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Two-body effects and deuteron photodisintegration with polarized and unpolarized gamma rays

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Employing the two-body charge effects owing to π exchange and the current effects owing to π-, ρ-, and ω-exchange processes, the angular distribution, asymmetry function, and polarization of nucleons from the ^{2}H(γ,n)^{1}H reaction are investigated. The cross section and polarization parameters are reported for the Paris, Yale, super-soft-core B, and Hamada-Johnston potentials. The changes in the parameters owing to exchange effects are found to be nearly the same for all the potentials, and all the potentials are found to reproduce the low energy angular distribution data provided a suitable normalization factor is chosen.

[NUCLEAR REACTIONS ^{2}H(γ,n)^{1}H. Two-body exchange effects, total and differential cross section, polarization, asymmetry function with realistic nucleon-nucleon interactions.]

I. INTRODUCTION

The main object of this paper is to present a systematic study of the exchange effects owing to two-body charge and current densities on the cross-section and polarization parameters for deuteron photodisintegration with polarized and unpolarized photon beams. In the last few years considerable attention has been given to the effects of two-body charge and current density on various calculations, and an appreciable contribution of these effects has been reported by numerous authors.[1-9] The influence of the isobar configuration has also been investigated.[8] The exchange current effects were first considered by Riska and Brown[1] to successfully explain the puzzle in n-p capture at thermal energy.

In the present calculations we have included the effects of the two-body charge density owing to one pion exchange and two-body current density owing to one pion, ρ-meson, and ω-meson exchanges. The calculations have been done for various nucleon-nucleon interactions having a wide range of percentages of D state (P_D) to study the effects of the variation of P_D on cross-section and polarization parameters. The various nucleon-nucleon interactions used are the Hamada-Johnston,[10] Hamada-Johnston (modified), Yale,[11] super-soft-core (SSC) versions A, B, and C,[12] and the Paris potential.[13] The P_D's for these potentials are listed by Vyas and Rustgi.[6]

A calculation parallel to that of Rustgi, Zernik, Breit, and Andrews (Ref. 14; this paper will be referred to as RZBA henceforth) is followed to include the exchange effects. The same notations and conventions regarding the geometry as used in RZBA are adopted here. The final-state interaction between the neutron and proton is taken into account, and transitions induced by electromagnetic multipoles $E1$, $M1$, and $E2$ are included.

It was found that the inclusion of the current density effects owing to π, ρ, and ω mesons, in the traditional interaction terms considered by RZBA (whose notation we follow), has the effect of increasing the coefficients a and b in the angular distribution. The change in b changes the angular distribution curve symmetrically about $\theta_{\text{c.m.}}=90°$. The further inclusion of the charge density effects leads to further increases in the coefficients a, b, c, and d of the angular distribution, but the coefficient e remains unchanged owing to the addition of the two-body charge and current density effects. In all cases considered, slightly higher peaks are obtained at lower energies for the angular distribution curves for the potentials with smaller P_D values. At higher energies larger coefficients are obtained for higher P_D value potentials. Except for the parameter d for the cross section, the relative change owing to the exchange effects in the cross section and polarization parameters are not very sensitive to the percentage of D state. In Sec. II the formalism for including exchange effects is given. The results are discussed in Sec. III.

II. CALCULATIONS

The coordinate system shown in Fig. 1 of RZBA is used for the present calculation. The direction of the incoming photon beam is the positive z axis of a Cartesian coordinate system with its electric vector along the x axis. The z' axis of the second coordinate system with colatitude and azimuthal angles θ and ϕ, respectively, coincides with the direction of the outgoing proton. The direction cosine of the x' and y' axes are $(\cos\theta\cos\phi, \cos\theta\sin\phi, -\sin\theta)$ and $(-\sin\phi, \cos\phi, 0)$, respectively.

The interaction Hamiltonian given by Eq. (4) of

TABLE I. Angular distribution parameters in μb/sr for the Paris potential in approximations I, II, and III.

E_γ (MeV)	Approximation	a	b	c	d	e
4.0	I	9.472	282.0	0.0318	24.41	0.5286
	II	11.14	282.0	0.0318	24.41	0.5286
	III	11.15	282.1	0.0256	24.42	0.5286
10.0	I	4.358	152.0	0.2876	28.57	1.345
	II	5.109	152.1	0.2876	28.57	1.345
	III	5.250	152.5	0.2822	28.60	1.345
16.0	I	4.865	81.52	0.5225	20.89	1.340
	II	5.342	81.80	0.5225	20.89	1.340
	III	5.626	82.23	0.5269	20.96	1.340
20.0	I	5.118	58.01	0.6391	17.17	1.270
	II	5.540	58.38	0.6391	17.17	1.270
	III	5.920	58.83	0.6522	17.25	1.270
50.0	I	5.229	10.07	0.8909	5.608	0.7572
	II	5.253	11.03	0.8909	5.608	0.7572
	III	5.975	11.30	0.9756	5.733	0.7572
100.0	I	3.614	1.709	0.7346	1.671	0.3728
	II	3.632	3.175	0.7346	1.671	0.3728
	III	4.454	3.075	0.9005	1.735	0.3728
150.0	I	2.482	0.5820	0.5883	0.7258	0.2202
	II	2.600	2.162	0.5883	0.7258	0.2202
	III	3.369	1.911	0.7906	0.7258	0.2202

