

Parity violation in $\vec{\gamma} + d \rightarrow n + p$

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We calculate the asymmetry $A_{\text{cir}} = [\sigma(+)-\sigma(-)]/[\sigma(+)+\sigma(-)]$ for the reaction $\vec{\gamma}d \rightarrow np$, where $\sigma(+)$ [$\sigma(-)$] is the total cross section for right [left] circularly polarized photons. The calculation is carried out for photon energies up to 30 MeV above threshold in the laboratory system. The result for A_{cir} is expressed in terms of the effective parity-violating $NN\pi$, $NN\rho$, and $NN\omega$ coupling constants.

I. INTRODUCTION

Studies of parity-violating effects in nonleptonic nuclear processes are of considerable importance since they give information on the strangeness conserving nonleptonic weak interactions. One of the outstanding puzzles in this field is the experimental value¹ of the photon circular polarization (P_γ) in the $n + p \rightarrow d + \gamma$ reaction, which is about 50 times larger than the predicted one.²

In this paper we report on a calculation of the asymmetry A_{cir} in the total cross section for the reaction $\vec{\gamma} + d \rightarrow n + p$ for circularly polarized incident photons, defined as

$$A_{\text{cir}} = [\sigma(+)-\sigma(-)]/[\sigma(+)+\sigma(-)] ,$$

where $\sigma(+)$ and $\sigma(-)$ are the total cross sections for right-handed and left-handed photons, respectively. As pointed out by Lee,³ for photon energies near threshold, A_{cir} is equal to the photon circular polarization in $n + p \rightarrow d + \gamma$. The latter depends only on the $\Delta I=0$ and $\Delta I=2$ parts of the parity-violating interaction.

The calculation of Lee was carried out for photon energies up to 1 MeV above threshold, using the Hulthén-Sugawara⁴ wave function. The results were given for specific values of the effective parity-violating nucleon-nucleon-meson coupling constants. Here we study A_{cir} for photon energies up to 30 MeV above threshold. For photon energies larger

than 1 MeV the contribution of the $\Delta I=1$ part of the interaction can no longer be neglected. For the strong nucleon-nucleon force we use the realistic potential proposed by Hamada and Johnston⁵ and express our results in terms of the seven parity-violating nucleon-nucleon-meson coupling constants involved in the parity-violating potential arising from the exchange of π^\pm , ρ , and ω mesons.

In Sec. II the parity-violating nucleon-nucleon potential is described. The formula for the asymmetry A_{cir} is given in Sec. III. In the final section we present our results and conclusions.

II. THE PARITY-VIOLATING NUCLEON-NUCLEON POTENTIAL

We shall assume, as usual, that the parity-violating nucleon-nucleon interaction can be represented by a parity-violating potential V_{PV} , arising from the exchange of single pseudoscalar and vector mesons: the π^\pm , $\rho^{\pm,0}$, and ω . In particular, we shall ignore the effects of 2π exchange. This potential is determined by seven effective parity-violating nucleon-nucleon-meson coupling constants, defined by⁶

$$H_\pi^{\text{PV}} = \frac{f_\pi}{\sqrt{2}} \bar{\psi}(\vec{\tau} \times \vec{\phi})_z \psi$$

and

$$H_V^{\text{PV}} = -\bar{\psi} \left[h_\rho^0 \vec{\tau} \cdot \vec{\rho}_\mu + h_\rho^1 \rho_\mu^z + \frac{h_\rho^2}{2\sqrt{6}} (3\tau_z \rho_\mu^z - \vec{\tau} \cdot \vec{\rho}_\mu) \right] \gamma^\mu \gamma_5 \psi - \bar{\psi} (h_\omega^0 \omega_\mu + h_\omega^1 \tau_z \omega_\mu) \gamma^\mu \gamma_5 \psi + \frac{h_\rho^1}{2M} \bar{\psi} \sigma^{\mu\nu} (p' - p)_\nu \gamma_5 (\vec{\tau} \times \vec{\rho}_\mu)_z \psi , \tag{1}$$

where ψ , ϕ , ρ , and ω are the fields of the nucleon, pion, ρ meson, and ω meson, respectively. The τ 's are Pauli matrices. For the γ matrices and the metric we follow the conventions of Ref. 7.

