LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR -88-3568

LA-UR--88-3568

DE89 002298

TITLE T-VIOLATION IN NUCLEAR INTERACTIONS -- AN OVERVIEW

AUTHOR(S) Peter Herczeg, T-5

SUBMITTED TO Invited talk presented at the "Workshop on On-line Nuclear Orientation and Related Topics", Oxford, England, August 31 - September 4, 1988. To appear in the Proceedings (to be published in Hyperfine Interactions).

MASTER

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

T-VIOLATION IN NUCLEAR INTERACTIONS-AN OVERVIEW

Peter Herczeg

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

We discuss time-reversal-violation in the nucleon-nucleon interaction, both parity-conserving and with simultaneous parity violation, and consider its effects in some low-energy nuclear processes.

1. INTRODUCTION

CP-violation was discovered twenty-four years ago through the decays $K_L \to 2\pi$. The interaction responsible for this effect has not been identified yet. Despite the many searches for CP- and T-violating effects in various processes, CP-violation has been seen so far only in the neutral kaon system. The present experimental values of the parameters ϵ and ϵ' describing CP-violation in $K_L \to 2\pi$ decays (for a review see Ref. /1/) are $|\epsilon| = (2.27 \pm 0.02) \times 10^{-3}$ /2/, and $\epsilon'/\epsilon = (3.2 \pm 2.8 \pm 1.2) \times 10^{-3}$ /3/; $\epsilon'/\epsilon = (3.3 \pm 1.1) \times 10^{-3}$ /4/. On the basis of the CPT theorem one expects a CP-violating interaction to violate T-invariance. There is some indirect experimental evidence that the interaction responsible for ϵ has a T-violating component /5,6/.

A simple explanation of ϵ is provided by the superweak model /7/. This postulates the existence of a new interaction of strength $10^{-9}G$ (G = Fermi constant) that can change strangeness by two units. The superweak model predicts a negligible value for ϵ'/ϵ and unobservably small effects also in all other processes. A consequence is that if the evidence /4/ for a non-null result for ϵ'/ϵ is confirmed, the superweak model could not account for all CP-violation in the neutral kaon system.

The most economical explanation of the observed CP-violation is within the minimal standard electroweak model (the standard $SU(2)_L \times U(1)$ model /8/ with three generations of leptons and quarks, containing only left-handed neutrino fields, and with a Higgs sector consisting of a single Higgs doublet). For three quark generations the quark mixing matrix contains a CP-violating phase δ (the Kobayashi-Maskawa phase /9/). The parameters ϵ and ϵ' are generated in second and first order in the weak interactions, respectively. The model can account for the observed value of ϵ, and predicts $|\epsilon'/\epsilon| \sim 10^{-2} - 10^{-3}$ /1,10,11/, consistent with the experimental results.

Alternatively, the interaction responsible for the observed CP-violation may reside in an extension of the minimal standard model. Extensions of the minimal standard model may also contain new CP-violating interactions unrelated to the observed effect. All this underlines the importance of experiments searching for CP- and T-violating effects outside of the neutral kaon system. They probe further manifestations of the interaction responsible for the observed CP-violation, and also possible new CP-violating interactions.

In this talk we shall discuss the information provided by searches for T-violating effects in low-energy nuclear processes.[1] Such experiments probe T-violation in the nucleon-nucleon interaction, in the couplings of the photon to hadrons, and (in β-decay) in the couplings of leptons to hadrons. In the subsequent two sections we shall discuss T-violation in the N-N interactions, first with simultaneous P-violation, and then P-conserving T-violation. In both cases we consider the implications for P,T- and T-violation in nuclear γ-decay, which have not been to our knowledge discussed recently. Effects in other processes are considered only very briefly. In the last part we summarize our conclusions. Apart from some general remarks a discussion of T-violation in nuclear β-decay, which is sensitive also to T-violating semileptonic interactions, is not included in the talk. For this subject we refer the reader to a recent discussion in Ref. /18/.

2. P,T-VIOLATION IN THE N-N INTERACTION

In analogy with the usual treatment of parity-violation in the low-energy nucleon-nucleon interaction /19/, one can describe simultaneous violation of parity-conservation and time-reversal invariance (P,T-violation) in terms of nonrelativistic potentials derived from single meson exchange diagrams (ignoring two-pion exchange) involving the lightest pseudoscalar and vector mesons.[2] In this description P,T-violation in the N-N interaction is parametrized in terms of the strength $\bar{g}_{MNN}^{(I)}$ of the $N \to NM$ matrix elements of the various isospin (I) components of the effective P,T-violating flavor-conserving ($\Delta F = 0$) nonleptonic Hamiltonian:

$$\langle MN \mid H_{P,T}^{(I)} \mid N \rangle \propto \bar{g}_{MNN}^{(I)} . \tag{1}$$

The longest range P,T-violating potential is due to pion-exchange.[2] Pion-exchange contributes for all possible ($I \leq 2$) isospin components of $H_{P,T}$. This is in contrast with T-invariant P-violation, where pion-exchange is present only for an isovector Hamiltonian. The pion-exchange potentials provide therefore a sufficiently complete description of P,T-violation[2] in the low-energy N-N interaction, unless the constants $\bar{g}_{\pi NN}^{(I)}$ are relatively suppressed. We shall assume here that this is not the case, and neglect the contributions of heavier mesons.

[1] Early reviews of T-violation in nuclear processes include Refs. /5/, /12/ and /13/. More recent discussions of various aspects of the subject include Refs. /14/-/18/.

[2] There is also a long-range contribution from P,T-violating single-photon exchange, which is governed by the nucleon electric dipole moment form factor. This term has not been yet, to our knowledge, investigated. If P,T-violation is due to a term of strength ef' in the electromagnetic interaction, it is of the order of $e^2 f'/(\alpha/\pi) f' g_{\pi NN} \sim 10$ relative to pion-exchange, and therefore probably the most important. For nonelectromagnetic P,T-violation it is of the order of $e^2 g_{\pi NN} \sim 10^{-2}$; even then, whether its effects in nuclei can be neglected will have to be investigated. For f' the experimental limit on the electric dipole moment of the neutron (see Eq. (8)) indicates $|f'| < 10^{-11}$. We hope to discuss the P,T-violating photon exchange in a forthcoming communication.

The P,T-violating pion-exchange potentials $V^{P,T}_{\pi(I)}$ are of the form[3]

$$V^{P,T}_{\pi(0)} = -\frac{1}{8\pi}\frac{m_\pi^2}{M}\,\bar{g}^{(0)}_{\pi NN}\,g_{\pi NN}\,\vec{\tau}_1\cdot\vec{\tau}_2(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\hat{r}\,\frac{e^{-m_\pi r}}{m_\pi r}\left(1+\frac{1}{m_\pi r}\right) \qquad (2)$$

$$V^{P,T}_{\pi(1)} = -\frac{1}{16\pi}\frac{m_\pi^2}{M}\,\bar{g}^{(1)}_{\pi NN}\,g_{\pi NN}\Big[(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\hat{r}(\tau_{1z}+\tau_{2z}) + (\vec{\sigma}_1+\vec{\sigma}_2)\cdot\hat{r}(\tau_{1z}-\tau_{2z})\Big]\frac{e^{-m_\pi r}}{m_\pi r}\left(1+\frac{1}{m_\pi r}\right)\,, \qquad (3)$$

and

$$V^{P,T}_{\pi(2)} = \frac{1}{8\pi}\frac{m_\pi^2}{M}\,\bar{g}^{(2)}_{\pi NN}\,g_{\pi NN}(3\tau_{1z}\tau_{2z}-\vec{\tau}_1\cdot\vec{\tau}_2)(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\hat{r}\,\frac{e^{-m_\pi r}}{m_\pi r}\left(1+\frac{1}{m_\pi r}\right)\,, \qquad (4)$$

where M is the mass of the nucleon, $g_{\pi NN}$ is the strong coupling constant; $\vec{r}_k, \vec{\sigma}_k$ and $\vec{\tau}_k (k = 1,2)$ are, respectively, the coordinates, spin and isospin Pauli matrices of the two nucleons, $\hat{r} = (\vec{r}_1 - \vec{r}_2)/r$ and $r = |\vec{r}_1 - \vec{r}_2|$. The constants $\bar{g}^{(I)}_{\pi NN}$ are defined by the effective couplings

$$L^{(I=0)}_{P,T} = \bar{g}^{(0)}_{\pi NN}\bar{N}\vec{\tau}N\cdot\vec{\pi}\,, \qquad (5)$$

$$L^{(I=1)}_{P,T} = \bar{g}^{(1)}_{\pi NN}\bar{N}N\pi^0\,, \qquad (6)$$

$$L^{(I=2)}_{P,T} = \bar{g}^{(2)}_{\pi NN}\,\bar{N}(3\tau_z\pi^0 - \vec{\tau}\cdot\vec{\pi})N\,. \qquad (7)$$

