ELEMENTARY PARTICLES

The following article is based on the Twenty-Ninth Joseph Henry Lecture of the Philosophical Society of Washington, which was delivered before the Society on May 6, 1960.

By ***T. D. Lee***

THE urge and the interest to find those ultimate elements in terms of which everything else is made of are almost as old as the human civilization. However, as our knowledge increases what were thought to be elementary may turn out to be composites. Consequently, the class of these supposedly fundamental elements changes with time. Such was, for example, the periodic table of atoms in the last century. Today we know that all different molecules, atoms, and nuclei are complexes resulting from the existence and the interactions of some thirty particles which are called "elementary particles".

1. History (1897–1932)

THE history of the present particle physics began in 1897 with the discovery of electrons by J. J. Thomson.[1] In the subsequent years, through the discovery of quantum theory, it was realized that the electromagnetic waves are quantized and composed of particles [2] called photons γ. Together with the hydrogen ion, or the proton p, these three were the earliest known members among the present long list of elementary particles.

It was only after the discovery of quantum mechanics that particle physics started to gain momentum. In 1929, in order to resolve the difficulty of negative energy states that occurred in his relativistic equation of the electron, Dirac proposed the hole hypothesis [3] in which he assumed that almost all the negative energy states are already occupied. The few remaining unoccupied negative energy states are called "holes". Dirac showed that, unlike the original electrons which have negative charges, these holes behave like particles of positive charges, and he thought that they might be protons. Later, through the efforts of Oppenheimer,[4] Weyl,[5] and others [6] it was realized that these holes cannot be protons and must be identified as new kinds of particles called positrons e^+, which have the same mass but opposite charge to that of the electrons e^-. In today's terminology the positron is called the antiparticle of the electron.

In a similar way, it was also anticipated that the presence of the proton p implies the existence of its antiparticle, the antiproton $\bar{p}$.

One may consider the first phase of particle physics ended in 1932 with both the discovery of e^+ by Anderson [7] and the discovery of the neutron by Chadwick.[8]

[1] J. J. Thomson, Phil. Mag. **46**, 528 (1898). An interesting and personal account of this discovery was given by Thomson in his book *Recollections and Reflections* (G. Bell and Sons, Ltd., 1936).

[2] A. Einstein, Ann. phys. **17**, 132 (1905).

[3] P.A.M. Dirac, Proc. Roy. Soc. **A126**, 360 (1929).

[4] J. R. Oppenheimer, Phys. Rev. **35**, 562 (1930).

[5] H. Weyl, *Gruppentheorie und Quantenmechanik* (1931), 2nd ed., p. 234.

[6] I. Tamm, Z. Physik **62**, 545 (1930). See also P.A.M. Dirac, Proc. Cambridge Phil. Soc. **26**, 361 (1930); Proc. Roy. Soc. **A133**, 60 (1931).

[7] C. D. Anderson, Science **76**, 238 (1932); Phys. Rev. **43**, 491 (1933). Compare also Blackett and Occhialini, Proc. Roy. Soc. **A139**, 699 (1933).

[8] J. Chadwick, Proc. Roy. Soc. **A136**, 692 (1932).

T. D. Lee, a member of the Physics Department at Columbia University since 1953, was named three years ago (at the age of 31) to share the 1957 Nobel Prize in physics with C. N. Yang for having predicted the nonconservation of parity in weak interactions.

