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Parity Experiments in Beta Decays*

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INTRODUCTION

THE frontier of parity study has now advanced to the field of strange particles. The atmosphere in the field of beta decay appears unusually calm and quiet after the storm. I will try to piece together the jigsaw picture and to see what sorts of puzzles in beta decay have fallen into shape. Most urgent of all is the question, whether there are still any missing pieces, and if there are, what are they?

In principle, parity experiments are simply experiments designed to study the screw senses of particles, decay processes, or nuclear reactions. This all originated from our concept of left and right symmetry; that is, left and right are indiscernible.[1] To scientific minds, from the time of Leibniz to 1957, there was no inner difference, no polarity between left and right. The inner structure of space does not permit us, except by arbitrary choice, to distinguish a left from a right screw. However, a right screw or a right spinning particle shows up as a left screw or a left spinning particle in a mirror reflection. So from the right-left symmetry we arrived at the space-reflection symmetry. This symmetry implies that if a particle exists, the one obtained by reflecting it in a mirror must also exist. If a decay process can take place, the one seen in a mirror is also a possible one. The symmetry of space-reflection clearly requires that events or particles do not exhibit definite screw senses. That is why all parity experiments are concerned with the measuring of the screw senses. This screw sense is now christened with the elegant name of helicity and is defined as $\boldsymbol{\sigma}\cdot\mathbf{p}/|p|$, the spin along p.

The first parity experiment[2] using polarized Co^{60} was designed to test whether there are any screw senses in beta decay. The essence of the experiment was to line up the spins of the Co^{60} nuclei along the same axis and then to determine whether the beta particles were emitted preferentially in one direction or the other along the axis. The results showed that the electrons were emitted preferentially in the direction opposite to that of nuclear spin and therefore conclusively proved that the beta decay of Co^{60} behaves like a lefthanded screw or possesses a negative helicity. So parity is not conserved in beta decay.

Moreover, the asymmetry observed is as large as possible. In the electron angular distribution $I(\theta) = 1+A\langle J_Z\rangle/J(v/c)\cos\theta$ (where θ is the angle between the nuclear spin and electron momentum direction), the measured asymmetry parameter A is nearly equal to -1. This implies that the parity interference effects are about as large as they could be. So this first experiment on parity tells us not only that parity and charge conjugation are not conserved in beta decay but points to something even more drastic and significant.

TWO-COMPONENT THEORY OF THE NEUTRINO

When the experimental value of the asymmetry parameter ($A\cong-1$) in Co^{60} beta decay was made known to Lee and Yang, they immediately realized that here one had to consider an extremely simple and appealing theory of the neutrino.[3] This theory requires that the spin of a neutrino always be either parallel or antiparallel to its momentum and the helicity of an antineutrino be opposite to that of a neutrino. Incidentally, this theory requires also the rigorous masslessness of the particle. If there were any mass associated with the particle, the particle could therefore be at rest or with momentum $\mathbf{P}$ reversed in a certain frame of reference. In that case, it is rather meaningless to impose the necessary requirement of alignment of spin $\boldsymbol{\sigma}$ and momentum $\mathbf{P}$ for such a particle. From experimental evidence, the mass of the neutrino is indeed vanishingly small. The most sensitive method of estimating the mass of the neutrino is to investigate the slope of the upper end of a beta spectrum. The low-energy beta spectrum of H^3 has been investigated for this purpose by many laboratories.[4] The upper limit of the mass of the neutrino m_ν is around 250 ev ($\sim 1/2000\ m_e$) and the evidence is also not inconsistent with mass m_ν equal to zero.

All through the years, theoretical physicists had entertained the idea of associating such unique properties with a massless neutrino. It had to be abandoned lest the law of parity be violated. Clearly, the two-component theory of the neutrino violates P and C invariance separately. A left-handed neutrino looks into a mirror and finds a right-handed neutrino, but according to the two-component theory of the neutrino, there is no such possible state. The charge conjugate of a neutrino is an antineutrino; one behaves like a left

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[1] H. Weyl, *Symmetry* (Princeton University Press, Princeton, New Jersey, 1952); E. P. Wigner, Proc. Am. Phil. Soc. **93**, 521 (1949); C. N. Yang, Science **127**, 565 (1958).

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

[3] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

[4] Curan, Angus, and Cockcroft, Phil. Mag. **40**, 36, 53 (1949); G. C. Hanna and B. Pontecorvo, Phys. Rev. **75**, 983 (1949); Hamilton, Alford, and Gross, Phys. Rev. **83**, 215 (1951); and L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952).

spinning particle, the other like a right spinning particle. This is a clear-cut violation of invariance of charge conjugation. In 1929, Weyl[5] proposed the mathematical possibility of such a particle, but it was discarded because it violated the law of parity and therefore could not be a physical reality! Landau[6] and Salam[7] reinvestigated this possibility shortly before the discovery of parity nonconservation. With the removal of both of these obstacles, interest in this theory was suddenly revived.

