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CP-VIOLATION IN EXTENSIONS OF THE STANDARD MODEL AND TIME REVERSAL VIOLATION IN LOW ENERGY NUCLEAR PROCESSES

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We review and discuss time reversal violation in beta-decay and in the nucleon-nucleon interaction.

1. INTRODUCTION

CP-violation has so far been seen only in the neutral kaon system. In the light of the standard model[1] neither the observed effect, nor the elusive character of CP-violation elsewhere are unexpected. This is so because the Kobayashi-Maskawa phase should be different from zero unless a new symmetry exist , and because even if CP-violation in the standard model is strong enough to explain ϵ, the contribution of the Kobayashi-Maskawa phase to other observables where CP violation has been so far looked for is either known to be too small to be seen (e.g. in the case of the electric dipole moment of the neutron), or can be small (as in the case of ϵ'/ϵ).

The standard model has been spectacularly successful in accounting for the existing data. Nevertheless, for many theoretical reasons the existence of new physics is expected. Among the new interactions some of them may have CP violating components. Some of the latter may even be responsible for the observed effect. Whether this is so or not, the new CP-violating interactions may give rise to observable CP-violation where the standard model contribution is invisible. This underlines the importance of searching for CP-violating and time reversal violating effects in many processes.

In this talk we shall discuss time-reversal violation in beta-decay and in the nucleon-nucleon interaction.[2] Our aim is to consider the possible sources of T-violation in the beta-decay and the nucleon-nucleon interaction, and to assess the sensitivities required for experiments to provide new information on the underlying physics.

In the next section we discuss time reversal violation in beta-decay. Section 3 deals with time reversal violation in the nucleon-nucleon interaction. The last section contains our conclusion.

2. TIME REVERSAL VIOLATION IN BETA-DECAY

Time reversal (T) violating components in the beta-decay interaction would manifest themselves in contributions to T-odd correlations in the beta-decay probability.[3] Experimental information is available on the coefficients D and R of the correlations $<\vec{J}> \cdot \vec{p}_e \times \vec{p}_\nu / J E_e E_\nu$ and $\vec{\sigma} \cdot <\vec{J}> \times \vec{p}_e / J E_e$ ($\vec{\sigma} \equiv$ electron spin, $\vec{J} \equiv$ nuclear spin), respectively. D and R can be written as $D = D_t + D_f$ and $R = R_t + R_f$, where D_t, R_t represent the T-violating contribution, and D_f, R_f are the T-invariant contributions due to electromagnetic final-state interactions.

In the standard model the effective interaction describing the $d \to u e^- \bar{\nu}_e$ (and $u \to d e^+ \nu_e$) transition is the V-A interaction

$$H = \frac{g^2}{8 M_W^2} V_{ud} \bar{e} \gamma^\mu (1 - \gamma_5) \nu_e \, \bar{u} \gamma_\mu (1 - \gamma_5) d + H.c. \tag{1}$$

There are two sources of CP violation in the standard model: the Kobayashi-Maskawa phase δ in the quark mixing matrix, and the P,T violating $\bar{\theta}$ term in the effective QCD Lagrangian. Both of them give negligible contributions to the T-odd correlations. The contributions of the Kobayashi-Maskawa phase are second-order in the weak interaction (the Hamiltonian (1) is T-invariant; more generally a T-violating phase in a V-A interaction can only be an overall phase, which does not contribute to beta-decay in lowest order), and therefore they are expected to be of the order of $\sim 10^{-6} s_1^2 s_2 s_3 s_\delta \lesssim 10^{-10}$ ($s_1 \equiv \sin\theta_1$, etc.; θ_i are the quark mixing angles). The upper limit for the contributions of the θ−term is also expected to be of the order of $10^{-9} - 10^{-10}$ (since θ is constrained by the experimental limit on the electric dipole moment of the neutron; see Ref. 4, and Eq. (37) below).

We shall consider now contributions to D_t and R_t from possible new interactions. In allowed transitions and in lowest order in the new interactions D_t is sensitive only to T-violating interactions built up from vector (V) and axial-vector (A) quark and lepton currents, while R_t is sensitive only to T-violating interactions with scalar (S) and tensor (T) quark and lepton currents (see Ref. 3).

2.1 THE D-COEFFICIENT

The most general interaction for $d \to ue^-\bar{\nu}$ constructed from vector and axial-vector currents can be written in the form

$$
\begin{aligned}
H_{V,A} = \; & \bar{e}\gamma^\lambda(1-\gamma_5)\Big(\sum_i U_{ei}\nu_i\Big)[a_{LL}\bar{u}\gamma_\lambda(1-\gamma_5)d \\
& + a_{LR}\bar{u}\gamma_\lambda(1+\gamma_5)d] \\
& + \bar{e}\gamma^\lambda(1+\gamma_5)\Big(\sum_i V_{ei}\nu_i\Big)[a_{RL}\bar{u}\gamma_\lambda(1-\gamma_5)d \\
& + a_{RR}\bar{u}\gamma_\lambda(1+\gamma_5)d] + H.c.
\end{aligned}
\tag{2}
$$

The contribution of (2) to D_t is given by

$$
D_t = a_D \,\mathrm{Im}(\eta_{LR} + \eta_{RR}\eta^*_{RL}\kappa_e) \; , \tag{3}
$$

where $\eta_{ik} = a_{ik}/a_{LL}$ ($ik = LR, RL, RR$) and $\kappa_e = \sum_i' |V_{ei}|^2 / \sum_i' |U_{ei}|^2$ (the summation is over the matrix elements associated with the neutrinos that are light enough to be produced in beta decay; the neutrino masses are neglected).

