THEORETICAL EXPECTATIONS FOR T-VIOLATION IN THE NUCLEON-NUCLEON INTERACTION

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We discuss the possible size of time-reversal violation in the nucleon-nucleon interaction from a phenomenological point of view, and also in gauge models with CP-violation.

1. Introduction

CP-violation was discovered more than 20 years ago through the decays $K_L \to 2\pi$. The source of this effect is still unknown. The experimental result $|\epsilon|_{expt} \simeq 2.3 \times 10^{-3}$ for ϵ—one of the parameters describing $K_L \to 2\pi$ decays—is still the only quantity associated with CP-violation for which a value different from zero was found [1]. On the basis of the CPT theorem one expects that CP-violation is accompanied with violation of time-reversal (T) invariance. There is some indirect experimental evidence that this is indeed the case for the observed CP-violation [2]. The presence of CP- and T-violation in the neutral kaon system implies that it must occur at some level in other systems as well.

In this talk we shall consider the possible size of T-violation in the nucleon-nucleon interaction, first from a phenomenological point of view, and then in gauge models with CP-violation. We shall start with a discussion of T-violation accompanied with parity-violation [3], and then consider the possible size of parity-conserving T-violation.

2. T-violation in the *N-N* Interaction with Simultaneous P-Violation

There is firm evidence at present that parity (P) is not conserved in the *N-N* interaction [4]. All data are consistent with the interpretation that this effect is due to the flavor conserving ($\Delta F = 0$) nonleptonic weak interaction contained in the minimal standard model. At low energies P-violation in the *N-N* interaction can be described in terms of nonrelativisitic P-violating *N-N* potentials (V^{P}) corresponding to single-meson exchange diagrams involving the lightest pseudoscalar and vector mesons. The link between P-violation in the *N-N* interaction and the weak Hamiltonian is given by the strength g'_{MNN} of the $N \to NM$ matrix elements of the P-violating Hamiltonian $\langle NM \mid H^{\mathrm{P}} \mid N\rangle \sim g'_{MNN}$ [5]. The experimental evidence indicates [6] that

$$g^{I=0'}_{\rho NN} \simeq 2 - 3 \times 10^{-6} \ . \tag{1}$$

For the other constants only upper bounds can be set.

Similarly, one can describe P,T-violation in the low-energy *N-N* interaction (ignoring 2π-exchange) in terms of P,T-violating potentials ($V^{\mathrm{P,T}}$) corresponding to single light meson exchanges, and characterize the size of P,T-violation by the strength $\overline{g}'_{MNN}$ of the $N \to NM$ matrix elements of the P,T-violating Hamiltonian: $\langle MN \mid H^{\mathrm{P,T}} \mid N\rangle \sim \overline{g}'_{MNN}$.

What are the available bounds on $\overline{g}'_{MNN}$? One constraint comes from the observed rate for the parity forbidden α-decay $^{16}\mathrm{O}(2^-,\ 8.87\ \mathrm{MeV}) \to {}^{12}\mathrm{C}(0^+) + \alpha$. Parity-forbidden rates, unlike other P-violating observables, depend on the square of the P-violating coupling constant and are sensitive therefore to both g'_{MNN} and $\overline{g}'_{MNN}$. The α-width for the above decay can be understood in terms of the weak interactions [4]. This implies $|\overline{g}^{I=0'}_{MNN}| \lesssim 10^{-6}$. A comparable limit is obtained from the only experiment that searched for a P-odd, T-odd observable in nuclear γ-decay [7]. The transition studied was one in ^{180}Hf which exhibits a large (of the order of 1%) P-violating effect, due to the severe hindrance of the parity-allowed transition and the existence of a nearby level of the same spin and opposite parity. From the measured P,T-violating asymmetry the authors find $(ImE2/ReE2) = -0.7 \pm 0.6$ ($E2 \equiv$ matrix element of the quadrupole transition operator). Since $ImE2/ReE2 \simeq \langle | V^{\mathrm{P,T}} |\rangle / \langle | V^{\mathrm{P}} |\rangle$, one can conclude that $|\overline{g}'_{MNN}| \lesssim 10^{-6}$.

