Two-body effects in triton photodisintegration sum rules

Reeta Vyas and M. L. Rustgi
Physics Department, State University of New York at Buffalo, Amherst, New York 14260
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The effect of two-body charge density due to one-pion exchange on the triton photodisintegration sum rules has been investigated. The inclusion of the two-body charge density modifies the Siegert form of the dipole operator, resulting in a change in the enhancement factor and the bremsstrahlung-weighted cross section. The expressions obtained for the integrated and the bremsstrahlung-weighted cross sections are quite general, as all the two- and three-body intermediate states have been included. The numerical work is carried out employing a variational wave function and two-body interactions having only central and tensor components. It is found that the change in the enhancement factor is quite significant ($\sim 16\%$) for the pseudoscalar coupling and only about 2% with the pseudovector coupling, and can provide information about the nuclear interaction and theories of meson exchange contributions to the triton photodisintegration sum rules.

It is a well-known fact that the photonuclear sum rules play a very important role in understanding the electromagnetic interaction with the nuclei. The main advantage of the sum rule calculations is that for conventional dipole interactions one can avoid using the complicated excited states. By knowing the ground-state wave function and the nuclear potential one can calculate the first few moments of the photodisintegration cross sections.

It is known that since the three-nucleon system is sensitive to the nuclear forces, its study can add to our knowledge of the interaction between the nucleons. The triton photoeffect can further provide a means for testing the theories of meson exchange contributions to the electromagnetic currents. It has been reported earlier[1,2] that the triton sum rules are quite sensitive to the ground-state wave functions used. The introduction of hard core, which is effectively equivalent to suppressing the two-body wave functions at short distances, changes the bremsstrahlung-weighted cross section and enhancement factor considerably.[1,2] Without meson exchange effects the triton photonuclear sum rules have been calculated by various authors.[1–6] They have used different formalisms and different forms of potentials, including the realistic ones.[4,5]

Over the past few years a significant contribution of the meson exchange and isobar configuration to the enhancement factor for the ^{2}H(γ,n)p reaction has been reported.[7–10] This strongly advocates the need of sum-rule calculations for the triton including the meson exchange effects, which can provide a sensitive way to examine the two-body effects.

The main object of this work is to study the two-body charge density effects due to one-pion exchange on the triton sum rules. In the present derivation we have followed the formalism outlined by Cambi, Mosconi, and Ricci[8] (CMR) to obtain the enhancement factor and the bremsstrahlung-weighted cross sections. To our knowledge this is the first calculation of the enhancement factor and bremsstrahlung-weighted cross section which includes the two-body effects.

It is convenient to use the following coordinate system, which simplifies the kinetic energy term:

$$\vec{y}_i=(\vec{R}_j-\vec{R}_k)\ ,\qquad \vec{x}_i=(1/\sqrt{3})(\vec{R}_j+\vec{R}_k-2\vec{R}_i)\ . \tag{1}$$

Here the natural system of units, $\hbar=1$ and $c=1$, is used. R_i represents the position of the ith nucleon. The three nucleons are labeled (i,j,k), where we assume a cyclic permutation. The transformation relations between $\vec{x}$ and $\vec{y}$ vectors in the above coordinate system are

$$\vec{x}_i=a_{ij}\vec{x}_j-b_{ij}\vec{y}_j\ ,\qquad \vec{y}_i=a_{ij}\vec{y}_j+b_{ij}\vec{x}_j\ , \tag{2}$$

where

$$a_{ij}=-(\tfrac{1}{2})\ \text{for}\ i\neq j\ ,\qquad b_{ij}=-\epsilon_{ijk}\frac{\sqrt{3}}{2}\ \text{for}\ i\neq j\neq k\ . \tag{3}$$

The two-body modification $D[2]$ to the Siegert form of the electric dipole operator for the three-body system can be written as

$$\vec{D}[2]=\vec{D}^{12}_{N\bar{N}}+\vec{D}^{23}_{N\bar{N}}+\vec{D}^{31}_{N\bar{N}}\ . \tag{4}$$

According to CMR, the dipole operator $D^{ij}_{N\bar{N}}$ can be written as

$$\vec{D}^{ij}_{N\bar{N}}=-f^2(m/2M)\phi(y_k)\{[\mu_s\vec{\tau}_i\cdot\vec{\tau}_j+\mu_v(\vec{\tau}_i+\vec{\tau}_j)_z/2]\hat{y}_k\times(\vec{\sigma}_i\times\vec{\sigma}_j)-\mu_v(\vec{\tau}_i-\vec{\tau}_j)/2[\vec{\sigma}_i(\vec{\sigma}_j\cdot\hat{y}_k)+\vec{\sigma}_j(\vec{\sigma}_i\cdot\hat{y}_k)]\}\ , \tag{5}$$

where $f^2=0.081$, and for pseudoscalar coupling $\mu_s=\mu_p+\mu_n$, $\mu_v=\mu_p-\mu_n$, and for pseudovector coupling $\mu_s=\mu_v=(\frac{1}{2})$. M is the nucleon mass, m is the pion mass, and $\vec{\tau}_i$ and $\vec{\sigma}_i$ are the isospin and spin operators for the ith nucleon, respectively. The mathematical form of $\phi(y_k)$ is given in Ref. 8. The retardation terms have been ignored in (5) because their contribution is known to be negligible.[8,9] The nonlocal terms are not included.

Following the pioneering work of Levinger and Bethe,[11] the enhancement factor k for the triton photodisintegration can be written as

$$1+k=(2M/3)\sum_m \langle \delta,m \mid [D_z,[H,D_z]] \mid \delta,m \rangle \ , \tag{6}$$

where $\mid \delta,m \rangle$ is the triton ground state wave function, D_z is the component of the dipole operator in z direction, and H is the Hamiltonian of the system.

