DISCRETE SPACE-TIME SYMMETRIES

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MASTER

DISCRETE SPACE-TIME SYMMETRIES

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Abstract

Symmetries have always fascinated human beings; they are found in nature, art, and architecture. Physicists, like other scientists have often used symmetries as a basis of their understanding of nature. When the dynamics is unknown, symmetries serve to delineate and define it. When the dynamics is known, symmetries are used to study structure.

In these two lectures, I will review the theory and present understanding and status of two discrete space-time symmetries, namely parity (P) and time reversal (T).

I. PARITY

A Introduction

It has been known for over 35 years that parity is a valid symmetry only for the strong and electromagnetic interactions. The symmetry is broken in a major way in the weak interactions. The breakdown of parity invariance at this level served to shape the theory of electroweak interactions. Nowadays parity nonconservation is used to test the limits of this theory and within the theoretical framework to learn about the structure of atoms, nuclei and hadrons.¹⁾

First let me remind you of some properties of operators under the parity operation, P:

Table I: Operator transformations under parity

Operator:	$t, \vec{r}$	$E, \vec{p}$	$\vec{J}$	$\rho, \vec{j}$	$A_0, \vec{A}$
POP ⁻¹ :	$t, -\vec{r}$	$E, -\vec{p}$	$\vec{J}$	$\rho, -\vec{j}$	$A_0, -\vec{A}$

Here $t, \vec{r}$ are time and position coordinates; $E, \vec{p}$ are energy, momentum; $\vec{J}$ is an angular momentum; $\rho, \vec{j}$ are a density and associated current; and $A_0, \vec{A}$ are scalar and vector electromagnetic potentials.

If the P symmetry is a valid one, then $PH P^{-1} = H$ or $[P, H] = 0$. We know that P holds in the strong and electromagnetic interactions. Tests show that the only violation of the symmetry is in the weak sector.

$$[P, H_h + H_{em}] = 0 \quad (1a)$$

$$[P, H_{wk}] \neq 0 \quad (1b)$$

Let us estimate the magnitude of the P violation to be expected in experiments. For $\nu(\bar{\nu})$ scattering the violation is $\sim 100\%$ because it is known that the weak charged and neutral currents consist of approximately equal parts of vector and axial-vector components. However at reasonable energies ($E \ll M_W c^2$) the ratios of the strong, electromagnetic and weak interactions are

$$\text{Hadronic : } em : wk \approx 1 : \alpha = \frac{e^2}{4\pi} = \frac{1}{137} : \mathcal{F} \sim 10^{-7} \quad (2)$$

Thus, the cross section for ν scattering from a proton is of the order of magnitude

$$\sigma_\nu \sim R^2 |\mathcal{F}|^2 \sim 10^{-26} \times 10^{-14} \sim 10^{-40} \text{cm}^2 \quad (3)$$

where R , the size of the proton, has been taken as 1 fm. The advantages of neutrinos are that there are no electromagnetic and strong interactions, but the disadvantage is that the reaction rate is very small. For a charged lepton, as in electron scattering, an asymmetry due to parity violation (PV) can occur due to the interference of the electromagnetic and weak interactions (see Figs. 1a and b). The rate for a semi-leptonic ($e^\pm, \mu^\pm$) scattering from a hadron, can be written as

$$\mathcal{R} = |A_{em} + A_{wk}|^2 \approx |A_{em}|^2 + 2\text{Re}(A_{em}^* A_{wk}), \quad (4)$$

with

$$A_{em} \propto j_{\mu,em} \frac{1}{q^2} J_{em}^{\mu} \propto \frac{e^2}{4\pi q^2} F_{em}(q^2, \nu), \quad (5)$$

and

$$A_{wk}^{PV} \propto v_{\mu, A^{\mu+}} + a_{\mu} V^{\mu} + h.c. \\ \propto \frac{GF}{4\pi} F_{wk}(q^2, \nu). \quad (6)$$

Fig. 1. Electron-hadron (a) electromagnetic interaction, (b) weak interaction, (c) anapole interaction.

In Eq. (5) $j_{\mu,em}(J_{\mu,em})$ is the leptonic (hadronic) electromagnetic current, $|e|$ is the charge of the electron and hadron, q^2 is the square of the 4-momentum transferred from the electron to the hadron, and ν is the energy lost by the electron (in the c.m.).

In Eq. (6) $v_{\mu}(V_{\mu})$ is the weak vector current of the lepton (hadron) and $a_{\mu}(A_{\mu})$ is the similar axial-vector current; F_{em} and F_{wk} are form factors. The asymmetry, a , due to PV is essentially the ratio of the interference term in Eq. (4) to the dominant electromagnetic scattering rate; for a proton target, we have

$$a \sim \frac{\text{Re} A_{em}^* A_{wk}}{|A_{em}|^2} \sim \left| \frac{A_{wk}}{A_{em}} \right| \sim \frac{GFq^2}{4\pi\alpha} \sim 10^{-4} \frac{q^2}{M^2}, \quad (7)$$

where M is the mass of the nucleon and I have used $GM^2 \approx 10^{-5}$.

For a non-leptonic scattering at energies $\lesssim 1$ GeV, such as p - p scattering, the asymmetry is of the order of

$$a \sim \left(\frac{A_{wk}}{A_{hadr.}} \right) \sim GFm_{\pi}^2 \sim 10^{-7}, \quad (8)$$

where $A_{hadr.}$ has been taken to be $\sim (\hbar/m_{\pi}c)$, the approximate size of the hadron.

How is the PV detected? The reaction rate is a scalar. To first order in H_{wk} , PV is determined through the measurement of a pseudoscalar. An example is the asymmetry in the cross section with regard to longitudinally polarized particles parallel and antiparallel to the direction of the incident beam, i.e.,

$$\sigma = \sigma_0 + a(\vec{\sigma}) \cdot \vec{p} \quad (9a)$$

$$a = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}. \quad (9b)$$

Another example is the correlation of the momentum of photons with the polarization of captured neutrons by a nucleus, or the circular polarization of photons.