The effective Hamiltonian for the strong nucleon-nucleon-meson couplings is given by

$$H_{\pi}^s = -ig_{\pi}\bar{\psi}\gamma_5\vec{\tau}\cdot\vec{\phi}\psi$$

and

$$H_V^s = g_{\rho}\bar{\psi}\left[\gamma^{\mu} + \frac{\chi_V}{2M}\sigma^{\mu\nu}i(p'-p)_{\nu}\right]\vec{\tau}\cdot\vec{\rho}_{\mu}\psi + g_{\omega}\bar{\psi}\left[\gamma^{\mu} + \frac{\chi_s}{2M}\sigma^{\mu\nu}i(p'-p)_{\nu}\right]\omega_{\mu}\psi. \quad (2)$$

The parity-violating potential resulting from (1) and (2) is⁶

$$V_{PV} = V_{\pi}^{\Delta I=1} + V_{\rho}^{\Delta I=0,1,2} + V_{\omega}^{\Delta I=0,1}, \quad (3)$$

where

$$V_{\pi}^{\Delta I=1} = \frac{g_{\pi}f_{\pi}}{2\sqrt{2}M}i\left[\frac{\vec{\tau}^1\times\vec{\tau}^2}{2}\right]_z(\vec{\sigma}^1+\vec{\sigma}^2)\cdot[\vec{p}^1-\vec{p}^2, f(m_{\pi}r)]_-, \quad (3a)$$

$$V_{\rho}^{\Delta I=0,1,2} = -\frac{g_{\rho}}{2M}\left[\left[h_{\rho}^0\vec{\tau}^1\cdot\vec{\tau}^2 + h_{\rho}^1\frac{\tau_z^1+\tau_z^2}{2} + h_{\rho}^2\frac{3\tau_z^1\tau_z^2-\vec{\tau}^1\cdot\vec{\tau}^2}{2\sqrt{6}}\right]\right. \\ \left.\times((\vec{\sigma}^1-\vec{\sigma}^2)\cdot\{\vec{p}^1-\vec{p}^2, f(m_{\rho}r)\})_+ + (1+\chi_V)i\vec{\sigma}^1\times\vec{\sigma}^2\cdot[\vec{p}^1-\vec{p}^2, f(m_{\rho}r)]_-\right. \\ \left.- h_{\rho}^1\frac{\tau_z^1-\tau_z^2}{2}(\vec{\sigma}^1+\vec{\sigma}^2)\cdot\{\vec{p}^1-\vec{p}^2, f(m_{\rho}r)\}_+ \right. \\ \left. + h_{\rho}^1i\frac{(\vec{\tau}^1\times\vec{\tau}^2)_z}{2}(\vec{\sigma}^1+\vec{\sigma}^2)\cdot[\vec{p}^1-\vec{p}^2, f(m_{\rho}r)]_-\right], \quad (3b)$$

and

$$V_{\omega}^{\Delta I=0,1} = -\frac{g_{\omega}}{2M}\left[\left[h_{\omega}^0 + h_{\omega}^1\frac{\tau_z^1+\tau_z^2}{2}\right]((\vec{\sigma}^1-\vec{\sigma}^2)\cdot\{\vec{p}^1-\vec{p}^2, f(m_{\omega}r)\})_+ \right. \\ \left. + (1+\chi_s)i\vec{\sigma}^1\times\vec{\sigma}^2\cdot[\vec{p}^1-\vec{p}^2, f(m_{\omega}r)]_-\right. \\ \left. + h_{\omega}^1\frac{\tau_z^1-\tau_z^2}{2}(\vec{\sigma}^1+\vec{\sigma}^2)\cdot\{\vec{p}^1-\vec{p}^2, f(m_{\omega}r)\}_+\right], \quad (3c)$$

where $f(m_i r) = e^{-m_i r}(4\pi r)$.

III. THE ASYMMETRY A_{cir} IN THE CROSS SECTION FOR THE PHOTODISINTEGRATION OF DEUTERON

In calculating the cross section for deuteron photodisintegration we shall include only the dipole transitions. The contributions from higher multipole transitions are negligible for photon energies we consider.^{4,8}

In the absence of parity violation there are four possible dipole transitions: an $M1$ transition to the $^1S_0(I=1)$ final state and $E1$ transitions to the $^3P_0(I=1)$, $^3P_1(I=1)$, and $(^3P_2+^3F_2)(I=1)$ states. These are shown in Figs. 1(a) and 1(b) by double solid lines. Owing to the presence of the parity-violating force (3), states of opposite parity [in Figs. 1(a), and 1(b) connected by dotted lines with the original states] are admixed into the 1S_0 , 3S_1 and 3P_0 , 3P_1 , $^3P_2+^3F_2$ states, allowing for further electromagnetic transitions [shown on Figs. 1(a) and 1(b) by single solid lines]. Only those admixed states are indicated which can be connected with the initial state by a dipole transition.

