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# Discover Potential in a Search for Time-Reversal Invariance Violation in Nuclei

**Vladimir Gudkov · Young-Ho Song**

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**Abstract** Time reversal invariance violating (TRIV) effects in low energy physics could be very important in searching for new physics, being complementary to neutron and atomic electric dipole moment (EDM) measurements. In this relation, we discuss a sensitivity of some TRIV observables to different models of time-reversal (CP) violation and their dependencies on nuclear structure. As a measure of a sensitivity of TRIV effects to the value of TRIV nucleon coupling constant, we introduce a coefficient of a "discovery potential", which shows a possible factor for improving the current limits of the EDM experiments by measuring nuclear TRIV effects.

**Keywords** Time reversal invariance violation · Electric Dipole Moment · Neutron

## 1 Introduction

Time reversal invariance violation (TRIV) in nuclear physics has been studied for several decades. There is a number of TRIV effects in nuclear reactions and nuclear decays, which are sensitive to either CP-odd and P-odd (or T - and P-violating) interactions or T -violating P-conserving (C-odd and P-even) interactions. The important advantage in searching for TRIV in nuclei interactions is the variety of nuclear systems to measure T-violating parameters. This provides assurance that a possible "accidental" cancelation of T-violating

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V. Gudkov
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, 29208
Tel.: +803-576-5573
Fax: +803-777-3065
E-mail: gudkov@sc.edu

Y.-H. Song
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, 29208

effects due to unknown structural factors related to the strong interactions in the particular system would be avoided. Taking into account that different models of the CP-violation may contribute differently to a particular T/CP-observable[1], which may have unknown theoretical uncertainties, TRIV nuclear effects could be considered valuable complementary experiments to electric dipole moment (EDM) measurements. Moreover,there is the possibility of an enhancement of T-violating observables by many orders of magnitude due to the complex nuclear structure (see, i.e. paper [1] and references therein).

## 2 TRIV in neutron scattering

One of the promising approaches to the search of TRIV in nuclear reactions is the measurement of TRIV effects in a transmission of polarized neutrons through a polarized target. For the observation of TRIV and parity violating (PV) effects, one can consider effects related to the $\boldsymbol{\sigma}_n \cdot (\mathbf{p} \times \mathbf{I})$ correlation, where $\boldsymbol{\sigma}_n$ is the neutron spin, $\mathbf{I}$ is the target spin, and $\mathbf{p}$ is the neutron momentum, which can be observed in the transmission of polarized neutrons through a target with a polarized nuclei. This correlation leads to a difference between the total neutron cross sections [2] $\Delta\sigma_{\not{T}\not{P}}$ for $\boldsymbol{\sigma}_n$ parallel and anti-parallel to $\mathbf{p} \times \mathbf{I}$ and to neutron spin rotation angle [3] $\phi_{\not{T}\not{P}}$ around the axis $\mathbf{p} \times \mathbf{I}$

$$\Delta\sigma_{\not{T}\not{P}} = \frac{4\pi}{p}\mathrm{Im}(f_+ - f_-), \qquad \frac{d\phi_{\not{T}\not{P}}}{dz} = -\frac{2\pi N}{p}\mathrm{Re}(f_+ - f_-). \tag{1}$$

Here, $f_{+,-}$ are the zero-angle scattering amplitudes for neutrons polarized parallel and anti-parallel to the $\mathbf{p} \times \mathbf{I}$ axis, respectively; $z$ is the target length and $N$ is the number of target nuclei per unit volume. The unique feature of these TRIV effects (as well as the similar effects related to TRIV and parity conserving correlation $\boldsymbol{\sigma}_n \cdot (\mathbf{p} \times \mathbf{I}) \cdot (\mathbf{p} \cdot \mathbf{I})$) is *the absence of false TRIV effects due to the final state interactions (FSI)* (see, for example [1] and references therein), because these effect are related to elastic scattering at a zero angle. The general theorem about the absence of FSI for TRIV effects in elastic scattering has been proved first by R. M. Ryndin [4] (see, also [5,6,1,7]). Since this theorem is very important, we give a brief sketch of the proof for the case of the zero angle elastic scattering following [4,1]. It is well known that the T-odd angular correlations in scattering and in a particle decay have no relation to TRIV, i.e. they have non-zero values in any process with strong, electromagnetic, and weak interactions. This is because TRI, unlike parity conservation, does not provide a constrain on amplitudes of any process, but rather relates two different processes: for example, direct and inverse channels of reactions. However, for the case when the process can be described in the