The rate of a parity-forbidden reaction, e.g. $A(1^+) \rightarrow (A-4)(0^+) + {}^4\text{He}(0^+)$ is a scalar and is thus of second order in the weak force, e.g. $\propto |\vec{F}|^2$ (see Eq. 2).

Charged current reactions have been known for over 50 years. It is the neutral weak currents, characteristic of the electroweak interactions, which are of primary interest for testing the theory.

The weak interaction, like the electromagnetic one, is a current-current one. However, unlike the long ($1/r$) range of the electromagnetic force, the weak force has a very short range

$$H_{wk} = g^2 \int d^3x d^3x' J_{\mu}(x) J^{\mu}(x') f_{wk}(x - x') \quad (10a)$$

with

$$f_{wk}(r) = e^{-r/R_W} / r, \quad (10b)$$

$$R_W \approx \frac{\hbar}{m_W c} \text{ or } \frac{\hbar}{m_W c} \quad (10c)$$

Since $m_W c^2 \gtrsim 80$ GeV, the range R_W is sufficiently short that for energies much lower than $m_W c^2$ we can write

$$\begin{aligned} H_{wk} &\approx g^2 \int d^3x J_\mu(x) J^\mu(x) \int d^3r \frac{e^{-r/R_W}}{r} \\ &= 4\pi g^2 R_W^2 \int d^3x J_\mu(x) J^\mu(x), \end{aligned} \quad (11)$$

so that the interaction is approximately a contact one.

The weak Fermi coupling constant

$$G_F \sim \sqrt{2} 4\pi g^2 R_W^2, \quad (12)$$

Since $G_F M^2 \sim 10^{-5}$, we find that if $g \sim e, m_W c^2 \sim 100$ GeV. This outline is the basis of the electroweak theory, which builds in other symmetries. I will briefly sketch elements of the theory as they are needed.

There are two aspects of PV experiments that have been pursued in recent years. The first one uses electrons as probes and the second one uses hadrons.

B. Charged Semileptonic Probes of PV

1. Theory

The weak neutral currents of the leptons involve the mixing of an isovector field (W_μ) and a singlet field (B_μ). The degree of mixing is given by the Weinberg angle, θ_W

$$W_\mu = \cos \theta_W Z_\mu - \sin \theta_W A_\mu,$$

$$B_\mu = \sin \theta_W Z_\mu + \cos \theta_W A_\mu,$$

where Z and A are the fields of the Z^0 and photon (γ). The neutral current Lagrangian density is

$$\begin{aligned} \mathcal{L}_{NC} = \frac{g}{4 \cos \theta_W} \{ &\bar{\nu}_e \gamma^\mu (1 - \gamma_5) \nu_e - \bar{e} [\gamma^\mu (1 - 4 \sin^2 \theta_W) \\ &- \gamma_\mu \gamma_5] e \} Z_\mu + e \bar{e} \gamma^\mu e A_\mu. \end{aligned} \quad (13)$$

with $g \sin \theta_W = e$. The theory predicts (for $\sin^2 \theta_W \simeq 0.22$)

$$\begin{aligned} M_W &= \sqrt{\frac{\pi \alpha}{\sqrt{2} G_F \sin \theta_W}} = \frac{37.3 \text{ GeV}}{\sin \theta_W} = 80 \text{ GeV} \\ M_Z &= \frac{74.6 \text{ GeV}}{\sin^2 \theta_W} \approx 91 \text{ GeV} \end{aligned} \quad (14)$$

It is noteworthy that the weak neutral vector current of electrons is $\propto (1 - 4 \sin^2 \theta_W) \simeq 0.12$; this reduction by an order of magnitude holds for all particles of the charge $|e|$, e.g., a proton.

For semi-leptonic reactions, we also need the currents of the quarks. As for the leptons, there are 3 families $\left(\frac{2}{3}\right)_L, \left(\frac{1}{3}\right)_L, \left(\frac{1}{3}\right)_L$, where L stands for left-handed. For the lowest mass family, the interaction Lagrangian density is

$$\begin{aligned} \mathcal{L} = &\frac{1}{3} \epsilon (2 \bar{u} \gamma^\mu u - \bar{d} \gamma^\mu d) A_\mu \\ &+ \frac{g}{4 \cos \theta_W} \{ \bar{u} [\gamma^\mu (1 - \gamma_5) - \frac{8}{3} \sin^2 \theta_W \gamma^\mu] u - \bar{d} [\gamma^\mu (1 - \gamma_5) - \frac{4}{3} \sin^2 \theta_W \gamma^\mu] d \} Z_\mu \end{aligned} \quad (15)$$

Similar terms appear for the other two families.

If we add up the current for the two up (two down) quarks and the down (up) quark in the proton (neutron), then we obtain the standard model neutral vector (V) and axial vector (A) currents

$$V^\mu(p) = \frac{g}{4 \cos \theta_W} \bar{p} \gamma^\mu (1 - 4 \sin^2 \theta_W) p \quad A^\mu(p) = \frac{-g}{4 \cos \theta_W} \bar{p} \gamma^\mu \gamma^5 p$$

$$V^\mu(n) = \frac{-g}{4 \cos \theta_W} \bar{n} \gamma^\mu n \quad A^\mu(n) = \frac{g}{4 \cos \theta_W} \bar{n} \gamma^\mu \gamma^5 n \quad (16)$$

or, in isospin notation, and including form factors, we have

$$\begin{aligned} V^\mu(N) = &\frac{g}{4 \cos \theta_W} \left[\bar{N} \gamma^\mu \frac{g_V^{(0)}}{2} + g_V^{(1)} \frac{\tau_3}{2} N F_1(q^2) \right. \\ &\left. + \bar{N} i \sigma^{\mu\nu} \frac{q_\nu}{2M} \frac{g_V^{(0)} \kappa_S + g_V^{(1)} \tau_3 \kappa_V}{2} N F_2(q^2) \right] \end{aligned} \quad (17a)$$

$$\begin{aligned} A^\mu(N) = &\frac{g}{4 \cos \theta_W} \left[\bar{N} \gamma^\mu \gamma^5 \frac{g_A^{(0)} F_A^{(0)}(q^2) + g_A^{(1)} F_A^{(1)}(q^2) \tau_3}{2} N \right. \\ &\left. + \bar{N} q^\mu \gamma^5 \frac{g_P F_P^{(0)}(q^2) + g_P F_P^{(1)}(q^2) \tau_3}{2} N \right] \end{aligned} \quad (17b)$$

