J. W. Shin · S.-I. Ando · C. H. Hyun · S. W. Hong

Parity-violating asymmetry in $\gamma d \rightarrow np$ with a pionless effective theory

Received: date / Accepted: date

Abstract
Nuclear parity violation is studied with polarized neutrons in the photodisintegration of the deuteron at low energies. A pionless effective field theory with di-baryon fields is used for the investigation. Hadronic weak interactions are treated by parity-violating di-baryon-nucleon-nucleon vertices, which have undetermined coupling constants. A parity-violating asymmetry in the process is calculated for the incident photon energy up to 30 MeV. If experimental data for the parity-violating asymmetry become available in the future, we will be able to determine the unknown coupling constants in the parity-violating vertices.

Keywords
Parity violation · Neutron spin asymmetry · $\gamma d \rightarrow np$ · Pionless effective field theory

1 Introduction
Parity-violating (PV) nuclear force has been treated in the framework of one-meson-exchange model, known as the DDH potential [1]. However, recently the PV nuclear force was derived in an effective field theory (EFT) of QCD up to one-loop order by considering two-pion-exchange contributions [2,3]. Meanwhile, another version of EFT, a pionless EFT in which pions are regarded as a heavy degree of freedom and thus integrated out, has been demonstrated efficient for describing both parity-conserving (PC) (see, e.g. [4,5]) and PV nuclear few-body processes at very low energies.

A PV two-nucleon process with a pionless theory was first studied by Savage [6]. Subsequently we have calculated PV observables in $np \rightarrow d\gamma$ at threshold in the pionless EFT [7,8,9]. In our previous works, we obtained a PV Lagrangian employing di-baryon fields which represent two-nucleon $^1S_0$ and $^3S_1$ states. (A similar Lagrangian was obtained independently in [10].) The weak $NN$ interaction is described in terms of the PV di-baryon-nucleon-nucleon ($dNN$) vertices, in which the two-nucleon S-wave states represented by the di-baryon fields make a transition to the P-wave states represented by the two nucleon fields, whereas the interactions are assumed to have unknown weak $dNN$ coupling constants.

J. W. Shin
Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
E-mail: shine8199@hanmail.net

S.-I. Ando
Department of Physics Education, Daegu University, Gyeongsan 712-714, Korea
E-mail: sando@daegu.ac.kr

C. H. Hyun
Department of Physics Education, Daegu University, Gyeongsan 712-714, Korea
E-mail: hch@daegu.ac.kr

S. W. Hong
Department of Physics and Department of Energy Science, Sungkyunkwan University, Suwon 440-746, Korea
E-mail: swhong@skku.ac.kr
Recently we considered the neutron spin polarization $P_n$ along the direction $\hat{y}$ in $\gamma d \rightarrow np$ with the pionless EFT [12], where $n$ refers to a polarized neutron. The neutron spin polarizations along the other directions $\hat{x}$ and $\hat{z}$ vanish with only the PC interactions, but they can be nonvanishing with the PV interactions. Interference terms between PC and PV amplitudes can give non-zero contributions to the neutron spin asymmetries.

Here, we report on our calculation of the PV neutron spin asymmetry in $\gamma d \rightarrow np$ process in terms of the undetermined PV coupling constants in the pionless EFT. We investigate the energy dependence of the asymmetry $P_n$ at a few colatitude angles with the photon energies up to 30 MeV. If measurements of the PV asymmetry can be made in future, we will be able to fix the undetermined PV coupling constants in the theory.

2 PV Lagrangian

A coefficient in an effective Lagrangian, known as a low-energy constant (LEC), is assumed to include contributions from degrees of freedom that are integrated out of a theory. In the pionless theory, because even the pion is integrated out, an interaction is described only by the nucleon-nucleon contact terms with undetermined LECs. In the case of pionless theory with di-baryon fields, we assume that a PV $dNN$ vertex subsumes the $NN$ interactions of the integrated-out degrees of freedom. Introducing dimensionless PV LECs $h_{d}^{\lambda}$, we have a PV $dNN$ Lagrangian for the $\Delta I = 0$ part as [3]

$$\mathcal{L}_{\text{PV}}^{0} = \frac{h_{d}^{0\lambda}}{2\sqrt{2}\rho d_{R_{0}}m_{N}}s_{a}^{1/2}N^{T}\sigma_{2}\tau_{2}\tau_{a}i\frac{\nabla}{2}(\nabla - \nabla)_{i}N + \text{h.c.}$$  \hspace{1cm} (1)

$$+ \frac{h_{d}^{0\lambda}}{2\sqrt{2}\rho d_{\sigma}m_{N}}s_{s}^{1/2}t_{l}^{i}N^{T}\sigma_{2}\tau_{2}\tau_{s}i\frac{\nabla}{2}(\nabla - \nabla)_{i}N + \text{h.c.},$$  \hspace{1cm} (2)

