Time reversal invariance violating and parity conserving effects in proton-deuteron scattering

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Time reversal invariance violating parity conserving (TVPC) effects are calculated for elastic proton-deuteron scattering with proton energies up to 2 MeV. The distorted-wave Born approximation is employed to estimate TVPC matrix elements, based on hadronic wave functions, obtained by solving three-body Faddeev-Merkuriev equations in configuration space with realistic potentials.

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I. INTRODUCTION

The study of time reversal invariance violating and parity conserving (TVPC) effects is an important approach for the search of new physics beyond the standard model. In the standard model, time reversal invariance violation requires also parity violation. Therefore, an observation of TVPC effects can be interpreted as a direct signal of new physics. Although TVPC interactions may be observed in neutron, atomic, and molecular electric dipole moment measurements due to the one-loop diagram with one TVPC vertex and with other time reversal conserving and parity violating vertexes (see, for example [1]), TVPC interactions cannot be distinguished from time reversal violating and parity violating ones in these experiments. From this point of view, the search for TVPC effects in scattering experiments has the advantage of being direct evidence of the existence of TVPC interactions up to the second order of weak interaction contributions ($\sim 10^{-14}$). TVPC effects in neutron-deuteron scattering have been calculated recently [2]. In this paper we consider similar effects of TVPC interaction in proton-deuteron scattering which are related to the $\boldsymbol{\sigma}_p \cdot [\boldsymbol{p} \times \boldsymbol{I}](\boldsymbol{p} \cdot \boldsymbol{I})$ correlation with a tensor polarized target, where $\boldsymbol{\sigma}_p$ is the proton spin, $\boldsymbol{I}$ is the target spin, and $\boldsymbol{p}$ is the proton momentum. This correlation can be observed by measuring the asymmetry of protons polarized in parallel and antiparallel to the $[\boldsymbol{p} \times \boldsymbol{I}](\boldsymbol{p} \cdot \boldsymbol{I})$ direction when transmitted through a deuteron target. This is the simplest system to realize the aforementioned correlation related to TVPC effects for proton scattering. The five-fold correlation $\boldsymbol{\sigma}_p \cdot [\boldsymbol{p} \times \boldsymbol{I}](\boldsymbol{p} \cdot \boldsymbol{I})$ is equal to zero, unless the target spin I is larger or equal to unity. As a consequence, this correlation cannot be observed in nucleon-nucleon scattering.

TVPC effects in proton-deuteron forward scattering for a few hundred MeV proton energy range have been calculated [3,4], in relation to the proposed experiment at the cooler synchrotron (COSY) at the Forschungszentrum Julich GmbH facility [5]. We consider TVPC effects for a proton energy range up to 2 MeV which could be calculated accurately in a formally exact framework based on Faddeev-Merkuriev equations [6] with realistic potentials. This gives us an opportunity to compare directly these TVPC effects with the case of TVPC [2] effects in neutron-deuteron scattering, as well as with the cases of parity violation in proton-deuteron and neutron-deuteron [7] scattering.

II. OBSERVABLES

In a contrast to neutron-deuteron scattering, the proton-deuteron scattering amplitude $f_{\rm full}$ diverges at zero scattering angle due to the Coulomb interaction. To avoid this divergence in the calculations of TVPC effects we estimate a "nuclear" amplitude $f = f_{\rm full} - f_{\rm Coul}$ with the Coulomb amplitude being subtracted. Since the Coulomb interaction does not violate time reversal invariance, it cannot contribute to TVPC effects. For further calculations we fix the direction of the proton momentum as axis z, and the direction of $[\boldsymbol{p} \times \boldsymbol{I}](\boldsymbol{p} \cdot \boldsymbol{I})$ as axis y. Then, zero-angle scattering amplitudes $f_\pm(E,\theta = 0)$, for protons, polarized along and opposite to the direction of $[\boldsymbol{p} \times \boldsymbol{I}](\boldsymbol{p} \cdot \boldsymbol{I})$, and propagating through the tensor polarized deuteron target are defined as

$$f_\pm(E,\theta = 0) \equiv \frac{1}{2} \sum_{m_d}{}' f\left(p\hat{z}, \left(\frac{1}{2}\frac{\pm 1}{2}\right)^{\hat{y}}, (1m_d)^{\hat{x}\hat{z}} \leftarrow p\hat{z}, \left(\frac{1}{2}\frac{\pm 1}{2}\right)^{\hat{y}}, (1m_d)^{\hat{x}\hat{z}}\right). \quad (1)$$

