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Space Inversion, Time Reversal and Particle-Antiparticle Conjugation

As we expand our observation, we extend our concepts. Thus the simple symmetries that once seemed self-evident are no longer taken for granted. Out of studies of different kinds of interactions we are learning that symmetry in nature is some complex mixture of changing plus into minus, running time backward and turning things inside out.

by T. D. Lee

THE MORE WE LEARN about symmetry operations—space inversion, time reversal and particle-antiparticle conjugation—the less we seem to understand them. At present, although still very little is known about the true nature of these discrete symmetries, we have, unfortunately, already reached the unhappy state of having lost most of our previous understanding. Let us, therefore, review the gradual evolution of our past concepts of these discrete symmetry operations.

P and T in classical physics

In classical mechanics, each particle is described by its space-time coördinates **r** and t, and every particle is assumed to be different from every other particle. The space-inversion (P) and time-reversal (T) invariances in classical mechanics simply mean that the dynamical laws remain unchanged under

$$\begin{aligned} &\mathrm{P:}\quad \mathbf{r}\to-\mathbf{r},\quad t\to t\\ &\mathrm{T:}\quad \mathbf{r}\to\mathbf{r},\quad t\to -t \end{aligned}\qquad (1)$$

Suppose we are given a record, say a movie record, of the motion of a system of particles. If P invariance holds, then by examining only the movie it is not possible to decide with certainty whether the movie represents the true sequence or whether it represents the mirror image of the true sequence. Similarly, the T invariance implies that if any movie of the motion of a system of particles is run backwards, then the time-reversed sequence also represents a possible solution of the dynamical equations.

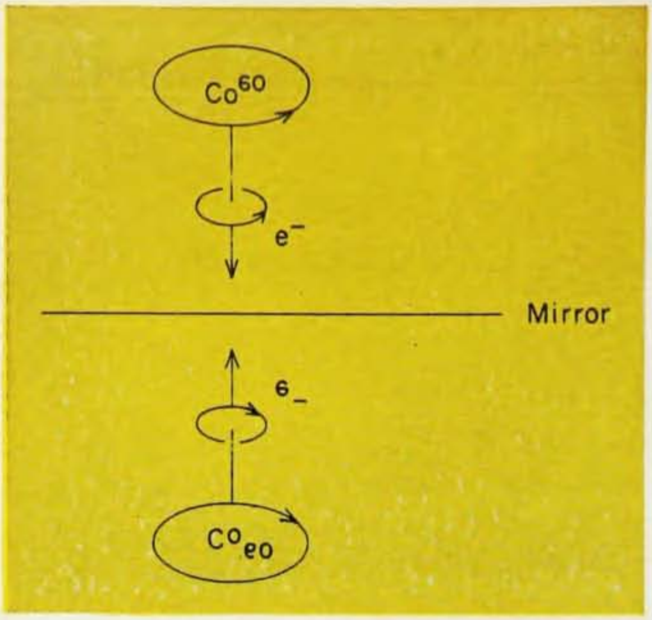
For a macroscopic system with a large number of particles, although the time-reversed sequence is always a possible one if T invariance holds, it is, in general, an improbable one. Thus although we cannot know for sure whether such a movie is being shown in its time-reversed order or not, we may try to guess. If the number of particles is sufficiently large, our guess will *almost always* be right. It is only in this statistical sense that we can differentiate for a macroscopic system any time-ordered sequence of events from its time-reversed sequence, and, thereby, determine the direction of our macroscopic time.

If the system contains only a very small number of particles, it is not possible, even in a statistical sense, to differentiate a time-ordered sequence from its time-reversed sequence (provided that T invariance holds). As we shall see, this last statement has to be *modified* in quantum mechanics.

Nonconservation of parity

The symmetry operations of P and T in quantum mechanics were first studied and analysed by Eugene Wigner of Princeton.[1] Both operations were

In 1957 the author shared the Nobel Prize in physics with C. N. Yang for the discovery of nonconservation of parity in weak interactions. This article is an adaptation of a lecture delivered on 15 Nov. at the Fourth Annual Science Conference of the Belfer Graduate School of Science, Yeshiva University, New York. Professor Lee's lecture will appear in the proceedings of the conference later this year.



PARITY NONCONSERVATION. Cobalt-60 decays into nickel-60 plus an electron and an antineutrino. When the original nucleus is polarized, the emitted electron is found to have a left-handed spin, and its preferred direction of motion is opposite to the polarization direction of the original cobalt nucleus. The mirror image (without charge conjugation) is not realized in nature; therefore right-left symmetry (that is, what we call "space-inversion symmetry") is violated. —FIG. 1

successfully applied to the atomic system, which involves only the electromagnetic interaction; later, these symmetry operations were extended to include other phenomena in which not only the electromagnetic interaction but also the strong and the weak interactions participate. It is through these applications in particle physics that the validity of these discrete symmetries was questioned,[2,3] and the questioning led to the discovery of the nonconservation of parity.