RZBA,[14] which includes the $E1$, $E2$, and $M1$ electromagnetic multipoles on incorporating the two-body charge[6] and current contributions[15] can be written as

$$H' = -e\mathscr{E}_x \mathscr{A} ,$$

where

$$\mathscr{A} = \tfrac{1}{2}(\vec{1}_E\cdot\vec{r}) + \frac{i}{8}(\vec{\kappa}\cdot\vec{r})(\vec{1}_E\cdot\vec{r}) + \frac{f^2}{4M}\{\tfrac{1}{3}[\phi_0\vec{\sigma}_1\cdot\vec{\sigma}_2 + \phi_2 S_{12}]\hat{r} + (2\mu_v\phi - \phi_1)(\vec{\sigma}_1(\vec{\sigma}_2\cdot\hat{r}) + \vec{\sigma}_2(\vec{\sigma}_1\cdot\hat{r}))\}\cdot\vec{1}_E$$
$$+\frac{3}{2}\frac{f^2}{M}\phi\mu_s[\vec{\sigma}_1(\hat{r}\cdot\vec{\sigma}_2) - \vec{\sigma}_2(\hat{r}\cdot\vec{\sigma}_1)]\cdot\vec{1}_E$$
$$+\frac{\hbar}{2Mc}[(\tfrac{1}{2}\mu_v + g_{\rm I} + h_{\rm I})(\vec{\sigma}_1 - \vec{\sigma}_2) + \tfrac{1}{2}(\mu_s - \tfrac{1}{2})(\vec{\sigma}_1 - \vec{\sigma}_2) + (g_{\rm II} + h_{\rm II})T_{12}^{(-)}]\cdot\vec{1}_H ,$$

where S_{12} is the usual tensor operator,

$$\mu_s = \mu_1 + \mu_2;\quad \mu_v = \mu_1 - \mu_2 , \tag{2}$$

$$T_{12}^{(-)} = (\vec{\sigma}_1 - \vec{\sigma}_2)\cdot\hat{r}\hat{r} - \tfrac{1}{3}(\vec{\sigma}_1 - \vec{\sigma}_2) , \tag{3}$$

and ϕ, ϕ_0, ϕ_1, and ϕ_2 are the functions defined by Cambi *et al.*[6] The functions $g_{\rm I}$, $g_{\rm II}$, $h_{\rm I}$, and $h_{\rm II}$ are real scalar functions of $|\vec{r}| = |\vec{r}_1 - \vec{r}_2|$ and are given by Chemtob and Rho[15] for the various meson exchange processes. The one-pion exchange processes consist of the pionic current, pair current (or seagull current), and nucleonic current. These three processes are illustrated in parts (a), (b), and (c) of Fig. 1. In addition, we take into account $\rho\pi\gamma$ and $\omega\pi\gamma$ currents illustrated in part (d) of Fig. 1.

The sum of the pionic and pair excitation term is given by[15]

$$g_{\rm I} = \frac{2}{3}\frac{1}{4\pi}f_{\pi\rm NN}^2\frac{M}{m_\pi}(2x_\pi - 1)Y_0(x_\pi) , \tag{4}$$

$$g_{\rm II} = -2\frac{f_{\pi\rm NN}^2}{4\pi}\frac{M}{m_\pi}(1 + x_\pi)Y_0(x_\pi) , \tag{5}$$

$$h_{\rm I} = h_{\rm II} = 0 , \tag{6}$$

where

$$Y_0(x) = e^{-x}/x,\quad x_\pi = m_\pi r,\quad f_{\pi\rm NN}^2/4\pi = 0.08 ,$$

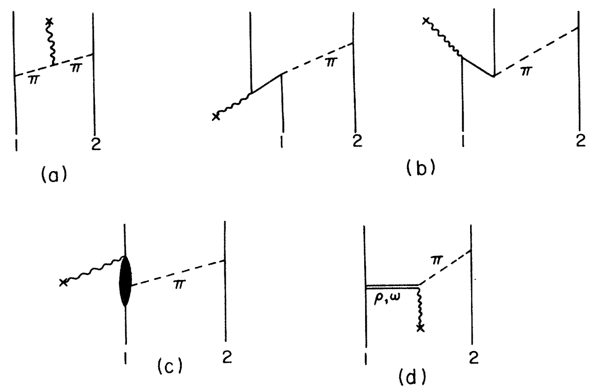

FIG. 1. Diagrams of the one-pion exchange current: (a) the pion current, (b) the pair excitation current, (c) the nucleonic current, and (d) the $\rho\pi\gamma$ and $\omega\pi\gamma$ currents.

and m_π and M denote the pion and nucleon mass, respectively.

The nucleonic current is given by[15]

$$g_{\rm I}=\tfrac{1}{9}\eta_1 Y_0(x_\pi)\ , \tag{7}$$

$$g_{\rm II}=-\tfrac{1}{6}\eta_1 Y_2(x_\pi)\ , \tag{8}$$

$$h_{\rm I}=-\tfrac{1}{9}\eta_2 Y_0(x_\pi)\ , \tag{9}$$

$$h_{\rm II}=-\tfrac{1}{3}\eta_2 Y_2(x_\pi)\ , \tag{10}$$

where

$$\eta_1=2\mu_v h_1(0)m_\pi^3=0.696\ , \tag{11}$$

$$\eta_2=2\mu_v h_2(0)m_\pi^3=0.619\ , \tag{12}$$

$$Y_2(x)=\left[1+\frac{3}{x}+\frac{3}{x^2}\right]Y_0(x)\ . \tag{13}$$

The $\omega\pi\gamma$ current is given by

$$h_{\rm I}=\zeta_\omega(m_\pi/m_\omega)^3 Y_0^\omega\ , \tag{14}$$

$$h_{\rm II}=3\zeta_\omega(m_\pi/m_\omega)^3 Y_2^\omega\ , \tag{15}$$

where from recent measurements[16]

$$\zeta_\omega=-g_{\omega NN}g_{\omega\pi\gamma}g_{\pi NN}/12\pi=-5.05 \tag{16}$$

and

$$Y_i=\frac{m_\omega^2}{m_\omega^2-m_\pi^2}\left[Y_i(x_\pi)-\left[\frac{m_\omega}{m_\pi}\right]^3 Y_i(x_\omega)\right]\ . \tag{17}$$

Here m_ω is the mass of the ω meson. In actual calculations the seagull term for ρ and ω mesons is also included.