A much better limit on P,T-violation—the most stringent at present—comes from the experimental result [8]

$$D_n < 2.6 \times 10^{-25} e\mathrm{cm} \quad (95\% \text{ confidence level}) \tag{2}$$

on the electric dipole moment of the neutron. Let $f_{\rm P}$ and $f_{\rm T}$ be, respectively, the strength of P- and T-violation in the hadronic interactions. Dimensional arguments give then the estimate [9]

$$D_n \simeq \frac{e}{M} f_{\rm P} f_{\rm T} \simeq (2 \times 10^{-14}) f_{\rm P} f_{\rm T} \ e\text{cm} \ , \tag{3}$$

where M is the nucleon mass. Taking $\overline{g}'_{MNN}$ to represent $f_{\rm P} f_{\rm T}$, one obtains from (2) and (3) the bound

$$| \, \overline{g}'_{MNN} \, | \lesssim 1.3 \times 10^{-11} \ . \tag{4}$$

For $\overline{g}'_{\pi NN}$ defined by the P,T-violating coupling

$$\overline{\mathcal{L}}'_{\pi NN} = \sqrt{2} \overline{g}'_{\pi NN} (\overline{p} n \pi_+ + \overline{n} p \pi_-) \tag{5}$$

a calculation using a sidewise dispersion relation, which was successfully used to calculate the nucleon magnetic moments, yields [10]

$$D_n \simeq 9 \times 10^{-15} \overline{g}'_{\pi NN} \ e\text{cm} \ , \tag{6}$$

implying

$$| \, \overline{g}'_{\pi NN} \, | \lesssim 3 \times 10^{-11} \ . \tag{7}$$

The contribution of heavier mesons to D_n is presumably smaller and therefore the limits for the corresponding $\overline{g}'_{MNN}$ weaker. However, in a given model the various constants $\overline{g}'_{MNN}$ are related, and generally expected to be of the same order of magnitude.

What are the prospects for improving these limits? Efforts to search for the electric dipole moment of the neutron are continuing; experiments with a sensitivity of 10^{-26} to 10^{-27} $e$cm can be foreseen.

A different class of experiments underway is searches for the electric dipole moment of neutral atoms (d). Electric dipole moments of certain atoms are sensitive probes of P,T-violating N-N forces [11]. $d(^{129}\text{Xe})$ and $d(^{199}\text{Hg})$ have been already searched for with a sensitivity of 10^{-26} [12]. The calculations of Ref. [13] imply that these limits set bounds of P,T-violating couplings which are near those implied by the limit (2) on D_n.

In the scattering of very low-energy neutrons on medium-heavy nuclei P-violating effects were found to be unusually large in several cases [14]. Such effects appear when a p-wave resonance occurs in the compound nucleus near threshold. They are due to the existence of nearby s-wave resonances, admixed by the P-violating force, and also due to the enhancement of the s-wave width relative to the p-wave width. Several experimental groups are actively planning experiments to search for a P,T-odd correlation $\langle \vec{\sigma}_n \rangle \cdot \vec{k}_n \times \langle \vec{J} \rangle$ in the neutron-nucleus elastic forward scattering amplitude on a p-wave resonance which exhibits large P-violation [15]. The idea is to compare on the same resonance the P,T-violating effect $\rho_{\rm P,T} \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ and the P-violating effect $\rho_{\rm P} \equiv (\sigma'_+ - \sigma'_-)/(\sigma'_+ + \sigma'_-)$ ($\sigma_\pm$ are the total cross sections for a neutron polarized parallel and antiparallel to $\vec{k}_n \times \langle \vec{J} \rangle$, and $\sigma'_\pm$ for neutrons polarized parallel and antiparallel to $\vec{k}_n$). The ratio $\lambda \equiv \rho_{\rm P,T}/\rho_{\rm P}$ for two-state mixing is given approximately by [16]