The first experiment[4] on parity nonconservation (that is, space-inversion asymmetry) was made on beta decay by Professor C. S. Wu of Columbia, in collaboration with Ernest Ambler, Raymond W. Hayward, Dale D. Hoppes and R. P. Hudson of the National Bureau of Standards (see figure 1). From the same experiment it was deduced that charge-conjugation symmetry is also violated. Immediately afterward the same noninvariance properties were established for pi and mu decay.[5]

In quantum mechanics, the space-inversion operator P is a unitary operator and its eigenvalue is the parity.

If space-inversion symmetry holds, the parity must be conserved. Under P, the state of a particle with momentum **k** and helicity λ (defined to be its spin component along the direction of **k** and in units of $\hbar$) transforms to a state of the *same* particle but with momentum $-\mathbf{k}$ and helicity $-\lambda$. The operator P satisfies

$$P|\mathbf{k},\lambda\rangle = \eta_P|-\mathbf{k},-\lambda\rangle \qquad (2)$$

Where η_P is a phase factor; P also satisfies similar equations for the multiparticle states. Here, the identity of a particle is defined through *all* of its interactions which include, in particular, its mass, charge and spin.

The suggestion that our known interactions are not strictly invariant under space-inversion symmetry was, at the beginning, based on the theta-tau puzzle[6]

$$K^+ = \begin{cases} \theta^+ \to \pi^+ + \pi^0 \\ \tau^+ \to \pi^+ + \pi^+ + \pi^- \end{cases} \qquad (3)$$

The two particles θ^+ and τ^+ were found to be of the same mass and lifetime, suggesting that they are two decay modes of the same particle, the K^+ meson. However, the parity of the pion had been previously determined through both its strong interaction and its electromagnetic interaction to be -1.

$$P_{st}(\pi) = P_\gamma(\pi) = -1 \qquad (4)$$

The subscripts st and γ indicate that the determinations are through H_{st}, the strong interaction and H_γ, the electromagnetic interaction, respectively. Based on the Dalitz analysis, the three pions in the tau decay mode are found to be in a zero-spin state. The same spin value can also be determined through the various production processes for θ^+ and τ^+. The parity that is determined by strong and electromagnetic interactions must, therefore, be different for the two final states, $+1$ for the two-pion state and -1 for the three-pion state; consequently we must have parity nonconservation if the θ^+ particle is identical with τ^+. There now exist numerous experiments that establish that both H_{st} and H_γ are invariant under the same space-inversion operation $P_{st}=P_\gamma$, but H_{wk}, the weak interaction, is not. Thus, it is *not possible* to construct a space inversion operator P that commutes with the *total* interaction Hamiltonian H.

At present, the best evidence for H_{st} and H_γ being invariant under $P_{st}=P_\gamma$ is from experiments in nuclear physics. These experiments[6] establish that for a nuclear level the magnitude of the parity-nonconserving amplitudes is smaller than that of the corresponding parity-conserving amplitudes by a factor of about 10^6.

Indistinguishable particles

If the identity of a particle could be taken for granted it would be possible to define P, the pure space inversion, and T, the pure time reversal, unambiguously. However, the distinguishability between different particles depends on all of their interactions, and degeneracies often arise if some of the interactions are absent. If the P and T symmetries are not valid for all interactions, then their definitions can only be given when some of the interactions are absent; consequently, such definitions are interaction dependent.

If strong and electromagnetic interactions could be switched off, it would not be possible to discover any parity nonconservation from the weak interaction alone. In fact under these hypothetical conditions many otherwise different particles would become degenerate and indistinguishable. As a result of such indistinguishability between particles, one can find a solution for the space-inversion operator under which the presently accepted form of the weak interaction is invariant.

For example, if $H_{st}=H_{\gamma}=0$, we might infer from reaction 3 that parity is conserved and the parity of the pion is +1. Indeed all known weak interactions are consistent with the assumption that H_{wk} is invariant under a different space-inversion symmetry operation called P_{wk}.[7] Inasmuch as we regard H_{wk} as violating conservation of parity where parity$=P_{st}=P_{\gamma}$, we could also regard H_{wk} as parity conserving where parity is P_{wk} and attribute the observed nonconservation of parity to violation of P_{wk} invariance by strong and electromagnetic interactions.

Time-reversal invariance

The question whether our known interactions are or are not invariant under time reversal was raised[3] when the possibility of parity nonconservation was being studied. After the discovery that parity is *not* conserved, several experiments were performed to test time-reversal invariance in both strong[8] and weak interactions,[9,10] and these experimental results were all consistent with time-reversal invariance. Recently, however, there has appeared an indirect evidence from the K_2^0 decay that time-reversal symmetry is, like space-inversion symmetry, only approximately valid for the known interactions.

Before discussing this indirect evidence, let us first review the meaning of time-reversal invariance. In quantum mechanics, the time-reversal operator T is an antiunitary operator.

