TSUNG DAO LEE

Weak interactions and nonconservation of parity

Nobel Lecture, December 11, 1957

In the previous talk Professor Yang[1] has outlined to you the position of our understanding concerning the various symmetry principles in physics prior to the end of last year. Since then, in the short period of one year, the proper roles of these principles in various physical processes have been greatly clarified. This remarkably rapid development is made possible only through the efforts and ingenuity of many physicists in various laboratories all over the world. To have a proper perspective and understanding of these new experimental results it may be desirable to review very briefly our knowledge about elementary particles and their interactions.

The family of elementary particles that we know today consists of numerous members. Each member is characterized, among other properties, by its mass, charge, and spin. These members are separated into two main groups: the « heavy particle » group and the « light particle » group. The well-known examples of the heavy particles are protons and neutrons; those of the light particles are photons and electrons. Apart from the obvious implication that a heavy particle is heavier than a light particle, this classification stems from the observation that a single heavy particle cannot disintegrate into light particles even if such disintegration should be compatible with the conservation laws of charge, energy, momentum, and angular momentum. This fact is more precisely formulated as the « law of conservation of heavy particles » which states that if to each heavy particle we assign a heavy particle number +1, to each anti-heavy particle a heavy particle number -1, and to each light particle a corresponding number 0, then in all known physical processes the algebraic sum of the heavy particle numbers is absolutely conserved. One of the simplest evidences of the validity of this law is the fact that ourselves, or our galaxy, have not disintegrated into radiation and other light particles.

Fig. 1 shows all the known heavy particles (and anti-heavy particles). All

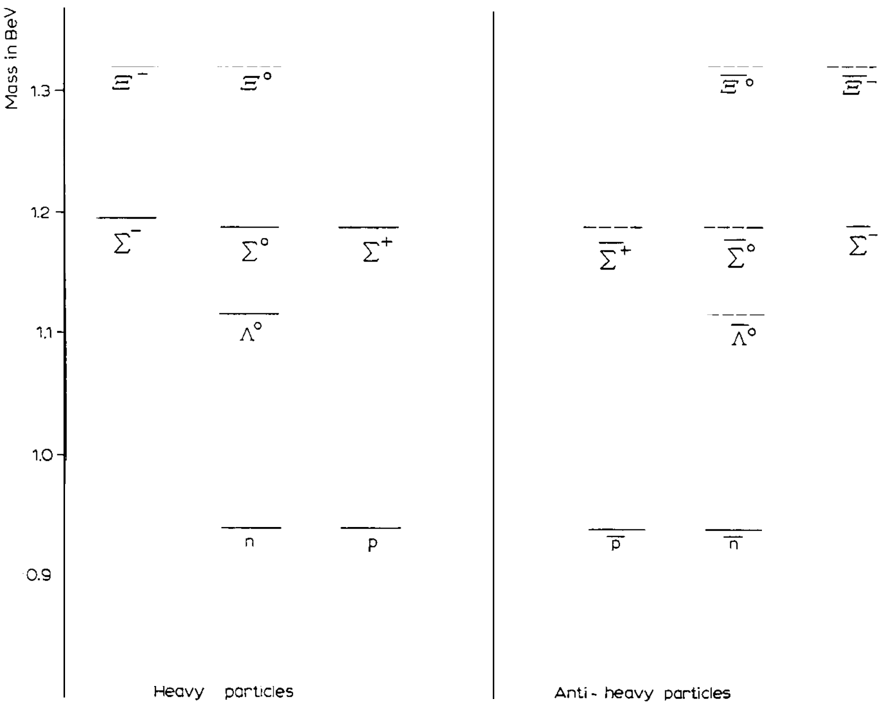

Fig. 1.

heavy particles except the nucleons are called hyperons and are labelled by capital Greek letters. The solid lines represent particles that are expected to exist from general theoretical arguments. All known heavy particles have half-integral spins. Fig. 2 shows all the known light particles. Among these, the $e^{\pm}$, $\mu^{\pm}$ and ν, $\bar{\nu}$ have half-integral spins. They are called leptons. The rest, photons, pions and K mesons, have integral spins.

The interactions (not including the gravitational forces) between these particles can be classified into three distinct groups:

1. *Strong Interactions.* This group is responsible for the production and the scattering of nucleons, pions, hyperons (i.e. Λ^0, Σ^-, etc.) and K mesons. It is characterized by a coupling constant $f^2/\hbar c \cong 1$.