What are the empirical constraints on the constants $\bar{g}^{(I)}_{\pi NN}$? A stringent bound on time-reversal violation in flavor-conserving hadronic interactions comes from the experimental limit on the electric dipole moment of the neutron /21/

$$|D_n| < 2.6\times 10^{-25}\,\mathrm{ecm} \qquad \text{(95\% confidence level).} \qquad (8)$$

If f_P and f_T represent the strength of P and T violation in flavor-conserving hadronic interactions, a rough estimate of D_n is given by /22/ $D_n \sim (e/M)f_P f_T \sim (2\times 10^{-14})f_P f_T$ ecm. Taking $\bar{g}^{(I)}_{\pi NN}$ to represent $f_P f_T$ one obtains $|\bar{g}^{(I)}_{\pi NN}| \lesssim 1.3\times 10^{-11}$. Given the constants $\bar{g}^{(I)}_{\pi NN}$ a well defensible, model independent calculation of D_n is possible through the use of sidewise dispersion relations /23/. Sidewise dispersion relations have been used successfully to calculate the anomalous magnetic moments of the nucleon /24/. The input for the calculation was the strong $N \to N\pi$ amplitude, and the pion photoproduction amplitude in the region near threshold. The calculation of D_n is analogous, with the P and T invariant $N \to N\pi$ amplitude replaced by a P,T violating one. For a coupling of the form

$$L_{P,T} = \sqrt{2}\bar{g}_{\pi NN}(\bar{p}n\pi^+ + \bar{n}p\pi^-) \qquad (9)$$

[3] The isoscalar potential (2) was given in Ref. /20/ and the potentials (3) and (4) in Ref. /18/

the result is /23/

$$D_n \simeq 9 \times 10^{-15} \bar{g}_{\pi NN} \text{ ecm} . \qquad (10)$$

The contribution of the P,T-violating couplings of the neutral pion ($\overline{N}\tau_z N\pi^0$ and $\overline{N}N\pi^0$) have not yet been calculated. The contribution of the $N\pi^0$ intermediate state to the dispersion relation is expected to be much smaller than the contribution of the $N\pi^{\pm}$ state, since the neutral pion photoproduction cross-section at threshold is about two orders of magnitude smaller than the threshold cross-section for charged-pion photoproduction /25/. Consequently, the contribution of the couplings (5) and (7) to D_n is about the same as the contribution of (9). Hence,

$$D_n \simeq (9 \times 10^{-15}) \bar{g}^{(I)}_{\pi NN} \text{ ecm} \qquad (I = 0, 2) . \qquad (11)$$

Eqs. (8) and (11) imply

$$| \bar{g}^{(0)}_{\pi NN} | \lesssim 3 \times 10^{-11} , \qquad (12)$$

$$| \bar{g}^{(2)}_{\pi NN} | \lesssim 3 \times 10^{-11} . \qquad (13)$$

For the contribution of the isovector coupling (6), which involves only the neutral pion, we guess (from the ratio of the experimental cross-sections for neutral and charged pion photoproduction at threshold) $D_n \simeq 10^{-15} \bar{g}^{(1)}_{\pi NN}$ ecm, and therefore[4]

$$| \bar{g}^{(1)}_{\pi NN} | \lesssim 3 \times 10^{-10} , \qquad (14)$$

Let us consider briefly the possible size of the constants $\bar{g}^{(I)}_{\pi NN}$ in some current models with CP-violation. For a more extensive discussion and further references we refer the reader to Ref. /18/.

Quantum electrodynamics, which is incorporated in all gauge models of the fundamental interactions, obeys P, C, and T-invariance. In the minimal standard model there are two sources of CP-violation: the Kobayashi-Maskawa (KM) phase δ /9/ in the quark mixing, and the θ-term /26/ in the effective QCD Hamiltonian. The KM phase gives no contribution to the first order flavor-conserving nonleptonic weak interactions /27/, since in the latter the elements of the quark mixing matrix U enter only through the quantities $| U_{ij} |^2$, which are not sensitive to a CP-violating phase. The constants $\bar{g}^{(I)}_{\pi NN}$ generated by δ are expected to be therefore of the order of $(10^{-6})^2 s_1^2 s_2 s_3 s_6 \sim 10^{-16}$ ($s_1 = \sin\theta_1$, etc.; the factor $s_1^2 s_2 s_3 s_6$ is mandatory in the KM-model for all CP-violating quantities /28/). The θ-term violates both P- and T-invariance. Its strength is governed by the parameter θ. Being an isoscalar, it contributes only to the constant $\bar{g}^{(0)}_{\pi NN}$. The result of a calculation is $| \bar{g}^{(0)}_{\pi NN} | \simeq 0.027\theta$ /29/. The contribution of the θ-term to D_n in the soft pion limit was calculated /29/ to be $| D_n | \simeq 1.3 \times 10^{-14} | \bar{g}^{(0)}_{\pi NN} |$ ecm, which nearly coincides with the value (11) obtained using sidewise dispersion relations. Thus $\bar{g}^{(0)}_{\pi NN}$ due to the θ-term can be as large as the upper limit in Eq. (12).

[4] In Ref. /18/ our guess was $D_n \simeq (3 \times 10^{-15}) \bar{g}^{(1)}_{\pi NN}$ ecm and therefore $| \bar{g}^{(1)}_{\pi NN} | \lesssim 1 \times 10^{-10}$, based on earlier experimental results on π^0 photoproduction.

New CP-violating interactions are present in many extensions of the minimal standard model. An example is the class of left-right symmetric models based on the group $SU(2)_L \times SU(2)_R \times U(1)$ /30/. These models shed a new light on the apparent V-A structure of the charged-current weak interactions. The gauge interactions in these models generate a first order $\Delta F = 0$ P,T-violating nonleptonic (quark-quark) interaction. This can give a contribution to $\bar{g}^{(1)}_{\pi NN}$ as large as the upper limit in Eq. (14) /18/.

We shall consider now the information on the constants $\bar{g}^{(I)}_{\pi NN}$ provided by some low-energy nuclear processes. As it turns out, the limits (12), (13) and (14) are the best ones that can be derived at present on P,T-violation in the N-N interaction. It must be emphasized however, that estimates of D_n involve unknown uncertainties (for example, even though the size of the contribution to D_n of a given $\bar{g}^{(0)}_{\pi NN}$ or $\bar{g}^{(2)}_{\pi NN}$ is well founded, the possibility of cancellations with other contributions cannot be ruled out). Improvements of limits on $\bar{g}^{(I)}_{\pi NN}$ from sources other than D_n are therefore important even if they would not quite reach the sensitivity of (12), (13) or (14).

2.1. P,T-Violation in Nuclear γ-Decay

Searches for T-violating effects in nuclear γ-decays are based on Lloyd's theorem /31/, which states that in a T-invariant theory the reduced matrix elements $< B \parallel \kappa L \parallel A >$ ($\kappa = E, M$) of the electromagnetic multipole operators between given nuclear states are relatively real.[5] Consequently, the mixing ratios

$$\delta(\kappa L/\kappa' L') \equiv < B \parallel \kappa L \parallel A > / < B \parallel \kappa' L' \parallel A > \tag{15}$$

are of the form

$$\delta = |\, \delta \,|\, e^{i(\eta + \xi)} \tag{16}$$

where the phase ξ is due to higher-order electromagnetic contributions[6] and η deviates from 0 or π only in the presence of T-violation.