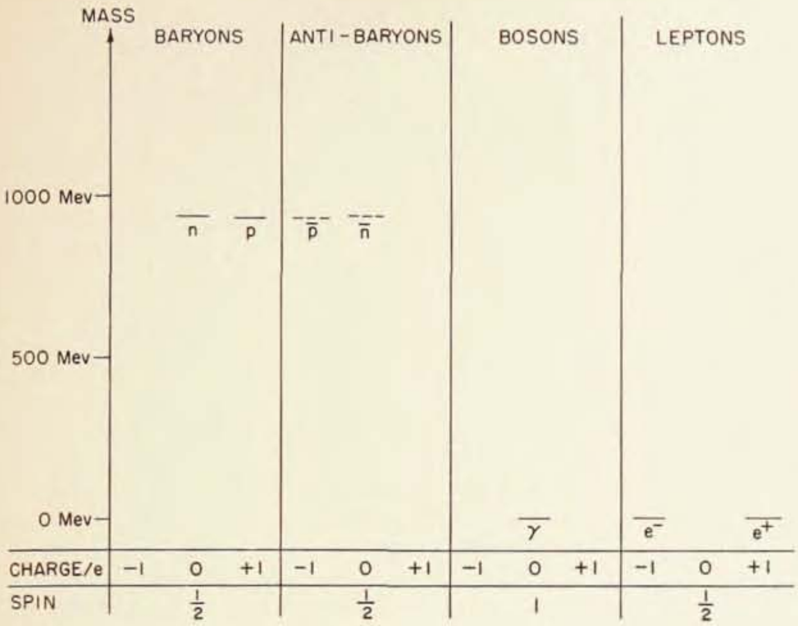

Fig. 1. A list of the elementary particles known in 1933. (The mass scale is only approximately accurate.)

Fig. 1 illustrates the particles known at that time. (The antiproton and the antineutron are indicated by dotted lines since they were not observed until recently.[9]) The interactions between these particles form three groups, namely: (i) the strong interactions between p and n which bind the nucleons to form various nuclei, (ii) the electromagnetic interactions between charged particles and photons through which all different atoms and molecules are formed, and (iii) the gravitation.

2. *History (1933–1947)*

THIS small group of particles was soon found to be inadequate. It was realized in the 1920's that by analyzing the energy spectrum of the electron in beta decay there was an apparent nonconservation of energy. Pauli [10] resolved this difficulty by postulating the existence of a neutral particle with spin $= \frac{1}{2}\ \hbar$ and zero (or very small) mass. Subsequently, Fermi [11] developed the theory of beta decay. This neutral particle was called the neutrino ν and its antiparticle the antineutrino $\bar{\nu}$.

$$Z \rightarrow (Z-1) + e^{+} + \nu$$

or

$$Z \rightarrow (Z+1) + e^{-} + \bar{\nu}$$

where Z and $(Z \pm 1)$ are, respectively, the charges of the initial and the final nuclei.

Further experimental confirmations of this particle came later from the measurement [12] of the recoil of the final nucleus, from the capture experiment of the antineutrinos [13] and from the over-all verifications of Fermi's beta-decay theory.[12]

Another addition to this growing family of particles came from the theoretical considerations made by Yukawa [14] in 1935. Yukawa suggested that the nuclear forces between the nucleons are due to the virtual emission and absorption of a new kind of charged particle which has integral spin and a mass of about $200m_e$ where m_e is the mass of the electron.

In 1936, a charged particle of such mass was found in cosmic radiations by Anderson and Neddermeyer [15] and by Street and Stevenson.[16] However, subsequent study of this particle showed that surprisingly this cosmic-ray particle does not seem to have any strong interactions with the nucleus [17] which, of course, makes it impossible to generate the observed strong nuclear interactions that would be expected from the Yukawa theory.

This puzzle was solved in 1947 by Lattes, Occhialini, and Powell [18] using the then newly developed photographic emulsion technique. They found that there actually existed two different kinds of particles which they called $\pi^{\pm}$ mesons and $\mu^{\pm}$ mesons. The π meson lives a very short lifetime of $\sim 10^{-8}$ seconds and decays into $\mu^{\pm}$ which subsequently decays into $e^{\pm}$ but with a much longer lifetime of $\sim 10^{-6}$ seconds. Because of this lifetime difference, the μ meson is more easily observed and was discovered in the previous cosmic-ray experi-

[9] The antiproton was first observed by Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. **100**, 947 (1955). The antineutron was first observed by Cork, Lambertson, Piccioni, and Wenzel, Phys. Rev. **104**, 1193 (1956).

[10] *Proceedings* of Solvay Congress, Brussels (1933). While the possible existence of a neutral particle in beta decay was first suggested by Pauli at the American Physical Society Meeting in Pasadena in 1931, serious discussions of its existence and its properties did not appear in any literature until 1933.

[11] E. Fermi, Z. Physik **88**, 161 (1934).

[12] For a detailed discussion of these experiments see, e.g., C. S. Wu, *The Neutrino, Memorial Volume to Wolfgang Pauli* (Pergamon Press, 1960) and J. S. Allen, *The Neutrino* (Princeton University Press, 1958).

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

[14] H. Yukawa, Proc. Phys.-Math. Soc. Japan **17**, 48 (1935).