where $s_{a}$ ($\tau_{0}$) and $t_{i}$ ($\rho_{d}$) are di-baryon fields (effective ranges) in the $^{1}S_{0}$ and $^{3}S_{1}$ channel, respectively. Spin-isospin operator $\sigma_{2}\tau_{2}$ with the operator $(i\nabla)$ in Eq. (1) projects a two-nucleon system to $^{3}P_{0}$ state. The PV vertex given in Eq. (1) therefore generates a $^{3}P_{0}$ admixture in the $^{1}S_{0}$ state. Similarly, $\sigma_{2}\tau_{2}$ with the operator $(i\nabla)$ in Eq. (2) is the projection operator for $^{3}P_{1}$ state, and thus the Lagrangian mixes $^{3}P_{1}$ state with the $^{3}S_{1}$ state. For the $\Delta I = 1$ part, we have $^{3}P_{1}$ admixture to the $^{3}S_{1}$ state, so the Lagrangian reads

$$\mathcal{L}_{\text{PV}}^{1} = i\frac{h_{d}^{1\lambda}}{2\sqrt{2}\rho d_{\sigma}m_{N}}s_{s}^{1/2}t_{l}^{i}N^{T}\sigma_{2}\tau_{2}\tau_{s}i\frac{\nabla}{2}(\nabla - \nabla)_{k}N + \text{h.c.}.$$  \hspace{1cm} (3)

3 Neutron spin polarization with PV interaction

In Figure 1 we show the leading-order diagrams for the PV $\gamma d \rightarrow np$ process. From the sum of all the amplitudes, we can obtain the transition amplitudes involving the PV interactions.

For the polarization of the neutron along an axis $\hat{n}$, we introduce the spin-isospin projection operator

$$P_{\pm} = \frac{1}{2}(1 - \tau_{3})\frac{1}{2}(1 \pm \sigma \cdot \hat{n}).$$  \hspace{1cm} (4)

Inserting the projection operator in the spin-isospin summation of the squared amplitude, we obtain

$$S^{-1} \sum_{\text{spin}} |A|^2 = 4(|X_{MS}|^2 + |Y_{MV}|^2 - 2Y_{MV}ReX_{MS})$$

$$+ 2(|X_{MV}|^2 + |Y_{MS}|^2 - 2Y_{MS}ReX_{MV})$$

$$+ 3(1 - (\hat{k} \cdot \hat{p})^2)(|X_{E}|^2 + |Y_{E}|^2 - 2X_{E}Y_{E})$$

1 Conventions for the directions are illustrated in [11].
neutron spin asymmetry 

P mentioned before, it can be nonvanishing in the presence of the PV interactions. We obtain the PV Y and are lengthy, they will be given in a forthcoming article [13]. The terms X are the interference terms of PC and PV amplitudes. Because the explicit expressions of these quantities n and the neutron spin polarized along \( \hat{s} \) where photons along \( \hat{a} \) a paper [13]. Another notable point is that the magnitudes of \( \sigma \) make the result nearly angle independent. More detailed analysis will be reported in our forthcoming paper [13].

Fig. 1 Leading order (\( Q^0 \)) PV diagrams for \( \gamma d \rightarrow np \). Single solid line denotes a nucleon, a wavy line represents a photon, and a double line with a filled circle refers to a dressed di-baryon propagator. A circle with a cross represents a PV \( dNN \) vertex.

\[
\begin{align*}
\mp 2\hat{n} \cdot (\hat{k} \times \hat{p})(X_E - Y_E)ImX_{MV} \\
\mp 2(\hat{k} \cdot \hat{n})Imf(pv1) \\
\mp 2(\hat{p} \cdot \hat{k})(\hat{k} \cdot \hat{n})Imf(pv2) \\
\mp 2(\hat{p} \cdot \hat{n})Imf(pv3) \\
\mp 2(\hat{p} \cdot \hat{k})(\hat{p} \cdot \hat{n})Imf(pv4),
\end{align*}
\]

where \( S \) is a symmetric factor \( S = 2 \). Following the conventions given in [11], we have the incoming photons along \( \hat{k} = (0, 0, 1) \), relative momentum of the nucleons along \( \hat{p} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \), and the neutron spin polarized along \( \hat{n} = \hat{z}'(= \hat{p}) \). \( Imf(pv1), Imf(pv2), Imf(pv3) \) and \( Imf(pv4) \) are the interference terms of PC and PV amplitudes. Because the explicit expressions of these quantities are lengthy, they will be given in a forthcoming article [13]. The terms \( \Delta X_{MV}, X_{MS}, X_E, Y_{MV}, Y_{MS} \) and \( Y_E \) in Eq. (5) are the same as those in Ref. [12].

The neutron spin asymmetry along the \( \hat{z}' \) direction vanishes only with the PC interactions, but, as mentioned before, it can be nonvanishing in the presence of the PV interactions. We obtain the PV neutron spin asymmetry \( P_{z'} \) for \( \gamma d \rightarrow np \) as

\[
P_{z'} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \\
= (-2)[\cos \theta(Imf(pv1) + Imf(pv4))] + \cos^2 \theta Imf(pv2) + Imf(pv3)] \\
/ \left[ 4(|X_{MS}|^2 + |Y_{MV}|^2 - 2Y_{MV}ReX_{MS}) + 2(|X_{MV}|^2 + |Y_{MS}|^2 - 2Y_{MS}ReX_{MV}) \\
+3(1 - \cos^2 \theta)(|X_E|^2 + |Y_E|^2 - 2X_EY_E) \right], \tag{6}
\]

where \( \sigma_\pm (\theta) \) are the differential cross sections with the spin-isospin projection operators \( P_{\pm} \).