Because of the existence of the noncentral nuclear forces, only the total angular momentum $\vec{J}_i$, its projection operator J_{iz}, and parity π are conserved. For a completely charge independent Hamiltonian the isotopic spin $\vec{\tau}_i$ and its projection operator $\vec{\tau}_{iz}$ are also good quantum numbers. However, the difference in proton and neutron masses and magnetic moments imply that total isotopic spin is only an approximation. The formation of stable nuclei, ^{3}H and ^{3}He of roughly equal binding energy, also supports this approximation and suggests that the ground state isotopic spin of these nuclei is $(\frac{1}{2})$ $(\tau_{iz}=\frac{1}{2}$ for ^{3}He and $\tau_{iz}=-\frac{1}{2}$ for ^{3}H). If ζ_1 and ζ_2 are the two orthonormal isotopic states for the three-nucleon system, where ζ_1 is antisymmetric and ζ_2 is symmetric under the interchange of nucleons 1 and 2, then the general form of the ground-state wave function for ^{3}H can be written as

$$\mid \delta,m \rangle = \Psi_{\zeta_1}\zeta_1 - \Psi_{\zeta_2}\zeta_2 \ , \tag{7}$$

where Ψ_{ζ_1} and Ψ_{ζ_2} are the space and spin dependent functions, Ψ_{ζ_1} being symmetric, and Ψ_{ζ_2} being antisymmetric under the interchange of the nucleons 1 and 2. Ψ_{ζ_1} and Ψ_{ζ_2} can be expanded in terms of the L-S or J-J basis states. In the L-S basis, these states are defined to be an eigenstate of the operators $(\vec{x}_3)^2$, $(\vec{y}_3)^2$, $(\vec{l}_i)^2$, $(\vec{L}_i)^2$, $(\vec{\mathscr{L}}_i)^2=(\vec{l}_i+\vec{L}_i)^2$, $(\vec{S}_i^{12})^2=(\vec{s}_1+\vec{s}_2)^2$, $(\vec{S}_i)^2=(\vec{S}_i^{12}+\vec{s}_3)^2$, $(\vec{J}_i)=(\vec{\mathscr{L}}_i+\vec{S}_i)^2$, and J_{iz}. Here, $\vec{l}_i$ is the relative angular momentum of particles 1 and 2, $\vec{L}_i$ is the relative angular momentum of particle 3 with respect to the center of mass of the pair (12), and $\vec{s}_1$, $\vec{s}_2$, and $\vec{s}_3$ are spin angular momenta of particles 1, 2, and 3, respectively.

The experiments[12] show that for the triton ground state, the total angular momentum and total isospin are $(\frac{1}{2})$, respectively, and the parity is positive. Thus there can be many possible angular momentum states which can yield total angular momentum $\vec{J}_i=(\frac{1}{2})$, total isospin $\vec{\tau}_i=(\frac{1}{2})$, and parity positive. But all these states are not equally important for the triton ground state. The probabilities of triton wave function components have been calculated by various authors using many realistic potentials, like the Hamada-Johnston,[13] super soft core,[14] and Reid soft core,[15] and employing the variational method[16,17] and Faddeev approach.[18–20] Approximate calculations based on the unitary pole approximation (UPA) were done by Bhatt, Levinger, and Harms.[21] According to these calculations the dominant component of the three-nucleon wave function is the spatially symmetric S state $[P(S)\approx 90\%]$. Probabilities of other important components are, for the mixed symmetry S' state, $P(S')\approx 1$–$2\,\%$; for D states, $P(D)\approx 8$–$9\,\%$; and for the P state, $P(P)\approx 0.05\%$.

Now the isospin matrix elements of Eq. (6) can be evaluated by inserting a complete isospin state $\mid \tau^{12},\tau\rangle$, where $\vec{\tau}^{12}=(\vec{\tau}_1+\vec{\tau}_2)$ is the isospin of the pair (12) and $\vec{\tau}=\vec{\tau}^{12}+\vec{\tau}_3$ is the total isospin. Evaluating the isospin matrix elements and exploiting the fact that the Hamiltonian operating on the ground state results in the binding energy with a negative sign, one obtains,

$$1+k=(4M/3)\sum_{\tau^{12}\tau\zeta'\zeta''} \langle \Psi_{\zeta'} \mid D^{\zeta'}_{\tau^{12}\tau}(H_{\tau^{12}\tau}+B)D^{\zeta''}_{\tau^{12}\tau} \mid \Psi_{\zeta''}\rangle \ , \tag{8}$$

where

$$H_{\tau^{12}\tau}=K+\langle \tau^{12}\tau \mid V \mid \tau^{12}\tau\rangle \ , \tag{9}$$

and K is the kinetic energy. Here, V is the potential energy and can be approximated in terms of two-nucleon interaction as

$$V=V^{12}+V^{23}+V^{31} \ . \tag{10}$$

The summation over ζ' and ζ'' implies that they can take values ζ_1 and ζ_2. The various dipole operators obtained by inserting the complete isospin states are found to be

$$\begin{aligned} D^{\zeta_1}_{1(1/2)}=\left[\frac{1}{4\sqrt{3}}\right](\vec{y}_3-(f^2m/M)\{&-2\mu_v\phi(y_3)(\vec{\sigma}_1\vec{\sigma}_2\cdot\hat{y}_3+\vec{\sigma}_2\vec{\sigma}_1\cdot\hat{y}_3) \\ &+\phi(y_2)[(\mu_v-6\mu_s)\hat{y}_2\times(\vec{\sigma}_3\times\vec{\sigma}_1)+\mu_v(\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2+\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2)] \\ &+\phi(y_1)[(6\mu_s-\mu_v)\hat{y}_1\times(\vec{\sigma}_2\times\vec{\sigma}_3)+\mu_v(\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1+\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1)]\}) \ , \end{aligned} \tag{11}$$

