6

Weak Interactions

From parity violation to two neutrinos, 1956–1962.

In 1930, Wolfgang Pauli postulated the existence of the neutrino, a light, feebly interacting particle. Pauli did this to account for the electron spectrum seen in beta decay. If the electron were the only particle emitted in beta decay, it would always have an energy equal to the difference between the initial and final nuclear state energies. Measurements showed, however, that the electron's energy was variable and calorimetric measurements confirmed that some of the energy was being lost. So disturbing was this problem that Bohr even suggested that energy might only be conserved on average!

Beta decay could not be understood without a successful model of the nucleus and that came after the discovery of the neutron by Chadwick in 1932. The neutrino and the neutron provided the essential ingredients for Fermi's theory of weak interactions. He saw that the fundamental process was $n \rightarrow pe\nu$. Using the language of quantized fields Fermi could write this as an interaction:

$$p^\dagger(x)n(x)e^\dagger(x)\nu(x)$$

where each letter stands for the operator that destroys the particle represented or creates its antiparticle. Thus the $n(x)$ destroys a neutron or creates an antineutron. The dagger makes the field into its adjoint, for which destruction and creation are interchanged. Thus $p^\dagger(x)$ creates protons and destroys antiprotons. The position at which the creation and destruction take place is x.

Fermi wrote the theory in terms of a Hamiltonian. It had to be invariant under translations in space. This is achieved by writing something like

$$H \propto \int d^3x \; p^\dagger(x)n(x)e^\dagger(x)\nu(x) \tag{6.1}$$

suitably modified to be Lorentz invariant.

The relativistic theory of fermions was developed by Dirac. Each fermion is represented by a column vector of four entries (essentially for spin up and down, for both particle and antiparticle). For

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a nonrelativistic particle, the first two entries are much larger than the last two. These "large components" are equivalent to Pauli's two component spinor representation of a nonrelativistic spin one-half particle. Explicitly, a particle of mass m, three-momentum $\mathbf{p}$, and energy $E = \sqrt{m^2 + p^2}$ and with spin orientation indicated by a two-component spinor χ is represented by a Dirac spinor

$$u(p) = \sqrt{E+m}\begin{pmatrix} \chi \\ \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+m}\chi \end{pmatrix}. \tag{6.2}$$

Indeed, in the nonrelativistic limit where $p << m$, E, the lower two components are much smaller than the upper two. Thus if $\chi = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\mathbf{p}$ has components p_x, p_y, p_z, then

$$u(p) = \begin{pmatrix} \sqrt{E+m} \\ 0 \\ p_z/\sqrt{E+m} \\ (p_x + ip_y)/\sqrt{E+m} \end{pmatrix}. \tag{6.3}$$

Despite their appearance, these spinors are not four-vectors because they transform in a completely different way. It is possible to make Lorentz scalars and four-vectors from pairs of spinors. Ordinary four-vectors, $a = (a_0, \mathbf{a})$ and $b = (b_0, \mathbf{b})$, can be combined to make a Lorentz-invariant product $a\cdot b = a_0 b_0 - \mathbf{a}\cdot\mathbf{b} = a_\mu b^\mu$, where $a_0 = a^0$, $a_i = -a^i$, for $i = 1, 2, 3$. Pairs of spinors are combined with the Dirac matrices which can be expressed as

$$\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & \sigma_1 \\ -\sigma_1 & 0 \end{pmatrix}, \quad \gamma^2 = \begin{pmatrix} 0 & \sigma_2 \\ -\sigma_2 & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & \sigma_3 \\ -\sigma_3 & 0 \end{pmatrix}. \tag{6.4}$$

where σ_i are the usual 2×2 Pauli spin matrices, and I is the 2×2 unit matrix. In this convention one writes $\gamma_0 = \gamma^0$, $\gamma_i = -\gamma^i$, $i = 1, 2, 3$. A Lorentz invariant is obtained by placing a γ^0 between a spinor (a column vector) and an adjoint spinor, $\psi^\dagger$, which is the row vector obtained by taking the complex conjugate of each component:

$$\psi^\dagger \gamma^0 \psi \equiv \overline{\psi}\psi \tag{6.5}$$

where ψ is a four component spinor and $\overline{\psi} = \psi^\dagger\gamma^0$, or equivalently, $\psi^\dagger = \overline{\psi}\gamma^0$. The combination $\overline{\psi}\gamma_\mu\psi$, $\mu = 0, 1, 2, 3$, transforms as a four-vector. Thus $\psi^\dagger\psi = \overline{\psi}\gamma_0\psi$ is not a scalar, but the zeroth component of a vector quantity.

Rather than using ψ or u for each spinor, it is often clearer to indicate the particle type, so a spinor for a proton is indicated simply by p, one for a neutrino by ν, and so on. Thus $\nu(x)$ is the neutrino field at x, a field that destroys neutrinos or creates antineutrinos. Similarly $p^\dagger$ and $\overline{p} = p^\dagger\gamma^0$ create protons or destroy antiprotons. An operator like $e(x)$ can be expressed in terms of momentum through a Fourier transform. For example, if $e(x)$ acts on a state with an electron of momentum p, a factor of the spinor $u(p)$ is produced.

A possible interaction that is Lorentz-invariant is of the form

$$H \propto \int d^3x\ \overline{p}(x)\, n(x)\, \overline{e}(x)\, \nu(x). \tag{6.6}$$

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This is not what Fermi chose. He noted that the usual electromagnetic current for an electron, which receives contributions from the motion of the charge and the magnetic moment, can be written in Dirac notation as

$$J_\mu(x) = \overline{e}(x)\gamma_\mu e(x). \tag{6.7}$$

This object transforms as a relativistic four-vector. Electrodynamics can be viewed as the interaction of such currents. By analogy, Fermi wrote

$$H = g \int d^3x\, \overline{p}(x)\gamma^\mu n(x)\, \overline{e}(x)\gamma_\mu \nu(x) \tag{6.8}$$

where g was a constant. There also had to be an interaction that was the Hermitian conjugate of this and would describe e^+ emission, a process discovered by Irène Curie and Frédéric Joliot in 1933:

$$H = g \int d^3x\, \overline{n}(x)\gamma^\mu p(x)\, \overline{\nu}(x)\gamma_\mu e(x). \tag{6.9}$$

Many consequences of Fermi's theory can be obtained without detailed computation, which is often prevented by lack of detailed information on the nuclear wave functions. By the Golden Rule, the decay rate is governed by

$$\Gamma \propto \int d^3p_e\, d^3p_\nu\, \delta(Q - E_e - E_\nu)|H_{fi}|^2 \tag{6.10}$$

where p_e is the electron's momentum and E_e is its energy and similarly for the neutrino. The total energy available in the decay is Q, the mass difference between the initial and final nuclei, minus the electron mass. The Dirac delta function guarantees energy conservation. The recoiling nucleus balances the momentum, but contributes negligibly to the energy. If we ignore the dependence of the matrix element, H_{fi}, on the momentum, we find

$$\frac{d\Gamma}{dp_e} \propto p_e^2(Q - E_e)^2|H_{fi}|^2. \tag{6.11}$$

Thus $(1/p_e)(d\Gamma/dp_e)^{1/2}$ should be a linear function of E_e. A plot of these quantities is called a Kurie plot and the expectation of linearity is borne out in many decays. The high energy portion of a Kurie plot for tritium decay is shown in Figure 6.1.

Looking at the Fermi theory in greater detail, we consider the term

$$\overline{p}(x)\gamma^\mu n(x) = p^\dagger(x)\gamma^0\gamma^\mu n(x) \tag{6.12}$$

involving the nucleons only. This operator changes the initial nuclear state to the final one, transforming a neutron into a proton. The nucleons can be considered nonrelativistic. Of their four components, only the first two are important and these represent spin-1/2 in the usual way. Since γ^1, γ^2 and γ^3 connect large components to small components, only $\overline{p}\gamma^0 n$

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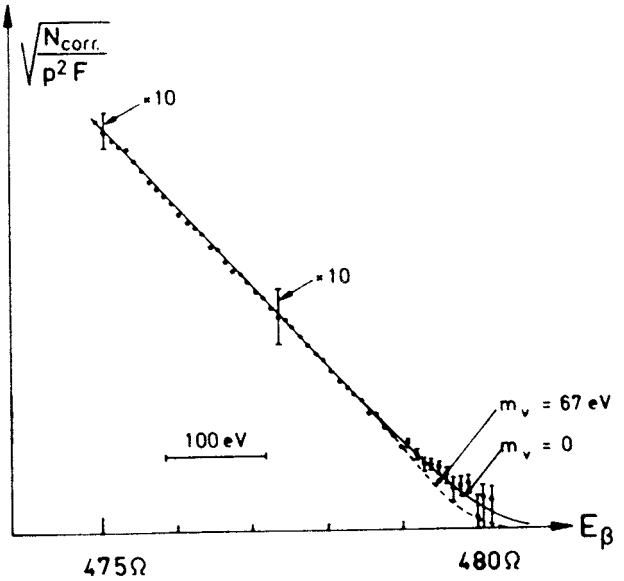


Figure 6.1. The Kurie plot for the beta decay of tritium showing the portion of the electron spectrum near the end point at 18.6 keV. As pointed out by Fermi in his 1934 paper setting out the principles of beta decay, if the neutrino mass is non-zero there will be a deviation of the plot from linearity near the end point. By studying this region with extreme care, Bergkvist was able to set an upper limit of 60 eV on the mass of the neutrino (more precisely, the electron-antineutrino) [K. E. Bergkvist, *Nucl. Phys.* **B39**, 317 (1972)]. The x-axis of the Figure shows the magnet setting of the spectrometer. The interval corresponding to 100 eV is indicated, as well as two sample error bars with a magnification of 10. The curves expected, including the effects of the apparatus resolution, for neutrino masses of 67 eV and 0 eV are shown. Without the resolution effects, the curve for 0 eV would be a straight line, while the 67 eV curve would fall more abruptly to zero.

will be important. Thus $\overline{p}\gamma^\mu n$ reduces to $p^\dagger n$ where in the final expression we consider the spinors to have just two components. This operator changes a neutron into a proton without changing its location or affecting its spin. It cannot change the angular momentum: It is a $\Delta J = 0$ operator. Moreover, it cannot change the parity. These are the selection rules analogous to, but different from, those familiar in radiative transitions between atomic states.

In fact, it is found that not all beta decays occur between nuclear states with identical angular momenta, so the Fermi interaction cannot be a complete description. To generalize it, we consider the possible forms made from two (four-component) fermion fields and combinations of Dirac matrices:

$$\begin{aligned}
\overline{p}n \quad & S \quad (scalar)\\
\overline{p}\gamma_5 n \quad & P \quad (pseudoscalar)\\
\overline{p}\gamma^\mu n \quad & V \quad (vector)\\
\overline{p}\gamma^\mu\gamma_5 n \quad & A \quad (axial\ vector)\\
\overline{p}\sigma^{\mu\nu} n \quad & T \quad (tensor)
\end{aligned}$$

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Here we have introduced

$$\sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^{\mu}, \gamma^{\nu}\right] = \frac{i}{2}(\gamma^{\mu}\gamma^{\nu} - \gamma^{\nu}\gamma^{\mu}) \tag{6.13}$$

and

$$\gamma_5 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}. \tag{6.14}$$

The names "scalar," "vector," etc., describe the behavior of the bilinears under the Lorentz group and parity. Lorentz invariant quantities can be obtained by combining with the corresponding forms like $\overline{e}\nu$, $\overline{e}\gamma_5\nu$, etc. Before 1956, it was presumed that parity was conserved in weak interactions. This allowed combinations like $\overline{p}n\ \overline{e}\nu$ but forbade $\overline{p}\gamma_5 n\ \overline{e}\nu$, $\overline{p}\gamma_\mu\gamma_5 n\ \overline{e}\gamma^{\mu}\nu$, etc.

Using the forms of the Dirac matrices and the rule that only the two upper two components of a spinor are important for a nonrelativistic particle, it is easy to see what kinds of terms are available for the nuclear part of the beta-decay amplitude:

$S:$	$\overline{p}n$	$\rightarrow$	$p^{\dagger}n$	
$P:$	$\overline{p}\gamma_5 n$	$\rightarrow$	0	
$V:$	$\overline{p}\gamma^{\mu}n$	$\rightarrow$	$p^{\dagger}n$	for $\mu = 0$, zero otherwise
$A:$	$\overline{p}\gamma^{\mu}\gamma_5 n$	$\rightarrow$	$p^{\dagger}\sigma^{i}n$	for $\mu = i = 1, 2, 3$, zero if $\mu = 0$
$T:$	$\overline{p}\sigma^{\mu\nu}n$	$\rightarrow$	$p^{\dagger}\sigma^{i}n$	if $\mu = j, \nu = k$ $(j, k = 1, 2, 3)$ and i, j, k cyclic, zero otherwise

In the right-hand column, the p and n represent two-component spinors and σ^{i} is a Pauli matrix.

Thus we see that two kinds of nuclear transitions are possible, ones like those in the original Fermi theory, due to $p^{\dagger}n$, and those due to $p^{\dagger}\sigma n$. The former are called Fermi transitions and the latter Gamow–Teller transitions. Because of the σ, the Gamow–Teller transitions can change the angular momentum of the nucleus by one unit. However, the operator still does not change parity. In summary, S and V give Fermi transitions, while T and A give Gamow–Teller transitions. Fermi transitions in which the angular momentum of the nucleus changes are not allowed. Thus from the existence of transitions like $O^{14} \rightarrow N^{14*} + e^{+} + \nu$ $(0^{+} \rightarrow 0^{+})$ and $He^{6} \rightarrow Li^{6} + e^{-} + \nu$ $(0^{+} \rightarrow 1^{+})$ we know that there must be at least one of S and V as well as at least one of T and A. It was also possible to show that if we have both S and V, or both T and A in a parity conserving theory, the Kurie plot would not be straight, in contradiction with the data. Thus the nuclear part of the transition was thought to be either S or V, together with T or A, and parity conserving.

Distinguishing between these choices required observing more than the electron energy spectrum. The angle between the electron and neutrino directions could be inferred by measuring the recoil of the nucleus. The dependence on this angle measured the relative amounts of V versus S and A versus T. The results before 1957 indicated a preference for T over A, especially in the $He^{6} \rightarrow Li^{6} + e^{-} + \nu$ decay.

