FORM FACTOR DETERMINATION IN NEUTRINO INTERACTIONS

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ABSTRACT

The energy dependence of the elastic cross section is expressed as a function of six form factors. The ability to separate the contributions of these form factors is discussed and the conclusion drawn that experiments should be performed in the neutrino energy region 0.5 - 5 GeV.

If we assume a local V-A theory of weak interactions, then the elastic neutrino interaction

$$\nu + n \to \mu^- + p$$

can be described by six form factors:

$$g_E \quad g_M \quad g_A \quad g_p \quad F_E \quad F_s.$$

g_E and g_M are the electric and magnetic vector form factors as defined by Ernest, Sachs, and Wali.[1] These are the same as those determined in electron scattering if the isotriplet hypothesis is correct.

g_A is the axial vector form factor whose value at $q^2 = 0$ is known experimentally but whose shape is completely unknown.

g_p is the induced pseudoscalar form factor whose value at $q^2 = 0$ is predicted by PCAC, whose high-q^2 behavior is expected to fall like a pion propagator, at least at small q^2, but whose shape is not really known.

F_E and F_s are CVC-violating form factors, assumed small but unknown. F_s is multiplied by the muon mass and is therefore less likely to be significant than F_E.

The cross section for the elastic reaction can be expressed in terms of these form factors as follows:

$$\frac{\partial\sigma}{\partial q^2} = \frac{1}{E^2}\, A \pm \frac{4ME - q^2}{E^2}\, B + \frac{(4ME - q^2)^2}{E^2}\, C, \tag{1}$$

where A, B, C are functions of the form factors, which are functions of q^2, and of q^2 explicitly. Providing the contributions from A, B, and C are of the same order of magnitude at some region of E, then the terms A, B, and C could be experimentally separated.

At low neutrino energies ($E \sim 1$ GeV) this is indeed the case. Assuming then that the terms A, B, and C are determined, each as a function of q^2, we can now see what we can learn from them. We find

$$A = A(g_A, g_M, g_E, g_p, F_E, F_s, q^2)$$
$$B = B(g_A \cdot g_M, q^2)$$
$$C = C(g_A, g_E, g_M, F_E, q^2).$$

Thus if we assume CVC to obtain g_M, g_E we can in principle obtain

1. $g_A(q^2)$ from term B
2. $F_E(q^2)$ from term C
3. Some combination of g_p and F_s from term A.

We would, in principle, learn nothing new by observing the $\bar{\nu}$ cross section, since the only difference is the change in the sign of term B whose magnitude we can derive from the energy distribution.

Polarization experiments, however, can give us new information. For instance, polarization in the x direction[2] (see Fig. 1) can at low E_ν give us g_p (assuming CVC) and provide a CVC check at high E_ν. Polarization in the y direction can give us information on F_s at low E_ν and on F_E at high E_ν.

I conclude that, provided the band of E_ν includes the region below 1 GeV, and provided differential cross section and polarization experiments can be performed, then one can in principle 1) check CVC and, 2) determine or fix upper limits for the four unknown form factors g_A, g_p, F_E, F_s. The determination will be for q^2 up to about 1 GeV^2, i.e., up to the point where the contribution from a form factor like g_E has fallen to 8% of its contribution at $q^2 = 0$.

The q^2 region between 1 GeV and 10 GeV can be explored with $E_\nu < 5$ GeV but the detailed separation of terms will be more difficult.

At neutrino energies greater than 5 GeV, the separation of terms by their energy dependence is not possible at all. If local V-A theory holds the differential cross section becomes independent of neutrino energy and ν and $\bar{\nu}$ cross sections and polarizations are the same.

The q^2 dependences and polarizations up to a q^2 of 10 GeV^2 could be determined by the low-energy data and the only new information would come from the relatively small number of events (~ 1%) with $q^2 > 10\ \text{GeV}^2$. Unless the axial vector form factor falls pathologically slowly, these high q^2 events will be dominated by weak magnetism (g_M^2) which is known from e-p scattering. A larger number of these high q^2 events could be attributed to a breakdown of CVC, a pathological axial vector current or a second class current, without any possibility of separation. A high-energy polarization experiment would allow a determination of g_A in this q^2 region, but the experiment is hard in view of the small fraction of events that can be used.

If the local theory does not hold, then the above analysis may not be valid. ν and $\bar{\nu}$ cross sections at high energy or q^2 could be different, the shape of the q^2 distribution might not fit equation (1) and a high-energy ν exposure could show us entirely new things. It should be noted, however, that the existence of an intermediate boson, for instance, would not exhibit any of these interesting phenomenon and thus this may not be the best way to test locality.

I conclude, therefore, that although it is clearly important to observe neutrino elastic scattering at high energies, it is as important, if not more important, to perform the best possible experiments at neutrino energies below 5 GeV.

If I consider the situation for N^* production or hyperon production for $\bar{\nu}$, in fact, if I consider almost any two-body final state, then I can follow a similar line of thinking and come out with similar conclusions with only a modest rise in the E_ν limit. In all cases detailed study of the form factors may be possible with the lower energies. In all cases the high energies will only provide extra information at very high q^2's where a negligible percentage of the events will be found. In all cases, the background problems will be much worse at the higher energies.

It is desirable, therefore, to build the best possible ν beam for the energy region 0.5 - 5 GeV. The best place to build such a beam is at NAL since its intensity is 2 - 5 times the improved AGS and the bubble chamber (if the 25-foot is built) is 3 - 10 times larger than that at BNL. Such a low-energy beam would employ a short (10-meter) uranium shield, a short (20-meter) decay path, and use the highest proton energy that the ingenuity of man could devise without flooding the bubble chamber with muons. Even if no ingenuity were forthcoming, the NAL machine could operate at 30 GeV at a high repetition rate, 30-GeV pulses could be inserted between normal pulses with no more time lost than a flat top. In either case the event rate would be an order of magnitude higher than at BNL. This would be important for the elastic polarization determination and very important for the detailed unraveling of the hyperon production from $\bar{\nu}$.

REFERENCES

[1] Ernest, Sachs, and Wali, Phys. Rev. 119, 1105 (1960).

[2] M. Block, Neutrino Physics, National Accelerator Laboratory 1968 Summer Study Report B.1-68-42, Vol. I, p. 215.

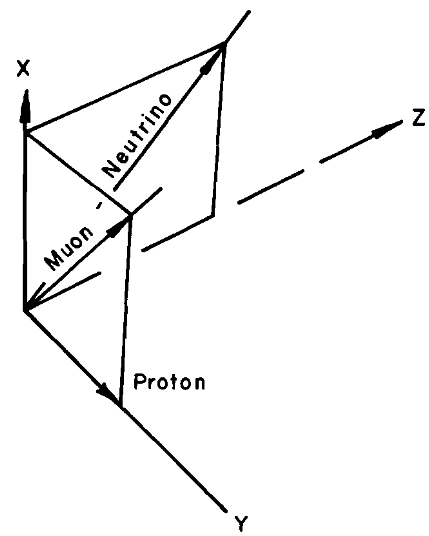

Fig. 1. Relations among momentum vectors.