Here, $\sum'$ means that the state with $m_d = 0$ is excluded from the summation, and the factor $\frac{1}{2}$ in front of the summation is a deuteron spin statistical factor. Then, using the optical theorem [8], the asymmetry in the transmission of the polarized proton through the tensor-polarized deuteron target can be written as

$$P(E) = \frac{\sigma_+^{\rm nuc} - \sigma_-^{\rm nuc}}{\sigma_+^{\rm nuc} + \sigma_-^{\rm nuc}} = \frac{{\rm Im}[f_+(E,\theta = 0) - f_-(E,\theta = 0)]}{{\rm Im}[f_+(E,\theta = 0) + f_-(E,\theta = 0)]}. \quad (2)$$

The corresponding "nuclear" S matrix (with the subtracted Coulomb scattering part) is defined from the asymptotic form of scattering wave function for partial waves α' and α, where

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$$\alpha = (L,S,J,T),$$
$$\frac{w_{\alpha',\alpha}(r;p)}{r} \to \frac{1}{2}\left[\delta_{\alpha',\alpha} H_{l'}^{(-)}(\eta,\rho) + S_{\alpha',\alpha} H_{l'}^{(+)}(\eta,\rho)\right] \quad \text{for } r \to \infty, \tag{3}$$

with

$$H_l^{(\pm)}(\eta,\rho) = \frac{1}{\rho}[F_l(\eta,\rho) \mp i G_l(\eta,\rho)], \tag{4}$$

where $F_l(\eta,\rho)$ and $G_l(\eta,\rho)$ are regular and irregular Coulomb functions, $\eta = \frac{Z_1 Z_2 \mu\alpha}{p}$ is a Sommerfeld parameter, μ is a reduced mass, and $\rho = pr$. Then, the nuclear scattering amplitudes in Eq. (1) are related to the nuclear S matrix as

$$f\left(\boldsymbol{p}',1m_d',\frac{1}{2}m' \leftarrow \boldsymbol{p},1m_d,\frac{1}{2}m\right) = \sum_{LS,L'S',J} f^J_{L'S',LS}(p)\left(Z^{(J),L'S'm_d'm'}_{LSm_dm}(\hat{p}',\hat{p})\right), \tag{5}$$

where

$$f^J_{L'S',LS}(p) = \left(e^{i\sigma_{L'}}\frac{S^J_{L'S',LS} - \delta_{LL'}\delta_{SS'}}{2ip}e^{i\sigma_L}\right),$$
$$Z^{(J),L'S'm_d'm'}_{LSm_dm}(\hat{p}',\hat{p}) = \sum_{L_z,L_z',J_z} 4\pi i^{-L'+L} Y_{L'L_z'}(\hat{p}') Y^*_{LL_z}(\hat{p}) \times \langle LL_z, Sm_d+m|JJ_z\rangle \times \left\langle 1m_d,\frac{1}{2}m|Sm_d+m\right\rangle \times \langle L'L_z', S'm_d'+m'|JJ_z\rangle \times \left\langle 1m_d',\frac{1}{2}m'\middle|S'm_d'+m'\right\rangle, \tag{6}$$

and $\sigma_l(\eta) \equiv \arg\Gamma(l+1+i\eta)$ is a Coulomb phase shift. Since the TVPC interaction is considered to be weak, we can use the distorted-wave Born approximation (DWBA) to express the symmetry violating scattering amplitudes related to the TVPC potential