The asymmetry

$$A_{\text{cir}} \equiv \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}, \quad (4)$$

is given by

$$A_{\text{cir}} = \frac{2\text{Re}\sum_{f_z i_z} [(M1)_{f_z i_z}^*(\tilde{E}1)_{f_z i_z} + (E1)_{f_z i_z}^*(\tilde{M}1)_{f_z i_z}]}{\sum_{f_z i_z} [|(M1)_{f_z i_z}|^2 + |(E1)_{f_z i_z}|^2]} = \frac{2\text{Re}(\hat{M}_1 + \hat{E}_1 + \hat{E}_2 + \hat{E}_3)}{M_1 + E_1 + E_2 + E_3}, \quad (5)$$

where

$$M_1 = \left[\frac{1+\mu_V}{M} \right]^2 \left| \int dr U^*(^1S_0) U_d(^3S_1) \right|^2, \quad (5a)$$

$$E_1 = \frac{1}{27} \left| \int r dr U^*(^3p_0) [U_d(^3S_1) - \sqrt{2} U_d(^3D_1)] \right|^2, \quad (5b)$$

$$E_2 = \frac{1}{9} \left| \int r dr U^*(^3p_1) \left[U_d(^3S_1) + \frac{1}{\sqrt{2}} U_d(^3D_1) \right] \right|^2, \quad (5c)$$

$$E_3 = \frac{5}{27} \left| \int r dr \left\{ U^*(^3p_2) \left[U_d(^3S_1) - \frac{1}{5\sqrt{2}} U_d(^3D_1) \right] + \frac{3\sqrt{3}}{5} U^*(^3F_2) U_d(^3D_1) \right\} \right|^2, \quad (5d)$$

$$\hat{M}_1 = \left[\frac{1+\mu_V}{M} \int dr U^*(^1S_0) U_d(^3S_1) \right]^* \left[\frac{i}{3} \int r dr \tilde{U}^*(^3p_0) [U_d(^3S_1) - \sqrt{2} U_d(^3D_1)] - \frac{i}{\sqrt{3}} \int r dr U^*(^1S_0) \tilde{U}_d(^1p_1) \right], \quad (5e)$$

$$\hat{E}_1 = \left[\frac{i}{9} \int r dr U^*(^3p_0) [U_d(^3S_1) - \sqrt{2} U_d(^3D_1)] \right]^* \times \left[\frac{1+\mu_V}{M} \int dr \left[\tilde{U}^*(^1S_0) U_d(^3S_1) - \frac{1}{\sqrt{3}} U^*(^3p_0) \tilde{U}_d(^1p_1) \right] - \frac{\sqrt{2}\mu_s}{\sqrt{3}M} \int dr U^*(^3p_0) \tilde{U}_d(^3p_1) \right], \quad (5f)$$

$$\hat{E}_2 = \left[\frac{i}{3\sqrt{6}} \int r dr U^*(^3p_1) \left[U_d(^3S_1) + \frac{1}{\sqrt{2}} U_d(^3D_1) \right] \right]^* \times \left[\frac{\sqrt{2}(1+\mu_V)}{M} \int dr U^*(^3p_1) \tilde{U}_d(^1p_1) + \frac{2+\mu_s}{M} \int dr U^*(^3p_1) \tilde{U}_d(^3p_1) \right], \quad (5g)$$

and

$$\hat{E}_3 = \left\{ -\frac{5i}{9\sqrt{3}} \int r dr \left[U^*(^3p_2) \left[U_d(^3S_1) - \frac{1}{5\sqrt{2}} U_d(^3D_1) \right] + \frac{3\sqrt{3}}{5} U^*(^3F_2) U_d(^3D_1) \right] \right\}^* \times \left[\frac{1+\mu_V}{M} \int dr \left[U^*(^3p_2) \tilde{U}_d(^1p_1) - \frac{\sqrt{3}}{\sqrt{5}} \tilde{U}^*(^1D_2) U_d(^3D_1) \right] - \frac{\mu_s}{\sqrt{2}M} \int dr \left[U^*(^3p_2) \tilde{U}_d(^3p_1) + \frac{3}{\sqrt{5}} \tilde{U}^*(^3D_2) U_d(^3D_1) \right] \right]. \quad (5h)$$

Here i_z and f_z are the third components of the spin of the initial and final nucleon systems, respectively. In Eq. (5) the wave functions U and U_d represent the np scattering state and the deuteron state, respectively. They are eigenstates of the Hamada-Johnston potential.⁵ The states admixed by the parity-violating potential are denoted by \tilde{U} and \tilde{U}_d . They satisfy the Schrödinger equations given in the Appendix.