$$D^{\zeta_1}_{1(3/2)}=(1/\sqrt{6})\{\vec{y}_3-(f^2m/M)[-\mu_v\phi(y_3)(\vec{\sigma}_1\vec{\sigma}_2\cdot\hat{y}_3+\vec{\sigma}_2\vec{\sigma}_1\cdot\hat{y}_3)+\phi(y_2)\mu_v(\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2)+\phi(y_1)\mu_v(\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1)]\} \ , \tag{12}$$

$$D^{\xi_1}_{0(1/2)}=\left[\frac{1}{2\sqrt{3}}\right]\{\vec{x}_3-(f^2m\sqrt{3}/M)[-3\mu_s\phi(y_3)\hat{y}_3\times(\vec{\sigma}_1\times\vec{\sigma}_2)+\mu_v\phi(y_2)(\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2)-\mu_v\phi(y_1)(\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1)]\}\ , \tag{13}$$

$$\begin{aligned}D^{\xi_2}_{1(1/2)}=\left[\frac{1}{2\sqrt{3}}\right](\vec{x}_3-(f^2m\sqrt{3}/M)\{&\phi(y_3)(\mu_s-2\mu_v/3)\hat{y}_3\times(\vec{\sigma}_1\times\vec{\sigma}_2)\\&-\phi(y_2)[(2\mu_s+\mu_v/6)\hat{y}_2\times(\vec{\sigma}_3\times\vec{\sigma}_1)+(\mu_v/2)(\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2+\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2)]\\&-\phi(y_1)[(2\mu_s+\mu_v/6)\hat{y}_1\times(\vec{\sigma}_2\times\vec{\sigma}_3)-(\mu_v/2)(\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1+\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1)]\})\ ,\end{aligned} \tag{14}$$

$$\begin{aligned}D^{\xi_2}_{1(3/2)}=(1/\sqrt{6})(\vec{x}_3-(f^2m\sqrt{3}/M)\{&\phi(y_3)(\mu_v/3)[\hat{y}_3\times(\vec{\sigma}_1\times\vec{\sigma}_2)]\\&+\phi(\hat{y}_2)[(-\mu_v/6)\hat{y}_2\times(\vec{\sigma}_3\times\vec{\sigma}_1)+(\mu_v/2)(\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2+\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2)]\\&+\phi(y_1)[(-\mu_v/6)\hat{y}_1\times(\vec{\sigma}_2\times\vec{\sigma}_3)-(\mu_v/2)(\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1+\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1)]\})\ ,\end{aligned} \tag{15}$$

$$\begin{aligned}D^{\xi_2}_{0(1/2)}=\left[\frac{1}{2\sqrt{3}}\right](\vec{y}_3-(f^2m/M)\{&-\phi(y_3)\mu_v(\vec{\sigma}_1\vec{\sigma}_2\cdot\hat{y}_3+\vec{\sigma}_2\vec{\sigma}_1\cdot\hat{y}_3)\\&+\phi(y_2)[(-3\mu_s+\mu_v/2)\hat{y}_2\times(\vec{\sigma}_3\times\vec{\sigma}_1)+(\mu_v/2)(\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2+\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2)]\\&+\phi(y_1)[(3\mu_s-\mu_v/2)\hat{y}_1\times(\vec{\sigma}_2\times\vec{\sigma}_3)+(\mu_v/2)(\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1+\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1)]\})\ .\end{aligned} \tag{16}$$

From now on, for the sake of brevity, the isospin state $|\tau^{12}\tau\rangle$ will be denoted by $|T\rangle$.

Applying the Wigner-Eckart theorem and introducing a complete set of spin-angle states, one can write Eq. (8) in the form

$$\begin{aligned}1+k=(4M/9)\sum_{\substack{JT\xi'\\ \xi''}}\Bigg[&\sum_{\alpha\alpha'}(-)^{J-J_i}{}_3\langle\Psi_{\xi'}||D^{\xi'}_T||J\rangle_{3\,3}\langle\alpha J\,|\,K^T+B+V^{12}\,|\,\alpha' J\rangle_{3\,3}\langle\alpha' J||D^{\xi''}_T||\Psi_{\xi''}\rangle_3\\&+\sum_{\beta\beta'}(-)^{J-J_i}{}_3\langle\Psi_{\xi'}||D^{\xi'}_T||\beta J\rangle_{2\,2}\langle\beta J\,|\,V^{31}\,|\,\beta' J\rangle_{2\,2}\langle\beta' J||D^{\xi''}_T||\Psi_{\xi''}\rangle_3\\&+\sum_{\gamma\gamma'}(-)^{J-J_i}{}_3\langle\Psi_{\xi'}||D^{\xi'}_T||\gamma J\rangle_{1\,1}\langle\gamma J\,|\,V^{23}\,|\,\gamma' J\rangle_{1\,1}\langle\gamma' J||D^{\xi''}_T||\Psi_{\xi''}\rangle_3\Bigg]\ ,\end{aligned} \tag{17}$$

where V^{ij} is the interaction between the nucleons i and j. The states $|\alpha J\rangle$, $|\beta J\rangle$, and $|\gamma J\rangle$ represent complete spin-angle states, where the subscripts 3, 2, and 1 on the angular brackets refer to spectator particles, respectively. Integrating by parts the second derivative terms that result from the kinetic energy terms, we obtain

