Note on the Photodisintegration of the Deuteron*

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The differential cross section $\sigma(\theta,\varphi)$ and proton polarization $P(\theta,\varphi)$ have been computed at γ-ray energies of 22.5, 32.8, 64.4, 107.8, 164.5, and 193.9 Mev. The nuclear force potential was a slightly modified form of that used by Signell and Marshak. In order to test recent claims regarding comparison with experiment not calling for the inclusion of effects of retardation and exchange currents, these effects have been neglected. The influence of the inclusion of different multipoles has been studied by employing successive approximations in which the transitions which are unimportant at low energies are introduced in turn. The inclusion of $M1$ transitions to triplets and of $E2$ effects has left discrepancies of several times the experimental error with data on σ at 65 and 108 Mev. The relative largeness of the effects of the transitions just mentioned at the higher energies complicates the employment of the photoeffect as a means of obtaining evidence regarding the nucleon-nucleon interaction.

THE differential cross section $\sigma(\theta,\varphi)$ and proton polarization $P(\theta,\varphi)$ have been computed for six gamma-ray energies in the range 20–200 Mev. Due to the complexity of this calculation at high energies the amplitudes were calculated directly and then combined numerically as described by Breit, Hull, and Ehrman[1,2] for nucleon-nucleon scattering. In the simpler cases the results were checked by independent analytic calculation.

Numerical radial wave functions for the n-p system were used for a potential of the Marshak-Signell type[3] with parameters adjusted in accordance with the work of Fischer, Pyatt, Hull, and Breit.[4]

Five approximations were used in order to determine the relative importance of the various transitions. In approximation A only the $E1$ transitions are considered and the coupling of $^3P_2$ to $^3F_2$ is neglected. The radial functions entering the P and F parts of the eigenstates originating adiabatically in pure P and F states were used. Although this procedure has no direct physical significance since the tensor term S_{12} was retained in the potential, it provides a useful check on account of simplifications in the formulas. In approximation B only $E1$ transitions are used with full account of the tensor coupling, and similarly in succeeding approximations S_{12} is fully considered. In approximation C the effect of $M1$ transitions to singlet states is considered in addition while in approximation D the effect of $M1$ transitions to triplets is used[5] as well. In approximation E there is further included the effect of $E2$ transitions to S, D and G states. The γ-ray energies quoted below are referred to the laboratory system. The plane-polarized γ ray is taken as incident along the positive z axis of a Cartesian coordinate system with electric vector along the x axis. The direction of the outgoing proton momentum defines the z' axis of a second coordinate system with θ and φ being the colatitude and azimuthal angles of z' with φ referred to x. The x' and y' axes have direction cosines $(\cos\theta\cos\varphi,\ \cos\theta\sin\varphi,\ -\sin\theta)$ and $(-\sin\varphi,\ \cos\varphi,\ 0)$, respectively. All directions are in the zero total momentum system.

The quantities $\sigma(\theta,\varphi)$ and $P(\theta,\varphi)$ were calculated numerically for $\varphi=0$, $\varphi=90°$ for linearly polarized and unpolarized γ rays. In approximations A, B, C, and E formulas were obtained for these quantities in terms of θ and φ. The components of polarization were computed in the primed coordinate system.

TABLE I. Angular distribution and polarization parameters in microbarns/steradian for approximations A and B.

E_γ	Approximation A			Approximation B		
Mev	a_E	b_E	B_E	a_E	b_E	B_E
22.5	4.68	50.7	5.55	4.92	51.0	5.25
32.8	5.06	28.1	5.28	5.42	28.3	4.87
64.4	4.46	6.40	3.00	5.31	6.74	2.87
107.8	3.09	1.40	1.50	3.95	1.79	1.60
164.5	1.90	0.170	0.715	2.69	0.639	0.942
193.9	1.58	0.00	0.546	2.27	0.672	0.811

TABLE II. Additional angular distribution and polarization parameters in microbarns/steradian for approximation C.

