Constraints on Parity-Even Time Reversal Violation in the Nucleon-Nucleon System and Its Connection to Charge Symmetry Breaking

Markus Simonius
Institut für Teilchenphysik, Eidgenössische Technische Hochschule, CH-8093 Zürich, Switzerland
(Received 8 November 1996)

Parity-even time reversal violation (TRV) in the nucleon-nucleon interaction is reconsidered. The TRV ρ-exchange interaction on which recent analyses of measurements are based is necessarily also charge symmetry breaking (CSB). Limits on its strength $\bar{g}_\rho$ relative to regular ρ exchange are extracted from recent CSB experiments in neutron-proton scattering. The result $\bar{g}_\rho \leq 6.7 \times 10^{-3}$ (95% C.L.) is considerably lower than limits inferred from direct TRV tests in nuclear processes. Properties of a_1 exchange and limit imposed by the neutron electric dipole moment are briefly discussed. [S0031-9007(97)03205-5]

PACS numbers: 11.30.Er, 11.30.Hv, 13.75.Cs, 24.70.+s

Investigations of time-reversal violation (TRV) orders of magnitude above the weak interaction scale and thus necessarily of nonweak origin continue to enjoy popularity in nuclear and nucleon-nucleon physics [1–8].

Since otherwise its presence would long have been detected in experimental investigations of parity violation, TRV above the weak interaction level must be parity even. This imposes severe restrictions on the possible ways a TRV interaction can be constructed. Indeed, contrary to the case of a parity-odd TRV interaction which naturally arises in the θ term of QCD, no "natural" implementation of P-even TRV is possible [2,9–11].

Also in an effective theory at the hadronic level, parity conservation imposes restrictions which render most of the experimental searches for P-even TRV rather elusive. For boson exchange interactions in the nucleon-nucleon system these constraints were analyzed in Ref. [12]. The main features, deduced for on-shell amplitudes, are the following:

(i) P-even TRV is restricted to partial waves with total angular momentum $J \geq 1$.

(ii) Total angular momentum zero exchange (one π or σ, etc.) cannot contribute.

(iii) Natural parity exchange (ρ) must be charged and necessarily contains the nucleon-nucleon isovector charge exchange operator $2i(\tau_1^+\tau_2^- - \tau_1^-\tau_2^+) = (\vec{\tau}_1 \times \vec{\tau}_2)^z$ and thus cannot contribute in the nn or pp system [13].

Restrictions due to parity conservation are found also directly in elastic scattering of nucleons on a spin zero nucleus: After decomposition into angular momentum and parity eigenstates the scattering matrix is diagonal and thus symmetric and automatically time-reversal invariant. This shows also that a T-odd interaction introduced at the nucleon-nucleon level is suppressed in nuclei since it is ineffective in the interaction of single nucleons with the spin zero core [14]. This ineffectiveness, emphasized already in Ref. [15] has recently been verified also for processes in heavy nuclei governed by the statistical model [3,4], for which high sensitivity has long been claimed, as well as in other calculations [5,7,8].

Since charged ρ is the lightest meson meeting the constraints (ii) and (iii) above, it provides the longest range possible P-even TRV one boson exchange interaction between nucleons. Following [3] most recent analyses of P-even TRV in nuclear systems are therefore based on the ρ-exchange interaction proposed in Refs. [12,15].

However, according to (iii) a P-even TRV ρ-exchange nucleon-nucleon interaction is necessarily CS odd as well as T odd, and thus invariant under combined application of both these symmetry operations. It is the main purpose of this paper to analyze the consequences of this fact and assess the limits imposed on the strength of this interaction by recent experimental measurements and theoretical analyses of charge symmetry breaking (CSB) in neutron-proton scattering.

TRV ρ-exchange interaction.—The starting point is the P-even TRV $\rho^{\pm}NN$ coupling (effective Lagrangian)

$$-i\bar{g}_\rho \frac{g_\rho \kappa}{2M} \bar{\psi} \sigma_{\mu\nu} q^\nu (\vec{\tau} \times \vec{\rho}^{\,\mu})^z \psi\,, \tag{1}$$

where M is the nucleon mass and q the momentum of the (emitted) ρ meson. TRV is implemented by the isospin structure which contains only charged ρ's and is odd under charge conjugation C. With the corresponding regular coupling

