Possibility of time reversal symmetry violation at proton deuteron forward elastic scattering

S.L. Cherkas

Institute of Nuclear Problems, Bobruiskaya 11, Minsk 220050, Belarus,
cherkas@inp.minsk.by

Abstract

We consider T-violating P-conserving proton-deuteron forward elastic scattering amplitude in a frame of the Glauber multiscattering theory, proceeding from T-odd, P-even N-N interaction.

PACS numbers: 24.80, 13.88+e, 11.80.La

keywords: time-reversal, symmetry

1 Introduction

Discovery of CP symmetry breaking in K-meson decay stimulated a search of T- and CP- non-invariant interactions in other systems. It is important to distinguish T- P- breaking interaction from T-breaking P-conserving one. While T-odd P-odd interaction naturally arises in the Standard model through CP-breaking phase of the Kobayashi-Maskawa matrix or in QCD through $\theta$ term, introduction of T-breaking P-conserving interactions has no natural implementation on a quark level. The investigation of P-even T-odd interaction (TRV) of non-weak origin continue to enjoy popularity in nuclear and nucleon-nucleon physics. Note, that the T-breaking, P-conserving interaction arising from interference of T- P- breaking interaction with P-odd weak one, should be very small and can not be considered.

Null test for the T-odd P-even interaction is finding of the

$$F_T(0) = \tilde{S}_T\{(\sigma \cdot S \times n)(S \cdot n) + (S \cdot n)(\sigma \cdot S \times n)\} \quad (1)$$
term [1–3] in the forward elastic scattering amplitude of the particle with the 1/2 spin by the nucleus with the spin $S \geq 1$. $S$ is the nucleus spin operator, $\mathbf{n}$ is the unit vector in the direction of the projectile particle momentum, $\sigma$ is the Pauli matrix of the nucleon spin.

The heavy nuclei exhibit the large enhancement of P-odd effects but for T-odd P-even interactions the enhancement can be suppressed [4]. So, the advantage of heavy nuclei compared to light is questionable. On the other hand, the proton-deuteron scattering considered here fully utilise a high luminosity of proton beams of COSY. Such an experiment is planed to be performed by TRV collaboration [5] as an internal target experiment in the cooler synchrotron COSY.

We consider the T-violating P-conserving p-d forward scattering amplitude in the frame of the Glauber multiscattering theory proceeding from T-odd, P-even terms of N-N interaction. The N-N forward elastic scattering amplitude does not contain T-odd, P-even terms; such a term exists in scattering amplitude only at non-zero angles. The mechanism of $\mathcal{F}_T$-term arising is double proton scattering by deuteron nucleons. In the first collision the proton is scattered by TRV interaction at a small angle $\theta$ and in the second collision it is scattered by T-even interaction at the angle $-\theta$, as a result, the T-odd, P-even term appears at the forward $p - d$ elastic scattering amplitude. The problem is discussed earlier [6], but we now take into account the deuteron non sphericity and calculate the contribution of the T-odd impurity at the deuteron density matrix.

2 Eikonal approximation for particles with spin

The Glauber multiscattering theory can be generalized to the case of particles with spins [7,8]. Let us consider the small-angle elastic scattering of the particle with spin by the $N$ scatterers also with spins and fixed at the points with the radius vectors $\mathbf{r}_\alpha$. The wave function of the system $\Psi(\mathbf{r},\mathbf{r}_\alpha)$ satisfies to the "relativized" Shredinger equation:

$$(\nabla^2 + k^2)\Psi(\mathbf{r},\mathbf{r}_\alpha) = 2EV(\mathbf{r},\mathbf{r}_1 \cdot \mathbf{r}_N)\Psi(\mathbf{r},\mathbf{r}_\alpha),$$

where $k$ and $E$ are the wave number and the particle energy accordingly. The particle interaction with the scatterers $V(\mathbf{r},\mathbf{r}_1 \cdot \mathbf{r}_N)$ is an operator at the particle spin space and at the every scatterer spin space. The solution of the equation (2) can be found in the form $\Psi(\mathbf{r}) = e^{ikz}\Phi(\mathbf{r})$. Substituting this value
to the (2) and neglecting the terms with second derivative of $\Phi(r)$ we come to

$$\frac{i k \partial \Phi(r)}{E \partial z} = V(r)\Phi(r).$$  \hspace{1cm} (3)$$

Equation (3) is analogous to to the interaction representation in the quantum field theory and consequently it has solution $Z exp$ being analogy to the $T exp$:

$$\Phi(b, z) = Z' exp\{-\frac{i E}{k} \int_{-\infty}^{z} V(b, z') dz'\}$$  \hspace{1cm} (4)$$