[15] Anderson and Neddermeyer, Phys. Rev. **51**, 884 (1937).

[16] Street and Stevenson, Phys. Rev. **51**, 1005 (1937).

[17] Convincing evidence of this was given by the experiment done by Conversi, Pancini, and Piccioni, Phys. Rev. **71**, 209 (1947); and by the theoretical analysis made by Fermi, Teller, and Weisskopf, Phys. Rev. **71**, 314 (1947) and by Fermi and Teller, Phys. Rev. **72**, 399 (1947).

[18] Lattes, Occhialini, and Powell, Nature **160**, 453 (1947).

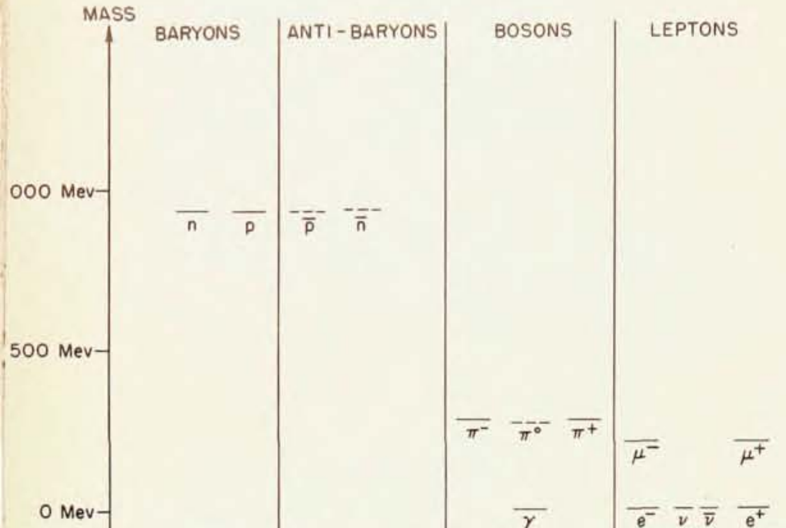

Fig. 2. Elementary particles known in 1947. (Mass scale is only approximately accurate.)

	INTERACTIONS	~ (COUPLING CONSTANT)^2
1.	STRONG	1
2.	ELECTROMAGNETIC	10^{-2}
3.	WEAK	10^{-12}
4.	GRAVITATION	10^{-38}

Table 1. Different types of interactions between elementary particles and their approximate relative strengths. Strong interactions are responsible for the bindings of different nuclei, for production of pions and strange particles, and for collisions between nucleons and pions. Weak interactions are responsible for beta decays, for the various decays of strange particles, $\pi^\pm$ mesons, $\mu^\pm$ mesons, and for the different capture processes of neutrinos, electrons, and μ^- mesons.

ments.[19] The π meson interacts strongly with the nucleus, thus gives the needed confirmation to Yukawa's idea.

Fig. 2 illustrates the family of particles known at that time and Table 1 shows the four different classes of their interactions. It was known from experiments in nuclear physics that the forces between two protons are about the same as those between a proton and a neutron in the appropriate state. This property is called charge independence, or isotopic spin invariance. Had there existed only charged mesons, then since a proton can only emit π^+ but can absorb only π^-, it is impossible to exchange a single charged meson between two protons. This would make the forces between protons quite different from that between the proton and the neutron. The charge independence property of nuclear forces therefore necessitates the existence of a neutral π° meson which is indicated by a dotted line in Fig. 2. (The π° meson was observed in 1950.[20])

3. Strange Particles (1947–   )

IN the same year in which the π meson was discovered (1947), Rochester and Butler[21] observed two forked tracks "of a very striking character" in their investigation of cosmic rays by using a cloud chamber. Both events (one charged and one neutral) were found to be due to particles of mass $\sim 1000m_e$ which decayed into light mesons. In 1949, by using the emulsion technique, the Bristol group[22] found in cosmic rays another unusual event which was the first example of τ^+ (called $K\pi_3{}^+$ in today's terminology)

$$\tau^+ \ (\text{or } K\pi_3{}^+) \rightarrow \pi^+ + \pi^+ + \pi^-. \tag{1}$$

In the succeeding years between 1949–1953 many new particles and their different decay modes were observed in cosmic rays. Among these, there were[23]

$$\Lambda^\circ \rightarrow p + \pi^-, \tag{2}$$

$$\Sigma^\pm \rightarrow n + \pi^\pm, \tag{3}$$

$$\Xi^- \rightarrow \Lambda^\circ + \pi^- \tag{4}$$

and the various decays of the K particles, such as

$$\theta^\pm \ (\text{or } K_{\pi 2}{}^\pm) \rightarrow \pi^\pm + \pi^\circ, \tag{5}$$

$$K_{\mu 2}{}^\pm \rightarrow \mu^\pm + \text{neutrino}, \tag{6}$$

$$\theta^\circ \ (\text{or } K_1{}^\circ) \rightarrow \pi^+ + \pi^-, \tag{7}$$

etc.

