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T-VIOLATING EFFECTS IN NEUTRON PHYSICS AND CP-VIOLATION IN GAUGE MODELS

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ABSTRACT

We review and discuss further the subject of T-violation in the transmission of polarized neutrons through polarized and oriented targets. We consider the possible size of the T-violating effects both from a phenomenological point of view, and also in gauge models with CP-violation. A brief discussion of T-violating effects in β-decay is included.

INTRODUCTION

CP-violation has been observed so far only in the decays of the K_L. The only CP-violating quantity associated with CP-violation found to be non-zero is the parameter ε involved in the K_L-state.[1] The source of this effect is unknown. One possibility is that it is a manifestation of the electroweak interactions of the minimal standard model.[2] Or it may be due to a new interaction contained in some extension of the minimal standard model.

On the basis of the CPT theorem one expects a CP-violating interaction to violate time-reversal (T) invariance. There is some indirect experimental evidence that this is indeed the case for the interaction responsible for the observed CP-violation.[3] The presence of CP- and T-violation in the neutral kaon system implies that it must occur at some level also in other systems. CP-violating and T-violating effects have been searched for in many processes. The results of the experiments set constraints on the thoeretical possibilities. More sensitive experiments of this kind, which would probe further the origin of CP-violation and the existence of new sources of CP- and T-violation, are of great importance.

In this talk we shall discuss the information one could obtain from some low-energy processes involving neutrons.[4] One observable associated with the neutron, which already played an important role in investigations of CP-violation and which will continue to do so, is the neutron electric dipole moment. Here we shall focus on a new class of experiments, involving the transmission of neutrons through polarized and oriented targets. These experiments probe time-reversal violation in the nucleon-nucleon interaction. We shall also discuss briefly T-violating effects in β-decay.

P,T-VIOLATION IN NEUTRON TRANSMISSION

The existence of a P-violating T-invariant component in the N-N interaction is firmly established.[5] All data are consistent with the interpretation that the observed P-violation 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 (ignoring 2π-exchange) in terms of a nonrelativistic P-violating N-N potential derived from single meson exchange diagrams involving the lightest pseudoscalar and vector mesons.[5] P-violation in the N-N interaction is characterized in this description by the strength $g^{(I)}_{MNN}$, of the $N \to NM$ matrix elements of the various isospin (I) components of the P-violating Hamiltonian[6]

$$\langle NM|H^{P}_{(I)}|N\rangle \propto g^{(I)}_{MNN}, \qquad (1)$$

The CP-invariant P-violating $N \to NM$ vertex vanishes for $M = \pi^0, \eta, \eta', S, \delta$ and other $C = +1$ neutral spinless mesons.[7] From the remaining mesons those usually included are the $\pi^{\pm}$, $\rho^{\pm,0}$ and the ω. The experimental evidence indicates that[8]

$$g_{\rho NN}^{(0)\prime} \simeq (2\text{-}3) \times 10^{-6} \quad . \tag{2}$$

For the other constants the data set only upper bounds. Thus for $g'_{\pi NN}$ (which is due entirely to the I = 1 component of H^P) one has $|g'_{\pi NN}|<6\times10^{-8}$; the other constants could have values comparable to the value of $g_{\rho NN}^{(0)\prime}$.

The characteristic size of P-violating effects in non-leptonic nuclear processes is 10^{-6} - 10^{-7}. However, in some transitions the effects are enhanced. One class of experiments where large (of the order of 10^{-2}) P-violating effects were observed are studies of low energy polarized neutron transmission through unpolarized targets.[9] A P-violating observable in transmission experiments is the quantity

$$\rho_P \equiv (\sigma'_+ - \sigma'_-)/(\sigma'_+ + \sigma'_-) \quad , \tag{3}$$

where σ'_+ (σ'_-) is the total cross-section for a neutron polarized parallel (antiparallel) to its momentum $\vec{k}_n$. Values of ρ_P as large as a few percent (7×10^{-2} in ^{139}La) have been observed for neutron energies near a p-wave compound nucleus resonance [9] The non-zero ρ_P is due to the presence of a $\vec{\sigma}_n \cdot \vec{k}_n$ term in the neutron-nucleus elastic forward scattering amplitude. The large effects have been explained[10,11] as due to dynamical enhancement (by a factor $\langle\psi_s|V^P|\psi_p\rangle/D$, where ψ_s and ψ_p are s- and p-states of the compound nucleus, and $D = |E_s - E_p|$), combined with resonance enhancement (by a factor $D^2/\Gamma_p\Gamma_s$, where Γ_p and Γ_s are the total width of the p-wave and the s-wave resonance).

In the presence of interactions which violate simultaneously P- and T-invariance, the neutron-nucleus elastic forward scattering amplitude contains (for polarized targets) a term proportional to $\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J}$ ($\vec{J}$ = spin of the target nucleus).[12] A P,T-violating observable is the quantity

$$\rho_{P,T} \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \quad , \tag{4}$$

where $\sigma_+(\sigma_-)$ is the total neutron-nucleus cross-section for a neutron polarized parallel (antiparallel) to $\vec{k}_n \times \vec{J}$. The quantity $\rho_{P,T}$ is enhanced near a p-wave resonance by the same factors as ρ_p (Ref. 13). The ratio $\lambda \equiv \rho_{P,T}/\rho_P$ is given for two-state mixing approximately by[13]

$$\lambda \equiv \rho_{P,T}/\rho_P \simeq \langle\psi_s|V^{P,T}|\psi_p\rangle/\langle\psi_s|V^P|\psi_p\rangle \quad , \tag{5}$$

where $V^{P,T}$ is the P,T-violating potential (to be discussed shortly).[14]

Several groups are considering or actively planning experiments to search for the $\vec{\sigma}_n\cdot\vec{k}_n \times \vec{J}$ correlation in neutron transmission.[15] The idea is to search for $\rho_{P,T}$ where ρ_P is large. A statistical accuracy as good as $\sim 10^{-6}$ is feasible for a measurement of $\rho_{P,T}$. Thus if $\rho_P \simeq 10^{-2} - 10^{-1}$, the measurement would be sensitive to $\lambda \simeq 10^{-4} - 10^{-5}$.