Let us consider in a simple case the effect of a P,T-violating N-N potential $V^{P,T}$. We shall denote the initial and final nuclear states in the absence of P- and P,T-violation by $| a >$ and $| b >$ respectively. Let $| a' >$ be a state of energy near that of $| a >$, of the same angular momentum as $| a >$, but of opposite parity. The potential $V^P + V^{P,T}$, where V^P is the T-invariant P-violating force due to the usual nonleptonic weak interactions, has the effect of changing $| a >$ to a state $| A >$, given by

$$| A > = | a > + \frac{| a' >}{E_a - E_{a'}} \left(< a' | V^P | a > + < a' | V^{P,T} | a > \right) . \tag{17}$$

We shall assume for simplicity that there are no appreciable admixtures of opposite parity states into $| b >$, so that

$$| B > \simeq | b > . \tag{18}$$

[5] For a review of the theory of nuclear γ decay see e.g. Ref. /32/. Our $< B \parallel \kappa L \parallel A >$ is identical to $\gamma(\kappa L; A \to B)$ in the notation of that reference. We shall choose a convention in which the $< B \parallel \kappa L \parallel A >$ are real.

[6] The phases ξ have been calculated for a wide range of transitions in Ref. /33/.

Let the regular electromagnetic transition in $| A > \to | B > +\gamma$ (i.e. the electromagnetic transition in the absence of $V^P + V^{P,T}$) be pure M2. P,T-violating and P-violating effects are proportional, respectively, to $O_{P,T}$ and O_P, given by

$$O_{P,T} = \mathrm{Im}\frac{< B \| E2 \| A >< B \| M2 \| A >^*}{|< B \| E2 \| A >|^2 + |< B \| M2 \| A >|^2}$$

$$= \frac{1}{1+|\delta|^2}\,\mathrm{Im}\frac{< B \| E2 \| A >}{< B \| M2 \| A >} , \qquad (19)$$

and

$$O_P = Re\frac{< B \| E2 \| A >< B \| M2 \| A >^*}{|< B \| E2 \| A >|^2 + |< B \| M2 \| A >|^2} = \frac{1}{1+|\delta|^2}\,\mathrm{Re}\,\frac{< B \| E2 \| A >}{< B \| M2 \| A >}, \qquad (20)$$

$(\delta = \delta(E2/M2))$. We have

$$< B \| M2 \| A > \simeq < b \| M2 \| a >_0 (1 + i\xi_{M2}) , \qquad (21)$$

$$< B \| E2 \| A > \simeq < b \| E2 \| a' >_0 (1+i\xi'_{E2})\frac{(< a' | V^P | a > + < a' | V^{P,T} | a >)}{E_a - E_{a'}} , \qquad (22)$$

so that

$$O_{P,T} \simeq \frac{< b \| E2 \| a' >_0}{< b \| M2 \| a >_0}\frac{\left[(\xi'_{E2} - \xi_{M2}) < a' | V^P | a > + < a' | (-i)V^{P,T} | a >\right]}{(E_a - E_{a'})(1+|\delta|^2)} , \qquad (23)$$

$$O_P \sim \frac{< b \| E2 \| a' >_0}{< b \| M2 \| a >_0}\,\frac{< a' | V^P | a >}{E_a - E_{a'}}\,\frac{1}{1+|\delta|^2} . \qquad (24)$$

In Eqs. (21-24) we have denoted the matrix elements first order in the electromagnetic interaction by a subscript zero. As seen from Eqs. (23) and (24), the observed effects are enhanced if $E_a - E_{a'}$ is small, and/or if the regular transition is hindered relative to the symmetry-violating one. Note that the factors which enhance the P,T-violating effects enhance also the effect of the final-state interaction.

It is useful to form the ratio $O_{P,T}/O_P$. From Eqs. (23) and (24) one has

$$O_{P,T}/O_P \sim \eta + \xi \sim (-i)\frac{< a' | V^{P,T} | a >}{< a' | V^P | a >} + \xi'_{E2} - \xi_{M2} . \qquad (25)$$

The P,T-violating interactions that contribute to P,T-violation in the N-N interaction generate also a contribution ($\vec{E}'L$ and $\vec{M}'L$) to the electric and magnetic multipole operators. These terms are single-particle operators proportional to the electric dipole moment of the nucleon D_N. Inspection shows that $\vec{E}'L(\vec{M}'L)$ is of the same form as the spin-dependent term in the usual $ML(EL)$ operator, but with the factor $\mu_N e/2M$

replaced by $D_N(-D_N)$. In the quantity $0_{P,T}$ considered above, the effect is a term $< b \parallel \overline{E}2' \parallel a >_0 \, / \, < b \parallel M2 \parallel a >_0$ to be added to the r.h.s. of Eq. (23). This quantity is presumably of the order of $D_n/(\mu_N e/2M)$ (unless there is a cancellation between the orbital and spin-dependent part of $M2$), and therefore $\lesssim 10^{-11}$ (cf. Eq. (8)).

2.2. Implications of the ^{180}Hf Experiment

As seen from Eq. (25), the larger is the P-violating effect, the more stringent limit can generally be obtained for $< a' \mid V^{P,T} \mid a >$ for an experiment of given sensitivity. This was the idea behind the experiment of Ref. /34/, - the only one where a P,T-violating effect in γ-decay was searched for. The transition studied was the 501 KeV γ-transition of the 8^-(1.142 MeV) metastable state of ^{180}Hf.[7] The large P-violating effects observed in this transition (1.7% forward-backward asymmetry and 0.2% circular polarization of γ-rays) can be accounted for in terms of the usual weak interactions /35/. Neglecting final-state interactions,[8] the experiment yielded /34/

$$\frac{\mathrm{Im} < 6^+ \parallel E2 \parallel 8^- >}{\mathrm{Re} < 6^+ \parallel E2 \parallel 8^- >} \simeq \frac{< 8^+ \mid V^{P,T} \mid 8^- >}{< 8^+ \mid V^P \mid 8^- >} = -\,0.7 \pm 0.6 \ . \qquad (26)$$

In Eq. (26) $\mid 8^- > \equiv \mid 8^-, 1.142\ MeV >$, $\mid 8+ > \equiv \mid 8^+, 1.085\ MeV >$, and $\mid 6^+ > \equiv \mid 6^+, 0.641 MeV >$. Eq. (26) implies

$$\left| \frac{< 8^+ \mid V^{P,T} \mid 8^- >}{< 8^+ \mid V^P \mid 8^- >} \right| < 1.7 \qquad \text{(90\% confidence level).} \qquad (27)$$

To obtain limits on the constants $\bar{g}^{(I)}_{\pi NN}$ from the bound (27), a calculation of the matrix elements involved is required. Such a calculation is not available yet. We shall give a rough estimate of the ratio of the matrix elements in (27) (see Ref. /18/), approximating the two body potentials $V^{P,T}$ and V^P by effective single-particle potentials.

Concerning the strength $g^{(I)}_{MNN}$ of the P-violating $N \to NM$ matrix elements, the experimental evidence indicates that /36/ $g^{(0)}_{\rho NN} \simeq 2 \times 10^{-6}$. For the other constants the data set only upper bounds; the bound for $g_{\pi NN}$ is such that the pion-exchange term in V^P is not more important for our estimate than the term proportional to $g^{(0)}_{\rho NN}$. The single particle potential $(V^P_{\rho(0)})_{s.p.}$ corresponding to the $g^{(0)}_{\rho NN}$-term is given by (neglecting the term proportional to (N-Z)/A) by /19/

$$(V^P_{\rho(0)})_{s.p.} \simeq (3W^\rho/2Mm_\rho^2)\,(1+\mu_v)\, g^{(0)}_{\rho NN}\, g_{\rho NN}\, \rho_n\, \vec{\sigma} \cdot \vec{p}\ , \qquad (28)$$

where $g_{\rho NN}$ is the strong ρNN coupling constant, μ_v is the isovector anomalous magnetic moment of the nucleon, ρ_n is the nucleon density in the nucleus, and $W^\rho \sim 0.8$. The

[7] For a review of this experiment and of other possible experiments on P,T-violation in γ-decays see the talk by F. Boehm in these proceedings.