$$g_\rho \bar{\psi}\left(\gamma_\mu + i\frac{\kappa}{2M}\sigma_{\mu\nu}q^\nu\right)(\vec{\tau} \cdot \vec{\rho}^{\,\mu})\psi \tag{2}$$

one obtains the TRV Born amplitude or momentum space potential

$$\tilde{V}_\rho^{\rm TRV}(q) = \bar{g}_\rho \frac{g_\rho^2 \kappa}{2M} (\vec{\tau}_1 \times \vec{\tau}_2)^z \frac{1}{m_\rho^2 + |\vec{q}|^2} \times i((\vec{p}_f + \vec{p}_i) \times \vec{q}) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \tag{3}$$

to lowest order in the momenta where $\vec{p}_i$ and $\vec{p}_f$ denote initial and final state relative momenta, respectively, and $\vec{q} = \vec{p}_f - \vec{p}_i$. Fourier transformation then yields the corresponding TRV configuration space potential

$$V_\rho^{\rm TRV}(r) = \bar{g}_\rho g_\rho^2 \kappa (\vec{\tau}_1 \times \vec{\tau}_2)^z \vec{l} \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \times \frac{m_\rho^2}{M^2} \frac{e^{-m_\rho r}}{4\pi r}\left(\frac{1}{m_\rho r} + \frac{1}{m_\rho^2 r^2}\right). \tag{4}$$

In these equations $g_\rho = 2.79$ is the usual ρNN coupling constant and $\bar{g}_\rho$ parametrizes the relative strength of the TRV coupling. For definiteness of the definition of $\bar{g}_\rho$ κ is identified in the TRV interaction with its vector dominance value $\kappa = \mu_V = 3.7$, the anomalous isovector nucleon magnetic moment, though a larger value is preferred in the strong nucleon-nucleon interaction.

It is emphasized that the structure of the interaction in Eqs. (3) and (4) is completely fixed by the fact that the total exchanged system has natural parity $\pi = (-1)^J$ where J (>0) is the total angular momentum of the exchanged system [12]. In fact, the same TRV NN interaction is obtained if the TRV coupling (1) is replaced by $\bar{g}_\rho g_\rho \bar{\psi} \gamma_\mu (\vec{\tau} \times \vec{\rho}^{\,\mu})^z \psi$. Moreover, the same spin-isospin structure would be obtained for two π exchange since two pions are always in a natural parity state and they also could not contribute if carrying total spin zero which in the regular interaction gives their dominant contribution.

Elastic neutron-proton scattering.—The observables of interest are the single-spin observables A^n, A^p, P^n, and P^p where A denotes the analyzing power for neutrons (n) or protons (p) polarized perpendicularly to the scattering plane and P the corresponding polarization of outgoing nucleons for unpolarized beam and target. In the absence of TRV and CSB these observables are all equal: $A^n = A^p = P^n = P^p$. T-odd effects are measured by $\Delta^p \equiv P^p - A^p$ and $\Delta^n \equiv P^n - A^n$ and CS-odd effects by $\Delta A \equiv A^n - A^p$. If time reversal and charge symmetry are broken by a purely T-odd *and* CS-odd interaction as introduced above, i.e., in the absence of any *other* (CS-even) T-odd or (T-even) CS-odd effects, then $P^n - A^p = P^p - A^n = 0$ and $\Delta A = \Delta_T^p = -\Delta_T^n \equiv \Delta$.

Of course, CS is broken also otherwise, without violation of TRI, by electromagnetic as well as quark mass effects which lead to a regular CSB contribution $\Delta A^{\rm TRI}$ to ΔA which is supposed to be understood and calculable [16]. Thus the actually measured quantity is $\Delta A = \Delta A^{\rm TRI} + \Delta$ where Δ is the contribution of the TRV *and* CSB term of interest in the present context.

Three experiments exist on CSB in neutron-proton scattering where ΔA was measured [17–19]. Their results, together with theoretical predictions of $\Delta A^{\rm TRI}$ [16], based on updated experimental and theoretical values collected in Ref. [19] are listed in Table I.