$$\begin{aligned}1+k=(\tfrac{4}{9})\sum_{JT\xi'\xi''}\Bigg[&\sum_{\alpha}\int\int dx_3dy_3\Bigg[\left[\frac{\partial g^3_{\alpha JT\xi'}}{\partial x_3}\right]\left[\frac{\partial g^3_{\alpha JT\xi''}}{\partial x_3}\right]+\left[\frac{\partial g^3_{\alpha JT\xi'}}{\partial y_3}\right]\left[\frac{\partial g^3_{\alpha JT\xi''}}{\partial y_3}\right]+(g^3_{\alpha JT\xi'})\\&\times\left\{(g^3_{\alpha JT\xi''})\left[\frac{L(L+1)}{x_3^2}+\frac{l(l+1)}{y_3^2}+\frac{MB}{m^2}\right]+\sum_{\alpha'}(g^3_{\alpha' JT\xi''})_3\langle\alpha J\,|\,U_{12}\,|\,J\alpha'\rangle_3\right\}\Bigg]\\&+\sum_{\beta\beta'}\int\int dx_2dy_2(g^2_{\beta JT\xi'})(g^2_{\beta' JT\xi''})_2\langle\beta J\,|\,U_{31}\,|\,\beta' J\rangle_2\\&+\sum_{\gamma\gamma'}\int\int dx_1dy_1(g^1_{\gamma JT\xi'})(g^1_{\gamma' JT\xi''})_1\langle\gamma J\,|\,U_{23}\,|\,\gamma' J\rangle_1\Bigg]\ ,\end{aligned} \tag{18}$$

where

$$U_{ij}=MV_T^{ij}/(m)^2 \, . \tag{19}$$

To obtain the preceding equation we have used the fact that the functions $(g^i_{\alpha JT\zeta'})$ vanish for the limits $x_i,y_i \to 0$ and $x_i,y_i \to \infty$. The various functions $(g^i_{\alpha JT\zeta'})$ appearing in the preceding equations are

$$g^3_{\alpha JT\zeta'}=x_3y_3 \int\int d\hat{x}_3 d\hat{y}_3 [\Psi_{\zeta'}(x_3y_3) D_T^{\zeta'}{}_3\langle \hat{x}_3\hat{y}_3 \,|\, \alpha J\rangle_3] \, , \tag{20}$$

$$g^2_{\alpha JT\zeta'}=x_2y_2 \int\int d\hat{x}_2 d\hat{y}_2 [\Psi_{\zeta'}(x_2y_2) D_T^{\zeta'}{}_2\langle \hat{x}_2\hat{y}_2 \,|\, \beta J\rangle_2] \, , \tag{21}$$

$$g^1_{\alpha JT\zeta'}=x_1y_1 \int\int d\hat{x}_1 d\hat{y}_1 [\Psi_{\zeta'}(x_1y_1) D_T^{\zeta'}{}_1\langle \hat{x}_1\hat{y}_1 \,|\, \gamma J\rangle_1] \, . \tag{22}$$

From now on, these functions will be denoted by g^i, where i can take the values 1, 2, and 3.

It is more convenient to choose the states $|\alpha J\rangle_3$, $|\beta J\rangle_2$, and $|\gamma J\rangle_1$ in the J-J coupling scheme which simplifies the matrix elements for the potential term. In this basis, the total angular momentum J is computed from $\vec{J}^{\,ij}=(\vec{l}^{\,k}+\vec{S}^{\,ij})$, the relative orbital plus spin angular momentum of the nucleon pair (ij), and $\vec{J}^{\,k}\,(=\vec{L}^{\,k}+\vec{s}_k)$ is the orbital plus spin angular momentum of the third nucleon, with respect to the center of mass of the nucleon pair (ij). Here, $\vec{S}^{\,ij}$ is equal to $\vec{s}_i+\vec{s}_j$. Thus $\vec{J}^{\,ij}$ is the angular momentum of the two-body system and $\vec{J}^{\,k}$ is the angular momentum of the kth particle with respect to the two-body system (ij).

The various terms g^i, which depend on x_i and y_i, may also depend on the magnitude of x_j and y_j, where j is not equal to i. Using the Legendre polynomial basis, a function of x_j and y_j can be expressed in terms of x_i, y_i, and u_i $(=\cos\hat{x}_i\hat{y}_j)$. If a function $f(x_i,y_i,x_j,y_j)$ is the product of (x_iy_i) with the radial part of the ground state $\Psi_{\zeta'}$ and dipole operator $D_T^{\zeta'}$, which is the radial part of g^i, then we can write

$$f(x_i,y_i,x_j,y_j)=\sum_{\mathscr{L}}[(\mathscr{L})^2/4]F_{\mathscr{L}}(x_i,y_i)P_{\mathscr{L}}(u_i) \, , \tag{23}$$

where

$$F_{\mathscr{L}}(x_i,y_i)=2\pi\int_{-1}^{1} f(x_i,y_i,x_j,y_j)P_{\mathscr{L}}(u_i)du_i \, . \tag{24}$$