<u>P,T-Violating N-N Potentials</u>

In analogy with the treatment of P-violation, one can describe P,T-violation in the low-energy N-N interaction (ignoring 2π-exchange) in terms of a nonrelativistic P,T-violating N-N potential ($V^{P,T}$) generated by the exchange of single light mesons. The size of P,T-violation in the N-N interaction is characterized then by the strength $\bar{g}^{(I)}_{MNN}$' of the N $\rightarrow$ NM matrix elements of the P,T-violating Hamiltonian

$$\langle MN|H^{P,T}_{(I)}|N\rangle \propto \bar{g}^{(I)}_{MNN}{}' \quad . \tag{6}$$

As the exchange of a neutral C = +1 spin-zero meson is not forbidden for $H^{P,T}$, the set of mesons employed to describe T-invariant P-violation has to be extended by a least the π^0. The longest range interaction is generated by pion-exchange which is present for a P,T-violating Hamiltonian of any ($I \leq 2$) isospin (see Eqs. (10), (11) and (12) below). Pion-exchange is expected therefore to dominate P,T-violating effects in the N-N interaction, unless the constants $\bar{g}^{(I)}_{\pi NN}$' are relatively suppressed. Here we shall assume that this is not the case and include pion exchange only.

The possible P,T-violating $NN\pi$ couplings (with all the particles on their mass-shell) are[7]

$$\mathcal{L}^{(I=0)}_{P,T} = \bar{g}^{(0)\prime}_{\pi NN}\ \bar{N}\ \vec{\tau}\ N\cdot\vec{\pi} \quad , \tag{7}$$

$$\mathcal{L}^{(I=1)}_{P,T} = \bar{g}^{(1)\prime}_{\pi NN}\ \bar{N}\ N\pi^0 \quad , \tag{8}$$

and

$$\mathcal{L}^{(I=2)}_{P,T} = \bar{g}^{(2)\prime}_{\pi NN}\ \bar{N}\ (3\tau_z\pi^0 - \vec{\tau}\cdot\vec{\pi})N \quad , \tag{9}$$

where the τ's are the isospin Pauli-matrices. The selection rules for P,T-violating pion-exchange between nucleons, reflected by (7), (8), and (9), are summarized in Table I.[16] We have included in Table I for comparison the selection rules for T-invariant P-violating pion-exchange.

TABLE I.
The pion states contributing to the one-pion-exchange N-N potential for various isospin (I) components of the P,T-violating and the P-violating T-invariant Hamiltonian.

	I = 0,2	I = 1
P,T-violation	$\pi^{\pm}$, π^0	π^0
P-violation	-	$\pi^{\pm}$

The P,T-violating N-N potentials generated by (7), (8) and (9) are[17]

$$V^{P,T}_{\pi(0)} = -\frac{1}{8\pi}\frac{m_\pi^2}{M}\ \bar{g}^{(0)\prime}_{\pi NN}\ g_{\pi NN}\ \vec{\tau}_1\cdot\vec{\tau}_2(\vec{\sigma}_1 - \vec{\sigma}_2)\cdot\hat{r}\ \frac{e^{-m_\pi r}}{m_\pi r}(1+\frac{1}{m_\pi r}) \tag{10}$$

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

$$(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\hat{r}\,(\tau_{1z}-\tau_{2z})\Big]\frac{e^{-m_\pi r}}{m_\pi r}\left(1+\frac{1}{m_\pi r}\right) \quad , \tag{11}$$

and

$$V^{P,T}_{\pi(2)} = -\frac{1}{8\pi}\frac{m_\pi^2}{M}\bar{g}^{(2)\prime}_{\pi NN}\, g_{\pi NN}(3\tau_{1z}\tau_{2z}-\vec{\tau}_1\cdot\vec{\tau}_2)(\vec{\sigma}_1-\vec{\sigma}_2)\cdot\hat{r}\,\frac{e^{-m_\pi r}}{m_\pi r}\left(1+\frac{1}{m_\pi r}\right) . \tag{12}$$

In Eqs. (10), (11) and (12) M is the mass of the nucleon, $g_{\pi NN}$ is the strong NNπ 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.

Representing P-violation by the term $V^P_{\rho(0)}$ in V^P proportional to $g^{(0)\prime}_{\rho NN}$, we can write Eq. (5) for λ as

$$\lambda \simeq \lambda^{(0)}_\pi + \lambda^{(1)}_\pi + \lambda^{(2)}_\pi \quad , \tag{13}$$

where

$$\lambda^{(I)}_\pi \simeq \langle\psi_s|V^{P,T}_{\pi(I)}|\psi_p\rangle/\langle\psi_s|V^P_{\rho(0)}|\psi_p\rangle \quad . \tag{14}$$

<u>Phenomenological Bounds on $\lambda^{(I)}_\pi$</u>

The absolute values of the matrix elements of $V^{P,T}$ and V^P between compound nuclear states, appearing in Eq. (14), can be approximated by $|\langle V^{P,T}\rangle_{s.p.}|N_c^{-1/2}$ and $|\langle V^{P,T}\rangle_{s.p.}|N_c^{-1/2}$, where $\langle V^{P,T}\rangle_{s.p.}$ and $\langle V^P\rangle_{s.p.}$ are average single-particle matrix elements, and N_c is the number of single-particle states contained in the expansion of the states of the compound nucleus.[18] To estimate $\langle V^{P,T}_{\pi(I)}\rangle_{s.p.}/\langle V^P_{\rho(0)}\rangle_{s.p.}$ we shall approximate the two-body potentials $V^{P,T}_{\pi(I)}$ and $V^P_{\rho(0)}$ by effective single-particle potentials. The single-particle potentials are obtained by summing the matrix elements of the two-body potentials over the nucleons in a closed spin-zero core (see Ref. 5). For the potentials (10), (11) and (12) we find

$$(V^{P,T}_{\pi(0)})_{s.p.} = -\frac{1}{Mm_\pi^2}\,\bar{g}^{(0)\prime}_{\pi NN}\;g_{\pi NN}\;\tau_z^{(i)}\,\frac{N-Z}{A}\,\vec{\sigma}^{(i)}\cdot\hat{r}^{(i)}\,\frac{\partial\rho_n}{\partial r^{(i)}}\,, \tag{15}$$