For the scattering amplitude we have:

$$F(q) = -\frac{E}{2\pi} \int e^{-iqb - ikz} V(r)\Psi(r) d^3r = \frac{ik}{2\pi} \int e^{-iqb(1 - \Phi(b, +\infty))} d^2b.$$  \hspace{1cm} (5)$$

where $q$ is the momentum transferred. If $V(b, z) = \sum_{\alpha=1}^{N} V_{\alpha}(b - b_{\alpha}, z - z_{\alpha})$ and $V_{\alpha}(b - b_{\alpha}, z - z_{\alpha})$ is concentrated near the point $z_{\alpha}$ so that the different $V_{\alpha}$ do not overlap it is possible to write:

$$Z' exp\{-\frac{i E}{k} \int_{-\infty}^{+\infty} V(b, z') dz'\} = \hat{Z}_{\alpha} \prod_{\alpha} Z exp\{-\frac{i E}{k} \int_{-\infty}^{+\infty} V_{\alpha}(b - b_{\alpha}, z - z_{\alpha}) dz\}.$$

The operator $\hat{Z}_{\alpha}$ orders the terms in this product in the direction of $z_{\alpha}$ increasing from the right side to the left one. By denoting

$$\Gamma_{\alpha}(b - b_{\alpha}) = 1 - Z exp\{-\frac{i E}{k} \int_{-\infty}^{+\infty} V_{\alpha}(b - b_{\alpha}, z - z_{\alpha}) dz\}$$  \hspace{1cm} (6)$$

we find

$$F(q) = \frac{ik}{2\pi} \int e^{-iqb} \langle 1 - \hat{Z}_{\alpha} \prod_{\alpha} (1 - \Gamma_{\alpha}(b - b_{\alpha})) \rangle d^2b.$$  \hspace{1cm} (7)$$

$\langle 1 \mid \rangle$ means the averaging over the displacements and the spin states of the scatterers in the target nucleus. Remember that the $\hat{Z}_{\alpha}$ orders the terms in the direction of $z_{\alpha}$ increasing.
3 T-odd P-even N-N elastic scattering amplitude

In view of absence of the fundamental model the T-odd P-even interaction is usually considered at the nucleon level in the framework of one meson exchange mechanism which is responsible for the long range component of nuclear forces. $A_1$ and $\rho$ are two easiest mesons, exchange of which can results to the T-odd P-even N-N scattering amplitude [9]. The Lagrangian of the interaction of $A_1$ and $\rho$ fields with nucleon field can be written down as [9]

$$L(x) = \bar{\psi}(x) \{ g_\rho \gamma_\mu \tau \cdot \rho^\mu(x) - \bar{\rho} \frac{g_\mu \kappa}{2m} \sigma_{\mu \nu} [\tau \times \partial^\nu \rho^\mu(x)] \}_3$$

$$+ g_A \gamma_\mu \gamma_5 \tau \cdot A^\mu(x) - \frac{i f_A}{2m} \sigma_{\mu \nu} \gamma_5 \tau \partial^\nu A^\mu(x) \} \psi(x) \quad \text{(8)}$$

The one meson exchange corresponds to the diagrams in Fig. 1.

![Fig. 1. One meson exchange diagrams. Black circle denote T-odd, P-even vertex.](image)

