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SEARCHES FOR T-ODD INTERACTIONS IN NUCLEAR PROCESSES: REVIEW OF THE THEORY

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Abstract

We review briefly the theoretical aspects of time reversal violation in nuclear processes.

1. Introduction

CP-violation has been seen so far only in the neutral kaon system. Its origin is still unknown. If the CPT theorem holds, as is the case in gauge theories, CP-violating interactions violate also time reversal (T) invariance. Regarding the CPT theorem there is some experimental evidence[1] that the interaction responsible for the observed CP-violation violates T-invariance.

The observed CP-violation may just be a manifestation of the weak interction of the Standard Model (SM), or it is due to an interaction beyond the SM. In both cases some of the new interactions may give rise to observable CP-violation where the SM contribution is invisible. This underlines the importance of searching for CP-violating and T-violating effects in many processes.

In this talk[2] we shall review what has been learned about T-violating interactions that can be probed in nuclear processes from experiments outside of and within nuclear physics, and consider the role of nuclear physics experiments in obtaining further information on such interactions.

2. T-Violation in the Nucleon-Nucleon Interaction

The T-violating part of the N-N interaction has both a parity violating and a parity conserving component. The theoretical features of these are different, and we shall therefore consider them separately.

2.1. Parity Violating Time Reversal Violation

As time reversal invariant parity violation (PV),[3] parity violating time reversal violation (PVTV) in the low energy N-N interaction can be described in terms of a nonrelativistic potential $V_{P,T}$ derived (ignoring two-pion exchange) from one-meson exchange diagrams involving the lightest pseudoscalar and vector mesons. PVTV in the N-N interaction is parametrized in this description by the strength $\overline{g}_{MNN}^{(I)\prime}$ of the $\mathrm{N} \to \mathrm{NM}$ matrix elements of the various isospin (I) components of the effective PVTV flavor conserving nonleptonic Hamiltonian:

$$\langle MN|H_{P,T}^{(I)}|N\rangle \;\propto\; \overline{g}_{MNN}^{(I)\prime}\,. \tag{1}$$

The set of mesons that can contribute to $V_{P,T}$ includes $\pi^{\pm}$, π^0, η, ρ and ω. There is a difference here with respect to PV, where the exchange of π^0 and η does not contribute to the P-violating potential V_P. Another difference is that PVTV pion-exchange exists for all the possible ($\mathrm{I} \leq 2$) isospin components of $H_{P,T}$, while V_P receives a pion-exchange contribution only from the isovector component of H_P. In the following we shall consider only the pion-exchange PVTV potentials, since for comparable PVTV $\mathrm{N} \to \mathrm{NM}$ coupling constants these provide the dominant contribution to $V_{P,T}$.[4]

The PVTV pion exchange potentials[5] are generated by the three independent P,T-violating πNN couplings[6]

$$L_{P,T}^{(I=0)} = \overline{g}_{\pi NN}^{(0)\prime} \, \overline{N} \vec{\tau} N \cdot \vec{\pi} \, , \tag{2}$$

$$L_{P,T}^{(I=1)} = \overline{g}_{\pi NN}^{(1)\prime} \, \overline{N} N \pi^0 \, , \tag{3}$$

$$L_{P,T}^{(I=2)} = \overline{g}_{\pi NN}^{(2)\prime} \, \overline{N} (3\tau_z \pi^0 - \vec{\tau} \cdot \vec{\pi}) N \, , \tag{4}$$

where the τ's are the isospin Pauli matrices.

2.1.1. Limits on $\overline{g}_{\pi NN}^{(I)\prime}$ from non-nuclear observables.

The most stringent bounds come from the experimental limits on the electric dipole moment of the neutron d_n and on the electric dipole moment of some atoms and molecules.

Neutron Electric Dipole Moment. The experimental limit on the electric dipole moment of the neutron is[7]

$$|(d_n)_{expt}| < 1.1 \times 10^{-25} \text{ ecm} \qquad (95\% \ c.l.) \, . \tag{5}$$

A dimensional argument[8] gives for the contribution of $\overline{g}_{\pi NN}^{(I)\prime}$ to d_n the size $d_n \simeq (e/m_N) \, \overline{g}_{\pi NN}^{(I)\prime} \simeq 2 \times 10^{-14} \, g_{\pi NN}^{(I)\prime}$ ecm, which would imply $|\overline{g}_{\pi NN}^{(I)\prime}| \lesssim 6 \times 10^{-12}$. A defensible calculation of d_n in terms of the PVTV πNN constants was made in Ref. 9 employing sidewise dispersion relations. The dominant contribution comes from the PVTV $\pi^{\pm} NN$ couplings. The calculation yielded $d_n \simeq 9 \times 10^{-15} (\overline{g}_{\pi NN}^{(0)\prime} - \overline{g}_{\pi NN}^{(2)\prime})$ ecm. The contribution of the $\pi^0 N$ intermediate state has not been yet calculated. Although this contribution to d_n is expected to be small relative to the charged pion contribution (owing to the smallness of the experimental cross-section for neutral pion photoproduction at threshold), it is nevertheless of interest, since the I=1 PVTV coupling does not involve the charged pions. From the two independent $\pi^0 NN$ coupling constants

$$\overline{g}'_{\pi pp} = (\overline{g}_{\pi NN}^{(0)\prime} + \overline{g}_{\pi NN}^{(1)\prime} + 2\overline{g}_{\pi NN}^{(2)\prime}) \, , \tag{6}$$

$$\overline{g}'_{\pi nn} = (-\overline{g}_{\pi NN}^{(0)\prime} + \overline{g}_{\pi NN}^{(1)\prime} - 2\,\overline{g}_{\pi NN}^{(2)\prime}) \tag{7}$$