So in the first parity experiment of beta decay of polarized Co^{60}, not only was the screw sense in beta decay found, but even more dramatic was the realization of the possible existence of the two intrinsic opposite screws associated with the neutrino and antineutrino. The success of the two-component theory of the neutrino greatly facilitated our understanding of many phenomena in weak interactions.

LAW OF CONSERVATION OF LEPTONS

At this point, we should review another important conservation law known as the law of conservation of leptons which was suggested by Konopinski and Mahmoud[8] to explain the nonoccurrence of certain decay processes. The law states that if a leptonic number is assigned to each particle, then the sum of leptonic numbers must be conserved in all reactions. The assignments generally agreed upon are

lepton l= same (say $+1$)	for e^-, μ^-, ν
$l=-1$	for e^+, μ^+, $\bar{\nu}$
$l=0$	for π, γ, K and all heavy particles.

The ν or $\bar{\nu}$ expected in various decays are shown in the following equations:

$$\begin{array}{llr} n\rightarrow p+e^-+\bar{\nu} & p\rightarrow n+e^++\nu & (1)\\ \pi^+\rightarrow \mu^++\nu; & \pi^-\rightarrow \mu^-+\bar{\nu} & (2)\\ \mu^+\rightarrow e^++\nu+\bar{\nu}; & \mu^-\rightarrow e^-+\nu+\bar{\nu} & (3)\\ \mu^-+p\rightarrow n+\nu; & \mu^++n\rightarrow p+\bar{\nu} & (4)\\ K^+\rightarrow \mu^++\nu; & K^-\rightarrow \mu^-+\bar{\nu} & (5)\\ \pi^+\rightarrow e^++\nu; & \pi^-\rightarrow e^-+\bar{\nu}. & (6) \end{array}$$

The confirmation of the assignments given by these decays should constitute a strong proof of the law of conservation of leptons. Particularly if the helicities of these two neutrinos are opposite, then the predictions of these decay processes become unique.

EVIDENCE OF TWO-COMPONENT NEUTRINOS AND LEPTON CONSERVATION OBTAINED FROM PARITY EXPERIMENTS

I. From Nuclear Beta Decays

In the nuclear beta decay as shown in (1), an antineutrino is expected to be associated with β^- decay and a neutrino with β^+ decay. Furthermore, if the two-component theory of the neutrino is valid, then there are several unique phenomena predicted theoretically. The validity of the two-component theory and lepton conservation depends largely on the closeness of the agreement between the experimental evidence and the theoretical predictions. Suppose now we examine each phenomenon separately.

(*A*) *Beta Asymmetry from Polarized Nuclei*[2]

The beta asymmetry of allowed transitions from polarized nuclei can be expressed in the following form:

$$\begin{aligned} A=\Bigg\{\lambda_{JJ'}\bigg[&\pm\mathrm{Re}(C_T{}^*C_T{}'-C_A{}^*C_A{}')\\ &-\frac{Ze^2}{\hbar cp}\,\mathrm{Im}(C_T{}^*C_A{}'+C_T{}'^*C_A)\bigg]|M_{GT}|^2\\ &+\delta_{JJ'}\left(\frac{J}{J+1}\right)^{\frac{1}{2}}\bigg[\mathrm{Re}(C_T{}^*C_S{}'+C_T{}'^*C_S-C_A{}^*C_V{}'\\ &-C_A{}'^*C_V)\pm\frac{Ze^2}{\hbar cp}\,\mathrm{Im}(C_A{}^*C_S{}'+C_A{}'^*C_S-C_T{}^*C_V{}'\\ &-C_T{}'^*C_V)\bigg]|M_F|\cdot|M_{GT}|\Bigg\}\times\frac{2}{\xi(1+b/W)} \end{aligned} \tag{7}$$

$$\begin{aligned} \xi=&(|C_S{}^2|+|C_V{}^2|+|C_S{}'^2|+|C_V{}'^2|)|M_F|^2\\ &+(|C_T{}^2|+|C_A{}^2|+|C_T{}'^2|+|C_A{}'^2|)|M_{GT}|^2\\ \xi b=&\pm2\gamma\,\mathrm{Re}[(C_SC_V{}^*+C_S{}'C_V{}'^*)|M_F|^2\\ &+(C_TC_A{}^*+C_T{}'C_A{}'^*)|M_{GT}|^2], \end{aligned}$$

where C_i and $C_i{}'$ are the even and odd beta coupling constants. This measurement gives unique information about the pure G-T interaction. Neglecting the imaginary term for the time being and setting the Fierz term $b/W=0$, then one can obtain a simple relation for "A" for the $J\rightarrow J'=J-1$ transition,

$$\begin{aligned} A(\beta_\pm)=\pm2[\mathrm{Re}(C_T{}^*C_T{}'-C_A{}^*C_A{}')]/\\ |C_T{}^2|+|C_A{}^2|+|C_T{}'|^2+|C_A{}'^2|. \end{aligned}$$

Furthermore, for the two-component neutrinos the even and odd beta coupling constants are related by $C_T=-C_T{}'$ (left-handed antineutrino) or $C_A=C_A{}'$ (right-handed antineutrino). Therefore, $A(\beta_\pm)=\mp1$ for the above pure G-T transition. As we all know, the β^- asymmetry A of polarized Co^{60} where the spin and

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[5] The possibility of a two component relativistic theory of a spin 1/2 particle was first discussed by H. Weyl, Z. Physik **56**, 330 (1929). It was rejected on the ground of parity violation. See W. Pauli, *Handbuch der Physik* (Verlag Julius Springer, Berlin, 1933), Vol. 24, pp. 226–227.