$$(V^{P,T}_{\pi(1)})_{s.p.} = \frac{1}{Mm_\pi^2}\,\bar{g}^{(1)\prime}_{\pi NN}\;g_{\pi NN}\;\tau_z^{(i)}\,\vec{\sigma}^{(i)}\cdot\hat{r}^{(i)}\,\frac{\partial\rho_n}{\partial r^{(i)}}\,, \tag{16}$$

$$(V^{P,T}_{\pi(2)})_{s.p.} = -\frac{2}{Mm_\pi^2}\,\bar{g}^{(2)\prime}_{\pi NN}\;g_{\pi NN}\;\tau_z^{(i)}\,\frac{N-Z}{A}\,\vec{\sigma}^{(i)}\cdot\hat{r}^{(i)}\,\frac{\partial\rho_n}{\partial r^{(i)}}. \tag{17}$$

In Eqs. (15-17) $\vec{r}^{(i)}$, $\vec{\sigma}^{(i)}$ and $\vec{\tau}^{(i)}$ are single-nucleon operators, $\hat{r}^{(i)} = \vec{r}^{(i)}/r^{(i)}$, and $r^{(i)} = |\vec{r}^{(i)}|$; ρ_n is the nucleon density in the nucleus, Z and N(= A-Z) are the atomic number and the number of neutrons, respectively.

A feature of the single-particle potentials (15-17) is that they all originate from the direct term in the sum over the core nucleons. and they are not suppressed therefore by the factor $W^\pi \simeq 0.14$ (see Ref. 5), which appears in the P-violating T-invariant pion-exchange potential. Another feature to be noted is that the isovector potential (Eq. (16)) is not suppressed by the factor (N-Z)/A.

The single particle potential corresponding to $V^P_{\rho(0)}$ is given (neglecting the term proportional to (N-Z)/A) by[5]

$$(V^P_{\rho(0)})_{s.p.} \simeq (3W^\rho/2Mm_\rho^2)(1+\mu_v)\,g^{(0)\prime}_{\rho NN}\;g_{\rho NN}\,\rho_n\,\vec{\sigma}^{(i)}\cdot\vec{p}^{(i)}\,, \tag{18}$$

where $g_{\rho NN}$ is the strong ρNN coupling constant, μ_v is the isovector anomalous magetic moment of the nucleon, and $W^\rho \simeq 0.8$. It follows that the contribution of $V^{P,T}_{\pi(I)}$ to $\lambda_\pi^{(I)}$ is given by[19]

$$|\lambda_\pi^{(I)}| = |(\bar{g}_{\pi NN}^{(I)\prime}/g_{\rho NN}^{(0)})|\ \kappa_\pi^{(I)} \qquad (I = 0,\ 1,\ 2) \quad , \tag{19}$$

where

$$\kappa_\pi^{(0)} = \kappa_\pi^{(2)}/2 = \ \kappa^{(1)}\ (N-Z)/A \quad , \tag{20}$$

$$\kappa_\pi^{(1)} = (m_\rho^2/m_\pi^2)(g_{\pi NN}/g_{\rho NN})(2/3(1+\mu_v)W^\rho)\ \alpha|\beta| \quad . \tag{21}$$

In Eq. (21) α is a factor which accounts for the suppression of a ρ-exchange relative to a pion-exchange contribution due to short-range correlations, and β is given by

$$\beta = \langle\vec{\sigma}\cdot\hat{r}\ (\partial\rho_n/\partial r)\ \tau_z\rangle_{s.p.}/\langle\vec{\sigma}\cdot\vec{p}\ \rho_n\rangle_{s.p.} \quad . \tag{22}$$

For a rough estimate of β we shall use $\langle\vec{\sigma}\cdot\hat{r}(\partial\rho_n/\partial r)\tau_z\rangle \simeq (\langle\rho_n\rangle/R)\langle\sigma\tau_z\rangle$, $\langle\vec{\sigma}\cdot\vec{p}\ \rho_n\rangle \simeq \langle\sigma\rangle\langle\rho_n\rangle/R$ (R=nuclear radius),[20] and $\langle\sigma\tau_z\rangle/\langle\sigma\rangle \simeq 1$. This implies $\beta \simeq 1$. Taking $\alpha \simeq 2.6$ (the value found for the case of T-invariant P-violating potentials[5]), $g_{\rho NN}^{(0)\prime} = 2 \times 10^{-6}$ (cf. Eq. (2)), and $(N-Z)/A = 0.18$ (which is the value for ^{139}La and approximately the value for $A \simeq 130 - 170$), we obtain $\kappa_\pi^{(0)} = \kappa_\pi^{(2)}/2 \simeq 12$, $\kappa_\pi^{(1)} \simeq 68$, and

$$|\lambda_\pi^{(0)}| \simeq (6 \times 10^6)|\bar{g}_{\pi NN}^{(0)\prime}| \quad , \tag{23}$$

$$|\lambda_\pi^{(1)}| \simeq (34 \times 10^6)|\bar{g}_{\pi NN}^{(1)\prime}| \quad , \tag{24}$$

$$|\lambda_\pi^{(2)}| \simeq (12 \times 10^6)|\bar{g}_{\pi NN}^{(2)\prime}| \quad . \tag{25}$$

The best limit[21] on the strength of P,T-violation in the flavor-conserving hadronic interactions comes from the experimental limit on the electric dipole moment of the neutron[22]

$$D_n < 2.6 \times 10^{-25}\ \text{ecm} \qquad (95\%\ \text{confidence level}) \quad . \tag{26}$$