If the theory is invariant under time reversal, then from a solution $\Psi(t)$ of the Schroedinger equation

$$H\Psi(t)=-\frac{\hbar}{i}\frac{d\Psi(t)}{dt} \qquad (5)$$

we can generate a different solution $\Psi_T(t)$ of the same equation. The Ψ_T is related to Ψ by

$$\Psi_T(t)=T\Psi(-t)=U_T\Psi^*(-t) \qquad (6)$$

U_T is a unitary operator in Hilbert space and the asterisk denotes complex conjugation.

An important consequence of time-reversal invariance is the *reciprocity relations* between the *transition probabilities:* the magnitude of the S-matrix element for any transition $a\rightarrow b$ is equal to that of $b_T\rightarrow a_T$

$$|\langle b|S|a\rangle|=|\langle b_T|S|a_T\rangle| \qquad (7)$$

Here $|a_T\rangle=T|a\rangle$ and $|b_T\rangle=T|b\rangle$. Direct tests of such reciprocity relations have been made for several strong reactions,[8] and these tests give good evidence that the strong interaction is invariant under a (certain) time-reversal operation called T_{st}. The upper limit on the ratio of the magnitude of the time-reversal-noninvariant amplitude to that of the time-reversal-invariant amplitude is about 2% in the proton-triton-deuterium reactions $p+t\rightleftarrows d+d$.

As an illustration of how time-reversal invariance can be tested in the weak interaction, we may consider the example of Λ^0 decay

$$\Lambda^0\rightarrow N+\pi \qquad (8)$$

The final $N+\pi$ system can be in either the $s_{1/2}$ or the $p_{1/2}$ spin-orbital state with relative amplitudes A_s and A_p, respectively; the total isospin of the final state is, predominantly, $I=1/2$. If the weak interaction satisfies the same T_{st} invariance, then the relative phase ϕ, defined by

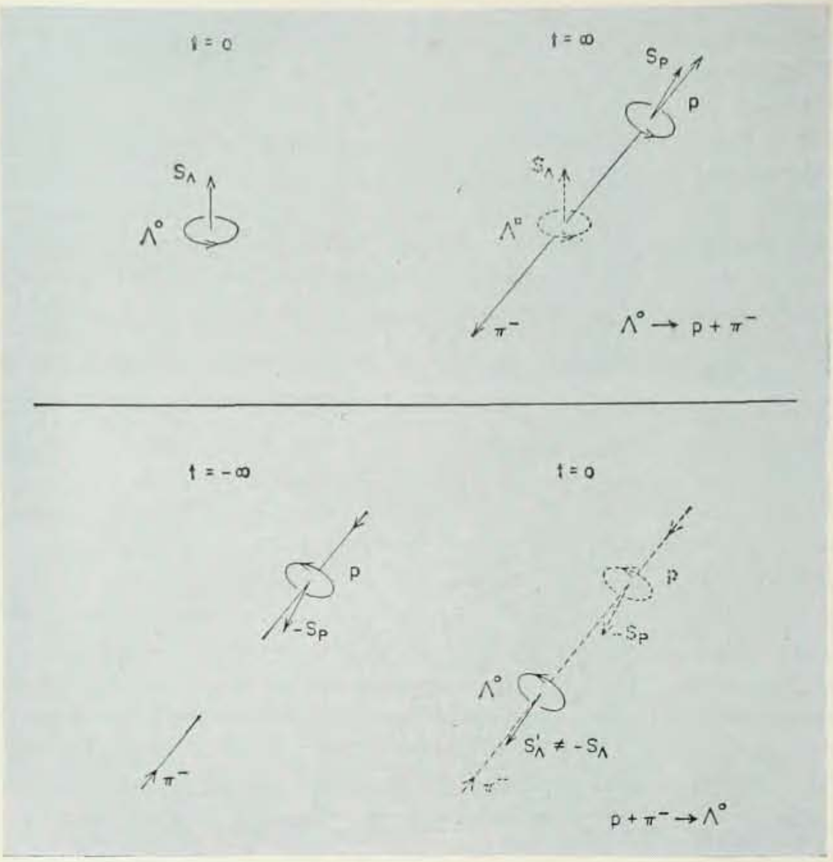
$$\frac{A_s}{A_p}=\left|\frac{A_s}{A_p}\right|e^{i\phi} \qquad (9)$$

is given by

$$\phi=(\delta_s-\delta_p)\text{ or }(\delta_s-\delta_p)+\pi \qquad (10)$$

where δ_s and δ_p are, respectively, the $s_{1/2}$ and $p_{1/2}$ phase shifts of the strongly interacting $N+\pi$ system in the $I=1/2$ state. The experimental results are $\delta_s-\delta_p\approx+7$ deg and[9] $\phi_{exp}=15\pm20$ deg which are consistent with H_{wk} being invariant under the same time-reversal invariance as the strong interaction. The same conclusion is also reached by a similar, but more accurate, experiment on beta decay.[10]

The relative phase θ between the Gamow-Teller coupling constant g_A and the Fermi constant g_V has been measured by M. T. Burgy and his collaborators.[10] If the weak interaction satisfies time-reversal symmetry, $\theta=0$ or 180 deg. The experimental value is 180 ± 8 deg. [In some theoretical models, however, the weak-interaction strangeness-conserving current J_μ of the nonleptons is assumed to satisfy