2. *Electromagnetic Interactions.* The electromagnetic coupling constant is $(e^2/\hbar c) = (1/137)$.

3. *Weak Interactions.* This group includes all known non-electromagnetic decay interactions of these elementary particles and the recently observed absorption process of neutrinoes by nucleons[2]. These interactions are characterized by coupling constants $g^2/\hbar c \cong 10^{-14}$.

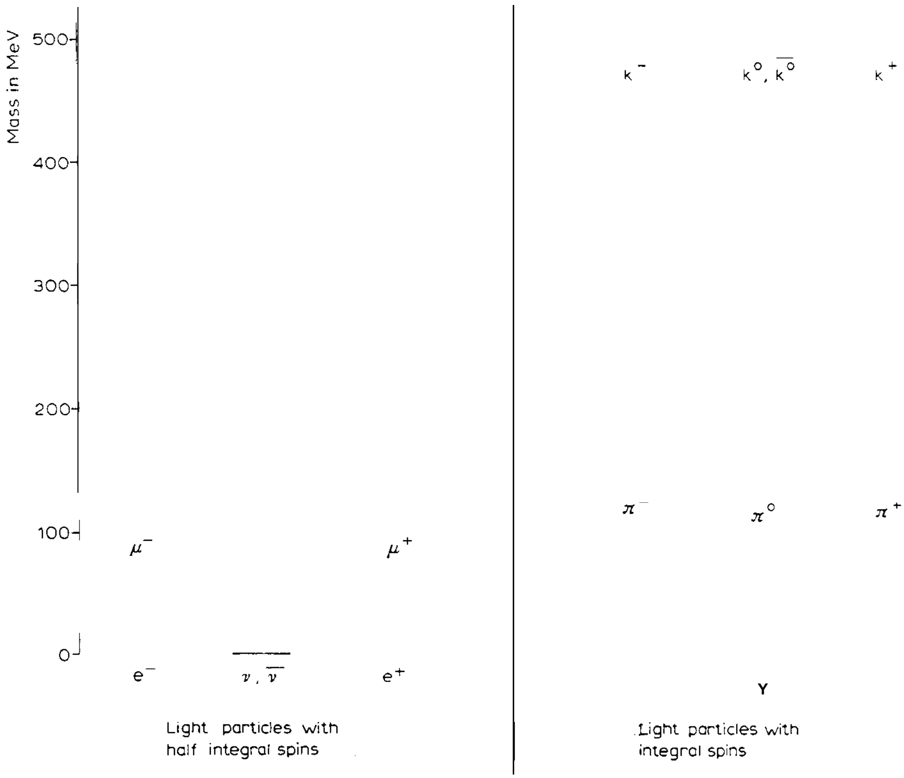

Fig. 2.

The law of conservation of parity is valid for both the strong and the electromagnetic interactions but is not valid for the weak interactions. Today's discussions will be mainly on the recently observed effects of nonconservation of parity in the various weak interactions.

II

The weak interactions cover a large variety of reactions. At present there are about 20 known phenomenologically independent reactions ranging from the decay of various hyperons to the decay of light particles. Within the last year, many critical experiments have been performed to test the validity of the law of conservation of parity in these reactions. We shall first summarize the experimental results together with their direct theoretical implications. Next, we shall discuss some further possible consequences and theoretical considerations.

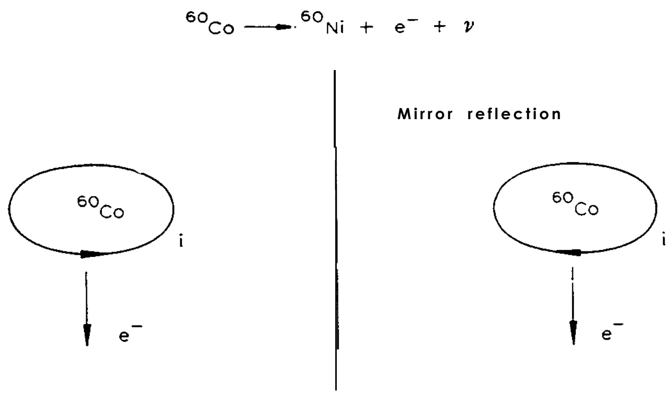

Fig. 3.

