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Effective *T*-odd *P*-even hadronic interactions from quark models

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Tests of time-reversal symmetry at low and medium energies may be analyzed in the framework of effective hadronic interactions. Here, we consider the quark structure of hadrons to make a connection to the more fundamental degrees of freedom. It turns out that for P-even T-odd interactions hadronic matrix elements evaluated in terms of quark models give rise to factors of 2 to 5. Also, it is possible to relate the strength of the anomalous part of the effective ρ-type T-odd P-even tensor coupling to quark structure effects. [S0556-2813(96)01209-5]

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I. INTRODUCTION

First evidence of the violation of time-reversal symmetry has been found in the Kaon system [1]. Despite strong efforts, no other signal of violation of time-reversal symmetry has been found to date. However, by now, studying time reversal symmetry has become a cornerstone of the search for physics beyond the standard model of elementary particles [2]. Some alternatives or extensions of the standard model are due to dynamical symmetry breaking, multi-Higgs models, spontaneous symmetry breaking, grand unified theories [e.g., SO(10)], extended gauge groups (leading, e.g., to right-handed bosons W_R in left-right symmetric models), supersymmetric (SUSY) theories, etc., each implying specific ways of CP violation. For a recent review of models relevant in the context of CP violation, see, e.g., [3], and reference therein.

These theories ''beyond'' the standard model are formulated in terms of quarks and leptons whereas nuclear low energy tests of CP involve hadronic degrees of freedom (mesons and nucleons) [4,5]. To extract hadronic degrees of freedom from observables one may introduce effective T-odd nucleon-nucleon potentials [6], or more specific T-odd mesonic exchange potentials [7–12]. As in the context of P violation see, e.g., [13], these potentials have been proven quite useful to treat the nuclear structure part involved and to extract effective T-odd hadronic coupling constants [14–19]. In turn, they allow one to compare the sensitivity of different experiments, which has been done recently in Ref. [3]. However, in order to compare upper bounds on a more fundamental level of T-odd interactions, it is necessary to relate hadronic degrees of freedom to quark degrees of freedom in some way. This step is hampered by the absence of a complete solution of quantum chromodynamics (QCD) at the energies considered here. In many cases a rough estimate in the context of time-reversal violation may be sufficient, and, in the simplest case, factors arising from hadronic structure may be neglected. In the context of P-odd time-reversal violation, e.g., concepts such as partially conserved axial current (PCAC) and current algebra [20] have been utilized to improve the evaluation of hadronic structure effects. In the P-even case, which is considered here, this approach is not applicable (no Goldstone bosons involved here). However, it may be useful to utilize quark models specifically designed for and quite successful in describing the low energy sector.

In fact, experimental precision tests still continue to make progress and so theorists face a renewed challenge to translate these experimental constrains to a more fundamental interaction level. The purpose of the present paper is to give estimates on hadronic matrix elements that arise when relating quark operators to the effective hadronic parametrizations of the P-even T-odd interaction. These are the charge ρ-type exchange and the axial-vector-type exchange nucleon-nucleon interaction [8–10]. They will shortly be outlined in the next section. The ansatz to calculate NN matrix elements from the quark structure is described in Sec. III. The last section gives the result for different types of quark models and a conclusion.

For completeness, note that, in general, also T-odd and P-odd interactions are possible, and in fact, most of the simple extensions of the standard model mentioned above give rise to such type of T violation. Parametrized as one-boson exchanges, they lead, e.g., to effective pion exchange potentials that are essentially long range, see [3]. Limits on P-odd T-odd interactions are rather strongly bound by electric dipole moment measurements, in particular, by that of the neutron [21–24]. In contrast, bounds on P-even T-odd interactions are rather weak. Note, also that despite theoretical considerations [25,26], new experiments testing generic T-odd P-even observables have been suggested; for the present status see, e.g., Refs. [4,5].