Let f_P and f_T be, respectively, the strength of P- and T-violation in hadronic interactions. Dimensional arguments give then the estimate[23]

$$D_n \simeq (e/M)\, f_P f_T \simeq (2 \times 10^{-14})\, f_P f_T \text{ ecm} , \qquad (27)$$

where M is the nucleon mass. The limit (26) implies

$$|f_P f_T| \lesssim 1.3 \times 10^{-11} \quad . \qquad (28)$$

If we take $\bar{g}^{(I)\prime}_{MNN}$ to represent $f_P f_T$, it follows that

$$|\bar{g}^{(I)\prime}_{MNN}| \lesssim 1.3 \times 10^{-11} \quad . \qquad (29)$$

More defensible bounds on the P,T-violating $NN\pi$ couplings can be obtained from a calculation of D_n based on sidewise dispersion relations[24]. The latter were successfully used to calculate the nucleon magnetic moments. For $\bar{f}'_{\pi NN}$ defined by the coupling

$$\mathcal{L}_{P,T} = \sqrt{2}\ \bar{f}'_{\pi NN}\ (\bar{p}n\ \pi_+ + \bar{n}p\pi_-) \qquad (30)$$

the authors of Ref. 24 obtain

$$D_n \simeq 9 \times 10^{-15}\ \bar{f}'_{\pi NN} \text{ ecm} \quad , \qquad (31)$$

implying

$$|\bar{f}'_{\pi NN}| \lesssim 3 \times 10^{-11} \quad . \qquad (32)$$

Adding the term $\bar{f}'_{\pi NN}\ \bar{N}\ \tau_3\ N\ \pi^0$ to the coupling (30) would not appreciably change the result (31), since the pion photoproduction amplitude near threshold, which is involved in the calculation, is relatively small for the neutral pion (the cross-section is roughly an order of magnitude smaller than the cross-section for charged pion photoproduction).[25] Hence

$$|\bar{g}_{\pi NN}^{(0)\prime}| \lesssim 3 \times 10^{-11} \quad . \tag{33}$$

For the same reason we have also

$$|\bar{g}_{\pi NN}^{(2)\prime}| \lesssim 3 \times 10^{-11} \quad . \tag{34}$$

A calculation analogous to the one in Ref. 24 would yield a somewhat less stringent limit for $\bar{g}_{\pi NN}^{(1)\prime}$, since the corresponding coupling involves only the neutral pion. Taking as a guide the ratio of the experimental cross-sections near threshold for the photoproduction of the neutral and the charged pions,[25] we expect the bound

$$|\bar{g}_{\pi NN}^{(1)\prime}| \lesssim 10^{-10} \quad . \tag{35}$$

Using the limits (33), (34) and (35) we obtain[26] for $\lambda_\pi^{(I)}$ from Eqs. (23), (24) and (25)

$$|\lambda_\pi^{(0)}| \lesssim 2 \times 10^{-4} \quad , \tag{36}$$

$$|\lambda_\pi^{(1)}| \lesssim 4 \times 10^{-3} \quad , \tag{37}$$

$$|\lambda_\pi^{(2)}| \lesssim 4 \times 10^{-4} \quad , \tag{38}$$

and for $\lambda \simeq \lambda_\pi^{(0)} + \lambda_\pi^{(1)} + \lambda_\pi^{(2)}$

$$|\lambda| \lesssim 4 \times 10^{-3} \quad . \tag{39}$$

We shall turn now to consider the possible values of $\bar{g}_{\pi NN}^{(I)\prime}$ and λ in current models with CP-violation.[27]

$\lambda_\pi^{(I)}$ in Models with CP-Violation

The minimal standard model

In the minimal standard model there are two sources of CP-violation: the

Kobayashi-Maskawa (KM) phase δ in the quark mixing matrix, and a P,T-violating term in the effective QCD Lagrangian.[2]

The KM phase. The coupling of the W to the quarks is given by

$$\mathcal{L} = \frac{g}{2\sqrt{2}}(\bar{P}\gamma_\lambda(1 - \gamma_5)UN)W^\lambda + \text{H.c.} \quad , \quad (40)$$

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

The Lagrangian (40) 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 $K_L \to 2\pi$ decays. Whether this mechanism can account for the observed value of ε is at present an open question.

The $\Delta S = 1$ nonleptonic weak interaction contains a CP-violating component; one of its effects is a contribution to the parameter ε' describing CP-violation in $K^0 \to 2\pi$ decays.[2] The $\Delta F = 0$ nonleptonic weak interaction, which is the relevant one for the N-N interaction is, however, CP-conserving.[28] The reason is that this interaction is composed of terms with a structure $U_{ij}\bar{q}_i\Gamma_L q_j(U_{ij}\bar{q}_i\Gamma_L q_j)^+ = |U_{ij}|^2\bar{q}_i\Gamma_L q_j\bar{q}_j\Gamma_L q_i$ ($\Gamma_L \equiv \gamma_\lambda(1-\gamma_5)$) and therefore not sensitive to CP-violating phases. A T-violating $\Delta F = 0$ 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} (Ref. 29). One expects therefore the order of magnitude of $\bar{g}^{(I)}_{\pi NN}$, to be $\sim(10^{-6})^2 s_1^2 s_2 s_3 s_\delta \simeq 10^{-16}$ (assuming $s_2 s_3 s_\delta \simeq 2 \times 10^{-3}$) (Ref. 30). Then (cf. Eqs. 23-25) $\lambda \simeq 5\times10^{-9}$, which is, of course, unobservably small. Other diagrams contributing to the P,T-violating N-N interaction include K-pole diagrams. The corresponding N-N potential can be written as[31]

$$V_K^{P,T} = \frac{G}{\sqrt{2}}\,\eta\,\frac{1}{2M}\,(\vec{\sigma}\cdot\hat{r}\,\frac{\partial\rho_n}{\partial r}) \qquad (41)$$

The contribution (λ_k) of (41) to the quantity λ (using β=1 and Eqs. (2) and (18)) is

$$\lambda_k \simeq (6 \times 10^{-2})\eta \quad . \tag{42}$$

The authors of Ref. 31 find $\eta \simeq 8 \times 10^{-9}$, with the dominant contribution provided by neutral kaon exchange. This would imply $\lambda_k \simeq 5 \times 10^{-10}$. A recent paper[32] notes however that the calculation of the P-conserving T-violating $N \to NK$ vertices in Ref. 31 is inconsistent with constraints imposed by chiral invariance. To correct this, additional diagrams have to be included which leads to a result for η roughly 20 times smaller than the original value,[32] implying $\lambda_k \simeq 3 \times 10^{-11}$.