In electron scattering the last term in A^μ does not contribute, because the electron vector current is a conserved one. The other coupling constants are

$$\begin{aligned} g_V^{(0)} &= -2 \sin^2 \theta_W & g_A^{(0)} &= 0 \\ g_V^{(1)} &= 1 - 2 \sin^2 \theta_W & g_A^{(1)} &= g_A = 1.26 \end{aligned} \quad (18)$$

The axial current is pure isovector and is renormalized to $g_A = 1.26$. This value is obtained from neutron decay lifetime measurements. The momentum transfer is q , and $\kappa_S \approx -0.12$ and $\kappa_V \approx 3.2$ are the isoscalar and isovector anomalous magnetic moments, respectively.

2. Experiments

Fig. 2. PV asymmetry measured by Prescott *et al.*²⁾ y is the fractional energy loss. The experimental asymmetry is compared to the Weinberg-Salam theory.

The first observations of parity nonconservations were obtained with high energy longitudinally polarized electrons²⁾ (Fig. 2) and agreed with the standard (Weinberg-Salam (W-S)) model. Since then, more accurate measurements have been carried out at many (very low to high) energies and all agree with the W-S theory.³⁾ Perhaps the most accurate PV ones are those carried out in atoms with the vector current for nucleons and axial current for electrons.³⁾ Like the Coulomb force, the wavelength is sufficiently long here that the nucleons act coherently to produce an effective current with a weak charge

$$Q_{wk} = (1 - 4 \sin^2 \theta_W) Z - N, \quad (19)$$

which gives an enhancement factor of about two orders of magnitude for heavy atoms. Both experiments^{3,4)} and theory^{3,5)} have been done to better than 1% for selected atoms, e.g. Cs, even though the asymmetry is extremely small $a \sim 10^{-7}$.

The interest today is in trying to test the theory in detail, e.g., to measure the various coupling strengths, $g_V^{(0)}, g_V^{(1)}, g_A^{(0)}, g_A^{(1)}$, etc. or to use the theory to discern structure effects.

I will discuss both aspects. In atoms, one can also try to measure the axial currents of nucleons; for PV this implies vector current for electrons. The expected asymmetry is small compared to the reverse experiments (1^μ for nucleons, a_μ for electrons) for two reasons: (i) the vector current of electrons is $\propto (1 - 4 \sin^2 \theta_W) \sim 0.1$ and (ii) the axial vector current for hadrons is not coherent, since $\langle p | A_\mu | p \rangle \sim \langle p | \vec{\sigma} | p \rangle$ nonrelativistically, and the spin of a nucleus comes from one or only a few nucleons. It turns out that there is then a competing process (Fig. 1c) coming from what has been coined by Zeldovich⁶⁾ an anapole moment. This anapole comes from a hadronic PV or effectively a parity non-conserving coupling of the photon to the nucleus.⁷⁾ It is a contact term, which vanishes for a point nucleus, and grows as R^2 , the square of the nuclear radius⁶⁾, and thus as $A^{2/3}$, where A is the nucleon number of the nucleus.

The amplitude for the scattering of an electron from the anapole is

$$A_{anap} \sim \frac{\alpha}{q^2} G_F m_\pi^2 f_{an}(q^2) \quad (20)$$

So that the ratio to the W-S model term is

$$\frac{A_{anap}}{A_{wk}} \sim \frac{\alpha}{q^2} G_F m_\pi^2 \frac{1}{G_F} \frac{f_{anap}}{(1 - 4 \sin^2 \theta_W)} \sim \alpha \frac{m_\pi^2}{q^2} \frac{f_{anap}}{(1 - 4 \sin^2 \theta)} \quad (21)$$

But the most general conserved anapole current is

$$\vec{N} [\gamma_\mu \gamma_5 q^2 - 2 M q_\mu \gamma] N h_{anap}(q^2)$$

so that

$$f_{anap}(q^2) \sim q^2 h_{anap}(q^2) \sim q^2 R^2 h_{anap}(q^2) \quad (22)$$

with $h_{anap}(0) \sim 1$. Thus, we find from Eq. (21) for $A \sim 200$

$$\frac{A_{anap}}{A_{wk}} \sim \alpha \frac{m_\pi^2 R^2 A^{2/3}}{(1 - 4 \sin^2 \theta_W)} \sim 3 - 4 \quad (23)$$

More serious calculations⁸⁾ have shown this order of magnitude to be correct. For heavy atoms the asymmetry due to the anapole moment is found to be about five times larger than the W-S model prediction, so that it becomes even more difficult to test this model. Experiments carried out at Boulder⁹⁾ appear to indicate the presence of this anapole moment, but more precise measurements are needed to establish it with certainty.

Atomic experiments on a series of isotopes have been proposed to obtain neutron distribution radii.¹⁰ There are almost no other techniques which are so sensitive to these distributions (see Eq. (19)). Such experiments have been proposed at Yale University.¹¹

Nuclear experiments still have not reached the accuracy needed to test the theory in detail, but they are getting there.¹² One experiment being undertaken at BATES (MIT) has been proposed by Beck, McKeown, Beise and others.¹³ In Eq. (18) we found $g_A^{(0)} = 0$ because in the W-S theory the axial current is purely isovector and the nucleon is composed only of up and down quarks. However, recently the "spin crisis" of the proton which arose from EMC measurements of the deep inelastic scattering of polarized electrons on polarized protons¹⁴ appears to show that the proton may contain appreciable ($\lesssim 20\%$) strangeness.¹⁵ Elastic neutrino and antineutrino scattering on protons seem to substantiate these results and suggest $g_A^{(0)} \approx -0.18 \pm 0.07$.