The inclusion of the two-body current terms amounts to simply following changes in the M_S and M_D radial integrals in Eqs. (18.1)—(18.3) of RZBA:

TABLE II. Angular distribution parameters in μb/sr for the Yale potential in approximations I, II, and III.

E_γ (MeV)	Approximation	a	b	c	d	e
4.0	I	9.476	281.3	0.0296	24.34	0.5270
	II	11.28	281.3	0.0296	24.34	0.5270
	III	11.30	281.5	0.0310	24.35	0.5270
10.0	I	4.200	151.7	0.2750	28.62	1.352
	II	5.014	151.9	0.2755	28.62	1.352
	III	5.147	152.3	0.268	28.66	1.352
16.0	I	4.720	81.36	0.5091	20.91	1.345
	II	5.242	81.65	0.5090	20.91	1.345
	III	5.512	82.16	0.5105	20.99	1.345
20.0	I	5.070	57.97	0.6282	17.18	1.273
	II	5.471	58.35	0.6284	17.18	1.273
	III	5.822	58.89	0.6378	17.28	1.273
50.0	I	5.319	10.19	0.9331	5.610	0.7551
	II	5.342	11.21	0.9331	5.610	0.7551
	III	6.041	11.62	1.013	5.766	0.7551
100.0	I	3.829	1.655	0.8372	1.601	0.3710
	II	3.807	3.255	0.8367	1.601	0.3710
	III	4.612	3.279	0.9981	1.711	0.3710
150.0	I	2.730	0.509	0.7061	0.619	0.2152
	II	2.803	2.267	0.7062	0.619	0.2152
	III	3.566	2.101	0.8962	0.6654	0.2152

$$M_S \to M_S + 2M_S^0 - \frac{2\sqrt{2}}{3} M_D^0 , \quad (18)$$

$$M_D \to M_D + 2M_D^2 - \frac{2\sqrt{2}}{3} M_S^2 , \quad (19)$$

where

$$M_S^0 = \frac{\hbar}{Mc}\gamma \int_0^\infty U\,{}^1\mathcal{F}_0(kr)[g_{\rm I}+h_{\rm I}]dr ,$$

$$M_S^2 = \frac{\hbar}{Mc}\gamma \int_0^\infty U\,{}^1\mathcal{F}_2(kr)[g_{\rm II}+h_{\rm II}]dr ,$$

$$M_D^0 = \frac{\hbar}{Mc}\gamma \int_0^\infty W\,{}^1\mathcal{F}_0(kr)[g_{\rm II}+h_{\rm II}]dr ,$$

$$M_D^2 = \frac{\hbar}{Mc}\gamma \int_0^\infty W\,{}^1\mathcal{F}_2(kr)[(g_{\rm I}+h_{\rm I})+\tfrac{1}{3}(g_{\rm II}+h_{\rm II})]dr .$$

The third term in Eq. (1) also leads to a modification of Eqs. (18.2) and (18.3) in RZBA, as it causes transitions to the ${}^1P_1$ state. This results in the addition of

$$-6(f^2/M)\cos\theta e^{ik_1} \int (U+W/\sqrt{2})Y_1(\mu r)\,{}^1\mathcal{F}_1(kr)dr \quad (20)$$

in Eq. (18.2) and

$$6(f^2/M)\sin\theta \sin\phi e^{ik_1} \int (U+W/\sqrt{2})Y_1(\mu r)\,{}^1\mathcal{F}_1(kr)dr \quad (21)$$

in Eq. (18.3).

The remaining two-body charge terms lead to the following modification of the $E-1$ radial integrals:

$$I_0 \to I_0 + \gamma \int_0^\infty \left\{ U\left[\frac{f^2}{6M}e^{-\mu r} - \frac{2}{3}\frac{f^2}{M}Y_2(\mu r) - \frac{6}{M}(\mu_v - \tfrac{1}{2})Y_1(\mu r)\right] - \sqrt{2}W\left[\frac{f^2}{6M}e^{-\mu r} - \frac{2}{3}\frac{f}{M}Y_2(\mu r)\right]\right\}\mathcal{F}_0^1(kr)dr , \quad (22)$$

$$I_1 \to I_1 + \gamma \int_0^\infty \left\{ U\left[\frac{f^2}{6M}e^{-\mu r} + \frac{f^2}{3M}Y_2(\mu r) + 4\frac{f^2}{M}(\mu_v - \tfrac{1}{2})Y_1(\mu r)\right] + \frac{W}{\sqrt{2}}\left[\frac{f^2}{6M}e^{-\mu r} + \frac{f^2}{3M}Y_2(\mu r) - \frac{2f^2}{M}(\mu_v - \tfrac{1}{2})Y_1(\mu r)\right]\right\}\mathcal{F}_1^1(kr)dr , \quad (23)$$

TABLE III. Angular distribution parameters in μb/sr for the super soft core potential B in approximations I, II, and III.