(which are the coefficient of the $\pi^0 pp$ and $\pi^0 nn$ terms in Eqs. (2)-(4)) only $\overline{g}'_{\pi nn}$ contributes to d_n. Including formally this contribution, we have

$$d_n \simeq 9 \times 10^{-15} \, (\overline{g}_{\pi NN}^{(0)\prime} + k\,\overline{g}_{\pi NN}^{(1)\prime} - \overline{g}_{\pi NN}^{(2)\prime}) \, , \tag{8}$$

where k is a constant smaller than unity, possibly as small as ~ 0.1. The experimental limit (5) implies

$$|\overline{g}_{\pi NN}^{(0)\prime} + k\,\overline{g}_{\pi NN}^{(1)} - \overline{g}_{\pi NN}^{(2)\prime}| < 1.2 \times 10^{-11} \, . \tag{9}$$

In Ref. 10 it was shown that in the $m_\pi \to 0$ limit the most singular contribution to d_n arises solely from the $\pi^- p$ intermediate state. The size of this contribution turns out to be very close to the value in (8).

A new experiment in preparation at the Institut Laue Langevin[11] is expected to improve the current limit on d_n by a factor of 5, and a proposed experimental technique offers the possibility of an additional improvement by about a factor of 400 (Ref. 12).

Atomic and Molecular Electric Dipole Moments. The electric dipole moments (EDM) of atoms and molecules are sensitive to PVTV in the N-N interaction through the Schiff moment of the nucleus, which is induced by the nuclear electric dipole moment, and (for nuclei with ground state spin larger than $\frac{1}{2}$) through the nuclear magnetic quadrupole moment.[13,14]

The most stringent limit on the constants $\overline{g}^{(I)\prime}_{\pi NN}$ comes from the experimental limit on the EDM of the ^{199}Hg atom[15]

$$|d(^{199}Hg)| < 9 \times 10^{-28} \text{ ecm} \qquad (95\% \; c.l.) \; . \tag{10}$$

Atomic calculations[14,16] yield the relation $d(^{199}\text{Hg}) = -4 \times 10^{-17} Q_S(^{199}\text{Hg})$ ecm (efm^3)$^{-1}$ between the ^{199}Hg electric dipole moment and Schiff moment. $Q_S(^{199}\text{Hg})$ has been calculated in Ref. 14 using the PVTV N-N potential

$$W_{ab} = (G_F/2\sqrt{2}\, m_N) \, [(\eta_{ab}\, \vec{\sigma}_a - \eta_{ba}\, \vec{\sigma}_b)\vec{\nabla}_a \delta(\vec{r}_a - \vec{r}_b) + \eta'_{ab}\, \vec{\sigma}_a \times \vec{\sigma}_b \{\vec{p}_a - \vec{p}_b, \; \delta(\vec{r}_a - \vec{r}_b)\}_+] \; , \tag{11}$$

where $\vec{\sigma}_k$, $\vec{r}_k$ and $\vec{p}_k (k = a, b; \; a = n, p; \; b = n, p)$ are the spin, coordinates and momenta of nucleons a and b, obtaining

$$Q_S(^{199}Hg) = 1.4 \times 10^{-8} \, \eta_{np} \text{ efm}^3 \; . \tag{12}$$

The contribution of the PVTV $\pi^0 NN$ couplings to the constants η_{ab} and η'_{ab} can be obtained by comparing the potential (11) with the zero-range limit of the PVTV pion exchange potentials given in Ref. 5. We find

$$(\eta_{pp})_{\pi^0} = -(\eta_{np})_{\pi^0} = (\sqrt{2}\, g_{\pi NN}/G_F\, m_\pi^2) \, \overline{g}'_{\pi pp} \; , \tag{13}$$

$$(\eta_{nn})_{\pi^0} = -(\eta_{pn})_{\pi^0} = -(\sqrt{2}\, g_{\pi NN}/G_F\, m_\pi^2) \, \overline{g}'_{\pi nn} \; , \tag{14}$$

$$(\eta'_{ab})_{\pi^0} = 0 \qquad (a = n, p; \;\; b = n, p) \; , \tag{15}$$

where $g_{\pi NN}$ is the strong πNN coupling constant, and $\overline{g}'_{\pi pp}$ and $\overline{g}'_{\pi nn}$ are given in Eqs. (6) and (7). In the local (zero-range) limit the potential (11) accounts also for the charged pion contribution,[14] but the corresponding constants η_{ab} and η'_{ab} have not been worked out yet. Ignoring the charged-pion contribution, we obtain from Eqs. (12) (13) and (10) the bound

$$|\overline{g}^{(0)\prime}_{\pi NN} + \overline{g}^{(1)\prime}_{\pi NN} + 2\overline{g}^{(2)\prime}_{\pi NN}| < 1.8 \times 10^{-11} \; . \tag{16}$$