[8] The effect searched for in this experiment involves also the final-state interaction phases ξ_{M2} and ξ_{E3} which, to our knowledge, have not been yet calculated for any transition.

single-particle potentials corresponding to the two-body potentials (2), (3) and (4) are /18/

$$(V^{P,T}_{\pi(0)})_{s.p.} = -\bar{g}^{(0)}_{\pi NN} \frac{N-Z}{A} v_\pi , \tag{29}$$

$$(V^{P,T}_{\pi(1)})_{s.p.} = \bar{g}^{(1)}_{\pi NN}\, v_\pi , \tag{30}$$

$$(V^{P,T}_{\pi(2)})_{s.p.} = -2\bar{g}^{(2)}_{\pi NN} \frac{N-Z}{A} v_\pi , \tag{31}$$

where

$$v_\pi = \frac{1}{Mm_\pi^2}\, g_{\pi NN}\, \tau_z \vec{\sigma}\cdot\hat{r}\, \frac{\partial \rho_n}{\partial r} , \tag{32}$$

$\vec{r}, \vec{\sigma}$ and τ_z are single nucleon operators, $\hat{r} = \vec{r}/r$, $r = |\vec{r}|$; Z and N(= A-Z) are the atomic number and the number of neutrons, respectively.

From Eqs. (27-31) we obtain

$$|\bar{g}^{(0)}_{\pi NN}| \lesssim 2.5 \times 10^{-7}\beta^{-1} , \tag{33}$$

$$|\bar{g}^{(1)}_{\pi NN}| \lesssim 5 \times 10^{-8}\beta^{-1} , \tag{34}$$

$$|\bar{g}^{(2)}_{\pi NN}| \lesssim 1.2 \times 10^{-7}\beta^{-1} , \tag{35}$$

where

$$\beta = \frac{< 8^+ \mid \vec{\sigma}\cdot\hat{r}(\partial\rho_n/\partial r)\tau_z \mid 8^- >}{< 8^+ \mid \vec{\sigma}\cdot\vec{p}\rho_n \mid 8^- >} . \tag{36}$$

In deriving the limits (33-35) we included a factor 2.6, found for the case of T-invariant P-violating potentials /19/, which accounts for the suppression of ρ-exchange relative to π-exchange due to short range correlations.

To obtain a rough estimate of β we shall use $<| \ \vec{\sigma}\cdot\hat{r}(\partial\rho_n/\partial r)\tau_z \ |> \simeq (< \rho_n > /R) <| \sigma\tau_z |>$, $<| \vec{\sigma}\cdot\vec{p}\rho_n |> \simeq <| \sigma |>< \rho_n > /R$ (R = nuclear radius) /37/ and $< \sigma\tau_z > / < \sigma > \simeq 1$. This implies $\beta \simeq 1$. With this value of β the limits (33-35) are

$$|\bar{g}^{(0)}_{\pi NN}| \lesssim 2.5 \times 10^{-7} , \tag{37}$$

$$|\bar{g}^{(1)}_{\pi NN}| \lesssim 5 \times 10^{-8} , \tag{38}$$

$$|\bar{g}^{(2)}_{\pi NN}| \lesssim 1.2 \times 10^{-7} . \tag{39}$$

Comparing the limit (38) with the bound (14), it follows that an improvement of the sensitivity of the ^{180}Hf experiment by two orders of magnitude would yield a limit for $g^{(1)}_{\pi NN}$ comparable to that indicated by D_n. For the other constents an improvement by four orders of magnitude would be required.

Considering the contribution of the P,T-violating multipole operators one has presumably $| \text{Im} (< 6^+ \| \tilde{E}2' \| 8^- > / < 6^+ \| M2 \| 8^- >) | \lesssim 10^{-11}$, as we discussed earlier. From the experimental result (26), and from $\text{Re}(< 6^+ \| E2 \| 8^- > / < 6^+ \| M2 \| 8^- >) \simeq 0.04$ (obtained from experimental results on P odd effects;

see Ref. /38/; $E2$ and $M2$ refer to here to the total $E2$ and $M2$ operators) we have $|\,\mathrm{Im}(< 6^{+} \parallel \overline{E}'2 \parallel 8^{-} > / < 6^{+} \parallel M2 \parallel 8^{-} >)\,| \lesssim 0.7$, i.e. a much weaker limit.

2.3. Other Processes

Another class of experiments sensitive to P,T-violation in the N-N interaction is investigations of polarized neutron transmission through polarized targets see the talk by H. Postma in these proceedings]. A P,T-violating observable is the quantity $\rho_{P,T} \equiv (\sigma_{+} - \sigma_{-})/(\sigma_{+} + \sigma_{-})$, where $\sigma_{+}(\sigma_{-})$ is the total neutron-nucleus cross section for a neutron polarized parallel (antiparallel) to $\vec{k}_n \times < \vec{J} >$ ($\vec{k}_n$ = neutron momentum, $\vec{J}$ = spin of the target nucleus). The larger in a given case is the T-invariant P-violating cross-section asymmetry $\rho_P [\equiv (\sigma'_{+} - \sigma'_{-})/(\sigma'_{+} + \sigma'_{-})$, where $\sigma'_{+}(\sigma'_{-})$ is the total cross-section for a neutron polarized parallel (antiparallel) to its momentum], the better limits can be established on the constants $\bar{g}^{(I)}_{\pi NN}$. An experiment searching for $\rho_{P,T}$ with a sensitivity of 10^{-6} (what appears to be feasible) in a case where ρ_P is say 5×10^{-2}, would set about an order of magnitude smaller upper limit on $\bar{g}^{(I)}_{\pi NN}$ (I = 0,2), and about three orders of magnitude smaller upper limit on $\bar{g}^{(1)}_{\pi NN}$ than the limits (12-14) from D_n /18/.

A further class of experiments sensitive to P,T-violation in the N-N interaction is searches for electric dipole moments of atoms (see the talk by P. G. H. Sanders in these proceedings).

3. P-CONSERVING T-VIOLATION IN THE N-N INTERACTION

In the same way as P- and P,T-violation, one can describe P-conserving T-violation (referred to often in the following as simply T-violation) in the low-energy N-N interaction in terms of nonrelativistic potentials, corresponding to single-meson exchange diagrams, with one of the $N \rightarrow NM$ vertices involving the T-violating Hamiltonian H^T. The strength of T-violation is characterized then by the effective coupling constants $\bar{g}_{MNN}$, defined by

$$< MN \mid H^T \mid N > \propto \bar{g}_{MNN} \; . \qquad (40)$$

Unlike in the case of P,T-violation, one-pion-exchange does not contribute to the T-violating N-N interaction /39/. Also, there is no contribution from ρ^0-exchange /39/. The exchange of $\rho^{\pm}$ generates the isovector T-violating potential /39,40/

$$V^T_\rho = \bar{g}_{\rho NN}(\mu_v g^2_{\rho NN} m^2_\rho / 8M^2 \pi) F(r) (\vec{\sigma}_1 - \vec{\sigma}_2) \times (\vec{p}_1 - \vec{p}_2) \cdot (\vec{r}_1 - \vec{r}_2)(\vec{\tau}_1 \times \tau_2)_z \qquad (41)$$

where $\bar{g}_{\rho NN}$ is defined as

$$L^T_{\rho NN} = \bar{g}_{\rho NN}(\mu_v g_{\rho NN}/M\sqrt{2}) \bar{N} \sigma^{\lambda\nu} q_\nu (\rho^{+}_{\lambda}\tau^{-} - \rho^{-}_{\lambda}\tau^{+}) N \qquad (42)$$

In Eq. (41) $g_{\rho NN}(\simeq 2.79)$ is the strong ρNN coupling constant, q_ν is the momentum of the ρ and $F(r) = (1/m_\rho r)\frac{d}{dr}(e^{-m_\rho r}/m_\rho r)$. A_1-exchange can generate T-violating potentials of any ($I \le 2$) isospin /39,40/.