$$f^{\not T P}_{\alpha\beta}(k) = e^{i\sigma_\alpha}\left(\frac{\hat{S}_{\not T P} - 1}{2ik}\right)_{\alpha,\beta} e^{i\sigma_\beta} \simeq -2\mu e^{i\sigma_\alpha}\langle\psi_\alpha^{(-)}|V_{\not T P}|\psi_\beta^{(+)}\rangle e^{i\sigma_\beta}, \tag{7}$$

where $\langle \boldsymbol{r}|\psi_\alpha^{(\pm)}\rangle = \sum_{\alpha'} \frac{w^{(\pm)}_{\alpha',\alpha}(r;p)}{r}\mathcal{Y}_{\alpha'}(\hat{r})$ represents wave function solutions with outgoing and incoming boundary conditions in partial wave α with $\mathcal{Y}_{\alpha'}(\hat{r})$ representing tensor spherical harmonics in partial wave α'. Thus, by calculating matrix elements $\langle\psi_\alpha^{(-)}|V_{\not T P}|\psi_\beta^{(+)}\rangle$, we can obtain the nuclear asymmetry P of the TVPC interaction in Eq. (2).

III. TIME REVERSAL VIOLATING PARITY CONSERVING POTENTIAL

The most general form of the time reversal violating and parity conserving part of the nucleon-nucleon Hamiltonian in the first order of relative nucleon momentum can be written as [9]

$$\begin{aligned}H^{\not T P} = &\left(g_1(r) + g_2(r)\tau_1\cdot\tau_2 + g_3(r)T^z_{12} + g_4(r)\tau_+\right)\hat{r}\cdot\bar{\boldsymbol{p}} + \left(g_5(r) + g_6(r)\tau_1\cdot\tau_2 + g_7(r)T^z_{12} + g_8(r)\tau_+\right)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\bar{\boldsymbol{p}}\\ &+ \left(g_9(r) + g_{10}(r)\tau_1\cdot\tau_2 + g_{11}(r)T^z_{12} + g_{12}(r)\tau_+\right)\left(\hat{r}\cdot\boldsymbol{\sigma}_1\bar{\boldsymbol{p}}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\bar{\boldsymbol{p}}\cdot\boldsymbol{\sigma}_1 - \tfrac{2}{3}\hat{r}\cdot\bar{\boldsymbol{p}}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right)\\ &+ \left(g_{13}(r) + g_{14}(r)\tau_1\cdot\tau_2 + g_{15}(r)T^z_{12} + g_{16}(r)\tau_+\right)\left(\hat{r}\cdot\boldsymbol{\sigma}_1\hat{r}\cdot\boldsymbol{\sigma}_2\hat{r}\cdot\bar{\boldsymbol{p}} - \tfrac{1}{5}(\hat{r}\cdot\bar{\boldsymbol{p}}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_1\bar{\boldsymbol{p}}\cdot\boldsymbol{\sigma}_2 + \hat{r}\cdot\boldsymbol{\sigma}_2\bar{\boldsymbol{p}}\cdot\boldsymbol{\sigma}_1)\right)\\ &+ g_{17}(r)\tau_-\hat{r}\cdot(\boldsymbol{\sigma}_\times\times\bar{\boldsymbol{p}} + g_{18}(r)\tau^z_\times\hat{r}\cdot(\boldsymbol{\sigma}_-\times\bar{\boldsymbol{p}}),\end{aligned} \tag{8}$$

where the exact form of $g_i(r)$ depends on the details of a particular theory of TVPC.

