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Tests of Time Reversal Symmetry in the Deuteron*

Michael Beyer

Max Planck AG "Vielteilchentheorie", Rostock University, 18051 Rostock, Germany, and Institute for Nuclear Theory, University of Washington, Seattle, 98195 Washington, U.S.A.

Abstract: Internal target experiments with high quality proton beams allow for a new class of experiments providing null tests of time reversal symmetry in forward scattering. This could yield more stringent limits on T-odd P-even observables. A excellent candidate for such experiments is the proton deuteron system. This system is analyzed in terms of effective T-violating P-conserving nucleon-nucleon interactions and bounds on coupling strengths that might be expected are given.

1 Introduction

First evidence of 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 corner stone of the search for physics beyond the Standard Model of elementary particles. Although the Standard Model has been enormously successful a sufficient part of it is unconfirmed. E.g. no evidence for the Higgs particle or of the origin of electroweak symmetry breaking, the Yukawa section contains a "random set of numbers" etc. [2]. Some alternatives or extensions of the Standard Model are due to dynamical symmetry breaking, technicolor etc, 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, Super Symmetric (SUSY) theories ... each implying specific ways of CP violation.

2 T-odd observables in forward scattering

Forward scattering seems an attractive way to search for violation of time reversal symmetry for several reasons. The most important is the absence of ambiguities, since the amplitude involved is "diagonal", viz. the forward, elastic scattering amplitude. This implies T-violation without any assumptions about phases of final state interaction etc. and therefore leads to a true null test. In turn this allows to use very efficient spin measuring techniques that have been proven to be extremely successful in the context of P violation, and lead to an accuracy of few 10^{-8} in the pp system [3]. In addition, new internal target techniques and high quality proton beams newly in operation (COSY) or under consideration (LISS) allow to open a new domain of experimental presicion in particular in the few body system [4]. Also, enhancement factors due to the target structure (heavy nuclei) allow for a very high precision and by now the first tests have been pursued [5, 6].

The generalized optical theorem, including the polarization matrix ρ of the initial state, has been given by Phillips [7], viz.

$$\sigma(\rho)_{tot} = \frac{4\pi}{k} Im\left[tr(\mathcal{F}\rho)/tr(\rho)\right] \qquad (1)$$

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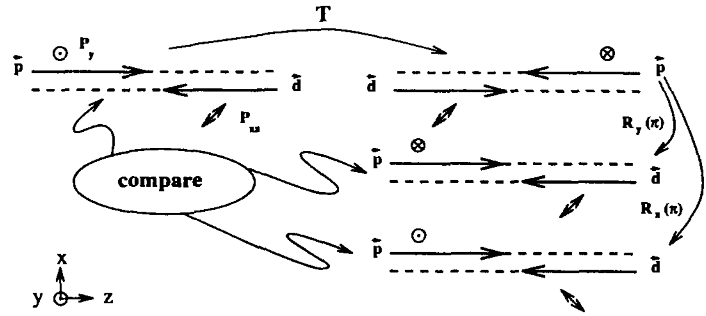


Figure 1: Pictorial demonstration of T-odd forward scattering experiment

The forward scattering amplitude $\mathcal{F}$ may be expanded in a basis according to its spin and momentum dependence, viz.

$$\mathcal{F} = \sum_{\lambda\kappa}\sum_{J} \mathcal{F}_{\lambda\kappa;J}\left[\left[\left\langle S_1^{[\lambda]}\right\rangle \otimes \left\langle S_2^{[\kappa]}\right\rangle\right]^{[J]} \otimes k^{[J]}\right]^{[0]} \qquad (2)$$

where S_i denotes the spin operator of the particles involved, and $k_M^{[J]} = \left[\frac{4\pi J!}{(2J+1)!!}\right]^{1/2} i^J Y_{JM}(\hat{k})$ where $\hat{k} = \mathbf{k}/k$. Note, that for $\mathbf{k} = k\hat{e}_z$ (Madison convention) only moments with $M = 0$, can contribute to the total cross section (rotational symmetry of forward scattering). For proton (spin 1/2) deuteron (spin 1) forward scattering there are ten possible observables, which transformation properties with respect to time reversal (T) and parity (P) are

violates:		P	P			TP		P	P	T
λ (p)	0	1	0	1	1	1	0	1	1	1
κ (d)	0	0	1	1	1	1	2	2	2	2
J	0	1	1	0	2	1	2	1	3	2