TIME REVERSAL. In the decay of a neutral lambda into a proton and a negative pion, if the initial lambda is assumed to be completely polarized along a unit vector s_Λ, then the final proton, at any given momentum k in the rest system of the original lambda, must be completely polarized, say, along s_p. In the reversed reaction when a proton combines with a pion to form a neutral lambda, the initial proton has reversed momentum −k and is completely polarized along the reversed direction $-s_p$; the final lambda is also completely polarized, but its polarization direction $s_{\Lambda'}$ is, in general, different from $-s_\Lambda$, even if time-reversal invariance holds. In these graphs all spin directions are drawn *in accordance* with time-reversal *invariance*. In quantum mechanics even a microscopic system is described by an infinite number of time-dependent variables; thus the time-reversed solution for any scattering problem is, in general, an improbable one (assuming that time reversal is an exact symmetry). —FIG. 2

charge symmetry: $J_\mu^* = -\exp(i\pi I_y)\, J_\mu \exp(-i\pi I_y)$ where I_y is the y component of the isospin operator. Under this assumption, independently of time-reversal invariance, g_A/g_V must be real.]

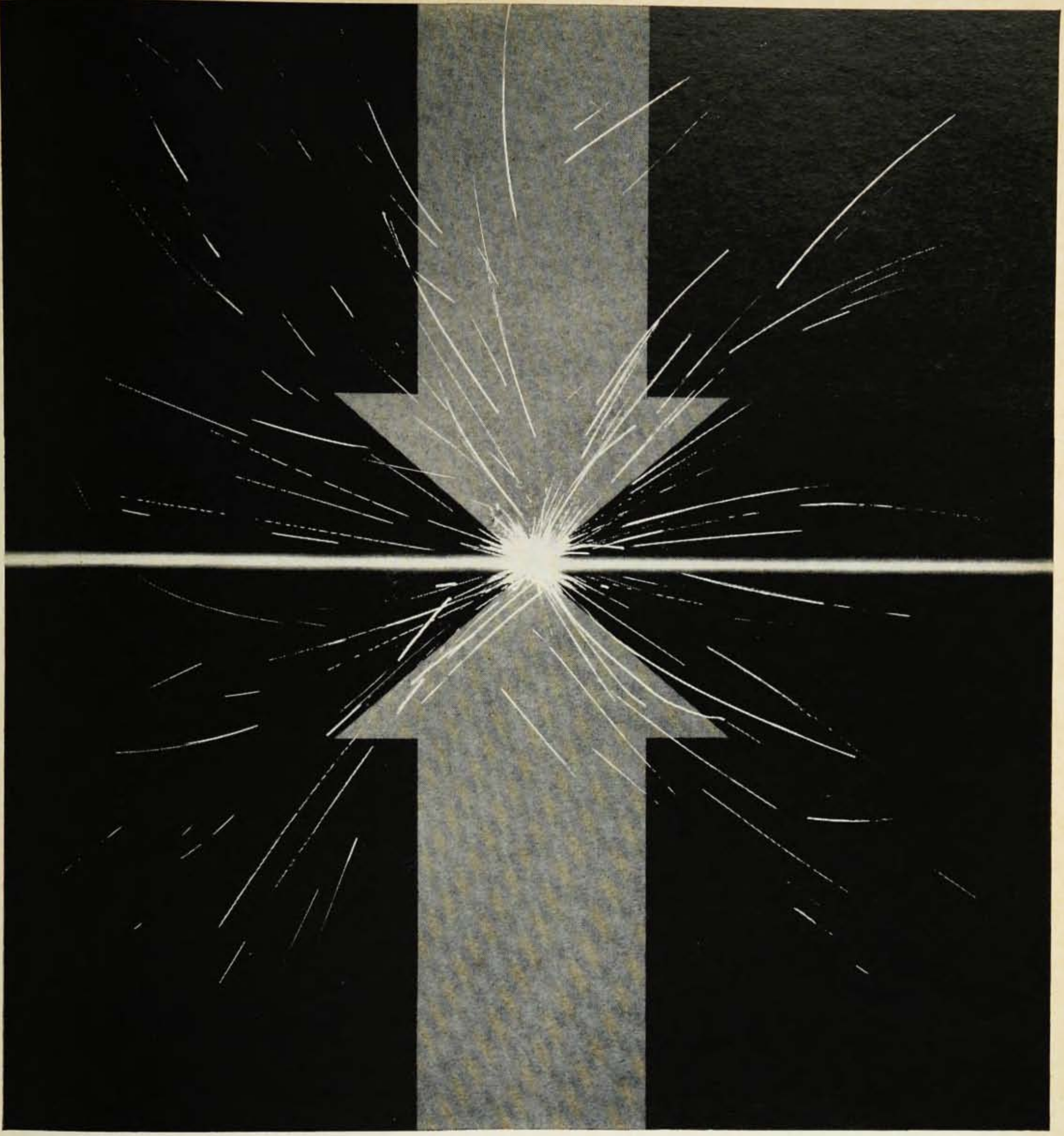
We note that in the Λ^0 decay, if the initial Λ^0 is completely polarized, say, along the unit vector $\mathbf{s}_\Lambda$ in its rest system, then at any given momentum $\mathbf{k}$ the final nucleon must also be completely polarized along a direction $\mathbf{s}_N$ which is uniquely determined by $\mathbf{s}_\Lambda$, $\mathbf{k}$ and the amplitudes A_s and A_p. Let us now consider the reversed reaction.