The angular part of the function g^i was calculated by graphical method,[22] which can be expressed in terms of the $3nj$ coefficients of Wigner. The various matrix elements required for calculating the g^i functions and contributing considerably to the integrated and bremsstrahlung-weighted cross section are given by

$$\begin{aligned}
{}_3\langle \alpha J||\vec{x}_3||\delta\rangle_3 &= [J_i\mathscr{L}_iS_iL_iJJ^{12}J^3L^3]\begin{pmatrix} L^3 & 1 & L_i \\ 0 & 0 & 0\end{pmatrix} \\
&\times \sum_Y (Y)^2(-)^{Y+S_i+s_3+J^3+J^{12}+S^{12}} \begin{Bmatrix} S_i & Y & l_i \\ L_i & \mathscr{L}_i & J_i \end{Bmatrix} \begin{Bmatrix} J_i & L_i & Y \\ L^3 & J & 1 \end{Bmatrix} \begin{Bmatrix} J & L^3 & Y \\ \frac{1}{2} & J^{12} & J^3 \end{Bmatrix} \begin{Bmatrix} S_i & Y & l_i \\ J^{12} & S_i^{12} & \frac{1}{2} \end{Bmatrix} f_1(x_3,y_3) \, ,
\end{aligned} \tag{25}$$

$$\begin{aligned}
{}_3\langle \alpha J||\vec{y}_3||\delta\rangle_3 &= [J_i\mathscr{L}_iS_il_iJJ^{12}J^3l^3]\begin{pmatrix} l^3 & 1 & l_i \\ 0 & 0 & 0\end{pmatrix} \\
&\times \sum_Y (Y)^2(-)^{Y+J+l_i+L_i+\mathscr{L}_i} \begin{Bmatrix} S_i & Y & L_i \\ J^3 & \frac{1}{2} & S_i^{12} \end{Bmatrix} \begin{Bmatrix} S_i^{12} & J^3 & Y \\ J & l^3 & J^{12} \end{Bmatrix} \begin{Bmatrix} l^3 & J & Y \\ J_i & l_i & 1 \end{Bmatrix} \begin{Bmatrix} S_i & Y & L_i \\ l_i & \mathscr{L}_i & J_i \end{Bmatrix} f_2(x_3,y_3) \, ,
\end{aligned} \tag{26}$$

$$\begin{aligned}
{}_2\langle \beta J||\vec{x}_3||\delta\rangle_3 &= \left[\frac{1}{4\pi}\right]^2 [J_i\mathscr{L}_iS_iS_i^{12}L_il_iJJ^{13}J^2S^{13}L^2l^2] \\
&\times \sum_{\mathscr{L}\lambda\Lambda k^c} F_{1\mathscr{L}}(x_2,y_2)B_{l_i\lambda}B_{k^c\Lambda}(a_{32}y_2)^{\lambda}(b_{32}x_2)^{l_i-\lambda}(-b_{32}y_2)^{\Lambda}(a_{32}x_2)^{k^c-\Lambda}[\lambda\Lambda(k^c-\Lambda)(l_i-\lambda)][k^c]^2 \\
&\times \sum_{k^ak^b} [k^ak^b\mathscr{L}]^2(-)^{k^c+\mathscr{L}+S_i^{12}+J_i+S_i+\mathscr{L}_i} \begin{pmatrix} k^c & 1 & L_i \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} k^a & \Lambda & \lambda \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} k^b & l_i-\lambda & k^c-\Lambda \\ 0 & 0 & 0 \end{pmatrix} \\
&\times \begin{pmatrix} L^2 & \mathscr{L} & k^a \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l^2 & \mathscr{L} & k^b \\ 0 & 0 & 0 \end{pmatrix} \begin{Bmatrix} \frac{1}{2} & S^{13} & \frac{1}{2} \\ \frac{1}{2} & S_i^{12} & S_i \end{Bmatrix} \\
&\times \sum_X (X)^2 \begin{Bmatrix} J & J_i & 1 \\ \mathscr{L}_i & X & S_i \end{Bmatrix} \begin{Bmatrix} L^2 & X & l^2 \\ k^b & \mathscr{L} & k^a \end{Bmatrix} \begin{Bmatrix} \mathscr{L}_i & L_i & l_i \\ k^c & X & 1 \end{Bmatrix} \\
&\times \begin{Bmatrix} S^{12} & \frac{1}{2} & S_i \\ J^{13} & J^2 & J \\ l^2 & L^2 & X \end{Bmatrix} \begin{Bmatrix} X & k^b & k^a \\ k^c & k^c-\Lambda & \Lambda \\ l_i & l_i-\lambda & \lambda \end{Bmatrix} \, ,
\end{aligned} \tag{27}$$

$$
{}_2\langle \beta J||\vec{y}_3||\delta\rangle_3 = \left[\frac{1}{4\pi}\right]^2 [J_i \mathscr{L}_i S_i S_i^{12} L_i l_i J J^{13} J^2 S^{13} L^2 l^2]
\times \sum_{\mathscr{L}\lambda\Lambda k^c} F_{2\mathscr{L}}(x_2,y_2) B_{L_i\Lambda} B_{k^c\Lambda} (a_{32}y_2)^{\lambda} (b_{32}x_2)^{k^c-\lambda} (-b_{32}y_2)^{\Lambda} (a_{32}x_2)^{L_i-\Lambda} [\lambda\Lambda(k^c-\lambda)(L_i-\Lambda)][k^c]^2
$$

$$
\times \sum_{k^a k^b} [k^a k^b \mathscr{L}]^2 (-)^{k^c+\mathscr{L}+S_i^{12}+J_i+S_i+L_i+l_i} \begin{pmatrix} l_i & k^c & 1 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} k^a & \lambda & \Lambda \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} k^b & L_i-\Lambda & k^c-\lambda \\ 0 & 0 & 0 \end{pmatrix}
$$

$$
\times \begin{pmatrix} L^2 & \mathscr{L} & k^a \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l^2 & \mathscr{L} & k^b \\ 0 & 0 & 0 \end{pmatrix} \begin{Bmatrix} \frac{1}{2} & S^{13} & \frac{1}{2} \\ \frac{1}{2} & S_i^{12} & S_i \end{Bmatrix}
$$