E_γ (MeV)	Approximation	a	b	c	d	e
4.0	I	8.994	290.9	0.0279	25.19	0.5455
	II	10.50	291.0	0.0279	25.19	0.5455
	III	10.51	291.1	0.0222	25.20	0.5455
10.0	I	3.830	157.5	0.2472	29.59	1.392
	II	4.479	157.6	0.2472	29.59	1.392
	III	4.612	157.9	0.2414	29.62	1.392
16.0	I	4.219	84.97	0.4464	21.74	1.392
	II	4.618	85.21	0.4464	21.74	1.392
	III	4.889	85.58	0.4494	21.80	1.392
20.0	I	4.496	60.69	0.5441	17.92	1.321
	II	4.794	61.02	0.5441	17.92	1.321
	III	5.147	61.39	0.5554	17.98	1.321
50.0	I	4.525	10.64	0.7308	5.893	0.7895
	II	4.544	11.48	0.7308	5.893	0.7895
	III	5.242	11.66	0.8125	5.994	0.7895
100.0	I	3.054	1.671	0.5577	1.713	0.3762
	II	3.092	2.966	0.5577	1.713	0.3762
	III	3.883	2.810	0.7151	1.751	0.3762
150.0	I	2.042	0.4589	0.4160	0.7353	0.2164
	II	2.167	1.921	0.4160	0.7353	0.2164
	III	2.911	1.638	0.6118	0.7108	0.2164

$$I_{u_\tau}^2 \rightarrow I_{u_\tau}^2 + \gamma \int_0^\infty \left\{ U \left[\frac{f^2}{6M} e^{-\mu r} - \frac{f^2}{15M} Y_2(\mu r) \right] - \frac{W}{5\sqrt{2}} \left[\frac{f^2}{6M} e^{-\mu r} - \frac{11}{3} \frac{f^2}{M} Y_2(\mu r) - 30 \frac{f^2}{M} (\mu_v - \tfrac{1}{2}) Y_1(\mu r) \right] \right\} u_2^\tau dr , \tag{24}$$

$$I_{v_\tau}^2 \rightarrow I_{v_\tau}^2 + \gamma \int_0^\infty \left\{ W \left[\frac{f^2}{6M} e^{-\mu r} - \frac{f^2}{3M} Y_2(\mu r) \right] + \sqrt{2} \frac{f^2}{3M} Y_2(\mu r) U \right\} v_2^\tau dr , \tag{25}$$

where $\tau = (\alpha, \beta)$.

The cross section and polarization of the outgoing nucleon can be calculated by substituting these modified amplitudes into Eqs. (9.5)–(9.8) of RZBA, which have been worked out for a combination of spin functions that transform like the components of a vector, both for the initial as well as the final states and are written as

$$\sigma(\theta,\phi) = \mathscr{C}(k) \sum_{ij} | a_j |^2 | S_{ji}^\xi |^2 = \mathscr{C}(k) \bar{\sigma} , \tag{26}$$

$$P_{x'} \bar{\sigma} = 2\Sigma_i | a_i |^2 [\mathrm{Re}\{ (S_{0i}^\xi)^* S_{1i}^\xi \} + \mathrm{Im}\{ (S_{2i}^\xi)^* S_{3i}^\xi \}] , \tag{27}$$

$$P_{y'} \bar{\sigma} = 2\Sigma_i | a_i |^2 [\mathrm{Re}\{ (S_{0i}^\xi)^* S_{2i}^\xi \} + \mathrm{Im}\{ (S_{3i}^\xi)^* S_{1i}^\xi \}] , \tag{28}$$

$$P_{z'} \bar{\sigma} = 2\Sigma_i | a_i |^2 [\mathrm{Re}\{ (S_{0i}^\xi)^* S_{3i}^\xi \} + \mathrm{Im}\{ (S_{1i}^\xi)^* S_{2i}^\xi \}] , \tag{29}$$

where

$$\mathscr{C}(k) = 2\omega e^2 / \hbar c v . \tag{30}$$

The cross section and polarization of the outgoing nucleon for an unpolarized photon beam can be calculated by averaging the observables for the photon beam polarized along the x axis and the y axis.

The differential cross section and polarization of the outgoing nucleon with unpolarized gamma rays including all $E1$, $E2$, and $M1$ transitions may be expanded in powers of $\sin\theta$ and $\cos\theta$, and following RZBA,[14] may be written as

$$\sigma(\theta) = a + b \sin^2\theta \pm c \cos\theta \pm d \cos\theta \sin^2\theta + e \sin^2\theta \cos^2\theta , \tag{31}$$

$$\sigma(\theta) P_{x'}(\theta) = \sigma(\theta) P_{z'}(\theta) = 0 , \tag{32}$$

$$\sigma(\theta) P_{y'}(\theta) = A \sin\theta + B \sin\theta \cos\theta + C \sin\theta \cos^2\theta + D \sin\theta \cos^3\theta . \tag{33}$$

TABLE IV. Angular distribution parameters in μb/sr for the Hamada-Johnston potential in approximations I, II, and III.

E_γ (MeV)	Approximation	a	b	c	d	e
4.0	I	10.75	286.6	0.0340	25.42	0.5638
	II	12.58	286.7	0.0340	25.42	0.5638
	III	12.60	286.8	0.0262	25.42	0.5638
10.0	I	4.685	165.4	0.3058	30.83	1.440
	II	5.557	165.6	0.306	30.83	1.440
	III	5.688	166.0	0.2971	30.87	1.440
16.0	I	5.008	91.25	0.5578	22.90	1.440
	II	5.575	91.54	0.5580	22.90	1.440
	III	5.841	92.06	0.5576	22.97	1.440
20.0	I	5.309	65.87	0.6865	18.96	1.368
	II	5.747	66.25	0.6865	18.96	1.368
	III	6.094	66.80	0.6944	19.05	1.368
50.0	I	5.578	12.22	1.017	6.416	0.8302
	II	5.610	13.20	1.017	6.416	0.8302
	III	6.307	13.63	1.099	6.570	0.8302
100.0	I	4.154	2.073	0.9047	1.907	0.4200
	II	4.136	3.607	0.9050	1.906	0.4200
	III	4.945	3.645	1.073	2.017	0.4200
150.0	I	3.013	0.6667	0.7542	0.7722	0.2464
	II	3.097	2.385	0.7542	0.772	0.2464
	III	3.863	2.228	0.9554	0.8194	0.2464

TABLE V. Polarization parameters in μb/sr for protons (p) and neutrons (n) in approximations I, II, and III for the super soft core B and Paris potentials.