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In addition to nuclear beta decay, information on weak interactions was available from decays of strongly interacting particles, especially kaons, and from the decay of the muon. A thorough analysis of the decay $\mu \rightarrow e\nu\nu$ was given by L. Michel in 1950, assuming parity conservation. He found that the shape of the energy spectrum was determined up to a single parameter, ρ, that was a function of the relative amounts of S, P, V, A, and T. With $x = 2p_e/m_\mu$, the intensity of the spectrum is

$$dN/dx \propto x^2\,[1 - x + (2/3)\rho(4x/3 - 1)]\,. \tag{6.15}$$

A measurement in 1955 gave $\rho = 0.64 \pm 0.10$. The currently accepted value is 0.7509 ± 0.0010, consistent with the maximal value allowed, 3/4. Two examples of the electron spectrum from muon decay are displayed in Figure 6.2.

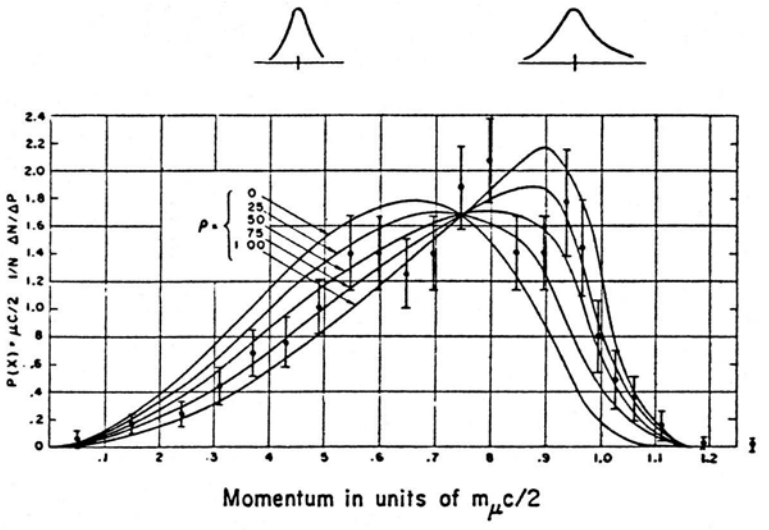
About the same time, the universality of the weak interaction was becoming evident. By universality one means that the interaction is of the same form and strength in all situations. Tiomno and Wheeler suggested that the pairs (e, ν), (μ, ν), and (n, p) entered into the weak interaction in an equivalent way. Nuclear beta decay involves (n, p) and (e, ν). The charged pion can be viewed as a bound state of a nucleon and an antinucleon. In this way, the weak interaction responsible for charged pion decay involves (n, p) and (μ, ν). The decay of the muon depends on (μ, ν) and (e, ν).

The giant step in understanding weak interactions came in 1956 when T. D. Lee and C. N. Yang pointed out that there was no evidence in favor of parity conservation in weak interactions. The precipitating issue was the $\tau - \theta$ puzzle. As described in Chapter 3, the τ was the 3π decay of the K^+. The analysis begun by Dalitz had shown that the 3π system had J^P in the series $0^-, 2^-, \ldots$ On the other hand, the θ^+ (or χ^+) decayed into $\pi^0\pi^+$ and had "natural" spin-parity: $J^P = 0^+, 1^-, \ldots$ Measurements showed that the masses and lifetimes of the θ and τ were very similar, perhaps equal. The θ and the τ seemed to be the same particle, except that they had different values of J^P. The Proceedings of the Sixth Annual Rochester Conference in April 1956 record that after Yang's talk,

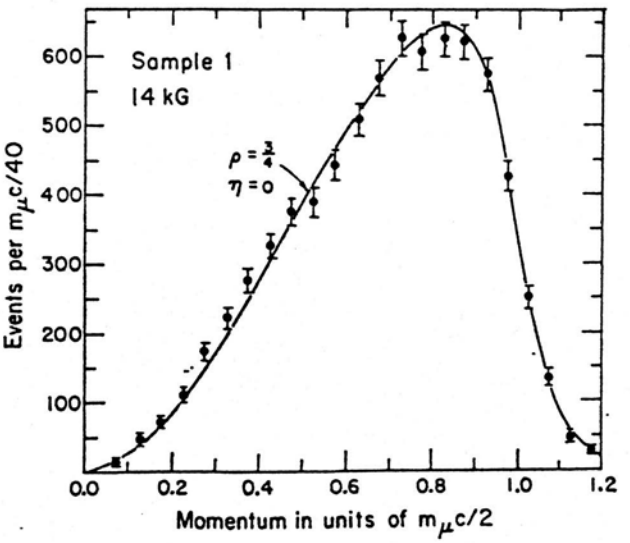
> Feynman brought up a question of [Martin] Block's: Could it be that the θ and τ are different parity states of the same particle which has no definite parity, *i.e.* that parity is not conserved. That is, does nature have a way of defining right or left-handedness uniquely. Yang stated that he and Lee looked into this matter without arriving at any definite conclusions.

A few months later, there were conclusions. Despite the overwhelming prejudice that parity must be a good symmetry because it was a symmetry of space itself just as rotational invariance is, Lee and Yang demonstrated that there was no evidence for or against parity conservation in weak interactions. To test for possible violation of parity it was necessary to observe a dependence of a decay rate (or cross section) on a term that changed sign under the parity operation. Parity reverses momenta and positions, but not angular momentum (or spins). In a nuclear decay, the momenta available are $\mathbf{p_e}$, $\mathbf{p}_\nu$, and $\mathbf{p_N}$, the momenta of the electron, neutrino and recoil nucleus. Terms like $\mathbf{p_e} \cdot \mathbf{p}_\nu$ cannot show parity violation. The invariant formed from the three momenta, $\mathbf{p}_e \cdot \mathbf{p}_\nu \times \mathbf{p}_N$, would change sign under parity, but vanishes because the momenta are coplanar. To test for parity violation in nuclear beta decay required consideration of spin. If the decaying nucleus were oriented, it would be

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(a)



(b)

Figure 6.2. Two examples of the electron momentum spectrum in muon decay. (a) An early measurement made in a high pressure cloud chamber at the Columbia University Nevis Cyclotron which gave the value $\rho = 0.64 \pm 0.10$. The variation with the parameter ρ of the spectrum shape, including the experimental resolution, is shown in the curves. The bell-shaped curves show the resolution of the experiment at two values of the electron momentum [C. P. Sargent *et al.*, *Phys. Rev.* **99**, 885 (1955)]. (b) A later spectrum obtained with a hydrogen bubble chamber which, when combined with earlier spark chamber measurements, gave $\rho = 0.752 \pm 0.003$ [S. E. Derenzo, *Phys. Rev.* **181**, 1854 (1969)].

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possible to measure the angular dependence of the decay, looking for a term proportional to $< \mathbf{J} > \cdot \mathbf{p_e}$, where $< \mathbf{J} >$ was the average nuclear spin. This was achieved by C. S. Wu in collaboration with E. Ambler and co-workers at the National Bureau of Standards, who had the necessary low temperature facility **(Ref. 6.1)**.

Wu and her co-workers chose to work with Co^{60}, whose ground state has $J^P = 5^+$. It beta-decays through a Gamow–Teller transition with a half-life of 5.2 y, yielding Ni^{60} in the 4^+ state. The excited Ni state decays through two successive γ emissions to 2^+ and then 0^+, with γ energies 1.173 and 1.332 MeV, respectively. The NBS team included experts in producing nuclear polarization through adiabatic demagnetization. The degree of polarization of the Co sample was monitored by observing the anisotropy of the gamma radiation. The polarization of the Co^{60} was transmitted to the Ni^{60}, giving a difference between the rates for gamma emission in the polar and equatorial directions, relative to the axis of the applied polarizing magnetic field.

The beta-decay rate along the direction of the magnetic field, that is, along the nuclear polarization direction was monitored. Reversing the magnetic field reversed the direction of $< \mathbf{J} >$. The counting rate indeed showed a dependence on $< \mathbf{J} > \cdot \mathbf{p_e}$. Not only was the rate different for the two magnetic field orientations, but as the sample warmed, the dependence of the rate on the field orientation disappeared at the same speed as the polarization itself disappeared, showing the connection of the decay angular distribution was with the nuclear orientation, not simply with the applied magnetic field.

Word of this *tour de force* spread rapidly and new experiments were undertaken even before the results of Wu's team appeared in print. Indeed, two further experiments appeared in rapid succession showing parity violation in the sequence $\pi^+ \to \mu^+ \to e^+$ (**Refs. 6.2, 6.3**). Rather than beginning with a polarized beam, these experiments exploited the prediction of Lee and Yang that parity violation would lead to polarization of the μ along its line of flight in the $\pi \to \mu\nu$ decay. The polarization of the μ is retained when it slows down in matter. A distribution of decay electrons relative to the incident beam direction of the form $1 + a\cos\theta$ is then expected, where a depends on the degree of polarization of the μ. Garwin, Lederman, and Weinrich, working with the Nevis Cyclotron at Columbia University, applied a magnetic field to the region where the muons stopped. This caused the spin of the muon to precess. In this elegant fashion, they demonstrated parity violation, measured its strength and simultaneously measured the magnetic moment of the μ^+ by measuring the rate of precession. At the same time, Friedman and Telegdi, at the University of Chicago, also found parity violation by observing the same decay sequence, but working in emulsions and without a magnetic field. The emulsion experiment was started before the others, but took longer to complete because of the laborious scanning procedure.

With the violation of parity, the number of terms to be considered in nuclear beta decay doubled. A general interaction could be written

$$H = \frac{G_F}{\sqrt{2}} \int d^3x \left(C_S \overline{p} n \, \overline{e} \nu + C'_S \overline{p} n \, \overline{e} \gamma_5 \nu + C_V \overline{p} \gamma^\mu n \, \overline{e} \gamma_\mu \nu + C'_V \overline{p} \gamma^\mu n \, \overline{e} \gamma_\mu \gamma_5 \nu + \cdots \right) \tag{6.16}$$

where $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is known as the Fermi constant. The terms with coefficients C_i are parity conserving, while those with coefficients C'_i are parity violating. The

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years 1957 and 1958 brought a wealth of experiments aimed at determining the constants $C_S, C'_S, C_V, C'_V, \ldots$ Parity violation allowed rates to depend on $\boldsymbol{\sigma}_e \cdot \mathbf{p}_e$, i.e. longitudinal polarization of the electron emitted in beta decay. Frauenfelder and co-workers (**Ref. 6.4**) found a large electron polarization, $< \boldsymbol{\sigma}_e \cdot \mathbf{p_e} > / p_e \approx -1$. This result was consistent with the proposal that the neutrino has a single handedness:

$$H = \frac{G_F}{\sqrt{2}} \int d^3x \left[C_S \overline{p} n \, \overline{e}(1 \pm \gamma_5)\nu + C_V \overline{p}\gamma_\mu n \, \overline{e}\gamma^\mu(1 \pm \gamma_5)\nu + \cdots \right] \tag{6.17}$$

If the negative sign is used, the neutrinos participating in the interaction are left-handed, that is, their spins are antiparallel to their momenta (helicity $-1/2$). If the positive sign is taken, they are right-handed (helicity $+1/2$). The experiment of Frauenfelder *et al.* showed that the electrons were mostly left-handed. This would follow from, say, $\overline{e}\gamma^\mu(1 - \gamma_5)\nu$ or from $\overline{e}(1 + \gamma_5)\nu$. More completely, if the neutrino has a single handedness and the nuclear part is V or A, then the neutrino should be left-handed, while if the nuclear part is S or T, the neutrino should be right-handed. Remarkably, it was possible to do an experiment to measure the handedness of the neutrino!

This was accomplished by M. Goldhaber, L. Grodzins, and A. W. Sunyar (**Ref. 6.5**). The experiment is based on a subtle point, the strong energy dependence of resonant scattering of X-rays. When an excited nucleus emits an X-ray, the energy of the X-ray is not exactly equal to the difference of the nuclear levels because the recoiling nucleus carries some energy. However, if the emitting nucleus is moving in the direction of the X-ray emission, the Doppler shift makes up for some of the energy loss. The resonant scattering of such X-rays is then much stronger since the X-ray's energy is closer to the energy of excitation of the nucleus. This could be exploited in $Eu^{152\,m}$ which decays by electron capture, with a half-life of about 9 hours. In electron capture, an inner shell electron interacts with the nucleus according to $e^- p \to n\nu$. In this case, the overall reaction was $e^- + \mathrm{Eu}^{152\,m} \to \mathrm{Sm}^{152*} + \nu$. The initial nucleus has $J = 0$ and the final nucleus, $J = 1$. The latter decays very rapidly by γ emission to the $J = 0$ ground state. If we take the neutrino direction as the z axis and assume the captured electron is in an s-wave, the intermediate Sm^{152*} state has $J_z = 1$ or 0 if the ν has $J_z = -1/2$ and $J_z = -1$ or 0 if the ν has $J_z = 1/2$. Now if a gamma ray is emitted in the negative z direction (where resonant scattering is greatest because the motion of the nucleus compensates for the energy lost in recoil), it has $J_z = 1$ or -1, and in fact its helicity has the same sign as that of the neutrino. By measuring the circular polarization of the gamma ray with magnetized iron, the neutrino helicity is measured. The result found was that the neutrino is left-handed.

The outcome of this and many of the experiments at the time were in agreement with the V-A theory proposed by Marshak and Sudarshan and by Feynman and Gell-Mann. The V and A terms for the nuclear beta decay were coupled to the $\overline{e}\gamma_\mu(1 - \gamma_5)\nu$ term:

$$H = \frac{G_F}{\sqrt{2}} \int d^3x \, \overline{p}(x)\gamma^\mu(g_v + g_a\gamma_5)n(x) \, \overline{e}(x)\gamma_\mu(1 - \gamma_5)\nu(x) \tag{6.18}$$

where g_v and g_a are the vector and axial vector couplings of the weak current to the nucleons. The value of g_v is very nearly one. It can be measured in pure Fermi transitions like

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O^{14} decay, in which the nuclear matrix element is calculable because the initial and final nuclei are members of the same isomultiplet. The axial coupling constant can be measured in neutron decay, either from the neutron lifetime or from more detailed measurements of the decay. By studying the decay of free polarized neutrons, Telegdi and co-workers were able to confirm the V-A form of the interaction and measure sign as well as the magnitude of g_a/g_v (Ref. 6.6). The currently accepted value of g_a/g_v is -1.2695 ± 0.0029.