The reason that strange constituents of the proton give rise to a non-zero value of $g_A^{(0)}$ is that for the weak interactions the strange quark is part of a doublet, $(\begin{smallmatrix} s \\ c \end{smallmatrix})$, of isospin $1/2$; but for the strong interactions the strange quark has isospin $= 0$. This mismatch of structure (strong interaction) and weak current (weak interaction) gives rise to an isoscalar weak axial current as well as to a new vector magnetic current form factor and modifications of other form factors. It is actually the new vector magnetic magnetic form factor that is more easily measured in the PV asymmetry in elastic longitudinally polarized electron scattering from protons.¹³

$$a = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} = \frac{-G_F Q^2}{\sqrt{2}\pi\alpha} \left\{ F_1^* F_1^* + \tau F_2^* F_2^* + 2\tau \tan^2 \frac{\theta}{2} (F_1^* + F_2^*) (F_1^* + F_2^*) \right. \\ \left. - \frac{E + E'}{2M} \tan^2 \frac{\theta}{2} (1 - 4\sin^2 \theta_W) (F_1^* + F_2^*) F_A^* \right\} \\ \times \left\{ F_1^* + \frac{Q^2}{4M^2} F_2^* + 2\tau \tan^2 \frac{\theta}{2} (F_1^* + F_2^*)^2 \right\}^{-1}. \quad (24)$$

In Eq. (24), $Q^2 = -q^2$, $\tau = Q^2/4M^2$, θ is the electron scattering angle, $F_1^{(*)}$ is an electromagnetic form factor, $F_2^{(*)}$ is a weak form factor, and $E(E')$ is the initial (final) electron energy. The last term in the numerator, sensitive to the axial-vector form factor F_A is reduced by $(1 - 4\sin^2 \theta_W)$, the first term is small at back angles, so that in this region the asymmetry is dominated by the second and third term. These terms are sensitive to F_2^* , which, in turn is sensitive to strangeness.

To measure $g_A^{(0)}$, it is better to use ν scattering, we have suggested a null experiment¹⁶ (null if $g_A^{(0)} = 0$), namely the measurement of

$$R = \frac{\sigma(\nu d \rightarrow \nu d) - \sigma(\bar{\nu} d \rightarrow \bar{\nu} d)}{\sigma(\nu d \rightarrow \nu d) + \sigma(\bar{\nu} d \rightarrow \bar{\nu} d)}$$

and G. Garvey has proposed quasi-elastic proton and neutron production from ^{12}C .

I mention these experiments to illustrate the present interest in PV in semi-leptonic experiments.

C. Non-leptonic Weak Interaction

The non-leptonic weak interaction is the least well understood of the weak interactions. Our lack of knowledge comes from the spoiling of the weak interaction by the hadronic ones. The interaction is of interest because (i) it is a diagonal one, i.e., a current multiplied by itself; (ii) it tests our understanding of the nucleon structure.

The main available knowledge comes from the decays of strange particles. However, in the W-S model, there are no neutral strangeness-changing weak currents. One of the results obtained from the decays is that the isospin-changing $\Delta I = 1/2$ amplitudes are enhanced over those with $\Delta I = 3/2$ by an order of magnitude.

The nucleus is a better laboratory for learning details of the weak non-leptonic force.¹⁷ PV can be measured in a variety of nuclei with states of different isospin. The theoretical program begins at the quark level, where the currents are known (see Eqs. (17)). It then uses QCD or rather, QCD and hadron models based on QCD to obtain a PV nucleon-nucleon force.¹⁷ This interaction is then used, together with the necessary nuclear structure information to relate to experiments. The experimental program began with measurements in heavy nuclei, where large enhancements can occur, proceeded to lighter ones where structural information is better, and now is back to heavier nuclei and statistical reactions.

1. Basic Theory

The non-leptonic currents of nucleons can be written as

$$J_\mu^{NL} = J_\mu^{(-)} \cos \theta_C + J_\mu^{(S)} \sin \theta_C + J_\mu^{(0)}, \quad (25)$$

where $J_\mu^{(-)}$, $J_\mu^{(S)}$, $J_\mu^{(0)}$ are charged, strangeness-changing, and neutral weak currents and θ_C is the Cabibbo angle. The isospin characteristics of these currents, $J_\mu^{(-)}$ has $\Delta I = 1$, $J_\mu^{(S)}$ has $\Delta I = 1/2$, $J_\mu^{(0)}$ has $\Delta I = 0$ and 1. allows some separation. The non-flavor changing interactions are proportional to

$$\begin{aligned} J_\mu^{(-)} J_\mu^{(-)} \cos^2 \theta_C & \quad \text{with } \Delta I = 0, \Delta I = 2 \\ J_\mu^{(S)} J_\mu^{(S)} \sin^2 \theta_C & \propto \sin^2 \theta_C \approx 0.06 \quad \text{with } \Delta I = 1 \\ J_\mu^{(0)} J_\mu^{(0)} & \quad \text{with } \Delta I = 0, 1, 2 \end{aligned} \quad (26)$$

The interactions crossed out vanish by symmetry for two like currents. Since $\sin^2 \theta_C \approx 0.06$, the primary source of the $\Delta I = 1$ interaction is due to neutral currents.

The weak forces between nucleons are assumed to come from meson exchanges, Fig. 4, and have ranges $\propto \hbar/m_{\pi C}$ proportional to the inverse mass of the exchanged

meson. Various quark-based models have been used to calculate the weak PV meson-nucleon coupling constants. Of primary interest here is $f_\pi^{(1)}$, which is found to be $(4.6 \pm 1.4) \times 10^{-7}$.