The first few terms of the expansion (2) are (with e.g $\sigma_p = S_1$ and $S_d = S_2$)

$$\mathcal{F} = \mathcal{F}_{00;0} + \frac{-1}{\sqrt{3}}\mathcal{F}^P_{10;1}\left\langle\sigma_p\right\rangle\cdot\mathbf{k} + \frac{-1}{\sqrt{3}}\mathcal{F}^P_{01;1}\left\langle\mathbf{S}_d\right\rangle\cdot\mathbf{k} + \frac{-1}{\sqrt{3}}\mathcal{F}_{11;0}\left\langle\sigma_p\right\rangle\cdot\left\langle\mathbf{S}_d\right\rangle + \frac{i}{\sqrt{6}}\mathcal{F}^T_{11;1}\left\langle\sigma_p\right\rangle\times\left\langle\mathbf{S}_d\right\rangle\cdot\mathbf{k} + \ldots$$

the factors arise from tensor algebra. The lowest order terms that are odd under time reversal symmetry are then the triple correlation ($\lambda = \kappa = J = 1$):

$$\mathcal{F}^{PT}_{11;1}\ \left\langle\sigma_p\right\rangle\cdot\mathbf{k}\times\left\langle\mathbf{S}_d\right\rangle,$$

which is also P-violating, and the five-fold correlation ($\lambda = 1$, $\kappa = J = 2$):

$$\mathcal{F}^T_{12;2}\left(\left\langle\sigma_p\right\rangle\cdot\mathbf{k}\times\left\langle\mathbf{S}\right\rangle_d\right)\left(\mathbf{k}\cdot\left\langle\mathbf{S}_d\right\rangle\right).$$

Note that the five-fold correlation is only accessible if one particle has a spin ≥ 1.

So far experiments have only been performed on heavy nuclei and lead to recent experimental bounds for the triple correlation $\mathcal{F}^{PT}_{11;1} \lesssim$ few $\times 10^{-3}$ [5] and the five-fold correlation $\mathcal{F}^T_{12;2} \lesssim$ few $\times$ 10^{-6} [6].

The polarization condition of the beam and target that picks out the $\mathcal{F}^T_{12;2}$ component is given by evaluating the trace in (1)

$$tr\left(\rho\ \left[\left[\left\langle\sigma_p^{[1]}\right\rangle\otimes\left\langle S_d^{[2]}\right\rangle\right]^{[2]}\otimes k^{[2]}\right]^{[0]}\right) = tr(\rho)\left[t_{12}^{[2]}\otimes k^{[2]}\right]^{[0]} \tag{3}$$

Here tensor moments $t_{12}^{[2]}$ have been introduced. In case of uncorrelated initial states, which holds for scattering,

$$t_{12}^{[2]} = t_{p,+1}^{[1]}t_{d,-2}^{[2]} \simeq P_{xz}p_y, \tag{4}$$

The last equation utilizes the Madison convention. In this case for a T-odd *P-even* experiment one may choose polarized protons (p_y) and aligned deuterons (P_{xz}), such that (Fig. 1)

$$\sigma(\rho)^T_{tot} = \sigma^0_{tot} + \sigma^T_{y,xz}\ P_{xz}p_y \tag{5}$$

The transmission factor is then defined as $T(Nd) = I(Nd)/I(0) = \exp\left[-\sigma(\rho)_{tot}\rho_t Nd\right]$, where N is the number of turns in the ring, I() intensity, d target thickness and ρ_t target density, one defines a T-odd, P-even asymmetry

$$\Delta T_{xz,y} = \frac{T^+ - T^-}{T^+ + T^-} = \tanh[-|p_yP_{xz}|\ N\rho_t d\ \sigma^T_{y,xz}] \simeq -|p_yP_{xz}|\ N\rho_t d\ \sigma^T_{y,xz} \tag{6}$$

T^+: sign(p_y) = sign(P_{xz}), T^-: sign(p_y) = $-$sign(P_{xz}). Two types of measurements are possible: The current loss of the polarized proton beam in the ring is measured i) with alternating polarization $p_y = \pm 1$, or ii) with alternating deuteron alignment, $P_{xz} = \pm 1$ (Fig.1). The last equation in (6) holds, since $\sigma^T_{y,xz}$ is small compared to the total cross section. An experiment has been proposed at COSY where a precision of 10^{-6} may be achieved [4]. It will be described in detail by D. Eversheim at the conference [8].