The θ term. The QCD Lagrangian contains the term

$$\mathcal{L}_\theta = -\theta(g_s^2/32\pi^2)\varepsilon_{\mu\nu\alpha\beta}F_i^{\mu\nu}F_i^{\alpha\beta} \quad , \tag{43}$$

which violates simultaneously P- and T-invariance. Since this interaction is isospin invariant, the resulting P,T-violating couplings are isoscalar. The P,T-violating $NN\pi$ coupling (which is of the form (7)) was estimated in Ref. 33 to be $|\bar{g}_{\pi NN}^{(0)\prime}| = 0.027\theta$. The limit on θ, and therefore on $\bar{g}_{\pi NN}^{(0)\prime}$ is dictated by the experimental limit on the neutron electric dipole moment. The contribution of (43) to D_n in the soft-pion limit is[33] $|D_n| \simeq (1.3 \times 10^{-14})|\bar{g}_{\pi NN}^{(0)\prime}|$. Given $\bar{g}_{\pi NN}^{(0)\prime}$, the sidewise dispersion relation calculation of Ref. 24 yields the nearly identical value (31). The P,T-violating N-N potential is of the form (10),[34] and its contribution to λ satisfies the bound(36):

$$|\lambda| = |\lambda^{(0)}| \simeq |\lambda_\pi^{(0)}| \lesssim 2 \times 10^{-4} \quad . \tag{44}$$

The superweak model

The observed value of ε can be explained by a new interaction which is CP-violating, has a $\Delta S = 2$ component, and strength of the order of 10^{-9} of the usual weak interactions.[35]

Assuming that this interaction has also a P-violating $\Delta S = 0$ component, one expects $\bar{g}^{(I),}_{\pi NN} \simeq 10^{-16}$ and (assuming the presence of an I=1 component)

$$|\lambda| \simeq 4 \times 10^{-9} \quad . \tag{45}$$

(see Eq. 24).

Horizontal interactions

A possible source of CP-violation is the exchange of horizontal gauge bosons.[36] The gauge symmetries underlying the horizontal interactions act on fermion generations. They have been proposed to distinguish the generations and to reduce the number of undetermined parameters of the minimal standard model. The superweak interaction considered above could be generated by the exchange of horizontal gauge bosons of mass ~ 10^4 TeV. The horizontal gauge bosons could be lighter, and consequently the $\Delta S = 1$ and the $\Delta F = 0$ components of the horizontal interactions stronger than superweak, if the contribution of the horizontal bosons to ε is suppressed by a small CP-violating phase (and/or small mixing angles) and/or if their contribution to the $K^o \to \bar{K}^o$ amplitude is suppressed by cancellations. Inspection shows that in order to have CP-violation in the $\Delta F = 0$ nonleptonic horizontal interactions the horizontal current involved must contain quark mass-eigenstates of different flavor. Since the current involves quarks of the same charge, the T-violating $\Delta F = 0$ interaction has only $I = 0$ and $I = 1$ components. For an interaction involving the d and s quarks, which is likely to dominate the $N \to N\pi$ matrix elements, there is in general an $I = 1$ component. In the scenario given in Ref. 37 the strength G_H of the horizontal interactions obeys $10^{-16} GeV^{-2} \lesssim G_H \lesssim 10^{-11} GeV^{-2}$. If we assume the same strength for the $\Delta F = 0$ component of the interaction, and also that $G_H/G_F \simeq \bar{g}^{(I),}_{\pi NN}/g^{(0),}_{\rho NN}$, we obtain[38]

$$7 \times 10^{-10} \lesssim |\lambda| \lesssim 7 \times 10^{-5} \quad . \tag{46}$$

Somewhat larger values of $|\lambda|$ cannot be ruled out.

$\underline{SU(2)_L \times SU(2)_R \times U(1)\ \text{models}}$.

$SU(2)_L \times SU(2)_R \times U(1)$ models[39] 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 of the quarks arise from

$$\mathcal{L} = g_L \bar{P} \Gamma_L U_L N W_L + g_R \bar{P} \Gamma_R U_R N W_R + H.c. \quad (47)$$

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

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

$$W_R = (-\sin\zeta W_1 + \cos\zeta W_2) e^{i\omega} \quad . \quad (48)$$

U_L and U_R are quark mixing matrices. U_R contains new CP-violating phases. The neutral current interactions conserve CP. The model can account for the observed CP-violation already at the four-quark level.[40]

For $\zeta = 0$ the first-order $\Delta F = 0$ nonleptonic weak interactions are CP-conserving[40] (the interaction consists of terms involving either products of V-A currents or products of V+A currents; hence neither of these terms is sensitive to CP-violating phases), and λ is therefore unobservably small. For $\zeta \neq 0$ there is a P,T-violating $\Delta F=0$ nonleptonic interaction in first order of the form[41]

$$H_{P,T}^{\Delta F=0} \simeq -(g_L^2/16m_1^2) \cos^2\theta_1^L \, \zeta_{g\theta} i \sin(\alpha+\omega) \{\bar{u}\Gamma_R d, \bar{d}\Gamma_L u\}_+ + H.c. + \ldots \quad (49)$$

where m_1 is the mass of W_1, $\zeta_{g\theta} = \zeta(g_R/g_L)(\cos\theta_1^R/\cos\theta_1^L)$; α is a CP-violating phase from U_R. The additional terms in Eq. (49) contain other quarks and CP-violating phases.