(1) *β-decay*

The first experiment that conclusively established the nonconservation of parity was that on β-angular distribution from polarized ^{60}Co nuclei [3] (see Fig. 3). The ^{60}Co nuclei are polarized by a magnetic field at very low temperatures. Indeed in this experiment, the circular direction of the electric current in the solenoid that produces the polarizing magnetic field together with the preferential direction of the β-ray emitted, differentiates in a most direct way a right-handed system from a left-handed system. Thus the nonconservation of parity or the non-invariance under a mirror reflection can be established without reference to any theory.

Furthermore from the large amount of angular asymmetry observed it can also be established[4] that the β-decay interaction is not invariant under a charge conjugation operation. That this can be concluded without performing the extremely difficult (in fact, almost impossible) experiment using anti-^{60}Co is based on certain theoretical deductions under the general framework of local field theory. In the following we shall try to sketch this type of reasoning [5].

Let us consider the β-decay process, say

$$n \rightarrow p + e^- + \nu \tag{1}$$

in which each particle is described by a quantized wave equation. In particular the neutrino is described by the Dirac equation [6]

$$\sum_{\mu=1}^{4} \gamma_\mu \frac{\partial}{\partial x_\mu} \psi_\nu = 0 \tag{2}$$

where $\gamma_1, \gamma_2, \gamma_3, \gamma_4$, are the four (4×4) anti-commuting Dirac matrices and $x_1, x_2, x_3, x_4 = ict$ are the four space-time coordinates. For each given momentum there exists two spin states for the neutrino and two spin states for the anti-neutrino. These may be denoted by $\nu_R, \nu_L, \bar{\nu}_R, \bar{\nu}_L$. If we define the helicity H to be

$$H \equiv \vec{\sigma} \cdot \hat{p} \tag{3}$$

with $\vec{\sigma}$ as the spin operator and $\hat{p}$ the unit vector along the momentum direction, then these four states have, respectively, helicities equal to $+1, -1, -1$ and $+1$ (Fig. 4). Mathematically, this decomposition of states corresponds to a separation of ψ_ν into a right-handed part ψ_R and a left-handed part ψ_L with

$$\psi_\nu = \psi_R + \psi_L \tag{4}$$

where
$$\psi_R = \tfrac{1}{2}(1 - \gamma_5)\,\psi_\nu \tag{5}$$
$$\psi_L = \tfrac{1}{2}(1 + \gamma_5)\,\psi_\nu \tag{6}$$

and
$$\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$$

It is easy to see that both ψ_R and ψ_L separately satisfy the Dirac equation [Eq. (2)]. With this decomposition the β process of a nucleus A can be represented schematically as

$$\mathrm{A} \rightarrow \mathrm{B} + \mathrm{e}^- + \begin{cases} C_i^R\,\nu_R & (H = +1) \quad (7) \\ C_i^L\,\nu_L & (H = -1) \quad (8) \end{cases}$$

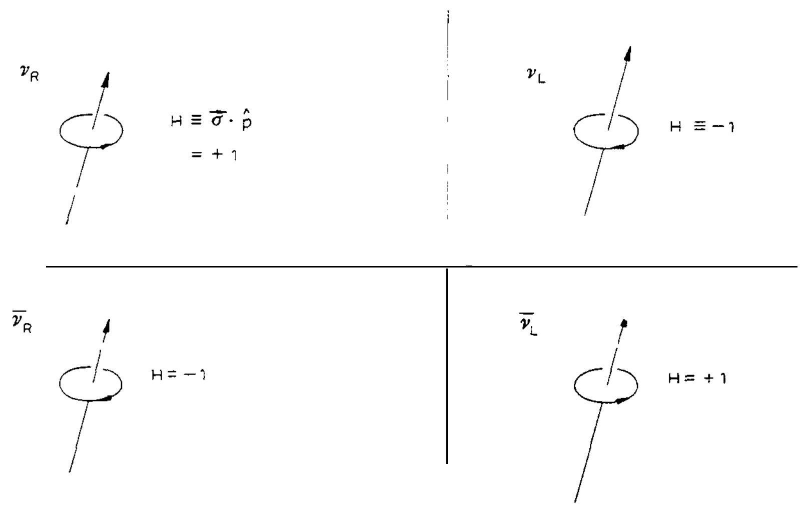

Fig. 4.