If CP invariance is (approximately) valid, then the pion contributes only to the $\Delta I = 1$ force. This is seen most easily by writing the most general forms of the pion-nucleon interaction Lagrangian

$$\begin{aligned} L_1 &\propto \bar{\psi}\psi\phi\,d^3x, \\ L_2 &\propto \int \bar{\psi}\gamma^\mu\psi\,\nabla_\mu\phi\,d^3x, \\ L_3 &\propto \int \bar{\psi}\sigma^{\mu\nu}\psi\,\nabla_\mu\nabla_\nu\phi\,d^3x. \end{aligned} \quad (27)$$

L_1 has odd CP since ϕ is even under charge-conjugation; L_2 vanishes by a partial integration and current conservation; L_3 vanishes because $\sigma^{\mu\nu}$ is odd and $\nabla_\mu\nabla_\nu$ is even under $\mu \leftrightarrow \nu$. The only form allowed is

$$L_\pi = f_\pi^{(1)} \int \bar{\psi}(\tau \times \phi)_3 \psi\,d^3x = f_\pi^{(1)} \int (\bar{\psi}\tau_+\psi\phi^{(-)} - \bar{\psi}\tau_-\psi\phi^{(+)})d^3x, \quad (28)$$

which is purely isovector in nature.

2. Experiments

Fig. 3. Low-lying level structure of ^{18}F relevant for a PV experiment.

By choosing appropriate nuclear transitions one can isolate $\Delta I = 1$ or other cases. An example is shown in Fig. 3 for ^{18}F and two levels of spin zero, but opposite parity separated by only 40 keV. Because of this small separation, one can neglect other levels. The impure parity admixture to the 0^- level, for instance, can be found by perturbation theory

$$|0^- \rangle = |0^- \rangle + \mathcal{F}|0^+ \rangle \quad (29a)$$

$$\mathcal{F} = \frac{(0^+ | H_{PV} | 0^-)}{E_0 - E_0^+}. \quad (29b)$$

The amplitude for the magnetic dipole transition to the ground state is 11 times faster than the electric dipole transition from the 0^- state. The rate for the parity-admixed state can be written as

$$\mathcal{R} = |(1^+ | E1 | 0^-) + \mathcal{F}(1^+ | M1 | 0^+)|^2. \quad (30)$$

The parity amplitude is thus enhanced by both the ratio of the $M1/E1$ amplitude and the small energy denominator in $\mathcal{F}$. ^{18}F has another advantage. The matrix element of the weak force can be directly related to a first forbidden beta-decay, so that it can be obtained in a relatively model-independent manner.¹⁸⁾ Other such examples exist.¹⁾

TABLE II. Some parity violating experiments in light nuclei.

Experiment	Details	Asymmetry or Polarization $\times 10^6$
$\bar{p}p$		
	σ_{total} at 15 MeV	$a = -0.17 \pm 0.08^a)$
	σ_{total} at 45 MeV	$a = -0.15 \pm 0.022^b)$
	σ_{total} at 800 MeV	$a = 0.24 \pm 0.11^a)$
	σ_{total} at 5300 MeV	$a = 2.65 \pm 0.6^a)$
$p\bar{d}$	σ_{elastic} and σ_{thermal} at 43 MeV	$a = 0.04 \pm 0.07^c)$
$np \rightarrow d\bar{\gamma}$	thermal capture	$P_\gamma = 0.18 \pm 0.18^a)$
$\bar{p}\alpha$	σ_{elastic} at 46 MeV	$a = -0.33 \pm 0.09^d)$
$^6\text{Li}(n, \alpha)^3\text{H}$	cold n's	$a = -0.0064 \pm 0.0055^c)$
$^{16}\text{O}(2^-) \rightarrow ^{12}\text{C}(0^+)_2$	rate	$\sqrt{F_\alpha} = 10 \pm 1 \text{ eV}^a)$
^{18}F	$0^- \rightarrow 1^+$	$P_\gamma = 80 \pm 390^a)$
^{19}F	$1/2^- \rightarrow 1^+ 2^-$	$a = -74 \pm 19^a)$
$^{20}\text{Ne}(1^+) \rightarrow ^{16}\text{O}(0^+)_2$	$^{19}\text{F}(\bar{p}, \alpha)^{16}\text{O}$	$a = 1500 \pm 760^f)$
^{21}Ne	$1/2^- \rightarrow 3^+ 2^-$	$P_\gamma = -8 \pm 14^a)$

Refs.

a) See E. G. Adelberger and W. Haxton, Ann. Rev. Nucl. Sci. 35, 501 (1985).

b) S. Kistryn *et al.*, Phys. Rev. Lett. 58, 1616 (1987).

c) S. Kistryn *et al.*, Phys. Lett. B219, 55 (1989).

d) J. Lang *et al.*, Phys. Rev. C34, 1545 (1986).

e) V. A. Vesna *et al.*, Pisma Zh. Eksp. Teor. Fiz. 52, 660 (1990), translated JETP 52, 7 (1990).

f) N. Kriest *et al.*, Phys. Rev. C41, 1336 (1990)

Experiments have been carried out in $\bar{p}p$ scattering at a number of energies and in a selected list of light nuclei, as summarized in Table II. From ^{18}F , in particular, it is found that $f_\pi^{(1)} \lesssim 2 \times 10^{-7}$ and could well be zero. Thus to-date no evidence has been found for the neutral non-leptonic current. Experiments have been proposed or are under way to set lower limits on $f_\pi^{(1)}$ or determine its value.

Recently experiments and theory have been connected with epithermal neutron transmission experiments in heavy nuclei. These experiments are carried out at a P-wave ($L=1$) compound nucleus resonance, with a PV admixture of a very nearby S-wave-resonance with a much larger decay width.¹⁹⁾ The asymmetry is thus again enhanced by two factors, γ_S/γ_P , and the small ΔE

$$a \sim \frac{2}{\gamma_P} \sum_{\nu=1}^{N_S} \frac{(\nu S_{1/2} | H_{PV} | P_{1/2})}{E_P - E_S} \gamma_{\nu, S} \quad (31)$$

where the sum is over all (N_S) near-by S-wave resonances, and γ_i is the partial width amplitude for neutron decay of the P- or S- state resonances. The enhancement is of order $(pR)^{-1} \sqrt{N}$, where p is the momentum of the neutrons, R is the nuclear radius, and N is the number of underlying levels at the resonance. This enhancement can be as large as $10^5 - 10^6$. However, when averaged over many resonances, we expect $a \approx 0$, since the signs of γ_P , γ_{11} , and (H_{PV}) should be random. Experimentally²⁰⁾, e.g. in ^{232}Th , a is found to be > 0 for most of the 23 resonances studied, which contradicts the statistical assumption and suggests that distant contributions of a non-statistical nature are present.²¹⁾ These results are not yet understood, so that it is not yet feasible to fully use the results to relate them to the PV nucleon-nucleon force.