IV. RESULTS AND CONCLUSIONS

Assuming for the tensor-type strong couplings the values $\chi_V = \mu_p - \mu_n = 3.71$ and $\chi_S = \mu_p + \mu_n$

$= -0.12$ and taking $m_p = m_n = 775$ MeV, we obtain the following result for the asymmetry A_{cir} as a function of the incident photon energy ω_L :

$$A_{\text{cir}}(\omega_L) = \alpha(\omega_L) g_\rho h_\rho^0 + \alpha'(\omega_L) g_\omega h_\omega^0 + \beta(\omega_L) g_\rho h_\rho^2 + \gamma(\omega_L) (g_\rho h_\rho^1 - g_\omega h_\omega^1) + \gamma'(\omega_L) g_\rho h_\rho^{1'} + \delta(\omega_L) g_\pi f_\pi. \quad (6)$$

Thus A_{cir} is sensitive to six independent combinations of the seven constants. This is due to the fact that there is no contribution from the spin-changing parts of the $\Delta I = 1$ parity-violating potential, and

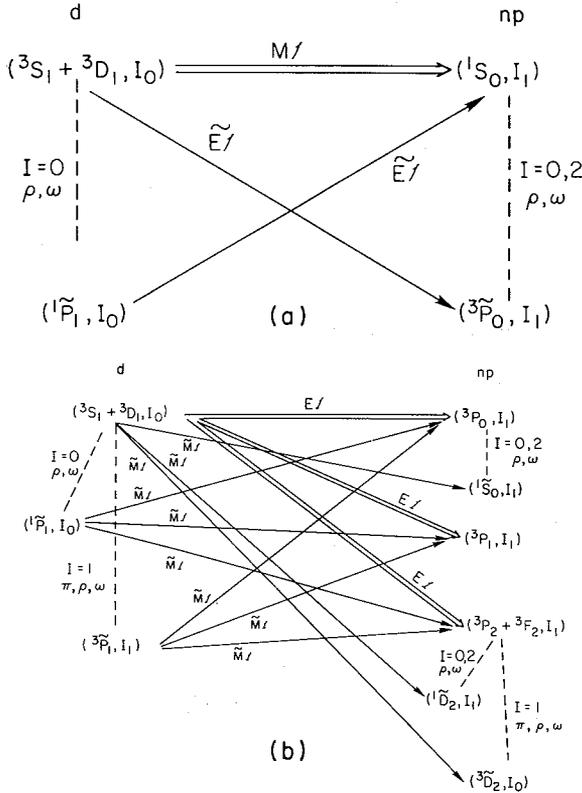


FIG. 1. (a) Electromagnetic transitions in $\bar{\gamma}d \rightarrow np$ with $M1$ -type regular transitions. (b) Electromagnetic transitions in $\bar{\gamma}d \rightarrow np$ with $E1$ -type regular transitions.

that the contributions of the $g_\rho h_\rho^1$ term in Eq. (3b) and of the $g_\omega h_\omega^1$ term in Eq. (3c) are (in view of $m_\rho \cong m_\omega$) equal and of opposite sign.

We shall discuss the values of the functions $\alpha, \alpha', \dots, \delta$ separately for the regions $\omega_L - E_B \leq 1$ MeV and $\omega_L - E_B \geq 1$ MeV. For photon energies $\omega_L - E_B \geq 1$ MeV the dominant regular transition is $E1$, while near threshold the regular $M1$ transition dominates.

A. $0 \leq \omega_L - E_B \leq 1$ MeV

In Fig. 2 we show the calculated values of the integrated cross sections for $M1$ and $E1$ transitions (plotted on the right-side vertical axis). The total cross section is obtained by adding the $M1$ and $E1$ parts. The values of α, α', β , and δ are also given in this figure (plotted on the left-side vertical axis). The values of γ and γ' are too small to be seen in this figure. The following features are to be noted. For comparable coupling strength the $\Delta I = 1$ contribution is suppressed in this energy region, and consequently A_{cir} is dominated by the $\Delta I = 0$ (involving α and α') and $\Delta I = 2$ (proportional to β) parts.