with C_i^R and C_i^L as the various probability amplitudes for emission of ν_R and ν_L respectively. The suffix *i* represents the various possible channels for such emissions. If the theory is invariant under proper Lorentz transformation, then there are five such channels: namely scalar S, tensor T, vector V, pseudo-scalar P and axial-vector term A. According to the general rules of quantum field theory with any interaction term representing the decay of a particle, there exists a corresponding hermitian conjugate term which represents decay of the antiparticle. Thus, the decay of the anti-nucleus A can be schematically represented by

$$\bar{A} \to \bar{B} + e^+ + \begin{cases} C_i^{R*}\, \bar{\nu}_R & (H = -1) \quad (7') \\ C_i^{L*}\, \bar{\nu}_L & (H = +1) \quad (8') \end{cases}$$

with C_i^{R*} and C_i^{L*} as the corresponding amplitudes for emission of $\bar{\nu}_R$ and $\bar{\nu}_L$. Under the charge conjugation operator we change a particle to its anti-particle but we do not change its spatial or spin wave functions. Consequently it must have the same helicity. Thus, if the β-decay process is invariant under the charge conjugation operator, then we should expect process (7) to proceed with the same amplitude as process (8′). The condition for invariance under charge conjugation is, then

$$C_i^R = C_i^{L*} \tag{9}$$

for all i = *S,* T, V, P, A.

In the decay of ^{60}Co, because there is a difference of spin values between ^{60}Co and ^{60}Ni, only the terms i = T and i = A contribute. From the large angular-asymmetry observed it can be safely concluded that for bot h i = T, A

$$|C_i^R| \neq |C_i^L|$$

which contradicts Eq. (9) and proves the non-invariance of β-interaction under charge conjugation. For illustration purposes, we assume in the above the neutrino to be described by a 4-component theory and further we assume that in the β-decay process only neutrino is emitted. Actually the same conclusion concerning the non-invariance property under charge conjugation can be obtained even if the neutrino should be described by a, say, 8-component theory, or, if in addition to neutrino, anti-neutrino may also be emitted.

Recently many more experiments [7] have been performed on the longitudinal polarization of electrons and positrons, th e β–γ, correlation together with the circular polarization of the γ radiation and the β angular distribution with various polarized nuclei other than ^{60}Co. The results of all these experiments confirm the main conclusions of the first ^{60}Co experiment, that both the parity operator and the charge conjugation operator are not conserved in β-decay processes.

Another interesting question is whether the β-decay interaction is invariant under the product operation of (charge conjugation x mirror reflection). Under such an operation we should compare the decay of A with that of $\bar{A}$ but with opposite helicities. Thus if β-decay is invariant under the joint operation of (charge conjugation x minor reflection) we should expect process (7) to proceed with the same amplitude as process (7′) and similarly for processes (8) and (8′). T he corresponding conditions are then

$$
\begin{aligned}
C_i^R &= C_i^{R*} \\
\text{and } C_i^L &= C_i^{L*}
\end{aligned}
\tag{10}
$$

Although experiments have been performed to test the validity of these conditions, at present, these experiments have not reached a conclusive stage and we still do not know the answer to this important question.

(2) π–μ–e decay

The $\pi^{\pm}$ meson decays into a $\mu^{\pm}$ meson and a neutrino. The $\mu^{\pm}$ meson, in turn, decays into an e $^{\pm}$ and two neutrinoes (or anti-neutrinoes). If parity is not conserved in π-decay, the μ meson emitted could be longitudinally po-

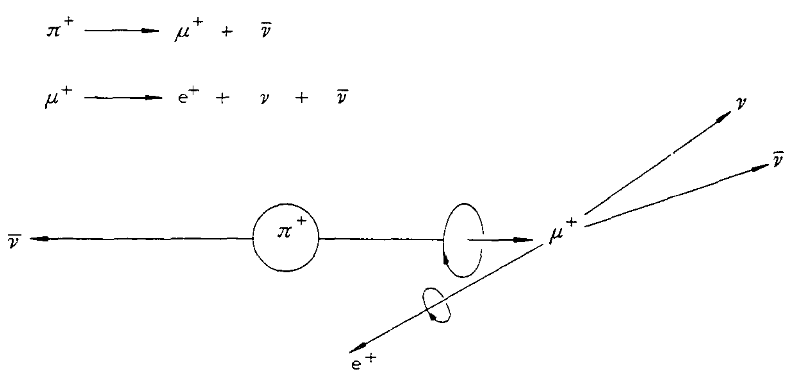

Fig. 5.