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[1] For example, the QCD $\theta$-term can contribute to the neutron EDM but cannot be observed in $K^0$-meson decays. On the other hand, the CP-odd phase of the Cabibbo-Kobayashi-Maskawa matrix was measured in $K^0$-meson decays, but its contribution to the neutron EDM is extremely small and beyond the reach of the current experimental precision.

first Born approximation, we can relate T-odd correlations to TRIV interactions. Indeed, the unitarity condition for the scattering matrix in terms of the reaction matrix $T$, which is proportional to the scattering amplitude, can be written as [8]

$$T^{\dagger} - T = iTT^{\dagger} \tag{2}$$

The first Born approximation can be used when the right side of the unitarity equation is much smaller than the left side, and results in hermitian $T$-matrix

$$< i|T|f > = < i|T^{*}|f >, \tag{3}$$

which with TRI condition

$$< f|T|i > = < -i|T| - f >^{*} \tag{4}$$

leads to the constrain on the $T$-matrix as

$$< f|T|i > = < -f|T| - i >^{*} . \tag{5}$$

This condition forbids T-odd angular correlations, as is the case with the P-odd correlations when parity is conserved. (Here the minus signs in matrix elements mean the opposite signs for particle spins and momenta in the corresponding states.) For the case of the zero angle elastic scattering, the initial and final states coincide ($i = f$), and when combined with TRI condition (4), result in Eq.(5) without the violation of unitarity (3). Therefore, in this case, FSI cannot mimic T-odd correlations, which originated from TRIV interactions. Therefore, an observation of a non-zero value of TRIV effects in neutron transmission directly indicates TRIV, exactly like in the case of neutron EDM [9].

Moreover, these TRIV effects are enhanced [10] by a factor of about $10^6$ in neutron induced nuclear reactions (the similar enhancement was observed for PV effects related to $(\boldsymbol{\sigma}_n \cdot \mathbf{p})$ correlation in neutron transmission through nuclear targets). Since TRIV and PV effects have similar enhancement factors, it is convenient to consider the ratio $\lambda$ of TRIV to PV effect at the same nuclei and at the same neutron energy as the measure of TRIV effect, because for this ratio, most nuclear structure effects cancel each other out. As a result, one can estimate $\lambda \sim g_T/g_P$, where $g_T$ and $g_P$ are TRIV and PV nucleon nucleon coupling constants. Theoretical predictions for $\lambda$ are varying from $10^{-2}$ to $10^{-10}$ for different models of the CP violation (see, for example, [11] and references therein). Therefore, one can estimate a range of possible values of the TRIV observable and relate a particular mechanism of the CP-violation to their values. These estimates show that these effects could be measured at the new spallation neutron facilities, such as the SNS at the Oak Ridge National Laboratory or the J-SNS at J-PARC in Japan.

Using the results of the recent calculations of PV and TRIV effects in neutron deuteron scattering [12, 13], one can calculate the parameter $\lambda$ for this reaction and compare it to the case of the complex nuclei. Let us consider the ratio of the TRIV difference of total cross sections in Eq.(1) given in [13]

$$P_{\not{T}\not{P}} = \frac{\Delta\sigma_{\not{P}\not{T}}}{2\sigma_{tot}} = \frac{(-0.185\ \mathrm{b})}{2\sigma_{tot}}[\bar{g}_\pi^{(0)} + 0.26\bar{g}_\pi^{(1)} - 0.0012\bar{g}_\eta^{(0)} + 0.0034\bar{g}_\eta^{(1)} \\ - 0.0071\bar{g}_\rho^{(0)} + 0.0035\bar{g}_\rho^{(1)} + 0.0019\bar{g}_\omega^{(0)} - 0.00063\bar{g}_\omega^{(1)}] \tag{6}$$

to the corresponding PV difference [12]

$$P_{\not{P}} = \frac{\Delta\sigma_{\not{P}}}{2\sigma_{tot}} = \frac{(0.395\ \mathrm{b})}{2\sigma_{tot}}[h_\pi^1 + h_\rho^0(0.021) + h_\rho^1(0.0027) \\ + h_\omega^0(0.022) + h_\omega^1(-0.043) + h_\rho^{'1}(-0.012)]. \tag{7}$$