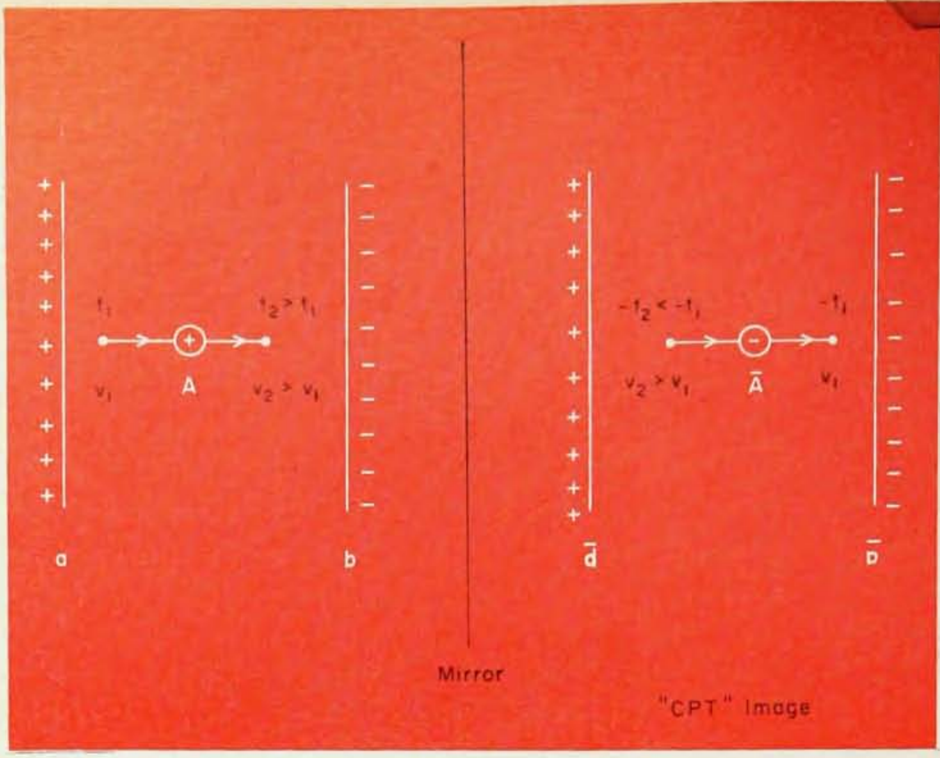
$$N + \pi \to \Lambda^0 \tag{11}$$

in which the initial nucleon is polarized along $-\mathbf{s}_N$ and its momentum is $-\mathbf{k}$. If the system obeyed *classical* mechanics, time-reversal invariance would imply that the final Λ^0 in the reversed reaction must be completely polarized along the reversed direction $-\mathbf{s}_\Lambda$. For the quantum-mechanical system, although the final Λ^0 in the reversed reaction does remain completely polarized, its direction is, in general, *different* from $-\mathbf{s}_\Lambda$ even if time-reversal invariance holds. This elementary property is demonstrated in figure 2.

To produce the final Λ^0 with its polarization along $-\mathbf{s}_\Lambda$, in case time-reversal invariance holds, we must not use just the $N+\pi$ state with the reversed spin and momentum, but we should start with an initially *coherent* mixture of the appropriate $s_{1/2}$ and $p_{1/2}$ incoming wave of $N+\pi$. Mathematically, such an initial state can be easily obtained by applying the antiunitary operator T onto the final state $\Psi(t=+\infty)$ in the decay $\Lambda^0 \to N+\pi$. Physically, however, it seems virtually impossible ever to construct the desired coherent time reversed state $T\Psi(t=+\infty)$ for a direct testing of the symmetry (or violation-of-symmetry) of the time-reversal operation. Here lies an important difference between the time-reversal operation in classical mechanics and that in quantum mechanics. In both cases time-reversal invariance means that the time-reversed solutions are always dynamically possible solutions. In classical mechanics such a time-reversed solution becomes an improbable one only for a macrosopic system. In quantum mechanics even a microscopic system is described by an infinite number of variables (that is, by a continuous function of space-time); thus the time-reversed solution for any scattering problem is, in general, an improbable one.