An improvement of the limit (16) by a factor of 10 seems possible.[12] A new calculation of $d(^{199}\text{Hg})$ using the two-body pion exchange potentials is in progress.[17] Experimental limits[18] and the pertinent calculations[14] are available also for the electric dipole moments of the ^{129}Xe atom and of the $T\ell F$ molecule. The corresponding bounds on the PVTV πNN constants are weaker than the bound in (16) by factors of ~ 300 and ~ 25, respectively. It should be noted however that $d(T\ell F)$ probes a combination of the PVTV πNN constants which is different from the one in (16).

2.1.2. Nuclear Physics Probes of PVTV in the N-N Interaction.

Among nuclear processes the most promising candidate for investigation of PVTV in the N-N interaction is the transmission of polarized neutrons through polarized targets. In the presence of a PVTV interaction the neutron-nucleus forward scattering amplitude contains a term proportional to $\langle\vec{\sigma}_n\rangle \cdot \vec{k}_n \times \langle\vec{J}\rangle$ ($\vec{\sigma}_n$ and $\vec{k}_n$ are the neutron spin and momentum, $\vec{J}$ is the spin of the target nucleus).[19] A PVTV observable is the quantity $\rho_{P,T} \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where $\sigma_+(\sigma_-)$ is the total neutron-nucleus scattering cross-section for a neutron polarized parallel (antiparallel) to $\vec{k}_n \times \langle\vec{J}\rangle$. A PV effect (due to the $\langle\vec{\sigma}_n\rangle \cdot k_n$ term) is the quantity $\rho_P \equiv (\sigma'_+ - \sigma'_-)/(\sigma'_+ + \sigma'_-)$, where $\sigma'_+(\sigma'_-)$ is the total neutron-nucleus cross-section for neutrons polarized parallel (antiparallel) to its momentum. Very large values of ρ_P have been observed near p-wave compound nucleus resonances (7×10^{-2} for the 0.734 eV p-wave resonance in ^{139}La).[20] Such large effects are the result of "dynamical" and "resonance" enhancements.[21] These enhancement factors are effective also for $\rho_{P,T}$, and therefore one can expect that the best candidates for PVTV searches are resonances for which ρ_P is large.

Assuming two-state mixing the ratio $\lambda = \rho_{P,T}/\rho_P$ is given by[21,22] $\lambda = n_J\langle\psi_s|V_{P,T}|\psi_p\rangle/\langle\psi_s|V_P|\psi_p\rangle$, where ψ_s and ψ_p are s- and p-states of the compound nucleus, and n_J is a factor which depends on the p-wave compound resonance spin and on the ratio of the neutron width of the p-wave resonance for the different channel spins.[23]

Let us consider λ for the I=1 PVTV pion exchange potential $V_{P,T}^{\pi(1)}$. For V_P it is adequate to take the I=0 P-violating ρ-exchange potential $V_P^{\rho(0)}$. We shall assume that $n_J \simeq 1$ and write

$$\lambda = \lambda^{(1)} \simeq \langle\psi_s|V_{P,T}^{\pi(1)}|\psi_p\rangle/\langle\psi_s|V_P^{\rho(0)}|\psi_p\rangle = \kappa^{(1)}\, \overline{g}_{\pi NN}^{(1)\prime}/g_{\rho NN}^{(0)\prime}\ , \tag{17}$$

where $\overline{g}_{\rho NN}^{(0)\prime} \simeq 2\times10^{-6}$ is the I=0 PV ρNN coupling constant. Assuming that $V_{P,T}^{\pi(1)}$ and $V_P^{\rho(0)}$ can be approximated by one-body potentials, the constant $\kappa^{(1)}$ is given by[24]

$$\kappa^{(1)} \simeq 31.7\beta\ , \tag{18}$$

where

$$\beta = \langle\psi_s|\vec{\sigma}\cdot(\vec{r}/r)\,(\partial\rho_n/\partial r)\,\tau_z|\psi_p\rangle/\langle\psi_s|\vec{\sigma}\cdot\vec{p}\,\rho_n|\psi_p\rangle\ . \tag{19}$$

In Eq. (19) ρ_n is the nucleon density in the nucleus, and $\vec{\sigma}$, $\vec{p}$, $\vec{r}$ and τ_z are single-particle operators; $r = |\vec{r}|$. Based on the investigations in the first paper of Ref. 4 and in Refs. 25 and 26, a reasonable value of β to use for estimates appears to be $\beta \simeq 0.2$. With this value the limit (16) implies

$$\lambda^{(1)} \lesssim 6\times10^{-5}\ . \tag{20}$$

For the $\overline{g}_{\pi NN}^{(0)\prime}$ and $\overline{g}_{\pi NN}^{(2)\prime}$ interactions the limits on the corresponding λ's are stronger than (20) by factors of A/(N-Z) and A/2(N-Z), respectively. Assuming that there are no cancellations in Eqs. (9) and (16), the implication is that to compete with the limit (16), $\rho_{P,T}$ has to be measured for $\rho_P = 7\times10^{-2}$ with a sensitivity of 4×10^{-6}.