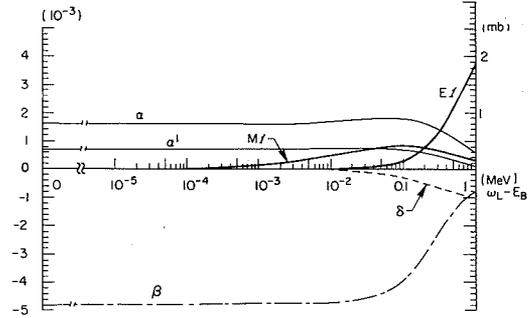


FIG. 2. The quantities α, α', β , and δ as functions of $\omega_L - E_B$ for $0 \leq \omega_L - E_B \leq 1$ MeV (plotted on the left-side vertical axis in units of 10^{-3}). Also shown are the integrated $\gamma d \rightarrow np$ cross sections for $M1$ and $E1$ transitions as functions of $\omega_L - E_B$ (plotted on the right-side vertical axis in units of mb).

For photon energies $0 < \omega_L - E_B < 0.01$ MeV the quantities α, α' , and β are almost constants, and the asymmetry is given to a good approximation by

$$A_{\text{cir}} \cong (1.60g_\rho h_\rho^0 + 0.72g_\omega h_\omega^0 - 4.74g_\rho h_\rho^2) \times 10^{-3}. \quad (7)$$

The same expression holds for the photon circular polarization in the capture of thermal neutrons by protons, $n + p \rightarrow d + \gamma$. Our numerical result (7) is consistent with previous calculations^{2,9} of P_γ . Thus, as emphasized by Lee,³ a measurement with low-energy photons provides a test of Lobashov's experimental result.¹

A_{cir} calculated with our α, α' , and β , with the coupling constants used in Ref. 3, shows the same behavior as Lee's calculation,³ which was carried out up to 1 MeV above threshold, employing the Hulthén-Sugawara⁴ wave function.

B. $1 \leq \omega_L - E_B \leq 30$ MeV

In Fig. 3 we give the integrated cross section for $E1$ and $M1$ transitions and the values for $\alpha, \alpha', \dots, \delta$. An important feature of our result is that in the energy region $1 \leq \omega_L - E_B \leq 30$ MeV the $\Delta I = 1$ component in A_{cir} can no longer be neglected. In fact, the weak pion-exchange term (proportional to δ) becomes more and more dominant (for comparable couplings) as the photon energy increases. To see this more precisely, in Table I we give $\alpha, \alpha', \dots, \delta$ for several values of $\omega_L - E_B$.

To estimate A_{cir} , we need information on the strength of the parity-violating couplings

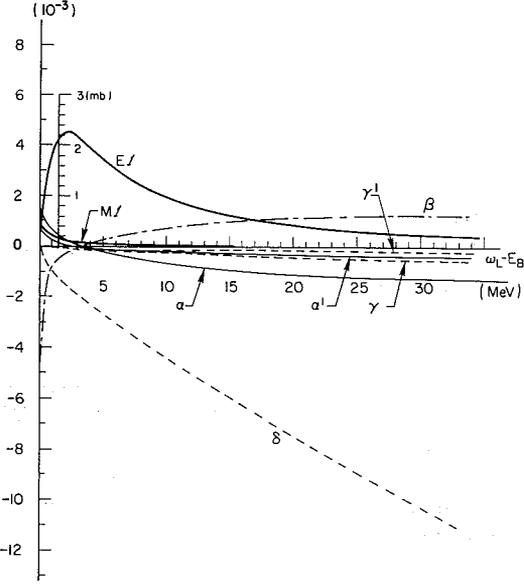


FIG. 3. The quantities α , α' , β , γ , γ' , and δ for $1 \leq \omega_L - E_B \leq 30$ MeV. See also figure caption for Fig. 2.