A stringent limit on the constants $\bar{g}_{MNN}$ comes from the experimental limit (8) for D_n. Denoting f_T the strength of T-violation in the $\Delta F = 0$ hadronic interactions, a rough estimate of D_n is /22/ $D_n \simeq (e/M)(GM^2/4\pi)f_T \simeq (2 \times 10^{-20})f_T$ ecm, so that $|f_T| \lesssim 1.3 \times 10^{-5}$. Judging from the limit (12) for $\bar{g}^{(0)}_{\pi NN}$, the bounds for D_n on $\bar{g}_{MNN}$ (= of the order of f_T, presumably) are probably weaker perhaps by an order of magnitude, since the masses of the mesons involved are higher. Thus a probably better guess of the implications of the limit (8) is

$$|\bar{g}_{MNN}| \lesssim 10^{-4} . \tag{43}$$

A weaker limit than (43) might be in conflict with the experimental results on ϵ'/ϵ in $K_L \to 2\pi$ decays.

The exchange of a single photon does not contribute to the P-conserving T-violating N-N interaction since the T-violating part of the matrix element of the electromagnetic current between nucleon states on the mass-shell vanishes due to current conservation /41/. The longest range P-conserving T-violating potential arises from $\pi\gamma$-exchange. If T-violation originates from nonelectromagnetic interactions, the strength of this contribution is suppressed by the factor e^2 relative to the single-meson-exchange diagrams.

Let us consider now the case when the source of T-violation is the electromagnetic interaction. This possibility was proposed originally /41,42/ to account for the observed CP-violation. The parameter ϵ would receive through radiative corrections a contribution of the order of $(\alpha/\pi)\bar{f}$, where we have denoted $e\bar{f}$ the strength of the T-violating electromagnetic coupling; for maximal T-violation (corresponding to $\bar{f} \simeq 1$) it would have the observed order of magnitude. The present limit on D_n (Eq. (8)) indicates however that, if present, T-violation in the electromagnetic interactions cannot be maximal. The rough estimate of D_n is $D_n \simeq (e/M)\bar{f}(GM^2/4\pi) \simeq 2 \times 10^{-20}\bar{f}$ ecm, so that $|\bar{f}| \lesssim 1.3 \times 10^{-5}$. A calculation /43/ using sidewise dispersion relations, with T-violation introduced in the $\Delta(1236)p\gamma$ vertex in the pion-photoproduction amplitude, yields for $g_{\pi NN} \simeq 6 \times 10^{-8}$ (the present experimental upper limit) the value $D_n \simeq 10^{-22}$ $sin\theta_\Delta$, where θ_Δ is the T-violating phase at the $\Delta p\gamma$ vertex. Assuming that sin $\theta_\Delta \simeq \bar{f}$ one has then from Eq. (8) $|\bar{f}| \lesssim 3 \times 10^{-3}$. For such a small value of $g_{\pi NN}$ some other contribution (e.g. the contribution involving $g^{(0)}_{\rho NN}$) could be more important. Given the uncertainties, a reasonable conclusion seems to be $|\bar{f}| \lesssim 10^{-2} - 10^{-3}$.

For electromagnetic T-violation the constants $\bar{g}_{MNN}$ are expected to be of the order of $(\alpha/\pi)\bar{f}$, and therefore (with $|\bar{f}| \lesssim 10^{-2} - 10^{-3}$) $|\bar{g}_{MNN}| \lesssim 10^{-5} - 10^{-6}$. The T-violating $\pi\gamma$-exchange potential was investigated in Refs. /44/ and /45/. In Ref. /44/ T-violation is introduced in the $NN\gamma$ vertes where one of the nucleons is off-shell; the average strength of the $\pi\gamma$-exchange potential relative to the P-conserving T-invariant one-pion-exchange potential was then found to be of the order of 10^{-4} for maximal T-violation, i.e. presumably it is of the order of $\lesssim 10^{-6} - 10^{-7}$ for $|\bar{f}| \lesssim 10^{-2} - 10^{-3}$. In Ref. /45/ the $\pi\gamma$-potential was calculated using the effective T-violating $NN\pi\gamma$ interaction introduced in Ref. /46/. The contribution of this interaction to D_n was calculated in Ref. /47/. Writing the strength of the $NN\pi\gamma$ interaction as $g_T e/m_\pi M$ the result and the limit (8) imply $|g_T| \lesssim 1.6 \times 10^{-3}$. It follows then from the calculation of Ref. /45/ that the average strength of this $\pi\gamma$-potential relative to the usual one-pion-exchange potential is $\sim 5 \times 10^{-9}$.

An effective T-violating interaction leads also to a T-violating three-body potential /46,48,49/, which in heavy nuclei might be more important than the two-body $\pi\gamma$ exchange potential because of the long range of the Coulomb potential /46/.

What are the expectations for the size of P-conserving T-violation in current models with CP-violation? In the minimal standard model the strength of P-conserving T-violation in Δ F = 0 nonleptonic weak interactions is expected to be comparable to the strength of Δ F = 0 P,T-violation, i.e. $|\bar{g}_{MNN}| \lesssim 10^{-16}$. The θ-term is both P-and T-violating, so that it can contribute to $\bar{g}_{MNN}$ only through interference with the usual weak interaction. We expect therefore $\bar{g}_{MNN}$ due to this term to be $\lesssim 10^{-15}$. In left-right symmetric models the first order Δ F = 0 nonleptonic interaction has no P-conserving T-violating component (while it does contain a P,T-violating part). One expects therefore $|\bar{g}_{MNN}| \lesssim 10^{-16}$.

The absence of a first order flavor-conserving P-conserving T-violating nonleptonic (quark-quark) interaction turns out to be a general feature of renormalizable gauge models with elementary quarks.[9] We expect therefore that the constants $\bar{g}_{MNN}$ in such models are not likely to be much larger than $\sim 10^{-15}$.[10] In composite models the constants $\bar{g}_{MNN}$ might be larger, but probably still much smaller than the strength of the weak interaction. A Δ F = 0 P-conserving T-violating quark-quark interaction in these models would be due to T-violating interactions at the preon level, which conceivably could induce T-violating derivative couplings at the quark level.

3.1. P-Conserving T-Violation in γ-Decay

Let us consider the γ-transition $| A > \to | B > + \gamma$, assuming, for example, that the dominant multipole radiations are M1 and E2. T-odd, P-even observables will be proportional to the quantity 0_T, given by

$$0_T = \frac{1}{1 + |\delta|^2} \operatorname{Im} \frac{< B \| E2 \| A >}{< B \| M1 \| A >} \tag{44}$$

($\delta = \delta(E2/M1)$). Denoting $| a >$ and $| b >$ the initial and final nuclear states in the absence of V^T, the states $| A >$ and $| B >$ are

$$| A > = | a > + \frac{| a' >}{E_a - E_{a'}} < a' | V^T | a > , \tag{45}$$

$$| B > \sim | b > , \tag{46}$$

[9] This was noted in Ref. 17. Recently I learned that this feature was noted also by J. Kambor, D. Wyler and M. Simonius /50/.