The constant a_D contains the nuclear matrix elements. For ^{19}Ne and for n-decay $a_D \simeq -1.03$ and $a_D \simeq 0.87$ respectively. The best limit on D_t/a_D comes from ^{19}Ne-decay. The experimental value $D = (0.1 \pm 0.6) \times 10^{-3}$ (Ref. 5) yields

$$-0.86 \times 10^{-3} < D_t/a_D < 1.05 \times 10^{-3} \qquad (90\%\ c.l.)\ , \tag{4}$$

The contribution D_f of the electromagnetic final-state interactions has been estimated to be of the order of $2 \times 10^{-4}(p_e/(p_e)_{max})$ (Ref. 6). A new experiment under way at Princeton expects to measure D with a sensitivity of 5×10^{-5} (Ref. 7)

Right-handed interactions can arise in beta-decay at the tree level in left-right symmetric models (or other models involving new gauge bosons with right-handed couplings to the fermions), in models with new quarks and leptons which mix with the usual ones and which have right-handed couplings to the W, and in models involving leptoquarks.

Left-Right Symmetric Models. Left-right symmetric models are attractive extensions of the standard electroweak model, which provide an understanding of the origin of parity-violation in the weak interactions.[8] The simplest models are based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$. In these models there are two distinct charged gauge boson field W_L and W_R. Their coupling to the fermions is described by the Lagrangian

$$\begin{aligned} L = & \frac{g_L}{2\sqrt{2}} W_L^\mu (\bar{P}\gamma_\mu \Gamma_L U_L N + \bar{N}^{(0)}\gamma_\mu \Gamma_L V^\dagger E) \\ & + \frac{g_R}{2\sqrt{2}} W_R^\mu (\bar{P}\gamma_\mu \Gamma_R U_R N + \bar{N}^{(0)}\gamma_\mu \Gamma_R V^\dagger E) + H.c., \end{aligned} \tag{5}$$

where g_L and g_R are gauge coupling constants, $\Gamma_L = (1 - \gamma_5)$, $\Gamma_R = (1 + \gamma_5)$, and $P = (u, c, \ldots)$, $N = (d, s, \ldots)$, $E = (e, \mu, \ldots)$ and $N^{(0)} = (\nu_1, \nu_2, \ldots)$. U_L, U_R and V are the quark and lepton mixing matrices, respectively. The fields W_L and W_R are linear combinations of the mass eigenstates W_1 and W_2,

$$W_L = \cos\zeta W_1 + \sin\zeta W_2$$

$$W_R = e^{i\omega}(-\sin\zeta W_1 + \cos\zeta W_2)\ , \tag{6}$$

where ζ is a mixing angle, and ω is a CP violating phase.

The quantity η_{LR} is given by

$$\eta_{LR} \simeq -e^{i(\alpha+\omega)} \frac{g_R}{g_L} \frac{\cos \theta_1^R}{\cos \theta_1^L} \zeta \quad . \tag{7}$$

where α is a CP-violating phase in U_R ($(U_R)_{ud} = e^{i\alpha} \cos \theta_1^R$). Assuming that $g_R^2 m_1^2 / g_L^2 m_2^2$ can be neglected relative to one (m_1 and m_2 are the masses of W_1 and W_2, respectively), as indicated by the analysis of Ref. 9, it can be shown that the second term in Eq. (3) can be neglected, so that D_t is given by[10]

$$D_t \simeq -a_D \frac{g_R}{g_L} \frac{\cos \theta_1^R}{\cos \theta_1^L} \zeta \sin(\alpha + \omega) \quad . \tag{8}$$

The phase $\alpha + \omega$ contributes also to the electric dipole moment of the neutron D_n and to ϵ'/ϵ. The upper limits on $|D_t/a_D|$ from these observables are $\simeq 3 \times 10^{-5}$ (Ref. 11), but they are not as reliable as the limit (4).

<u>Exotic Fermions.</u> The interaction responsible for $d \rightarrow ue^-\bar{\nu}_e$ can contain terms involving right-handed currents even in models where the gauge group remains the standard $SU(2) \times U(1)$ group. This happens if new quarks and leptons exist which mix with the usual ones, and whose right-handed components are in non-singlet representations of $SU(2)$ (Ref. 12). The new fermions have to be heavy (heavier than about 20 GeV) in view of limits from direct production at accelerators (see Ref. 13).

A comprehensive analysis of constraints on mixings between the usual and possible new fermions was made in Ref. 13 in a framework where the electric charge and color assignments of the new fermions are assumed to be the standard ones, and which requires that the light-heavy fermion mixing does not lead to flavor changing neutral currents involving the usual quarks and charged leptons (which are severely constrained by experiment).