[6] L. Landau, Nuclear Phys. **3**, 127 (1957).

[7] A. Salam, Nuovo cimento **5**, 299 (1957).

[8] E. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953); T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

parity change is $5^+ \rightarrow 4^+$ is indeed nearly -1 to within a systematic uncertainty not larger than 20%. This is the first strong evidence of the possible existence of the two-component neutrino. On the other hand, what evidence do we have of the β^+ asymmetry in a pure G-T transition of β^+ decay? Unfortunately, with the present technique of nuclear alignment, the nuclei which can be substantially polarized belong to a very exclusive club. In order to obtain the same type of information which can be extracted from polarized nuclei, we have to resort to an indirect method which is easier to apply although far less sensitive. This is shown in the following.

(*B*) *β-γ* (*Circular Polarization*) *Correlation*

It is quite obvious from the observed beta-asymmetry distribution of polarized nuclei that the β decay should leave the nucleus partly polarized with respect to the direction in which the β particle is detected. If a γ ray follows immediately after the β decay, it should have circular polarization proportional to the cosine of the angle between the β particle and γ ray. The circular polarization of the γ ray can be analyzed with a cylindrical electromagnet which could be magnetized to saturation either parallel or anti-parallel to the photon direction. The principle of this analysis is based on the existence of a spin dependent part of the Compton cross section of circularly polarized photons and is treated in detail by Gunst and Page.[9] The correlation for the most frequent decay sequence such as

$$J \xrightarrow[\beta \text{ transition}]{\text{allowed}} J' \xrightarrow{2^L \text{ pole } \gamma} J''=J'-L$$

can be expressed by

$$W(\theta)=1+A\frac{v}{c}\cos\theta,$$

where

$$A+\frac{1}{L+1}\left\{\mu_{JJ'}\left[\pm\mathrm{Re}(C_T{}^*C_T{}'-C_A{}^*C_A{}')\right.\right.$$
$$\left.-\frac{Ze^2}{\hbar cp}\,\mathrm{Im}(C_T{}^*C_A{}'+C_T{}'^*C_A)\right]|M_{GT}|^2$$
$$+\delta_{JJ'}\left(\frac{J+1}{1}\right)^{\frac{1}{2}}\left[\mathrm{Re}(C_T{}^*C_S{}'+C_T{}'^*C_S-C_A{}^*C_V{}'\right.$$
$$-C_A{}'^*C_V)\pm\frac{Ze^2}{\hbar cp}\,\mathrm{Im}(C_A{}^*C_S{}'+C_A{}'^*C_S-C_T{}^*C_V{}'$$
$$\left.\left.-C_T{}'^*C_V)\right]|M_F|\cdot|M_{GT}|\right\}\frac{2}{\xi(1+b/W)}. \quad (8)$$

Schopper[10] first applied this β-γ (circular) correlation method to Co^{60} and obtained the parameter $A\cong-\frac{1}{3}$. This is in excellent agreement with the conclusion derived from the polarized Co^{60} experiment, that is, $C_T=-C_T{}'$ or $C_A=C_A{}'$. When this method was applied to Na^{22}, which is a pure G-T positron emitter ($3^+ \rightarrow 2^+$), the sign of the circular polarization was found to be opposite to that of the electron emitter Co^{60} as theoretically predicted. However, none of these experiments[11] has an accuracy of much better than 20%.

(*C*) *Longitudinal Polarization of β Rays*[12]

Since parity is not conserved, the pseudoscalar term $(\sigma\cdot p_e)$ formed from the measured spin and momentum vector of electrons may occur. In other words, the decay electrons from unpolarized nuclei can be longitudinally polarized. The general expression of the $\beta^\pm$ polarization is

$$P(\beta^\mp)=\pm\frac{v}{c}\,\frac{2\,\mathrm{Re}[(C_SC_S{}'^*-C_VC_V{}'^*)|M_F|^2+(C_TC_T{}'^*-C_AC_A{}'^*)|M_{GT}|^2}{(|C_S{}^2|+|C_V{}^2|+|C_S{}'^2|+|C_V{}'^2|)|M_F|^2+(|C_T{}^2|+|C_A{}^2|+|C_A{}'^2|+|C_T{}'^2|)|M_{GT}|^2}. \quad (9)$$