E_γ (MeV)	Approximation	Super soft core B A	B	C	D	Paris A	B	C	D
4.0	I (p)	−39.2	−1.26	0.020	0.00	−38.7	−1.19	0.022	0.00
	I (n)	−39.6	2.19	−0.020	0.00	−39.2	2.22	−0.022	0.00
	II (p)	−42.6	−1.41	0.020	0.00	−42.2	−1.35	0.022	0.00
	II (n)	−43.0	2.34	−0.020	0.00	−42.7	2.37	−0.022	0.00
	III (p)	−42.6	−1.41	+0.020	0.00	−42.2	−1.34	0.022	0.00
	III (n)	−43.0	2.34	−0.020	0.00	−42.7	2.38	−0.022	0.00
10.0	I (p)	−12.2	1.98	0.271	0.00	−12.5	2.23	0.296	0.00
	I (n)	−12.7	4.23	−0.271	0.00	−13.1	4.53	−0.296	0.00
	II (p)	−14.8	1.75	0.271	0.00	−15.2	1.98	0.296	0.00
	II (n)	−15.2	4.46	−0.271	0.00	−15.8	4.77	−0.296	0.00
	III (p)	−14.8	1.81	0.275	0.00	−15.3	2.04	0.296	0.00
	III (n)	−15.3	4.52	−0.275	0.00	−15.9	4.83	−0.296	0.00
16.0	I (p)	−6.12	3.72	0.488	−0.002	−6.41	3.97	0.522	−0.002
	I (n)	−6.49	5.08	−0.488	−0.002	−6.89	5.40	−0.522	−0.002
	II (p)	−8.09	3.50	0.488	−0.002	−8.55	3.74	0.522	−0.002
	II (n)	−8.46	5.30	−0.488	−0.002	−9.03	5.63	−0.522	−0.002
	III (p)	−8.16	3.60	0.499	−0.002	−8.62	3.84	0.533	−0.002
	III (n)	−8.52	5.40	−0.499	−0.002	−9.10	5.73	−0.533	−0.002
20.0	I (p)	−4.38	4.18	0.580	−0.004	−4.66	4.40	0.612	−0.004
	I (n)	−4.69	5.20	−0.580	−0.004	−5.07	5.48	−0.612	−0.004
	II (p)	−6.10	3.99	0.580	−0.004	−6.54	4.19	0.612	−0.004
	II (n)	−6.41	5.39	−0.580	−0.004	−6.95	5.69	−0.612	−0.004
	III (p)	−6.18	4.11	0.596	−0.004	−6.62	4.31	0.628	−0.004
	III (n)	−6.49	5.52	−0.596	−0.004	−7.02	5.81	−0.628	−0.004
50.0	I (p)	−1.20	3.25	0.669	0.00	−1.40	3.32	0.676	0.001
	I (n)	−1.25	3.45	−0.669	0.00	−1.48	3.56	−0.676	0.001
	II (p)	−2.16	3.19	0.669	0.00	−2.44	3.26	0.676	0.001
	II (n)	−2.22	3.51	−0.669	0.00	−2.52	3.62	−0.676	0.001
	III (p)	−2.28	3.39	0.706	0.00	−2.57	3.48	0.715	0.001
	III (n)	−2.31	3.71	−0.706	0.00	−2.62	3.85	−0.715	0.001
100.0	I (p)	−0.528	1.38	0.486	0.034	−0.676	1.49	0.515	0.038
	I (n)	−0.455	1.51	−0.486	0.034	−0.597	1.65	−0.515	0.038
	II (p)	−1.15	1.36	0.486	0.034	−1.32	1.47	0.515	0.038
	II (n)	−1.08	1.53	−0.486	0.034	−1.24	1.66	−0.515	0.038
	III (p)	−1.32	1.66	0.543	0.034	−1.51	1.82	0.582	0.038
	III (n)	−1.21	1.84	−0.543	0.034	−1.38	2.02	−0.582	0.038
150.0	I (p)	−0.333	0.641	0.341	0.047	−0.451	0.750	0.399	0.053
	I (n)	−0.266	0.777	−0.341	0.047	−0.377	0.932	−0.399	0.053
	II (p)	−0.833	0.596	0.341	0.047	−0.945	0.706	0.399	0.053
	II (n)	−0.766	0.822	−0.341	0.047	−0.871	0.976	−0.399	0.053
	III (p)	−1.03	0.956	0.415	0.047	−1.16	1.12	0.483	0.053
	III (n)	−0.921	1.18	−0.415	0.047	−1.03	1.39	−0.483	0.053

The plus sign (minus sign) refers to protons (neutrons). Knowing the cross section and polarizations at various angles, these coefficients can easily be calculated.

III. RESULTS AND DISCUSSION

Employing the results of Sec. II, we calculated the cross-section and polarization parameters for the following potentials: Yale, Hamada-Johnston, Hamada-Johnston (modified), Paris, and super-soft-core versions A, B, and C at various photon energies. These parameters are reported in three approximations at photon energies $E_\gamma = 4$, 10, 16, 20, 50, 100, and 150 MeV. In approximation I the exchange effects are neglected and a calculation parallel to that of RZBA is carried out. In approximation II the

TABLE VI. Polarization parameters in μb/sr for protons (p) and neutrons (n) in approximations I, II, and III for the Hamada-Johnston and Yale potentials.