One should note that pions, being spin zero particles, do not contribute to the TVPC on-shell interaction [10]. Therefore to describe the TVPC nucleon-nucleon interaction in a one-meson-exchange potential model, by assuming CPT (Charge, Parity, Time reversal) symmetry conservation, one should consider the contribution from heavier mesons: $\rho(770)$, $I^G(J^{PC}) = 1^+(1^{--})$ and $h_1(1170)$, $I^G(J^{PC}) = 0^-(1^{+-})$ (see, for example, [11–13] and references therein). The Lagrangians for the strong and TVPC interactions with explicit ρ and h_1 meson exchanges are expressed as

$$\mathcal{L}^{\rm st} = -g_\rho\bar{N}\left(\gamma_\mu\rho^{\mu,a} - \frac{\kappa_V}{2M}\sigma_{\mu\nu}\partial^\nu\rho^{\mu,a}\right)\tau^a N - g_h\bar{N}\gamma^\mu\gamma_5 h_\mu N, \tag{9}$$

$$\mathcal{L}^{\not T P} = -\frac{\bar{g}_\rho}{2m_N}\bar{N}\sigma^{\mu\nu}\epsilon^{3ab}\tau^a\partial_\nu\rho^b_\mu N + i\frac{\bar{g}_h}{2m_N}\bar{N}\sigma^{\mu\nu}\gamma_5\partial_\nu h_\mu N, \tag{10}$$

where we neglected terms $\bar{N}\gamma_5\partial^\mu h_\mu N$, which are small at low energy. The parameters g and $\bar{g}$ are meson-nucleon coupling constants for strong and TVPC interactions, respectively. Then, one can separate the TVPC potential due to ρ and h_1 meson exchange as

$$V^{\not T P}_\rho = \frac{g_\rho\bar{g}_\rho m_\rho^2}{8\pi m_N}Y_1(m_\rho r)\tau^z_\times\hat{r}\cdot\left(\boldsymbol{\sigma}_-\times\frac{\bar{\boldsymbol{p}}}{m_N}\right), \quad V^{\not T P}_{h_1} = -\frac{g_h\bar{g}_h m_h^2}{2\pi m_N}Y_1(m_h r)\left(\boldsymbol{\sigma}_1\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_2\cdot\hat{r} + \boldsymbol{\sigma}_2\cdot\frac{\bar{\boldsymbol{p}}}{m_N}\boldsymbol{\sigma}_1\cdot\hat{r}\right), \tag{11}$$

TABLE I. Scattering amplitudes at various energies calculated with AV18UIX potential in fm^{-1} units. The second column corresponds to the time reversal invariant $\mathrm{Im}(f_+ + f_-)(E,\theta = 0)$ for the tensor-polarized deuteron target and other columns correspond to time reversal violating scattering amplitudes $\frac{1}{c_n}\mathrm{Im}(f_+ - f_-)(E,\theta = 0)$ for operator n and scalar function $Y_1(r,m)$.

$E_{\text{c.m.}}$ (keV)	$\mathrm{Im}(f_+ + f_-)$	$n = 5$ $(m = m_h)$	$n = 9$ $(m = m_h)$	$n = 18$ $(m = m_\rho)$
15	0.0907	0.116×10^{-7}	0.131×10^{-6}	-0.540×10^{-8}
100	1.76	0.437×10^{-6}	0.348×10^{-5}	-0.136×10^{-6}
300	3.59	0.177×10^{-5}	0.471×10^{-5}	-0.396×10^{-6}
1000	6.75	0.118×10^{-4}	-0.658×10^{-5}	0.482×10^{-5}
2000	8.04	0.327×10^{-4}	-0.229×10^{-4}	0.296×10^{-5}
n-d 100	2.85	0.107×10^{-6}	-0.217×10^{-5}	-0.711×10^{-7}

where $Y_1(x) = (1 + \frac{1}{x})\frac{e^{-x}}{x}$, $x_a = m_a r$. Comparing these potentials with Eq. (8), one can see that in the meson-exchange (ME) model, all $g_i(r)^{\text{ME}} = 0$, except for

$$\begin{aligned}
g_5^{\text{ME}}(r) &= \left(-\frac{g_h \bar{g}_h m_h^2}{3m_N^2 \pi}\right) Y_1(m_h r) = c_5^h Y_1(m_h r),\\
g_9^{\text{ME}}(r) &= \left(-\frac{g_h \bar{g}_h m_h^2}{2m_N^2 \pi}\right) Y_1(m_h r) = c_9^h Y_1(m_h r), \qquad (12)\\
g_{18}^{\text{ME}}(r) &= \left(\frac{g_\rho \bar{g}_\rho m_\rho^2}{8m_N^2 \pi}\right) Y_1(m_\rho r) = c_{18}^\rho Y_1(m_\rho r).
\end{aligned}$$