4. Associated Production and Conservation of Strangeness

THESE new particles were soon found to be produced copiously in high-energy nucleon-nucleon and pion-nucleon collisions. This fact proves that there must exist strong interactions between these new particles and the nucleons and pions. On the other hand, the lifetimes of these particles for decaying into nucleons and/or pions are quite long, thus indicating the presence of *only* very weak interactions between these particles and the nucleons and pions. This paradoxical

[19] Such possibilities have been discussed theoretically, prior to the discovery of π meson, by Sakata and Ionue, Progr. Theoret. Physics (Kyoto) **1**, 143 (1946) and by Marshak and Bethe, Phys. Rev. **72**, 506 (1947).

[20] Bjorklund, Crandall, Moyer, and York, Phys. Rev. **77**, 213 (1950); Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950).

[21] Rochester and Butler, Nature **160**, 855 (1947).

[22] Brown, Camerini, Fowler, Muirhead, Powell, and Ritson, Nature **163**, 47 (1949).

[23] For a detailed list of references of these discoveries see, e.g., Franzinetti and Morpurgo, Nuovo cimento Supplemento **6**, No. 2, 469 (1957).

behavior was resolved by Pais [24] who suggested the associated production hypothesis in which these new particles are assumed to be produced strongly only in pairs. Thus, the strong interactions deduced from the production processes are not in conflict with the weak decay processes in which these new particles disappear singly.

Shortly after Pais' suggestion, Gell-Mann [25] and, independently, Nishijima and Nakano [26] proposed in 1953 a simple rule, called the conservation of strangeness, which implies as one of its consequences the pair-production hypothesis. In this rule one assigns to every particle a strangeness quantum number 0, or ± 1, or ± 2. All interactions that conserve the algebraic sum of the strangeness quantum numbers are assumed to be strong. Otherwise, they are assumed to be weak. The nucleons, antinucleons, and pions all have zero strangeness quantum number. These new particles all have nonzero strangeness numbers and are therefore called strange particles. Thus, in collisions between nucleons and pions the conservation law of strangeness requires that the strange particles can be abundantly produced in pairs but not singly. For example, the strangeness numbers for Λ° and K° are assumed to be -1 and $+1$ respectively. The observed production reactions such as

$$\pi^- + p \rightarrow \Lambda^\circ + K^\circ$$

conserve the strangeness and are, therefore, fast reactions. The decay process, such as

$$\Lambda^\circ \rightarrow p + \pi^-,$$

does not conserve the strangeness and is, therefore, a slow process.

[24] A. Pais, Phys. Rev. **86**, 633 (1952).
[25] M. Gell-Mann, Phys. Rev. **93**, 933 (1953).
[26] Nakano and Nishijima, Progr. Theoret. Phys. (Kyoto) **10**, 581 (1953).

Furthermore, the conservation of strangeness rule can be incorporated as a part of a generalized scheme of charge independence, or isotopic spin symmetry. In a way similar to the prediction of π° discussed in Section *2* it was expected from this generalized isotopic spin symmetry that there must exist in addition a Σ° which has about the same mass as that of $\Sigma^\pm$ and a Ξ° which has about the same mass as that of Ξ^-.

5. Experimental Developments

On the experimental side since 1953 the study of particle physics has been greatly helped by the construction of many high-energy accelerators which make possible the artificial productions of these new particles. The invention of the bubble chamber [27] added a new and powerful detection technique to the already existing methods of using cloud chambers, counters, and photographic emulsions.