		Hamada-Johnston				Yale			
E_γ (MeV)	Approximation	A	B	C	D	A	B	C	D
4.0	I (p)	−40.2	−1.42	0.017	0.00	−38.6	−1.19	0.022	0.00
	I (n)	−40.8	2.21	−0.017	0.00	−39.2	2.21	−0.022	0.00
	II (p)	−43.7	−1.57	0.017	0.00	−42.3	−1.35	0.022	0.00
	II (n)	−44.3	2.36	−0.017	0.00	−42.9	2.37	−0.022	0.00
	III (p)	−43.7	−1.56	0.017	0.00	−42.3	−1.35	0.022	0.00
	III (n)	−44.3	2.36	−0.017	0.00	−43.0	2.38	−0.022	0.00
10.0	I (p)	−13.9	1.63	0.256	0.00	−12.2	2.27	0.301	0.00
	I (n)	−14.7	4.20	−0.256	0.00	−13.0	4.54	−0.301	0.00
	II (p)	−16.8	1.37	0.256	0.00	−15.2	2.01	0.301	0.00
	II (n)	−17.6	4.46	−0.256	0.00	−15.9	4.81	−0.301	0.00
	III (p)	−16.8	1.42	0.259	0.00	−15.2	2.06	0.305	0.00
	III (n)	−17.6	4.50	−0.259	0.00	−16.0	4.86	−0.305	0.00
16.0	I (p)	−7.12	3.45	0.470	−0.002	−6.21	4.03	0.538	−0.001
	I (n)	−7.76	5.06	−0.470	−0.002	−6.84	5.44	−0.538	−0.001
	II (p)	−9.46	3.19	0.470	−0.002	−8.53	3.78	0.538	−0.001
	II (n)	−10.1	5.32	−0.470	−0.002	−9.16	5.70	−0.538	−0.001
	III (p)	−9.54	3.28	0.479	−0.002	−8.60	3.89	0.549	−0.001
	III (n)	−10.2	5.41	−0.479	−0.002	−9.23	5.80	−0.549	−0.001
20.0	I (p)	−5.14	3.99	0.565	−0.003	−4.50	4.46	0.634	−0.002
	I (n)	−5.69	5.22	−0.565	−0.003	−5.04	5.52	−0.634	−0.002
	II (p)	−7.21	3.76	0.565	−0.003	−6.55	4.23	0.634	−0.002
	II (n)	−7.76	5.46	−0.565	−0.003	−7.09	5.75	−0.634	−0.002
	III (p)	−7.29	3.87	0.578	−0.003	−6.63	4.36	0.650	−0.002
	III (n)	−7.84	5.57	−0.578	−0.003	−7.16	5.88	−0.650	−0.002
50.0	I (p)	−1.47	3.45	0.715	0.004	−1.35	3.33	0.704	0.005
	I (n)	−1.61	3.75	−0.715	0.004	−1.50	3.59	−0.704	0.005
	II (p)	−2.62	3.36	0.715	0.004	−2.49	3.26	0.704	0.005
	II (n)	−2.75	3.84	−0.715	0.004	−2.65	3.67	−0.704	0.005
	III (p)	−2.75	3.59	0.752	0.004	−2.63	3.51	0.745	0.005
	III (n)	−2.86	4.07	−0.752	0.004	−2.77	3.92	−0.745	0.005
100.0	I (p)	−0.723	1.64	0.575	0.042	−0.675	1.46	0.515	0.034
	I (n)	−0.659	1.86	−0.575	0.042	−0.651	1.65	−0.515	0.034
	II (p)	−1.42	1.62	0.575	0.042	−1.36	1.45	0.515	0.034
	II (n)	−1.36	1.89	−0.575	0.042	−1.33	1.66	−0.515	0.034
	III (p)	−1.62	2.00	0.648	0.042	−1.56	1.84	0.586	0.034
	III (n)	−1.50	2.27	−0.648	0.042	−1.49	2.04	−0.586	0.034
150.0	I (p)	−0.528	0.848	0.452	0.060	−0.493	0.719	0.393	0.048
	I (n)	−0.453	1.10	−0.452	0.060	−0.449	0.935	−0.393	0.048
	II (p)	−1.07	0.807	0.452	0.060	−0.999	0.697	0.393	0.048
	II (n)	−0.992	1.14	−0.452	0.060	−0.955	0.957	−0.393	0.048
	III (p)	−1.29	1.25	0.546	0.060	−1.22	1.23	0.483	0.048
	III (n)	−1.15	1.59	−0.546	0.060	−1.11	1.38	−0.483	0.048

current density effects owing to π, ρ, and ω meson exchanges are included. In approximation III the charge density effects owing to π-meson exchange are also included. Owing to the striking similarity between the parameters of the Yale and Hamada-Johnston (modified) potentials and among the parameters of the various versions of the super-soft-core potentials, only the parameters for the Yale and SSC-B potentials are reported.

The cross section parameters for protons for the various potentials are listed in Tables I—IV. It is clear from these

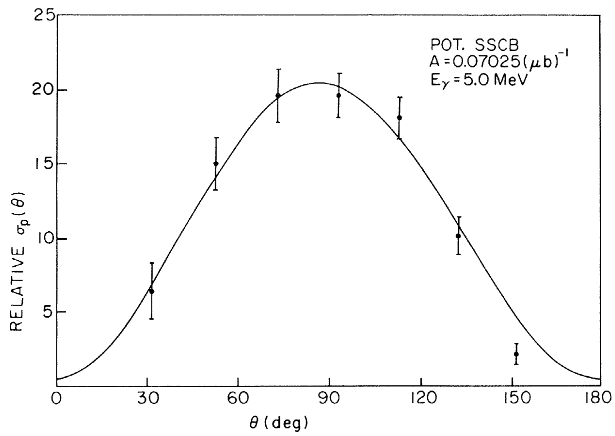

FIG. 2. Comparison of the present calculation in approximation III with the data of Fuller (Ref. 17) for the super soft core potential B. The normalization parameter is denoted by A.