E_γ (Mev)	a_M	b_M	A_{EM}	E_{EM}	G_{EM}
22.5	0.308	0.737	−4.69	−1.22	−3.48
32.8	0.0969	0.838	−2.99	0.330	−1.87
64.4	0.021	0.886	−1.40	1.38	−0.762
107.8	0.0939	0.769	−0.853	1.33	−0.565
164.5	0.124	0.579	−0.618	1.03	−0.486
193.9	0.121	0.492	−0.533	0.874	−0.473

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[1] G. Breit and M. H. Hull, Jr., Phys. Rev. **97**, 1047 (1955).

[2] Breit, Ehrman, and Hull, Phys. Rev. **97**, 1051 (1955).

[3] P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958), referred to as SM.

[4] Fischer, Pyatt, Hull, and Breit, Bull. Am. Phys. Soc. Ser. II, **3**, 183 (1958). For singlet even states μ, the reciprocal of the SM range parameter, was reduced by 16% and the depth parameter correspondingly. The core radius for triplet odd states was $x_c=0.408$ in the notation of SM. The SM spin-orbit potential was used in all but the triplet even states. Alternative calculations including the $\mathbf{L}\cdot\mathbf{S}$ effect in these states are in progress.

[5] The transition $^3D_1\rightarrow{}^3D_2$ has been considered here for the first time.

TABLE III. Angular distribution parameters and total cross section in approximation E. The coefficients are in microbarns/steradian and σ_T in microbarns.

E_γ (Mev)	a	b	c	d	e	f	σ_T
22.5	5.33	51.8	0.913	15.9	1.24	50.3	503
32.8	5.68	29.2	1.15	11.3	1.12	27.5	318
64.4	5.62	7.51	1.16	4.85	0.775	5.83	135
107.8	4.37	2.41	1.06	2.41	0.514	1.06	76.0
164.5	3.13	1.07	0.946	1.37	0.312	0.132	48.8
193.9	2.70	1.01	0.946	1.20	0.258	0.267	42.9

In approximations A and B

$$\sigma = a_E + b_E(1+\cos 2\varphi)\sin^2\theta, \tag{1.1}$$

$$\sigma(P_x)' = B_E \sin\theta \sin 2\varphi, \tag{1.2}$$

$$\sigma(P_y)' = B_E(1+\cos 2\varphi)\sin\theta\cos\theta, \tag{1.3}$$

The z' component of P vanishes. The quantities a_E, b_E and B_E are tabulated in Table I. In approximation C

$$\sigma = a_E + b_E \sin^2\theta(1+\cos 2\varphi) + a_M + b_M \sin^2\theta(1-\cos 2\varphi), \tag{2.1}$$

$$\sigma(P_x)' = B_E \sin\theta \sin 2\varphi + E_{EM} \sin\theta\cos\theta \sin 2\varphi, \tag{2.2}$$

$$\sigma(P_y)' = B_E \sin\theta\cos\theta(1+\cos 2\varphi) + A_{EM}\sin\theta + E_{EM}\sin\theta\cos 2\varphi, \tag{2.3}$$

$$\sigma(P_z)' = G_{EM}\sin^2\theta \sin 2\varphi, \tag{2.4}$$

with additional parameters as in Table II. In approximation E

$$\sigma = a + b\sin^2\theta + c\cos\theta + d\cos\theta\sin^2\theta + e\sin^2\theta\cos^2\theta + \cos 2\varphi(f\sin^2\theta + d\cos\theta\sin^2\theta + e\sin^2\theta\cos^2\theta), \tag{3.1}$$

which gives for the total cross section

$$\sigma_T = 4\pi a + 8\pi b/3 + 8\pi e/15. \tag{3.2}$$

The coefficients and the total cross section are shown in Table III. The three components of the polarization in approximation E can be expressed as:

$$\sigma(P_x)' = \{L\sin\theta + M\sin\theta\cos\theta + N\sin\theta\cos^2\theta\}\sin 2\varphi, \tag{3.3}$$

$$\sigma(P_y)' = A\sin\theta + B\sin\theta\cos\theta + C\sin\theta\cos^2\theta + D\sin\theta\cos^3\theta + \cos 2\varphi\{E\sin\theta + F\sin\theta\cos\theta + C\sin\theta\cos^2\theta + D\sin\theta\cos^3\theta\}, \tag{3.4}$$

$$\sigma(P_z)' = \{G\sin^2\theta + H\cos\theta\sin^2\theta\}\sin 2\varphi. \tag{3.5}$$

These coefficients are shown in Table IV.