If we assign $C_S=-C_S{}'$; $C_T=-C_T{}'$ (for left-handed antineutrino) or $C_V=C_V{}'$; $C_A=C_A{}'$ (for right-handed antineutrino) then $P(\beta^\mp)=\mp v/c$. First to observe this polarization was the Frauenfelder group. There are, at present, three major methods being used for the determination of electron polarization. They are: (1) Coulomb scattering from heavy nuclei (Mott scattering); (2) circular polarization of forward Bremsstrahlung or annihilation radiation; and (3) free electron-electron scattering (Møller or Bhabha scattering). The results are startling and simple, and all agree that β^- particles emitted in radioactive decay behave like left-handed screws and all β^+ particles behave like right-handed screws. For relativistic energy $v/c\cong1$, we have practically completely polarized elec-

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[9] S. B. Gunst and L. A. Page, Phys. Rev. **92**, 970 (1953); Wheathly, Huiskamp, Diddens, Steenland, and Tolhoek, Physica **2**, 841 (1955). W. J. Huiskamp, thesis, Leiden, 1958; and H. Schopper, Nuclear Instr. **3**, 158 (1958).

[10] H. Schopper, Phil. Mag. **2**, 710 (1957).

[11] F. Boehm and A. N. Wapstra, Phys. Rev. **106**, 1364 (1957); P. Debrunner and W. Kündig, Helv. Phys. Acta **30**, 261 (1957).

[12] *Proceedings of the Rehovoth Conference on Nuclear Structure*, (North-Holland Publishing Company, Amsterdam, 1958). (a) Mott Scattering: H. A. Tolhoek, Revs. Modern Phys. **28**, 177 (1956); Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, Phys. Rev. **106**, 386 (1957); Alikhanov, Yeliseyev, Linbimov, and Ershler, Cavanagh, Turner, Coleman, Gard, and Ridley, Phil. Mag. **2**, 1105 (1957); H. de Waard and O. J. Poppema, Physica **23**, 597 (1957); de-Shalit, Kuperman, Lipkin, and Rothem, Phys. Rev. **107**, 1459 (1957); and Langevin-Joliot, Marty, and Sergent, Compt. rend. **244**, 3142 (1957).

(b) Circular polarization of bremsstrahlung and annihilation radiation: K. M. McVoy, Phys. Rev. **106**, 828 (1957); *ibid.* **110**, 1484 (1958); Goldhaber, Grodzins, and Sunyar, Phys. Rev. **106**,

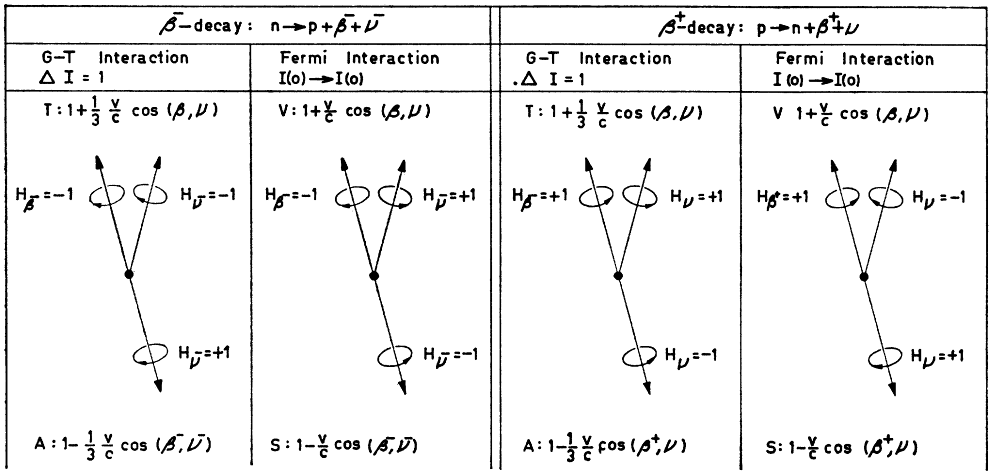

FIG. 1. Correlations of neutrino helicities and β interactions.

tron or positron beams. We have been working with the polarized beam of β particles for the past sixty years, yet we were completely unaware of it because of the faultiness of our left-right symmetry conception. However, many systematic uncertainties in the measurements, such as the backscattering effect, depolarization effect, instrumental asymmetry, and the screen correction factor, etc., are rather difficult to assess or to estimate. Probably it is fair to say that in the high-energy region of $v/c \geq 0.6$, the polarization is nearly v/c with an accuracy of not better than 10%. Below $v/c=0.6$ very few results have been reported and the picture in that region is not clear.[13]

(*D*) *Correlations between the Helicities of Leptons and Beta Interactions*

The helicity of the neutrino can be correlated to the electron polarization and the form of beta interaction as shown in Fig. 1.