Analysis of limits on $\bar{g}_\rho$.—In order to deduce the limits on $\bar{g}_\rho$ listed in the last columns of Table I helicity amplitudes $\langle \gamma\delta|T|\alpha\beta\rangle$ [20,21] are used. All (P-even) T-odd *and* CS-odd effects are contained in one P-even combination N of single-spin-flip helicity amplitudes defined by

$$\begin{aligned} N = 1/8(&\langle + + |T| + -\rangle - \langle - - |T| - +\rangle \\ &+ \langle + + |T| - +\rangle - \langle - - |T| + -\rangle \\ &+ \langle + - |T| + +\rangle - \langle - + |T| - -\rangle \\ &+ \langle - + |T| + +\rangle - \langle + - |T| - -\rangle). \end{aligned} \quad (5)$$

Its symmetry properties should be compared to those of the corresponding regular spin-flip amplitude M_5 [20] (the relative minus sign between the two columns is imposed by parity conservation in both cases while the second and third lines have the opposite sign in the regular amplitude M_5). The symmetry properties of all other helicity amplitudes ($M_1 \dots M_4$) [20] are completely fixed by parity conservation. By convention the first helicity refers to the neutron and the second to the proton on both sides of the matrix elements. Taking this into account and adjusting the normalization, the ρ-exchange TRV Born amplitude (3) translates into

$$N^{\rm Born} = i\bar{g}_\rho \frac{g_\rho^2 \kappa}{4\pi M} \frac{2p^2 \sin\theta}{m_\rho^2 + 2p^2(1 + \cos\theta)}, \quad (6)$$

where θ is the center-of-mass scattering angle.

Using the definition (5) the evaluation of the TRV and CSB asymmetry Δ yields $\Delta = 4\,{\rm Im}(N^* C)/\sigma$ where k is the center-of-mass momentum, $\sigma = d\sigma/d\Omega$ stands for the normalizing differential cross section, and

$$C = \frac{1}{2}(-M_1 + M_2 + M_3 + M_4) = \frac{1}{2k}(-H_1 + H_2) \quad (7)$$

in terms of the regular helicity amplitudes M_i or dimensionless "Virginia" amplitudes H_i [20,22].

In order to proceed with the analysis consider the partial wave decomposition of N which contains only singlet-triplet $l = J$ transitions with $J \neq 0$ [12]

$$N(\theta) = \frac{1}{2k} \sum_{J \geq 1} (2J + 1) N_J d_{10}^J(\theta), \quad (8)$$

where $d_{10}^J(\theta)$ is the appropriate Wigner rotation function and N_J are TRV and CSB $l = J$ singlet-triplet partial wave transition amplitudes whose normalization will play

TABLE I. Summary of CSB experiments in elastic np scattering, theoretical calculations of regular contributions $\Delta A^{\rm TRI}$, and ensuing limits for the TRV contribution Δ. At 183 MeV the asymmetries are averaged over the angular range indicated, for the others they are at the zero-crossing angle of the (average) analyzing power. The last three columns give the values of $\bar{g}_\rho$ obtained from Δ using the bracketed sensitivities $\bar{K}(\alpha_1 = \frac{1}{2})$ given in Table II and corresponding 80% and 95% confidence limits.

$T_{\rm lab}$ (MeV)	$\theta_{\rm cm}$ (deg)	$\Delta A[10^{-4}]$	$\Delta A^{\rm TRI}[10^{-4}]$	$\Delta[10^{-4}]$	$\bar{g}_\rho[10^{-4}]$	$\lvert\bar{g}_\rho\rvert$ 80% C.L.	$\lvert\bar{g}_\rho\rvert$ 95% C.L.
183	82.2–116.1	34.8 ± 7.4	33	1.8 ± 7.4	20 ± 83	≤0.011	≤0.017
347	72.8	59 ± 10	53	6 ± 10	22 ± 37	≤0.0056	≤0.0084
477	69.7	47 ± 23	55	-8 ± 23	-27 ± 77	≤0.011	≤0.016
Weighted average of $\bar{g}_\rho$ and corresponding limits:					14 ± 31	≤0.0044	≤0.0067

no role. To lowest order in the TRV interaction and in the absence of inelasticity they are real by unitarity [12] up to a phase factor $i\exp[i(\delta_J^s + \delta_J^t)]$ where δ_J^s and δ_J^t are the (experimentally known) singlet and triplet $l = J$ scattering phases. Neglecting small inelasticities ($\sim$1% at 347 and $\sim$10% at 477 MeV) the dependence of Δ on $\overline{g}_\rho$ due to the TRV ρ-exchange interaction (3) can therefore be written

$$\Delta = \overline{g}_\rho \sum_{J\geq 1} \alpha_J K_J(\theta) \equiv \overline{g}_\rho \overline{K}(\alpha), \tag{9}$$