The quantity η_{LR} in such models is given by

$$\eta_{LR} \simeq s_R^u s_R^d (V_R)_{ud} \quad , \tag{9}$$

where $s_R^{u,d} = \sin \theta_R^{u,d}$, θ_R^u and θ_R^d are the light-heavy mixing angles associated with the u quark and the d quark, and V_R is a matrix. The elements of V_R are in general complex. The phase in $(\widehat{V}_R)_{ud}$ contributes to D_t (Ref. 14). Writing $(\widehat{V}_R)_{ud} = e^{i\phi}(\widehat{V}_R^{'})_{ud}$, where $(\widehat{V}_R^{'})_{ud}$ is real, we have

$$D_t \simeq a_D s_R^u s_R^d \, (\widehat{V}_R^{'})_{ud} \;\; \sin\phi \quad . \tag{10}$$

An upper limit of $\sim 3 \times 10^{-5}$ on $| \, s_R^u s_R^d (\widehat{V}_R^{'})_{ud} \sin\phi \, |$ follows again from D_n and ϵ'/ϵ.

<u>Leptoquark Exchange.</u> Leptoquarks are bosons (spin-one or spin-zero) which induce quark $\to$ lepton transitions. They appear in many extensions of the minimal standard model.[15] In models where they do not induce proton decay, leptoquarks could be light enough to cause observable effects in some low-energy processes. The couplings of leptoquarks to fermions may be CP-violating and could even be responsible for the observed CP-violation.[16]

The $d \to ue^-\nu_e$ transition can be mediated by either leptoquarks of Q ($\equiv$ electric charge) $= \frac{2}{3}$ or Q $= \frac{1}{3}$ (Ref. 17). We shall denote spin-one and spin-zero leptoquarks of charge Q by $X_{(Q)}$ and $Y_{(Q)}$, respectively. Assuming lepton-number conservation, the most general four-fermion interaction for $d \to ue^-\nu_e$ generated by the exchange of these leptoquarks can be written as[18]

$$H_{X(2/3)} = \sum_{i,j=V,A} f_{ij} \; \bar{e}\gamma_\mu \Gamma_i d \bar{u}\gamma^\mu \Gamma_j \nu_e \; + \; H.c. \; , \tag{11}$$

$$H_{X(1/3)} = \sum_{i,j=V,A} h_{ij} \; \bar{e}\gamma_\mu \Gamma_i u^c \bar{d}^c \gamma^\mu \Gamma_j \nu_e \; + \; H.c. \; , \tag{12}$$

$$H_{Y(2/3)} = \sum_{i,j} f_{ij} \; \bar{e}\Gamma_i d \bar{u}\Gamma_j \nu_e + H.c. \; , \tag{13}$$

$$H_{Y(1/3)} = \sum_{i,j} h_{ij} \; \bar{e}\Gamma_i u^c \bar{d}^c \Gamma_j \nu_e + H.c. \; , \tag{14}$$

where $\Gamma_V = \gamma_\mu$, $\Gamma_A = \gamma_\mu\gamma_5$, $\Gamma_S = 1$, and $\Gamma_P = \gamma_5$. All the fields in Eqs. (11)–(14) are mass eigenstates. After Fierz transformations the Hamiltonians (11), (12) take the form of beta decay interactions involving V, A, S and P couplings, and the Hamiltonians (13), (14) the form of beta decay interactions with V, A, S, P and T couplings. The $V-A$ part of these interactions has the following features:[11]

- the product $a_{RL}a'_{RR}$ vanishes for all the Hamiltonians (11)–(14);

- $a_{LR} = 0$ for $X_{(2/3)}$ and $Y_{(1/3)}$ – exchange.

It follows that only $X_{(1/3)}$ - $Y_{(2/3)}$ - exchange can contribute to D_t and also that D_t receives contributions only from terms involving the left-handed neutrino. For $X_{(1/3)}$ - and $Y_{(2/3)}$ - exchange one has[14]

$$D_t = \frac{a_D}{(g^2/8M_W^2)U_{ud}} \; \frac{1}{4} \; Im\,(h_{VV} + h_{AA} - h_{VA} - h_{AV}) \tag{15}$$

and

$$D_t = \frac{a_D}{(g^2/8M_W^2)U_{ud}} \; \frac{1}{8} \; Im\,(f_{SS} - f_{PP} - f_{SP} + f_{PS})\,, \tag{16}$$

respectively.

Including only the fermions contained in the standard model, and assuming lepton-number conservation, there can be nine types of spin-one and nine types of spin-zero leptoquark states for a given fermion generation (see Ref. 19): two weak isospin singlets, two doublets and a triplet in each case. The $X_{(1/3)}$ - and $Y_{(2/3)}$ - type leptoquarks are the weak isospin doublet states $(R_2)_-, (\tilde{R}_2)_+$ and $(V_{2\mu})_-, (\tilde{V}_{2\mu})_+$, respectively.[20] Their couplings to the fermions are given in Ref. 19. Let us consider $(V_{2\mu})_-$ and $(\tilde{V}_{2\mu})_+$. Their couplings relevant for $d \to u e^- \bar{\nu}_e$ are given by

$$\begin{aligned} L = {} & \frac{1}{2} g_{2L} \beta_L \bar{d}^c \gamma^\mu (1 - \gamma_5) \nu_e (V_{2\mu})_- + \frac{1}{2} g_{2R} \beta_R \bar{u}^c \gamma^\mu (1 + \gamma_5) e (V_{2\mu})_- \\ & + \frac{1}{2} \tilde{g}_{2L} \tilde{\beta}_L \bar{u}^c \gamma^\mu (1 - \gamma_5) e (\tilde{V}_{2\mu})_+ + H.c.\,, \end{aligned} \tag{17}$$