For all practical purposes the only *direct* and tangible test of time-reversal invariance seems to be the *reciprocity relations between various differential cross sections;* that is, equation 7 restricted to those states $|a\rangle$ and $|b\rangle$ that represent asymptotically the appropriate initial and final states in which every particle has a definite, but arbitrary, set of





CPT SYMMETRY. The figure shows the motion of a positively charged particle A in an electric field and its "CPT" image. v_1 and v_2 are, respectively, the initial (at time t_1) and the final (at time t_2) velocities of A. CPT invariance requires for the existence of any particle an antiparticle of the same mass, opposite charge, opposite baryon number and opposite lepton number. It is important to note that the antiparticle state of A is *different* from the usual charge-conjugation state of A because charge conjugation is not an exact symmetry. —FIG. 3

spin and momentum. In this connection it is relevant to mention that all the presently known tests of time-reversal symmetry, such as equation 10, can be derived directly by using the reciprocity relations between the appropriate differential cross sections.[11] The violation of time-reversal invariance means, simply, that such reciprocity relations are not valid.

CPT invariance and particle-antiparticle relations

To understand the recent indirect evidence of time-reversal noninvariance, it is necessary to review the CPT theorem[12] and the experimental evidence for its validity.

In the framework of a local field theory, it can be shown that if a theory is invariant under the continuous group of Lorentz transformations without any discrete element (such as space inversion and time reversal), the theory is automatically invariant under a discrete symmetry operation, called "CPT." If CPT invariance holds for the total Hamiltonian H, the matrix element of H between any two states $|A\rangle$ and $|B\rangle$ is related to that between their CPT-conjugate states $|\bar{A}\rangle$ and $|\bar{B}\rangle$

$$\langle B|H|A\rangle = \langle \bar{B}|H|\bar{A}\rangle^* \qquad (12)$$

where

$$|\bar{A}\rangle = \mathrm{CPT}|A\rangle$$
$$|\bar{B}\rangle = \mathrm{CPT}|B\rangle \qquad (13)$$

From CPT invariance it follows that if A is a stable particle, then its CPT conjugate $\bar{A}$ is also a stable particle with exactly the same mass. This can be easily proved by setting A=B in equation 12.

The CPT operator is an antiunitary operator; furthermore it relates the state A with a momentum **k** and a helicity λ to that of $\bar{A}$ with the same momentum **k** but the opposite helicity $-\lambda$. It can be easily shown that the electromagnetic fields **E** and **H** are invariant under CPT. Thus by comparing the energy spectrum in an external electromagnetic field, one can prove that A and $\bar{A}$ have opposite charges but otherwise the same electromagnetic form factors (see figure 3). Within the same framework of local field theory it can also be proved that the baryon numbers, or the lepton numbers, of the states A and $\bar{A}$ must be equal in magnitude but opposite in sign. (We assume implicitly that charge, baryon number and lepton number are all strictly conserved.) In the following the state $\bar{A}$ is called the "*antiparticle* state" of A.

Among the mass equalities between particles and antiparticles, the most accurate one is that between K^0 and $\bar{K}^0$

$$\langle K^0|H|K^0\rangle = \langle \bar{K}^0|H|\bar{K}^0\rangle \qquad (14)$$

From the experimental mass difference[13] Δm, between K_1^0 and K_2^0, it is found that equation 14 holds to the accuracy $|\Delta m/m_K| \approx 10^{-14}$. Thus, we should regard H_{st}, H_γ and the strangeness conserving nonleptonic part of H_{wk} to be invariant under CPT.

For the other parts of H_{wk}, evidences for CPT invariance come from the lifetime equalities between the states A and $\bar{A}$ which decay through the weak interaction. Such lifetime equalities hold, at least, to the lowest order in H_{wk} and can be easily proved by substituting H_{wk} for H in equation 12.

The present upper limits on such lifetime differences $\Delta\tau$ are given for muons,[14] pions[15] and K mesons[16] by

$$\left|\frac{\Delta\tau}{\tau}\right| < \begin{cases} 0.001 \text{ for } \mu^{\pm} \\ 0.08 \text{ for } \pi^{\pm} \\ 0.15 \text{ for } K^{\pm} \end{cases} \qquad (15)$$

Among these, the limit for the strangeness-nonconserving part of the weak interaction is rather inaccurate.

In the following we shall assume that CPT invariance holds; therefore for each particle state A there exists an antiparticle state $\bar{A}$ that has the same physical mass, the opposite charge, the opposite baryon number (or the opposite lepton number) and, if A is unstable, the same lifetime.

The C_{st} symmetry

As I remarked earlier, the strong interaction is found experimentally to be invariant under a space inversion P_{st} (to an accuracy of about 10^{-6}), a time reversal T_{st} (to an accuracy of a few percent) and the CPT operation (to an accuracy of about 10^{-14}). We can define an operator C_{st}

$$C_{st} \equiv (CPT)T_{st}^{-1}P_{st}^{-1} \qquad (16)$$

The strong interaction is expected to satisfy the C_{st} invariance to the same accuracy as the T_{st} invariance. Under C_{st} we must have at least approximately, $p \rightarrow \bar{p}$ and $n \rightarrow \bar{n}$, but with their momenta and helicities unchanged; consequently we also have $\pi^{+} \rightarrow \pi^{-}$, $\pi^{0} \rightarrow \pi^{0}$, etc., since the transformation properties of these mesons are determined by those of baryons and antibaryons.