These new experimental developments contributed much to the detailed verification of the Gell-Mann—Nishijima scheme including the observations of the Σ° particle [23] and the Ξ° particle.[28]

Another important contribution of the high-energy machines to particle physics is the detection of antiheavy particles. At present, $\bar{p}$, $\bar{n}$, and $\bar{\Lambda}$ have all been observed.[9, 29] Fig. 3 gives the present list of elementary particles.[30] Some of the important properties of these

[27] D. A. Glaser, Phys. Rev. **87**, 665 (1952).
[28] Alvarez, Eberhard, Good, Grazino, Ticko, and Wojcicki, Phys. Rev. Letters **2**, 215 (1959).
[29] The $\bar{\Lambda}$ particle was first observed by Prowse and Baldo Ceolin, Nuovo cimento **10**, 635 (1958).
[30] In Fig. 3 (and also in Table 2) it is shown that, unlike the neutral π meson, the K° particle is different from its antiparticle $\bar{K}^\circ$. This was first predicted by Gell-Mann and Pais, Phys. Rev. **97**, 1387 (1955). Furthermore, it can be shown that these two neutral particles, K° and $\bar{K}^\circ$, possess some extremely interesting properties. For example, a K° particle once produced may later change automatically into its antiparticle $\bar{K}^\circ$. Such unusual conversions have recently been observed by Muller, Birge, Fowler, Good, Hirsch, Matsen, Oswald, Powell, White, and Piccioni, Phys. Rev. Letters **4**, 418 (1960).

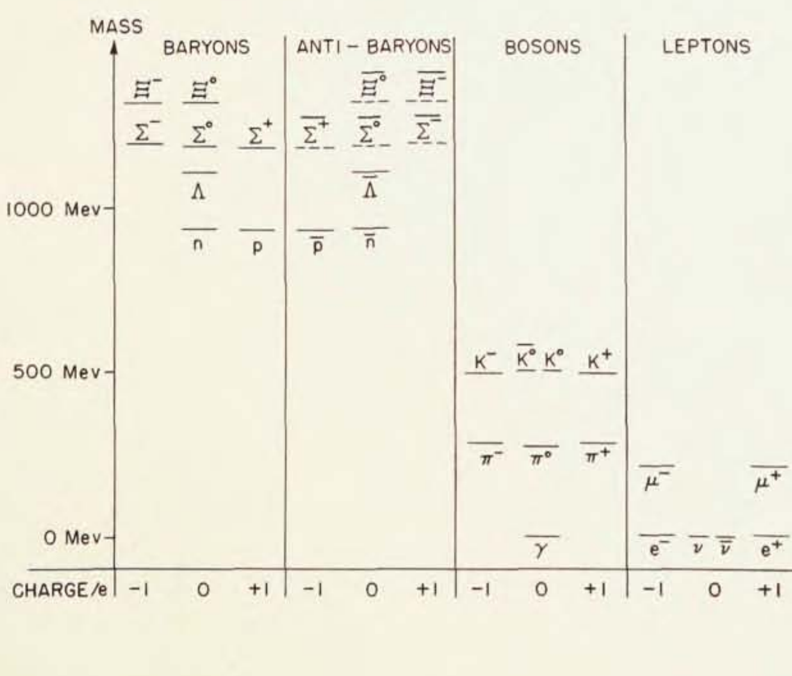

Fig. 3. A list of the elementary particles known at the present time. (The mass scale is only approximately accurate.)

particles are summarized in Table 2. The interactions between these particles can be classified into the four groups listed in Table 1.

6. *Right-Left Asymmetry (Nonconservation of Parity)*

THE study of the decays of these strange particles uncovered still another paradoxical behavior, called the $\theta-\tau$ puzzle, which led in 1956 to the discovery of a fundamental asymmetry between right and left among weak interactions.

The concept that nature (i.e., physical law) is symmetrical with respect to right and left dates back to the early history of physics. Of course, in our daily life left and right are quite distinct from each other. Our hearts, for example, are usually on our left sides. However, such asymmetry in daily life is attributed to either the accidental asymmetry of our environment or the initial condition in organic life.

The principle of the symmetry between right and left has been found to be true in classical physics, in atomic physics, and in nuclear physics. The application of quantum mechanics to this symmetry principle gives as a consequence the law of conservation of parity which states that to every (pure) state of a particle or a complex of particles one can assign a parity quantum number $+1$ or -1 and this parity number is conserved in all reactions.