$$
\times \sum_X (X)^2 \begin{Bmatrix} J & J_i & 1 \\ \mathscr{L}_i & X & S_i \end{Bmatrix} \begin{Bmatrix} L^2 & X & l^2 \\ k^b & \mathscr{L} & k^a \end{Bmatrix} \begin{Bmatrix} \mathscr{L}_i & l_i & L_i \\ k^c & X & 1 \end{Bmatrix}
$$

$$
\times \begin{Bmatrix} S^{13} & \frac{1}{2} & S_i \\ J^{13} & J^2 & J \\ l^2 & L^2 & X \end{Bmatrix} \begin{Bmatrix} X & k^b & k^a \\ k^c & k^c-\lambda & \lambda \\ L_i & L_i-\Lambda & \Lambda \end{Bmatrix}, \tag{28}
$$

$$
{}_3\langle \alpha J||\phi(y_3)(\vec{\sigma}_1\vec{\sigma}_2\cdot\hat{y}_3)||\delta\rangle_3 = 6[J_i S_i S_i^{12} \mathscr{L}_i l_i][J J^{12} J^3 S^{12} l^3] \begin{pmatrix} l_i & l^3 & 1 \\ 0 & 0 & 0 \end{pmatrix} (-)^{J+J_i+S_i+s_3+l_i+l^2}
$$

$$
\times \sum_X (X)^2 (-)^{X+J^3} \begin{Bmatrix} l_i & X & J^{12} \\ S^{12} & l^3 & 1 \end{Bmatrix} \begin{Bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & X & S_i^{12} \end{Bmatrix} \begin{Bmatrix} X & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & S^{12} & 1 \end{Bmatrix}
$$

$$
\times \sum_Y (Y)^2 (-)^Y \begin{Bmatrix} J_i & S_i^{12} & Y \\ \frac{1}{2} & \mathscr{L}_i & S_i \end{Bmatrix} \begin{Bmatrix} \mathscr{L}_i & \frac{1}{2} & Y \\ J^3 & l_i & L_i \end{Bmatrix} \begin{Bmatrix} l_i & J^3 & Y \\ J & X & J^{12} \end{Bmatrix}
$$

$$
\times \begin{Bmatrix} Y & J_i & S_i^{12} \\ 1 & X & J \end{Bmatrix} f_3(x_3,y_3), \tag{29}
$$

$$
{}_3\langle \alpha J||\phi(y_3)(\vec{\sigma}_2\vec{\sigma}_1\cdot\hat{y}_3)||\delta\rangle_3 = (-)^{S^{12}+S_i^{12}}\, {}_3\langle \alpha J||\phi(y_3)(\vec{\sigma}_1\vec{\sigma}_2\cdot\hat{y}_3)||\delta\rangle_3, \tag{30}
$$

$$
{}_3\langle \alpha J||\phi(y_2)(\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2)||\delta\rangle_3 = 6\left[\frac{1}{4\pi}\right]^{3/2} [J_i S_i \mathscr{L}_i S_i^{12} L_i l_i][J J^{12} J^3 S^{12} L^3 l^3] \begin{Bmatrix} S_i^{12} & 1 & S^{12} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{Bmatrix}
$$

$$
\times \sum_{k^a k^b \mathscr{L}\lambda} B_{1\lambda} \mathscr{F}_{\mathscr{L}}(x_3,y_3)(a_{23}y_3)^{\lambda}(b_{23}x_3)^{1-\lambda}[k^a k^b \mathscr{L}]^2[\lambda(1-\lambda)](-)^{\mathscr{L}+\mathscr{L}_i+s_3+J_i+1}
$$

$$
\times \begin{pmatrix} L^3 & k^a & \mathscr{L} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l^3 & \mathscr{L} & k^b \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \lambda & k^b & l_i \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} k^a & (1-\lambda) & L_i \\ 0 & 0 & 0 \end{pmatrix}
$$

$$
\times \sum_X (X)^2 \begin{Bmatrix} k^b & X & k^a \\ L^3 & \mathscr{L} & l^3 \end{Bmatrix} \begin{Bmatrix} (1-\lambda) & \lambda & 1 \\ L_i & l_i & \mathscr{L}_i \\ k^a & k^b & X \end{Bmatrix}
$$

$$\times\sum_{Y}(Y)^2\begin{Bmatrix} J & \frac{1}{2} & Y \\ \frac{1}{2} & J_i & 1\end{Bmatrix}\begin{Bmatrix}\mathscr{L}_i & J_i & S_i \\ \frac{1}{2} & S_i^{12} & Y\end{Bmatrix}\begin{Bmatrix} X & \mathscr{L}_i & 1 \\ S_i^{12} & S^{12} & Y\end{Bmatrix}$$

$$\times\begin{Bmatrix} X & S^{12} & Y \\ J^{12} & L^3 & l^3\end{Bmatrix}\begin{Bmatrix}\frac{1}{2} & J & Y \\ J^{12} & L^3 & J^3\end{Bmatrix}, \tag{31}$$

$${}_3\langle \alpha J||\phi(y_2)(\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2)||\delta\rangle_3 = 6\left[\frac{1}{4\pi}\right]^{3/2}[J_iS_i\mathscr{L}_iS_i^{12}L_il_i][JJ^{12}J^3S^{12}L^3l^3]\begin{Bmatrix} S_i^{12} & 1 & S^{12} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{Bmatrix}$$

$$\times\sum_{k^ak^b\mathscr{L}\lambda} B_{l\lambda}\mathscr{F}_{\mathscr{L}}(x_3,y_3)(a_{23}y_3)^{\lambda}(b_{23}x_3)^{1-\lambda}[k^ak^b\mathscr{L}]^2[\lambda(1-\lambda)]$$