Inspection shows that the term written out in Eq. (49) transforms as a pure isovector. It contributes therefore only to $\bar{g}_{\pi NN}^{(1)}$. The remaining part of $H_{P,T}^{\Delta F=0}$ has both I=0 and I=1 (but no

I=2) components. Considering $\bar{g}^{(1)\prime}_{\pi NN}$, an important diagram is the W_L-W_R exchange diagram (containing a left-handed and a right-handed vertex) for the $\bar{u}d \to \bar{d}u$ transition.[42] The corresponding $\bar{g}^{(1)\prime}_{\pi NN}$ can be written as

$$\bar{g}^{(1)\prime}_{\pi NN} \simeq k\, G_F m_\pi^2 \zeta_{g\theta} \sin(\alpha+\omega) \simeq (2\times 10^{-7}) k \zeta_{g\theta} \sin(\alpha+\omega) \quad , \quad (50)$$

where, presumably, $1 < k \lesssim 10$ because of the left-right structure of the operator.[42] From the bound (35) one has $|k\zeta_{g\theta} \sin(\alpha+\omega)| \lesssim 5\times 10^{-4}$, which is consistent for $k \lesssim 5$ with the limit[41] $|\zeta_{g\theta} \sin(\alpha+\omega)| \lesssim 10^{-4}$ from the experimental bound on ε', and the bound (26) used with a quark model calculation of D_n (it is also consistent with the bound on $\zeta_{g\theta} \sin(\alpha+\omega)$ from the experimental limit on the D-coefficient in β-decay (see Eq. (60) further on)). For $|k\zeta_{g\theta} \sin(\alpha+\omega)| \simeq 5\times 10^{-4}$ one would have $\lambda \simeq 4 \times 10^{-3}$. The value $\lambda \simeq 4 \times 10^{-3}$ is possible even for k smaller than 5, since a value of $|\zeta_{g\theta} \sin(\alpha+\omega)|$ larger than 10^{-4} (but smaller than 2×10^{-3} [cf. Eq. (60)]) cannot be ruled out Hence we conclude that[43]

$$|\lambda| \lesssim 4 \times 10^{-3} \quad . \quad (51)$$

Weinberg's Higgs model

This is the standard model extended to contain three Higgs doublets.[44] The model can account for the observed CP-violation and is consistent with other data on CP-violation.[45] A P,T-violating $\Delta F = 0$ nonleptonic interaction appears in first order. Both charged and neutral Higgs exchange contribute. The P,T-violating $NN\pi$ couplings have been estimated in Ref. 42. For the neutral pion coupling, which in general has an I = 1 component, the authors obtain $\bar{g}'_{\pi^0 NN} \simeq 4 \times 10^{-4} (\mathrm{Im}B)\ \mathrm{GeV}^4$, where ImB is associated with the mixing of the neutral Higgs bosons. Using the bound $|\mathrm{Im}B| \lesssim 8 \times 10^{-9}\ \mathrm{GeV}^{-4}$ (Ref. 45) we obtain $|\bar{g}'_{\pi^0 NN}| \lesssim 3\times 10^{-12}$ (the bound on the coupling of the charged pions is comparable). This implies (cf. Eq. (24))

$$|\lambda| \lesssim 10^{-4} \quad . \tag{52}$$

P-CONSERVING T-VIOLATION IN NEUTRON TRANSMISSION

In a way analogous to P- and P,T-violation, one can describe the strength of a T-violating, P-conserving component in the low-energy N-N interaction by the effective N→NM coupling constants $\bar{g}_{MNN}$ defined by

$$\langle MN|H^T|M\rangle \propto \bar{g}_{MNN} \quad , \tag{53}$$

where H^T is the T-violating, P-conserving Hamiltonian. The T-violating P-conserving N-N interaction has a short range, since there is no contribution from pion exchange.[46]

The best limit on the constants $\bar{g}_{MNN}$ comes from the experimental limit (26) for D_n. Taking in Eq. 28 $f_p \simeq 10^{-6}$ and $f_T \simeq \bar{g}_{MNN}$, one obtains

$$|\bar{g}_{MNN}| \lesssim 1.3 \times 10^{-5} \quad . \tag{54}$$

Judging from the limit (33) for the pion coupling, the bounds from D_n on $\bar{g}_{MNN}$ are probably weaker (perhaps by an order of magnitude) than (54), because of the higher mass of the mesons involved and also because of the relatively small strong NNM couplings.

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 $\sim 5 \times 10^{-4}$ [Refs. 1 and 47]. A limit of the order of 10^{-3} is indicated by the experimental value of ε and the experimental bound on ε'/ε.

As emphasized in Ref. 11, a neutron transmission experiment searching for P,T-violation probes also the presence of a T-violating P-conserving interaction, since the interference of the T-violating interaction with the usual weak interactions generates a P,T-violating effect. Thus a measurement of λ with a sensitivity of 10^{-4}-10^{-5} would give a more stringent bound on $\bar{g}_{MNN}$ than (54) by 1-2 orders of magnitude.

The presence of a P-conserving T-violating interaction can be probed in neutron transmission experiments also directly, i.e. through a P-conserving T-violating observable. In the presence of T-violation the elastic neutron-nucleus forward scattering amplitude contains for targets of spin ≥ 1 a term of the form $(\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J})(\vec{k}_n \cdot \vec{J})$[Ref. 48]. A T-violating P-conserving observable is the quantity

$$\rho_T \equiv (\bar{\sigma}_+ - \bar{\sigma}_-)/(\bar{\sigma}_+ + \bar{\sigma}_-) \quad , \tag{55}$$

where $\bar{\sigma}_+(\bar{\sigma}_-)$ is the neutron-nucleus total cross section for neutrons polarized parallel (antiparallel) to $\vec{k}_n \times \vec{J}$ with the angle between $\vec{k}_n$ and $\vec{J}$ fixed at $\pi/4$.

In the vicinity of a p-wave resonance one can have[11]

$$\rho_T \simeq \sin \phi \tag{56}$$

where ϕ is approximately given by the ratio of the average magnitudes of the matrix elements of the T-violating and the T-invariant potentials. Thus the bound (54) corresponds, roughly, to $\rho_T \lesssim 10^{-5}$. Searches for ρ_T are considered or planned in several laboratories.[15] A measurement of ρ_T with a statistical accuracy as good as $\sim 10^{-6}$ is feasible.