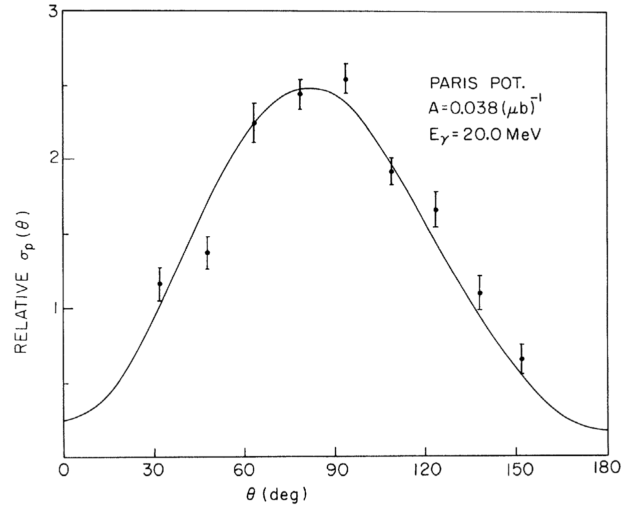

FIG. 4. Comparison of the present calculation in approximation III with the data of Halpern and Weinstock (Ref. 19) for the Paris potential. The normalization parameter is denoted by A.

tables that the current density only changes parameters a and b which only amounts to shifting the whole curve and changing the curve symmetrically about $\theta_{\mathrm{c.m.}}=90°$, whereas the charge density affects not only parameters a and b, but also changes parameters c and d. Thus, charge density can change the shape of the curve also. However, the changes owing to exchange effects at lower energies are too small to affect the curve significantly. At lower energies, potentials with a larger value of P_D are found to yield smaller values of parameter b. At higher energies, potentials with a larger percentage of D state give higher values of parameters a, b, and c. The change owing to exchange effects in all the parameters except d is found to be nearly the same for all the potentials. At higher energies the change in parameter d owing to exchange effects is small, but it has an opposite sign for the SSC-B and Yale potentials.

Tables V an VI list the polarizaton parameters of the outgoing proton and neutron for the Hamada-Johnston, Yale, SSC-B, and Paris potentials. Coefficients A and B are changed by both the charge and current density effects, but coefficient C is only changed by the charge effect. Different potentials yield slightly different values of the parameters. But the relative change owing to exchange effects in the parameters are nearly the same for all the potentials.

A comparison with the experimental data for the angular distribution, the polarization, and the asymmetry parameter is made in Figs. 2–6. All the potentials in approximation III reproduce the low energy angular distri-

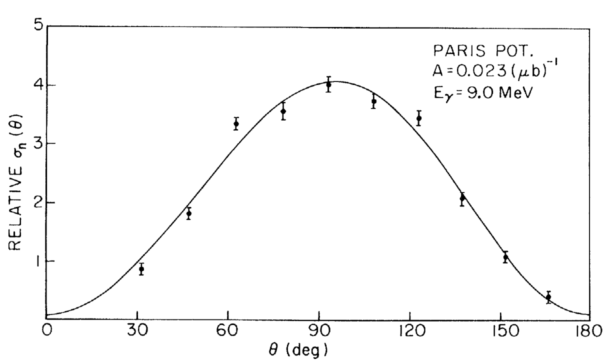

FIG. 3. Comparison of the present calculation in approximation III with the data of Bösch *et al.* (Ref. 18) for the Paris potential. The normalization parameter is denoted by A.

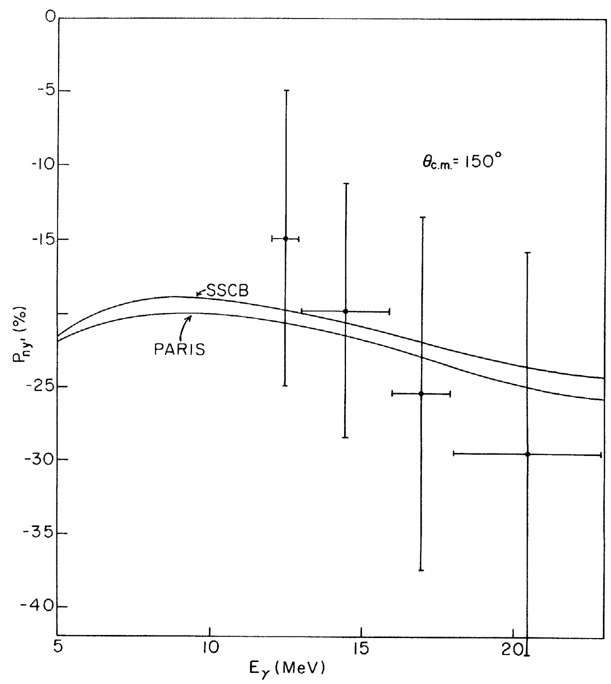

FIG. 5. Comparison of the present calculation in approximation III with the data of Frederick (Ref. 20) for the Paris and super soft core B potentials.