The possible contributions from heavier vector isovector mesons, like a_1 and b_1, correspond to g_6 and g_{10} functions of TVPC potential. However, for the sake of simplicity, in this work we focus only on the contribution from the exchange of the lightest mesons, by considering ρ and h_1.

Because the function $Y_1(\mu r)$ for ρ and h_1 mesons is singular at short distances, the calculation of potential matrix elements requires a careful treatment. One way to regulate the singular behavior of the $Y_1(\mu r)$ Yukawa function is by introducing a regulated Yukawa function $Y_{1\Lambda}(r,m)$ with a momentum cutoff Λ as

$$Y_{1\Lambda}(r,m) = -\frac{1}{m}\frac{d}{dr}\int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{r}} e^{-\frac{k^2}{\Lambda^2}} \frac{1}{k^2 + m^2}. \qquad (13)$$

From the point of view of effective field theory (EFT), we may regard Eq. (8) as a leading order potential of EFT. In this approach, the cutoff represents our ignorance on short distance dynamics. Therefore, the low energy constants should be renormalized to absorb the cutoff dependence to make the final results not sensitive to short distance uncertainties. This approach, which was adopted in our previous work on neutron-deuteron scattering, is preferable from a theoretical point of view. However, it introduces many unknown low energy constants which have to be fixed from a number of TVPC experiments. Therefore, to be able to make a prediction for the value of the TVPC observable, instead of following a rigorous EFT approach, we use a one-meson-exchange model of the TVPC potential. Then, by calculating the potential matrix elements using both $Y_1(\mu r)$, and $Y_{1\Lambda}(r,\mu)$ with $\Lambda = 1.5$ GeV, one can attribute the difference of these two calculations to the uncertainty in short-range interactions.

IV. RESULTS AND DISCUSSIONS

For the calculations of TVPC amplitudes in the DWBA approach we used the nonperturbed (time reversal invariance conserving) three-body wave functions for proton-deuteron scattering obtained by solving Faddeev-Merkuriev equations in configuration space [6] for the AV18 nucleon-nucleon potential in conjunction with the UIX three-nucleon force. The detailed procedure for these calculations is described in our papers [2,7,14].

The main results of the calculations are summarized in Table I where imaginary parts of time-reversal invariant scattering amplitudes $(f_+ + f_-)(E,\theta = 0)$ and TVPC scattering amplitudes $(f_+ - f_-)(E,\theta = 0)$ in one-meson-exchange models are calculated with the AV18UIX potential. To compare TVPC effects in proton-deuteron scattering with the case of neutron-deuteron scattering, we include the corresponding TVPC scattering amplitudes of neutron-deuteron scattering at $E_{\text{c.m.}} = 100$ keV in the last line of Table I. [Note that the convention we use is different from the one in Ref. [2], and the unpolarized total proton-deuteron cross section can be written as $\sigma_{\text{tot}}^{\text{el}} = \frac{1}{2}\frac{4\pi}{p}\mathrm{Im}(f_+ + f_-)(E,\theta = 0)$.] The energy dependence of scattering amplitudes for different operators in Table I in general follows the expected behavior of TVPC effect (which is increasing with energy as $\sim E_{\text{c.m.}}$ for $E_{\text{c.m.}} <$ 2 MeV, when only the elastic channel is open). However, since each amplitude contains many partial waves, one can see changes of the amplitude signs at some energies due to occasional destructive interferences.