where β_L, β_R and $\tilde{\beta}_L$ are products of fermion mixing matrix elements. Inspection shows that if $(V_{2\mu})_-$ coincides with the mass-eigenstate, the contribution of (17) to a_{LR} vanishes. A nonzero a_{LR} can arise due to $(V_{2\mu})_-$ – $(\tilde{V}_{2\mu})_+$ mixing. Let

$$\begin{aligned} (V_{2\mu})_- &= \cos\phi\, X_{1\mu} + \sin\phi\, X_{2\mu} \\ (\tilde{V}_{2\mu})_+ &= -\sin\phi\, X_{1\mu} + \cos\phi\, X_{2\mu} \end{aligned} \tag{18}$$

where $X_{1\mu}$ and $X_{2\mu}$ describe leptoquarks of masses m_{X1} and m_{X2}, respectively. From Eq. (15) we find for the contribution of (17) to D_t

$$D_t = \frac{a_D}{(g^2/8M_W^2)U_{ud}} \sin\phi\cos\phi\,(Im\, g_{2L}\tilde{g}_{2L}\beta_L\tilde{\beta}_L^*)\,\frac{1}{4}\left(\frac{1}{m_{X1}^2} - \frac{1}{m_{X2}^2}\right). \tag{19}$$

For $(R_2)_-, (\widetilde{R}_2)_+$ the couplings involved in $d \to u e^- \nu_e$ are given by

$$
\begin{aligned}
L = {} & \frac{1}{2} h_{2L} \gamma_L \bar{u}(1-\gamma_5)\nu_e \, (R_2)_- - \frac{1}{2} h_{2R}\gamma_R \bar{d}(1+\gamma_5) e (R_2)_- \\
& - \frac{1}{2} \widetilde{h}_{2L} \widetilde{\gamma}_L \bar{d}(1-\gamma_5) e (\widetilde{R}_2)_+ \; + H.c.,
\end{aligned}
\tag{20}
$$

where γ_L, γ_R and $\widetilde{\gamma}_L$ are products of fermion mixing-matrix elements. Again, a contribution to D_t arises only if there is a mixing between the two leptoquark states. It is given by (see Eq. 16)

$$
D_t = \frac{a_D}{(g^2/8M_W^2)U_{ud}} \sin\psi \cos\psi \; (Im \; h_{2L} \widetilde{h}^*_{2L} \gamma_L \widetilde{\gamma}^*_L) \; \frac{1}{8}\left(\frac{1}{m^2_{y1}} - \frac{1}{m^2_{y2}}\right) , \tag{21}
$$

where ψ is the $(R_2)_- - (\widetilde{R}_2)_+$ mixing angle, defined in a way analogous to (18), and m_{1y}, m_{2y} are the masses of the mass-eigenstates.

As the couplings (17) and (20) do not contribute in lowest order in leptoquark-exchange to nonleptonic processes, D_t is not constrained significantly by D_n and ϵ'/ϵ. $|D_t|$ due to leptoquark-exchange could therefore be as large as the experimental limit (4).

2.2 THE R–COEFFICIENT

For a scalar type interaction R_t is given by (keeping only terms linear in the coupling constants of the new interactions)

$$
(R_t)_S = a_R \; Im \, (\bar{C}_S \;\; \bar{C}_S') \, , \tag{22}
$$

where $\bar{C}_S = C_S/(g^2/8M_W^2)U_{ud}, \bar{C}_S' = C_S'/(g^2/8M_W^2)U_{ud}$, and a_R is a constant containing the nuclear matrix elements ($a_R \approx 0.26$ for ^{19}Ne decay). C_S and C_S' are defined by

$$
H_S = \bar{e}(C_S + C_S'\gamma_5)\nu_e \, \bar{p} n \, . \tag{23}
$$

A direct measurement of R in ^{19}Ne-decay yielded $R = 0.079 \pm 0.053$ (Ref. 21), i.e.

$$
|R| < 0.18 \qquad\qquad (95\% \; c.l.) \, . \tag{24}
$$

A comprehensive analysis of beta-decay data yields[22] $(|\overline{C}_S|^2 + |\overline{C}_S'|^2) < 0.2$ (95% c.l.). It follows that $|Im(\overline{C}_S - \overline{C}_S')| < 0.28$, and thus

$$|(R_t)_S| < 7.3 \times 10^{-2} \qquad (95\% \text{ c.l.}) \,. \tag{25}$$

For a tensor interaction

$$(R_t)_T = a_R' Im(\overline{C}_T - \overline{C}_T') \,, \tag{26}$$

where $\overline{C}_T = C_T/(-g^2/8M_W^2)U_{ud}, \overline{C}_T' = C_T'/(-g^2/8M_W^2)U_{ud}; a_R' \simeq 0.18$ for Ne-decay. C_T, C_T' are defined by

$$H_T = \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C_T'\gamma_5)\nu_e \, \bar{p} \, \frac{\sigma^{\lambda\mu}}{\sqrt{2}} \, n \tag{27}$$