More generally, for processes with an electron and a neutrino in the final state, like $K^- \to \pi^0 e^- \nu$, the V-A theory postulates an interaction

$$H = g \int d^3x \; J^{\dagger}_{\mu\,\mathrm{had}}(x) J^{\mu}_{\mathrm{lep}}(x) + \text{Hermitian conjugate} \tag{6.19}$$

where

$$J^{\mu}_{\mathrm{lep}}(x) = \overline{e}(x)\gamma^{\mu}(1-\gamma_5)\nu(x). \tag{6.20}$$

The hadronic current, J^{μ}_{had} cannot be specified so precisely. For nuclear beta decay one can limit the possible forms since the nucleons are nonrelativistic. For decays like $\pi^- \to \pi^0 e^- \nu$ and $n \to p e^- \nu$, Feynman and Gell-Mann proposed that the vector part of the hadronic currents that raised or lowered the charge of the hadrons by one unit and did not change strangeness was part of an isotriplet of currents. The third, or charge-nonchanging, component of the triplet was the isovector part of the electromagnetic current, that is, the part responsible for the difference in the electromagnetic behavior of the neutron and proton. Since the electromagnetic current is conserved, so would be the vector part of the hadronic weak current. This proposal was known as the conserved vector current hypothesis (CVC) and was actually first given by the Soviet physicists S. S. Gershtein and Ya. B. Zeldovich.

CVC has been tested in pion beta decay, $\pi^+ \to \pi^0 e^+ \nu$ and in a comparison of the weak decays $B^{12} \to C^{12} e^- \overline{\nu}$, $N^{12} \to C^{12} e^+ \nu$ with the electromagnetic decay $C^{12*} \to C^{12}\gamma$. The three nuclei B^{12}, C^{12*}, and N^{12} form an isotriplet and C^{12} is the isosinglet ground state. In these processes, the weak decay rates can be calculated because the decay depends on the vector current and the weak vector current matrix elements can be obtained from the isovector electromagnetic current matrix elements measured in C^{12*} decay.

The V-A theory proved very successful and has survived as the low energy description of weak interactions. The weak hadronic current has two pieces, $\Delta S = 0$ (e.g. $n \to p e^- \nu$) and a $\Delta S = 1$ piece (e.g. $K \to \mu\nu$, $K \to \pi\mu\nu$). The strengths of the strangeness-changing and the strangeness-nonchanging interactions are not the same. N. Cabibbo described this by proposing that while in leptonic decays (like $\mu \to e\nu\nu$) the interaction could be written as

$$\frac{G_F}{\sqrt{2}} J^{\mu}_{\mathrm{lep}}(x) J^{\dagger}_{\mathrm{lep}\;\mu}(x), \tag{6.21}$$

in semileptonic decays, in which both hadrons and leptons participate, it should be

$$\frac{G_F}{\sqrt{2}} \left[\cos\theta_c J^{\mu}_{\Delta S=0} + \sin\theta_c J^{\mu}_{\Delta S=1}(x)\right] J^{\dagger}_{\mathrm{lep}\;\mu}(x) + \text{Herm. conj.} \tag{6.22}$$

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The Cabibbo angle, θ_c, expresses a rotation between the $\Delta S = 0$ and $\Delta S = 1$ currents. The cosine of the Cabibbo angle can be determined by measuring beta decays in $0^+ \rightarrow 0^+$ transitions in which the nuclei belong to the same isospin multiplet and comparing with G_F as measured in muon decay. In these circumstances, CVC determines the relevant nuclear matrix element. The results give $\cos\theta \approx 0.970 - 0.977$, so $\theta_c \approx 13^\circ$. Values of $\sin\theta_c$ derived from $\Delta S = 1$ decays are consistent with this value. The significance of the Cabibbo angle became clearer in subsequent years, as we shall see in Chapters 9 and 11.

A regularity noted by Gell-Mann when he invented strangeness was that in semileptonic decays $\Delta S = \Delta Q$. Thus in $K^+ \rightarrow \pi^0\mu^+\nu$, the hadronic system loses one unit of strangeness and one unit of charge. The decay $\Sigma^- \rightarrow ne^-\nu$ ($\Delta S = 1$, $\Delta Q = 1$) is observed while $\Sigma^+ \rightarrow ne^+\nu$ ($\Delta S = 1$, $\Delta Q = -1$) is not. Even more striking is the absence of processes in which the strangeness of the hadronic system changes, but its charge does not. Thus $K^+ \rightarrow \pi^+\nu\overline{\nu}$ and $K^+ \rightarrow \pi^+e^+e^-$ are extremely rare. The absence of strangeness changing neutral weak currents was to play a profound role in later developments.

The success of the Fermi theory was convincing evidence for the existence of the neutrino. Still, although the helicity of the neutrino was indirectly measured, there had been no detection of interactions initiated by the neutrinos themselves. This was first achieved by Cowan and Reines using antineutrinos produced in beta decays inside a nuclear reactor. When Reines began to think about means for detecting them, he began by considering the neutrinos that would be emitted from a fission bomb. The nuclear reactor turned out to be much more practical.

The enormous number of beta decays from neutron-rich radionuclei produced by fission provide a prolific source of antineutrinos. However, the environment around a reactor is far from ideal. Reines' idea was to show that his signal for neutrino-induced processes was greater when the reactor was on than when it was off. Early results were obtained in 1956, but a greatly improved experiment was reported in 1958 (**Ref. 6.7**). In the 1958 version of the experiment, the process $\overline{\nu}_e p \rightarrow e^+n$ was observed by detecting both the e^+ and the neutron. The positron annihilation produced two photons, which were detected as a prompt signal using liquid scintillator. The neutrons slowed down by collisions with hydrogen and then were captured by cadmium, whose subsequent gamma decay was observed. The positron and neutron signatures were required to be in coincidence, with allowance for the time required for the neutron to slow down. The experiment is displayed schematically in Figure 6.3.

Bruno Pontecorvo and Melvin Schwartz independently proposed studying neutrino interactions with accelerators, using the decays $\pi \rightarrow \mu\nu$ and $K \rightarrow \mu\nu$ as neutrino sources. The cross sections for neutrino reactions are fantastically small, on the order of $\sigma \propto G_F^2 s$, where s is the center-of-mass energy squared. Thus for $s = 1$ GeV^2, using the convenient approximations, $G_F \approx 10^{-5}$ GeV^{-2}, 0.389 mb GeV ≈ 1 with $\hbar$=c=1, $\sigma \approx 10^{-10} \times 0.4$ mb, some 12 orders of magnitude smaller than hadronic cross sections. Still, with a sufficiently large target and neutrino flux, such experiments are possible.

Neutrino beams could not be effectively produced at the accelerators available in the mid-1950s. These included the 3-GeV Cosmotron at Brookhaven and the 6-GeV Bevatron

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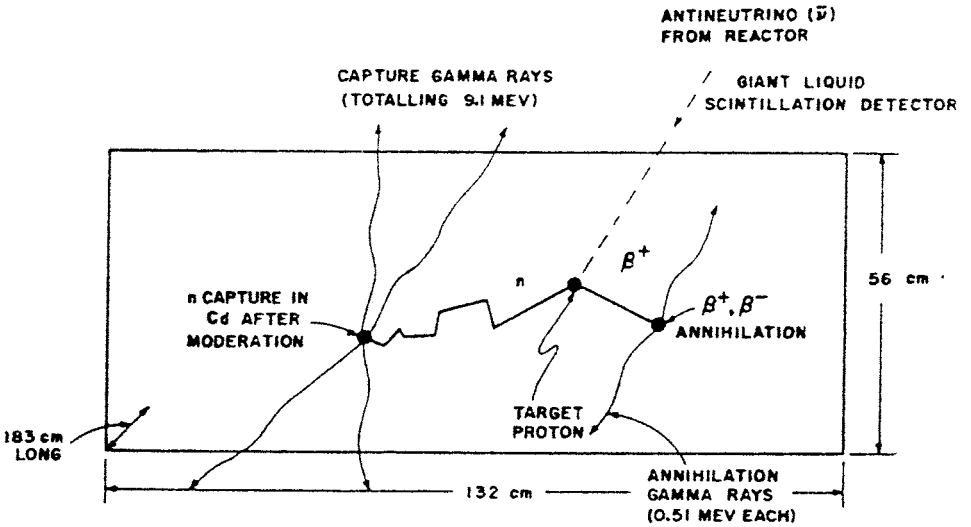


Figure 6.3. A schematic diagram of the experiment of Reines and Cowan in which antineutrinos from a nuclear reactor were detected. The dashed line entering from above indicates the antineutrino. The antineutrino transmutes a proton into a neutron and a positron. The annihilation of the positron produces two prompt gamma rays, which are detected by the scintillator. The neutron is slowed in the scintillator and eventually captured by cadmium, which then also emits delayed gamma rays. The combination of the prompt and delayed gamma rays is the signature of the antineutrino interaction (**Ref. 6.7**).

at Berkeley, and the 10-GeV machine at Dubna in the Soviet Union, all of which were proton synchrotrons. The next generation of machines were based on a new principle, strong focusing. In 1952, E. Courant, M. S. Livingston, and H. Snyder at Brookhaven discovered that by arranging bending magnets so that the gradients of successive magnets alternated between increasing radially and decreasing radially, the overall effect was to focus the beam in both the vertical and horizontal directions. Moreover, the beam excursions away from the central orbit were much decreased in amplitude. As a result, it was possible to make much smaller beam tubes and magnets with much smaller apertures.

Strong focusing can also be done with pairs of quadrupole magnets, one focusing in the horizontal plane and the next in the vertical plane. It is this arrangement that is most often employed in proton accelerators. This strong focusing principle was employed as early as 1955 (**Refs. 3.13, 4.1, 4.4, 4.6**) in the construction of beam lines. Subsequent to the work of Courant, Livingston, and Snyder, it was learned that the principle had been discovered earlier by N. Christofilos, working independently and alone in Athens. His idea had been communicated to the Lawrence Radiation Laboratory in Berkeley where it languished in the files unnoticed.

Strong focusing led to the construction of much higher energy proton machines. The first, the 28-GeV Proton Synchrotron (PS), was completed at CERN, the European Nuclear Research Center in Geneva, in 1959. A similar machine, the Alternating Gradient Synchrotron (AGS), was completed at Brookhaven in 1960.

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In 1962, a team including Schwartz, Lederman, and Steinberger **(Ref. 6.8)** reported results from an accelerator experiment in which neutrino interactions were observed. The neutrino beam was generated by directing the 15-GeV proton beam from the AGS on a beryllium target. Secondary π's and K's produced the neutrinos by decay in flight.

Since the interaction rate of the neutrinos was expected to be minute, extreme care was taken to prevent extraneous backgrounds from reaching the detector. Shielding included a 13.5-m iron wall. Detection was provided by a 10-ton spark chamber with aluminum plates separated around the edges by lucite spacers. The detector was surrounded on top, back, and front by anticoincidence counters to exclude events initiated by charged particles. Background was reduced by accepting only those events that coincided with the 20-ns bursts of particles from the accelerator, separated by 220-ns intervals. Even with these precautions, many triggered events were due to muons or neutrons that made their way into the detector. Most of these could be rejected by scanning the photographic record of the spark chamber output.

Of the remaining events, those showing a single charged particle with momentum less than 300 MeV (assuming the track to be that of a muon) were rejected as possibly due to background including neutron-induced events. This left 34 events apparently with single muons of energy greater than 300 MeV, candidates for $\nu n \rightarrow p\mu^-$ and $\overline{\nu}p \rightarrow n\mu^+$. In addition, there were 22 events with more than one visible track. These were candidates for $\nu n \rightarrow n\pi^+\mu^-$ and $\nu n \rightarrow p\mu^-$. Eight other events appeared "showerlike." Careful analysis showed that only a few of these were likely to be due to electrons.

The substantial difference between the number of muons produced and the number of electrons produced showed clearly that the neutrinos obtained from $\pi \rightarrow \mu\nu$ (which is vastly more frequent than the decays $\pi \rightarrow e\nu$ or $K \rightarrow \pi^0 e\nu$) generated muons rather than electrons. In this way, it was shown that there were two neutrinos, ν_μ and ν_e, and two conserved quantum numbers, muon number (+1 for μ^- and ν_μ) and electron number (+1 for e^- and ν_e). The ν_μ is created in $\pi^+ \rightarrow \mu^+\nu_\mu$, the $\overline{\nu}_\mu$ in $\pi^- \rightarrow \mu^-\overline{\nu}_\mu$, the ν_e in $\pi^+ \rightarrow e^+\nu_e$, and the $\overline{\nu}_e$ in $n \rightarrow pe^-\overline{\nu}_e$. The process $\nu_\mu n \rightarrow pe^-$ was forbidden by these rules. Separately conserved electron and muon numbers also forbid the unobserved decay $\mu \rightarrow e\gamma$. In addition to establishing the existence of two distinct neutrinos, the experiment demonstrated the feasibility of studying high energy neutrino interactions at accelerators. Subsequent neutrino experiments played a critical role in the development of particle physics.

The V-A theory provided a comprehensive phenomenological picture of weak interactions. The leptonic, semileptonic, and nonleptonic weak interactions were encompassed. The $\Delta S = 0$ and $\Delta S = 1$ processes were described by Cabibbo's proposal. Nevertheless, it was clear that the theory was incomplete. The Fermi interaction occurred at a point and was thus an s-wave interaction. The cross section for an s-wave interaction is limited by unitarity to be no greater than $4\pi/p_{cm}^2$. However, we have seen that in the V-A theory cross sections grow as $G_F^2 s \propto G_F^2 p_{cm}^2$. A contradiction occurs roughly when $p_{cm} = 300$ GeV. This circumstance can be improved, though not completely cured, by supposing that the Fermi interaction does not occur at a point, but is transmitted by a massive vector boson, the W. The idea goes back to Yukawa who had hoped his meson would explain

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both strong and weak interactions. If the W were heavy, it would produce a factor in the beta-decay amplitude of roughly f^2/m_W^2, where m_W is the W mass and f is its coupling to the nucleon and $e\nu$. Crudely then, $G_F \approx f^2/m_W^2$. The smallness of G_F could be due to f being small or m_W being large, or both. Experimental searches for the W in the mass range up to a few GeV were unsuccessful.