larized. If in the subsequent μ-decay parity is also not conserved, the electron (or positron) emitted from such a μ meson at rest would in general exhibit a forward and backward angular asymmetry with respect to the polarization of μ meson (Fig. 5). Consequently in the π-μ-e decay sequence we may observe an angular correlation between the momentum of $\mu^{\pm}$ meson measured in the rest system of π meson and the momentum of $e^{\pm}$ measured in the rest system of $\mu^{\pm}$. If this angular correlation shows a forward backward asymmetry, then parity must be nonconserved in both π-decay and μ-decay. The experimental results [8] on these angular correlations appeared within a few days after the results on β-decay were known. These results showed conclusively that not only parity is not conserved but the charge conjugation operator is also not conserved in π-decay as well as in μ-decay.

Later, direct measurements [9] on the longitudinal polarization of the positron from μ^{+}-decay was done establishing the same conclusion concerning μ -decay.

(3) K-μ-e *decay*

In this case we have instead of the π meson the heavier K meson which decays into a μ meson and a neutrino (Fig. 6). Experiment [10] on the angular correlation between the μ^{+} momentum from the decay of K^{+} meson and the positron momentum from the $\mu^{\pm}$-decay establishes that in K-decay the parity as well as the charge conjugation operator is not conserved.

(4) Λ°-*decay*

The Λ° particle can be produced by colliding an energetic π^{-} on proton. The

$$K^{+} \longrightarrow \mu^{+} + \bar{\nu}$$

$$\mu^{+} \longrightarrow e^{+} + \nu + \bar{\nu}$$

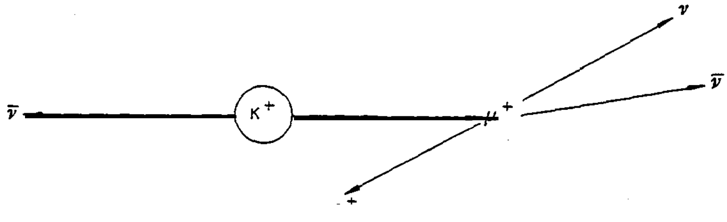

Fig. 6.

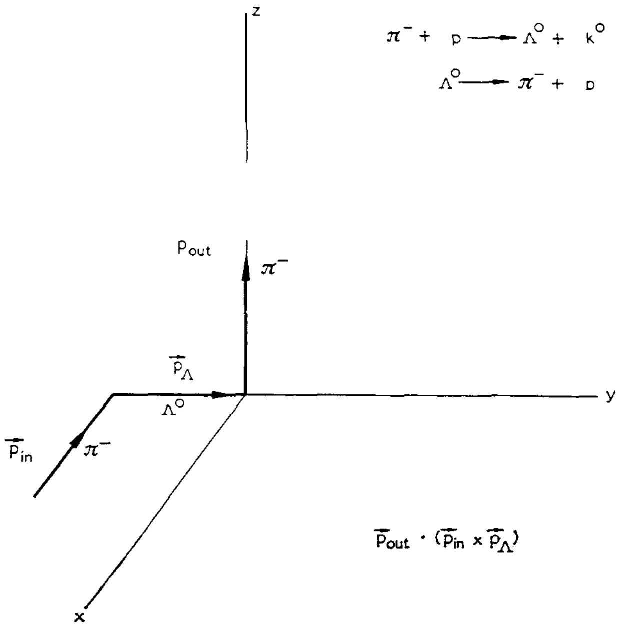

Fig. 7.

Λ^0 subsequently decays into a proton plus a π^- (Fig. 7). The observation of an a symmetrical distribution with respect to the sign of the product $\vec{p}_{out}$ $(\vec{p}_{in} \times \vec{p}_\Lambda)$ formed from the momentum of the incoming pion $\vec{p}_{in}$, the momentum of the lambda particle, $\vec{p}_\Lambda$, and that of the decay pion $\vec{p}_{out}$ would constitute an unequivocal proof that parity is not conserved in this decay. Recent experiments [11] on these reactions demonstrates that in these reactions there is indeed such an angular correlation between $\vec{p}_{out}$ and $(\vec{p}_{in} \times \vec{p}_\Lambda)$. Furthermore, from the amount of the large up-down asymmetry it can be concluded that the Λ^0-decay interaction is also not invariant under the charge conjugation operation.