A measurement of $\rho_{P,T}$ was carried out in the experiment of Ref. 27, using a polarized ^{165}Ho target and 7-12 MeV incident neutrons. The experiment yielded $|\rho_{P,T}| < 5\times10^{-3}$ (95% c.l.). A measurement of the P-violating effect has also been performed, with the result $|\rho_P| < 5\times10^{-4}$ (95% c.l.). The implications for the P,T-violating πNN constants are not known. A neutron spin rotation experiment to search for PVTV is under preparation at KEK.[28]

In γ-decay and β-decay PVTV in the N-N interaction gives rise to contributions to T-odd correlations in the decay probability. In γ-decay PVTV has been searched for in a transition in ^{180}Hf (Ref. 29), where the PV effect is unusually large. For the $\overline{g}^{(1)}_{\pi NN}$ interaction the sensitivity of this experiment would have to be improved by four orders of magnitude to compete with the limit (16).[24] This appears to be beyond reach in the foreseeable future.[30] The same is true for an otherwise attractive case in ^{182}W (Ref. 30).

In β-decay an enhancement by 2-3 orders of magnitude of the effect due to PVTV in the N-N interaction can occur in some cases for first forbidden beta decays where the beta decay from the admixed state is superallowed or allowed.[31] The implication of the bounds (9) and (16) is that even with such enhancements the expected size of the PVTV effect would be about four orders of magnitude below where the effects of the final state interactions can be expected.

2.1.3. PVTV in the N-N Interaction in Models with CP-Violation.

The Standard Model. In the SM there are two sources of CP-violation: the Kobayashi-Maskawa (KM) phase δ_{KM} in the quark mixing matrix and the PVTV θ-term in the QCD Langrangian.

The KM phase contributes to PVTV in the N-N interaction only in second order in the weak interaction. The dominant diagrams have been found to be the K-exchange diagrams involving weak baryon-nucleon transitions.[32] The strength of the corresponding four-nucleon interaction is $\sim 10^{-9}\,G_F$, to be compared with the present limit of $\sim 10^{-3}\,G_F$ from $d(^{199}\mathrm{Hg})$.

The θ-term is isospin invariant, and therefore it induces only an isoscalar πNN coupling. The constant $\overline{g}^{(0)}_{\pi NN}$ has been calculated in Ref. 10 using PCAC and current algebra, obtaining $|\overline{g}^{(0)\prime}_{\pi NN}| \simeq 0.027|\theta|$. The best limit on $|\overline{g}^{(0)\prime}_{\pi NN}|$ is from d_n (Eq. (9)), which implies

$$|\theta| < 4 \times 10^{-10}\,. \qquad (21)$$

Left–Right Symmetric Models. These models[33] provide a framework for the understanding of parity violation in the weak interactions. The simplest models are based on the gauge group $SU(2)_L\times SU(2)_R\times U(1)_{B-L}$. In $SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ models there is a PVTV flavor conserving nonleptonic interaction first order in the weak interaction. The part of this interaction involving the u, d quarks, which presumably dominates the $N \to N\pi$ matrix elements, is a pure isovector.[34] The constant $\overline{g}^{(1)\prime}_{\pi NN}$ is of the form $\overline{g}^{(1)\prime}_{\pi NN} = G_F\, m_\pi^2 k \zeta_{g\theta}$ $\sin(\alpha+\omega)$, where k is a constant, $\zeta_{g\theta} = (g_R/g_L)(\cos\theta_1^R/\cos\theta_1^L)\zeta$, ζ is the $W_L - W_R$ mixing angle, θ_1^R and θ_1^L are quark mixing angles in the right-handed and left-handed sectors, α and ω are CP-violating phases. The bound (16) implies

$$|\zeta_{g\theta}\,\sin(\alpha+\omega)| < 8.5 \times 10^{-5}/k. \qquad (22)$$

Calculations[35] find values of k in the range from ~ 4 to ~ 270. Quark model calculations of d_n lead to upper limits on $|\zeta_{g\theta}\,\sin(\alpha+\omega)|$ as weak as $\sim 10^{-3}$ and as strong as $\sim 3\times 10^{-5}$. The experimental limit on $Re\epsilon'/\epsilon$ and the calculation in Ref. 36 yields $|\zeta_{g\theta}\,\sin(\alpha+\omega)| \lesssim 10^{-}$. An upper limit of 10^{-3} on $|\zeta_{g\theta}\,\sin(\alpha+\omega)|$, which is free of theoretical uncertainties, is provided by beta decay (see Section 3).