$$\times(-)^{\mathscr{L}+S^{12}+J^{12}+L^3+l^3+J+S_i+J_i+1}\begin{bmatrix} L^3 & k^a & \mathscr{L} \\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix} l^3 & \mathscr{L} & k^b \\ 0 & 0 & 0\end{bmatrix}$$

$$\times\begin{bmatrix} l_i & k^b & \lambda \\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix} k^a & (1-\lambda) & L_i \\ 0 & 0 & 0\end{bmatrix}$$

$$\times\sum_{X}(X)^2\begin{Bmatrix} k^b & X & k^a \\ L^3 & \mathscr{L} & l^3\end{Bmatrix}\begin{Bmatrix} X & k^b & k^a \\ 1 & \lambda & (1-\lambda) \\ \mathscr{L}_i & l_i & L_i\end{Bmatrix}$$

$$\times\sum_{Y}(Y)^2\begin{Bmatrix} J^{12} & S^{12} & l^3 \\ Y & J^3 & J\end{Bmatrix}\begin{Bmatrix} S^{12} & 1 & S_i^{12} \\ J_i & Y & J\end{Bmatrix}\begin{Bmatrix} J_i & S_i & \mathscr{L}_i \\ \frac{1}{2} & Y & S_i^{12}\end{Bmatrix}$$

$$\times\begin{Bmatrix} J^3 & Y & l^3 \\ X & L & \frac{1}{2}\end{Bmatrix}\begin{Bmatrix} X & Y & \frac{1}{2} \\ \frac{1}{2} & 1 & \mathscr{L}_i\end{Bmatrix}, \tag{32}$$

where $[J]=(2J+1)^{1/2}$,

$$B_{l\lambda}=\{4\pi(2l+1)!/[(2\lambda+1)!(2l-2\lambda+1)!]\}^{1/2},$$

and $3j$, $6j$, and $9j$ coefficients are used in the convention of Ref. (23).

In the preceding equations the various radial part can be obtained by multiplying the radial part of the ground state wave function with the radial part of the dipole operator. The mathematical form of the various radial parts can be written as

$$f_1(x_3,y_3)=x_3R_\delta, \tag{33}$$

$$f_2(x_3,y_3)=y_3R_\delta, \tag{34}$$

$$f_3(x_3,y_3)=\phi(y_3)R_\delta, \tag{35}$$

$$F_{1\mathscr{L}}(x_2,y_2)=2\pi\int_{-1}^{1}(x_3)^{1-k^c}\times(y_3)^{-l_i}R_\delta P_{\mathscr{L}}(u_2)du_2, \tag{36}$$

$$F_{2\mathscr{L}}(x_1,y_1)=2\pi\int_{-1}^{1}(y_3)^{1-k^c}\times(x_3)^{-L_i}R_\delta P_{\mathscr{L}}(u_2)du_2, \tag{37}$$

$$\mathscr{F}_{\mathscr{L}}(x_3,y_3)=2\pi\int_{-1}^{1}[\phi(y_2)/y_2]\times R_\delta P_{\mathscr{L}}(u_3)du_3. \tag{38}$$

Here, R_δ represents the radial part of the ground state wave function, which corresponds to the angular momentum configuration δ. As an example, δ can represent a spherically symmetric S state or mixed symmetry S' state or a D state. Thus for an S state we choose $l_i=0$, $L_i=0$, $\mathscr{L}_i=0$, $S_i^{12}=0$, and $S_i=\frac{1}{2}$. Similarly, for an S' state

$l_i=0$, $L_i=0$, $\mathscr{L}_i=0$, $S_i^{12}=1$, and $S_i=\frac{1}{2}$, and for one of the D states we can have $l_i=1$, $L_i=1$, $\mathscr{L}_i=2$, $S_i^{12}=1$, and $S_i=\frac{3}{2}$.

The terms ${}_1\langle\gamma J||\vec{x}_3||\delta\rangle_3$ and ${}_1\langle\beta J||\vec{y}_3||\delta\rangle_3$ can be obtained by interchanging the first and second particles in the terms ${}_2\langle\beta J||\vec{x}_3||\delta\rangle_3$ and ${}_2\langle\beta J||\vec{y}_3||\delta\rangle_3$, and multiplying by a phase factor $(-)^{(S^{12}+S_i^{12})}$. Similarly, the terms

$$ {}_3\langle\alpha J||\phi(y_1)(\vec{\sigma}_2\vec{\sigma}_3\cdot\hat{y}_1)||\delta\rangle_3 $$

and

$$ {}_3\langle\alpha J||\phi(y_1)(\vec{\sigma}_3\vec{\sigma}_2\cdot\hat{y}_1)||\delta\rangle_3 $$

can be obtained by interchanging b_{23} and b_{13} in the terms

$$ {}_3\langle\alpha J||\phi(y_2)(\vec{\sigma}_1\vec{\sigma}_3\cdot\hat{y}_2)||\delta\rangle_3 $$

and

$$ {}_3\langle\alpha J||\phi(y_2)(\vec{\sigma}_3\vec{\sigma}_1\cdot\hat{y}_2)||\delta\rangle_3 , $$

and multiplying by a phase factor of $(-)^{(S_i^{12}+S^{12})}$.