In 1953, Dalitz[31] pointed out that by analyzing the angular distribution of the three pions in $\tau^{\pm}$ decay [Eq. (1)] it is possible to determine the parity of the $\tau^{\pm}$ particle. Between 1954 and 1956 as experimental data accumulated the parity of the final 3π state in $\tau^{\pm}$ decay was determined quite accurately to be -1. On the other hand, the final 2π state in $\theta^{\pm}$ decay [Eq. (5)] can be easily shown to be of parity $+1$. Since parity was always assumed to be conserved it was then concluded that $\theta^{\pm}$ and $\tau^{\pm}$ must be two different particles

[31] R. H. Dalitz, Phil. Mag. **44**, 1068 (1953); Phys. Rev. **94**, 1046 (1954). E. Fabri, Nuovo cimento **11**, 479 (1954).

Particle	*Lifetime (sec)*	*Mass (Mev)*	*Spin*	*Strangeness*	*Isotopic Spin (I)*
Ξ^-	$(4.6<\tau<200)\times10^{-10}$	1321 ± 3.5	Not known	-2	$\frac{1}{2}$
Ξ^0	$\approx1.5\times10^{-10}$	1311 ± 8			
Σ^-	$(1.58\pm0.17)\times10^{-10}$	1196.5 ± 0.4	$\frac{1}{2}$	-1	1
Σ^0	$(<1)\times10^{-11}$	$1190.3_{-2}^{+1.2}$	$\frac{1}{2}$	-1	
Σ^+	$(0.78\pm0.074)\times10^{-10}$	1189.5 ± 0.3	$\frac{1}{2}$	-1	
Λ^0	$(2.77\pm0.15)\times10^{-10}$	1115.2 ± 0.13	$\frac{1}{2}$	-1	0
n	$(1.04\pm0.13)\times10^{3}$	939.506 ± 0.01	$\frac{1}{2}$	0	$\frac{1}{2}$
p	Stable	938.213 ± 0.01	$\frac{1}{2}$	0	
K^+	$(1.224\pm0.13)\times10^{-8}$	494.0 ± 0.2	0	$+1$	$\frac{1}{2}$
K^0	K_1^0: $(0.95\pm0.08)\times10^{-10}$	497.7 ± 0.8	0	$+1$	
$\bar{K}^0$	K_2^0: $(0.81_{-0.24}^{+0.32})\times10^{-7}$	497.7 ± 0.8	0	-1	$\frac{1}{2}$
K^-	$(1.224\pm0.13)\times10^{-8}$	494.0 ± 0.2	0	-1	
$\pi^{\pm}$	$(2.56\pm0.05)\times10^{-8}$	139.63 ± 0.06	0	0	1
π^0	$<0.4\times10^{-15}$	135.04 ± 0.16	0	0	
$\mu^{\pm}$	$(2.22\pm0.2)\times10^{-6}$	105.70 ± 0.06	$\frac{1}{2}$		
$e^{\pm}$	Stable	0.510976	$\frac{1}{2}$		
ν, $\bar{\nu}$	Stable	0	$\frac{1}{2}$		
γ	Stable	0	1		

Table 2. A table of the elementary particles. Notice that all of the particles, with the exception of the leptons and the photon, are divided into various isotopic groups of different isotopic spins I. These groups are separated from one another by horizontal lines. Each of the groups has $(2I+1)$ members which have different charges but the same spin, the same strangeness, and approximately equal masses.

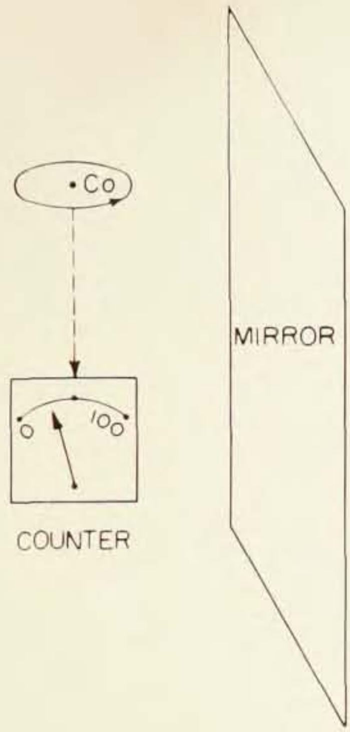

Fig. 4. A schematic diagram illustrating the test of right-left symmetry in the Co^{60} beta decay. If the Co^{60} decay were symmetrical with respect to right and left, the two arrangements shown, being mirror images of each other, must give identical numbers of counts. The experiment by Wu, et al.,[32] showed that the numbers of counts received by these two counters were completely different. Thus, it was established that the right-left symmetry is not preserved in beta decay.

with the parity of $\theta^{\pm}$ being $+1$ and that of $\tau^{\pm}$ being -1. Meanwhile, however, accurate measurements on $\theta^{\pm}$ and $\tau^{\pm}$ decays showed the surprising result that both the lifetime and the mass of these supposedly different particles seemed to be exactly the same.