Models with Exotic Fermions. A PVTV flavor conserving nonleptonic interaction for the u, d quarks of the same structure as in left-right symmetric models can arise[37] also in models with exotic fermions (fermions with noncanonical $SU(2)_L \times U(1)$ assignments).[38] The parameter $\zeta_{g\theta}\,\sin(\alpha+\omega)$ is replaced in this case by $Im[s_R^u s_R^d (\hat{V}_R)_{ud}]$, where $s_R^{u,d} \equiv \sin\theta_R^{u,d}$, $\theta_R^{u,d}$ are light-heavy mixing angles, and $\hat{V}_R$ is a generation mixing matrix. The limits on $Im[s_R^u s_R^d (\hat{V}_R)_{ud}]$ are the same as on $\zeta_{g\theta}\,\sin(\alpha+\omega)$.

Multi-Higgs Models. Higgs sectors containing two or more Higgs doublets arise in many extensions of the Standard Model. Such models can contain CP-violating interactions mediated by Higgs bosons. An example is the Weinberg model,[39] which contains three Higgs doublets. In this model flavor changing neutral current Higgs interactions are absent, and therefore the Higgs bosons can be relatively light, and with unsuppressed couplings. Both d_n and $d(^{199}Hg)$ can have values near the present experimental limits (see Ref. 40).

Supersymmetric Models. In supersymmetric models there are new CP-violating phases, which can contribute to the electric dipole moments. In the supersymmetric standard model d_n and $d(^{199}Hg)$ can have values near the present experimental limits (see Ref. 40).

We note yet that stringent limits from the electric dipole moments are available on the coefficients of various effective PVTV operators.[41]

2.2. Parity Conserving Time Reversal Violation

The lightest meson contributing to the parity conserving time reversal violating (PCTV) N-N potentials is the $\rho^{\pm}$ (Ref. 42). The PCTV ρNN coupling has the form[43]

$$\mathcal{L}_T^{(\rho NN)} = (\overline{g}_{\rho NN}/2m_N)\,\overline{N}\sigma^{\lambda\nu} q_\nu(\rho_\lambda^+ \tau^- - \rho_\lambda^- \tau^+)N\ , \tag{23}$$

where $\overline{g}_{\rho NN}$ is the PCTV ρNN coupling constant. The next meson-exchange contribution is from the $A_1^{\pm,0}$.

A dimensional argument[8] suggests for the contribution of (23) the size $d_n \simeq (e/m_N)$ $(G_F m_N^2/4\pi)\overline{g}_{\rho NN} \simeq 2\times 10^{-20}\,\overline{g}_{\rho NN}$, which would imply $|\overline{g}_{\rho NN}| \lesssim 6\times 10^{-6}$. A calculation[44] of the contribution of $\overline{g}_{\rho NN}$ to d_n gives $|\overline{g}_{\rho NN}| \lesssim 1\times 10^{-2}$ (95% c.l.). The limits from $d(^{199}Hg)$ are weaker.[44]

From nuclear processes a limit of $|\overline{g}_{A_1 NN}| \lesssim 0.17$ (95% c.l.) is implied by a study of a γ-transition in ^{57}Fe (Ref. 45). The limit from studies of detailed balance and nuclear energy-level fluctuations in compound nuclei is $|\overline{g}_{\rho NN}| \lesssim 2.5$. An experiment[46] measuring neutron transmission (the $(\vec{\sigma}_n\cdot\vec{k}_n\times\vec{J})(\vec{k}_n\cdot\vec{J})$ term) in ^{165}Ho yields $|\overline{g}_{\rho NN}| \lesssim 23$ (Ref. 47). It is anticipated that the latter limit will be improved by a factor of ~ 150. In suppressed beta decays it may be possible to obtain limits on $\overline{g}_{\rho NN}$ similar to those from γ-decay.[48]

An example of a PCTV flavor conserving interaction at the quark level is

$$H = (g_X^2/m_X^2)(1/2m_N)\partial_\nu(\overline{u}\sigma_{\mu\nu} i\gamma_5 u)\overline{d}\gamma_\mu\gamma_5 d\ , \tag{24}$$

where m_X is the mass of the boson mediating the interaction. In Ref. 49 a limit of $g_X^2 \lesssim 4 \times 10^{-6}$ has been set on g_X^2 from two-loop contributions to d_n involving the interaction (24) and Z-exchange. Similar limits follow for other PCTV interactions. If $\overline{g}_{\rho NN} \simeq (g_X^2/m_X^2)m_\rho^2$, this implies $|\overline{g}_{\rho NN}| \lesssim (2 \times 10^{-6}\ \mathrm{GeV}^2)/m_X^2$ ($|\overline{g}_{\rho NN}| \lesssim 3 \times 10^{-10}$ for $m_X \geq m_W$).