3. Summary

We have learned that PV can be understood in terms of the W-S model of the electroweak interactions. Semi-leptonic interactions are being used both to test the limits of the model and to discern the structure of nucleons and nuclei. The non-leptonic weak interaction is of primary interest to learn about that sector of the weak interaction and also to obtain nuclear structure information. The neutral weak non-leptonic current is weaker than expected and has yet to be seen.

II. TIME REVERSAL INVARIANCE

A. Introduction

The situation with regard to time reversal invariance (TRI) differs considerably from that with parity.^{1),22)} Whereas we have a theory for the latter, we have, at best, a glimmer of a model for the small violation of time reversal invariance that has been observed. Experiments are difficult and sometimes give contradictory results. So far, TRI violation (TRIV) has only been seen in one system, namely in $K^0 - \bar{K}^0$ decays. It is difficult to test proposed models and theories without further data from other systems. What I will do is to review the operation of time reversal (T), some proposed models, and experiments that have been carried out or have been proposed.

The operator transformations under T are as follows:

Table III. Operator transformations under T

Operator	$t, \vec{r}$	$E, \vec{p}$	$\vec{J}$	$A_0, \vec{A}$	$\rho, \vec{j}$
$TO T^{-1}$	$-t, \vec{r}$	$E, -\vec{p}$	$-\vec{J}$	$A_0, -\vec{A}$	$\rho, -\vec{j}$

B. Theoretical Framework

The Schroedinger equation, unlike classical ones, is a diffusion equation, which is first order in time

$$i \frac{\partial \psi}{\partial t} = H \psi, \quad i \frac{\partial \psi^*}{\partial(-t)} = H^* \psi^*.$$

If H is real, $\psi(t)$ and $\psi^*(-t)$ satisfy the same equation and $[H, T] = 0$. It follows that TRI forbids an interaction of the form $\vec{r} \cdot \vec{p} + \vec{p} \cdot \vec{r}$. Because complex conjugation (K) is required, T is not unitary; it is said to be antiunitary. It follows that

$$T \psi_T(\vec{r}, t) = U_T \psi^*(\vec{r}, -t) = U_T K \psi(\vec{r}, -t), \quad (32)$$

where U_T is a unitary operator. For a spinless particle we can take $U_T = 1$, but for a particle with spin (s) $U_T = e^{-i\pi S_y}$, where S_y is the y-component of the spin. Thus, we find

$$T|n, s, m_s\rangle = (-1)^{s-m_s} |n_T, s, -m_s\rangle, \quad (33)$$

where n stands for other quantum numbers and m is the magnetic spin quantum number. We also have

$$\langle \psi_T | O_T | \phi_T \rangle = \langle \psi | O | \phi \rangle^* \quad (34a)$$

and if O is Hermitian (observable)

$$\langle \psi_T | O_T | \phi_T \rangle = \langle \phi | O | \psi \rangle. \quad (34b)$$

There are some immediate consequences of these results. If we apply T twice, then we get back to the same state

$$T^2|n, j, m\rangle = a|n, j, m\rangle \quad (35)$$

and from Eq. (33) we have $a = (-1)^{2j}$. Thus for a particle with Bose-Einstein statistics $a = +1$, whereas it is -1 for a system or particle which obeys Fermi-Dirac statistics. For a scattering state

$$T\psi^{(+)}(n, \vec{p}, s, m) = (-1)^{s-m}\psi^{(-)}(n_T, -\vec{p}, s, -m) \quad (36)$$

where the $+$ ($-$) refers to an outgoing (incoming) wave boundary condition. For the scattering matrix S , we then have

$$T S T^{-1} = S^\dagger, \quad (37)$$

and

$$\langle f|s\rangle = \langle i\tau|S|f\rangle. \quad (38)$$

If TRI is a valid symmetry, it follows that

$$\langle \vec{p}', s', m'|S|p, s, m\rangle = (-1)^{s+s'-m-m'} \langle -\vec{p}, s, -m|S|-\vec{p}', s', -m'\rangle. \quad (39)$$

That is the initial and final states are interchanged as well as having the spins and momenta reversed. This is to be expected on physical grounds; Eq. (39) is called a "reciprocity" relation. For elastic scattering of a spin $\frac{1}{2}$ particle on a spin zero target, a scattering matrix term proportional to $\vec{\sigma} \cdot (\vec{p}_i + \vec{p}_f)$ is forbidden by parity, but allowed by time reversal invariance whereas $\vec{\sigma} \cdot (\vec{p}_i - \vec{p}_f)$ is forbidden by both P and T invariances. If we do not measure spins (polarizations), then we have

$$\begin{aligned} \sum_{m, m'} |\langle \vec{p}', s', m'|S|\vec{p}, s, m\rangle|^2 &= \sum_{m, m'} |(-\vec{p}, s, -m|S|-\vec{p}', s', -m')|^2 \\ &= \sum_{m, m'} |\langle \vec{p}, s, m|S|\vec{p}', s', m\rangle|^2. \end{aligned} \quad (40)$$

Eq. (40) is called a "detailed balance" relation.