This paradoxical property (called θ–τ puzzle) led to the questioning of parity conservation in weak interactions.[32] Since the law of conservation of parity has been applied in the past with great success to all branches of physics including weak interactions (e.g., Fermi's theory of beta decay), it appeared at first that such questioning might be in conflict with other already existing experiments. A detailed investigation of the foundation of parity conservation was made in 1956. It showed that while there are numerous experiments supporting the symmetry between right and left for both the strong and the electromagnetic interactions there was no evidence of such symmetry for the weak interactions. All the experiments on weak interactions that were performed up to that time could be explained by theories that do not assume parity conservation. A series of experiments that could test more directly (as compared to the θ–τ puzzle) the question of parity conservation was then proposed.

The first experiment which showed conclusively that weak interaction does not possess the right-left symmetry property was made by Wu, Ambler, Hayward, Hoppes, and Hudson[33] near the end of 1956 by investigating the angular distribution of e^- from the beta decay of the polarized Co^{60} nucleus. The principle of this Co experiment is very simple and is illustrated in Fig. 4. Shortly after the first observation of parity nonconservation in beta decay, the same conclusion was confirmed in π decay and in μ decay by Garwin, Lederman, and Weinrich[34] and by Friedman and Telegdi.[35] At present parity nonconservation has also been observed in Λ^0 decay, in Σ^+ decay, and in $K_{\mu 2}^{\pm}$ decay.

The θ and τ decays are now regarded simply as two decay modes of a single particle, the K meson.

7. *Two-Component Theory of the Neutrino*

THE discovery of the nonconservation of parity makes possible a very simple theory of the neutrino[36] (called the two-component theory) in which the spin of a neutrino (i.e., the neutral particle emitted in β^+ decay) is always antiparallel to its momentum while the spin of an antineutrino (i.e., the neutral particle emitted in a β^- decay) is always parallel to its momentum.[37] In this theory, the neutrino appears to be a perfect left-hand screw and the antineutrino appears to be a perfect right-hand screw. For example, in Co^{60} decays only antineutrinos can be emitted. Therefore, in this two-component theory, Co^{60} decay dis-

[32] Lee and Yang, Phys. Rev. **104**, 254 (1956).
[33] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).

[34] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).
[35] Friedman and Telegdi, Phys. Rev. **105**, 1681 (1957).
[36] The possibility of a two-component relativistic theory of a spin ½ particle was first discussed by H. Weyl, Z. Physik **56**, 330 (1929). However, in such a theory parity is not manifestly conserved; therefore it was always rejected before the discovery of right-left asymmetry. (Cf. W. Pauli, *Handbuch der Physik*, Verlag Julius Springer, Berlin, 1933, Vol. 24, pp. 226–7.) The possible use of this two-component theory for expressing the nonconservation property of parity in neutrino processes was independently considered by Lee and Yang, Phys. Rev. **105**, 1671 (1957); A. Salam, Nuovo cimento **5**, 299 (1957); and L. Landau, Nuclear Phys. **3**, 127 (1957).
[37] The first conclusive proof that neutrino behaves like a *left*-hand screw (and not like a right-hand screw) was given by Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

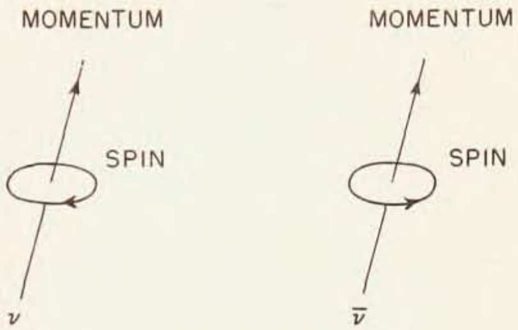

Fig. 5. Kinematic relationships between the momenta and the spins of ν and $\bar{\nu}$ in a two-component theory. (In the old four-component theory the spin of the neutrino—and, similarly, that of the antineutrino—can be either parallel or antiparallel to its momentum.)

tinguishes automatically left from right. Further experiments on weak interactions seem to confirm the various detailed predictions of this two-component theory of the neutrino. The kinematics of this two-component theory of the neutrino is illustrated in Fig. 5.