In renormalizable gauge theories flavor-conserving ($\Delta f = 0$) PCTV quark-quark (q-q) interactions are fundamentally different from $\Delta f = 0$ PVTV q-q interactions: while in some extensions of the SM (e.g. in left-right symmetric models) $\Delta f = 0$ PVTV q-q interactions can occur in second order in the boson-fermion couplings, this is not so for $\Delta f = 0$ PCTV q-q interactions. For the PCTV case one can prove[50] that neglecting the θ-term $\Delta f = 0$ PCTV q-q interactions are absent to order $g_\alpha^{(i)} g_\alpha^{(j)}$, where Y_α is any boson mass-eigenstate other than a gluon and a photon from the set $\{Y_\alpha\}(\alpha = 1, 2 \ldots)$ in the theory, and $g_\alpha^{(i)}$ and $g_\alpha^{(j)}(i = 1, 2, \ldots;\ j = 1, 2, \ldots)$ are the coupling constants of Y_α to the bilinears involving the fermion mass-eigenstates. This conclusion holds to all orders in the CP-invariant component of the QCD interactions and to all orders in the QED interactions. Consequently, without the θ term the lowest order in which $\Delta f = 0$ PCTV q-q interactions can be induced is the fourth order in the boson-fermion and boson-boson coupling constants: through diagrams involving three Y_α-fermion and one three-boson couplings (triangle-type diagrams), or through diagrams with four Y_α-fermion couplings (box diagrams). For example, the interaction (24) can be induced by a triangle-type X-exchange diagram.[50] The two-loop contributions of (24) to d_n become then three-loop diagrams and, as we note in Ref. 50, the corresponding limit from d_n will have to be therefore reexamined. The maximal size of the strength of a triangle diagram is of the order of $(1/8\pi^2)(q/M)(|\bar{g}^4|/M_X^2)$, where M is the mass of the heaviest particle in the triangle, and $\bar{g}^4$ is a product of four coupling constants. A rough estimate of $\overline{g}_{\rho NN}$ is $\overline{g}_{\rho NN} \simeq (1/8\pi^2)(m_N/M)(m_\rho^2/m_X^2)|\bar{g}|^4 \sin\phi$, where ϕ is a CP-violating phase. With $|\bar{g}|^4 = (e/\sin\theta_W)^4$ one would have $|\overline{g}_{\rho NN}| \lesssim 2 \times 10^{-9}$ for $M \geq m_W,\ M_X \geq m_W$. Presently we are investigating the constraints on some models where X is very light, with a mass of the order of a few GeV (Ref. 51).

3. Time Reversal Violation in Beta Decay

T-violating contributions to beta decay can arise also from T-violating charged current quark-lepton interactions. Experimental information is available on the coefficients D and R of the correlations $\langle \vec{J} \rangle \cdot \vec{p}_e \times \vec{p}_\nu / J E_e E_\nu$ and $\langle \vec{\sigma} \rangle \cdot \langle \vec{J} \rangle \times \vec{p}_e / J E_e$ ($\vec{\sigma} \equiv$ electron spin, $\vec{J} \equiv$ nuclear spin), respectively.

The D–Coefficient. To lowest order in the new interactions the T-violating contribution D_t to the D-coefficient is given by[52]

$$D_t \simeq a_D\, Im\eta_{LR}\ , \tag{25}$$

where η_{LR} is the strength of an interaction involving a V-A leptonic and a V+A quark current relative to $G_F/\sqrt{2}$, and a_D is a constant involving the nuclear matrix elements. The present experimental limit on $Im\eta_{LR}$ from beta decay is

$$|Im\eta_{LR}| < 1.1 \times 10^{-3} \qquad (95\%\ c.l.) \qquad (26)$$

In the Standard Model T-violating lepton-quark interactions arise only in second order in the weak interaction or in order θG_F, and therefore they are expected to be unobservably small. A nonzero $Im\eta_{LR}$ can arise at the tree level in models involving right-handed gauge bosons (e.g. in left-right symmetric models), in models with exotic fermions, and in models with leptoquarks.[52] In left-right symmetric models and in exotic fermion models one has $Im\eta_{LR} = -\zeta_{g\theta}\sin(\alpha+\omega)$ and $Im\eta_{LR} = Im[s_R^u s_R^d (\hat{V}_R)_{ud}]$, respectively. As we have noted in Section 2.1.3, there are stringent limits on these parameters from the dipole moments, and from ϵ'/ϵ. Unlike the limit (26), these limits may involve unknown theoretical uncertainties. For the leptoquark contributions to $Im\eta_{LR}$ there are no significant limits from the electric dipole moments, nor from ϵ'/ϵ. New experiments to search for T-violation in neutron decay[53] and ^{19}Ne decay[54] are under preparation, aiming at improving the limit (26) by about an order of magnitude.

The R–Coefficient. The R-coefficient is sensitve to T-violating scalar and tensor interactions. Scalar interactions can arise from charged Higgs exchange, slepton exchange (in R-parity violating supersymmetric models) and from leptoquark exchange.[52] A recent measurement of R in ^{8}Li decay yielded a limit of $\sim 10^{-2}G_F$ on tensor interactions.[55] Indirect limits on scalar and tensor interactions derived[56,41] from the experimental bounds on PVTV e-N interactions are more stringent by ~ 2 and ~ 3 orders of magnitude, respectively. However the theoretical uncertainties associated with these limits could be large.[56,41]

4. Conclusions

The PVTV N-N interaction is dominated (for comparable coupling constants) by pion exchange. The experimental bounds on the electric dipole moment of the neutron and of the ^{199}Hg atom set stringent limits on the PVTV πNN coupling constants. It appears that from nuclear physics processes only neutron transmission remains as a possible candidate for improving these limits. Based on the existing calculations, and barring cancellations in d_n and $d(^{199}\mathrm{Hg})$, in a case where the PV asymmetry is 7×10^{-2} the PVTV asymmetry would have to be measured with a sensitivity of 4×10^{-6} to compete with the existing limits.