After the application ordinary diagram technique [10] we obtain the appropriate matrix element of transition due to T-odd $\rho$-meson exchange:

$$M_\rho = i g_\rho \frac{g_\rho \kappa}{2m} \{(\bar{u}_4 \gamma_\mu \tau_j u_2) (\bar{u}_3 \sigma_{\zeta \nu} e_{3 lj} \tau \nu \zeta u_1) (p_4 - p_2)^\mu D_\rho^{\mu \zeta}(p_4 - p_2)$$

$$- (\bar{u}_3 \gamma_\mu \tau_j u_1) (\bar{u}_4 \sigma_{\xi \nu} e_{3 lj} \tau \nu \xi u_2) (p_4 - p_2)^\mu D_\rho^{\mu \xi}(p_4 - p_2)$$

$$- (\bar{u}_4 \gamma_\mu \tau_j u_1) (\bar{u}_3 \sigma_{\xi \nu} e_{3 lj} \tau \nu \xi u_2) (p_4 - p_1)^\nu D_\rho^{\mu \xi}(p_4 - p_1)$$

$$+ (\bar{u}_3 \gamma_\mu \tau_j u_2) (\bar{u}_4 \sigma_{\xi \nu} e_{3 lj} \tau \nu \xi u_1) (p_4 - p_1)^\nu D_\rho^{\mu \xi}(p_4 - p_1) \} \quad \text{(9)}$$

$$D_\rho^{\mu \nu}(q) = \frac{g_\mu q_\nu/m_\rho^2 - g_{\mu \nu}}{q^2 - m_\rho^2}$$ represents the $\rho$-meson propagator, $e_{ijkl}$ is the antisymmetric tensor, $\sigma_{\mu \nu} = \frac{i}{2} (\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$. Let’s substitute $u_1 \equiv u(p_1)\theta_1$, 


\( u_2 \equiv u(p_2)\theta_2 \ldots \) to the expression (9), where \( u(p) = \left( \frac{\sqrt{\varepsilon + m \phi}}{\sqrt{\varepsilon - m (\sigma n) \phi}} \right) \), \( \phi \) and \( \theta \) are spin and isospin nucleon wave functions. Setting \( p_1 = p \), \( p_2 = -p \), \( p_3 = p + q \), \( p_4 = -p + q \),

\[
\theta_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \theta_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad \theta_3 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \theta_4 = \begin{pmatrix} 0 \\ 1 \end{pmatrix},
\]

we find the T-odd amplitude of the scattering of a proton by a neutron due to \( \rho \)-meson exchange:

\[
f^{\rho}_{T \rho}(q) = -\frac{M}{16\pi\varepsilon p} \frac{\bar{g}_\rho g_\rho^2 \kappa(I_{32}\sigma_{41} \times n \cdot q - I_{41}\sigma_{32} \times n \cdot q)}{2\pi m(m_\rho^2 + 4p^2)} = i\bar{g}_\rho g_\rho^2 \kappa((n\sigma_{31})(q\sigma_{42}) - (n\sigma_{42})(q\sigma_{31})) \frac{2\pi m(m_\rho^2 + 4p^2)}{2}, \quad (10)
\]

where \( \sigma_{41} = \phi_1^+ \sigma_1, \ I_{31} = \phi_3^+ \phi_1 \) and so on, \( p \) and \( \varepsilon \) are the center of mass nucleon momentum and the energy, \( n = \frac{p}{|p|} \). The Fierz transform \( \sigma_{41}I_{32} - \sigma_{32}I_{41} = i\sigma_{31} \times \sigma_{42} \) was used to put the exchange amplitude to the direct channel. Here and everywhere further we shall use the scattering amplitude normalized by the condition: \( \sigma_{tot} = 4\pi \text{Im} f(0) \). The amplitude is derived from ordinary amplitude (7) through division by the incident particle wave number. In such a normalization the amplitude of scattering is invariant relative to the Lorenz transform along the incident particle momentum (small angle scattering is implied). The T-odd P-even \( p - p \) and \( n - n \) amplitudes corresponding to \( \rho \)-meson exchange is absent. The amplitude (10) gives nonrelativistic T-odd N-N potential

\[
V_\rho^T = \bar{g}_\rho g_\rho^2 \kappa(\tau_1 \times \tau_2)3r \times p \cdot (\sigma_1 - \sigma_2) \frac{m_\rho^2 e^{-m_\rho r}}{m^2} \frac{1}{4\pi r} \left( \frac{1}{m_\rho r} + \frac{1}{m_\rho^2 r^2} \right). \quad (11)
\]