$$\lambda = \langle \psi_s \mid V^{\rm P,T} \mid \psi_p \rangle / \langle \psi_s \mid V^{\rm P} \mid \psi_p \rangle \ , \tag{8}$$

which is approximately the ratio of the strength of P,T-violation and P-violation [16]. Thus

$$\lambda \simeq (\overline{g}'_{MNN} / g^{I=0'}_{\rho NN}) \kappa \ , \tag{9}$$

where we have included a factor κ to account for the possibility that $\overline{g}'_{\pi NN}$ is comparable or larger than the other P,T-violating coupling constants. Inspection of the P-violating single-particle potential [4], which is analogous to the P,T-violating one, indicates that in such a case κ would be as large as

10 or 60, depending on the spin and isospin structure of the two-body potential. Otherwise κ is of the order of one. In the following we shall assume that $\overline{g}'_{\pi NN}$ is not smaller than the other P,T-violating coupling constants.

Taking $g_{\rho NN}^{I=0'} = 2\times10^{-6}$ [see Eq. (1)] and using the limit (7), we obtain for λ the phenomenological upper bound

$$\lambda \lesssim 10^{-3} \ . \tag{10}$$

A statistical accuracy of $\sim 10^{-6}$ is feasible for a measurement of $\rho_{P,T}$. Thus, if $\rho_P \simeq 10^{-2} - 10^{-1}$, the experiment would be sensitive to $\lambda \simeq 10^{-4} - 10^{-5}$. We shall turn now to consider what are the possible values of $\overline{g}'_{MNN}$ and λ in current models of CP-violation.

The minimal standard model.

There are two sources of CP-violation in the minimal standard model: the Kobayashi-Maskawa (KM) phase δ in the quark mixing matrix, and a P,T-violating term in the effective QCD Lagrangian.

The KM phase.

The coupling of the W to the quarks is given by

$$\mathcal{L} = \frac{g}{2\sqrt{2}}(\overline{P}\gamma_\lambda(1-\gamma_5)UN)W^\lambda + \text{H.c.} \ , \tag{11}$$

where $\overline{P} = (\overline{u},\overline{c},\overline{t})$, $\overline{N} = (\overline{d},\overline{s},\overline{b})$. The matrix U can be parameterized by three mixing angles (θ_1, θ_2, and θ_3) and the CP-violating phase δ.

The Lagrangian (1) generates in fourth order (second order in the weak interaction) an effective $\Delta S = 2$ nonleptonic CP-violating interaction which contributes to the parameter ϵ in $K_L \rightarrow 2\pi$ decays. Whether this mechanism can account for the observed value of ϵ is at present an open question [1].

The first-order nonleptonic weak interaction includes a $\Delta S = 1$ term and a flavor-conserving part. The $\Delta S = 1$ term contains a CP-violating component; one of its effects is a contribution to the parameter ϵ' describing CP-violation in $K^0 \rightarrow 2\pi$ decays [18]. The $\Delta F = 0$ part, which is the relevant one for the N-N interaction is, however, CP-conserving [19]. The reason is that this interaction is composed of terms with a structure $U_{ij}\overline{q}_i\Gamma_L q_j(U_{ij}\overline{q}_i\Gamma_L q_j)^+ = |U_{ij}|^2\, \overline{q}_i\Gamma_L q_j \overline{q}_j \Gamma_L q_i$ ($\Gamma_L \equiv \gamma_\lambda(1-\gamma_5)$) and therefore is not sensitive to CP-violating phases. An effective $\Delta F = 0$ nonleptonic interaction arises only in second order in the weak interaction (this, in part, is the reason why the KM contribution to D_n is of the order of 10^{-30} to 10^{-32} [20]). One expects therefore the strength of the P,T-violating N-N interaction relative to the P-violating, T-invariant N-N interaction to be of the order of $10^{-6}\ s_1^2 s_2 s_3 s_\delta \simeq 5\times10^{-11}$. The P,T-violating N-N interaction due to the KM phase was investigated in Ref. [21]. The authors find that an important class of diagrams (possibly the dominant ones) are the K-pole diagrams with one of the NNK vertices P-conserving, T-violating, and the other P-violating, T-invariant. For the strength $G\eta_0/\sqrt{2}$ of the corresponding four-nucleon interaction they obtain (assuming that the KM mechanism explains the observed CP-violation) $G\eta_0/\sqrt{2} \simeq 7\times10^{-9}\ G/\sqrt{2}$. Using the P,T-violating single-particle potential given in Ref. [21], we find