To test how TVPC amplitudes depend on the choice of strong interaction potentials we calculated these amplitudes with three different phenomenological potentials: AV18, AV18UIX, and INOY. We found that time reversal conserving scattering amplitudes calculated with these three different potentials are in very good agreement for the considered proton energy range $E_{\text{c.m.}} \leqslant 2$ MeV. For example, the amplitudes at $E_{\text{c.m.}} = 1$ MeV (see second column of Table II) shows that AV18UIX and INOY potential results agree well with each other and comparison with AV18 implies that three-body force effects contribute only at the level of 2%. This result is not surprising because these amplitudes, which reproduce the total cross sections, are mostly sensitive to the long-range part of the interaction.

For the TVPC and PV matrix elements, which are more sensitive to a short-range behavior of the potential, we can

TABLE II. Scattering amplitudes calculated at $E_{\text{c.m.}} = 1$ MeV for various potential models in fm^{-1} units. The second column corresponds to time reversal invariant $\text{Im}(f_+ + f_-)(E,\theta = 0)$ for the tensor-polarized deuteron target and other columns correspond to TVPC scattering amplitudes $\frac{1}{c_n}\text{Im}(f_+ - f_-)(E,\theta = 0)$ for operator n and scalar function $Y_1(r,m)$.

Potential	$\text{Im}(f_+ + f_-)$	$n = 5$ $(m = m_h)$	$n = 9$ $(m = m_h)$	$n = 18$ $(m = m_\rho)$
AV18UIX	6.75	0.118×10^{-4}	-0.658×10^{-5}	0.482×10^{-5}
AV18	6.90	0.102×10^{-4}	0.258×10^{-5}	0.403×10^{-5}
INOY	6.75	-0.324×10^{-5}	0.482×10^{-4}	0.103×10^{-4}

expect stronger dependence on the strong interaction input. Moreover, singularities of Yukawa functions at short distances result in a finite residue of the radial integrals for TVPC matrix elements at two-nucleon contact which requires careful treatment of short-range integrals. Nevertheless, the results of calculations for most TVPC matrix elements with AV18 and AV18UIX potentials agree with each other rather well. The operator 9 (see Table II) is an exception, which shows large sensitivity to the presence of a three-nucleon force. Calculations based on INOY *NN* interaction deviate from the AV18. It should be noted that similar discrepancies with the INOY potential were also observed in our previous calculations [15,16] of parity and time reversal violating effects in neutron-deuteron interactions, which resulted in 10%–20% differences in final amplitudes after a summation of contributions from all operators. This issue is clearly related to a softness of the INOY potential and the qualitative difference of calculated nuclear wave functions at the short distances.

To test the sensitivity of TVPC operators to a short-range behavior of the potentials, we calculated TVPC amplitudes with Yukawa-type meson-exchange potentials Eq. (12) and with regulated Yukawa potentials Eq. (13) with a cutoff parameter $\Lambda = 1.5$ GeV. Thus, comparing corresponding results in Tables I and III, one can see rather good agreement between TVPC amplitudes calculated with AV18UIX strong potential for different energies. The comparison of Tables II and IV shows good agreement between the same amplitudes calculated at $E_{\text{c.m.}} = 1$ MeV with AV18UIX, AV18, and INOY potentials.

To be able to test the consistency our calculations in the future when measurements of parity violating effects in proton-deuteron scattering will be available, we calculated time reversal invariant parity violating scattering amplitudes for opposite helicities $f_\pm^{\text{pv}}(E,\theta = 0)$ defined as

$$f_\pm^{\text{pv}}(E,\theta=0) \equiv \frac{1}{3}\sum_{m_d} f\left(p\hat{z},\left(\frac{1}{2}\frac{\pm 1}{2}\right)^{\hat{z}},\right.$$
$$\left.(1m_d)^{\hat{z}} \leftarrow p\hat{z},\left(\frac{1}{2}\frac{\pm 1}{2}\right)^{\hat{z}},(1m_d)^{\hat{z}}\right). \quad (14)$$