The matrix element describing \( A_1 \)-meson exchange is:

\[
M_A = -\frac{g_A f_A}{2m} \left\{ \left( \bar{u}_4\gamma_\mu\gamma_5\tau_j u_2 \right)(\bar{u}_3\sigma_{\nu\mu}\gamma_5\tau_j u_1)(p_4 - p_2)\nu D_A^{\mu\nu}(p_4 - p_2) - (\bar{u}_3\gamma_\mu\gamma_5\tau_j u_1)(\bar{u}_4\sigma_{\nu\mu}\gamma_5\tau_j u_2)(p_4 - p_2)\nu D_A^{\mu\nu}(p_4 - p_2) - (\bar{u}_4\gamma_\mu\gamma_5\tau_j u_1)(\bar{u}_3\sigma_{\nu\mu}\gamma_5\tau_j u_2)(p_4 - p_1)\nu D_A^{\mu\nu}(p_4 - p_1) + (\bar{u}_3\gamma_\mu\gamma_5\tau_j u_2)(\bar{u}_4\sigma_{\nu\mu}\gamma_5\tau_j u_1)(p_4 - p_1)\nu D_A^{\mu\nu}(p_4 - p_1) \right\}. \quad (12)
\]

After similar calculations we obtain
\[ f_{TA}^{pp}(q) = \frac{i g_A}{\pi m} \frac{p^2}{m_A^2 (m_A^2 + 4p^2)} (\sigma_{42}(p) (\sigma_{31}q) + (\sigma_{42}q) (\sigma_{31}p)) \] (13)

for the \( p - p \) scattering and

\[ f_{TA}^{pn}(q) = -\frac{ig_A}{4\pi m} \frac{3m_A^2 + 4p^2}{m_A^2 (m_A^2 + 4p^2)} ((\sigma_{42}(p) (\sigma_{31}q) + (\sigma_{42}q) (\sigma_{31}p)) \] (14)

for the \( p - n \) scattering. The corresponding potential is

\[ V_{TA}^T = g_A \frac{m_A^2}{m^2} ((\sigma_1 p)(\sigma_2 r) + (\sigma_2 p)(\sigma_1 r) - (\sigma_1 \sigma_2)(pr)) \times (\tau_1 \tau_2) \frac{e^{-m_A r}}{8\pi r} \left( \frac{1}{m_A r} + \frac{1}{m_A^2 r^2} \right) + h.c. \] (15)

The T-even constants are approximately equal to \( g_\rho = 2.79 \), \( g_A = \frac{5}{3\sqrt{2}} g_\rho \), \( \kappa = 3.7 \) [9]. For T-odd constants the following restrictions were derived: \(|\bar{g}_\rho| < 6.7 \times 10^{-3} \), \(|f_A| < 3 \times 10^{-5} \) [9].

### 4 T-odd P-even forward \( p - d \) elastic scattering amplitude

For the nucleon-deuteron scattering we have from (7):

\[ F(0) = i \frac{2\pi}{\rho_{\sigma_1 \sigma_2}} \left\{ (\Gamma_1 (b - b_1) + \Gamma_2 (b - b_2) - \Gamma_1 (b - b_1) \Gamma_2 (b - b_2) \theta(z_1 - z_2) - \Gamma_2 (b - b_2) \Gamma_1 (b - b_1) \theta(z_2 - z_1)) \times \delta(r_1 - r_2) \rho(r_1) \right\} d^3r_1 d^3r_2 d^2b , \] (16)

where \( \theta(z) \) is the step-function and \( r_\alpha = \{b_\alpha, z_\alpha\} \). We again use the amplitudes normalized by the condition \( \sigma_{tot} = 4\pi \text{Im} F(0) \). The double scattering terms of the expression (16) imply that the incident particle spin wave function is acted by \( \Gamma_1 \), and then by \( \Gamma_2 \) if the particle firstly strikes with the nucleon 1. If the first collision occurs with nucleon 2 the \( \Gamma_2 \) acts firstly.