II. EFFECTIVE *T*-ODD *P*-EVEN NUCLEON-NUCLEON INTERACTIONS

Due to the moderate energies involved in nuclear physics tests of time-reversal symmetry, hadronic degrees of freedom are useful and may be reasonable to analyze and to compare different types of experiments. For a recent discussion see

Ref. [3]. In the following only T-odd and P-*even* interactions will be considered. They may be parametrized in terms of effective one-boson exchange potentials. Due to the behavior under C-, P-, and T-symmetry transformations, see, e.g., [27], two basic contributions are then possible: a charged ρ-type exchange [9,10] and an axial-vector exchange [8]. The effective ρ-type T-odd interaction is C odd due to the phase appearing in the isospin sector and is only possible for charged ρ exchange. It has been suggested by Simonius and Wyler, who used the tensor part to parametrize the interaction [10],

$$\mathcal{L}^T_{\rho NN}=g^T_{\rho NN}\overline{N}\sigma_{\mu\nu}\frac{(p_f-p_i)^\nu}{2m_N}\frac{1}{\sqrt{2}}(\rho^{+\mu}\tau^- - \rho^{-\mu}\tau^+)N. \tag{1}$$

There is some question whether to choose an ''anomalous'' coupling [3,28], viz., $g^T_{\rho NN}=\kappa\tilde{g}^T_{\rho NN}$. The numerical value of κ is usually taken to be 3.7, close to the strong interaction case [10]. We shall see in the following that it is not unreasonable to introduce such a factor since it may be related to ''nucleonic structure effects,'' which are not of T-violating origin (similar to nuclear structure effects that are also treated separately). Combining the T-odd vertex with the appropriate T-even vertex leads to the following effective T-odd P-even one-boson exchange NN interaction,

$$V^T_\rho = i\frac{g^T_{\rho NN}g_{\rho NN}}{8m_N^2(\mathbf{q}^2+m_\rho^2)}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\mathbf{q}\times\mathbf{p}\quad(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_0, \tag{2}$$

where $\mathbf{q}=\mathbf{p}_f-\mathbf{p}_i$, and $\mathbf{p}=(\mathbf{p}_f+\mathbf{p}_i)/2$, and $g_{\rho NN}$ is the strong coupling constant, as, e.g., provided by the Bonn potential [39].

The axial-vector-type interaction has been suggested by [8]. Unlike the ρ-type interaction, the isospin dependence is not restricted and may be isoscalar, vector-, and/or tensor-type. The effective Lagrangian for the a_1NN coupling, for example, is given by

$$\mathcal{L}_{a_1NN}=g^T_{a_1NN}\overline{N}\gamma_5\sigma_{\mu\nu}\frac{(p_f-p_i)^\nu}{2m_N}\boldsymbol{\tau}N\mathbf{a}_1^\mu. \tag{3}$$

Combined with the appropriate T-even vertex, this leads to an effective axial-vector-type exchange NN potential [8],

$$V^T_{a_1}=i\frac{g^T_{a_1NN}g_{a_1NN}}{8m_N^2(\mathbf{q}^2+m_{a_1}^2)}\times\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2(\boldsymbol{\sigma}_1\cdot\mathbf{p}\boldsymbol{\sigma}_2\cdot\mathbf{q}+\boldsymbol{\sigma}_2\cdot\mathbf{p}\boldsymbol{\sigma}_1\cdot\mathbf{q}-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\mathbf{q}\cdot\mathbf{p}). \tag{4}$$

The bounds on the T-odd coupling strengths arising from various experiments have been discussed in Ref. [3]. A more recent bound not included there is from an improved analysis [29] of the ^{57}Fe γ-decay experiment [30]. Bounds are in the order of 10% if derived from generic T-odd P-even observables and slightly more than an order of magnitude smaller, if related to the electric dipole moments [3]. To complete this section, note that although possible, two-boson exchanges have not been considered up to now.