The PCTV N-N interaction is governed by $\rho^{\pm}$-exchange and the exchange of heavier mesons. The best limit on the PCTV ρNN coupling constant ($|\overline{g}_{\rho NN}| \lesssim 10^{-2}$, and possibly a much more stringent limit) comes from the electric dipole moment of the neutron. The theoretical expectation for PCTV in the N-N interaction is that it is small, most likely below the strength of the weak interaction, and probably considerably so.

Searches for the D-coefficient in beta decay constrain left-right symmetric models, models with exotic fermions, and models with leptoquarks. The leptoquark contribution to D can be as large as the present experimental limit for D. In the other models more stringent limits on $Im\eta_{LR}$ (see Eq. 25) than from the D-coefficient have been derived from the experimental bounds on $d(^{199}\text{Hg})$, d_n and ϵ'/ϵ. However these limits are not as reliable as the direct limits, in view of the uncertainties in the calculations.

Searches for the R-coefficient provide information on scalar- and tensor-type T-violating interactions. For such interactions stringent limits have been deduced from the experimental bound on the PVTV tensor e-N interaction. However the theoretical uncertainties associated with these limits may be large.

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References

1. R. Carosi *et al.*, Phys. Lett. B **237**, 303 (1990); M. Karlsson *et al.*, Phys. Rev. Lett. **64**, 2976 (1990); M. Dejardin, in these Proceedings.
2. This talk is an abbreviated version of the review article P. Herczeg, "Time Reversal Violation in Nuclear Processes," in *Symmetries and Fundamental Interactions in Nuclei*, edited by W. C. Haxton and E. M. Henley, to be published by World Scientific. We refer the reader to this article for a more detailed discussion and more complete references.
3. For a review see E. G. Adelberger and W. C. Haxton, Ann. Rev. Nucl. Part. Sci. **35**, 501 (1985).
4. I. S. Towner and A. C. Hayes, Phys. Rev. C **49**, 2391 (1994); V. P. Gudkov, X-G. He, and B. H. J. McKellar, Phys. Rev. C **47**, 2365 (1993).
5. W. C. Haxton and E. M. Henley, Phys. Rev. Lett. **51**, 1937 (1983); P. Herczeg, in *Tests of the Time Reversal Invariance in Neutron Physics*, ed. N. R. Robertson, C. R. Gould and J. D. Bowman (World Scientific, Singapore, 1987), p. 24.
6. G. Barton, Nuovo Cim. **19**, 512 (1961).
7. I. S. Altarev *et al.*, Phys. Lett. B **276**, 242 (1992); K. F. Smith *et al.*, Phys. Lett. B **234**, 191 (1990); see also Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994).
8. See e.g. L. Wolfenstein, Nucl. Phys. **B77**, 375 (1974).
9. G. Barton and E. G. White, Phys. Rev. **184**, 1660 (1969).
10. R. H. Crewther, P. di Vecchia, G. Veneziano, and E. Witten, Phys. Lett. B **88**, 123 (1979); Phys. Lett. B **91**, 487(E) (1980).
11. J. M. Pendlebury, in these Proceedings.
12. S. K. Lamoreaux and R. Golub, in these Proceedings.
13. G. Feinberg, Trans. N. Y. Acad. Sci. **28**, 6 (1977); W. C. Haxton and E. M. Henley, Ref. 5; P. V. Coveney and P. G. H. Sandars, J. Phys. **B16**, 3727 (1983); V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Zh. Eksp. Teor. Fiz. **87**, 1521 (1984) [Sov. Phys. JETP **60**, 873 (1984)].
14. V. V. Flambaum, I. B. Khriplovich and O. P. Sushkov, Phys. Lett. B **162**, 213 (1985); Nucl. Phys. **A449**, 750 (1986).
15. J. P. Jacobs, W. M. Klipstein, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson, to be submitted to Phys. Rev. A.
16. A.-M. Mårtensson-Pendrill, Phys. Rev. Lett. **54**, 1153 (1985).
17. W. C. Haxton and K. Lee, in preparation, reported in W. C. Haxton, invited talk at the First International Symposium on Symmetries in Subatomic Physics, May 16-18, 1994,