$h_\rho^0, \dots, h_\rho^{1'}$ and f_π , as well as on the strong coupling constants g_ρ , g_ω , and g_π . For g_ρ we take $g_\rho^2/4\pi = 0.50$. This value follows, assuming vector-meson dominance for the $NN\rho$ vertex, from the $\rho \rightarrow e^+e^-$ decay with $\Gamma_{\rho \rightarrow e^+e^-} = 6.8 \pm 1.0$ keV.¹⁰ For g_ω we shall take the value $g_\omega^2/4\pi = 4.5$, obtained using SU(3) symmetry with ideal ω - ϕ mixing. The pion-nucleon coupling constant is $g_\pi^2/4\pi = 14.4$.¹¹ As mentioned earlier, the magnetic coupling χ_V is taken to be $\chi_V = \mu_p - \mu_n = 3.71$, in accordance with the vector-dominance assumption. The value $\chi_S = \mu_p + \mu_n = -0.12$ used follows again from SU(3) symmetry with ideal ω - ϕ mixing.

For the parity-violating constant h_ρ^0, \dots, f_π no firm prediction can be made at present, in view of the uncertainties involved in treating the effects of the strong interactions. To estimate A_{cir} , we shall take the recommended values of Desplanques, Donoghue, and Holstein^{6,12}:

TABLE I. Values of $\alpha, \alpha', \dots, \delta$ (in units of 10^{-3}) as functions of $\omega_L - E_B$.

	1 MeV	10 MeV	20 MeV	30 MeV
α	0.600	-0.701	-1.098	-1.273
α'	0.197	-0.220	-0.343	-0.395
β	-0.704	0.674	1.051	1.195
γ	-0.022	-0.100	-0.186	-0.277
γ'	0.046	0.215	0.407	0.615
δ	-1.074	-4.392	-7.484	-10.294

$$\begin{aligned} h_\rho^0 &= -1.14 \times 10^{-6}, & h_\omega^0 &= -0.19 \times 10^{-6}, \\ h_\rho^2 &= -0.95 \times 10^{-6}, & h_\rho^1 &= -0.02 \times 10^{-6}, \\ h_\omega^1 &= -0.11 \times 10^{-6}, & h_\rho^{1'} &= -0.07 \times 10^{-6}, \end{aligned} \quad (8)$$

and

$$f_\pi = 0.46 \times 10^{-6}.$$

With the strong coupling constants we use, these give

$$\begin{aligned} g_\rho h_\rho^0 &= -2.86 \times 10^{-6}, \\ g_\omega h_\omega^0 &= -1.43 \times 10^{-6}, \\ g_\rho h_\rho^2 &= -2.38 \times 10^{-6}, \\ g_\rho h_\rho^1 - g_\omega h_\omega^1 &= 0.78 \times 10^{-6}, \\ g_\rho h_\rho^{1'} &= -0.18 \times 10^{-6}, \end{aligned} \quad (9)$$

and

$$g_\pi f_\pi = 6.19 \times 10^{-6}.$$

The parity-violating vector-meson and pion-exchange contributions to A_{cir} are given in Table II. As seen, the weak pion-exchange contribution dominates even at photon energies as low as $\omega_L - E_B \cong 1$ MeV. This is in part due to the fact that for $1 \leq \omega_L - E_B \leq 30$ MeV there is a cancellation among the contributions of the vector-meson terms. In addition, for $10 \leq \omega_L - E_B \leq 30$ MeV the magnitude of the function δ is larger than the magnitudes of the other functions $\alpha, \alpha', \dots, \gamma'$.

Recently calculations of the parity-violating asymmetry in the differential cross section in the electrodisintegration of the deuteron by longitudinally polarized electrons were reported.^{13,14} At the $q^2 \rightarrow 0$ limit this asymmetry is related to the asymmetry A_{cir} in $\vec{\gamma}+d \rightarrow n+p$ and when the energy is near the threshold of disintegration, both asymmetries are related to the P_γ in $n+p \rightarrow d+\gamma$. Like us, Hwang, Henley, and Miller¹³ find that as the energy of the incident electron increases the weak

TABLE II. A_{cir} as a function of $\omega_L - E_B$, calculated with $g_\rho h_\rho^{1'} = -0.18 \times 10^{-6}$ (Ref. 12) and the recommended values of Desplanques, Donoghue, and Holstein (Ref. 6) for the remaining coupling constants. A_{cir}^V and A_{cir}^π denote the vector-meson and pion contributions, respectively. $A_{\text{cir}} = A_{\text{cir}}^V + A_{\text{cir}}^\pi$. All values are quoted in units of 10^{-8} .