$$\lambda \lesssim 2\times10^{-9} \ , \tag{12}$$

where the equality sign holds if the KM mechanism accounts for the observed CP-violation.

The θ-term.

The QCD Lagrangian contains the term

$$\mathcal{L}_\theta = -\theta(g_s^2/32\pi^2)\epsilon_{\mu\nu\alpha\beta}F_i^{\mu\nu}F_i^{\alpha\beta} \ , \tag{13}$$

which violates simultaneously P- and T-invariance. It contributes therefore to the constants $\overline{g}'_{MNN}$. The strength $\overline{g}'_{\pi NN}$ of the P,T-violating πNN coupling, which is of the form

$$\mathcal{L}^{\mathrm{P,T}}_{\pi NN} = \overline{g}'_{\pi NN}\vec{\pi}\cdot\overline{N}\vec{\tau}N \tag{14}$$

has been estimated in Ref. [22] to be $\mid \overline{g}'_{\pi NN} \mid = 0.027 \mid \theta \mid$. The contribution of (13) to the neutron electric dipole moment in the soft-pion limit is [22] $\mid D_n \mid \simeq (1.3 \times 10^{-14}) \mid \overline{g}'_{\pi NN} \mid$. Given $\overline{g}'_{\pi NN}$, the sidewise dispersion relation calculation of Ref. [10] yields the nearly identical value (6). The P,T-violating N-N potential arising from (14) is given in Ref. [11]. For λ we find

$$\lambda \lesssim 10^{-4} \tag{15}$$

[corresponding to $\kappa = 10$ in Eq. (9)].

The superweak model.

The observed value of ϵ can be explained by a new interaction which has a $\Delta S = 2$ component and a strength of the order of 10^{-9} of the usual weak interactions [23]. One expects therefore in this model $\overline{g}'_{MNN} \simeq 10^{-15}$ and $\lambda \simeq 3 \times 10^{-8}$ (assuming $\kappa = 60$). A superweak interaction could be generated, for example, by the exchange of horizontal gauge bosons of mass $\sim 10^4$ TeV. The $\Delta S = 1$ and $\Delta F = 0$ component of the horizontal interactions can be stronger if the contribution of the horizontal bosons to ϵ is suppressed by a small CP-violating phase and/or if their contribution to the $K^0 \to \overline{K}^0$ amplitude is suppressed by cancellations. In the scenario given in Ref. [24] the strength of the horizontal interactions obey 10^{-16} GeV$^2 \leq G_H \leq 10^{-11}$ GeV^2. Then one expects (assuming $\kappa = 60$) $6 \times 10^{-10} \lesssim \lambda \lesssim 6 \times 10^{-5}$ [25].

$SU(2)_L \times SU(2)_R \times U(1)$ models.

$SU(2)_L \times SU(2)_R \times U(1)$ models [26] are attractive extensions of the standard model which shed a new light on the apparent V-A structure of the charged current weak interactions.

The charged current weak interactions stem from

$$\mathcal{L} = g_L\overline{P}\Gamma_L U_L N W_L + g_R\overline{P}\Gamma_R U_R N W_R\ , \tag{16}$$

where $\Gamma_L \equiv \gamma^\lambda(1-\gamma_5)$, $\Gamma_R = \gamma^\lambda(1+\gamma_5)$; W_L and W_R are linear combinations of the mass-eigenstates W_1 and W_2:

$$\begin{aligned} W_L &= \cos\zeta W_1 + \sin\zeta W_2 \\ W_R &= (-\sin\zeta W_1 + \cos\zeta W_2)e^{i\omega}\ . \end{aligned} \tag{17}$$

U_L and U_R are quark mixing matrices. U_R contains new CP-violating phases. The model can account for the observed CP-violation already at the four-quark level [27].