3 Effective T-odd nucleon nucleon Interactions

Due to the moderate energies involved in nuclear physics tests of T, hadronic degrees of freedom are useful and may be reasonable to analyze and compare different types of experiments. In the following only T-odd and *P-even* interactions will be considered. The limits on T-odd and P-odd forces are rather strongly bound by electric dipole moment measurements, in particular of the neutron [9]. The lowest order effective quark quark interaction that is T-odd and P-even is

$$\mathcal{L}^T_{qq} = \phi^T_q\ \bar{q}_1\gamma_5\sigma_{\mu\nu}\frac{q^\nu}{2m_q}q_1\ \bar{q}_2 i\gamma_5\gamma_\mu q_2 \quad + \quad (1\leftrightarrow 2) \tag{7}$$

This has to be connected to hadronic degrees of freedom in order to draw conclusions from experimentally observable quantities. The simplest way is to assume QCD corrections to be of order unity. However, uncertainties may be connected to this simple assumption. In order to get an estimation of the uncertainties, in the following, I shall evaluate the above given Lagrangian in the two nucleon system. Since this interaction is essentially short range one may assume that the interaction only takes place when the quarks bound in the two system are "close" to each other. This situation is depicted in Fig. 2. The evaluation is done along the lines used to derive the Virgina-Potential from quark degrees of freedom [10]. Further, assuming factorization, and that the two nucleons are in separate color singlet states as well as utilizing the wave function of the non relativistic quark model, the integration of the internal degrees of freedom reads,

$$\langle\mathcal{O}\rangle = \int d^3\lambda d^3\rho\bar{\psi}(\rho,\lambda)\mathcal{O}\psi(\rho,\lambda)\exp\left[-i\sqrt{2/3}\ q\cdot\lambda\right] \tag{8}$$

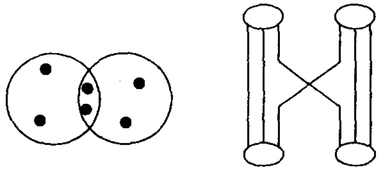


Figure 2: Short range NN T-odd force

with $\psi(\rho,\lambda)$ the three quark wave internal function, which depend on the three quark coordinates ρ and λ, and $m_N/3 = m_q$. The symbol $\mathcal{O}$ denotes either of the vertices in (7). Including a lower component in the quark wave function to have some treatment of the relativistic effects, a relation between the quark coupling strengths ϕ_q^T and the effective nucleonic strengths ϕ_M^T can be achieved, viz.

$$\phi_M^T = \frac{2}{3}\frac{m_N^2}{m_q^2}\left(1+\frac{\alpha^2}{4m_q^2}\right)^{-2}\left(1-\frac{\alpha^2}{12m_q^2}\right)\left(\frac{5}{3}\right)^{2\tau}\phi_q^T \tag{9}$$

inserting numbers this results in $\phi_{A_0}^T \simeq 1.8\ \phi_q^T$, and $\phi_{A_1}^T \simeq 5\ \phi_q^T$, depending on the isospin degrees of freedom, $\tau = 0,1$. Due to the quantum numbers involved, the interaction maybe mediated by an effective (short range) axial vector meson exchange. The isospin dependence of the axial vector exchange is not restricted. In general it might be isoscalar, -vector or -tensor. The lightest axial vector mesons are e.g. a_0, and a_1. The nucleonic strengths are simply defined by replacing the quark fields in (7) by nucleon fields. As a result one may keep in mind that a factor of five may easily achieved when relating quark to hadronic degrees of freedom.