	1 MeV	10 MeV	20 MeV	30 MeV
A_{cir}^V	-0.04	0.06	0.09	0.10
A_{cir}^π	-0.66	-2.72	-4.63	-6.37
A_{cir}	-0.70	-2.66	-4.54	-6.27

pion-exchange term becomes more and more dominant. However as the kinematics of electrodisintegration and photodisintegration are different, a precise comparison of our results with theirs is difficult.

It is also interesting to give an upper limit for A_{cir} implied by the bounds on the parity-violating coupling constants deduced from the existing experimental data. The bound

$$-4.1 \times 10^{-6} < f_\pi < 2.9 \times 10^{-6}, \quad 90\% \text{ C.L.} \quad (10)$$

obtained by Bowman, Gibson, Herczeg, and Henley¹⁵ (from their fit A in which data on parity violation in heavy nuclei and the experimental result on the photon circular polarization in $np \rightarrow d\gamma$ are excluded) implies

$$\begin{aligned} |A_{\text{cir}}| &\leq 0.6 \times 10^{-7} \quad \text{for } \omega_L - E_B = 1 \text{ MeV}, \\ |A_{\text{cir}}| &\leq 2.4 \times 10^{-7} \quad \text{for } \omega_L - E_B = 10 \text{ MeV}, \\ |A_{\text{cir}}| &\leq 5.7 \times 10^{-7} \quad \text{for } \omega_L - E_B = 30 \text{ MeV}, \end{aligned} \quad (11)$$

provided that the weak vector-meson couplings are not much larger than the limits (10) on f_π . To have A_{cir}^V comparable to A_{cir}^π would require $h_{\rho,\omega}/f_\pi \cong 3$ for $\omega_L - E_B \cong 1$ MeV, $h_{\rho,\omega}/f_\pi \cong 12$ for $\omega_L - E_B \cong 10$ MeV, and $h_{\rho,\omega}/f_\pi \cong 15$ for $\omega_L - E_B \cong 30$ MeV.

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APPENDIX

In this appendix we give the equations for the parity-violating scattering and deuteron states. The scattering states $\tilde{U}(^1S_0)$, $\tilde{U}(^3P_0)$, $\tilde{U}(^1D_2)$, and $\tilde{U}(^3D_2)$ satisfy

$$\begin{aligned} (D_0 + V_s)\tilde{U}(^1S_0) = & 8i \left\{ g_\rho \left[h_\rho^0 - \frac{2}{\sqrt{6}} h_\rho^2 \right] \left[\chi_V \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right. \\ & \left. + g_\omega h_\omega^0 \left[\chi_S \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U(^3P_0), \end{aligned} \quad (A1)$$

$$\begin{aligned} (D_1 + V_s)\tilde{U}(^3P_0) = & -8i \left\{ g_\rho \left[h_\rho^0 - \frac{2}{\sqrt{6}} h_\rho^2 \right] \left[(2 + \chi_V) \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[\frac{1}{\chi} - \frac{\vec{\partial}}{\partial\chi} \right] \right] \right. \\ & \left. + g_\omega h_\omega^0 \left[(2 + \chi_S) \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[\frac{1}{\chi} - \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U(^1S_0), \end{aligned} \quad (A2)$$

$$\begin{aligned} (D_2 + V_s)\tilde{U}(^1D_2) = & -8 \frac{\sqrt{2}}{\sqrt{5}} i \left\{ g_\rho \left[h_\rho^0 - \frac{2}{\sqrt{6}} h_\rho^2 \right] \left[\chi_V \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[-\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right. \\ & \left. + g_\omega h_\omega^0 \left[\chi_S \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[-\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U(^3P_2) \\ & + 8 \frac{\sqrt{3}}{\sqrt{5}} i \left\{ g_\rho \left[h_\rho^0 - \frac{2}{\sqrt{6}} h_\rho^2 \right] \left[\chi_V \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[\frac{3}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right. \\ & \left. + g_\omega h_\omega^0 \left[\chi_S \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[\frac{3}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U(^3F_2), \end{aligned} \quad (A3)$$