We will make use of these relationships in what follows. Because one can prove the CPT theorem, i.e. $(CPT)H(CPT)^{-1} = H$ on very general grounds, it follows that TRI and CP invariance are directly related. Experimentally it has been shown that the CPT theorem holds to better than 10^{-14} . The $K^0, \bar{K}^0$ is a wonderful two-level quantum system; it has been full of surprises:

$$CP|K^0\rangle = |\bar{K}^0\rangle, \quad CP|\bar{K}^0\rangle = |K^0\rangle \quad (41)$$

Define K_1 and K_2 as the even and odd CP particles, respectively

$$K_1 = \frac{K_0 + \bar{K}^0}{\sqrt{2}}, \quad K_2 = \frac{K_0 - \bar{K}^0}{\sqrt{2}} \quad (42)$$

It follows that if CP is conserved, $[CP, H] = 0$, K_1 can decay to 2π , but K_2 cannot do so and decays to at least 3π . The argument is simple:

$$\begin{aligned} P|\pi^+\pi^-\rangle &= (-1)^L|\pi^+\pi^-\rangle \\ C|\pi^+\pi^-\rangle &= (-1)^L|\pi^+\pi^-\rangle \\ CP|\pi^+\pi^-\rangle &= |\pi^+\pi^-\rangle, \end{aligned} \quad (43)$$

where L is the relative orbital angular momentum. For 3 pions, there are two relative orbital motions to consider

$$\begin{aligned} P|\pi^+\pi^-\pi^0\rangle &= (-1)^{L+\ell+1}|\pi^+\pi^-\pi^0\rangle \\ C|\pi^+\pi^-\pi^0\rangle &= \text{same state with } L \text{ and } \ell \text{ interchanged,} \end{aligned} \quad (44a)$$

where L is the angular momentum between the π^+ and π^0 , whereas ℓ is that between the π^- and π^0 . Since the K^0 and $\bar{K}^0$ have spin zero, $L = \ell$, and

$$CP|\pi^+\pi^-\pi^0\rangle = -|\pi^+\pi^-\pi^0\rangle \quad (44b)$$

Experimentally, it is found that $\tau(K_2) \gg \tau(K_1)$, as expected from the above argument. However, it is also found that K_2 decays to two pions about 0.2% of the time. Thus CP is not conserved with a strength of about 10^{-3} of the weak interaction strength. One defines

$$\begin{aligned} K_S &= K_1 + \varepsilon K_2, \\ K_L &= K_2 - \varepsilon K_1, \end{aligned} \quad (45)$$

where ε is a measure of CP or TRI violation.

The origin of CP-violation could be in the $K^0, \bar{K}^0$ mass-mixing matrix, in the decay amplitudes, or in both. If we define

$$\eta_{+-} = \frac{\mathcal{A}(K_L \rightarrow \pi^+\pi^-)}{\mathcal{A}(K_S \rightarrow \pi^0\pi^0)}, \quad \eta_{00} = \frac{\mathcal{A}(K_L \rightarrow \pi^0\pi^0)}{\mathcal{A}(K_S \rightarrow \pi^0\pi^0)}, \quad (46)$$

then we can write

$$\eta_{+-} = \varepsilon + \varepsilon', \quad \eta_{00} = \varepsilon - 2\varepsilon'$$

and $\varepsilon' = 0$ if the CP violation is only in the mass matrix. Recent experiments carried out at CERN and FNAL give contradictory results. Experiments show $|\varepsilon| \approx 2.3 \times 10^{-3}$ and $|\varepsilon'/\varepsilon| \sim 10^{-3}$ but could be zero.²³⁾

Within the standard model several sources have been proposed for CP-violation;

(1) The QCD Lagrangian allows a term²⁴⁾

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi^2} \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu}^a F_{\alpha\beta}^a \quad (47)$$

where $\alpha_s = g_s^2/4\pi$ is the strong fine structure constant. Experiments show that θ is so small that this term cannot be responsible for the CP-violation in the K^0 - $\bar{K}^0$ system.

(2) For quarks, the weak interaction for the 3 families can be written as²⁵⁾

$$\mathcal{L} = \frac{g}{2\sqrt{2}} (\bar{u}\bar{c})\gamma_\mu(1 - \gamma_5)U \begin{pmatrix} d \\ s \end{pmatrix} W^\mu + h.c. \quad (48)$$

with

$$U = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 c_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}, \quad (49)$$

where W^μ is the charged W -boson field, c_i and s_i represent $\cos i$ and $\sin i$, and δ is the CP- or T-odd phase. This matrix can be written approximately as

$$U \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^2(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \quad (50)$$

where A, ρ, η, λ are parameters and λ is small, of the order of the sine of the Cabibbo angle ≈ 0.22 . CP violation is seen to be of order λ^3 . The K-M model is in accord with data and provides a framework for understanding the CPV effects in the neutral kaon system. However, in first order of the weak interactions, the phase δ does not contribute to flavor-conserving reactions; these are second order in U , or of magnitude

$$a_T \sim \left(\frac{G_F M^2}{4\pi} \right)^2 (0.22)^3 \sim 10^{-16} \quad (51)$$

There are theories of CP- and T-violation outside of the standard model. Examples are L-R symmetric models, milliwak and Higgs models²⁶⁻²⁷⁾ If $\epsilon' = 0$, then Wolfenstein's superweak model could be correct²⁷⁾; CP and TRI violations would then be due to a superweak interaction and may only show up in the K^0 - $\bar{K}^0$ system.

At low energies and for nucleons, it is known that mesons are effective QCD degrees of freedom. In scattering experiments with hadronic targets, TRIV can occur

either through admixing in the initial or final state wavefunction, or through a T-odd interaction that connects initial and final states. Since there is no theory, we consider the most general interaction that is T-odd. As in PV this occurs for two nucleons through a T-odd meson-nucleon vertex. We already noted that $\bar{\psi}\phi_3\psi$, or $\bar{\psi}\vec{r} \cdot \vec{\phi}\psi$ are CP- and therefore T-odd vertices. Neglecting isospin, this gives rise to a potential, which is P-odd as well as T-odd²⁸⁾

$$V_{PT}^{\pi} = -\frac{1}{8\pi} \frac{m_\pi^2}{\Lambda^2} f_\pi^T g_{\pi NN} (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{r} \left(1 + \frac{1}{r} \right) \frac{e^{-r}}{r}, \quad (52)$$

where $r = m_\pi r$, $g_{\pi NN}$ is the strong π - N coupling constant, $g_{\pi NN}^2/4\pi \approx 14$, and $f_\pi^{(T)}$ is the T-odd coupling constant. The QCD θ model gives $|f_\pi^T| = 0.027|\theta|$, whereas the K-M model gives $|f_\pi^T| \approx 10^{-16}$ (see Eq. (51)). This is the longest-range T-odd NN force and gives rise to an effective one-body potential for nucleon-nucleus scattering of the form

$$V_{PT} = V_0^{PT} \vec{\sigma} \cdot \vec{r} \rho(r)/\rho(0), \quad (53)$$

where V_0^{PT} is the strength of the potential. ρ is the nuclear density, and $\vec{r}$ is a unit vector in the radial direction from the center of the nucleus.