Following a similar procedure, the bremsstrahlung-weighted cross section including two-body effects can be expressed in terms of the g functions. Thus,

$$ \sigma_{-1}=\int(\sigma/W)dW =(4\pi^2e^2/9m^2)\sum_{\substack{\alpha J\\ T\zeta'\zeta''}}\int\int dx_3dy_3(g^3_{\alpha JT\zeta'})(g^3_{\alpha JT\zeta''}) . \tag{39} $$

The numerical calculations are carried out for the potential given by Gerjuoy and Schwinger.[24] This potential has a central as well as a tensor component and is given by

$$ V^{ij}=-[1-0.5G+0.5G(\vec{\sigma}_i\cdot\vec{\sigma}_j)+RS_{ij}]Z(y_k) , \tag{40} $$

where

$$ S_{ij}=[3(\vec{\sigma}_i\cdot\hat{y}_k)(\vec{\sigma}_j\cdot\hat{y}_k)-(\hat{\sigma}_i\cdot\vec{\sigma}_j)] . \tag{41} $$

The parameters G, R, and the function $Z(y_k)$ are given in Ref. 24.

The ground-state wave function used for the calculations has a spatially symmetric S state and a D state. The radial parts of the wave function are chosen to be of the Gaussian form. The mathematical form of the wave function in the coordinate system given by Eqs. (1) and (2) is given by

$$ \Psi_{\zeta_2}=\left\{\frac{N_s(3)^{3/4}}{(1+C^2)^{1/2}}\exp[-(3\mu/4m^2)(x_3^2+y_3^2)]+\frac{CN_d(3)^{5/4}}{2(1+C^2)^{1/2}}\exp[-(3\nu/4m^2)(x_3^2+y_3^2)]\right. $$
$$ \left.\times[3(\vec{\sigma}_1\cdot\vec{x}_3)(\vec{\sigma}_3\cdot\vec{y}_3)+3(\vec{\sigma}_3\cdot\vec{y}_3)(\vec{\sigma}_1\cdot\vec{x}_3)-2(\vec{x}_3\cdot\vec{y}_3)(\vec{\sigma}_1\cdot\vec{\sigma}_3)]\right\}\chi , \tag{42} $$

where χ, the spin wave function for the spherically symmetric S state, is

$$ \chi=\left[\frac{1}{4\pi}\right](1/\sqrt{2})(\chi_1^+\chi_1^- -\chi_1^-\chi_2^+)\chi_3^m , \tag{43} $$

with χ_i^m representing the spin wave function for the ith nucleon of magnetic quantum number m. N_s and N_d are given by

$$ N_s=\frac{2(2\mu)^{3/4}(3\mu/2)^{3/4}}{\Gamma(\frac{3}{2})(m)^{3/2}} , \tag{44} $$

$$ N_d=\frac{2(2\nu)^{5/4}(3\nu/2)^{5/4}}{\sqrt{20}\Gamma(\frac{5}{2})(m)^{5/4}} . \tag{45} $$

The parameters in the wave functions were obtained by variational method by Gerjuoy and Schwinger.[24] The value of parameters used for the present calculations are $C=0.168$, $\mu=0.109$, and $\nu=0.266$. The numerical integration is performed by using the Gauss-quadrature method. Since the potential is independent of parity and isospin the integrated cross section can be compared only with the Thomas-Reiche-Kuhn (TRK) sum rule value. The experimental data available on deuteron and two-nucleon scattering indicate the presence of exchange forces in the nucleon-nucleon interaction, such as Majorana, Bartlett, and Heisenberg forces. Hence the nucleon-nucleon interaction is different for singlet-even, singlet-odd, triplet-even, and triplet-odd forces. Besides this, the tensor, spin-orbit, and velocity-dependent components are also present in the nucleon-nucleon interaction. Thus the actual N-N potential does not commute with the Siegert form of the dipole operator. This results in a higher value of integrated cross section than the TRK sum rule value. Thus agreement with the experiments cannot be expected. Hence, comparison with the experiments is not made. The integrated cross section is compared with the TRK sum rule value and the bremsstrahlung-weighted cross section is checked by calculating the expectation value of the dipole operator for the ground state in two different ways.

Table I shows the enhancement factor and the bremsstrahlung-weighted cross section without and with the two-body effects. The enhancement factor without meson exchange effect agrees with the TRK sum rule value. Inclusion of two-body effects changes $1+k$ to 1.16 for the pseudoscalar coupling, but only to 1.02 for the pseudovector coupling. The bremsstrahlung-weighted cross section changes from 1.937 to 1.957 for pseudoscalar coupling, and to 1.940 for pseudovector coupling. For reasons already given, no comparisons with the experimental data are made.[25–28]

It should be pointed out that there is ambiguity in the two-body charge density operator coming from the arbi-

TABLE I. Triton enhancement factor and bremsstrahlung-weighted cross sections without and with meson exchange effects.

	Without exchange effect	With exchange effect Pseudoscalar coupling	Pseudovector coupling
$1+k$	1.00	1.16	1.02
σ_{-1} (mb)	1.937	1.957	1.940

trariness of the unitary transformation which has been resolved by Cambi *et al.* by choosing the free parameter so that $\rho_{N\bar{N}}$ reduces to the form given by Kloet and Tjon in pseudoscalar coupling. The unitary ambiguity makes a definite calculation impossible until a potential model and wave functions are constructed which resolve the ambiguity problem. The necessity of a consistent treatment for the exchange current has been pointed out by Friar.[8]

The present calculations may undergo changes when calculations with modern potentials and wave functions are carried out. It should also be pointed out that pseudovector coupling, which gives satisfactory agreement with experiment for threshold pion production from nucleons, was employed by Jaus and Woolcock[29] in the two-body charge density for deuteron photodisintegration in the forward direction, and yielded a reduced cross section. However, one does not know whether it will give improved agreement for the entire angular distribution and for other observables like the nucleon polarization and the asymmetry function.

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