What are the expectations for the size of P-conserving T-violation in the N-N interaction in the models considered in the previous section? In the minimal standard model the strength of P-conserving T-violation is expected to be comparable to the strength of P,T-violation, i.e. of the order of 10^{-16} relative to the strong interactions. The θ-term violates both P and T, and can therefore contribute to the constants $\bar{g}_{MNN}$ only through interference with the usual weak interactions. Hence we expect $\bar{g}_{MNN} \lesssim 10^{-16} - 10^{-17}$. In the remaining models a T-violating $\Delta F=0$ four-quark interaction appears already in first order (second order in the quark-boson couplings), but, as simple inspection shows, in none of the models does it have a P-conserving part. As a result, we expect in the horizontal model considered in Ref. 37 $\bar{g}_{MNN} \simeq 10^{-18} - 10^{-23}$, in $SU(2)_L \times SU(2)_R \times U(1)$ models $\bar{g}_{MNN} \lesssim 10^{-16}$ and in Weinberg's Higgs model $\bar{g}_{MNN} \lesssim 10^{-17} - 10^{-18}$. The absence of a first order P-conserving T-violating $\Delta F=0$ nonleptonic interaction is a general feature of gauge models with elementary quarks.[49] The constants $\bar{g}_{MNN}$ in such models are therefore not likely to be much larger than 10^{-15}. In composite models $\bar{g}_{MNN}$ may be larger, but most likely still much weaker than the weak interaction.

T-VIOLATION IN BETA-DECAY

The effects we discussed so far arise from T-violation in the nonleptonic interactions of the quarks. Semileptonic processes probe the T-violating interactions in the nonleptonic sector in a different way, and can also be sensitive to additional sources of T-violation which involve the leptonic sector. Among the most sensitive tests are searches for T-odd correlations in β-decay, and in particular searches for the correlation $D\langle\hat{J}\rangle\cdot\vec{p}_e\times\vec{p}_\nu/E_eE_\nu$ ($\langle\hat{J}\rangle$=polarization of the decaying nucleus) in ^{19}Ne and n-decay[1,50]. The D-coefficient, which was searched already at the level of $\sim 10^{-3}$ is sensitive to a V,A-type T-violating interaction:

$$D \propto \mathrm{Im}(C_V C_A^* + C_V' C_A'^*) \quad . \tag{57}$$

An experimental result, though considerably less accurate, is available on the correlation $R\vec{\sigma}\cdot\langle\hat{J}\rangle\times\vec{p}_e/E_e$ ($\vec{\sigma}$ = electron polarization), which is sensitive to scalar-type couplings:

$$R \propto \mathrm{Im}(C_S C_A'^* + C_S' C_A^*) \quad . \tag{58}$$

T-odd correlations in β-decay, unlike the correlations discussed for neutron transmission, receive contributions also from T-invariant electromagnetic final state interactions. The present experiments have not yet reached the level where they enter.

Let us consider the possible size of the T-violating contributions to D and R in the models discussed earlier.

T-violation due to the KM phase δ of the minimal standard model arises in semileptonic processes only in second order in the weak interactions.[51] Hence its contribution to D and R (and to other T-odd correlations in β-decay) is negligible - of the order of $\sim 10^{-6} s_1^2 s_2 s_3 s_\delta \sim 10^{-10}$. The θ-term is expected to give a contribution which is comparable or smaller. The contribution of T-violating horizontal interactions is also negligible: horizontal interactions are mediated by neutral gauge bosons, and their contribution to β-decay arises only at the one-loop level.

In $SU(2)_L \times SU(2)_R \times U(1)$ models the D-coefficient receives a T-violating contribution in first order, proportional to the W_L-W_R mixing angle ζ (see Eq. 48).[52] To lowest order in the parameters involving ζ and the parameter m_1^2/m_2^2 (m_1 and m_2 are the masses of W_1 and W_2) it is given by[52,41]

$$D \simeq - a_D \, \zeta_{g\theta} \, \sin(\alpha + \omega) \quad , \tag{59}$$

where $a_D \simeq -1.03$ for ^{19}Ne, and $a_D \simeq 0.87$ for n-decay. The factors $\zeta_{g\theta}$ and $\sin(\alpha+\omega)$ are those encountered in Eq. (49); hence D probes one of the phases involved in the nonleptonic interaction (49). The best limit ($D = (0.4 \pm 0.8) \times 10^{-3}$) on D comes from an experiment on ^{19}Ne-decay[53], implying

$$|\zeta_{g\theta} \sin(\alpha+\omega)| < 1.7 \times 10^{-3} \quad \text{(90\% confidence level)} \tag{60}$$

The most accurate neutron-decay experiment[54] yields an upper bound on $|\zeta_{g\theta} \sin(\alpha+\omega)|$ of 4.5×10^{-3}.

An upper bound on $|\zeta_{g\theta} \sin(\alpha+\omega)|$ of $\sim 10^{-4}$ can be derived from the experimental limit for ε'/ε and also from the experimental limit for D_n (Ref. 41). These bounds are however not as reliable as the bound (60).

The next generation experiment on ^{19}Ne-decay hopes to achieve a sensitivity of 5×10^{-5} (Ref. 55). A new experiment is planned to measure D in n-decay[50], which expects to improve the existing neutron-decay result by an order of magnitude. Beyond these experiments the neutron-decay experiments will have ultimately the advantage of a smaller final-state interaction ($\sim 2\times10^{-5}$ compared to $\sim 2\times10^{-4}$ for ^{19}Ne).

In Weinberg's model there is a first order T-violating semileptonic interaction involving a scalar-type coupling, generated by the exchange of charged Higgs bosons. Its contribution to R (resulting from the interference of the scalar interaction with the usual weak interactions) is expected to be however too small to be observable, since it is proportional to the product of the electron mass and the mass of the u- or the d-quark. In models with a more involved Higgs sector a contribution to R near the present experimental limit cannot be ruled out[56]. Let us consider for illustration the Higgs-fermion interaction

$$\mathcal{L}_\phi = f' \, \bar{\nu} e \phi + f'' \, \bar{u} d \phi + \text{H.c.} \tag{61}$$

where ϕ is a charged Higgs field. The complete Higgs-fermion Lagrangian will contain further couplings and other Higgs fields. We shall be assuming that all the dangerous couplings, such as those associated with flavor-changing neutral currents are suppressed. Note that the term (61) does not contribute in lowest order to the electric dipole moment of the neutron, nor to T-violation in neutron transmission.