In a G-T β^- interaction, the angular momentum carried away by the leptons is one unit. In the tensor interaction, both leptons are emitted preferentially in the same direction. Since the electron is found to possess negative helicity (left-handed screw), the antineutrino must have the same helicity. On the other hand, in the axial vector interaction, the electron and the antineutrino are emitted preferentially in opposite directions; so positive helicity is predicted for the antineutrino and negative helicity for the neutrino. The helicity of the neutrino[14] observed in the electron capture process of Eu^{152*} is indeed negative and therefore supports the axial-vector interaction. In a similar manner, one can figure out the helicity of the antineutrino for scalar and vector interactions. The relations between the helicities of various leptons in different beta interactions are shown in Table I. This table also points out two more significant conclusions: First, the much used Fierz interference term between S and V expressed as $(C_SC_V^*+C_S'C_V'^*)$ and A and T such as $(C_TC_A^*+C_T'C_A'^*)$ now automatically vanishes because the neutrino or antineutrino associated with S and T or V and A has opposite helicity. Therefore, no interference occurs. Secondly, for the same reason, combinations of (V and T) and (S and A) will not result in interference between Fermi and Gamow-Teller terms.

Many beautiful β-γ (circular polarization) correlation studies[15] on the mixed (G-T and Fermi) transitions such as Sc^{46}, Au^{198}, etc., showed nearly maximum amount of interference between G-T and Fermi interactions. This evidence strongly ruled out a pure VT or SA combination. Incidentally, this conclusion had been reached also by Mahmoud and Konopinski[16] by the study of the first forbidden beta spectra alone in the pre-parity era.

TABLE I. Helicities of ν, $\bar{\nu}$, β^-, and β^+.
Helicity: $\boldsymbol{\sigma}\cdot\mathbf{p}/|p|$.

Helicities	ν	$\bar{\nu}$	β^-	β^+
S, T	$+1$	-1	$-\frac{v}{c}$	$+\frac{v}{c}$
V, A	-1	$+1$	$-\frac{v}{c}$	$+\frac{v}{c}$

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826 (1957); Deutsch, Gittelman, Bauer, Grodzins, and Sunyar, Phys. Rev. **107**, 1733 (1957); and Boehm, Novey, Barnes, and Stech, Phys. Rev. **108**, 1497 (1957).

(c) Møller Scattering: C. Møller, Ann. Physik **14**, 531 (1932); L. A. Page, Phys. Rev. **106**, 394 (1957); A. M. Bincer, Phys. Rev. **107**, 1434, 1469 (1957); G. W. Ford and C. J. Mullin, Phys. Rev. **108**, 477 (1957); Frauenfelder, Hanson, Levine, Rossi, and De Pasquali, Phys. Rev. **107**, 643, 909, 910 (1957); and Benczer-Koller, Schwarzschild, Vise, and Wu, Phys. Rev. **109**, 193 (1958).

[13] Tumer, Gard and Cavanagh, Paper S1, Bulletin of Conference on Weak Interactions, Gatlinburg, Tennessee, 1957.

[14] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

[15] F. Boehm and A. H. Wapstra, Phys. Rev. **109**, 456 (1958); Lundby, Patro, and Stroot, Nuovo cimento **6**, 745 (1957); Steffen and Alexander, Proceedings of Rehovoth Conference (1957); and W. Güngst and H. Schopper, Z. Naturforsch **13a**, 505 (1958).

[16] H. M. Mahmoud and E. J. Konopinski, Phys. Rev. **88**, 1266 (1952).

(*E*) *Inverse Beta Decays and the Double Beta Decays*

There are also three experiments, initiated long before the parity crisis, which originally had no bearing on the parity question. However, it turns out now that they have important implications for the two-component neutrino and the conservation of leptons. As a matter of fact, a voice of dissension fron these investigations could cause serious troubles.

1. Capture cross section for the antineutrinos in the Cowan and Reines Experiments.[17]—$\bar{\nu}+p\rightarrow n+\beta^+$. For two-component neutrinos, the outgoing neutrinos from the reactor have only one spin state instead of the usual two. By a detailed balancing method, the absorption cross section will be twice as great as the old one. The latest experimental results[18] are no longer in disagreement with the two-component theory of the neutrino. The cross section per fission $\bar{\nu}$ (assuming 6.1 $\bar{\nu}$ per fission) for the inverse beta decay of the proton is

$$\sigma_{\mathrm{exp}}=(11\pm4)\times10^{-44}\ \mathrm{cm}^2,$$

which is comparable to the theoretical cross section calculated for the two-component theory of the neutrino and based on the antineutrino spectrum from the fission fragments.

$\sigma_{\mathrm{theo}}=9.5\times10^{-44}$ Reines *et al.*[18]
$=12\times10^{-44}$ Muehlhause and Oleksa[18]
$=15\times10^{-44}$ King and Perkins.[18]

2. Capture process for the neutrino.—In the Davis experiment[19] $\nu+\mathrm{Cl}^{37}\rightarrow \mathrm{A}^{37}+\beta^-$. Here a neutrino, not an antineutrino, is required for the absorption process. The intensive flux of antineutrinos pouring out of a power nuclear reactor does not provide the right kind of neutrino for this process and therefore no A^{37} activity should be attributed to the reactor neutrinos. The very small A^{37} counts (0.3 ± 3.4 counts per day) which Davis observed in his one thousand gallons of CCl_4 are equivalent to a cross section for neutrino capture of $(0.1\pm0.6)\times10^{-45}$ cm². This could be accounted for by the muon activation from the cosmic radiation, and no evidence for a positive effect from the reactor neutrinos exists at the present time. At least, there is no dissension about the two-component theory of the neutrino from the capture process of the neutrino.

