy, whereas those involved here take about one half of it.

Finally one might consider the possibility that the apparent increase of cross-section is due to a gross underestimate of the high energy neutrino spectrum. But then there should also be too many high energy "elastic" events 19); the possibility of confusion between elastic and inelastic depends on q^2 rather than E.

This rise in inelastic, or total, cross-section is one of the most striking features of the experiment. It would be interesting to have corresponding results for ν_e, and for $\bar{\nu}_\mu$ and $\bar{\nu}_e$, the above data having come from the predominantly ν_μ beam.

7. LEPTOH PAIRS

In events with pairs of long tracks, these tracks show fewer interactions than would be compatible with one of them in each case being a strongly interacting particle. There are also events in which a single such little interacting track appears in association with a single-electron-type shower. The tentative interpretation is that lepton pairs occur, $\bar{\mu}\mu$ and $\bar{e}\mu$. Such a pair appears to occur in about 1 % (uncertain by a factor of two either way) of all events. The data is consistent with the occurrence of $\bar{\mu}\mu$ and $\bar{e}\mu$ at equal rates.

These lepton pairs might be accounted for by the associated production (in the nuclear Coulomb field) of a muon and an intermediate meson W, the latter decaying at once into a charged lepton and a neutrino Further and more detailed experiments would be needed to measure the mass of W. In the meantime one can try to estimate a mass which would account for the event rate. With the available theory of W production 18) calculations of Veltman give production rates relative to all processes of

$$35\ \%\ \text{for}\ M_W = M_p = 938\ \text{MeV}$$

$$6\ \%\ \text{for}\ M_W = 1300\ \text{MeV}.$$

Pursuing such calculations, and ignoring the possibility of other decay modes of W, the observed 1 % of lepton pairs would correspond to a mass somewhat higher than 1300 MeV. The W must certainly have none leptonic decays, so that more W's than lepton pairs are produced. This reduces the required mass. But as has been mentioned in Section 6, it could not be much lower, and certainly not as low as the proton mass, without the process showing up in the bubble chamber.

The W production theory so far worked out is oversimplified with respect to nuclear complications, and omits processes in which pions are also produced. Allowance for the latter will increase the required mass of W. We would be very surprised if it rose as far as say 2 GeV.

There are other possible mechanisms for lepton pairs. One which has again been considered recently is inverse muon decay in the Coulomb field, leading to $\mu\bar{e}$, and the related process leading to $\mu\bar{\mu}$. Even if this should be the explanation, it would be interesting to have confirmed, in the $\mu\bar{\mu}$ events, the existence of "diagonal" interactions

$$(\bar{\mu}\nu)^{+}(\bar{\mu}\nu)$$

as well as the usual muon decay interaction

$$(\bar{e}\nu)^{+}(\bar{\mu}\nu)$$

A number of theoretical estimates, of lepton pair production in this way exist in the literature. The latest is that of Shabalin 20). His figures indicate a production rate more than two orders of magnitude below that required. However, the question is under re-examination by Walecka and Czyz. Their preliminary indications are that the process may be rather more probable than estimated by Shabalin, but still smaller than required by more than an order of magnitude,

Another proposal is that of a direct six-fermion interaction 21) This proposal springs from the idea of Efiniov 22) that a finite field theory might result from interactions which are not low degree polynomials in field variables, but more complicated functions. On expansion, such functions yield polynomials of every degree. For the fermions, we might then have in addition to the four-fermion interaction others of six and more. Lepton pairs can then be produced directly. The energy dependence associated with such diagrams is so high that they cannot be ruled out (on the basis of low energy decay information), from contributing in this experiment. Such a theory is rather flexible, for there are many interaction types possible and the coupling constant is adjustable. This possibility has therefore to be borne in mind until one of the other possibilities is confirmed,, for example by energy and angular distribution studies, or by a direct demonstration of the V/ resonance in more extensive bubble chamber data.

EEFEEENCES

1) G. Danby et al., Phys.Rev. Letters 9, 36 (1962),

H. Bingham et al., (CERN neutrino experiment; bubble chamber) this conference.

G. Bernardini et al., (CERN neutrino experiment; spark chamber) this conference.

4) S. van der Meer, (CERN neutrino experiment; horn) this conference.

5) G. Feinberg, F. Gürsey and A. Pais, Phys.Rev. Letters 7, 208 (1961).

6) A, Ghani and G. von Dardel, CERN EP 62-9 (1962).

8) W.Ho Barkas. W. Birnbaum and P.M. Smith, Phys.Rev. 101, 778 (1956).

J, Bernstein, M.Ruderwan and G. Feinberg, "Electromagnetic Properties of the Neutrino", to be published.

9) H.A. Bethe,, Proc.Camb.Phil.Soc. 31 , 108 (1935).

10) S,M. Berman. Int,Conf. on Theor. Aspects of Very High Energy Phenomena? CERN 1961. p. 17.

11) J. Bernstein and T.D. Lees to be published:

P. Meyer and L.I. Schiff, to be published.

12) N. Cabibbo and R. Gatto, Nuovo Cimento J_^_, 304 (1960)-

Y. Yamaguchi? ProgoTheor.PhySo 23, 1117 (1960) and GEEN 61-2 (

ToDo Lee and C.N. Yangs Phys.Bev Letters £s 307 (1960).

13) J. L^vsetho Physics Letters ^ 199 (1963).

14) T.D. Lee and C.N. Yang, Phys,Rev. Letters 4, 307 (1960);

A. Pais, Phys.Eev. Letters 9, 117 (1962).

15) J.S. Bell and S.M. Berman, Nuovo Cimento 25, 404 (1962).
Accounts of the relativistic dispersion formalism have been given by
N. Dombey, Phys.Rev. 127, 653 (1962);
Ph. Dennery, Phys.Rev. 127, 664 (1962);
Nguyen Van-Hieu, Soviet Physics JETP 16, 920 (1963), and Dubna preprint R-905.

16) N. Cabibbo and G. da Prato, Nuovo Cimento 25, 611 (1962).

17) Nguyen Van-Hieu, Dubna preprint R-1152 (1962).

18) T.D. Lee, P. Markstein and C.N. Yang, Phys.Rev. Letters 7, 429 (1961
J.S. Bell and M. Veltman, Physics Letters 5, 94 (1963).

19) It is assumed here that $d^2\sigma/dq^2$ is constant for small q^2 above a few GeV. On the unlikely hypothesis that W is strongly Reggeize [C. Iso, Annals of Physics 23, 304 (1963)] $d^2\sigma/dq^2$ actually decreases.

20) E.P. Shabalin, Soviet Physics JETP 16, 125 (1962).

21) T. Ericson and S.L. Glashow, CERN preprint 7039/TH.365.

22) G. Efimov, Physics Letters 4, 314 (1963).