[10] The constants $\bar{g}_{MNN}$ can arise in second order (fourth order in the boson fermion coupling constants) through interference of a T-violating P- and/or flavor-violating nonleptonic interaction with the usual weak interaction. If the T-violating $\Delta F \neq 0$ interaction conserves strangeness, there are no constraints from CP-violation in the neutral kaon system, and therefore $\bar{g}_{MNN}$ is allowed to be larger, perhaps of the order of 10^{-12}. Additional contributions to P-conserving T-violating Δ F = 0 nonleptonic (quark-quark) interaction, which we did not analyze, may come from CP-violating couplings among the bosons in the theory. In Ref. /50/ it was shown, taking into account the CP-violating couplings among the bosons, that in renormalizable gauge models which contain the standard $SU(3)_c \times SU(2)_L \times U(1)$ model there can be no Δ F = 0 P-conserving T-violating force between the quarks at a level stronger than the usual weak interaction.

where $| a' >$ is a state of the same angular momentum and parity as $| a >$, and we have assumed that only one state dominates the mixing in $| A >$ and that there is no appreciable mixing in $| B >$. For 0_T we find

$$0_T = \frac{1}{1+|\delta|^2} \frac{< b \| E2 \| a >_0}{< b \| M1 \| a >_0} \Big[(\xi_{E2} - \xi_{M1})$$

$$+ \frac{1}{E_a - E_{a'}} < a' | (-i) V^T | a > \left(\frac{< b \| E2 \| a' >_0}{< b \| E2 \| a >_0} - \frac{< b \| M1 \| a' >_0}{< b \| M1 \| a >_0} \right) \Big]. \quad (47)$$

Thus a search for a T-odd effect provides a constraint on the matrix element(s) $< a' | V^T | a >$ provided that all the other matrix elements involved are known. As emphasized in Ref. /51/, the sensitivity of an experiment to $< a' | V^T | a >$ is larger if the $a \to b\gamma$ multipole amplitudes are suppressed relative to those in $a' \to b\gamma$ (unless $| \delta |$ is too small), and also if $E_a - E_a'$ is small. Note that the final-state interaction effects are not enhanced by these factors.

To obtain constraints on the T-violating coupling constants $\bar{g}_{MNN}$, a calculation of the matrix element(s) $< a' | V^T | a >$ is required. P-even T-odd effects have been searched for in many nuclei (see the talk by F. Boehm in these proceedings). To our knowledge, an interpretation of the experimental result obtained was attempted so far only for two cases.

One of these is a search for T-odd effects in ^{192}Pt. From the experimental result /52/

$$| sin\ \eta_1 + 0.12\ sin\ \eta_2 | \simeq (4 \pm 5) \times 10^{-3} \quad (48)$$

(η_1 and η_2 refer to T-violating phases in two γ-decays in ^{192}Pt; the final-state interaction phases have been neglected) the authors of Ref. /53/ deduce

$$|< 2^+ B | V^T | 2^+ A >| \simeq (90 \pm 110) \mathrm{eV} \quad (49)$$

for the matrix element of V^T between the $| 2^+ A > = | 2^+, 0.612 MeV >$ and the $| 2^+ B > = | 2^+, 0.317 MeV >$ states of ^{192}Pt. To estimate the matrix element in (49), the single particle potential[11]

$$V_{t.v.} = G_{t.v.} \Sigma_i \frac{1}{2} (\vec{p}_i \cdot \hat{r}_i + \hat{r}_i \cdot \vec{p}_i) \quad (50)$$

was used for V^T. Assuming that the strong N-N interaction H_0 has no other velocity-dependent component than a spin-orbit term, $V_{t.v.}$ can be cast in the form /53/

$$V_{t.v.} = i M G_{t.v.} [H_0, \Sigma_i r_i] , \quad (51)$$

where M is the nucleon mass. The conclusion is /53/

$$| G_{t.v.} MR | \simeq (3 \pm 4) \times 10^{-4} , \quad (52)$$

where $R = < 2^+ B | \Sigma_i r_i | 2^+ A >$. Taking R to be the nuclear radius, one obtains

$$| G_{t.v.} | \simeq 3 \times 10^{-5} . \quad (53)$$

[11] The most general P-even, T-odd single particle potential linear in $\vec{p}$ is of the form $(V^T)_{s.p.} = \vec{r} \cdot \vec{p} [\beta_1(r) + \beta_2(r) \tau_z] + H.c.$ /54/; eq. (50) corresponds to $\beta_1(r) = G_{t.v.}/2r$, $\beta_2(r) = 0$.

To be able to make some assessment of the significance of the limit (53), one would have to know how the constant $G_{t.v.}$ is related to the strength of the two-body potentials. This has not been yet, to our knowledge, explored. For the two-body potential (41) we find that in the approximation used in Ref. /55/ to derive a P-violating single-particle potential, its contribution to $G_{t.v.}$ vanishes. If we assume – what may not be unreasonable – that $G_{t.v.}/G_{p.v.} \simeq \bar{g}_{MNN}/g^{(0)}_{\rho NN}$, where $G_{p.v.}$ is the factor multiplying the T-invariant P-violating single-particle potential $\vec{\sigma}\cdot\vec{p}$ in Eq. (28), we obtain

$$| \bar{g}_{MNN} | \lesssim 3 \times 10^{-4} \quad , \tag{54}$$

a limit that would be near the bound (43).

The other case which was analyzed to some extent is the experimental result ($sin\ \eta = 0.048 \pm 0.087$) for the 501 KeV–transition in ^{180}Hf (the same transition where a P,T-odd effect was searched for) /56/. The authors of Ref. /56/ find

$$|< \tilde{8}^- \mid H^T \mid 8^- >| = (0.4 \pm 0.7)\text{eV} \quad , \tag{55}$$

where $\tilde{8}^-$ is a K = 2 or K = 3 octupole vibrational state. Although the limit (55) is two orders of magnitude smaller than (49), the implied bound on $G_{t.v.}$ may not be more stringent, since the matrix element in (55) is likely to be considerably suppressed due to the large difference in the K-values of the two states.

In discussing T-violation in the γ-transition $A \to B\gamma$ we have not included so far the effect of the T-violating interactions on the electromagnetic transition operators. Denoting $\bar{E}L(\bar{M}L)$ the T-violating contribution to the EL(ML) operator, the effect on 0_T (Eq. (44)) is a term $(< b \mid (-i)\bar{E}2 \mid a > / < b \mid E2 \mid a >) - (< b \mid (-i)\bar{M}1 \mid a > / < b \mid M1 \mid a >)$, to be added to the terms in the square bracket in Eq. (47). (In Eq. (44) E2 and M1 refer to the sum of the usual and T-violating multipole operators; in the subsequent equations they refer to the usual multipole operators).

As the matrix element of the electromagnetic current between physical nucleon states is not sensitive to T-violation, there is no single-particle contribution to $\bar{E}L$ and $\bar{M}L$. The two-body contributions have been investigated in Refs. /46/, /48/, and /49/. The matrix element ratios $< \mid \bar{E}L \mid > / < \mid EL \mid >$ and $< \mid \bar{M}L \mid > / < \mid ML \mid >$ have been found to be generally much smaller than 10^{-3} for maximal T-violation in the electromagnetic interaction. Given the present limits on T-violation, they are therefore much smaller than $10^{-3} \mid f \mid \lesssim 10^{-5} - 10^{-6}$ (or $10^{-3} \mid g_T \mid \lesssim 2 \times 10^{-6}$) in the case of electromagnetic T violation, and much smaller than $10^{-3} \mid g_{MNN} \mid < 10^{-7}$ for T violation of a nonelectromagnetic origin. Thus $\bar{E}L$ and $\bar{M}L$ could play a role only in cases where the matrix elements of the usual multipole operators are strongly hindered relative to those of $\bar{E}L$ and $\bar{M}L$.

3.2. *Other Processes*

T violation in the N N interaction has been searched for also through tests of detailed balance in nuclear reactions and in polarization asymmetry comparisons in nucleon nucleon and nucleon nucleus scattering. For reviews of the experimental results and aspects of the theory we refer the reader to Refs. /12 16/. The best upper limit from such studies for the ratio ξ of the T-violating and T-invariant amplitude is $|\xi| < 5 \times 10^{-4}$ (80% confidence level), obtained in a search for violation of detailed balance in the reaction $^{27}Al(p,\alpha)^{24}Mg$ /57/. To translate this bound into an upper limit on the coupling constants $\bar{g}_{MNN}$ would require an analysis in terms of the T-violating N-N potentials.