3. Double beta-decay.[20a]—The theoretically calculated rates of double beta-decay depend on many assumptions concerning the properties of the neutrinos and whether one or both kinds of neutrinos are emitted in β^- decay. The existence of the conservation law of leptons, together with the two-component neutrino, limits the possible alternatives and demands that the rate of double beta decay be its minimum value. Experimentally no single electron line of discrete energy equal to the sum of the two disintegration energies has ever been observed. The observed upper limit of the rate of double beta decay also strongly rejects the short lifetime based on Majorana neutrinos and favors the longer time of Dirac neutrinos. For example, the predicted half-life of double beta decay of Ca^{48} (4.3 ± 0.1 Mev) is 4×10^{15} yr for no neutrino emissions and 4×10^{18} yr for Dirac neutrinos. The observed decay rate of Ca^{48} is $>2\times10^{18}$[20b] or 6×10^{18} yr.[20b] In the case of Nd^{150} (3.7 ± 0.1 Mev), the observed decay rate is $>2\times10^{18}$ yr[20c] in comparison with that predicted for Dirac neutrinos of 2×10^{18} yr. However, it is desirable to increase the sensitivity of the detector so one can actually observe the Dirac type double beta decay.

So, all in all, the experimental evidence in favor of two-component neutrinos and the conservation law of leptons is overwhelming. Not even a faint voice of dissension has been raised. On the other hand, neither can a great accuracy be claimed. A greatly improved accuracy to strengthen its ultimate validity is much to be desired.

II. From $\pi-\mu-e$ Decays

Here we review briefly how successfully the two-component theory of the neutrino and the conservation of leptons can interpret the observed phenomena in $\pi-\mu-e$ decays. Particularly, we show that the observed helicities of the neutrino and the antineutrino in $\pi-\mu-e$ decays are the same as those found in nuclear beta decays.

(*A*) *Polarization of Muons and Electrons*

Consider the decay of a positive pion in its own rest frame [Fig. 2(a)]. Since π^+ is spinless, the neutrino angular momentum (its spin 1/2) about its direction of motion must be balanced by the muon angular momentum about its direction of motion. Now the neutrino in nuclear beta decay is found to possess a negative helicity, so negative helicity is predicted for the μ^+. So far no direct determination of μ^+ helicity has been reported.

However, the information may be inferred from the helicity of the decay electrons within the two-component theory. In the extreme case [Fig. 2(a)] when the neutrino and the antineutrino go in the same direction, the electron which goes in the opposite direction has to carry away the angular momentum of the muon. If μ^+ has a negative helicity, the decay e^+ must possess positive helicity. The experimental results on the polarization of the negative and positive electrons from

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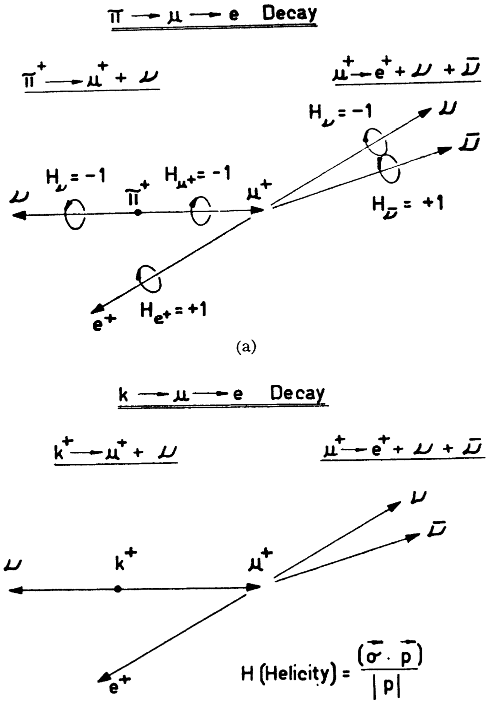
[17] F. Raines and C. L. Cowan, Phys. Rev. **92**, 830 (1953); Cowan, Reines, Harrison, Kruse, and McGuire, Science **124**, No. 3212, 103 (1956).

[18] F. Reines *et al.*, *Second Atoms for Peace Conference, Geneva*, 1958, Paper No. 1026.

[19] R. Davis, Phys. Rev. **97**, 766 (1955); Bull. Am. Phys. Soc. Ser. II, 1, 219 (1956); and private communication (1957).

[20] (a) H. Primakoff and S. P. Rosen, "Double beta decay," Washington University, 1958 (unpublished). (b) Ca^{48}: M. Awschalom, Phys. Rev. **101**, 1041 (1956); Dobrokhotov, Lazarenko, and Luk'yanov, *CERN High Energy Conference, 1958*. Nd^{150}: Cowan, Harrison, Langer, and Reines, Nuovo cimento **3**, 649 (1956).