8. Particle-Antiparticle Asymmetry

ANOTHER consequence of the discovery of right-left asymmetry is the conclusion that physical laws do not exhibit complete symmetry with respect to particles and antiparticles. This can be most easily seen by using the two-component theory of the neutrino in which the different screw sense of the neutrino and the antineutrino gives a clear demonstration of the asymmetry between particles and antiparticles. (The conclusion of an asymmetry between particles and antiparticles was first reached without the assumption of the two-component theory.[38])

It was, however, suggested that in spite of the breakdown of these symmetries the physical laws may still be symmetrical with respect to the product of a mirror reflection times an exchange between particles and antiparticles.[39] Such a symmetry would predict, for example, that the angular distribution of beta particles in the decays of polarized Co^{60} nuclei must be identical with the mirror reflection of the corresponding distribution in the decays of polarized anti-Co^{60} nuclei.

9. Universal Character of Weak Interactions

AS early as 1948 it was already suggested by several different groups of physicists[40] that the different weak processes such as β decay, μ decay and μ capture may be characterized by a single universal form of interaction. However, at that time because of the lack of detailed and accurate knowledge of these reactions it was difficult to subject this attractive idea to quantitative tests.

Since the establishment of nonconservation of parity, the discovery that in a decay process the neutrino carries away not only energy and momentum but also a definite (longitudinal) angular momentum gives a new possibility of investigating the dynamics of weak interactions by measuring angular momenta. These new measurements on angular momenta together with other already existing experiments lead now to a much simpler phenomenological description of the weak interactions.[41] Indeed, it was found[42] quantitatively that a certain coupling constant in the beta decay appears to be *exactly* the same as that which occurs in the μ decay in spite of the difference that nucleons have strong interactions but $\mu^{\pm}$ and $e^{\pm}$ have only electromagnetic and weak interactions. Such identity and other universal characters of these interactions may lead to a deeper and unifying principle underlying all different weak reactions.

10. Remarks

THE history of particle physics has been full of surprising discoveries which, in turn, lead to new exciting developments. In its evolution we have witnessed many examples that showed both the wisdom and the follies of physicists. It seems more than likely that our present long list of the so-called "elementary particles" is but of a transitory character and that our basic theories and principles may undergo further major changes. Indeed, it has long ago been said:[43]

> The tao that can be stated
> cannot be the Absolute Tao.
> The name that can be given
> cannot be the Permanent Name.

[38] Lee, Oehme, and Yang, Phys. Rev. **106**, 340 (1957).

[39] C. N. Yang, International Congress on Theoretical Physics, Seattle, 1956, Revs. Modern Phys. **29**, 231 (1957); Lee and Yang, Phys. Rev. **105**, 1671 (1957). This possibility was also considered by L. Landau, Nuclear Phys. **3**, 127 (1957), and by E. P. Wigner, Revs. Modern Phys. **29**, 255 (1957). See also footnote (9) of an earlier paper by Wick, Wightman, and Wigner, Phys. Rev. **88**, 101 (1952).

[40] G. Puppi, Nuovo cimento **5**, 587 (1948); O. Klein, Nature **161**, 897 (1948); Lee, Rosenbluth, and Yang, Phys. Rev. **75**, 905 (1949); Tiomno and Wheeler, Revs. Modern Phys. **21**, 144 (1949). See also the discussions by Serber and Oppenheimer in the *Proceedings* of Solvay Congress, Brussels (1948).

[41] More recent analysis on Universal Fermi Interactions were made by Feynman and Gell-Mann, Phys. Rev. **109**, 193 (1958); Sudarshan and Marshak, Phys. Rev. **109**, 1860 (1958); J. J. Sakurai, Nuovo cimento **7**, 649 (1958).

[42] See, especially, Feynman and Gell-Mann, Phys. Rev. **109**, 193 (1958).

[43] Laotse, Tao Tê Chin, p. 1 (about 550 B.C.).