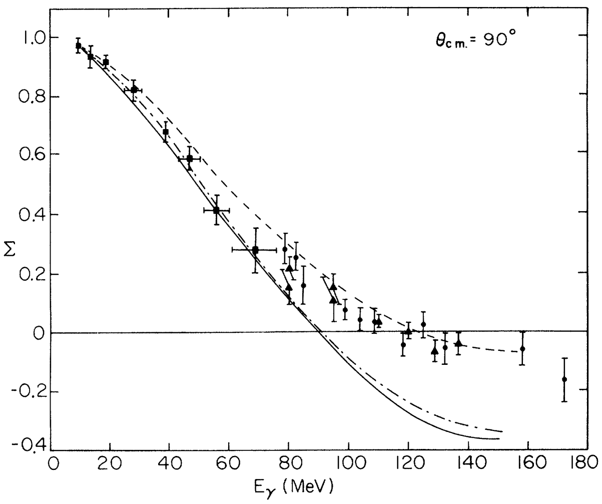

FIG. 6. Plot of $\Sigma(\theta)$ versus E_γ at $\theta_{\text{c.m.}}=90°$ for the Paris potential points which are taken from Refs. 24—26. The dashed line displays the theoretical results in approximation I, the dotted-dashed line in approximation II, and the solid line in approximation III.

bution quite well provided a normalization factor is used for each energy. The normalization factor, which is different for different potentials, is needed because the published cross sections are relative and not absolute. While the charge effects have a negligible effect at low energy (2.75—20 MeV), magnetic effects increase the cross section in the forward direction by about 12%, and by about 2% at 90°. The comparison with the polarization measurements (Fig. 5) cannot distinguish between the various potentials because of the large error bars on the measurements. However, there is clear evidence of a discrepancy between theory and experiment with the measurements of Jewell *et al.*[21] at $E_\gamma=2.75$ MeV, and of Nath *et al.*[22] and Holt *et al.*[23] for E_γ varying from 5.0 to 14 MeV at $\theta=90°$, as was pointed out earlier by Rustgi, Vyas, and Chopra.[9]

A comparison with the asymmetry measurements of Liu[24] and of Del Bianco *et al.*[25,26] is shown in Fig. 6. The two-body effects tend to lower the asymmetry in the cross section, and yield fine agreement between 10 and 70 MeV. The agreement is not improved in any significant way at the higher energies when the zero momentum limit of the exchange current operators is not made and the q^2 dependence of the exchange current operators[15] is included. Similar results are obtained with all the potentials.

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[1] D. O. Riska and G. E. Brown, Phys. Lett. 38B, 193 (1972).
[2] H. Hyuga, A. Arima, and K. Shimizu, Nucl. Phys. A336, 363 (1980).
[3] E. Hadjimichael, Phys. Rev. Lett. 31, 183 (1973).
[4] J. Hockert, D. O. Riska, M. Gari, and A. Huffman, Nucl. Phys. A217, 14 (1973).
[5] S. Rab and D. S. Koltun, Phys. Rev. C 26, 658 (1982).
[6] A. Cambi, B. Mosconi, and P. Ricci, Phys. Rev. C 23, 992 (1981); R. Vyas and M. L. Rustgi, *ibid.* 26, 1399 (1982).
[7] E. Hadjimichael, Phys. Lett. 46B, 147 (1973).
[8] H. Arenhövel, W. Fabian, and H. G. Miller, Phys. Lett. 52B, 303 (1974).
[9] M. L. Rustgi, R. Vyas, and M. Chopra, Phys. Rev. Lett. 50, 236 (1983); M. L. Rustgi and R. Vyas, Phys. Lett. 121, 365 (1983).
[10] T. Hamada and I. D. Johnston, Nucl. Phys. 34, 382 (1962).
[11] K. E. Lassila, M. H. Hull, Jr., H. M. Ruppel, F. A. McDonald, and G. Breit, Phys. Rev. 126, 881 (1962).
[12] R. deTourreil and D. W. L. Sprung, Nucl. Phys. A201, 193 (1973).
[13] M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côte, P. Pires, and R. deTourreil, Phys. Rev. C 21, 861 (1980).
[14] M. L. Rustgi, W. Zernik, G. Breit, and D. J. Andrews, Phys. Rev. 120, 1881 (1960).
[15] M. Chemtob and M. Rho, Nucl. Phys. A163, 1 (1971).
[16] B. Gobbi, J. L. Rosen, H. A. Scott, S. L. Shapiro, L. Straweznski, and C. M. Meltzer, Phys. Rev. Lett. 33, 1450 (1974).
[17] E. G. Fuller, Phys. Rev. 79, 303 (1950).
[18] R. Bösch, J. Lang, R. Müller, and W. Wölfle, Helv. Phys. Acta 36, 657 (1963).
[19] J. Halpern and E. V. Weinstock, Phys. Rev. 91, 934 (1953).
[20] D. E. Frederick, Phys. Rev. 130, 1131 (1963).
[21] R. W. Jewell, W. John, J. E. Sherwood, and D. H. White, Phys. Rev. 139, B71 (1965).
[22] R. Nath, F. W. K. Firk, and H. L. Schultz, Nucl. Phys. A194, 49 (1972).
[23] R. J. Holt, K. Stephenson, and J. R. Specht, Phys. Rev. Lett. 50, 577 (1983).
[24] F. F. Liu, Phys. Rev. 138, B1443 (1965).
[25] W. Del Bianco, H. Jeremie, M. Irshad, and G. Kajrys, Nucl. Phys. A343, 121 (1980).
[26] W. Del Bianco, L. Federici, G. Giordano, G. Matone, G. Pasquariello, P. Picozza, R. Caloi, L. Casano, M. P. De Pascale, L. Ingrosso, M. Mattioli, E. Poldi, C. Schaerf, P. Pelfer, D. Prosperi, S. Frullani, B. Giorlami, and H. Jermie, Phys. Rev. Lett. 47, 1118 (1981).