III. QUARK OPERATORS AND EFFECTIVE NN INTERACTION

We now turn to effective T-odd P-even quark operators. The simplest operator that leads to an effective T-odd P-even vector-type vertex Vqq analogous to the ρ-type interaction [Eq. (1)] is

$$\mathcal{L}^T_{Vqq}=g^T_{Vqq}(\overline{u_1}\gamma_\mu d_1\overline{d_2}\gamma^\mu u_2-\overline{d_1}\gamma_\mu u_1\overline{u_2}\gamma^\mu d_2). \tag{5}$$

Here, u, d denote flavored quark fields. Again, the flavor dependence is responsible for C, viz. T violation due to the phase dependence. A tensor term has not been introduced for simplicity. On the basis of Eq. (5), such a term will arise in a natural way in the effective hadronic ρNN T-odd Lagrangian through the quark structure effects as will be explained below. The second generic quark operator utilizing axial-vector bilinear operators is given by [31],

$$\mathcal{L}^T_{Aqq}=g^T_{Aqq}\underbrace{\bar{q}_1\gamma_5\sigma_{\mu\nu}\frac{(p_{f,1}-p_{i,1})^\nu}{2m_q}q_1}_{\mathcal{O}_1^T}\underbrace{\bar{q}_2 i\gamma_5\gamma^\mu q_2}_{\mathcal{O}_2^E}+(1\leftrightarrow 2) \tag{6}$$

with the on-shell equivalent

$$\mathcal{O}_1^T\mathcal{O}_2^E=\overline{q_1}i\gamma_5\frac{(p_{f,1}+p_{i,1})_\mu}{2m_q}q_1\overline{q_2}i\gamma_5\gamma^\mu q_2. \tag{7}$$

In order to recover Eqs. (1) and (3), we utilize the constituent quark model. This model has been rather successful and valuable in reproducing gross features of low energy phenomena, such as mass spectra, form factors, coupling constants, magnetic moments, etc., see, e.g., [32].

To relate quark operators to effective hadronic operators we utilize the Fock space representation of hadrons in terms of constituent quarks, viz.,

$${}_{6q}\langle NN|\mathcal{O}^T\mathcal{O}^E|NN\rangle_{6q}\to\langle NN|V^T_{MNN}|NN\rangle. \tag{8}$$

Since there is no low energy solution of QCD, the evaluation of the matrix elements of the left-hand side (LHS) of Eq. (8) needs further consideration. In general, the same problem arises in the context of strong interactions. An extensive overview of the different approaches to tackle the problem in this case has been given by Ref. [33]. Here, we follow the ideas first formulated in Ref. [34], and extensively studied for different quark models in [35,36]. The resulting strong interaction potential is a generic hybrid model connecting quark degrees of freedom with effective meson-nucleon degrees of freedom. The basic idea is summarized in the following.

Suppose the two nucleons overlap, and two quarks are sufficiently close together. This situation is depicted in Fig. 1(a). Then, to begin with, the matrix elements may be evaluated without introducing any mesonic fields. In terms of the constituent quark model, $q\overline{q}$ excitations are neglected (or partially parametrized in the constituent quark mass). Only at larger distances of the nucleons, mesons are essential and may appear as $q\overline{q}$ correlations on the nonperturbative QCD vacuum [34] that might be the physical vacuum of the low energy regime [37,38]. However, the appearance of mesons

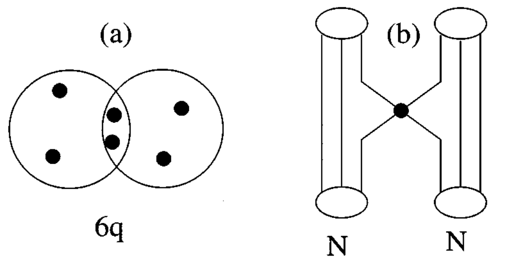

FIG. 1. Pictorial demonstration of short-range T-odd NN interaction: (a) NN system as six-valence quarks, (b) factorization approximation.

is disconnected from the problem of T-odd force. Therefore, in the following we assume that the hadronization mechanism is the *same for both T-odd and the usual T-even strong interaction* and investigate the relative strength of the T-odd matrix elements to the T-even matrix elements. This is done in the framework of the Virginia potential that assumes a quark pairing mechanism to generate effective meson-nucleon coupling constants [34–36]. To illustrate the quality of this ansatz, Table I shows the resulting coupling constants using different quark models compared to the values of a recent version of the Bonn potential [39].