Data on $e^{\pm}$–longitudinal polarizations imply[23] $|Im(\overline{C}_T - \overline{C}_T')| < 9.1 \times 10^{-2}$ (95%c.l.), and therefore

$$|(R_t)_T| < 1.6 \times 10^{-2} \,. \tag{28}$$

A possible source of scalar-type couplings is charged Higgs-boson exchange. Charged Higgs bosons are present already in the standard model if the Higgs sector is extended for example by adding additional Higgs doublets. Charged Higgs bosons that contribute to R will contribute also to the electric dipole moments of the electron (D_e) and the neutron (D_n), resulting generally in stringent bounds on R. It is possible, however, that these contributions are suppressed. Let us consider for illustration the interaction

$$L_\phi = f'\bar{\nu}(1 + \gamma_5)e\,\phi + f''\bar{u}d\,\phi + H.c. \,, \tag{29}$$

where ϕ is the charged Higgs field. The coupling constants f' and f'' are generally undetermined. We have $C_S = C_S' = g_S f' f''/m_\phi^2$, where $g_S = g_S(0)$ is defined by $\langle p|\bar{u}d|n\rangle = -g_S(q^2)\bar{u}_p u_n$. Contributions from (29) to D_e and D_n arise only in order $g^2 f' f''$, through two loop diagrams which in the case of D_e (D_n) involve a nucleon loop (electron loop) attached to the electron (neutron) line by a Higgs and a W propagator. A crude estimate of these diagrams[24] leads to the conclusion that the limit on $(R_t)_S$ from the experimental limit on D_n (see Eq. (37) in Section 3) is weaker than (24), but that the new experimental limit on $D_e((D_e)_{\text{expt}} = (-2.8 \pm 8.3) \times 10^{-27}$ecm (Ref. 25)) implies a limit

$$|(R_t)_S| \lesssim 3 \times 10^{-3} . \tag{30}$$

The upper limit on $|(R_t)_T|$ from D_e is $\sim 2 \times 10^{-3}$. The contributin R_f of electromagnetic final-state interactions is $\sim 10^{-3}$ (Ref. 26).

Another possible source of scalar-type beta-decay couplings is the exchange of spin-one or spin-zero leptoquarks. Spin-zero leptoquark-exchange leads simultaneously to tensor-type effective interactions. In renormalizable gauge theories with elementary fermions this is the only mechanism which can generate tensor-type beta-decay couplings at the tree level. There is an upper limit of a few times 10^{-4} for the leptoquark contribution to R_t, due to a constraint from the experimental result on the ratio of $\pi \to e\nu$ to $\pi \to \mu\nu$ rates (see Ref. 14).

This concludes our discussion of T-violation in beta-decay. Another potential source of information on T-violating interactions, this time on those involving the muon, is nuclear muon-capture. Nimai C. Mukhopadhyay and I are currently investigating the available constraints on T-violating muon-quark couplings, and the sensitivity of muon capture observables to such couplings.[27]

3. TIME REVERSAL VIOLATION IN THE NUCLEON-NUCLEON INTERACTION

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

3.1. T-VIOLATION IN THE N-N INTERACTION WITH SIMULTANEOUS PARITY VIOLATION

Simultaneous violation of parity-conservation and time-reversal invariance ($P,T-$violation) in the N-N interaction can be described, in analogy with the description of parity-violation,[28] in terms of nonrelativistic potentials, derived (ignoring two-pion exchange) from single-meson exchange diagrams involving the lightest pseudoscalar and vector mesons. $P,T-$violation in the N-N interaction is parametrized in this description by the strength $\bar{g}^{(I)}_{MNN}{}'$ of the $N \rightarrow NM$ matrix elements of the various isospin (I) components of the effective $P,T-$violating flavor conserving nonleptonic Hamiltonian

$$< MN \mid H^{(I)}_{P,T} \mid N > \propto \bar{g}^{(I)}_{MNN}{}' \, . \tag{31}$$

We shall consider only the contribution of pion exchange. In contrast with T-invariant P-violation, where pion-exchange contributes only for an isovector Hamiltonian, a $P,T-$violating pion-exchange force exists for all the possible ($I \leq 2$) isospin components of $H_{P,T}$. The $P,T-$violating couplings (with the nucleons and the pion on their mass-shells) are[29]

$$L^{(I=0)}_{P,T} = \bar{g}^{(0)}_{\pi NN}{}' \, \bar{N} \vec{\tau} N \cdot \vec{\pi} \, , \tag{32}$$

$$L^{(I=1)}_{P,T} = \bar{g}^{(1)}_{\pi NN}{}' \, \bar{N} N \pi^0 \, , \tag{33}$$

$$L^{(I=2)}_{P,T} = \bar{g}^{(2)}_{\pi NN}{}' \, \bar{N} (3\tau_z \pi^0 - \vec{\tau} \cdot \vec{\pi}) N \, , \tag{34}$$

where the τ's are the isospin Pauli matrices. Note that for an isovector Hamiltonian only the neutral pion contributes. The isovector potential, for example, is given by[30]

$$V^{P,T}_{(1)} = \frac{1}{16\pi} \frac{m_\pi^2}{M} \bar{g}^{(1)}_{\pi NN} g_{\pi NN} \Big[(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \hat{r} (\tau_{1z} + \tau_{2z}) + (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{r} (\tau_{1z} - \tau_{2z}) \Big] \frac{e^{-m_\pi r}}{m_\pi r} \left(1 + \frac{1}{m_\pi r}\right) , \tag{35}$$

where $\vec{r}_k$, $\vec{\sigma}_k$ and $\vec{\tau}_k$ ($k = 1,2$) are the coordinates, spin and isospin Pauli matrices of the two nucleons, $\hat{r} = (\vec{r}_1 - \vec{r}_2)/r$ and $r = |\vec{r}_1 - \vec{r}_2|$; M is the mass of the nucleon, $g_{\pi NN}$ is the strong coupling constant. The isoscalar[31] and isotensor[30] potentials have a similar form.[32]

Let us consider the empirical constraints on the constants $\bar{g}^{(I)}_{\pi NN}{}'$.