Exercises

6.1 Tritium, H^3, decays to $He^3 + e^- + \overline{\nu}_e$ with a half-life of 12.33 y. The maximum electron energy is close to 18.6 keV. Show what the high energy end of the Kurie plot would look like if the neutrino were (a) massless and if (b) it had a mass of 67 eV. Compare with Fig. 6.1.

6.2 What is the source of the dependence of Mott scattering, which was used by Frauenfelder *et al.*, on the polarization of the electron?

6.3 The decay amplitude for $\mu \to e\nu\overline{\nu}$ is proportional to G_F, so the decay rate is proportional to G_F^2. By dimensional analysis, the decay rate is proportional to $G_F^2 m_\mu^5$. The complete result is

$$\Gamma(\mu \to e\nu\overline{\nu}) = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

and the lifetime is 2.2×10^{-6} s. In 1975, a new lepton analogous to the μ, called the τ was discovered. What are the expected partial decay rates of $\tau \to \mu\nu\overline{\nu}$ and $\tau \to e\nu\overline{\nu}$ if $m_\tau = 1.8$ GeV? Compare with the data.

6.4 Estimate on dimensional grounds the lifetime of the neutron. Compare with experiment.

6.5 The branching ratios for $\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$ are 64.2% and 35.8%, respectively. What would we expect if the nonleptonic Hamiltonian were a $\Delta I = 1/2$ operator? A $\Delta I = 3/2$ operator?

6.6 * The decays $\pi \to \mu\nu$ and $\pi \to e\nu$ are governed by the V-A interaction

$$\mathcal{H} = \int d^3x \, \frac{G_F}{\sqrt{2}} J_\lambda^{had}(x) \, \overline{\nu}_e(x) \gamma^\lambda (1 - \gamma_5) e(x).$$

The hadronic matrix element

$$< 0 | J_\lambda^{had} | \pi >$$

must be proportional to the pion four-momentum, q_λ. Show that this means the decay amplitudes for the two processes are proportional to m_μ and m_e, respectively, and thus

$$\frac{\Gamma(\pi \to \mu\nu)}{\Gamma(\pi \to e\nu)} \propto \left(\frac{m_\mu}{m_e}\right)^2 \times \text{phase space}.$$

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6.7 * The matrix element squared for the decay $\mu^- \to e^- \nu_\mu \overline{\nu}_e$ is

$$\mathcal{M}^2 = 64 G_F^2 (P + ms) \cdot p_{\overline{\nu}_e} \; p_e \cdot p_{\nu_\mu}$$

where P is the muon four-momentum, m is its mass, and s is the four-vector spin of the muon. In the rest frame of the muon, s has only space components and is a unit vector in the direction of the spin. Use the formula

$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \delta^4(P - p_1 - p_2 - p_3)$$

to establish

(a) $\Gamma = \dfrac{G_F^2 M^5}{192\pi^3}$,

(b) $d\Gamma/dx \propto x^2(1 - 2x/3)$ where $x = 2E_e/m$,

(c) $\dfrac{d\Gamma}{dx\, d\cos\theta} \propto x^2[(3 - 2x) + (2x - 1)\cos\theta]$,

where θ is the angle between the muon spin and the electron direction.

(d) $\dfrac{d\Gamma}{d\cos\theta} \propto 1 + \frac{1}{3}\cos\theta$.

Further Reading

Weak interactions are covered quite thoroughly in the text by E. D. Commins and P. H. Bucksbaum, *Weak Interactions of Leptons and Quarks*, Cambridge University Press, Cambridge, 1983.

A personal recollection of the two-neutrino experiment by Melvin Schwartz appears in *Adventures in Experimental Physics*, α, B. Maglich, ed., World Science Education, Princeton, NJ, 1972.

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Experimental Test of Parity Conservation in Beta Decay*

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AND

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(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.[2] To apply this technique to the present problem, two major difficulties had to be overcome. The beta-particle counter should be placed *inside* the demagnetization cryostat, and the radioactive nuclei must be located in a *thin surface* layer and polarized. The schematic diagram of the cryostat is shown in Fig. 1.

To detect beta particles, a thin anthracene crystal $\frac{3}{8}$ in. in diameter$\times\frac{1}{16}$ in. thick is located inside the vacuum chamber about 2 cm above the Co^{60} source. The scintillations are transmitted through a glass window and a Lucite light pipe 4 feet long to a photomultiplier (6292) which is located at the top of the cryostat. The Lucite head is machined to a logarithmic spiral shape for maximum light collection. Under this condition, the Cs^{137} conversion line (624 kev) still retains a resolution of 17%. The stability of the beta counter was carefully checked for any magnetic or temperature effects and none were found. To measure the amount of polarization of Co^{60}, two additional NaI gamma scintillation counters were installed, one in the equatorial plane and one near the polar position. The observed gamma-ray anisotropy was used as a measure of polarization, and, effectively, temperature. The bulk susceptibility was also monitored but this is of secondary significance due to surface heating effects, and the gamma-ray anisotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60}. One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of

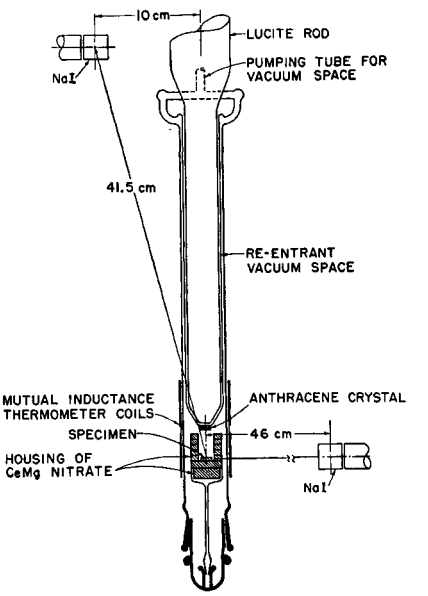


Fig. 1. Schematic drawing of the lower part of the cryostat.

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one unit and no change of parity, it can be given only by the Gamow-Teller interaction. This is almost imperative for this experiment. The thickness of the radioactive layer used was about 0.002 inch and contained a few microcuries of activity. Upon demagnetization, the magnet is opened and a vertical solenoid is raised around the lower part of the cryostat. The whole process takes about 20 sec. The beta and gamma counting is then started. The beta pulses are analyzed on a 10-channel pulse-height analyzer with a counting interval of 1 minute, and a recording interval of about 40 seconds. The two gamma counters are biased to accept only the pulses from the photopeaks in order to discriminate against pulses from Compton scattering.

A large beta asymmetry was observed. In Fig. 2 we have plotted the gamma anisotropy and beta asymmetry *vs* time for polarizing field pointing up and pointing down. The time for disappearance of the beta asymmetry coincides well with that of gamma anisotropy. The warm-up time is generally about 6 minutes, and the warm counting rates are independent of the field direction. The observed beta asymmetry does not change sign with reversal of the direction of the demagnetization field, indicating that it is not caused by remanent magnetization in the sample.

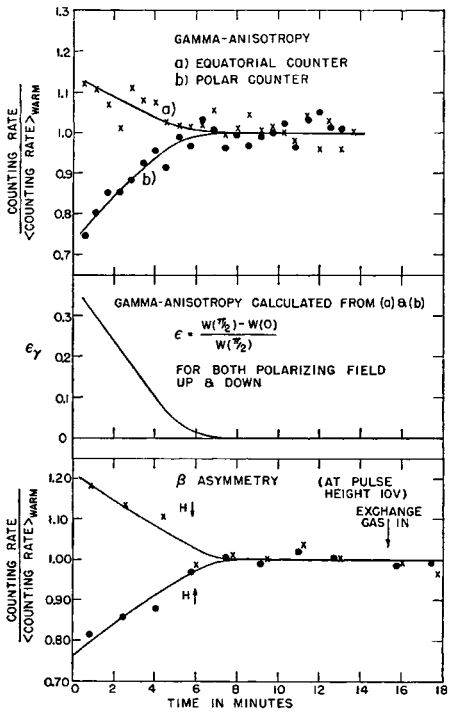


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

The sign of the asymmetry coefficient, α, is negative, that is, the emission of beta particles is more favored in the direction opposite to that of the nuclear spin. This naturally implies that the sign for C_T and C_T' (parity conserved and parity not conserved) must be opposite. The exact evaluation of α is difficult because of the many effects involved. The lower limit of α can be estimated roughly, however, from the observed value of asymmetry corrected for backscattering. At velocity $v/c \approx 0.6$, the value of α is about 0.4. The value of $\langle I_z \rangle / I$ can be calculated from the observed anisotropy of the gamma radiation to be about 0.6. These two quantities give the lower limit of the asymmetry parameter $\beta(\alpha = \beta \langle I_z \rangle / I)$ approximately equal to 0.7. In order to evaluate α accurately, many supplementary experiments must be carried out to determine the various correction factors. It is estimated here only to show the large asymmetry effect. According to Lee and Yang[3] the present experiment indicates not only that conservation of parity is violated but also that invariance under charge conjugation is violated.[4] Furthermore, the invariance under time reversal can also be decided from the momentum dependence of the asymmetry parameter β. This effect will be studied later.

The double nitrate cooling salt has a highly anisotropic g value. If the symmetry axis of a crystal is not set parallel to the polarizing field, a small magnetic field will be produced perpendicular to the latter. To check whether the beta asymmetry could be caused by such a magnetic field distortion, we allowed a drop of $CoCl_2$ solution to dry on a thin plastic disk and cemented the disk to the bottom of the same housing. In this way the cobalt nuclei should not be cooled sufficiently to produce an appreciable nuclear polarization, whereas the housing will behave as before. The large beta asymmetry was not observed. Furthermore, to investigate possible internal magnetic effects on the paths of the electrons as they find their way to the surface of the crystal, we prepared another source by rubbing $CoCl_2$ solution on the surface of the cooling salt until a reasonable amount of the crystal was dissolved. We then allowed the solution to dry. No beta asymmetry was observed with this specimen.

More rigorous experimental checks are being initiated, but in view of the important implications of these observations, we report them now in the hope that they may stimulate and encourage further experimental investigations on the parity question in either beta or hyperon and meson decays.

The inspiring discussions held with Professor T. D. Lee and Professor C. N. Yang by one of us (C. S. Wu) are gratefully acknowledged.

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[4] Their arguments are as follows: From the He^6 recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2)\lesssim\frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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LEE and Yang[1-3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+\rightarrow\mu^++\nu, \quad (1)$$

$$\mu^+\rightarrow e^++2\nu. \quad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of this proposal in the form of preliminary results on β decay of oriented nuclei by Wu *et al.* reached us before this experiment was begun.[6]

By stopping, in carbon, the μ^+ beam formed by forward decay in flight of π^+ mesons inside the cyclotron, we have performed the meson experiment, which establishes the following facts:

I. A large asymmetry is found for the electrons in (2), establishing that our μ^+ beam is strongly polarized.

II. The angular distribution of the electrons is given by $1+a\cos\theta$, where θ is measured from the velocity vector of the incident μ's. We find $a=-\frac{1}{3}$ with an estimated error of 10%.

III. In reactions (1) and (2), parity is not conserved.

IV. By a theorem of Lee, Oehne, and Yang,[2] the observed asymmetry proves that invariance under charge conjugation is violated.

V. The g value (ratio of magnetic moment to spin) for the (free) μ^+ particle is found to be $+2.00\pm0.10$.

VI. The measured g value and the angular distribution in (2) lead to the very strong probability that the spin of the μ^+ is $\frac{1}{2}$.[7]

VII. The energy dependence of the observed asymmetry is not strong.

VIII. Negative muons stopped in carbon show an asymmetry (also leaked backwards) of $a\sim-1/20$, i.e., about 15% of that for μ^+.

IX. The magnetic moment of the μ^-, bound in carbon, is found to be negative and agrees within limited accuracy with that of the μ^+.[8]

X. Large asymmetries are found for the e^+ from polarized μ^+ beams stopped in polyethylene and calcium. Nuclear emulsion (as a target in Fig. 1) yields an asymmetry of about half that observed in carbon.

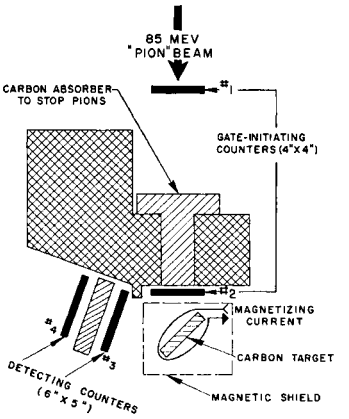


FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

The experimental arrangement is shown in Fig. 1. The meson beam is extracted from the Nevis cyclotron in the conventional manner, undergoing about 120° of magnetic deflection in the cyclotron fringing field and about −30° of deflection and mild focusing upon emerging from the 8-ft shielding wall. The positive beam contains about 10% of muons which originate principally in the vicinity of the cyclotron target by pion decay-in-flight. Eight inches of carbon are used in the entrance telescope to separate the muons, the mean range of the "85-"Mev pions being ~5 in. of carbon. This arrangement brings a maximum number of muons to rest in the carbon target. The stopping of a muon is signalled by a fast 1–2 coincidence count. The subsequent beta decay of the muon is detected by the electron telescope 3–4 which normally requires a particle of range >8 g/cm^2(~25-Mev electrons) to register. This arrangement has been used to measure the lifetimes of μ^+ and μ^- mesons in a vast number of elements.[9] Counting rates are normally ~20 electrons/

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min in the μ^+ beam and ~150 electrons/min in the μ^- beam with background of the order of 1 count/min.