Here, we use one meson exchange model, known as the DDH model for PV nucleon interactions, to calculate both effects; in the above expressions, $\bar{g}$ and $h$ are meson- nucleon TRIV and PV coupling constants, correspondingly (see for details [12,13]). From these expressions, one can see that contributions from the pion exchange are dominant for both TRIV and PV parameters. Then, taking into account only the dominant pion meson contributions, one can estimate $\lambda$ as

$$\lambda = \frac{\Delta\sigma_{\not{T}\not{P}}}{\Delta\sigma_{\not{P}}} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right), \tag{8}$$

which is in a good agreement with the estimate for the complex nuclei [14].

Also, we can relate the obtained parameter $\lambda$ to the existing experimental constrains obtained from EDM measurements, even though the relationships are model dependent. For example, the CP-odd coupling constant $\bar{g}_\pi^{(0)}$ could be related to the value of the neutron EDM $d_n$ generated via a $\pi$-loop in the chiral limit [15]. Then, using the experimental limit [16] on $d_n$, one can estimate $\bar{g}_\pi^{(0)}$ as less than $2.5 \times 10^{-10}$. The constant $\bar{g}_\pi^{(1)}$ can be bounded using the constraint [17] on the $^{199}Hg$ atomic EDM as $\bar{g}_\pi^{(1)} < 0.5 \times 10^{-11}$ [18].

The comparison of the $\lambda$ parameter with the constrains on the coupling constants from the EDM experiments gives us the opportunity to estimate the possible sensitivity of TRIV effects to the value of TRIV nucleon coupling constant, which we call a "*discovery potential*" for neutron scattering experiments [19], since it shows a possible factor for improving the current limits of the EDM experiments. Then, taking the DDH "best value" of $h_\pi^1 \sim 4.6 \cdot 10^{-7}$, nuclear enhancement factors, and assuming that the parameter $\lambda$ could be measured with an accuracy of $10^{-5}$ on the complex nuclei, one can see from Eq.(8) that the existing limits on the TRIV coupling constants could be improved by two orders of magnitude. It should be noted that to obtain Eq.(8), the assumption was made that the $\pi$-meson exchange contribution is dominant for PV effects. However, there is an indication [20] that the PV coupling constant $h_\pi^1$ is much smaller than the "best value" of the DDH. Should it be confirmed by the $\vec{n} + p \to d + \gamma$ experiment, the estimate for the sensitivity of $\lambda$ to the TRIV coupling constant may be increased up to two orders of magnitude, as can be seen from Eqs.(6-8). This might increase the relative values of TRIV effects by two orders of magnitude, and as a consequence, the discovery potential of the TRIV experiments could be about $10^4$.

It should be noted that for the case of TRIV which conserves parity [13, 21] (a correlation $\boldsymbol{\sigma}_n \cdot (\mathbf{p} \times \mathbf{I}) \cdot (\mathbf{p} \cdot \mathbf{I})$) the similar consideration leads to a discovery potential of about $10^2$ - $10^3$.

## 3 Conclusions

To conclude, the TRIV effects in neutron transmission through a nuclei target are very unique TRIV observables being free from FSI, and are of the same quality as the EDM experiments. These TRIV effects are enhanced by about $10^6$ due to the nuclear enhancement factor. In addition to this enhancement, the sensitivity to TRIV interactions in these effects might be structurally enhanced by about $10^2$ if PV $\pi$-nucleon coupling constant is less than the “best value” DDH estimate. Therefore, these types of experiments with high intensity neutron sources have a discovery potential of about $10^2 - 10^4$ for the improvement of the current limits on the TRIV interaction obtained from the EDM experiments.

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