The C_{st} symmetry has also been directly tested[17] by studying the equality between the energy distributions of π^{+} and π^{-} in the annihilation of protons by antiprotons

$$\bar{p} + p \rightarrow \pi^{+} + \pi^{-} + \cdots \qquad (17)$$

The result puts an upper limit on the C_{st}-noninvariant amplitude; it cannot be more than about 1% of the C_{st}-invariant amplitude. A similar upper limit of about 2% is obtained by studying the energy distributions of K^{+} and K^{-} in the same (proton-antiproton) annihilation experiment.

However, the weak interaction is known to violate C_{st} invariance. This can be inferred by using the properties that H_{wk} has large violations of P_{st}, but it is (at least to a good approximation) invariant under $C_{st}P_{st}T_{st} = CPT$ and T_{st}. The same conclusion can also be directly reached by considering K^{0} decays. Let K_1^0 be the neutral K meson with the short lifetime and K_2^0 that with the long lifetime. If C_{st} symmetry were conserved in their weak decays, K_1^0 and K_2^0 would be eigenstates of C_{st}, and their C_{st} eigenvalues must be of opposite signs. But in the decays $K_1^0 \rightarrow 2\pi$ and $K_2^0 \rightarrow 3\pi$ the final 2π and 3π are both in the $C_{st} = +1$ states. Thus C_{st} invariance must be violated, and the C_{st} symmetry is not exact. If $|p\rangle$ is the physical proton state, the state $CPT|p\rangle$ is the physical antiproton state, but the state $C_{st}|p\rangle$ is only *approximately* the antiproton state.

Two-pion decay of neutral K mesons

It was discovered last year by Christenson, Cronin, Fitch and Turlay[18] that the long-lived component K_2^0 of the neutral K meson has a two-pion decay mode

$$K_2^0 \rightarrow \pi^{+} + \pi^{-} \qquad (18)$$

Since both C_{st} and P_{st} (in the center-of-mass system) interchange π^{+} and π^{-}, the final (two-pion) system in this decay must be of $C_{st}P_{st} = +1$. On the other hand, the same long-lived component K_2^0 also decays into three pions

$$K_2^0 \rightarrow \pi^{+} + \pi^{-} + \pi^{0} \qquad (19)$$

All pions produced are observed to be predominantly in the *s* state. Thus, the final three-pion state is (or at least *predominantly* is) of $C_{st}P_{st} = -1$.

Now, K_2^0 is, by definition, a particle with a definite lifetime. That it can decay into different states with opposite $C_{st}P_{st}$ values shows conclusively that $C_{st}P_{st}$ is not conserved in the K_2^0 decays. The $C_{st}P_{st}$ violation is, therefore, established independently of the detailed theory of the K_1^0, K_2^0 system.

The observed $C_{st}P_{st}$ noninvariance implies that

$$[H, C_{st}P_{st}] \neq 0 \qquad (20)$$

where H represents the total interaction. In this decay, both the initial and the final states are eigenstates of $H_{st} + H_{\gamma}$ and the transition is due to H_{wk}. This means that the $C_{st}P_{st}$ violation could be due to the strong interaction[19] or to the electromagnetic interaction[20] or to the weak interaction,[21] or a combination of these interactions, or the presence of some new interactions, such as the superweak interaction,[22] which, however, I will not discuss further here. From this single experiment, it is not possible to decide which interaction is responsible for this violation.

If we *assume* the validity of CPT invariance in the K_2^0 decay, then it follows from equations 16 and 20 that T_{st} invariance is also violated; that is

$$T_{st}HT_{st}^{-1} \neq H \qquad (21)$$

The amount of the observed $C_{st}P_{st}$ violation in the K_2^0 decay is a small one, characterized by a parameter

$$|\varepsilon| = \left| \frac{\text{Rate}\ (K_2^0 \to \pi^+ + \pi^-)}{\text{Rate}\ (K_1^0 \to \pi^+ + \pi^-)} \right|^{1/2} \approx 2\times 10^{-3} \qquad (22)$$

K_1^0 is the short-lived component of the neutral K meson. The smallness of this parameter is, perhaps, one of the most puzzling features of this new discovery. To explain ε, we may invoke a small C_{st}-noninvariant term in H_{st}, or, if ε is a typical example of a $C_{st}P_{st}$-noninvariant amplitude, a small $C_{st}P_{st}$-noninvariant term in H_{wk}. There is no difficulty in doing either of these; one is only puzzled by the smallness of such violation and by the multitudes of different ways to construct such a violation.

An alternative, and perhaps more attractive, possibility is to assume that H_{st} and H_{wk} are invariant under $C_{st}P_{st}$, but H_γ has a large violation of C_{st} invariance. In this case all strong and weak processes can have a small C_{st}- and $C_{st}P_{st}$-noninvariant amplitude through virtual emission and absorption of photons. In particular K_2^0 can decay into two pions with a fractional amplitude $\varepsilon \approx \alpha/\pi$, (where α is the fine-structure constant) and this gives a natural explanation of the smallness of the observed $C_{st}P_{st}$-noninvariant amplitude.