In the present investigation, the 1–2 pulse initiates a gate of duration $T=1.25$ μsec. This gate is delayed by $t_1=0.75$ μsec and placed in coincidence with the electron detector. Thus the system counts electrons of energy >25 Mev which are born between 0.75 and 2.0 μsec after the muon has come to rest in carbon. Consider now the possibility that the muons are created in reaction (1) with large polarization in the direction of motion. If the gyromagnetic ratio is 2.0, these will maintain their polarization throughout the trajectory. Assume now that the processes of slowing down, stopping, and the microsecond of waiting do not depolarize the muons. In this case, the electrons emitted from the target may have an angular asymmetry about the polarization direction, e.g., for spin $\frac{1}{2}$ of the form $1+a\cos\theta$. In the absence of any vertical magnetic field, the counter system will sample this distribution at $\theta=100°$. We now apply a small vertical field in the magnetically shielded enclosure about the target, which causes the muons to precess at a rate of $(\mu/s\hbar)H$ radians per sec. The probability distribution in angle is carried around with the μ-spin. In this manner we can, with a fixed counter system, sample the entire distribution by plotting counts as a function of magnetizing current for a given time delay. A typical run is shown in Fig. 2. As an example of a systematic check, we have

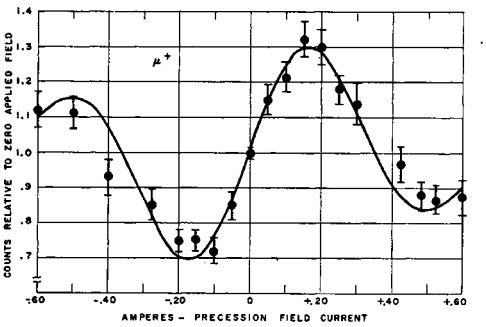


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

reduced the absorber in the telescope to 5 in. so that the end-of-range of the main pion beam occurred at the carbon target. The electron rate rose accordingly by a factor of 10, indicating that now electrons were arising from muons isotropically emitted by pions at rest in the carbon. No variation in counting rate with magnetizing current was then observed, the ratio of the rate for $I=+0.170$ amp to that for $I=-0.150$ amp, for example, being 0.989 ± 0.028. The highest field produced at the target was ~50 gauss which generates a stray field outside of the magnetic shield of $<\frac{1}{10}$ the cyclotron fringing field of 20 gauss. The only conceivable effect of the magnetizing current is the precession of muon spins and we are, therefore, led to conclusions I–IV as necessary consequences of these observations.

The solid curve in Fig. 2 is a theoretical fit to a distribution $1-\frac{1}{3}\cos\theta$, where

(1) the gyromagnetic ratio is taken to be $+2.00$;[10]

(2) the angular breadth of the electron telescope and the gate-width smearing are folded in, as well as (to first order) the exponential decay rate of muons within the gate;

(3) the small residual cyclotron stray field (*up* for Fig. 2, the positive magnetizing current producing a *down* field) is included. This has the accidental effect of converting the 100° initial angle ($H=0$) to 89° as in Fig. 2. We note that this experiment establishes only a lower limit to the magnitude of a, since the percent polarization at the time of decay is not known. If polarization is complete, $a=-0.33\pm0.03$.

Proof of the 2π symmetry of the distribution and the sign of the moment was obtained by shifting the electron counters to 65° with respect to the incident muon direction. The repetition of a magnetizing run yielded a curve as in Fig. 2 but shifted to the right by 0.075 ampere (5.9 gauss) corresponding to a precession angle of 37°, in agreement with the spatial rotation of the counter system. Thus we are led to conclusions V and VI.

A specific model, the two-component neutrino theory, has been proposed by Lee and Yang[3] in an attempt to introduce parity nonconservation naturally into elementary particle theory. This theory predicts, for our experimental arrangement and on the basis of 1.86 for the integrated spectrum (Fig. 2), a ratio of the order of 2.5 for energies greater than 35 Mev. We have increased the amount of absorber in the electron telescope to exclude electrons of less than ~35 Mev. The resulting peak-to-valley ratio was then observed to be 1.92 ± 0.19.[11]

We have also detected asymmetry in negative muon decay and have verified that the moment is negative and roughly equal to that of the positive muon.[7] The asymmetry in this case is also peaked backwards.

Various other materials were investigated for μ^+ mesons. Nuclear emulsion as a target was found to have a significantly weaker asymmetry (peak-to-valley ratio of 1.40 ± 0.07) and it is interesting to note that this did not increase with reduced delay and gate width. Neither was there any evidence for an altered moment. It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

The authors wish to acknowledge the essential role of Professor Tsung-Dao Lee in clarifying for us the papers of Lee and Yang. We are also indebted to Professor C. S. Wu[6] for reports of her preliminary results in the Co^{60} experiment which played a crucial part in the

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Columbia discussions immediately preceding this experiment.

* Research supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Also at International Business Machines, Watson Scientific Laboratories, New York, New York.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] Lee, Oehme, and Yang, Phys. Rev. (to be published).

[3] T. D. Lee and C. N. Yang, Phys. Rev. (to be published).

[4] R. Dalitz, Phil. Mag. **44**, 1068 (1953).

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[6] Wu, Ambler, Hudson, Hoppes, and Hayward, Phys. Rev. **105**, 1413 (1957), preceding Letter.

[7] The Fierz-Pauli theory for spin $\frac{3}{2}$ particles predicts a g value of $\frac{2}{3}$. See F. J. Belinfante, Phys. Rev. **92**, 997 (1953).

[8] V. Fitch and J. Rainwater, Phys. Rev. **92**, 789 (1953).

[9] M. Weinrich and L. M. Lederman, *Proceedings of the CERN Symposium, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956).

[10] The field interval, ΔH, between peak and valley in Fig. 2 gives the magnetic moment directly by $(\mu\Delta H/s\hbar)(l_1+\frac{1}{2}T)\delta=\pi$, where $\delta=1.06$ is a first-order resolution correction which takes into account the finite gate width and muon lifetime. The 5% uncertainty comes principally from lack of knowledge of the magnetic field in carbon. Independent evidence that $g=2$ (to $\sim$10%) comes from the coincidence of the polarization axis with the velocity vector of the stopped μ's. This implies that the spin precession frequency is identical to the μ cyclotron frequency during the 90° net magnetic deflection of the muon beam in transit from the cyclotron to the 1–2 telescope. We have designed a magnetic resonance experiment to determine the magnetic moment to $\sim$0.03%.

[11] *Note added in proof.*—We have now observed an energy dependence of a in the $1+a\cos\theta$ distribution which is somewhat less steep but in rough qualitative agreement with that predicted by the two-component neutrino theory ($\mu\rightarrow e+\nu+\bar{\nu}$) without derivative coupling. The peak-to-valley ratios for electrons traversing 9.3 g/cm², 15.6 g/cm², and 19.8 g/cm² of graphite are observed to be 1.80±0.07, 1.84±0.11, and 2.20±0.10, respectively.

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Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ - \mu^+ - e^{+*}$†

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(Received January 17, 1957)

LEE and Yang[1] recently re-examined the problem as to whether parity is conserved in nature and emphasized the fact that one actually lacks experimental evidence in support of this most natural hypothesis in the case of weak interactions (such as β decay). Violation of parity conservation can be inferred essentially only by measuring the probability distribution of some *pseudoscalar* quantity, e.g., of the projection of a polar vector along an axial vector, and measurements of this kind had not been reported. Lee and Yang suggested several experiments in which a spin direction is available as a suitable axial vector; in particular, they pointed out that the initial direction of motion of the muon in the process $\pi \rightarrow \mu + \nu$ can serve for this purpose, as the muon will be produced with its spin axis along its initial line of motion if the Hamiltonian responsible for this process does not have the customary invariance properties. If parity is further not conserved in the process $\mu \rightarrow e + 2\nu$, then a forward-backward asymmetry in the distribution of angles $W(\theta)$ between this initial direction of motion and the momentum, $\mathbf{p}_e$, of the decay electron is predicted.

It is easy to observe the pertinent correlation by bringing π^+ mesons to rest in a nuclear emulsion in which the μ^+ meson also stops. One has only to bear in mind two facts: (1) even weak magnetic fields, such as the fringing field of a cyclotron, can obliterate a real effect, as the precession frequency of a Dirac μ meson is $(2.8/207)\times 10^6$ sec^{-1}/gauss; (2) μ^+ can form "muonium," i.e., $(\mu^+ e^-)$, and the formation of this atom can be an additional source of depolarization, both through its internal hyperfine splitting and the precession of its total magnetic moment around the external field. In the absence of specific experiments on muonium formation, one can perhaps be guided by analogous data on positronium in solids.[2,3]

With these facts in mind, we exposed (in early October, 1956) nuclear emulsion pellicles (1 mm thick) to a π^+ beam of the University of Chicago synchrocyclotron. The pellicles were contained inside three concentric tubular magnetic shields and subject to $\leq 4\times 10^{-3}$ gauss. Over 1300 complete $\pi - \mu - e$ decays have been recorded to date, and the space angle θ defined above has been calculated for each. From these preliminary data we find[4]

$$\left\{\int_{90^\circ}^{180^\circ} |W(\theta)|\,d\Omega - \int_{0}^{90^\circ} |W(\theta)|\,d\Omega\right\} \Big/ \int_{0}^{180^\circ} W(\theta)\,d\Omega = 0.062 \pm 0.027,$$

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or

$$W(\theta)=1-0.12\cos\theta,$$

i.e., the presence of an excess in the backward hemisphere to a 95% confidence level. This effect agrees in sign and magnitude with one observed in a recent analogous experiment[5] performed electronically at Columbia University.

In connecting our result with basic theoretical principles, one has to remember (a) that the asymmetry observed here is only a lower limit owing to the possibility of muonium formation[6] and other conceivable depolarization effects; (b) that existence of an asymmetry implies the joint violation of parity conservation and charge conjugation invariance rather than of parity conservation alone.[7]

In view of the intrinsic importance of the subject, we consider it worthwhile to present our data at this preliminary stage.

We would like to thank the Columbia workers, in particular R. L. Garwin, for communicating their unpublished results to us. We are grateful to R. Oehme for illuminating theoretical discussions and to R. Levi-Setti for criticism of the experimental techniques.

* This work was supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† For technical reasons, this Letter could not be published in the same issue as that of Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

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[3] Telegdi, Sens, Yovanovitch, and Warshaw, Phys. Rev. **104**, 867 (1956).

[4] *Note added in proof.*—From 2000 events, we get for this ratio 0.091 ± 0.022.

[5] Garwin, Lederman, and Weinrich (private communication from R. L. Garwin, January 13, 1957).

[6] The Columbia workers find that the observed asymmetry appears to depend on the material stopping the μ^+ mesons. This is consistent with (μ^+e^-) formation and suggests the use of μ^- mesons for absolute measurements, in low-Z materials with no nuclear magnetic moment.

[7] R. Oehme (private communication); Lee, Oehme, and Yang, Phys. Rev. (to be published).

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Parity and the Polarization of Electrons from Co^{60}†

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(Received March 1, 1957)

LEE and Yang[1] recently proposed that parity may not be conserved in weak interactions and suggested various experiments to verify their hypothesis. Two of the experiments have since been performed with positive result—the asymmetry of the electron emission from aligned nuclei[2] and the polarization of muons.[3,4] In a second paper,[5] Lee and Yang discuss a two-component theory of the neutrino and consider some more experimental tests. Among these, they list the measurement of momentum and polarization of electrons emitted in beta decay. If parity is not conserved, the electrons should be longitudinally polarized. For tensor and scalar interaction, the degree of polarization is simply equal to (v/c).[6,7] We have found this polarization in the case of Co^{60}.

The observation of the expected longitudinal polarization of the electrons is difficult. However, by means of an electrostatic deflector, the longitudinal polarization can be transformed into a transverse one.[8] The transverse polarization can be measured by scattering the electrons with a thin foil of a high-Z material (Mott scattering). Because of the spin-orbit interaction, the elastically scattered electrons show a strong left-right asymmetry, especially at scattering angles between 90° and 150°.[9] From this measurable asymmetry, the initial longitudinal polarization can be calculated.

The experimental arrangement is housed in a cylindrical vacuum chamber of 30-cm diameter. The electrons from a Co^{60} source are deflected in a cylindrical electrostatic field (radius of curvature 6 cm) by about 108° and then impinge on the scattering foil. The left-right asymmetry of electrons scattered into the angular interval 95° to 140° is measured with two end-window Geiger counters (3.5 mg/cm² mica windows). Two electroplated Co^{60} sources are used, one of about 1 mC strength on aluminum (1.7 mg/cm²), the other of 6 mC strength on a silver-covered rubber hydrochloride film (0.6 mg/cm²). The electrostatic deflector is designed so that electrons of about 100-kev energy completely change their polarization from longitudinal to transverse. The scattering foils (0.05 mg/cm² gold, 0.15 mg/cm² gold, 1.7 mg/cm² aluminum, all backed by 0.9 mg/cm² Mylar) can be interchanged from the outside.

For an ideal arrangement, the left-right asymmetry in the counters would be $L/R=[1+Pa(\theta)]/[1-Pa(\theta)]$.[10] P is the initial longitudinal polarization of the electrons and $a(\theta)$ the polarization asymmetry factor after scattering by an angle θ in the analyzer foil. In the actual experiment, however, the determination of P from L/R involves corrections for (1) the asymmetry of the two counters, (2) the finite extension of scatterer and counters, and (3) incomplete transformation from longitudinal to transverse polarization. The first correction was performed experimentally by using the nearly isotropic scattering from aluminum foils; the second and third corrections were calculated in a first approximation. A correction for depolarization in the source and the analyzer was neglected completely.

The results of some runs are given in Table I. Even though these data are only very preliminary, some conclusions can be drawn.

Table I. The polarization of electrons from Co^{60}.

Electron energy kev	$\beta=v/c$	Gold scattering foil mg/cm²	Left-right asymmetry L/R	Longitudinal polarization P
50	0.41	0.15	1.03±0.03	−0.04
68	0.47	0.15	1.13±0.02	−0.16
77	0.49	0.05	1.35±0.06	−0.40
77	0.49	0.15	1.30±0.09	−0.35

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1. The violation of parity conservation is obvious. Every run (about five in addition to the ones shown in Table I) shows a definite left-right asymmetry.

2. The negative sign of the polarization P indicates that the beta particles are polarized in the direction opposite to their momentum. This conclusion agrees with the experiment of Wu *et al.*[2]

3. The values of P are not in disagreement with the two-component theory, which gives $P=-v/c$. The deviations, especially at lower energies, can easily be due to depolarization in the source and in the analyzer. More accurate measurements and further investigation of the corrections are required for a detailed comparison between theory and experiment.

We are very much indebted to Dr. J. Weneser for many illuminating discussions.

† Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[4] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
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[6] L. Landau (to be published).
[7] Jackson, Treiman, and Wyld (to be published).
[8] H. A. Tolhoek, Revs. Modern Phys. **28**, 277 (1956).
[9] N. Sherman, Phys. Rev. **103**, 1601 (1956).
[10] We use $P=(I_+-I_-)/(I_++I_-)$, where I_+ is the intensity of electrons polarized along their initial momenta and I_- is the intensity of electrons polarized in the opposite direction. We define "left" by $\mathbf{p}_3\cdot(\mathbf{p}_1\times\mathbf{p}_2)>0$, where $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$ are, respectively, the electron momenta immediately after emission from the source, before scattering from the analyzer, and after scattering from the analyzer.

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Helicity of Neutrinos*

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(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_{I}, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus

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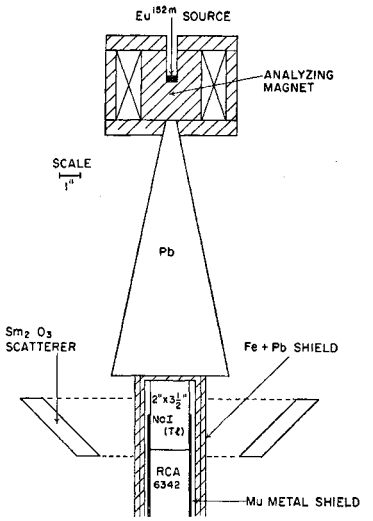


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

B, formed when a neutrino is emitted in the Z direction, are $m=-1$, 0 if the neutrino has positive helicity, and $m=+1$, 0 if the neutrino has negative helicity. In either case, the helicity of the γ ray emitted in the $(-Z)$ direction is the same as that of the neutrino. Thus, a measurement of the circular polarization of the γ rays which are resonant-scattered by the nucleus B, yields directly the helicity of the neutrino, if one assumes only the well-established conservation laws of momentum and angular momentum.

To carry out this measurement we have used a nucleus which appears to have the properties postulated in the example given: ${}_{63}Eu^{152m}$(9.3 hr). It probably has spin 0 and odd parity.[1] It decays to an excited state of ${}_{62}Sm^{152}(1-)$ with emission of neutrinos which have an energy of 840 kev in the most prominent case of K-electron capture. This is followed by an $E1$ γ-ray transition of 960 kev to the ground state $(0+)$. The excited state has a mean life of $(3\pm1)\times10^{-14}$ sec, as determined by Grodzins.[1] Thus, even in a solid source most of the γ-ray emission takes place before the momentum of the recoil nucleus has changed appreciably.

The experimental arrangement used is shown in Fig. 1. The Eu^{152m} source is inserted inside an electromagnet which is alternately (every three minutes) magnetized in the up or down direction. The γ rays which pass through the magnet are resonant-scattered from a Sm_2O_3 scatterer (26.8% Sm^{152}), and detected in a 2-in.$\times3\frac{1}{2}$-in. cylindrical NaI(Tl) scintillation counter. The photomultiplier (RCA 6342) is magnetically shielded by an iron cylinder and a mu-metal shield. The effectiveness of this magnetic shield was demonstrated by check experiments with a Cs^{137} γ-ray source in a manner similar to that described previously.[2] No significant effect of magnetic field reversal on the photomultiplier output was noticed when two narrow acceptance channels were set on the steeply sloping low- and high-energy wings of the 661-kev photopeak, respectively.

The source was produced by bombarding ~10 mg of Eu_2O_3 in the Brookhaven reactor. In typical runs the intensity varied from 50–100 mC. Nine runs varying in length from 3 to 9 hours were carried out. The scattered radiation is shown in Fig. 2. It contains both γ rays emitted from the 960-kev state (960 and 840 kev). Counts were accumulated simultaneously in 3 channels A, B, and C as shown in Fig. 2. A cycle of field reversals was used such that the decay corrections were negligible. No effects of field reversal or decay were noticed in channel C. Channel A exhibited a possible small magnetic field effect which was less than one-tenth of that observed in channel B. In channel B, which bracketed the photopeaks, a total of $\sim3\times10^6$ counts were accumulated. In 6 runs carried out in the arrangement shown in Fig. 1, an effect $\delta=(N_--N_+)/\frac{1}{2}(N_-+N_+)=+0.017\pm0.003$ was found in channel B after the nonresonant background had been subtracted. Here N_+ is defined as the counting rate with the magnetic field pointing up, and N_- as the counting rate with the field pointing down.

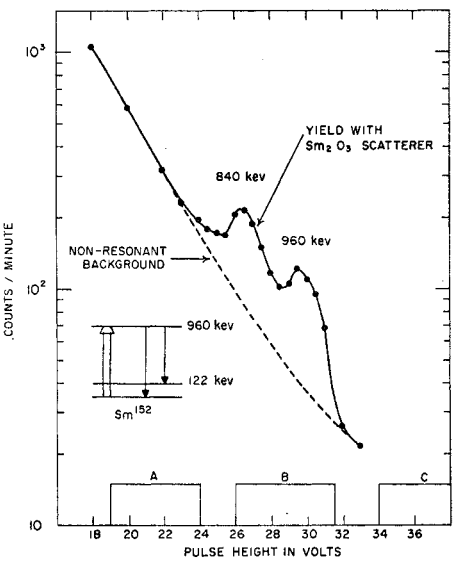


FIG. 2. Resonant-scattered γ rays of Eu^{152m}. Upper curve is taken with arrangement shown in Fig. 1 with unmagnetized iron. Lower curve shows nonresonant background (including natural background).

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The magnet response was tested with the bremsstrahlung from a $Sr^{90}+Y^{90}$ source, for which the helicity is negative,[2] $\boldsymbol{\sigma}_\gamma \cdot \hat{p}_\gamma = -1$. Eu^{152m} runs were made with both solid and dissolved sources (HCl solution), and both gave similar results. The effective path length of the 960-kev γ ray in the magnet was somewhat uncertain, partly because of the extent of the source and partly because of a lack of knowledge of the field distribution in the return path. We estimate that the average path is equivalent to 3 ± 0.3 mean free paths in fully magnetized iron. From this we expect an effect of $\delta=\pm0.025$ with an accuracy of 10%, if the 960-kev γ rays are 100% circularly polarized, with the $-$ sign corresponding to positive helicity (spin parallel to their direction of propagation) and the $+$ sign to negative helicity. Thus we find that in our case the γ rays are $(68\pm14\%)$ circularly polarized, and that their helicity is negative. As a further check, 3 runs were carried out with a shorter magnet of length $3\frac{1}{2}$ in. with the source on top of the magnet. In this case also a negative helicity was found, the circular polarization being $(66\pm15\%)$.

From the energy of the neutrinos emitted, the width of the γ-ray line, and the fact that the circular polarization varies with the direction of emission of the γ ray relative to the neutrino as $\cos\theta$, we calculate that a circular polarization, which in the ideal case discussed above would be 100%, would be reduced to $\sim$75%. This should be further reduced to a slight extent because of the effect of thermal motion and because some γ rays are emitted after the recoil has changed momentum. Thus our result seems compatible with spin 0$-$ for Eu^{152m}, and 100% negative helicity of the neutrinos emitted in orbital electron capture.[3]

In all formulations of β-decay theory no distinction is made between the neutrino emitted in orbital electron capture and that emitted in β^+ decay. Taken together with the fact that the helicity of the positrons in a Gamow-Teller transition is positive[4] or with the fact that positrons are emitted from oriented nuclei in the direction in which the nuclear spin is pointing,[5] our result indicates that the Gamow-Teller interaction is axial vector (A) for positron emitters, in agreement with the conclusions of Hermannsfeldt *et al.*[6] These authors show that all recoil experiments with β^+ emitters are compatible with AV, but not with TS interactions which have been reported for β^- emitters (largely based on He^6 recoil experiments).[7] The AV combination may be compatible with lepton conservation and a universal Fermi interaction as pointed out by Sudarshan and Marshak[8] and by Feynman and Gell-Mann.[9] This view is strengthened by the recent results showing positive helicity for the positrons from μ^+ decay.[10] It would therefore seem desirable to apply the method described here to a β^- emitter in order to determine the helicity of the antineutrino. Although the analysis of such an experiment is considerably more complicated, it may prove possible to reach a decision between A and T, which is independent of the "classical" recoil experiments.

We wish to thank J. Weneser for many valuable discussions.†

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] L. Grodzins, Phys. Rev. **109**, 1015 (1958), preceding Letter.

[2] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **106**, 826 (1957).

[3] It is worthwhile to inquire how our conclusions are affected if the less plausible spin-parity assignments of $1\mp$ are assumed for Eu^{152m}. For the case of a $1^-\xrightarrow{\epsilon}1^-\xrightarrow{\gamma}0^+$ transition, J. Weneser (unpublished) finds

$$\boldsymbol{\sigma}_\gamma \cdot \hat{p}_\gamma = \frac{(\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu)[\frac{1}{2}|G_{GT}|^2 \pm \sqrt{2}|G_{GT}|\cdot|G_F|]}{|G_{GT}|^2+|G_F|^2},$$

where $G_{GT}=M_{GT}C_{GT}$ and $G_F=M_FC_F$. This has been calculated on the simplifying assumption that the two-component neutrino theory and time-reversal invariance hold [see T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957)]. For a neutrino helicity of -1 the photon helicity varies from $+0.5$ to -1.0, and for a neutrino helicity of $+1$ the photon helicity varies from -0.5 to $+1.0$. Considering the reduction factors discussed above, the experimentally found helicity of the γ rays is in agreement with the assumption of neutrinos of negative helicity, even if Eu^{152m} has spin-parity $1-$. In the other very unlikely case of a $1+$ assignment to Eu^{152m}, we could not at present draw a definite conclusion concerning the neutrino helicity. The theory for first forbidden transitions is being investigated by A. M. Bincer.

[4] L. A. Page and M. Heinberg, Phys. Rev. **106**, 1220 (1957).

[5] Ambler, Hayward, Hoppes, Hudson, and Wu, Phys. Rev. **106**, 1361 (1957); Postma, Huiskamp, Miedema, Steenland, Tolhoek, and Gorter, Physica **23**, 259 (1957).

[6] Hermannsfeldt, Maxson, Stähelin, and Allen, Phys. Rev. **107**, 641 (1957).

[7] B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955).

[8] E. C. G. Sudarshan and R. Marshak, Phys. Rev. (to be published).

[9] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[10] Culligan, Frank, Holt, Kluyver, and Massam, Nature **180**, 751 (1957).

† *Note added in proof.*—According to a private communication from Professor V. L. Telegdi, a refinement of the experiment of Burgy, Epstein, Krohn, Novey, Raboy, Ringo, and Telegdi, [Phys. Rev. **107**, 1731 (1957)] favors $V-A$ for the β interaction.

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PHYSICAL REVIEW VOLUME 113, NUMBER 1 JANUARY 1, 1959

Free Antineutrino Absorption Cross Section. I. Measurement of the Free Antineutrino Absorption Cross Section by Protons*

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(Received September 8, 1958)

The cross section for the reaction $p(\bar{\nu},\beta^+)n$ was measured using antineutrinos ($\bar{\nu}$) from a powerful fission reactor at the Savannah River Plant of the United States Atomic Energy Commission. Target protons were provided by a 1.4×10^3 liter liquid scintillation detector in which the scintillator solution (triethylbenzene, terphyenyl, and POPOP) was loaded with a cadmium compound (cadmium octoate) to allow the detection of the reaction by means of the delayed coincidence technique. The first pulse of the pair was caused by the slowing down and annihilation of the positron (β^+), the second by the capture of the neutron (n) in cadmium following its moderation by the scintillator protons. A second giant scintillation detector without cadmium loading was used above the first to provide an anticoincidence signal against events induced by cosmic rays. The antineutrino signal was related to the reactor by means of runs taken while the reactor was on and off. Reactor radiations other than antineutrinos were ruled out as the cause of the signal by a differential shielding experiment. The signal rate was 36 ± 4 events/hr and the signal-to-noise ratio was $\frac{1}{5}$, where half the noise was correlated and cosmic-ray associated and about half was due to non-reactor-associated accidental coincidences. The cross section per fission $\bar{\nu}$ (assuming 6.1 $\bar{\nu}$ per fission) for the inverse beta decay of the proton was measured to be $(11\pm2.6)\times10^{-44}$ cm$^2/\bar{\nu}$ or $(6.7\pm1.5)\times10^{-43}$ cm^2/fission. These values are consistent with prediction based on the two-component theory of the neutrino.

I. INTRODUCTION

A DETERMINATION of the cross section for the reaction: antineutrino ($\bar{\nu}$) on a proton (p^+) to yield a positron (β^+) and a neutron (n),

$$\bar{\nu}+p^+\rightarrow\beta^++n, \tag{1}$$

permits a check to be made on the combination of fundamental parameters on which the cross section depends. Implicit in a theoretical prediction of the cross section are (1) the principle of microscopic reversibility, (2) the spin of the $\bar{\nu}$, (3) the particular neutrino theory employed: e.g., two- or four-component, (4) the neutron half-life and its decay electron spectrum, and (5) the spectrum of the incident $\bar{\nu}$'s.

An experiment which was performed to identify antineutrinos from a fission reactor[1] yielded an approximate value for this cross section. Following this work, however (and prior to the parity developments involved in point 3), the equipment was modified in order to obtain a better value of the cross section. The modification consisted in the addition of a cadmium salt of 2-ethylhexanoic acid to the scintillator solution[2] of one of the detectors of reference 1, utilizing the protons of the solution as targets for antineutrinos, and making the necessary changes in circuitry to observe both positrons and neutron captures in the detector resulting from antineutrino-induced beta decay in the detector. In addition, a second detector used in the experiment of reference 1 was now used as an anticoincidence shield against cosmic-ray-induced backgrounds, and static shielding was increased by provision of a water tank about 12-inches thick below the target detector. The delayed-coincidence count rate resulting from the positron pulse followed by the capture of the neutron was observed as a function of reactor power, and an analysis of the reactor-associated signal yielded, in addition to an independent identification of the free antineutrino, a measure of the cross section for the reaction and a spectrum of first-pulse (or $\bar{\nu}$) energies. Since the antineutrino spectrum is simply related to the β^+ spectrum, the measurement yields an antineutrino spectrum above the 1.8-Mev reaction threshold. The spectrum is, however, seriously degraded by edge effects in the detector.