where $\overline{K}(\alpha) = \sum_{J\geq 1} \alpha_J K_J(\theta)$ and

$$\alpha_J = \mathrm{Re}(N_J e^{-i(\delta_J^s+\delta_J^t)}/N_J^{\mathrm{Born}}) = |N_J/N_J^{\mathrm{Born}}| \tag{10}$$

is the ratio between the exact first order amplitude N_J calculated from the TRV ρ-exchange interaction [e.g., in distorted-wave Born approximation (DWBA)] and the corresponding amplitude N_J^{Born} obtained in Born approximation. All the kinematics, known strong amplitudes, and phases are contained in

$$K_J(\theta) = \frac{g_\rho^2 \kappa}{\pi M \sigma} \frac{(-1)^{J-1}(2J+1)}{\sqrt{J(J+1)}} \sqrt{w^2-1}\, Q_J^1(w) \times d_{10}^J(\theta)\, \mathrm{Re}[e^{-i(\delta_J^s+\delta_J^t)} C(\theta)], \tag{11}$$

where $w = (m_\rho^2/2k^2) + 1$ and $Q_J^1(w)$ is the usual associated Legendre function of the second kind arising from the partial wave projection of the Born amplitude (6). $\alpha_J \leq 1$ accounts for the reduction in the matrix elements due to strong short range repulsion between the nucleons (which is not expected to change the sign).

Numerical values of the coefficients K_J for angles and energies of available CBS experiments [17–19], evaluated with phase parameters and amplitudes obtained from [23], are listed in Table II together with the corresponding values for $\overline{K}(\alpha) = \Delta/\overline{g}_\rho$. The 183 MeV results are averaged over the angular range of the measurement as the experimental value ΔA [24]. In order to exhibit the sensitivity to short range correlations between neutron and proton, α_1 is varied between 1 and 1/3 while the others are kept fixed at $\alpha_J = 1$. Note the disproportionate sensitivity of $\Delta/\overline{g}_\rho$ on α_1 due to destructive contribution of the higher partial waves. Since the lowest partial waves that contribute are p waves, $\alpha_1 = \frac{1}{2}$ is considered to be adequate rather than $\frac{1}{3}$ which would be adequate for s waves in similar situations. The bracketed entries in Table II are therefore used for the determination of limits on $\overline{g}_\rho$.

The final limit

$$|\overline{g}_\rho| \leq 6.7 \times 10^{-3}, \qquad 95\%\ \text{C.L.} \tag{12}$$

($|\overline{g}_\rho| \leq 4.4 \times 10^{-3}$, 80% C.L.) is obtained from the weighted average of the three values for $\overline{g}_\rho$ extracted from the three CSB measurements in Table I. This limit is considerably lower than those obtained so far from the analysis of nuclear processes [3–7]. It is also slightly better than the constraints obtained from atomic electric dipole moments (EDM's) [3,4]. Only the limit $\sim 10^{-3}$ due to the neutron EDM obtained in Ref. [4] is lower numerically though its dependence on the elusive parity violating πNN coupling constant f_π [25] renders it somewhat uncertain [4].

How reliable are the theoretical calculations on which this limit is based? The only appreciable uncertainty of the calculation of Δ as a function of $\overline{g}_\rho$ presented here lies in the somewhat crude estimate of α_J which could (and should) be improved by explicit calculations of the matrix elements. More subtle are the theoretical predictions of ΔA^{TRI} which have to be subtracted from the experimental values for ΔA in order to deduce experimental limits on Δ. In order to assess their reliability several aspects should be noted: The neutron being uncharged, the main contributions are from the electromagnetic interaction between proton and the magnetic moment of the neutron, the n-p mass difference in the usual Boson exchange interaction, and $\rho - \omega$ mixing. Only the latter has some inherent uncertainty stemming from the extrapolation of the mixing parameter off the mass shell. Fortunately, however, this affects only the analysis of the 183 MeV measurement [18]. The others are, at the angles measured, essentially insensitive to this contribution and thus to its uncertainty [19,26]. Since the limit (12) is dominated by the 347 MeV result it is therefore not affected by this uncertainty. An uncertainty of 10%, say, in ΔA^{TRI} leads to an overall systematic error of 0.0020 in the average $\overline{g}_\rho$ extracted. Added in quadrature this increases the error of $\overline{g}_\rho$ by a factor of 1.2 and the final upper limits to 0.0077 (95% C.L.) and 0.0051 (80% C.L.). Careful scrutiny of the calculations of ΔA^{TRI} in view of the present analysis would clearly be desirable.