This last possibility naturally raises many questions; among these the most urgent one is whether the hypothesis of H_γ being noninvariant under C_{st} is already in contradiction with some other known experiments. In an extensive study[20] that I have made in collaboration with Jeremy Bernstein and Gerald Feinberg, we find that there exists at present no experimental evidence that H_γ of the nonleptons is, or is not, invariant under C_{st}, nor is there any evidence that H_γ satisfies, or does not satisfy, the same time-reversal invariance T_{st} as the strong interaction. If the electromagnetic interaction is noninvariant under C_{st}, since H_γ is experimentally found to be invariant under both P_{st} and CPT, it follows that H_γ must also violate T_{st} invariance.

The possibility that H_γ may violate C_{st} and T_{st} invariances is, of course, only a theoretical possibility. Nevertheless, the present absence of evidence that H_γ is, or is not, invariant under C_{st} and T_{st} should provide sufficient incentive for further experimental efforts in this direction. Various tests have been proposed, and some of these are already in progress.

A possible mismatch pattern for C_i, P_i and T_i where i stands for wk, γ or st

H_{st}	C_{st}	T_{st}	P_{st}
	$\nparallel$	$\nparallel$	$\parallel$
H_γ	C_γ	T_γ	P_γ
	$\nparallel$	$\nparallel$	$\nparallel$
H_{wk}	C_{wk}	T_{wk}	P_{wk}
		$\parallel$	
		T_{st}	

$$C_{st}\,P_{st}\,T_{st} = C_\gamma P_\gamma\, T_\gamma = C_{wk}\,P_{wk}\,T_{wk} = \text{CPT}$$

What is charge conjugation?

The electromagnetic interaction of the leptons is well known to be invariant under *charge conjugation* C_γ. Furthermore we know that the minimal electromagnetic interaction of any system of spin-zero and spin-one-half particles is always invariant under charge conjugation; it is also invariant under a time reversal T_γ and a space inversion P_γ. The electromagnetic interaction of the leptons is well described by such a minimum interaction. It seems, therefore, aesthetically appealing to *assume* that there exists a charge conjugation operation C_γ under which all electromagnetic currents change sign and that *all electromagnetic interactions,* including that of the nonleptons, are invariant under this *charge conjugation symmetry* C_γ. From the experimental evidences of P_{st} and CPT invariances, we know that H_γ must also be invariant under P_γ and T_γ where

$$P_\gamma = P_{st}$$

$$C_\gamma P_\gamma T_\gamma = C_{st}P_{st}T_{st} = \text{CPT}$$

The question whether the electromagnetic interaction does, or does not, satisfy the C_{st} symmetry can be simply viewed as whether the charge-conjugation operator C_γ is, or is not, the same as the operator C_{st}. (The C_{st} may, for example, be regarded as the baryon-number conjugation, and can, in principle, be different from the charge conjugation.) If the electromagnetic interaction does violate the C_{st} symmetry, then $C_{st} \neq C_\gamma$ and, therefore $T_{st} \neq T_\gamma$.

As I have already remarked, the presently known form of weak interaction H_{wk} is invariant under its own space inversion P_{wk}; it can also be shown that H_{wk} is invariant under a time reversal T_{wk} and a C_{wk} conjugation.[7] Indeed, all our experimental results are consistent with the *assumption* that each of these interactions H_i is invariant under its own C_i, P_i and T_i where i=st, γ and wk, and

$$C_iP_iT_i = \text{CPT} \qquad (23)$$

The well known parity nonconservation is due to the mismatches

$$P_{wk} \neq P_{\gamma} = P_{st} \qquad C_{st} \neq C_{wk} \neq C_{\gamma}$$

It remains an open question whether the recent discovery of the $C_{st}P_{st}$ nonconservation in $K_2^0 \rightarrow \pi^+ + \pi^-$ can also be attributed to a similar mismatch—one between C_{st} and C_{γ}. A possible pattern of such mismatches is given in the table on page 30.

Our concept of "C" started with the charge conjugation C_{γ} determined by the electromagnetic interaction of the electron.[23] Later, the operator C_{γ} was extended to other interactions and was called "particle-antiparticle conjugation." After the discovery of parity nonconservation, it was already known that charge-conjugation invariance cannot be extended to the weak interaction and that the concept of particle and antiparticle rests, instead, on CPT invariance. Nevertheless, the hypothesis that charge-conjugation invariance C_{γ} is applicable to the strong interaction was assumed without question, and that the electromagnetic interaction and the strong interaction satisfy the same time-reversal invariance was taken for granted.

The progress of science has always been the result of a close interplay between our concepts of the universe and our observations of nature. The former can only evolve out of the latter, and yet the latter are also conditioned to a remarkable degree by the former. As we expand our fields of observation, naturally, we also extend our basic concepts. At times, these two factors, the concept and the observation, may become so interlocked that even some of the fundamental principles used in an entire domain of familiar phenomena may, to our chagrin, turn out to have no actual experimental basis. The history of these discrete symmetries has been a particularly rich one, full of such surprises.

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