For $\zeta = 0$ the first-order $\Delta F = 0$ nonleptonic weak interactions are CP-conserving (for the same reason as in the standard model) [27]. For three generations with $\zeta = 0$ we find the upper limit for λ to be an order of magnitude smaller than in the standard model.

For $\zeta \neq 0$ there is a P,T-violating $\Delta F = 0$ nonleptonic interaction in first order of the form [28]

$$H^{\Delta S=0}_{\mathrm{P,T}} \simeq (g_L^2/8m_1^2)\cos^2\zeta\cos^2\theta_1^L\zeta_{g\theta}\sin(\alpha+\omega)(\overline{u}\Gamma_R d\overline{d}\Gamma_L u + \ldots) + \ldots \mathrm{H.c.}\ , \tag{18}$$

where $\zeta_{g\theta} = \zeta(g_R/g_L)(\cos\theta_1^R/\cos\theta_1^L)$; α is a CP-violating phase from U_R. Considering $\overline{g}'_{\pi NN}$, an important diagram is the W_L-W_R exchange diagram (containing a left-handed and a right-handed vertex) for the $\overline{u}d \to \overline{d}u$ transition [3]. The corresponding $\overline{g}'_{\pi NN}$ is of the order of $kG_F m_\pi^2\zeta_{g\theta}\sin(\alpha+\omega)$, where, presumably, $1 < k \lesssim 10$, because of the left-right structure of the operator. Since $\mid \zeta_{g\theta}\sin(\alpha+\omega) \mid \lesssim 10^{-4}$ (from the experimental limits on ϵ' and D_n; an upper limit of 2×10^{-3}

follows from the experimental limit on the D-coefficient in β-decay) [28], one obtains $|\,\overline{g}'_{\pi NN}\,| \lesssim 2\times 10^{-11}$. For λ we find [29]

$$\lambda \lesssim 10^{-3}\,. \qquad (19)$$

Weinberg's Higgs model.

This is the standard model extended to contain three Higgs doublets [30]. If CP is broken spontaneously, CP-violation comes only from the Higgs sector. The model can account for the observed CP-violation and is consistent with other data on CP-violation [31]. A P,T-violating $\Delta F = 0$ non-leptonic interaction appears in first order. Both charged and neutral Higgs exchange contributes. $\overline{g}'_{\pi^0 NN}$ and $\overline{g}'_{\pi^+ NN}$ was estimated in Ref. [3]. The authors find $\overline{g}'_{\pi^+ NN} \simeq 10^{-5}(ImA)$ GeV^4 and $\overline{g}'_{\pi^0 NN} \simeq 4\times 10^{-4}(ImB)$ GeV^4. The quantities ImA and ImB are associated with the mixing of the charged and the neutral Higgs bosons, respectively. Using the bounds [31] $ImA \lesssim 3.2\times 10^{-7}$ (dictated by the experimental limit for the charged Higgs boson mass and by the value of ϵ) and $ImB \lesssim (2.4\times 10^{-2})ImA$ (implied by experimental limit on D_n; $ImB \equiv \langle Hx\rangle/v^2$ in the notation of Ref. [31]) one obtains $|\,\overline{g}_{\pi^+ NN}\,| \leq 3.4\times 10^{-12}$ and $|\,\overline{g}'_{\pi^0 NN}\,| \leq 3\times 10^{-12}$. This implies (assuming $\kappa = 60$)

$$\lambda \lesssim 10^{-4}\,. \qquad (20)$$

3. P-conserving T-violation in the N-N Interaction

In a way analogous to P- and P,T-violation, we can describe the strength of a T-violating, P-conserving component in the low-energy N-N interaction by the effective $N \to NM$ coupling constants $\overline{g}_{MNN}$, defined by $\langle MN \mid H^{\mathrm{T}} \mid M\rangle \sim \overline{g}_{MNN}$, where H^{T} is the T-violating, P-conserving Hamiltonian.

