Neutrino Experiments.

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PART I.

The First High-Energy Neutrino Experiment.

In this lecture we will review what seems, in light of succeeding work, to be almost ancient history. In the course of six months of difficult experimentation, a result was obtained which can now be duplicated in less than a day at either the CERN or Brookhaven accelerators. Nevertheless, it seems useful to recount the history of the first high-energy neutrino experiment and show how the nonidentity of the electron neutrino and the muon neutrino was first demonstrated.

The experimental work was carried out by the group of G. DANBY, J. M. GAILLARD, K. GOULIANOS, L. LEDERMAN, N. MISTRY, M. SCHWARTZ and J. STEINBERGER. Two publications in the «Physical Review Letters» describe this work and the theoretical consequence of it. The first of these [1] by the above-named experimenters details the experimental result. The second [2] applies the CVC theory of Feynman and Gell-Mann [3] to draw some additional consequences and includes among its authors Prof. T. D. LEE, at whose suggestion this application was made.

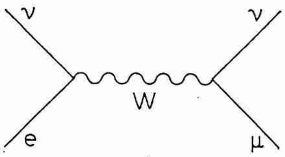
Let us begin by outlining the prevailing situation in the theory of weak interactions at the time this experiment began. It had been well known for many years that the Fermi theory of weak interactions gave approximately correct results at low energies and indeed, as formulated by FEYNMAN and GELL-MANN, it appeared to be almost exact and quite universal up to momentum transfers of the order of 100 MeV/c. In this theory, the weak interaction takes the form of a simple four-fermion vertex with constant, momentum-independent matrix element. As a consequence if one were to calculate a weak process like $\nu+e\to\mu+\nu$ one would obtain a result which depended only on phase space. That is to say, the cross-section would rise as p^2 in the center-of mass sysem, where p is the neutrino momentum.

This however, if taken literally, would soon lead to difficulty. Since there is no physical dimension to the interaction region, the only partial waves which can enter are S-waves and the cross-section must be limited by unitarity to $\pi\bar{\lambda}^2/2$ At 300 GeV in the center of mass the proiected Fermi cross-sections would pass the unitarity limit and so the FERMI theory must of necessity break down before this point.

It had been known for a long time that the simplest way out of this difficulty was through the mediation of an intermediate boson (W). If there were some virtual propagator for the weak interactions, then the matrix element would have a momentum dependence corresponding to this propagator and the interaction region would have some physical dimension. Thus, for example one could decompose the reaction $\nu+e\rightarrow\mu+\nu$ as follows:

$$\nu+e\rightarrow W\,,$$

$$W\rightarrow\nu+\mu\,.$$



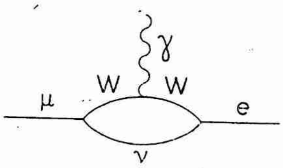
Now, until the Feynman-Gell-Mann theory, the intermediate boson looked hopeless because the interaction was thought to be T and S. With the advent of V—A it was most reasonable to think of a simple vector meson as mediating the interaction.

There was one « fly in the ointment » however. FEINBERG [4] and independently FEYNMAN and GELL-MANN [5] carried out a calculation which showed that the existence of an intermediate vector boson would lead to a branching ratio of $(\mu\rightarrow e+\gamma)/(\mu\rightarrow e+\nu+\bar{\nu})$ of 10^{-4}. In carrying out this calculation, it was of course assumed that the same neutrino which coupled to the muon, also coupled to the electron. The diagram which was calculated to obtain this branching ratio was the following:

$$\mu\rightarrow W+\nu\,,$$

$$W\rightarrow\gamma+W\,,$$

$$W+\nu\rightarrow e\,.$$



This calculation seemed to spell the end to the W since the experimental upper limit on this branching ratio was about 10^{-8}.

At this point it was pointed out by LEE and YANG [6] that any theory which would keep us out of the unitarity predicament would almost certainly lead to a rate of $\mu\rightarrow e+\gamma$ not too different from the above, if there was only one neutrino. The argument pointed out that in order to keep within the unitarity