(a)

(b)

FIG. 2.

muon decays obtained by measuring the circular polarization of the bremsstrahlung and annihilation radiation[21] or by the Møller scattering method[22] conclusively show positive helicity for e^+ and negative helicity for e^-. Here the results on the helicities of the neutrinos in nuclear beta-decays and from $\pi-\mu-e$ decays are in excellent accord.

(B) *Michel Parameter "ρ"*

The shape of the energy spectrum of e^+ from μ^+ decay is characterized by a single parameter "ρ" discussed by Michel. In the two-component theory of the neutrino, ρ must equal zero if the electron is accompanied by two neutrinos or two antineutrinos, and equal 3/4 if one neutrino and one antineutrino are emitted. The present experimental values[23] of ρ vary from 0.68 to 0.72, which is close to 0.75, for one neutrino and one antineutrino emission, and confidently reject the assumption of two neutrinos or two antineutrinos in muon decay. The ultimate determination of the value of ρ is highly desirable because of its significant theoretical implications.

(C) *Energy Dependence of the Asymmetry Coefficient*[24]

The two-component theory of the neutrino predicts closely the energy dependence of the asymmetry coefficient of electron distribution in muon decay. In the high-energy end of the spectrum, the data are in good agreement with the theory. At the low-energy region, measurements are difficult and the accuracy has been poor. However, as a whole, the energy dependence of the asymmetry coefficient in μ^- decay agrees with the prediction of the two-component theory.

III. Muon Capture

The process of muon capture has been studied only in complex nuclei and very little information is available in the literature. At present one side of the Puppi triangle, which represents the muon capture process, is attracting much attention. Before the conference is over we will hear several interesting papers[25] and communications[25] on this topic.

IV. $K-\mu-e$ Decays[26]

The $K-\mu-e$ decay is analogous to $\pi-\mu-e$ decay [Fig. 2(b)]. If the conservation law of leptons holds, the same kind of neutrinos are expected in these two parallel cases. This should, therefore, result in the same asymmetry distribution of electrons with respect to the direction of μ motion. The observance of this predicted asymmetry in $K-\mu-e$ decay further strengthens the validity of lepton conservation.

V. $\pi-e$ Decays[27]

The existence of $\pi-e$ decays is finally confirmed by several laboratories, and the measured ratio R of $\pi \rightarrow e$ to $\pi \rightarrow \mu+\nu$ decay is very close to that predicted by a simple calculation which gives $R=(\pi-e)/(\pi-\mu)=1.36 \times 10^{-4}$. It is interesting to note that the helicity of the electron from $\pi-e$ decay should be opposite to that from $\mu-e$ decays.

So there is overwhelming evidence in favor of the two-component theory of the neutrino and the conservation of leptons in all the beta-decay phenomena. To establish firmly the validity of these two assumptions, more precision measurements are required.

INTERACTIONS RESPONSIBLE FOR BETA DECAY

I. From Classical Beta-Decay Experiments

Prior to the discovery of parity nonconservation in beta decay, the (S,T) combination had been the

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favorite choice based mainly on $He^6(\beta\text{-}\nu)$ angular correlation results.[28] In fact, the $(\beta\text{-}\nu)$ angular correlation was the only means used to investigate the type of beta interaction in those days. But this type of experiment was known to be difficult. Wu and Schwarzschild[29] made a detailed examination of the old He^6 experiment and pointed out that the effective volume of the He^6 source in the hole of the pumping diaphragm was not correctly taken into account. Had this been done properly, the results of He^6 would not then have implied the tensor interaction. However, in spite of its many limitations, $\beta\text{-}\nu$ correlation is still an effective and powerful method in yielding information on the beta interactions. The first sign of warning against the (S,T) combination in beta interaction came in May of 1957 when Herrmannsfeldt *et al.*[30] published their $(\beta\text{-}\nu)$ correlation results on A^{35}, which decays mainly through Fermi interaction, and the results strongly supported the vector interaction instead of scalar as was once believed.

Recently,[31] this group has remeasured the $(\beta\text{-}\nu)$ correlation in He^6 with the same apparatus and obtained the correlation coefficient $\lambda=-0.39\pm0.02$, which certainly favors axial vector in He^6.

Meantime the $\beta\text{-}\nu$ angular correlation in

$$Li^8 \xrightarrow{\beta} Be^8 \rightarrow 2\alpha$$

was reinvestigated with greatly improved technique at California Institute of Technology[32] and at Heidelberg University.[33] They measured either the angular distribution of the two α particles or the α spectra in coincidence with the β particles emitted at either 180° or 90° from the α direction. The results from Heidelberg strongly favor the axial vector, and the California Institute of Technology results are accurate enough to put the upper limit of tensor mixture in G-T interaction to less than 10%.