and

$$\begin{aligned}
(D_2 + V_s)\tilde{U}(^3D_2) = & -4 \frac{\sqrt{6}}{\sqrt{5}} i g_\pi f_\pi \tilde{V}_\pi \left[U(^3P_2) + \frac{\sqrt{2}}{\sqrt{3}} U(^3F_2) \right] + 8 \frac{\sqrt{3}}{\sqrt{5}} i g_\rho h_\rho^1 \tilde{V}_{B\rho} \left[U(^3P_2) + \frac{\sqrt{2}}{\sqrt{3}} U(^3F_2) \right] \\
& + 8 \frac{\sqrt{3}}{\sqrt{5}} i g_\rho h_\rho^1 \left\{ \left[\tilde{V}_{B\rho} - 2\tilde{V}_{E\rho} \left[-\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U(^3P_2) + \frac{\sqrt{2}}{\sqrt{3}} \left[\tilde{V}_{B\rho} - 2\tilde{V}_{E\rho} \left[\frac{3}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U(^3F_2) \right\} \\
& - 8 \frac{\sqrt{3}}{\sqrt{5}} i g_\omega h_\omega^1 \left\{ \left[\tilde{V}_{B\omega} - 2\tilde{V}_{E\omega} \left[-\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U(^3P_2) \right. \\
& \quad \left. + \frac{\sqrt{2}}{\sqrt{3}} \left[\tilde{V}_{B\omega} - 2\tilde{V}_{E\omega} \left[\frac{3}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U(^3F_2) \right\}. \tag{A4}
\end{aligned}$$

The equations for the deuteron state $\tilde{U}_d(^1P_1)$ and $\tilde{U}_d(^3P_1)$ are

$$\begin{aligned}
(D_1 + V_s)\tilde{U}_d(^1P_1) = & 8\sqrt{3}i \left\{ g_\rho h_\rho^0 \left[\chi_V \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[-\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right. \\
& \left. - \frac{g_\omega h_\omega^0}{3} \left[\chi_S \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[-\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U_d(^3S_1) \\
& - 8\sqrt{6}i \left\{ g_\rho h_\rho^0 \left[\chi_V \tilde{V}_{B\rho} + 2\tilde{V}_{E\rho} \left[\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] - \frac{g_\omega h_\omega^0}{3} \left[\chi_S \tilde{V}_{B\omega} + 2\tilde{V}_{E\omega} \left[\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] \right\} U_d(^3D_1) \tag{A5}
\end{aligned}$$

and

$$\begin{aligned}
(D_1 + V_s)\tilde{U}_d(^3P_1) = & \frac{8i}{\sqrt{3}} g_\pi f_\pi \tilde{V}_\pi \left[U_d(^3S_1) + \frac{1}{\sqrt{2}} U_d(^3D_1) \right] - 8 \frac{\sqrt{2}}{\sqrt{3}} i g_\rho h_\rho^1 \tilde{V}_{B\rho} \left[U_d(^3S_1) + \frac{1}{\sqrt{2}} U_d(^3D_1) \right] \\
& + 8 \frac{\sqrt{2}}{\sqrt{3}} i g_\rho h_\rho^1 \left\{ \left[\tilde{V}_{B\rho} - 2\tilde{V}_{E\rho} \left[-\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U_d(^3S_1) + \frac{1}{\sqrt{2}} \left[\tilde{V}_{B\rho} - 2\tilde{V}_{E\rho} \left[\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U_d(^3D_1) \right\} \\
& - 8 \frac{\sqrt{2}}{\sqrt{3}} i g_\omega h_\omega^1 \left\{ \left[\tilde{V}_{B\omega} - 2\tilde{V}_{E\omega} \left[-\frac{1}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U_d(^3S_1) \right. \\
& \quad \left. + \frac{1}{\sqrt{2}} \left[\tilde{V}_{B\omega} - 2\tilde{V}_{E\omega} \left[\frac{2}{\chi} + \frac{\vec{\partial}}{\partial\chi} \right] \right] U_d(^3D_1) \right\}. \tag{A6}
\end{aligned}$$

In Eqs. (A1)–(A6)

$$\tilde{V}_{Bi} = \frac{m_\pi^2}{16\pi\chi^2} (1 + \alpha_i\chi) e^{-\alpha_i\chi} \quad (i = \rho, \omega),$$

$$\tilde{V}_{Ei} = \frac{m_\pi^2}{16\pi\chi} e^{-\alpha_i\chi} \quad (i = \rho, \omega), \quad \tilde{V}_\pi = \frac{m_\pi^2}{16\pi\chi^2} (1 + \chi) e^{-\chi},$$

where $\alpha_i = m_i/m_\pi$ and $\chi = m_\pi r$. V_s denotes the strong-interaction potential and $D_l = d^2/dr^2 + k^2 - l(l+1)/r^2$ ($l \equiv$ orbital angular momentum.)

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