This experiment was identical in principle with that performed at Hanford in 1953.[3] It was, however, definitive from the point of view of antineutrino identification (whereas the Hanford experiment was not) because of a series of technical improvements, coupled with the better shielding against cosmic rays achieved by going underground. The improvements consisted in the use of an isolated power supply to diminish electrical noise from nearby machinery, better shielding from the reactor gamma-ray and neutron background, a more complete anticoincidence shield against charged cosmic rays through the use of a liquid scintillation detector, and use of a large detector containing 6.5 times as many proton targets.[4] In addition, oscilloscopic presentation and photographic recording of the data assisted materially in analyzing the signals and rejecting electrical noise.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† Now at the Department of Physics, George Washington University, Washington, D. C.

[1] Cowan, Reines, Harrison, Kruse, and McGuire, Science **124**, 103 (1956).

[2] Ronzio, Cowan, and Reines, Rev. Sci. Instr. **29**, 146 (1958), describe the preparation and handling of liquid scintillators developed for the Los Alamos neutrino program.

[3] F. Reines and C. L. Cowan, Jr., Phys. Rev. **90**, 492 (1953).

[4] The gain, times 6.5, due to the increase in target protons was largely balanced by a decrease in the neutron detection efficiency, times $\frac{1}{3}$, made necessary by other experimental considerations.

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VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu}). \qquad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

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borhood of 10^{-38} cm^2 at about 1 BeV. Lee and Yang[1] first calculated the detailed cross sections for

$$\nu+n\rightarrow p+e^-, \qquad \bar{\nu}+p\rightarrow n+e^+, \tag{2}$$

$$\nu+n\rightarrow p+\mu^-, \qquad \bar{\nu}+p\rightarrow n+\mu^+, \tag{3}$$

using the vector form factor deduced from electron scattering results and assuming the axial vector form factor to be the same as the vector form factor. Subsequent work has been done by Yamaguchi[2] and Cabbibo and Gatto.[3] These calculations have been used as standards for comparison with experiments.

Unitarity and the absence of the decay $\mu\rightarrow e+\gamma$. A major difficulty of the Fermi theory at high energies is the necessity that it break down before the cross section reaches $\pi\lambda^2$, violating unitarity. This breakdown must occur below 300 BeV in the center of mass. This difficulty may be avoided if an intermediate boson mediates the weak interactions. Feinberg[4] pointed out, however, that such a boson implies a branching ratio $(\mu\rightarrow e+\gamma)/(\mu\rightarrow e+\nu+\bar{\nu})$ of the order of 10^{-4}, unless the neutrinos associated with muons are different from those associated with electrons.[5] Lee and Yang[6] have subsequently noted that any general mechanism which would preserve unitarity should lead to a $\mu\rightarrow e+\gamma$ branching ratio not too different from the above. Inasmuch as the branching ratio is measured to be $\lesssim 10^{-8}$,[7] the hypothesis that the two neutrinos may be different has found some favor. It is expected that if there is only one type of neutrino, then neutrino interactions should produce muons and electrons in equal abundance. In the event that there are two neutrinos, there is no reason to expect any electrons at all.

The feasibility of doing neutrino experiments at accelerators was proposed independently by Pontecorvo[8] and Schwartz.[9] It was shown that the fluxes of neutrinos available from accelerators should produce of the order of several events per day per 10 tons of detector.

The essential scheme of the experiment is as follows: A neutrino "beam" is generated by decay in flight of pions according to reaction (1). The pions are produced by 15-BeV protons striking a beryllium target at one end of a 10-ft long straight section. The resulting entire flux of particles moving in the general direction of the detector strikes a 13.5-m thick iron shield wall at a distance of 21 m from the target. Neutrino interactions are observed in a 10-ton aluminum spark chamber located behind this shield.

The line of flight of the beam from target to detector makes an angle of 7.5° with respect to the internal proton direction (see Fig. 1). The operating energy of 15 BeV is chosen to keep the muons penetrating the shield to a tolerable level.

The number and energy spectrum of neutrinos from reaction (1) can be rather well calculated, on the basis of measured pion-production rates[10] and the geometry. The expected neutrino flux from π decay is shown in Fig. 2. Also shown is

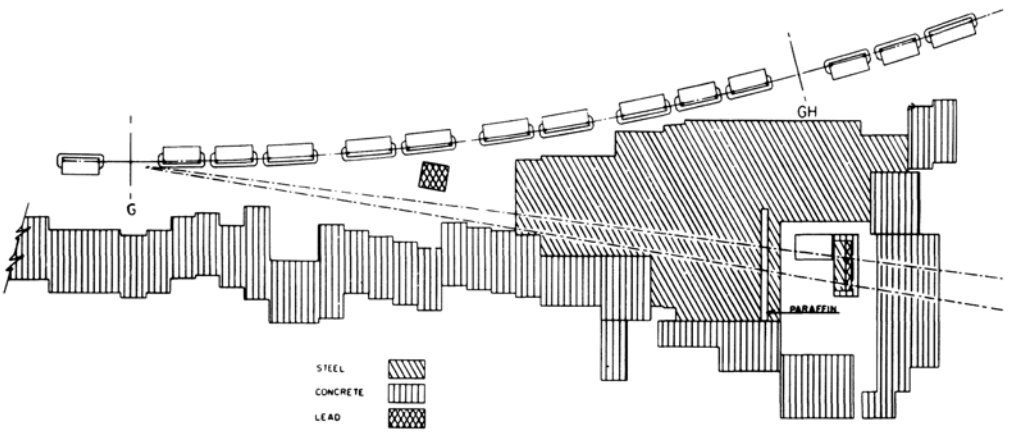


FIG. 1. Plan view of AGS neutrino experiment.

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VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

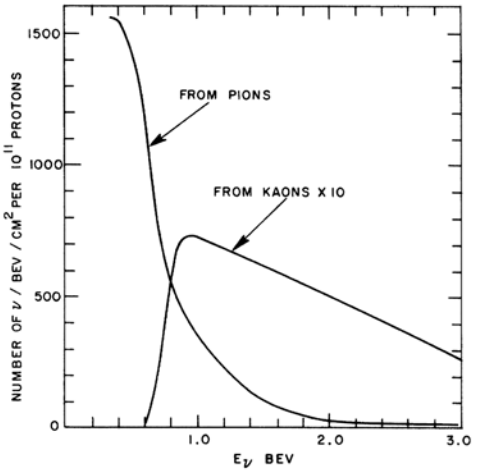


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.

an estimate of neutrinos from the decay $K^{\pm} \to \mu^{\pm} + \nu(\bar{\nu})$. Various checks were performed to compare the targeting efficiency (fraction of circulating beam that interacts in the target) during the neutrino run with the efficiency during the beam survey run. (We believe this efficiency to be close to 70%.) The pion-neutrino flux is considered reliable to approximately 30% down to 300 MeV/c, but the flux below this momentum does not contribute to the results we wish to present.

The main shielding wall thickness, 13.5 m for most of the run, absorbs strongly interacting particles by nuclear interaction and muons up to 17 BeV by ionization loss. The absorption mean free path in iron for pions of 3, 6, and 9 BeV has been measured to be less than 0.24 m.[11] Thus the shield provides an attenuation of the order of 10^{-24} for strongly interacting particles. This attenuation is more than sufficient to reduce these particles to a level compatible with this experiment. The background of strongly interacting particles within the detector shield probably enters through the concrete floor and roof of the 5.5-m thick side wall. Indications of such leaks were, in fact, obtained during the early phases of the experiment and the shielding subsequently improved. The argument that our observations are not induced by strongly interacting particles will also be made on the basis of the detailed structure of the data.

The spark chamber detector consists of an array of 10 one-ton modules. Each unit has 9 aluminum plates 44 in. $\times$ 44 in. $\times$ 1 in. thick, separated by $\frac{3}{8}$-in. Lucite spacers. Each module is driven by a specially designed high-pressure spark gap and the entire assembly triggered as described below. The chamber will be more fully described elsewhere. Figure 3 illustrates the arrangement of coincidence and anticoincidence counters. Top, back, and front anticoincidence sheets (a total of 50 counters, each 48 in. $\times$ 11 in. $\times \frac{1}{2}$ in.) are provided to reduce the effect of cosmic rays and AGS-produced muons which penetrate the shield. The top slab is shielded against neutrino events by 6 in. of steel and the back slab by 3 ft of steel and lead.

Triggering counters were inserted between adjacent chambers and at the end (see Fig. 3). These consist of pairs of counters, 48 in. $\times$ 11 in. $\times \frac{1}{2}$ in., separated by $\frac{3}{4}$ in. of aluminum, and in fast coincidence. Four such pairs cover a chamber; 40 are employed in all.

The AGS at 15 BeV operates with a repetition period of 1.2 sec. A rapid beam deflector drives the protons onto the 3-in. thick Be target over a period of 20-30 μsec. The radiation during this interval has rf structure, the individual bursts being 20 nsec wide, the separation 220 nsec. This structure is employed to reduce the total "on" time and thus minimize cosmic-ray background. A Čerenkov counter exposed

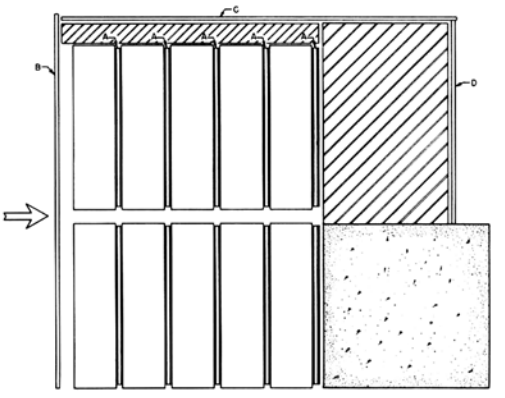


FIG. 3. Spark chamber and counter arrangement. A are the triggering slabs; B, C, and D are anticoincidence slabs. This is the front view seen by the four-camera stereo system.

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to the pions in the neutrino "beam" provides a train of 30-nsec gates, which is placed in coincidence with the triggering events. The correct phasing is verified by raising the machine energy to 25 BeV and counting the high-energy muons which now penetrate the shield. The tight timing also serves the useful function of reducing sensitivity to low-energy neutrons which diffuse into the detector room. The trigger consists of a fast twofold coincidence in any of the 40 coincidence pairs in anticoincidence with the anticoincidence shield. Typical operation yields about 10 triggers per hour. Half the photographs are blank, the remainder consist of AGS muons entering unprotected faces of the chamber, cosmic rays, and "events." In order to verify the operation of circuits and the gap efficiency of the chamber, cosmic-ray test runs are conducted every four hours. These consist of triggering on almost horizontal cosmic-ray muons and recording the results both on film and on Land prints for rapid inspection (see Fig. 4).

A convenient monitor for this experiment is the number of circulating protons in the AGS machine. Typically, the AGS operates at a level of $2\text{-}4\times10^{11}$ protons per pulse, and 3000 pulses per hour. In an exposure of 3.48×10^{17} protons, we have counted 113 events satisfying the following geometric criteria: The event originates within a fiducial volume whose boundaries lie 4 in. from the front and back walls of the chamber and 2 in. from the top and bottom walls. The first two gaps must not fire, in order to exclude events whose origins lie outside the chambers. In addition, in the case of events consisting of a single track, an extrapolation of the track backwards (towards the neutrino source) for two gaps must also remain within the fiducial volume. The production angle of these single tracks relative to the neutrino line of flight must be less than 60°.

These 113 events may be classified further as follows:

(a) 49 short single tracks. These are single tracks whose visible momentum, if interpreted as muons, is less than 300 MeV/c. These presumably include some energetic muons which leave the chamber. They also include low-energy neutrino events and the bulk of the neutron produced background. Of these, 19 have 4 sparks or less. The second half of the run (1.7×10^{17} protons) with improved shielding yielded only three tracks in this category. We will not consider these as acceptable "events."

(b) 34 "single muons" of more than 300 MeV/c. These include tracks which, if interpreted as muons, have a visible range in the chambers such that their momentum is at least 300 MeV/c. The origin of these events must not be accompanied by more than two extraneous sparks. The latter requirement means that we include among "single tracks" events showing a small recoil. The 34 events are tabulated as a function of momentum in Table I. Figure 5 illustrates 3 "single muon" events.

(c) 22 "vertex" events. A vertex event is one whose origin is characterized by more than one track. All of these events show a substantial energy release. Figure 6 illustrates some of these.

(d) 8 "showers." These are all the remaining events. They are in general single tracks, too irregular in structure to be typical of μ mesons, and more typical of electron or photon showers. From these 8 "showers," for purposes of comparison with (b), we may select a group of 6 which are so located that their potential range within the chamber corresponds to μ mesons in excess of 300 MeV/c.

In the following, only the 56 energetic events of type (b) (long μ's) and type (c) (vertex events) will be referred to as "events."

Arguments on the neutrino origin of the ob-

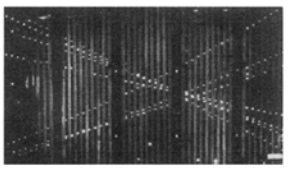


FIG. 4. Land print of Cosmic-ray muons integrated over many incoming tracks.

Table I. Classification of "events."

Single tracks			
$p_\mu < 300$ MeV/c[a]	49	$p_\mu > 500$	8
$p_\mu > 300$	34	$p_\mu > 600$	3
$p_\mu > 400$	19	$p_\mu > 700$	2
Total "events"	34		
Vertex events			
Visible energy released < 1 BeV	15		
Visible energy released > 1 BeV	7		

[a]These are not included in the "event" count (see text).

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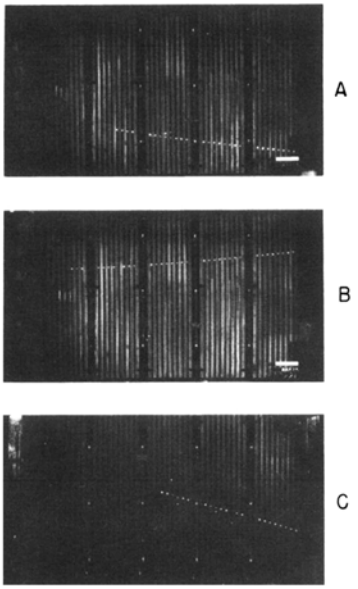


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

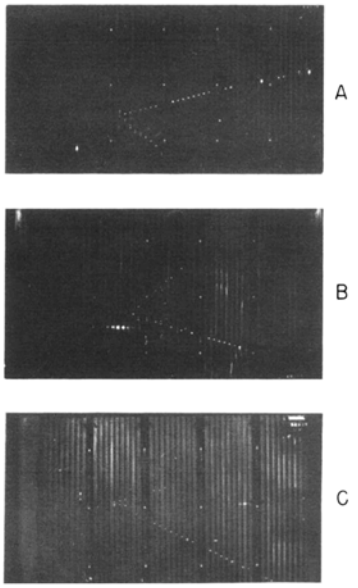


FIG. 6. Vertex events. (A) Single muon of $p_\mu > 500$ MeV and electron-type track; (B) possible example of two muons, both leave chamber; (C) four prong star with one long track of $p_\mu > 600$ MeV/c.

served "events."