In this framework we utilize the factorization approximation to evaluate the matrix element of Eq. (8), see Fig. 1(b)

$$\langle \mathcal{O}^T \mathcal{O}^E \rangle = \langle \mathcal{O}^T \rangle_{3q} \times \langle \mathcal{O}^E \rangle_{3q} . \tag{9}$$

To demonstrate the calculation, we use the simple constituent quark model. This model is supplemented by an explicit lower component, which already occurs implicitly in the Dirac magnetic moments [40] and in the two-body pair current through electromagnetic gauge invariance [41,42]. This way, a treatment of relativistic effects has been introduced, see, e.g., [43] and references therein. The integration of the internal degrees of freedom reads

$$\langle \mathcal{O} \rangle_{3q} = \int d^3\lambda \, d^3\rho \, \overline{\psi(\rho,\lambda)} \, \mathcal{O} \, \psi(\rho,\lambda) \exp[-i\sqrt{2/3}\mathbf{q}\cdot\boldsymbol{\lambda}] \tag{10}$$

with $\psi(\rho,\lambda)$ the three-quark wave internal function. In the rest system the space part of the wave function is given by [35,42,43]

$$\psi(\rho,\lambda) = N_0 \left(\frac{\alpha^2}{\sqrt{\pi}} \right)^{3/2} \begin{pmatrix} 1 \\ -i \dfrac{\boldsymbol{\nabla}_\lambda \cdot \boldsymbol{\sigma}_3}{3m_q} \end{pmatrix} \exp[-\alpha^2(\rho^2+\lambda^2)/2] \tag{11}$$

where numerical values may be chosen as $\alpha \simeq m_q \simeq m_N/3$, and $N_0^{-2} = (1+\alpha^2/4m_q^2)$. The coordinates are normalized Lovelace coordinates, viz., ρ for the pair and λ for the odd quark. Integration is done in the Breit system. The symbol $\mathcal{O}$ denotes either one of the vertices in Eq. (9).

Evaluation for the different type of operators leads to the expressions (using the isospin formalism for u,d quarks)

$$\langle i\gamma_5 \boldsymbol{\tau}^I \rangle_{3q} \rightarrow \left(\frac{5}{3} \right)^I N_0^2 \frac{2m_N}{3m_q} \langle i\gamma_5 \boldsymbol{\tau}_N^I \rangle_N , \tag{12}$$

$$\langle i\gamma_5 \gamma_\mu \boldsymbol{\tau}^I \rangle_{3q} \rightarrow \left(\frac{5}{3} \right)^I N_0^2 \left(1 - \frac{\alpha^2}{12m_q^2} \right) \langle i\gamma_5 \gamma_\mu \boldsymbol{\tau}_N^I \rangle_N , \tag{13}$$

$$\langle \gamma_\mu \boldsymbol{\tau} \rangle_{3q} \rightarrow \langle \gamma_\mu \boldsymbol{\tau} \rangle_N + \left(\frac{10m_N}{9m_q} N_0^2 - 1 \right) \times \left\langle \sigma_{\mu\nu} \frac{(p_{f,1}-p_{i,1})^\nu}{2m_N} \boldsymbol{\tau}_N \right\rangle_N . \tag{14}$$

The factors arising are related to the quark structure of nucleons. Note, that in Eq. (13) one recognizes the well-known coupling of the axial-vector current (for $I=1$), viz., $g_A = 5/3$ of the nonrelativistic constituent quark model, in addition to the factors arising from relativistic corrections due to the lower Dirac component. The latter reduce the value of g_A close to the experimental one [43]. In Eq. (14) a tensor coupling appears, which belongs to the ρ-type T-odd exchange. Indeed, due to the quark structure factors its relative strength is larger than the first term of the right-hand side (RMS) of Eq. (14), and therefore, preferable in an ansatz of a ρ-type T-odd force as done by Simonius and Wyler [10]. The factor in front the tensor term may be interpreted as ''anomalous'' coupling. It appears in analogy to the electromagnetic interaction, where the Pauli term of the electromagnetic photon-nucleon interaction can be recovered from a pure Dirac coupling on quark level. This has been explained and shown in Ref. [35].