Stringent limits on $\bar{g}^{(I)}_{\pi NN}{}'$ follow from the experimental limit on the electric dipole moment of the neutron D_n. The contribution of the charged pion-nucleon, P,T-violating couplings to D_n has been calculated in Ref. 33 employing sidewise dispersion relations. Sidewise dispersion relations have been used successfully to calculate the anomalous magnetic moment of the nucleons.[34] The input for these calculations 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. The contributions of the $P,T-$violating $\pi^0 NN$ couplings have not been yet estimated. Judging from the ratio ($\sim 10^{-2}$) of the experimental cross-section for neutral and charged pion photoproduction at threshold,[35] we shall assume (see Ref. 36) that the contributions of the neutral pion couplings are suppressed relative to the charged pion ones by about an order of magnitude. This assumption and the results of Ref. 33 yield

$$D_n \simeq 9 \times 10^{-15} \mathrm{ecm}(\bar{g}^{(0)}_{\pi NN}{}' + 0.1\bar{g}^{(1)}_{\pi NN}{}' - \bar{g}^{(2)}_{\pi NN}{}') \tag{36}$$

for the contribution of $\bar{g}^{(I)}_{\pi NN}{}'$ to D_n. The experimental limit[37]

$$D_n < 1.2 \times 10^{-25} \mathrm{ecm} \qquad (95\% \mathrm{c.l.}) \tag{37}$$

implies

$$|\bar{g}^{(0)}_{\pi NN}{}' + 0.1\bar{g}^{(1)}_{\pi NN}{}' - \bar{g}^{(2)}_{\pi NN}{}'| \lesssim 1.4 \times 10^{-11} . \tag{38}$$

Another source of information on the constants $\bar{g}^{(I)}_{\pi NN}{}'$ is the class of experiments searching for electric dipole moments of atoms and molecules (see Ref. 31). The best limit comes from a search for an electric dipole moment of ^{199}Hg atoms.[38] The experiment has yielded $d(^{199}\mathrm{Hg}) = (0.7 \pm 1.5) \times 10^{-28}$ ecm. The dipole moment $d(^{199}\mathrm{Hg})$ can be related through atomic physics calculations to the Schiff moment of the nucleus; the latter is sensitive to $P,T-$violation in the NN interaction. The calculations of Ref. 39 and the above experimental result imply (see Ref. 32)

$$|\bar{g}^{(0)}_{\pi NN}{}' + \bar{g}^{(1)}_{\pi NN}{}' + 2\bar{g}^{(2)}_{\pi NN}{}'| \lesssim [illegible] \times 10^{-10} \tag{39}$$

The experimental result $d(^{129}\mathrm{Xe}) = (-0.3 \pm 11) \times 10^{-26}$ for Xe atoms (Ref. 40) gives a weaker limit (by about a factor of 6) on the same quantity.[39] An experiment on P,T-violation in TlF (Ref. 41) sets a limit comparable to (39), but the corresponding calculations involve large uncertainties.[39]

A new version of the mercury experiment is under way, and is expected to improve the accuracy of the previous experiment by at least an order of magnitude.[42]

Among nuclear transitions highly hindered γ-decays, where the initial or the final state has a nearby state of opposite parity, can be sensitive to P, T-violation in the N-N interaction. Only one experiment of this kind has been performed so far, studying the γ-decay of a metastable state of ^{180}Hf (Ref. 43). A rough estimate of the effect[36] indicates that an improvement of the sensitivity of the experiment by about a factor of 500 would result in a limit for $\bar{g}^{(1)}_{\pi NN}$ comparable to the limit from (38). For the other constants an improvement by four orders of magnitude would be required.