Another possible way to probe the presence of P-conserving T-violation is through searches for a term of the form $(\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J})(\vec{k}_n \cdot \vec{J})$ in the transmission of polarized neutrons through oriented targets (see the talk by H. Postma in these proceedings). A T-violating observable is the quantity $\rho_T \equiv (\bar{\sigma}_+ - \bar{\sigma}_-)/(\bar{\sigma}_+ + \bar{\sigma}_-)$, where $\bar{\sigma}_+(\bar{\sigma}_-)$ is the neutron-nucleus total cross-section for neutrons polarized parallel (antiparallel) to $\vec{k}_n \times \vec{J}$. Such experiments may be able to improve considerably the existing limits on the ratios of ~~T-violating~~ to ~~T-invariant~~ amplitudes. In the vicinity of a compound p-wave resonance in medium-heavy nuclei ρ_T is enhanced: $\rho_T \simeq (10^3 - 10^5)\phi$, where ϕ is, roughly, the ratio of the matrix elements of the T-violating and T-invariant potentials /58/. To obtain limits on the constants $\bar{g}_{MNN}$ from limits on ρ_T will require here also an analysis in terms of the T-violating potentials.

A T-violating N-N interaction can induce T-odd correlations (such as e.g. $\langle \vec{J} \rangle \cdot \vec{p}_e \times \vec{p}_\nu$; see the talk by F. Boehm in these proceedings) in nuclear β-decay, of size generally of the order of $\bar{g}_{MNN}$. In isospin hindered β-decays the effect could be amplified by a factor of ~ 100 /59/. Note that the effect of a P,T-violating N-N interaction would be negligible, of the order of $\lesssim 10^{-8}$ even with such amplification.

The experiments that probe P,T-violation in the N-N interaction constrain also P-conserving T-violation, since a P-conserving T-violating interaction can generate a P,T-violating effect through interference with the usual weak interaction.

4. CONCLUSIONS

In this talk we discussed the information on P,T-violating and T-violating interactions provided by low-energy nuclear processes. In low-energy nuclear physics P,T- and T-violating interactions manifest themselves through P,T- and T-violating components in the nucleon-nucleon interaction, and through P,T- and T-violating components in the coupling of the photon and of the leptons to the nucleons and some other hadrons. We investigated the available information on these effective P,T- and T-violating interactions, and considered the implications for searches for T-violating effects.

The most stringent limits on P,T-violation in the N-N interaction come from the experimental limit on the electric dipole moment of the neutron. The upper limits on the P,T-violating $NN\pi$ coupling constants are roughly four orders of magnitude smaller than the strength of a typical weak amplitude. In some current models with CP violation the P,T-violating coupling constants could have values near these limits. P,T-violation of such strength would produce unobservably small effects in strong and electromagnetic processes, unless there is a strong dynamical amplification of the observed effect. Such an enhancement is expected to occur in a decay of a metastable state in ^{180}Hf, since this transition exhibits very large P-violating effects (see Section 2.2). Based on a rough estimate we found that the experimental result on P,T-violation in this transition implies for $g^{(1)}_{\pi NN}$ (see Section 2) an upper limit which is only two orders of magnitude weaker than that indicated by D_n. For $g^{(0)}_{\pi NN}$ and $g^{(2)}_{\pi NN}$ the limits are four orders of magnitude weaker than those from D_n. It would be of interest to repeat this experiment with an improved sensitivity, and also to look for other transitions where the P-violating effect is strongly enhanced. When comparing limits from other processes with those obtained from D_n, one has to keep in mind that the estimates of D_n are subject to unknown uncertainties. Limits from other processes are therefore important even if they would not be quite as stringent as those from D_n. Further experiments which can provide stringent limits on P,T-violation in the N-N interaction are searches for P,T-odd effects in neutron transmission and searches for electric dipole moments of atoms.

Upper limits on the P-conserving T-violating coupling constants $\bar{g}_{MNN}(M = \rho, A_1, ...)$ indicated by the experimental limit on D_n (and by the experimental value of ϵ'/ϵ) are of the order of 10^{-4}, i.e. much weaker than the limits on P,T-violation. This is understandable, since P-violation needed for D_n has to be supplied here by the weak interaction. These limits are based only on a rough estimate, since unlike for $\bar{g}^{(0)}_{\pi NN}$ and $\bar{g}^{(2)}_{\pi NN}$ there is no well founded calculation of the contribution of a given $\bar{g}_{MNN}$ to D_n. The best upper limit on T-violation from tests of detailed balance is 5×10^{-4} for the ratio of the T-violating and T-invariant amplitudes. The limits from polarization-asymmetry comparisons are weaker. The constraints on $\bar{g}_{MNN}$ from the results of detailed balance and polarization asymmetry tests are not known. From the many experimental results on T-violation in γ-decay only for one case (^{192}Pt) a limit on a T-violating coupling constant was derived. This may not be far from the one indicated by D_n, but one cannot be certain since it was obtained only by a rough estimate, and also because the limit refers to the coupling constant of a single-particle potential and the relation between this constant and the constants $\bar{g}_{MNN}$ has not been explored. Concerning the theoretical expectations for the constants $\bar{g}_{MNN}$, in models within the current theoretical framework they are likely to be much smaller than $\sim 10^{-6}$, the strength of a typical weak $N \to NM$ amplitude. A discovery of effects associated with larger values of $\bar{g}_{MNN}$ would have far-reaching consequences. Significant improvements of the existing limits on T-violation in various types of experiments are of interest since they could lead to a discovery of an effect. For null results there is interest in improving the limits on the constants $\bar{g}_{MNN}$. These would be obtained, of course, only if in the given case a calculation in terms of T violating potentials is feasible.

In addition to P,T- and T-violation of nonelectromagnetic origin, we discussed briefly possible P,T- and T-violation in the electromagnetic interactions. For P,T-violation the most important contribution to the P,T-violating N-N interaction might be single-photon exchange (see footnote 2). The strength of this contribution is of the order of $|e^2 f| \lesssim 10^{-12}$, where ef' denotes the strength of electromagnetic P,T-violation. The effects of electromagnetic P,T-violation (and also of P,T-violation of nonelectromagnetic origin) on the electromagnetic multipole operators in nuclear γ-decay are expected to be negligibly small. The limit from D_n on the strength ef of electromagnetic T-violation is $|ef| \lesssim (10^{-2} - 10^{-3})e$. The constants $\bar{g}_{MNN}$ are expected to be of the order of $\sim 10^{-5} - 10^{-6}$. The average strength of the $\pi\gamma$ exchange potential, which is the longest range contribution to the T-violating N-N interaction, does not appear to be larger. The contribution of the T-violating interactions (both electromagnetic and nonelectromagnetic) to the electromagnetic multipole operators is not expected to be larger than $\sim 10^{-6}$ relative to the contribution of the T-invariant multipole operators, unless the matrix elements of the latter are hindered.

Given the limits on P,T-violation in the N-N interaction, the effects of a P,T-violating N-N force on β-decay observables are negligible. The contribution of P-conserving T-violating N-N interactions to T-odd (and P,T-odd) correlations could be of the order of 10^{-4}, or larger if a dynamical enhancement of the observed effect occurs. In addition to T-violation in the N-N interaction β-decay probes also T-violating and P,T-violating semileptonic interactions. The coefficients D and R of the correlations $< \vec{J} > \cdot \vec{p}_e \times \vec{p}_\nu / E_e E_\nu$ and $< \vec{\sigma}_e > \cdot < \vec{J} > \times \vec{p}_e / E_e$, respectively (see the talk by F. Boehm in these proceedings), could be—both phenomenologically and also in some models—as large as the present experimental upper limits (see Ref. /18/).

ACKNOWLEDGEMENTS

I would like to thank F. Boehm, J. N. Ginocchio, L. Heller and P. Vogel for useful conversations, and the organizing committee for asking me to give a talk on this subject. This work was supported by the United States Department of Energy.

I would like to remember with this paper the late Bill Steyert, a good friend, who would have been keenly interested in this workshop, and with whom I had many discussions on tests of time-reversal invariance.

References

/1/ L. Wolfenstein, Ann. Rev. Nucl. Part. Sci. 36(1986)137.