The best limit on the constants $\overline{g}_{MNN}$ comes from the experimental limit (2) on the electric dipole moment of the neutron. Taking $f_{\mathrm{P}} \simeq 10^{-6}$ and $f_{\mathrm{T}} \simeq \overline{g}_{MNN}$ in Eq. (3) we obtain

$$|\,\overline{g}_{MNN}\,| \lesssim 1.3\times 10^{-5}\,. \qquad (21)$$

Other experiments, such as studies of detailed balance in nuclear reactions, polarization-asymmetry comparisons in nucleon-nucleus scattering, and studies of T-odd correlations in nuclear γ-transitions all set a weaker limit, not better than $\sim 5\times 10^{-4}$ [32]. A limit of the order of 10^{-3} is indicated by the experimental value of ϵ and the experimental bound on ϵ'/ϵ.

The limit (21) will be improved in future more sensitive searches for D_n. A new class of experiments will be searches for a T-odd, P-even correlation in polarized neutron transmission through oriented materials. A sensitivity of 10^{-6} for this effect appears to be feasible [15].

What is the possible strength of the P-conserving T-violating N-N interaction in gauge models with CP-violation?

In the minimal standard model the strength of P-conserving T-violation generated by the KM mechanism is expected to be of the order of 10^{-14}-10^{-15}, i.e., comparable to the strength of P,T-violation. The θ-term violates both P and T, and therefore its contribution to $\overline{g}_{MNN}$ is expected to be of the order of 10^{-17}.

As discussed earlier, in $SU(2)_L\times SU(2)_R\times U(1)$ models with $\zeta \neq 0$, in the Higgs model, and in models with horizontal gauge interactions a $\Delta F = 0$ four-quark interaction appears already in first order. A simple inspection shows that in all of these models this interaction has no P-conserving T-violating part. We would like to note that this feature of the first-order $\Delta F = 0$ four-quark interaction is much more general: it holds in any gauge model in which the quarks are elementary. The underlying reason is that, since the couplings of the quarks to the gauge bosons and to Higgs bosons are nonderivative, the parity-conserving $\Delta F = 0$ four-quark interaction contains only terms of the form $\overline{q}\Gamma q\overline{q}\Gamma q$, $\overline{q}\Gamma q\overline{q}'\Gamma q' + \overline{q}'\Gamma q'\overline{q}\Gamma q$ and $\overline{q}\Gamma q'\overline{q}'\Gamma q$ $(q,q' = u,d,c,s,t,b;\ q' \neq q)$ which are already

Hermitian. Thus if any of these terms is multiplied by a complex phase, the imaginary part will be eliminated upon adding the Hermitian conjugate term [33]. A parity conserving T-violating $\Delta F = 0$ interaction will arise in second order (fourth order in the fermion-boson couplings). One expects therefore $\overline{g}_{MNN} \lesssim 10^{-15}$ to 10^{-17}. In composite models CP-violation in the preon gauge theory may induce CP-violating derivative couplings at the quark level, allowing in general a P-conserving T-violating interaction. In such a case the constants $\overline{g}_{MNN}$ may be larger, but most likely still much weaker than the weak interaction.

4. Conclusions

In this talk we have considered the possible size of T-violating effects in the N-N interaction, both with and without P-violation.

For T-violation with P-violation we found that in several gauge models P,T-violating effects in the N-N interaction could be large enough to be observable in some current and contemplated experiments.

Concerning P-conserving T-violating effects we have noted that in gauge models with elementary quarks the flavor-conserving nonleptonic interactions of the quarks do not contain in first order a P-conserving T-violating component. The P-conserving T-violating coupling constants $\overline{g}_{MNN}$ in such models are not expected to be therefore much larger than 10^{-15}.

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