Figure 2 shows our results as functions of the photon energy \( E_{\gamma}^{lab} \) at \( \theta = 30^\circ, 60^\circ, 90^\circ \). Because the LECs \( h_d^{11}, h_d^{10}, h_d^{00} \) are not known yet, we cannot determine the numerical values of \( P_{z'} \) at present. Instead, we define \( P_{z'} \equiv a_{01}h_d^{01} + a_{00}h_d^{00} + a_{11}h_d^{11} \), and Fig. 2 shows \( a_{01}, a_{00} \) and \( a_{11} \) as functions of the photon energy. The angle dependence of the curves for \( a_{01} \) and \( a_{11} \) shows similar features; as the angle increases, the dependence on the incoming photon energy becomes small. However, the curves of \( a_{00} \) do not have angle dependence. This is because cancellations between E1 and M1 contributions make the result nearly angle independent. More detailed analysis will be reported in our forthcoming paper [13]. Another notable point is that the magnitudes of \( a_{01}, a_{00}, a_{11} \) are similar in the energy
range considered. In terms of DDH potential, $\rho$- and $\omega$-meson exchange interactions correspond to the vertices represented by the coupling constants $h^0_{\omega}$ and $h^0_{\rho}$, and $\pi$-exchange interaction corresponds to $h^1_{\pi}$. Thus our results on $P_{\gamma}$ in this work seem to suggest that the coefficients of the $\rho$- and $\omega$-meson exchange contributions will be similar to the ones by the $\pi$-exchange in the DDH potential. Therefore the calculation with DDH potential will provide a counter check of the results in the present work.

4 Summary

In this contribution, we have considered the $\gamma d \rightarrow np$ process with the pionless EFT employing the di-baryon fields. We have calculated the PV neutron spin asymmetry $P_{\gamma}$ energy up to 30 MeV. Our results could be useful to fix the PV $dNN$ LECs appearing in the pionless PV Lagrangian.

Acknowledgements J.W. Shin was supported by National Nuclear R & D Program (No. 2011-0006347) and S.W. Hong was supported in part by the WCU program (R31-2008-10029) through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology.

References

1. Desplanques, B., Donoghue, J.F., Holstein, B.R.: Unified treatment of the parity violating nuclear force. Ann. of Phys. 124, 449-495 (1980)
2. Zhu, S.L., Maekawa, C.M., Holstein, B.R., Ransey-Musolf, M.J., van Kolck, U.: Nuclear parity violation in nucleosynthesis energies. Phys. Rev. C 83, 064002 (2011)
3. Shin, J.W., Ando, S.-I., Hyun, C.H., Kubodera, K.: Spin polarization in $\gamma d \rightarrow np$ at low energies with a pionless effective field theory. Phys. Rev. C 83, 064002 (2011)
4. Ando, S.-I., Song, Y.H., Hyun, C.H., Kubodera, K.: Spin polarization in $\gamma d \rightarrow np$ at low energies with a pionless effective field theory. Phys. Rev. C 83, 064002 (2011)
5. Phillips, D.R., Schindler, M.R., Springer, P.: An effective-field-theory analysis of low-energy parity-violation in nucleon-nucleon scattering. Nucl. Phys. A 822, 1-19 (2009)
6. Rustgi, M.L., Zernik, W., Breit, G., Andrews, D.J.: Cross section and polarization in the photodisintegration of the deuteron. Phys. Rev. A 81, 055501 (2010)
7. Phillips, D.R., Schindler, M.R., Springer, P.: An effective-field-theory analysis of low-energy parity-violation in nucleon-nucleon scattering. Nucl. Phys. A 822, 1-19 (2009)
8. Ando, S.-I., Song, Y.H., Hyun, C.H., Kubodera, K.: Spin polarization in $\gamma d \rightarrow np$ at low energies with a pionless effective field theory. Phys. Rev. C 83, 064002 (2011)
9. Shin, J.W., Ando, S., Hyun, C.H.: Parity-violating polarization in $np \rightarrow d\gamma$ with a pionless effective field theory. Phys. Rev. C 81, 055501 (2010)
10. Phillips, D.R., Schindler, M.R., Springer, P.: An effective-field-theory analysis of low-energy parity-violation in nucleon-nucleon scattering. Nucl. Phys. A 822, 1-19 (2009)
11. Rustgi, M.L., Zernik, W., Breit, G., Andrews, D.J.: Cross section and polarization in the photodisintegration of the deuteron. Phys. Rev. A 81, 055501 (2010)
12. Ando, S.-I., Song, Y.H., Hyun, C.H., Kubodera, K.: Spin polarization in $\gamma d \rightarrow np$ at low energies with a pionless effective field theory. Phys. Rev. C 83, 064002 (2011)
13. Shin, J.W., Ando, S.-I., Hyun, C.H., Hong, S.W., in preparation.