P,T-violation in the N-N interaction can also be probed in studies of polarized neutron transmission through polarized targets.[44] A P,T-violating observable is the quantity $\rho_{P,T} = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, 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). One would like to search for $\rho_{P,T}$ at an isolated p-wave compound nucleus resonance, whose parameters are known, and which exhibits a large parity-violating effect $\rho_P = (\sigma_+' - \sigma_-')/(\sigma_+' + \sigma_-')$ ($\sigma_+'(\sigma_-')$ is the total cross section for a neutron polarized parallel (antiparallel) to $\vec{k}_n$). Values of ρ_P as large as 7% have been observed near a p-wave compound nucleus resonance. Such a large effect is a result of the so-called "dynamical enhancement" and "resonance enhancement" (see Ref. 44). The latter are effective also for $\rho_{P,T}$. The ratio $\lambda = \rho_{P,T}/\rho_P$ for two-state mixing is proportional to $r_P = \langle \psi_s | V^{PT} | \psi_p \rangle / \langle \psi_s | V^{P} | \psi_p \rangle$, where V^{PT} and V^{P} are the P,T-violating and P-violating potentials respectively; ψ_s and ψ_p are s- and p-states of the compound nucleus. If $\rho_P \sim 10^{-2} - 10^{-1}$, a measurement of $\rho_{P,T}$ with a sensitivity of $\sim 10^{-6}$ would be sensitive to $r_P \sim 10^{-4} - 10^{-5}$ (we are assuming that the nuclear factor involved in λ, which in general could change the expectations (Ref. 45) is of the order of one). A rough estimate[30] indicates that for $\bar{g}^{(1)}_{\pi NN}{}' \simeq 10^{-10}$ one would have $\lambda \simeq 4 \times 10^{-3}$. For $\bar{g}^{(0)}_{\pi NN}{}'$ and $\bar{g}^{(2)}_{\pi NN}{}'$ λ is (barring cancellations in (38)) smaller by about a factor of 20. A measurement of $\rho_{P,T}$ with a statistical accuracy of $10^{-5} - 10^{-6}$ appears feasible at the LANSCE (see Ref. 44) facility, but some difficulties involving systematic effects have not been eliminated yet.

In the standard model the contribution of the Kobayashi-Maskawa phase to $\bar{g}^{(I)}_{\pi NN}{}'$ is too small to be observable; a T-violating flavor-conserving nonleptonic interaction arises only in second order in the weak interaction. One expects therefore $\bar{g}^{(I)}_{\pi NN}{}' \sim (10^{-6})^2 s_1^2 s_2 s_3 s_6 \simeq 10^{-16}$. A detailed estimate finds the P, T-violating $\pi^0 NN$ coupling constant to be of the order of 10^{-17}. The θ-term gives rise to $\bar{g}^{(0)}_{\pi NN}{}'$ (Ref. 4). This contribution can be as large as allowed (barring cancellations) by the limit (38).

P, T-violation in the N-N interaction could also be large in some extensions of the standard model.[47] An example of a class of models where there is a P, T-violating flavor-conserving nonleptonic interaction first order in the weak interaction is $SU(2)_L \times SU(2)_R \times U(1)$ models with $\zeta \neq 0$ (see Eq. 6). The part of this interaction involving only the u, d-quarks is

$$H_{P,T} = \frac{g_L^2}{16 m_1^2}\cos^2\theta_1^L \frac{g_R}{g_L}\frac{\cos\theta_1^R}{\cos\theta_1^L}\zeta\, i\sin(\alpha+\omega)\{\bar{u}\gamma_\mu\Gamma_R d, \bar{d}\gamma^\mu\Gamma_L u\}_+ + H.c. \quad (40)$$

The Hamiltonian (40) is a pure isovector.[30] The corresponding constant $\bar{g}^{(1)}_{\pi NN}{}'$ could be as large as allowed (barring cancellations) by the limit (38) (see Refs. 30 and 11). The additional terms in the interaction contribute to $\bar{g}^{(1)}_{\pi NN}{}'$ and $\bar{g}^{(0)}_{\pi NN}{}'$.

We note that an interaction analogous to (40) can be present also in models with exotic fermions (see Section 2.1). The structure of this interaction is the same as that of (40), except that the quantity $(g_R/g_L)(\cos\theta_1^R/\cos\theta_1^L)\zeta\sin(\alpha+\omega)$ is replaced by $s_R^u s_R^d (V_R' V_R)_{ud} \sin\phi$ (see Eq. 9). The resulting constant $\bar{g}^{(1)}_{\pi NN}{}'$ can again be as large as allowed by (38).

3.2 PARITY CONSERVING T-VIOLATION IN THE N-N INTERACTION

In a model where P-conserving T-violation in the N-N interaction is described by single meson exchange diagrams, the strength of T-violation is characterized by the effective coupling constants $\bar{g}_{MNN}$, defined by

$$< MN \mid H^T \mid N > \propto \bar{g}_{MNN} , \tag{41}$$

where H^T is the P-conserving T-violating Hamiltonian. The lightest single meson state that can contribute in this case is the $\rho^{\pm}$ (Ref. 48).

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 give rise to a P,T-violating effect through interference with the weak interaction. The most stringent limit on $\bar{g}_{MNN}$ from such experiments comes from the limit (37) on D_n. There is no well founded calculation of the contribution of a given $\bar{g}_{MNN}$ to D_n. Taking $\bar{g}_{MNN}$ to represent the strength of T-violation in the flavor-conserving hadronic interactions, a rough estimate of D_n is[49] $D_n \simeq (e/M)(GM^2/4\pi)\bar{g}_{MNN}$ (M = nucleon mass), so that $|\bar{g}_{MNN}| \lesssim 6 \times 10^{-6}$. Allowing an order of magnitude for the uncertainty, we shall take the limit from D_n to be

$$|\bar{g}_{MNN}| \lesssim 10^{-4} \tag{42}$$

A weaker limit than (42) might be in conflict with the experimental result on ϵ'/ϵ.