Effective T-odd P-even NN potentials mediated by such axial vector exchange is then

$$V_A^T = i\phi_A^T\,\frac{g_{ANN}^2}{8m_p^2(\mathbf{q}^2+m_A^2)}\,(\sigma_1\cdot\mathbf{p}\,\sigma_2\cdot\mathbf{q}+\sigma_2\cdot\mathbf{p}\,\sigma_1\cdot\mathbf{q}-\sigma_1\cdot\sigma_2\,\mathbf{q}\cdot\mathbf{p}) \tag{10}$$

where $\mathbf{q} = \mathbf{p}_f - \mathbf{p}_i$, and $\mathbf{p} = (\mathbf{p}_f + \mathbf{p}_i)/2$. In addition, an effective ρ-type vector exchange has been suggested, which is C-odd due to the specific isospin dependence [11]. The effective T-odd P-even NN potential due to this assumption is given by

$$V_\rho^T = i\phi_\rho^T\,\frac{\kappa_\rho g_{\rho NN}^2}{8m_p^2(\mathbf{q}^2+m_\rho^2)}\,(\sigma_1-\sigma_2)\cdot\mathbf{q}\times\mathbf{p}\quad(\tau_1\times\tau_2)_0 \tag{11}$$

In the following the bounds implied on the strengths ϕ_A^T, ϕ_ρ^T through proton forward scattering on the deuteron will be analyzed. Two boson exchanges have not been considered up to now. Though experimental accuracy for T-odd P-even case varies, there is no one outstanding experimental bound. Limitations on the coupling strengths need further analysis. From the upper bounds of the edm of the neutron, a recent calculation by Musolf et al. gives $\phi_\rho^T \lesssim 10^{-3}$, which is more stringent than earlier estimates given by Herzceg and less than estimates given by Khriplovich, see ref. [12]. From the γ correlation experiment done on ^{57}Fe, $\phi_A^T \lesssim 10^{-2}$[13]. Limits on ρ type T-odd forces from the ^{57}Fe experiments are currently under consideration.

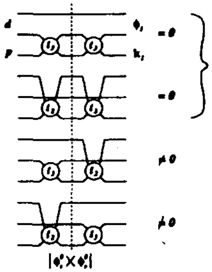
4 Analysis for the Proton Deuteron System

The dominant contribution to the T-odd correlation emerges from the *break-up* channel. The elastic channel for the axial case is suppressed by one order of magnitude. Due to the isovector character of the ρ type exchange, its contribution to the elastic channel is strongly suppressed. Other possible channels, such a π production have not been included in the analysis. They are probably important above the pion threshold.

The break-up cross section in impuls approximation (lowest order rescattering series) is given by

$$\sigma_{b-up} \propto tr\left\{\frac{\rho}{6}\int \langle\phi_1 \mathbf{k}_1 \left| t_2+t_3,\phi_S^0\right\rangle \left\langle\phi_S^0\right| t_2+t_3,\phi_1 \mathbf{k}_1\rangle^* \delta(E-E_0)\right\}. \tag{12}$$

The contributions due to the different channels are shown in Fig. 3.



due to $\left\langle N \left| [\sigma\otimes\sigma]^2 \right| N\right\rangle$

due to contributions from
$\sigma^T_{y,xz} \propto \left\langle t^T_{NN} t^E_{NN}\right\rangle \lesssim ?$
$\sigma^T_{y,xz} \propto \left\langle t^{TP}_{NN} t^P_{NN}\right\rangle \lesssim 10^{-17}$
from edm

Figure 3: Different three body channels that may contribute to the T-odd observable

The effect would emerge from the interference of a T-odd and a T-even amplitude. For the T-even amplitude the Bonn potential has been utilized. If the T-odd potential is not specified, the resulting limit is one order of magnitude more restrictive. In both cases however, the best momentum to conduct the experiment is about $k_{cm} \simeq 200-400$ MeV/c, where the generic T-odd contribution has its maximum (see Fig. 4). The T-odd contribution drops about one order of magnitude for $k_{cm} \geq 1$GeV/c, however, as already mentioned pionic contributions may become more important here. For more details see [14] and references therein.