The profile-function \( \Gamma(b) \) is connected with the \( N - N \) nucleon scattering amplitude by the relation: \( f(q) = \frac{i}{2\pi} \int \Gamma(b) e^{-iqb} d^2b \). If we rewrite the equation (16) in terms of amplitudes and form factors \( G^{(+)}(q) = \int_{0}^{+\infty} \rho(r)dz \) \( e^{iqb} d^2b \),
\[ G^{(-)}(q) = \int \left\{ \int_{-\infty}^{0} \rho(r) \, dz \right\} e^{iqb} \, d^2b \] 
\( \equiv \{b, z\} \) we can see that in the expression derived

\[ F(0) = S p_{\sigma_1 \sigma_2} \left\{ (f_1(0) + f_2(0)) G(0) \right\} \]
\[ + \frac{i}{2\pi} S p_{\sigma_1 \sigma_2} \left\{ \int (f_1(-q) f_2(q) G^{(+)}(2q) + f_2(q) f_1(-q) G^{(-)}(2q)) \, d^2q \right\} \]

the area of integration over the momentum transferred \( q \) is restricted by the deuteron form factor, which dependence on the momentum transferred is sharper than that for \( N - N \) scattering amplitude. It allows one to take out the \( N - N \) amplitude from the integral or, that is equivalent, to use the formal profile-function giving the correct expression for the \( N - N \) amplitude in a vicinity of small angles:

\[ \Gamma_\alpha(b) = \frac{2\pi}{i} \left\{ a_\alpha + v_\alpha(\sigma_\alpha) + e_\alpha(\sigma_\alpha n)(\sigma n) - \frac{c_\alpha}{m}(\sigma + \sigma_\alpha) \times n \cdot \frac{\partial}{\partial b} \right. \]
\[ - \frac{d_\alpha}{m^2}(\sigma_\alpha \frac{\partial}{\partial b})(\sigma \frac{\partial}{\partial b}) - \frac{i h_\alpha}{m}(\sigma_\alpha n)(\sigma \frac{\partial}{\partial b}) - \frac{i h'_\alpha}{m}(\sigma n)(\sigma_\alpha \frac{\partial}{\partial b}) \left\} \delta^{(2)}(b) \right\}

Here \( \delta^{(2)}(b) \) is a two dimensional delta-function, \( m \) is the nucleon mass. Although the approximation is very rough, especially for the spin-dependent form factors \( G \) [11], we use it to simplify calculations. The expression (17) corresponds to the scattering amplitude of the incident proton by the \( \alpha \) deuteron nucleon (\( \alpha = 1 \) denotes the p-p scattering and \( \alpha = 2 \) denotes the \( p - n \) one) with constant \( a_\alpha, v_\alpha, e_\alpha, c_\alpha, d_\alpha, h_\alpha, h'_\alpha \):

\[ f_\alpha(q) = a_\alpha + v(\sigma_\alpha \sigma) + e(\sigma_\alpha n)(\sigma n) + \frac{ic_\alpha}{m}(\sigma + \sigma_\alpha) \cdot q \times n \]
\[ + \frac{d_\alpha}{m^2}(\sigma_\alpha q)(\sigma q) + \frac{ih_\alpha}{m}(\sigma_\alpha n)(\sigma q) + \frac{ih'_\alpha}{m}(\sigma n)(\sigma_\alpha q) \]

It follows from (10), (14), (13) that \( \rho \)-meson exchange gives

\[ h_1^{\rho} = h_1'^{\rho} = 0, \quad h_2^{\rho} = h_2'^{\rho} = -\frac{i g_\rho g_{\rho^*}^2}{2\pi (m_\rho^2 + 4p^2)} \]

and \( A_1 \)-meson exchange gives

\[ h_1^{A} = h_1'^{A} = \frac{ig_A f_{A^0}}{\pi m_A^2 (m_A^2 + 4p^2)} , \quad h_2^{A} = h_2'^{A} = \frac{ig_A f_{A^0} (3m_A^2 + 4p^2)}{4\pi m_A^2 (m_A^2 + 4p^2)} \]

Let us represent the nucleon density at deuteron \( \rho(r) \) as:

\[ \]
\[
\rho(r) = \frac{1}{4} \{ A_0 + A_1 S_1 + A_2 S_2 + A_3 (S_3)^2 
+ A_4 (S_1 S_2) + A_5 (S_1 S_2) + A_6 (S_1 S_2) + (S_2 S_2) (S_1 S_2) 
+ A_7 (S_1 S_2) (S_3) + A_8 (S_1 S_2) (S_3)^2 + A_9 (S_1 S_2) (S_3)^2 \}
\]