From all these results it appears that the property of nonconservation of parity in the variou s weak interactions and the noninvariance property of these interactions under charge conjugation are well established. In connection with these properties we find an entirely new and rich domain of natural phenomena which, in turn, gives us new tools to probe further into the structure of our physical world. These interactions offer us natural ways to polarize and to analyze the spins of various elementary particles. Thus, for example, the magnetic moment of the μ meson can now be measured to an extremely high degree of accuracy [12] which, otherwise, would be unattainable; the spins of some hyperons now may perhaps be determined [13] unambiguously through the observed angular asymmetries in their decays; new aspects of the electromagnetic fields of various gas, liquid and solid materials can now be studied by using these unstable, polarized particles. However, perhaps the most significant consequences are the opening of new possibilities and the re-examination of our old concepts concerning the structure of elementary particles. We shall next discuss two such considerations - the two-component theory of neutrino, and the possible existence of a law of conservation of leptons.

III

Before the recent developments on nonconservation of parity, it was customary to describe the neutrino by a four-component theory in which, as we mentioned before, to each definite momentum there are the two spin states of the neutrino ν_R and ν_L, plus the two spin states of the antineutrino $\bar{\nu}_R$ and $\bar{\nu}_L$. In the two-component theory, however, we assume two of these states, say, ν_L and $\bar{\nu}_L$ simply do not exist in nature. The spin of the neutrino is then always parallel to its momentum while the spin of the antineutrino is always antiparallel to its momentum. Thus in the two-component theory we have only half of the degrees of freedom as in the four-component theory. Graphically we may represent the spin and the velocity of the neutrino by the spiral motion of a right-handed screw and that of the antineutrino by the motion of a left-handed screw (Fig. 8).

The possibility of a two-component relativistic theory of a spin ½ particle was first discussed by H. Weyl [14] as early as 1929. However, in the past, because parity is not manifestly conserved in the Weyl formalism, it was always rejected [15]. With the recent discoveries such an objection becomes completely invalid [16].

To appreciate the simplicity of this two-component theory in the present situation it is best if we assume further the existence of a conservation law for leptons [17]. This law is in close analogy with the corresponding conservation law for the heavy particles. We assign to each lepton a leptonic number l equal to $+1$ or -1 and to any other particle the leptonic number zero. The leptonic number for a lepton must be the negative of that for its antiparticle. The law of conservation of leptons then states that « in all physical processes the algebraic sum of leptonic numbers must be conserved ».

Some simple consequences follow immediately if we assume that this law is valid and that the neutrino is described by the two-component theory.
(I) The mass of the neutrino and the antineutrino must be zero. This is true

$$(\vec{\sigma}\cdot\vec{p})\,\phi = i\,\dot{\phi}$$

Fig. 8.

for the physical mass even with the inclusion of all interactions. To see this let us consider a neutrino moving with a finite momentum. From the two-component theory the spin of this neutrino must be parallel to its momentum. Suppose now it has a non-vanishing physical mass. Then, we can always send an observer travelling along the same direction as the neutrino but with a velocity faster than that of the neutrino. From this observer's point of view this « neutrino » now becomes a particle with the spin along its original direction but the direction of momentum reversed; i.e. it becomes an « antineutrino». However since the leptonic number for neutrino is different from that of the antineutrino, these two particles cannot be transformed into each other by a Lorentz transformation. Consequently, the physical mass of a neutrino must be zero.
(2) The theory is not invariant under the parity operator P which by definition inverts all spatial coordinates but does not change a particle into its antiparticle state. Under such an operation one inverts the momentum of a particle but not its spin direction. Since in this theory these two are always parallel for a neutrino, the parity operator P applied to a neutrino state leads to a non-existing state. Consequently the theory is not invariant under the parity operation.
(3) Similarly one can show the theory is not invariant under the charge conjugation operation which changes a particle into its antiparticle but not its spin direction or its momentum.