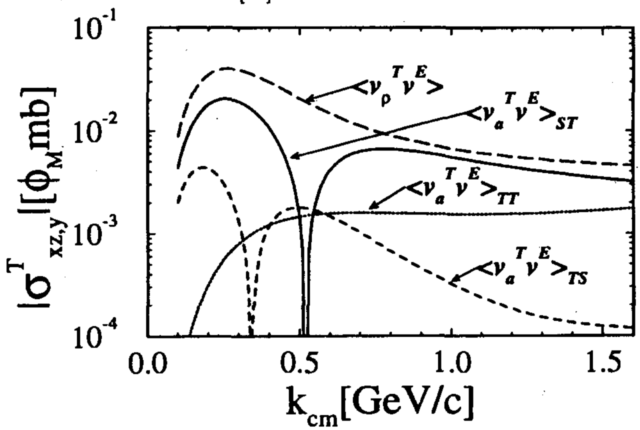


Figure 4: T-odd break-up cross section: $\left\langle v^E\right\rangle$ T-even Bonn potential, $\left\langle v^T_{\rho,a}\right\rangle$ T-odd potential, S,T: scalar, tensor interaction

5 Conclusion

Proton deuteron forward scattering provides a direct and unambigious test of T-odd interactions. Due to the accuracy that might be reached, the experiment is well suited to improve on the T-odd P-even limits. The expected limits (within the above framework and mentioned accuracy) would be $\phi_\rho \lesssim 10^{-3}$, $\phi_A \lesssim 2 \times 10^{-3}$, or $|\langle v^T_{NN}\rangle| \lesssim 10^{-4} \, |\langle v^E_{NN}\rangle|$, if the T-odd potential is not specified. The sources of uncertainties are due to the approximation of the strong amplitude, using Born approximation, and due to pionic production channels that might be of importance at higher energies.

Other experiments utilizing the deuteron have been suggested, viz. thermal neutron transmission with neutron energies at several keV, which essentially means elastic nd scattering [15] and pd backward elastic scattering [16]. However, the latter is not a null experiment in the strict sence, because it does not use "diagonal" matrix elements as in forward scattering or measurments of electric dipole moments.

References

[1] J.H. Christenson, J.W. Cronin, V.L.Fitch, R.Tulay Phys. Rev. Lett. **13** (1964) 138

[2] L. Wolfenstein, INT Program on "Physics beyond the Standard Model" (1995)

[3] P.D. Eversheim et al. Phys. Lett. **B256** (1991) 11

[4] P.D. Eversheim, F. Hinterberger, J. Bisplinghoff, R. Jahn, J. Ernst, H.E. Conzett, M. Beyer, H. Paetz gen. Schieck, W. Kretschmer, COSY-proposal, H.E. Conzett (LBL, Berkeley). LBL-32672 (1992), LBL-27A-October 1990, H.E. Conzett, Phys. Rev. C48 (1993) 423-428

[5] D.G. Haase et al., Hyp. Int. **43** (1988) 133

[6] J.E. Koster et al, Phys. Lett. **B267** (1991) 23; Ch. Gould, private comunication.

[7] R.J.N. Phillips, Nucl. Phys. **43** (1969) 413

[8] D. Eversheim, this conference

[9] I.S. Altarev et al., Phys. Lett. **B102** (1981) 13, I.S. Altarev et al., JETP Lett. **67** (1986) 1735, K.F. Smith, Phys. Lett. **B234** (1990) 191, J. Last in *Massive neutrinos. Test of fundamental symmetries* ed. O. Fackler et al. (Editions Frontiers, Gif-sur-Yvette, 1991) S. 365

[10] see e.g. M. Beyer, H.J. Weber, Phys. Lett. **146B** (1984) 383; Phys. Rev. **C35** (1987) 14

[11] M. Simonius, Phys. Lett. **58B** (1975) 147, M. Simonius, Phys. Lett. **B58** (1975) 147

[12] W.C. Haxton, A. Höring, M.J. Musolf, Phys. Rev. D50 (1994) 3422

[13] M. Beyer, Phys. Rev. **C48** (1993) 906, and references therein

[14] M. Beyer, Nucl. Phys. **A 560** (1993) 895

[15] V.P. Gudkov, Z. Phys. A337 (1990) 247

[16] M.P. Rekalo, I.M. Sitnik, Preprint Dubna 1995, E4-95-209