In these calculations we used a short-range isovector pion-exchange part of the Desplanques-Donoghue-Holstein (DDH) parity violating potential [17]

$$V_{1\pi}^{\text{pv,DDH}} = \left(\frac{g_\pi h_\pi^1}{2\sqrt{2}m_N}\right)(\tau_1 \times \tau_2)^z(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot\hat{r}\,\frac{d}{dr}\left(\frac{e^{-m_\pi r}}{4\pi r}\right). \quad (15)$$

The results for $\text{Im}(f_+^{\text{pv}} - f_-^{\text{pv}})(E,\theta = 0)$ are presented in Table V, where the last line presents corresponding parity violating amplitudes for neutron-deuteron scattering at $E_{\text{c.m.}} = 100$ keV. One can see that the PV amplitude is much less sensitive to the particular choice of the strong interaction. This is not surprising, since PV effects are dominated by pion exchange with much longer range of interactions.

Finally, by comparing our results for proton-deuteron and neutron-deuteron scattering [2] at an energy of 100 keV (see the second and the last rows in Table I), one can see that corresponding amplitudes for these two processes have different sensitivity to TVPC h_1 an ρ-meson interactions. Therefore, they are rather complimentary to each other in the search for new physics, which can be manifested by TVPC interactions of h_1 an ρ mesons with nucleons.

TABLE III. Scattering amplitudes at various energies calculated with AV18UIX potential in fm^{-1} units. Each column corresponds to time reversal violating and parity conserving scattering amplitudes $\frac{1}{c_n}\text{Im}(f_+ - f_-)(E,\theta = 0)$ for operator n and scalar function $Y_{1\Lambda}(r,m)$ with $\Lambda = 1.5$ GeV.

$E_{\text{c.m.}}$ (keV)	$n = 5$ $(m = m_h)$	$n = 9$ $(m = m_h)$	$n = 18$ $(m = m_\rho)$
15	0.174×10^{-7}	0.185×10^{-6}	-0.540×10^{-8}
100	0.633×10^{-6}	0.492×10^{-5}	-0.168×10^{-6}
300	0.258×10^{-5}	0.680×10^{-5}	-0.246×10^{-6}
1000	0.173×10^{-4}	-0.759×10^{-5}	0.327×10^{-5}
2000	0.484×10^{-4}	-0.274×10^{-4}	0.509×10^{-5}

TABLE IV. Scattering amplitudes calculated at $E_{\text{c.m.}} = 1$ MeV for various potential models in fm^{-1} units. Each column corresponds to Time-reversal violating and parity conserving scattering amplitudes $\frac{1}{c_n}\text{Im}(f_+ - f_-)(E,\theta = 0)$ for operator n and scalar function $Y_{1\Lambda}(r,m)$ with $\Lambda = 1.5$ GeV.

potential	$n = 5$ $(m = m_h)$	$n = 9$ $(m = m_h)$	$n = 18$ $(m = m_\rho)$
AV18UIX	0.173×10^{-4}	-0.759×10^{-5}	0.327×10^{-5}
AV18	0.150×10^{-4}	0.242×10^{-5}	0.243×10^{-5}
INOY	0.875×10^{-5}	0.282×10^{-4}	0.996×10^{-5}

TABLE V. Parity violating scattering amplitudes $\frac{1}{c_1^{\rm DDH}}{\rm Im}(f_+^{\rm pv} - f_-^{\rm pv})(E,\theta=0)$ from PV DDH potential of isovector pion exchange in fm^{-2} units, where $c_1^{\rm DDH} = \frac{g_\pi h_\pi^1}{2\sqrt{2}m_N}$.

$E_{\rm c.m.}$ (keV)	AV18UIX	AV18	INOY
15	0.130×10^{-2}		
100	-0.425×10^{-1}		
300	$-0.248 \times 10^{+0}$		
1000	$-0.729 \times 10^{+0}$	$-0.728 \times 10^{+0}$	$-0.751 \times 10^{+0}$
2000	$-0.941 \times 10^{+0}$		
n-d 100	0.124×10^{-1}		

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