It is more difficult to write down a P-even, T-odd interaction; there is none between quarks. The longest-range one-meson exchange potential between nucleons would come from ρ -exchange²⁹⁾

$$V_T^\rho = -f_\rho^T g_{\rho NN} \frac{m_\rho^3}{8\pi M^2} (\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \vec{L}(\vec{r}_1 \times \vec{r}_2)_3 \left(\frac{1}{y^2} + \frac{1}{y^3} \right) e^{-y}, \quad (54)$$

with $y = m_\rho r$. A one-body phenomenological potential odd under T, but even under a P transformation is

$$U_T = \frac{1}{2} V_0^{PT} \{ \vec{p}, \vec{r} \rho(r) \} / \rho(0) \quad (55)$$

C. Experiments

Since TRIV is not understood, experiments to find signals of the violation have been sought at all strengths of interactions.

The most accurate detailed balance test has been in the reaction $p + {}^3\text{He} \leftrightarrow {}^4\text{He} + {}^2\text{H}$ and shows no asymmetry at a level of $a_T \lesssim 5 \times 10^{-4}$.³⁰⁾

Recently there has been particular interest in neutron transmission experiments through a polarized sample.³¹⁾ This is a reciprocity test of TRI, as can be seen from Fig. 4. One seeks a TRIV asymmetry of the form

$$a_{PT}(\vec{\sigma}_n) \cdot \langle \vec{J} \rangle \times \vec{p} \quad (56)$$

Fig. 4. A reciprocity test of T with coherent forward scattering of polarized (σ) neutrons of incident momentum $\vec{p}$ and outgoing momentum $\vec{p}' = \vec{p}$ on a polarized ($\vec{s}$) target.

where $\langle \vec{\sigma}_n \rangle$ and $\vec{p}$ are the polarization and momentum of the neutron and $\langle \vec{J} \rangle$ is the polarization of the sample. If the experiment is carried out in a heavy nuclear target near a P-wave resonance, large enhancements similar to those of the parity experiments [$\sim \sqrt{N}(pR)^{-1}$] are expected. In ^{165}Ho an upper limit of $a_{PT} \approx 3 \times 10^{-3}$ has been established³²⁾ but these experiments are continuing and improved limits can be set. By measuring a T-odd P-even correlation

$$a_T(\vec{\sigma}_n) \cdot \langle \vec{J} \rangle \times \vec{p} \cdot \langle \vec{J} \rangle \cdot \vec{p} \quad (57)$$

near a P-wave resonance one can seek a pure TRIV.³¹⁾

Electromagnetic transitions have the advantage that they can be calculated perturbatively. The operator is therefore Hermitian and Eq. (34b) applies. Angular correlations between two competing multipolarities can seek a relative phase in the wavefunctions of the two states (i and f) involved in the transition.³³⁾ A P- and T-odd correlation is

$$a_{PT} = \vec{J}_i \cdot \vec{J}_f \times \vec{k} \sin \eta_{PT}, \quad (58)$$

and a P-even one is

$$a_T = \vec{J}_i \cdot \vec{J}_f \times \vec{k} \cdot \vec{J}_f \sin \eta_T, \quad (59)$$

where $\vec{k}$ is the momentum of the photon. Higher order corrections would spoil the test, but they are small. The most precise measurements find no phase η_T to $\lesssim 10^{-3}$ in ^{197}Ir and ^{57}Fe .³⁴⁾

There have also been tests in beta-decays of n , ^8Li , and ^{19}Ne .²²⁾ Once again perturbation theory holds and Eq. (34b) applies. Correlations of the form $D\vec{J}_i \times \vec{p}_e \times \vec{p}_\nu$ or $\vec{\sigma}_e \cdot \vec{J}_i \times \vec{p}_\nu$ are sought, but no asymmetry has been observed to $\lesssim 10^{-3}$.³⁵⁾ We have recently proposed tests in first-forbidden beta decays.³⁶⁾

The most precise tests of combined P and TR outside of the neutral kaons are the measurements of the electric dipole moments of the neutron and atoms. For the neutron³⁷⁾ $d_e(n) = (6 \pm 2 \pm 4) \times 10^{-26} e \cdot \text{cm}$ or $d_e(n) \lesssim 2 \times 10^{-25} e \cdot \text{cm}$.

In heavy atoms, it is found that³⁸⁾

$$d_e(\text{Xe}) = -(0.3 \pm 1.1) \times 10^{-26} e \cdot \text{cm},$$

$$d_e(^{199}\text{Hg}) = (0.7 \pm 1.5) \times 10^{-26} e \cdot \text{cm}.$$

Both of these measurements restrict θ in Eq. (47) to be $\theta \lesssim 5 \times 10^{-10}$ and $f_T^T \lesssim 10^{-11}$ (see Eq. (52)). In the K-M model, $d_e(n)$ is predicted to be (see Eq. (51)) $< 10^{-13} e \cdot \text{cm} \times 10^{-16} < 10^{-29} e \cdot \text{cm}$ (actually $\sim 10^{-31} e \cdot \text{cm}$).

Experiments paralleling those in the $K^0\bar{K}^0$ system have been proposed for the $B^0\bar{B}^0$, which are known to be strongly mixed. Others are in the reaction $p\bar{p} \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^-\bar{p}\pi^+$, with the measurement of the correlation $\vec{p}_\Lambda \times \vec{\Lambda} \cdot (\vec{p}_\pi + \vec{p}_\pi')$, where $\vec{\Lambda}$ is the momentum of the Λ and $\vec{p}_\pi(\vec{p}_\pi')$ is the momentum of the final proton (antiproton). Other experiments try to reach ever higher precision and use large enhancements.

Until violations of T or CP are found elsewhere than for $K^0\bar{K}^0$, it is doubtful that much progress will be made in our understanding of the basic cause of TRIV. Experimentation continues.

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