1. The "events" are not produced by cosmic rays. Muons from cosmic rays which stop in the chamber can and do simulate neutrino events. This background is measured experimentally by running with the AGS machine off on the same triggering arrangement except for the Čerenkov gating requirement. The actual triggering rate then rises from 10 per hour to 80 per second (a dead-time circuit prevents jamming of the spark chamber). In 1800 cosmic-ray photographs thus obtained, 21 would be accepted as neutrino events. Thus 1 in 90 cosmic-ray events is neutrino-like. Čerenkov gating and the short AGS pulse effect a reduction by a factor of $\sim 10^{-6}$ since the circuits are "on" for only 3.5 μsec per pulse. In fact, for the body of data represented by Table I, a total of 1.6×10^6 pulses were counted. The equipment was therefore sensitive for a total time of 5.5 sec. This should lead to $5.5 \times 80 = 440$ cosmic-ray tracks which is consistent with observation. Among these, there should be 5 ± 1 cosmic-ray induced "events." These are almost evident in the small asymmetry seen in the angular distributions of Fig. 7. The remaining 51 events cannot be the result of cosmic rays.

2. The "events" are not neutron produced. Several observations contribute to this conclusion.

(a) The origins of all the observed events are uniformly distributed over the fiduciary volume, with the obvious bias against the last chamber induced by the $p_\mu > 300$ MeV/c requirement. Thus there is no evidence for attenuation, although the mean free path for nuclear interaction in aluminum is 40 cm and for electromagnetic interaction 9 cm.

(b) The front iron shield is so thick that we can expect less than 10^{-4} neutron induced reactions in the entire run from neutrons which have penetrated this shield. This was checked by removing 4 ft of iron from the front of the thick shield. If our events were due to neutrons in line with the target, the event rate would have increased by a factor of one hundred. No such effect was observed (see Table II). If neutrons penetrate the shield, it must be from other di-

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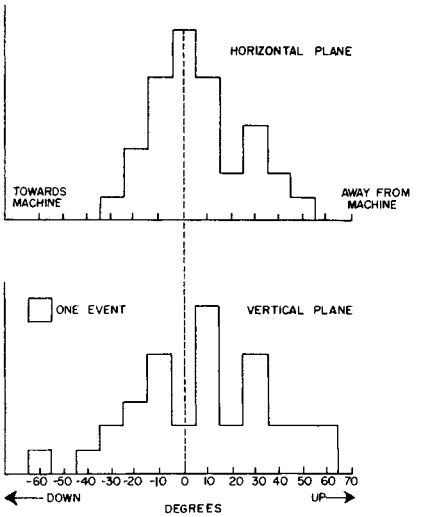


FIG. 7. Projected angular distributions of single track events. Zero degree is defined as the neutrino direction.

rections. The secondaries would reflect this directionality. The observed angular distribution of single track events is shown in Fig. 7. Except for the small cosmic-ray contribution to the vertical plane projection, both projections are peaked about the line of flight to the target.

(c) If our 29 single track events (excluding cosmic-ray background) were pions produced by neutrons, we would have expected, on the basis of known production cross sections, of the order of 15 single π^0's to have been produced. No cases of unaccompanied π^0's have been observed.

Table II. Event rates for normal and background conditions.

	Circulating protons $\times 10^{16}$	No. of Events	Calculated cosmic-ray[c] contribution	Net rate per 10^{16}
Normal run	34.8	56	5	1.46
Background I[a]	3.0	2	0.5	0.5
Background II[b]	8.6	4	1.5	0.3

[a] 4 ft of Fe removed from main shielding wall.
[b] As above, but 4 ft of Pb placed within 6 ft of Be target and subtending a horizontal angular interval from 4° to 11° with respect to the internal proton beam.
[c] These should be subtracted from the "single muon" category.

3. The single particles produced show little or no nuclear interaction and are therefore presumed to be muons. For the purpose of this argument, it is convenient to first discuss the second half of our data, obtained after some shielding improvements were effected. A total traversal of 820 cm of aluminum by single tracks was observed, but no "clear" case of nuclear interaction such as large angle or charge exchange scattering was seen. In a spark chamber calibration experiment at the Cosmotron, it was found that for 400-MeV pions the mean free path for "clear" nuclear interactions in the chamber (as distinguished from stoppings) is no more than 100 cm of aluminum. We should, therefore, have observed of the order of 8 "clear" interactions; instead we observed none. The mean free path for the observed single tracks is then more than 8 times the nuclear mean free path.

Included in the count are 5 tracks which stop in the chamber. Certainly a fraction of the neutrino secondaries must be expected to be produced with such small momentum that they would stop in the chamber. Thus, none of these stoppings may, in fact, be nuclear interactions. But even if all stopping tracks are considered to represent nuclear interactions, the mean free path of the observed single tracks must be 4 nuclear mean free paths.

The situation in the case of the earlier data is more complicated. We suspect that a fair fraction of the short single tracks then observed are, in fact, protons produced in neutron collisions. However, similar arguments can be made also for these data which convince us that the energetic single track events observed then are also noninteracting.[12]

It is concluded that the observed single track events are muons, as expected from neutrino interactions.

4. The observed reactions are due to the decay products of pions and K mesons. In a second background run, 4 ft of iron were removed from the main shield and replaced by a similar quantity of lead placed as close to the target as feasible. Thus, the detector views the target through the same number of mean free paths of shielding material. However, the path available for pions to decay is reduced by a factor of 8. This is the closest we could come to "turning off" the neutrinos. The results of this run are given in terms of the number of events per 10^{16} circulating protons in Table II. The rate of "events" is reduced from 1.46 ± 0.2 to 0.3 ± 0.2 per 10^{16} in-

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cident protons. This reduction is consistent with that which is expected for neutrinos which are the decay products of pions and K mesons.

Are there two kinds of neutrinos? The earlier discussion leads us to ask if the reactions (2) and (3) occur with the same rate. This would be expected if ν_μ, the neutrino coupled to the muon and produced in pion decay, is the same as ν_e, the neutrino coupled to the electron and produced in nuclear beta decay. We discuss only the single track events where the distinction between single muon tracks of $p_\mu > 300$ MeV/c and showers produced by high-energy single electrons is clear. See Figs. 8 and 4 which illustrate this difference.

We have observed 34 single muon events of which 5 are considered to be cosmic-ray background. If $\nu_\mu = \nu_e$, there should be of the order of 29 electron showers with a mean energy greater than 400 MeV/c. Instead, the only candidates which we have for such events are six "showers" of qualitatively different appearance from those of Fig. 8. To argue more precisely, we have exposed two of our one-ton spark chamber modules to electron beams at the Cosmotron. Runs were taken at various electron energies. From these we establish that the triggering efficiency for 400-MeV electrons is 67%. As a quantity characteristic of the calibration showers, we have taken the total number of observed sparks. The mean number is roughly linear with electron energy up to 400 MeV/c. Larger showers saturate the two chambers which were available. The spark distribution for 400 MeV/c showers is plotted in Fig. 9, normalized to the $\frac{2}{3}\times 29$ expected showers. The six "shower" events are also plotted. It is evident that these are not consistent with the prediction based on a universal theory with $\nu_\mu = \nu_e$. It can perhaps be argued that the absence of electron events could be understood in terms of the coupling of a single neutrino to the electron which is much weaker than that to the muon at higher momentum transfers, although at lower momentum transfers the results of β decay, μ capture, μ decay, and the ratio of $\pi \to \mu + \nu$ to $\pi \to e + \nu$ decay show that these couplings are equal.[13] However, the most plausible explanation for the absence of the electron showers, and the only one which preserves universality, is then that $\nu_\mu \neq \nu_e$; i.e., that there are at least two types of neutrinos. This also resolves the problem raised by the forbiddenness of the $\mu^+ \to e^+ + \gamma$ decay.

It remains to understand the nature of the 6 "shower" events. All of these events were obtained in the first part of the run during conditions in which there was certainly some neutron background. It is not unlikely that some of the events are small neutron produced stars. One or two could, in fact, be μ mesons. It should also be remarked that of the order of one or two electron events are expected from the neutrinos produced in the decays $K^+ \to e^+ + \nu_e + \pi^0$ and

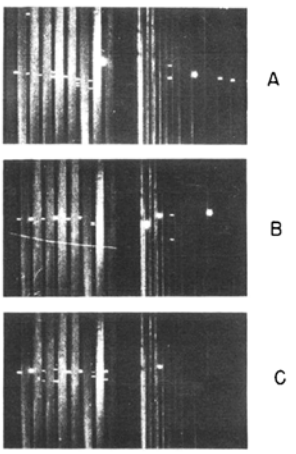


FIG. 8. 400-MeV electrons from the Cosmotron.

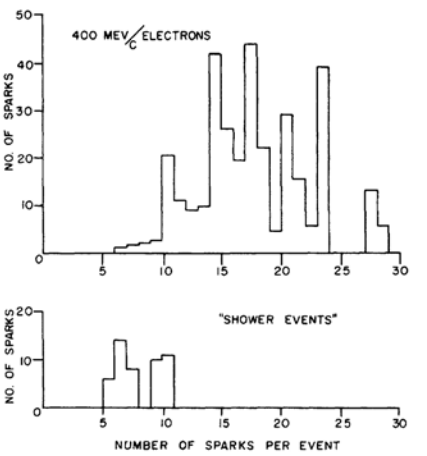


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

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$K_2^0 \to e^{\pm} + \nu_e + \pi^{\mp}$.

The intermediate boson. It has been pointed out[1] that high-energy neutrinos should serve as a reasonable method of investigating the existence of an intermediate boson in the weak interactions. In recent years many of the objections to such a particle have been removed by the advent of V-A theory[14] and the remeasurement of the ρ value in μ decay.[15] The remaining difficulty pointed out by Feinberg,[4] namely the absence of the decay $\mu \to e + \gamma$, is removed by the results of this experiment. Consequently it is of interest to explore the extent to which our experiment has been sensitive to the production of these bosons.

Our neutrino intensity, in particular that part contributed by the K-meson decays, is sufficient to have produced intermediate bosons if the boson had a mass m_w less than that of the mass of the proton (m_p). In particular, if the boson had a mass equal to $0.6\,m_p$, we should have produced ~20 bosons by the process $\nu + p \to w^+ + \mu^- + p$. If $m_w = m_p$, then we should have observed 2 such events.[16]

Indeed, of our vertex events, 5 are consistent with the production of a boson. Two events, with two outgoing prongs, one of which is shown in Fig. 6(B), are consistent with both prongs being muons. This could correspond to the decay mode $w^+ \to \mu^+ + \nu$. One event shows four outgoing tracks, each of which leaves the chamber after traveling through 9 in. of aluminum. This might in principle be an example of $w^+ \to \pi^+ + \pi^- + \pi^+$. Another event, by far our most spectacular one, can be interpreted as having a muon, a charged pion, and two gamma rays presumably from a neutral pion. Over 2 BeV of energy release is seen in the chamber. This could in principle be an example of $w^+ \to \pi^+ + \pi^0$. Finally, we have one event, Fig. 6(A), in which both a muon and an electron appear to leave the same vertex. If this were a boson production, it would correspond to the boson decay mode $w^+ \to e^+ + \nu$. The alternative explanation for this event would require (i) that a neutral pion be produced with the muon; and (ii) that one of its gamma rays convert in the plate of the interaction while the other not convert visibly in the chamber.

The difficulty of demonstrating the existence of a boson is inherent in the poor resolution of the chamber. Future experiments should shed more light on this interesting question.

Neutrino cross sections. We have attempted to compare our observations with the predicted cross sections for reactions (2) using the theory.[1-3] To include the fact that the nucleons in (2) are, in fact, part of an aluminum nucleus, a Monte Carlo calculation was performed using a simple Fermi model for the nucleus in order to evaluate the effect of the Pauli principle and nucleon motion. This was then used to predict the number of "elastic" neutrino events to be expected under our conditions. The results agree with simpler calculations based on Fig. 2 to give, in terms of number of circulating protons,

from $\pi \to \mu + \nu$,	0.60 events/10^{16} protons,
from $K \to \mu + \nu$,	0.15 events/10^{16} protons,
Total	0.75 events/10^{16} ± ~30%.

The observed rates, assuming all single muons are "elastic" and all vertex events "inelastic" (i.e., produced with pions) are

"Elastic": 0.84 ± 0.16 events/10^{16} (29 events),

"Inelastic": 0.63 ± 0.14 events/10^{16} (22 events).

The agreement of our elastic yield with theory indicates that no large modification to the Fermi interaction is required at our mean momentum transfer of 350 MeV/c. The inelastic cross section in this region is of the same order as the elastic cross section.

Neutrino flip hypothesis. Feinberg, Gursey, and Pais[17] have pointed out that if there were two different types of neutrinos, their assignment to muon and electron, respectively, could in principle be interchanged for strangeness-violating weak interactions. Thus it might be possible that

$$\pi^+ \to \mu^+ + \nu_1 \qquad \text{while} \qquad K^+ \to \mu^+ + \nu_2$$
$$\pi^+ \to e^+ + \nu_2 \qquad\qquad K^+ \to e^+ + \nu_1.$$

This hypothesis is subject to experimental check by observing whether neutrinos from $K_{\mu 2}$ decay produce muons or electrons in our chamber. Our calculation of the neutrino flux from $K_{\mu 2}$ decay indicates that we should have observed 5 events from these neutrinos. They would have an average energy of 1.5 BeV. An electron of this energy would have been clearly recognizable. None have been seen. It seems unlikely therefore that the neutrino flip hypothesis is correct.

The authors are indebted to Professor G. Feinberg, Professor T. D. Lee, and Professor C. N. Yang for many fruitful discussions. In particular, we note here that the emphasis by Lee and Yang on the importance of the high-energy behavior of

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weak interactions and the likelihood of the existence of two neutrinos played an important part in stimulating this research.

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