Finally, it is reiterated that the structure of the interaction analyzed is unique up to radial or $|q|$ dependence [12]. Any total natural parity $[\pi = (-1)^J]$ exchange

TABLE II. Coefficients K_J for the partial wave contributions to Δ and sensitivities $\overline{K} = \Delta/\overline{g}_\rho = \sum_{J\geq 1} \alpha_J K_J$ of Δ on $\overline{g}_\rho$ calculated as indicated with reduction factors $\alpha_1 = 1$, $\frac{1}{2}$, and $\frac{1}{3}$ for the lowest contributing partial wave $J = 1$, and $\alpha_J = 1$ for $J > 1$. The case with $\alpha_1 = 1$ is the strong phase modified Born approximation result. In the last column the unmodified Born approximation result is given for comparison, demonstrating the importance of including the right phases. The bracketed entries ($\alpha_1 = \frac{1}{2}$) are used for the extraction of limits on $\overline{g}_\rho$ in Table I.

T_{lab} (MeV)	θ_{cm} (deg)	K_1	K_2	K_3	K_4	$\overline{K}(\alpha_1 = 1)$	$\overline{K}(\alpha_1 = \frac{1}{2})$	$\overline{K}(\alpha_1 = \frac{1}{3})$	$\overline{K}^{\mathrm{Born}}$
183	82.2–116.1	0.1679	0.0082	−0.0027	−0.0001	0.173	[0.089]	0.061	0.317
347	72.8	0.7921	−0.1132	−0.0205	0.0065	0.665	[0.269]	0.137	1.195
477	69.7	0.9833	−0.1776	−0.0303	0.0154	0.789	[0.297]	0.133	1.440

contribution must be of the same form. Since total spin zero exchange cannot contribute, the only way to circumvent the limit given is to turn to unnatural parity exchange, generically $a_1(1260)$ or (at least) three-π exchange [12].

In nuclear tests a TRV a_1-exchange interaction would be even more elusive than ρ exchange due to its even shorter range (higher mass) and its smaller regular coupling. Moreover, in contrast to ρ exchange, there is ample freedom in isospin structure [12] in order to escape limits. On the other hand, the P-even TRV coupling of the a_1 to the neutron is of the EDM form [15,27]

$$\frac{f_T}{2M}\,\overline{\psi}\sigma_{\mu\nu}\gamma^5 q^\nu a_1^\mu \psi\,. \tag{13}$$

This allows one to connect it directly to the neutron EDM d_n using vector meson dominance of the electromagnetic current (leading to the identification $\kappa = \mu_V = 3.7$) in conjunction with (parity violating) $\rho - a_1$ mixing. Neglecting a similar ω contribution this yields

$$d_n \approx f_T\,\frac{e}{2M}\,\frac{h_{\rho A}}{g_\rho} = (3.8 \times 10^{-15}) f_T h_{\rho A}\; e\,\mathrm{cm}\,, \tag{14}$$

where $h_{\rho A} \approx 10^{-6}$ represents weak $\rho - a_1$ mixing which gives rise to the so-called factorization contribution to parity violating ρNN coupling [28] whose magnitude is experimentally verified [25,29]. With the experimental limit $d_n \leq 1.1 \times 10^{-25}\ e$ cm 95% C.L. [30], this leads to the limit $f_T \leq 3 \times 10^{-5}$ in the TRV $a_1 nn$ coupling (13).

A roughly 10 times lower limit ($4\pi\beta_{qq} < 3.8 \times 10^{-6}$) is presented in Ref. [31] for axial vector exchange at the quark level based on loop calculation of the neutron EDM with nonrenormalizable coupling of the form (13). Their conclusion that the P-even TRV nucleon-nucleon interaction cannot exceed 10^{-4} of the usual weak interaction, however, is based on the additional assumption that the exchanged object must have a mass $\mu > 100$ GeV (which does not affect the EDM) and thus rests on the explicit assumption that the interaction must involve the weak scale. The object of the present analysis, on the other hand, is to analyze evidence obtained from experiments and long range physics directly without imposing such additional restrictions.

Note finally that limits obtained for axial vector exchange should not be taken over to vector exchange (and vice versa) without further examination due to their different symmetry properties [12]. Unless both are isovector interactions they cannot even generate one another without intervention of additional isospin violation.