The density is simultaneously the spin density matrix of the both deuteron nucleons. The operator of the deuteron spin \( S \) is a parameter describing deuteron orientation. To find density for the concrete deuteron orientation we must take matrix element of \( \rho(r) \) over deuteron spin state. The terms \( T_0, T_1 \) and \( T_2 \) are the T-odd terms. The real functions \( A_0...A_{10} \) can be found from the deuteron wave function.

\[
\phi_m = \frac{1}{\sqrt{4\pi}} \left( \frac{U(r)}{r} + \frac{1}{\sqrt{8}} \frac{W(r)}{r} S_{12} \right) \chi_m,
\]

where \( U(r) \) is the radial deuteron S-wave function and \( W(r) \) is the radial D-function, \( \chi_m \) is the spin wave function of two nucleons with the spin \( m \), \( S_{12} = 3(S_1 n)(S_3 n) - (S_1 S_2) \). Taking into account that \( \rho(r) = 8\phi(2r)\phi^+(2r) \) we can find the nucleon density matrix for the deuteron being at the state with the spin projection 1:

\[
\langle 1 \mid \rho(r) \mid 1 \rangle = \frac{1}{\pi} \left( \frac{U(2r)}{r} + \frac{W(2r)}{\sqrt{8r}} S_{12} \right) \chi_1 \chi^+_1 \left( \frac{U(2r)}{r} + \frac{W(2r)}{\sqrt{8r}} S_{12} \right)
\]

From the other side, \( \langle 1 \mid \rho \mid 1 \rangle \) can be obtained by taking the matrix element from expression (20) over the state with the spin projection 1. By comparing these expressions we find:

\[
A_0(r) = u^2 - 8uw + 16w^2, \quad A_1 = u^2 - 2uw - 8w^2, \quad r^2A_2 = 6uw + 12w^2, \\
r^2A_3 = 12uw - 12w^2, \quad A_4 = 8w^2 + 8uw - u^2, \quad r^2A_5 = -24w^2, \\
A_6 = u^2 - 2uw + 4w^2, \quad r^4A_7 = 72w^2, \quad r^2A_8 = -12w^2, \\
r^2A_9 = -6uw, \quad r^2A_{10} = -12w^2.
\]

The functions \( u \) and \( w \) are connected with \( U \) and \( W \) by: \( W(2r) = \sqrt{8\pi}rw(r) \), \( U(2r) = \sqrt{\frac{1}{\pi}}ru(r) \). Substituting the expressions for \( \rho(r) \) and for the profile-function to the equation (16) it is possible to calculate the T-odd P-even \( p-d \) forward scattering amplitude.
\[ F_T(0) = \pi i((\sigma \cdot S \times n)(Sn) + (Sn)(\sigma \cdot S \times n)) \]
\[ \times \int \left\{ ((a_1 v_2 + v_1 a_2)z^2 T_2 - \frac{1}{4m^2}(a_1 d_2 + d_1 a_2)(zT_2') + T_2 - \frac{c_1 c_2}{2m^2}(zT_2' - 3T_2) + \frac{i}{2k}(c_1 v_2 + c_2 v_1 + c_1 e_2 + c_2 e_1)zT_2 - \frac{1}{2k}(h_1 v_2 + h_2 v_1)(z^3 A_7 + z A_8 + 2z A_{10}) + \frac{1}{2k}(h_1' v_2 + h_2' v_1)(z A_8 + 3z A_{10} - \frac{i}{4m^2}(c_1 h_2 + c_2 h_1)(\frac{A_6'}{z} - z^2 A_7 - 3A_9 + z A_{10}' - A_{10}) + \frac{1}{2m}(h_1 e_2 + h_2 e_1)(z^3 A_7 + z A_8 + 2z A_{10})) \right\} dz . \] (21)

Everywhere in (21) \( A_n, T_n \) are the functions of \( z \), the prime means the derivative with respect to \( z \). The two different contributions to the T-odd scattering amplitude exist. The first one is due to T-odd N-N scattering taking part in the double scattering of the incident proton by the deuteron nucleons. For spherical deuteron \( A_2, A_3, A_5, A_7, A_8, A_9, A_{10} \) are equal to zero and the only term proportional to the \((c_1 h_2 + c_2 h_1)\frac{A_6'}{z}\) remains. In any case the spin-dependent N-N scattering amplitude is needed to generate T-odd effect in the p-d amplitude. The spin-dependent N-N amplitude decreases with the energy, so the T-odd p-d amplitude decreases too. We don’t speak here about possible short range T-odd N-N forces which, in principle, can grow with the energy and compensate decreasing of the spin-dependent N-N amplitude.