To test the complete validity of the conservation law of leptons and the two-component theory we have to investigate in detail all the neutrino processes. For example in β-decay we must have either

$$n \rightarrow p + e^- + \nu \ (H_\nu = +1)$$
or
$$n \rightarrow p + e^- + \bar{\nu} \ (H_{\bar{\nu}} = -1)$$

This can be determined by measuring the spin and the momentum of the neutral lepton; i.e. to see whether it is a neutrino (right-handed helicity) or an antineutrino (left-handed helicity). Through the law of conservation of angular momentum, measurements on polarizations and angular distributions of the nucleus and the electrons can lead to determination of the spin states of the neutrino. Similarly, through the recoil momentum measurements we can find out information about the linear momentum of the neutrino. In the same way we can use not only β-decay but π-decay, μ-decay and K-decay to test the validity of either the two-component theory or the law of conservation of leptons. At present, these measurements have not yet reached a definitive stage. Much of our future may depend on the results of these experiments.

IV

The progress of science has always been the result of a close interplay between our concepts of the universe and our observations on nature. The former can only evolve out of the latter and yet the latter is also conditioned greatly by the former. Thus in our exploration of nature, the interplay between our concepts and our observations may sometimes lead to totally unexpected aspects among already familiar phenomena. As in the present case, these hidden properties are usually revealed only through a fundamental change in our basic concept concerning the principles that underly natural phenomena. While all this is well-known, it is nevertheless an extremely rich and memorable experience to be able to watch at close proximity in a single instance the mutual influence and the subsequent growth of these two factors - the concept and the observation. It is, indeed, a privilege that I am able to tell you part of this experience in the recent developments concerning the nonconservation of parity and the weak interactions.

1. C. N. Yang, *Nobel Lecture,* this volume, p. 393.
2. C. L. Cowan, Jr., F. Rines, F. B. Harrison, H. W. Kruse, and A. D. McGuire, *Science,* 124 (1956) 103.
3. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.,* 105 (1957) 1413.
4. T. D. Lee, R. Oehme, and C. N. Yang, *Phys. Rev.,* 106 (1957) 340; B. L. Ioffe, L. B. Okun, and A. P. Rudik, *J.E.T.P. (U.S.S.R.),* 32 (1957) 396.
5. We remark here that if the neutrino is described by a two-component theory (see Section III) then the result of the large angular asymmetry in ^{60}Co decay establishes in a trivial way the non-Invariance property of β-decay under the charge conjugation operation. However, this non-invariance property can also be proved under a much wider framework. In this section we take as an example the case of a four-component theory of neutrino to illustrate such a proof
6. For notations and definitions of γ matrices see, e.g., W. Pauli, *Handbuch der Physik,* Julius Springer Verlag, Berlin, 1933, Vol. *24.*
7. For a summary of these experiments see, e.g., *Proceedings of the Seventh Annual Rochester Conference,* Interscience, New York, 1957.
8. R. L. Garwin, L. M. Lederman, and M. Weinrich, *Phys. Rev.,* 105 (1957) 1415 ; J. I. Friedman and V. L. Telegdi, *Phys. Rev.,* 105 (1957) 1681.
9. G. Culligan, S. G. F. Frank, J. R. Holt, J. C. Kluyver, and T. Massam, *Nature,* 180 (1957) 751.
10. C. A. Coombes, B. Cork, W. Galbraith, G. R. Lambertson, and W. A. Wenzel, *Phys. Rev.,* 108 (1957) 1348.
11. J. Crawford, et. al., *Phys. Rev.,* 108 (1957) 1102; F. Eisler et al., *Phys. Rev.,* 108 (1957) 1353; R. Adair and L. Leipuner, *Phys. Rev.,* (to be published).
12. T. Coffin, R. L. Garwin, L. M. Lederman, S. Penman, and A. M. Sachs, *Phys. Rev.,* 107 (1957) 1108.
13. T. D. Lee and C. N. Yang, *Phys. Rev.,* 109 (1958) 1755.
14. H. Weyl, *Z. Physik, 56* (1929) 330.
15. Cf. W. Pauli, *Handbuch der Physik,* Julius Springer Verlag, Berlin, 1933, Vol. 24, pp. 226-227.
16. The possible use of a two-component theory for expressing the nonconservation property of parity in neutrino processes was independently proposed and discussed by T. D. Lee and C. N. Yang, *Phys. Rev.,* 105 (1957) 1671; A. Salam, *Nuovo Cimento,* 5 (1957) 299; and L. Landau, *Nucl. Phys., 3* (1957) 127.
17. The possible existence of a conservation law for leptons has been discussed before the discovery of nonconservation of parity. Cf. E. Konopinski and H. M. Mahmoud, *Phys. Rev., 92* (1953) 1045.