/2/ Particle Data Group, Phys. Lett. 170B(1986)1.

/3/ M. Woods et al., Phys. Rev. Lett. 60(1988)1695.

/4/ H. Burkhardt et al., Phys. Lett. 206B(1988)163.

/5/ K. Kleinknecht, Ann. Rev. Nucl. Sci. 26(1976)1.

/6/ V. V. Barmin et al., Nucl. Phys. B247(1984)293;
N. W. Tanner and R. H. Dalitz, Ann. Phys. 171(1986)463.

/7/ L. Wolfenstein, Phys. Rev. Lett. 13(1964)562.

/8/ S. L. Glashow, Nucl. Phys. 22(1961)579;
A. Salam, in Proc. Eighth Nobel Symposium, Elementary Particle Theory: Relativistic Groups and Analyticity, ed. N. Svartholm (Almqvist and Wiksell, Stockholm, 1968);
S. Weinberg, Phys. Rev. Lett. 19(1967)12;.

/9/ M. Kobayashi and T. Maskawa, Prog. Th. Phys. 49(1973)652.

/10/ J. F. Donoghue, B. R. Holstein and G. Valencia, Int. J. Mod. Phys. A2(1987)319.

/11/ J. Ellis, J. S. Hagelin, S. Rudaz and D. D. Wu, Nucl. Phys. B304(1988)205.

/12/ E. M. Henley, Ann. Rev. Nucl. Sci. 19(1969)367.

/13/ R. J. Blin Stoyle, Fundamental Interactions and the Nucleus (North Holland, Amsterdam, 1973).

/14/ F. Boehm, Comments Nuc. Part. Phys. 11(1983)251.

/15/ E. G. Adelberger, in Proc. Conf. on Intersections Between Particle and Nuclear Physics, Steamboat Springs, May 1984, AIP Conference Proceedings No. 123, ed. R. E. Mischke (AIP, New York, 1984), p. 300.

/16/ M. Simonius, in Proc. Conf. on Intersections Between Particle and Nuclear Physics, Steamboat Springs, May 1984, AIP Conference Proceedings No. 123, ed. R. E. Mischke (AIP, New York, 1984), p. 1115.

/17/ P. Herczeg, in New and Exotic Phenomena, Proc. of the 7th Moriond Workshop: Searches for New and Exotic Phenomena, Jan. 1987, Les Arcs, France, ed. O. Fackler and J. Trân Thanh Vân (Editions Frontières, France, 1987), p. 71.

/18/ P. Herczeg, in Tests of Time Reversal Invariance in Neutron Physics, Proc. Workshop on Tests of Time Reversal Invariance in Neutron Physics, Chapel Hill, 1987, ed. N. R. Roberson, C. R. Gould and J. D. Bowman (World Scientific, Singapore, 1987), p. 24.

/19/ E. G. Adelberger and W. C. Haxton, Ann. Rev. Nucl. Part. Sci. 35(1985)501.

/20/ W. C. Haxton and E. M. Henley, Phys. Rev. Lett. 51(1983)1937.

/21/ V. M. Lobashev in Proc. of the International Symposium on Weak and Electromagnetic Interactions in Nuclei, Heidelberg 1986, ed. H. V. Klapdor (Springer-Verlag, 1986), p. 866.

/22/ L. Wolfenstein, Nucl. Phys. B77(1974)375.

/23/ G. Barton and E. G. White, Phys. Rev. 184(1969)1660.

/24/ S. D. Drell and H. R. Pagels, Phys. Rev. 140(1965)B397.

/25/ E. Mazzucato et al., Phys. Rev. Lett. 57(1986)3144.

/26/ A. A. Belavin, A. M. Polyakov, A. S. Schwartz, and Yu. S. Tyupkin, Phys. Lett. 59B(1975)85;
V. N. Gribov, unpublished;
G. 't Hooft, Phys. Rev. Lett. 37(1976)8;
R. Jackiw and C. Rebbi, Phys. Rev. Lett. 37(1976)172;
C. G. Callan, Jr., R. F. Dashen, and D. J. Gross, Phys. Lett. 63B(1976)334.

/27/ L. Maiani, Phys. Lett. 62B(1976)183.

/28/ C. Jarlskog, Phys. Rev. Lett. 55(1985)1039;
O. W. Greenberg, Phys. Rev. D32(1985)1841;
D.-D. Wu, Phys. Rev. D33(1986)860.

/29/ R. J. Crewther, P. Di Vecchia, G. Veneziano and E. Witten, Phys. Lett. 88B(1979)123.

/30/ J. C. Pati and A. Salam, Phys. Rev. Lett. 31(1973)661;
J. C. Pati and A. Salam, Phys. Rev. D10(1974)275;
R. N. Mohapatra and J. C. Pati, Phys. Rev. D11(1975)566;
G. Senjanović and R. N. Mohapatra, Phys. Rev. D12(1975)1502.

/31/ S. P. Lloyd, Phys. Rev. 81(1951)161.

/32/ K. Alder and R. M. Steffen, in The Electromagnetic Interaction in Nuclear Spectroscopy, ed. W. D. Hamilton (North-Holland, Amsterdam 1975), p. 1.

/33/ B. R. Davis, S. E. Koonin and P. Vogel, Phys. Rev. C22(1980)1233.

/34/ B. T. Murdoch, C. E. Olsen, S. S. Rosenblum and W. A. Steyert, Phys. Lett. 52B(1974)325.

/35/ P. Vogel, California Institute of Technology Report CALT 63-155, 1971.

/36/ E. G. Adelberger, in Proc. of the International Symposium on Weak and Electromagnetic Interactions in Nuclei, Heidelberg, 1986, ed. H. V. Klapdor (Springer-Verlag, 1986), p. 592.

/37/ Z. Szymanski, Nucl. Phys. A113(1968)385.

/38/ K. S. Krane, C. E. Olsen, J. R. Sites and W. A. Steyert, Phys. Rev. C4(1971)1906;
E. D. Lipson, F. Boehm and J. C. Vanderleeden, Phys. Rev. C5(1972)932;
B. Jenschke and P. Bock, Phys. Lett. 31B(1970)65;

E. Kuphal, Z. Physik 253(1972)314.
/39/ M. Simonius, Phys. Lett. 58B(1975)147.
/40/ M. Simonius and D. Wyler, Nucl. Phys. A286(1977)182.
/41/ J. Bernstein, G. Feinberg and T. D. Lee, Phys. Rev. 139(1965)B1650.
/42/ S. Barshay, Phys. Lett. 17(1965)78.
/43/ D. J. Broadhurst, Nucl. Phys. B20(1970)603.
/44/ A. H. Huffman, Phys. Rev. D1(1970)882.
/45/ A. R. Neghabian and W. Glöckle, Nucl. Phys. A319(1979)364.
/46/ C. F. Clement and L. Heller, Phys. Rev. Lett. 27(1971)545.
/47/ D. J. Broadhurst, Phys. Rev. D5(1972)1228.
/48/ C. F. Clement, Ann. Phys. 75(1973)219.
/49/ F. A. B. Coutinho, Nucl. Phys. A220(1974)520.
/50/ J. Kambor, D. Wyler and M. Simonius, unpublished.
/51/ W. A. Steyert and K. S. Krane, Phys. Lett. 47B(1973)294.
/52/ M. J. Holmes, W. D. Hamilton and R. A. Fox, Nucl. Phys. A199(1973)401.
/53/ R. J. Blin-Stoyle and F. A. B. Coutinho, Nucl. Phys. A211(1973)157.
/54/ P. Herczeg, Nucl. Phys. 75(1966)655.
/55/ F. C. Michel, Phys. Rev. 133(1964)B329.
/56/ K. S. Krane, B. R. Murdoch and W. A. Steyert, Phys. Rev. C10(1974)840.
/57/ E. Blanke et al., Phys. Rev. Lett. 51(1983)355.
/58/ V. E. Bunakov, Phys. Rev. Lett. 60(1988)2250.
/59/ A. Barroso and R. J. Blin-Stoyle, Phys. Lett. 45B(1973)178.