The coefficient R generated by (61) is given by

$$R = - a_R \, \mathrm{Im}\, h_s \quad , \tag{62}$$

where $h_s = \sqrt{2}(f')^* f''/Gm_H^2$ (m_H = Higgs mass, G = Fermi constant); $a_R \simeq 0.26$ for ^{19}Ne and $a_R \simeq 0.22$ for the neutron[57]. The experimental result R = -0.079±0.053 (Ref. 58) implies

$$|R| < 0.17 \quad \text{(90\% confidence level)} \quad , \tag{63}$$

or, equivalently, $|\mathrm{Im} h_s| < 0.64$. $\mathrm{Re} h_s$ is constrained by the limit on the Fierz interference term[59] as $|\mathrm{Re} h_s| < 1.1 \times 10^{-2}$, so that $|h_s| < 0.64$. The best limit on $|h_s|$ comes from the experimental value of the ratio of the rates for $^{14}O \to {}^{14}N\, e^+ \nu$ and $\pi^+ \to \pi^o e^+ \nu$ decays[60], implying $|h_s| \lesssim 0.4$. It follows that $|R| \lesssim 0.1$.

Returning to the Lagrangian (61), in models with more than one Higgs doublet (which is necessary to have here), the Higgs-fermion couplings are undetermined. In particular, they need not be proportional to the masses of the fermions the Higgs couples to. Consider the special case, when they are proportional to large fermion masses (M_ℓ, M_q) in the theory[60], and take

$$f' = 2^{\frac{1}{4}} \sqrt{G}\, M_\ell \, a \, e^{i\psi}$$

$$f'' = 2^{\frac{1}{4}} \sqrt{G}\, M_q \, b \quad , \tag{64}$$

where a and b are some combinations of mixing angles in the fermion and Higgs sectors, and ψ is a CP-violating phase. It follows that $h_s = 2M_\ell M_q \, abe^{i\psi}/m_H^2$, and

$$R = 2M_\ell M_q a_R \, ab \, \sin\psi/m_H^2 \quad . \tag{65}$$

With $|\sin\psi| \simeq 1$, $a,b \simeq 1$ $M_\ell \simeq 2$ GeV, $M_q \simeq 40$ GeV, and $m_H \simeq 20$ GeV one would have $|R| \simeq 0.1$. There is, of course, no compelling model with the features used here. The purpose was to show that a modest improvement of the present experimental limit on R would provide alrea'y new information. Searches for R in ^{19}Ne-decay with a sensitivity of 10^{-2} - 10^{-3} appears to be feasible.[55] The final state interactions are of the order of 10^{-3} (Ref. 58). In neutron decay a search for R with a significant sensitivity would be exceedingly difficult.

CONCLUSIONS

Equations (36)-(39) summarize our conclusions concerning the poss'ble size of P,T-violating effects in neutron transmission (ents, allowed by the available experimental information on t rength of P,T-violation in the N-N interaction. The bounds (36)-(39) depend on the size of the parameter β (Eq. (22)), which we have set equal to one, as suggested by a rough estimate. Detailed calculations may yield other values for β. The bounds (36)-(39) are also subject to the uncertainties in the limits from the neutron electric dipole moment and in the various approximations that were used. Based on (36)-(39), an experiment sensitive to λ (Eq. 5) at the level of 10^{-5} would improve the bound (35) on $\bar{g}_{\pi NN}^{(1)}$, by a factor of 400 and the other P,T-violating $NN\pi$ constants by factors an order of magnitude smaller. In several models with CP-violation λ could be in the observable ($\lambda \gtrsim 10^{-4}$ - 10^{-5}) range. In $SU(2)_L \times SU(2)_R \times U(1)$ models we find that λ could be as large as the upper bound (39).

The limits on the constants $\bar{g}_{\pi NN}^{(I)}$, can also be improved through more sensitive searches for the electric dipole moment of the neutron. Efforts to lower the limit for D_n are continuing; improvements of the present limit by 1-2 orders of magnitude can be foreseen.[61]

A further class of experiments which can provide information on P,T-violation is searches for electric dipole moments of atoms[1]. Electric dipole moments of certain atoms are sensitive probes of P,T-violating N-N forces[34,62]. The dipole moments of ^{129}Xe and ^{199}Hg atoms have been searched for with a sensitivity of 10^{-26} (Refs. 63 and 64). The calculations of Ref. 65 and the present limit on d(^{199}Hg) imply a limit on the P,T-violating coupling $\bar{g}'\bar{p}p\pi^{o}$ which is only an order of magnitude weaker than the bounds (33)-(35) on the constants $\bar{g}^{(I)}_{\pi NN}$, from D_n. The existing limits on $d(^{199}Hg)$ and $d(^{129}Xe)$ can be improved by several orders of magnitude[66].

It should be noted that while all three types of experiments mentioned above are sensitive to P,T-violation in the flavor conserving nonleptonic interactions, they measure different matrix elements, subject to different theoretical uncertainties.

Neutron transmission experiments, as well as more sensitive searches for the neutron electric dipole moment and for the electric dipole moment of atoms can improve also the limits for P-conserving T-violation in the N-N interaction. In gauge models with elementary quarks the flavor conserving NMM coupling constants $\bar{g}_{MNN}$ are not expected to be much larger than 10^{-15}. Observation of P-conserving T-violation at levels that can be presently reached would be evidence for new physics not present in extensions of the minimal standard model considered so far.

Searches for T-violation in β-decay give complementary information on T-violation in the nonleptonic sector, and probe also different types of T-violating interactions. Among the models we considered observable effects are possible in $SU(2)_L \times SU(2)_R \times U(1)$ models and for T-violation mediated by charged Higgs-exchange.

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$\mathrm{Im}\,E2/\mathrm{Re}E2 \simeq \langle|V^{P,T}|\rangle/\langle|V^{P}|\rangle$, one can conlcude that $|\bar{g}_{MNN}^{(0)\prime}| \lesssim 2\times10^{-6}$. For $\bar{g}_{\pi NN}^{(0)\prime}$, $\bar{g}_{\pi NN}^{(1)\prime}$ and $\bar{g}_{\pi NN}^{(2)\prime}$ one obtains the more stringent bounds $|\bar{g}_{\pi NN}^{(0)\prime}| \lesssim 2\times10^{-7}$, $|\bar{g}_{\pi NN}^{(1)\prime}| \lesssim 3\times10^{-8}$, and $|\bar{g}_{\pi NN}^{(2)\prime}| \lesssim 8\times10^{-8}$.

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