Taipei, Taiwan, R.O.C., PRINT-94-0203, Univ. of Washington, Seattle, to appear in the Proceedings.
18. See T. G. Vold, F. J. Raab, B. Heckel, and E. N. Fortson, Phys. Rev. Lett. **52**, 2229 (1984) for $d(^{129}Xe)$, and D. Cho, K. Sangster, and E. A. Hinds, Phys. Rev. A **44**, 2783 (1991) for $d(T\ell F)$.
19. P. K. Kabir, Phys. Rev. D **25**, 2013 (1982); L. Stodolsky, Nucl. Phys. **B197**, 213 (1982).
20. For a review see S. J. Seestrom, in these Proceedings.
21. V. E. Bunakov and V. P. Gudkov, Nucl. Phys. **A401**, 93 (1983).
22. V. E. Bunakov and V. P. Gudkov, Z. Phys. A **308**, 363 (1982).
23. V. P. Gudkov, Phys. Lett. B **243**, 319 (1990); C. R. Gould *et al.*, Int. J. Mod. Phys. A **5**, 2181 (1990); see also Ref. 21.
24. For more details and for the pertinent references see P. Herczeg, Ref. 2.
25. A. Griffiths and P. Vogel, Phys. Rev. C **44**, 1195 (1991).
26. I. B. Khriplovich, preprint BINP 95-13, February 1995, Budker Institute of Nuclear Physics, Novosibirsk, Russia.
27. J. P. Soderstrum *et al.*, Phys. Rev. C **38**, 2424 (1988).
28. Y. Masuda, in these Proceedings.
29. B. T. Murdoch, C. E. Olsen, S. S. Rosenblum, and W. A. Steyert, Phys. Lett. B **52**, 325 (1974).
30. For a review see F. Boehm, in *Symmetries and Fundamental Interactions in Nuclei*, edited by W. C. Haxton and E. M. Henley, to be published by World Scientific.
31. E. M. Henley and I. B. Khriplovich, Phys. Lett. B **289**, 223 (1992).
32. V. V. Flambaum, I. B. Khriplovich and O. P. Sushkov, Zh. Eksp. Teor. Fiz. **87**, 1521 (1984) [Sov. Phys. JETP **60**, 873 (1984)]; J. F. Donoghue, B. R. Holstein and M. J. Musolf, Phys. Lett. B **196**, 196 (1987); V. M. Khatsymovsky, I. B. Khriplovich, and A. S. Yelkovsky, Ann. Phys. **186**, 1 (1988); X-G. He and B. McKellar, Phys. Rev. D **46**, 2131 (1992).
33. J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975); **11**, 2558 (1975); G. Senjanović, and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975).
34. P. Herczeg, Ref. 5.
35. V. E. Bunakov and V. P. Gudkov, in the *Proceedings of the LNPI Winter School on High Energy Physics*, Leningrad, 1985, p. 189; Leningrad preprint LNPI-1064 (1985) (see also V. P. Gudkov, Phys. Lett. B **243**, 319 (1990)); V. M. Khatsymovsky *et al.*, Ref. 32; X-G. He and B. McKellar, Ref. 32; Phys. Rev. D **47**, 4055 (1993); S. M. Barr, Int. J. Mod. Phys. **A 8**, 209 (1993). For quark model calculations of d_n see G. Beall and A. Soni, Phys. Rev. Lett. **47**, 552 (1981); G. Ecker, W. Grimus and H. Neufeld, Nucl. Phys. **B229**, 421; 1983; X-G. He, B. H. J. McKellar, and S. Pakvasa, Phys. Rev. Lett. **61**, 1267 (1988); Int. J. Mod. Phys. A **4**, 5011 (1989).
36. X-G. He and B. H. J. McKellar, Phys. Rev. Lett. **61**, 1267 (1988).
37. P. Herczeg, in *Progress in Nuclear Physics*, edited by W-Y. Pauchy Hwang *et al.* (North-Holland, New York, 1991), p. 171.
38. For a review see D. London, in *Precision Tests of the Standard Electroweak Model*, Advanced Series on Directions in High Energy Physics, edited by P. Langacker (World Scientific, Singapore, 1995), p. 951.
39. S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
40. S. M. Barr, Ref. 35; X-G. He and B. McKellar, Ref. 32.
41. For a review see I. B. Khriplovich, in these Proceedings.
42. M. Simonius, Phys. Lett. B **58**, 147 (1975).
43. M. Simonius and D. Wyler, Nucl. Phys. **A286**, 182 (1977).
44. W. C. Haxton, A. Höring, and M. J. Musolf, Phys. Rev. D **50**, 3422 (1994).

45. M. Beyer, Phys. Rev. C 48, 906 (1993).
46. J. E. Koster *et al.*, Phys. Lett. B **267**, 23 (1991).
47. J. Engel, C. R. Gould, and V. Hnizdo, Phys. Rev. Lett **73**, 3508 (1994).
48. A. Barroso and R. J. Blin-Stoyle, Phys. Lett B **45**, 178 (1973).
49. R. S. Conti and I. B. Khriplovich, Phys. Rev. Lett. **68**, 3262 (1992).
50. P. Herczeg, J. Kambor, M. Simonius, and D. Wyler, "Parity Conserving Time Reversal Violation in Flavor Conserving Quark-Quark Interactions," to be published.
51. P. Herczeg, J. Kambor, M. Simonius, and D. Wyler, in preparation.
52. For a review see P. Herczeg, in *Precision Tests of the Standard Electroweak Model*, Advanced Series on Directions in High Energy Physics, edited by P. Langacker (World Scientific, 1995), p. 786.
53. E. Wasserman, in these Proceedings.
54. A. Young, in these Proceedings.
55. J. Sromicki, in these Proceedings.
56. I. B. Khriplovich, Nucl. Phys. **B352**, 385 (1991).