TABLE I. Effective MNN coupling constants $g_{MNN}^2(\mathbf{q}^2=0)/4\pi$ calculated from quark-pairing mechanism [36]. Only one overall quark-meson coupling constant needs to be fitted. For comparison, values of the Bonn potential have also been included. In brackets [f/g] is shown.

Meson	(J^{PC},I^G)	MIT		Lin. conf.		CQM		Bonn	
$f_0(1200)$	$(0^{++},0^+)$	4.1		4.5		7.09			
$a_0(960)$	$(0^{++},1^-)$	0.5		0.5		0.79		1.62	
$\eta(550)$	$(0^{-+},0^+)$	5.1		5.32		5.04			
$\pi(138)$	$(0^{-+},1^-)$	14.0		14.8		14.0		14.08	
$\omega(782)$	$(1^{--},0^-)$	6.3	[−0.4]	3.8	[−0.5]	9.85	[−0.49]	10.6	[0.0]
$\rho(763)$	$(1^{--},1^-)$	0.7	[2.2]	0.42	[3.2]	1.10	[1.53]	0.41	[6.1]
$f_1(1285)$	$(1^{++},0^+)$	0.5	[−1.5]	0.22		0.59	[0]		
$a_1(119)$	$(1^{++},1^-)$	1.0	[−1.5]	0.6		1.64	[0]		

IV. RESULTS AND CONCLUSION

The resulting relation between quark and hadronic T-odd coupling strength on the basis of the constituent quark model is, for ρ-type exchange,

$$g^T_{\rho NN}=\left(\frac{10m_N}{9m_q}N_0^2-1\right)g^T_{Vqq}\,, \tag{15}$$

and for axial-type of exchange,

$$g^T_{aNN}=\frac{2}{3}\,\frac{m_N}{m_q}\left(1-\frac{\alpha^2}{12m_q^2}\right)^{-1}g^T_{Aqq}\,. \tag{16}$$

Here, the expression for isoscalar and isovector are the same.

Similar results may be obtained using different types of quark models. In the context of the Virginia potential those studied are the MIT bag model and a relativistic model with linear confining potential, see Ref. [36]. These are used here in the same way as demonstrated for the constituent quark model in the previous section. The values for the quark structure effects evaluated using typical quark model parameters of low energy phenomenology are given in Table II.

In fact, due to the symmetries inherent in the quark-pairing mechanism (viz., the Virginia potential), it is possible to arrive at the relations between the coupling constants, viz.,

$$g^T_{\rho NN}=(f_{\rho NN}/g_{\rho NN})g^T_{Vqq}=\kappa g^T_{Vqq}\,, \tag{17}$$

$$g^T_{aNN}=(g_{\pi NN}/g_{a_1NN})g^T_{Aqq}=(g_{\eta NN}/g_{f_1NN})g^T_{Aqq}\,. \tag{18}$$

TABLE II. Factors arising from the quark structure of the NN system, for the constituent quark model: (a) $m_q=0.33$ GeV, (b) $m_q=0.22$ GeV.

	MIT bag	Lin. conf.	CQM (a)	CQM (b)
$g^T_{a_1NN}/g^T_{a_1qq}$	3.5	5.0	2.9	4.9
$g^T_{\rho NN}/g^T_{\rho qq}$	2.2	3.2	1.5	2.0

Equation (17) shows that the factor appearing in the ρ-type exchange may be related to the anomalous coupling $\kappa=f/g$. So, inclusion of κ might give a bound closer to the more basic quark degrees of freedom.

In conclusion, provided the hadronization process does not substantially differ for T-odd and T-even interactions, the factors arising reflect the *nucleon* structure effects. The origin of the structure factors are due to the spin, isospin structure, and the different mass scales (i.e., m_q vs m_N). These have also been essential in deriving the relative strength of the strong coupling constants as given in Table I.

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