I would like to thank W.T.H. van Oers for bringing the insensitivity of the TRIUMF CSB measurements [17,19] to $\rho - \omega$ mixing to my attention, and P. Herczeg for valuable comments.

[1] F. Boehm, in *Symmetries and Fundamental Interactions in Nuclei*, edited by Wick C. Haxton and Ernest M. Henley (World Scientific, Singapore, 1995), p. 67.
[2] P. Herczeg, in *Symmetries and Fundamental Interactions in Nuclei* (Ref. [1]), p. 89.
[3] W. C. Haxton and A. Höring, Nucl. Phys. **A560**, 469 (1993).
[4] W. C. Haxton, A. Höring, and M. J. Musolf, Phys. Rev. D **50**, 3422 (1994).
[5] J. Engel, C. R. Gould, and V. Hnizdo, Phys. Rev. Lett. **73**, 3508 (1994).
[6] P. R. Huffman *et al.*, Phys. Rev. Lett. **76**, 4681 (1996).
[7] O. K. Vorov, Phys. Lett. B **386**, 191 (1996).
[8] M. Beyer, Phys. Rev. C **48**, 906 (1993).
[9] M. Simonius, AIP Conf. Proc. **123**, 1115 (1984).
[10] P. Herczeg, J. Kambor, M. Simonius, and D. Wyler (to be published).
[11] J. Engel, P. H. Frampton, and R. P. Springer, Phys. Rev. D **53**, 5112 (1996).
[12] M. Simonius, Phys. Lett. B **58**, 147 (1975).
[13] The argument excluding a TRV vector interaction in I. B. Khriplovich, Nucl. Phys. **B352**, 385 (1991), is based on assignment of C and CP eigenvalues to fermion-antifermion states which is impossible unless they are neutral (neutral exchange). For the non-neutral case the more general method used in [12] must be used.
[14] In nuclear calculations one has to be careful not to loose the destructive interference leading to this suppression in inadequate approximations.
[15] M. Simonius and D. Wyler, Nucl. Phys. **A286**, 182 (1977).
[16] B. H. Holzenkamp, K. Holinde, and A. W. Thomas, Phys. Lett. B **195**, 121 (1987); M. J. Iqbal and J. A. Niskanen, Phys. Rev. C **38**, 229 (1988).
[17] R. Abegg *et al.*, Phys. Rev. D **39**, 2464 (1989).
[18] S. E. Vigdor *et al.*, Phys. Rev. C **46**, 410 (1992).
[19] R. Abegg *et al.*, Phys. Rev. Lett. **75**, 1711 (1995).
[20] J. Bystricky, F. Lehar, and P. Winternitz, J. Phys. (Paris) **39**, 1 (1978).
[21] M. Simonius, in *Polarization Nuclear Physics*, edited by D. Fick, Lecture Notes in Physics Vol. 30 (Springer-Verlag, Berlin, 1974), p. 38. The helicity amplitudes used there differ in the case of nucleons by a phase factor $(-1)^{\beta-\delta}$ from those in Ref. [20] which are adopted here.
[22] R. A. Arndt *et al.*, Phys. Rev. D **28**, 97 (1983).
[23] R. A. Arndt, Interactive dial-in program SAID, solution FA95.
[24] At 347 and 477 MeV the sensitivities at the angles of the measurements are within about 10% of their maximum. At 183 MeV, however, one would gain almost a factor of 2 around 75°; over the angular range of the measurement $\overline{K}(\alpha_1 = \frac{1}{2})$ decreases from 0.156 to 0.011.
[25] W. Haeberli and B. R. Holstein, in *Symmetries and Fundamental Interactions in Nuclei* (Ref. [1]), p. 17.
[26] G. A. Miller and W. T. H. van Oers, in *Symmetries and Fundamental Interactions in Nuclei* (Ref. [1]), p. 127.
[27] E. C. G. Sudarshan, Proc. R. Soc. London A **305**, 315 (1968).
[28] B. Desplanques, J. F. Donoghue, and B. R. Holstein, Ann. Phys. (N.Y.) **124**, 449 (1980).
[29] F. Nessi-Tedaldi and M. Simonius, Phys. Lett. B **215**, 159 (1988).
[30] I. S. Altarev *et al.*, Phys. Lett. B **276**, 242 (1992); Particle Data Group, Phys. Rev. D **54**, 1 (1996).
[31] R. S. Conti and I. B. Khriplovich, Phys. Rev. Lett. **68**, 3262 (1992).