Fig. 2. T-odd P-even p-d forward elastic scattering amplitude calculated with T-odd P-even N-N amplitude due to \( A_1 \)-meson exchange (a) and due to \( \rho \)-meson exchange (b). Solid curve is real part and dashed curve is imaginary part. Black and empty circles correspond to the real and imaginary parts respectively calculated for ”spherical” deuteron.

The second contribution is due to T-odd impurity in the nucleon density at
deuteron. We can see from the expression (21) that only the $T_2$ term gives rise to the p-d amplitude. $T_1$ and $T_0$ terms do not contribute to the p-d amplitude because they contain less than 2 deuteron spin operators. The T-even spin dependent p-d scattering amplitude was considered in [11].

5 Results

The T-even amplitudes $a, b, c...$ are taken from the SAID phase shift analysis [12] and the deuteron S-,D- radial functions are taken from [13]. Setting T-odd constants equal $\bar{g}_\rho = 10^{-3}$ and $f_A = 10^{-5}$ we obtain results shown in Fig. 2a. The restriction on $f_A$ is more rigorous due to strict contribution of the $A_1$-exchange mechanism to the neutron dielectric moment and the accuracy $10^{-9} - 10^{-10} \, fm^2$ for amplitude measurements or $10^{-7} - 10^{-8} \, mb$ for T-odd cross section measurements is needed to find $f_A = 10^{-5}$. The restriction for $\bar{g}_\rho$ is more gentle and requires the accuracy $10^{-6} - 10^{-7} \, fm^2$ for the amplitude (Fig. 2b) and $10^{-4} - 10^{-5} \, mb$ for the cross section measurements. We see that deuteron non sphericity makes results more optimistic.

For $T_2$ impurity to the density we take $T_2 = 10^{-4} A_9$ because the T-even $A_9$ term has similar structure as $T_2$. To test the impurity at this level we need the accuracy $10^{-6} - 10^{-7} \, fm^2$ and $10^{-4} - 10^{-5} \, mb$ for the amplitude (Fig. 3) and cross section measurements respectively.

So, the accuracy of TRV collaboration ($10^{-6} \, mb$) will allow to obtain new constraints for $f_A$ and $\bar{g}_\rho$. Note, that the real part of the T-odd P-even forward
amplitude can be measured in the spin rotation [14] experiment.

The author is grateful to the Prof. V. G. Baryshevsky for the remark concerning the importance of a deuteron non sphericity and to the Dr. K. G. Batrakov and Dr. I. Ya. Dubovskaya for discussions and remarks.

References

[1] V. G. Baryshevsky, Yad. Fiz. 37 (1983) 255
[2] V. G. Baryshevsky, Yad. Fiz. 38 (1983) 1162 (Sov. J. Nucl. Phys. 38 699)
[3] J. E. Koster et al, Phys. Lett. B267 (1991) 267
[4] W. C. Haxton and A. Horing, Nucl. Phys. A560 (1993) 468
[5] F. Hinterberger, Los Alamos pre-print library nucl-ex/9810003 (1998)
[6] M. Beyer, Nucl. Phys. A560 (1993) 895
[7] R. G. Glauber and V. Franco, Phys. Rev. 156 (1967) 1685
[8] A. V. Tarasov and Ch. Tsaren, Yad. Fiz. 12 (1970) 978
[9] M. Simonius, Los Alamos pre-print library nucl-th/9702013 (1997)
[10] V. B. Berestetsky, E. M. Lifshitz and L. P. Pitaevsky, Quantum Electrodynamics (Pergamon Press, Oxford 1982)
[11] V. G. Baryshevsky, K. G. Batrakov and S. Cherkas, Los Alamos pre-print library hep-ph/9907464 (1999)
[12] R. A. Arndt, I. I. Strakovsky and R. Workman, Phys. Rev. C50 (1994) 2731
[13] V. G. J. Stoks et al, Phys. Rev. C49 (1994) 2950
[14] V. G. Baryshevsky, Phys. Lett. B120 (1983) 267