Limits from tests of detailed balance in nuclear reactions, polarization-asymmetry comparisons, nuclear γ-decay, nucleon-nucleon and nucleon-nucleus scattering, are not better than (42). The best upper limit from such experiments for the ratio ξ of the T-violating and T-invariant amplitude is $\xi < 5 \times 10^{-3}$ (80% c.l.), obtained from a detailed balance study in $^{27}Al(p,\alpha)^{24}Mg$ (Ref. 50). An analysis of this result in terms of T-violating potentials has not been yet, to our knowledge, carried out.

The effects of a P-conserving T-violating N-N interaction can also be studied in the transmission of polarized neutrons through oriented targets, looking for the presence of a $(\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J})\,(\vec{k}_n \cdot \vec{J})$ term.[44] In the vicinity of a compound p-wave resonance in medium heavy nuclei the corresponding cross-section asymmetry 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.[51] To derive limits from an experimental limit on ρ_T will require here also an analysis in terms of T-violating potentials.

In the standard model the constants $\bar{g}_{MNN}$ are negligibly small: the contribution of the Kobayashi-Maskawa phase is expected to be of the order of $\lesssim 10^{-16}$ (like the contribution to the P,T-violating constants); $\bar{g}_{MNN}$ due to the $\theta-$term is also negligible ($\lesssim 10^{-15}$), since the $\theta-$term can contribute to $\bar{g}_{MNN}$ only through interference with the weak interaction.

The first order flavor-conserving nonleptonic interaction in $SU(2)_L \times SU(2)_R \times U(1)$ models, and in models with exotic fermions has no P-conserving T-violating part. One expects therefore $|\,\bar{g}_{MNN}\,| \lesssim 10^{-16}$. The absence of a first order flavor-conserving P-conserving T-violating quark-quark interaction turns out to be a general feature of renormalizable gauge models with elementary quarks. One can prove that in a renormalizable gauge theory with elementary quarks a coupling of a boson of any kind to fermion pairs cannot generate a flavor-conserving P-conserving T-violating quark-quark interaction to second order in the boson-fermion couplings.[52] The size of the constants $\bar{g}_{MNN}$ in such models is therefore expected to be generally much below the present limit. In models with composite quarks flavor-conserving P-conserving T-violating effective quark-quark interactions may be induced by four-preon interactions that do not conserve flavor.[53] We find that in such models $\bar{g}_{MNN}$ of the order of $10^{-5} - 10^{-6}$ are not ruled out.[53]

CONCLUSIONS

In this talk we discussed possible sources of time reversal violation in beta decay and in the nucleon nucleon interaction, and considered the available empirical information on the corresponding interactions. Our aim was to consider what type of new physics can be probed by experiments searching for T-violation in low-energy nuclear processes, and to assess the sensitivities required for experiments to advance our knowledge about the new interactions. Below we summarize our conclusions.

- The T-violating component of the D-coefficient in beta-decay can receive a tree-level contribution in left-right symmetric models (or other models involving new gauge bosons with right handed couplings), in models with exotic fermions, and in models with leptoquarks. Experiments on the D-coefficient have excluded the presence of the associated interactions with strength above $\sim 10^{-3}G$. The leptoquark contribution can be as large as the present upper limit for D. In left-right symmetric models and in models with exotic fermions more stringent limits than the present experimental limit on D follow from the experimental result on D_n and ϵ'/ϵ. However these bounds are not rigorous, in view of the uncertainties in the calculations.

- The R-coefficient in beta-decay can receive tree-level contributions from charged Higgs bosons and from leptoquarks. Based on a rough estimate, the bound $|R_t| \lesssim 3 \times 10^{-3}$ follows on these contributions from the present experimental limit on the electric dipole moment of the electron. This is about two orders of magnitude better than the limit obtained from a direct measurement. For the leptoquark contribution to R_t there is also an upper limit of a few times 10^{-4} from the experimental result on the ratio of $\pi \to e\nu$ to $\pi \to \mu\nu$ rates.

- Searches for the electric dipole moment of the neutron and for electric dipole moments of atoms and molecules set stringent bounds on the possible size of P,T violation in the N-N interaction. The upper limits from D_n on the P,T violating pion-nucleon couplings are roughly four to five orders of magnitude smaller than the strength of a typical weak amplitude. The present limits from atomic dipole moment searches are only 1-2 orders of magnitude weaker.

In some current models with CP violation the P,T violating pion nucleon coupling constants could have values near the limits from D_n.

In nuclear processes the existing limits on P,T violation cannot be improved.

unless there is a strong dynamical amplification of the studied effect. Possible candidates are some hindered γ-decays, and neutron transmission experiments in some medium-heavy nuclei. When comparing limits from other processes with those obtained from the electric dipole moments, one has to keep in mind that the estimates of the dipole moments are subject to unknown uncertainties. Limits from other processes are therefore important even if they would not be quite as stringent as those from the dipole moment.

• The upper limit from D_n on the P-conserving T-violating meson-nucleon coupling constants $\bar{g}_{MNN}$ is of the order of 10^{-4}. This limit is based only on a rough estimate, since unlike for the P,T-violating $\pi^{\pm}NN$ coupling constants, 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 nuclear processes is 5×10^{-4} (from a detailed balance test) for the ratio of the T-violating to T-invariant amplitude. The implication for $\bar{g}_{MNN}$ is not known.

On the theoretical side, the size of the P-conserving T-violating meson-nucleon coupling constants is expected to be much below the present limit from D_n, although values not far from this limit cannot be ruled out.

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