Thus the (V,A) combination is strongly favored from $(\beta\text{-}\nu)$ correlation experiments. Let us now look into the information on beta interactions obtained from parity experiments.

II. From Parity Experiments

(*A*) *Electron Capture Process in* Eu^{152*} [34]

In an electron capture process, a neutrino and the recoil nucleus are emitted in opposite directions $e^- + p \rightarrow n + \nu$. If the capture process is followed by the emission of a gamma ray and the spin and parity changes are favorable as shown in the following decay process

$$A(0^-) \xrightarrow{e^-\text{ capture}} B^*(1^-) \xrightarrow{\gamma\text{ ray}} B(0^+)$$

then, by applying the conservation laws of momentum and angular momentum, one can deduce a simple correlation that the helicity of the downward gamma ray will be the same as that of the upward neutrino. So the problem of determining the neutrino helicity becomes that of measuring the circular polarization of the gamma ray. However, to select only those downward gamma rays following the emission of the upward neutrinos, many conditions must be fulfilled. First, the gamma ray must have an energy comparable to that of the neutrino and the lifetime of the excited level B^* must be very short ($\sim 10^{-14}$ sec) in order to permit the use of solid material. Even then one has to detect only the resonantly scattered gamma ray.

The requirements were indeed strict, but the radioisotope Eu^{152*} seemed heaven-sent to do this job. Goldhaber, Grodzins, and Sunyar knew of this radioisotope Eu^{152*} from their previous investigations and it fulfills all the requirements stated above. By measuring the circular polarization of the gamma rays from Eu^{152*} which are resonantly scattered by Sm, they found that the helicity of the gamma ray is *negative*! ($H=-0.67\pm0.10$). From this result one concludes that the helicity of the neutrino in electron capture is negative and therefore the Gamow-Teller interaction in electron capture is dominantly "A" and not "T."

(*B*) *Beta Decay of Polarized Neutrons*[35]

Meanwhile, at the Argonne National Laboratory, a highly polarized neutron beam had been successfully completed since 1957. Burgy *et al.*[35] had been measuring two asymmetry coefficients from the beta decays of polarized neutrons. One is the coefficient "A," the β^- distribution asymmetry $(\langle J\rangle \cdot p_{e-})$; the other is the coefficient "B," the $\langle\nu\rangle$ distribution asymmetry $(\langle J\rangle \cdot p_{\langle\nu\rangle})$. From the value $A=-0.11\pm0.02$ and $B=0.88\pm0.15$, they concluded that the interaction in β^- decay is dominantly V and A with opposite phase relations $(V-A)$.

Look back at the history of the theory of beta decay. It has been filled with surprises and excitement. Now, after a period of nearly sixty years of continuous investigation, finally along comes the nonconservation of parity. These two (classical beta theory and nonconservation of parity) joined forces in reaching the conclusion on the beta interaction.

However, we must be cautioned here that whether there is any small mixture of (S,T) in beta interaction is still unknown and is waiting to be proved.

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III. Universal Fermi Interaction

The great similarity in the strength of the coupling constants in beta decay, μ decay and μ capture suggests that the interaction forms of the three decay processes may also be the same. When beta-decay coupling was concluded to be (S,T) and μ-decay coupling was deduced to be dominantly V and A from the negative sign of the asymmetry coefficient, this possibility of a universal Fermi interaction was naturally ruled out. Now that the interaction (V,A) has replaced (S,T) in beta decay, the situation is quite altered. This is particularly intriguing because this specific form of (V and A) has been prophesied independently by Marshak and Sudershan[36] and also by Feynmann and Gell-Mann[37] by different deductions. The interactions which are responsible for the muon capture process are now under intensive investigation.

CONCLUSION

We have come a long way since the overthrow of the law of parity in weak interactions. A great advance has been made in the theory of the neutrino. We have two-component neutrinos and the law of conservation of leptons. A vast amount of experimental data is accounted for by the $V-A$ theory, and therefore the idea of the universal $(V-A)$ Fermi interaction is again made acceptable.

However, there are still many questions unanswered. Is there any connection between the beta interactions and the gravitational forces? Why should the ratio of the coupling constants between G-T and Fermi interactions $|C_{GT}/C_F|^2$ be what was observed? Are there any possible theoretical explanations for this? The ratio of $|C_{GT}/C_F|^2$ calculated from the recent neutron half-life[38] of (11.7 ± 0.3) min and the O^{14} ft value[39] is 1.42 ± 0.08. The ratio of $|C_{GT}/C_F|^2$ from the asymmetry distribution of electrons from polarized neutrons is 1.56 ± 0.14.[35] On the other hand, the ratio of $|C_{GT}/C_F|^2$ obtained from the analysis of the ft values of beta decays of mirror nuclei by the "B-X" diagram is only 1.16 ± 0.05.[40] The last method relies largely on the evaluation of the matrix elements. Would this apparent discrepancy eventually show us a way to improve our evaluation of the matrix elements? We are all eagerly anticipating hearing many interesting discussions on these subjects at this conference.

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