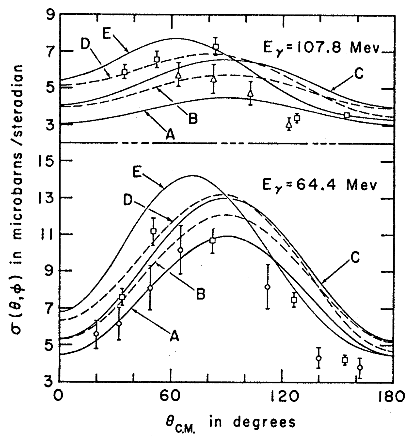

FIG. 1. Differential cross section for the $D(\gamma,n)p$ reaction with unpolarized gamma rays of energy 64.4 Mev and 107.8 Mev in the laboratory system. The experimental points of various investigators are represented as follows: circles for those of L. Allen, Jr., at 66 Mev [Phys. Rev. **98**, 705 (1955)]; squares for those of Whalin, Schriever, and Hanson at 65 and 105 Mev [Phys. Rev. **101**, 377 (1956)]; triangles for those of J. C. Keck and A. V. Tollestrup at 105 Mev [Phys. Rev. **101**, 360 (1956)].

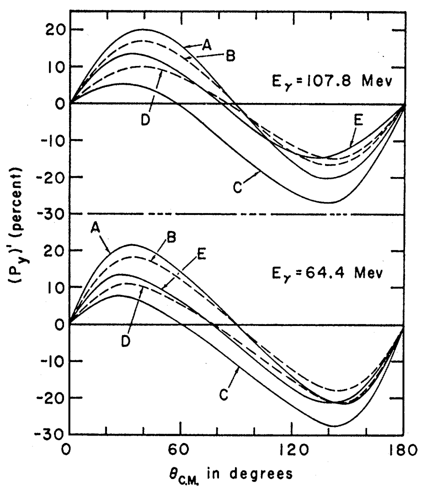

FIG. 2. Percentage polarization of protons from the $D(\gamma,n)p$ reaction with unpolarized gamma rays of energy 64.4 Mev and 107.8 Mev in the laboratory system.

The results for unpolarized γ rays are obtained by integrating over φ. In this case $(P_x)'$ and $(P_z)'$ vanish as is required by parity conservation.

In Figs. 1 and 2 are shown some typical intercomparisons of the different approximations and in the case

TABLE IV. Polarization parameters in microbarns/steradian for approximation E.

E_γ (Mev)	A	B	C	D	E	F	G	H	L	M	N
22.5	−3.74	5.03	0.857	0.0029	−0.180	5.02	−3.05	−0.529	5.22	0.678	−0.202
32.8	−2.16	4.78	1.02	0.0030	1.17	4.91	−1.96	−0.387	4.95	2.19	−0.0323
64.4	−0.657	2.78	1.09	0.0556	1.93	3.26	−1.59	−0.286	3.08	3.02	0.234
107.8	−0.246	1.42	0.927	0.126	1.74	2.10	−1.32	−0.326	1.79	2.67	0.439
164.5	−0.154	0.714	0.671	0.149	1.38	1.41	−0.972	−0.352	1.05	2.05	0.507
193.9	−0.106	0.587	0.601	0.146	1.22	1.25	−0.856	−0.343	0.888	1.81	0.503

of Fig. 1 some available experimental values are shown as well.

The results for σ in approximation A are reasonably consistent with those of De Swart and Marshak[6] for a slightly different potential. The values of P with unpolarized 64-Mev γ rays are qualitatively similar to those of Czyż and Sawicki[7] from a less accurate calculation. Comparison of approximations C and D for σ shows appreciable effects of the inclusion of $M1$ transitions to triplet states and for P these effects are seen to be major. Similarly the effect of including $E2$ is appreciable for σ even at 30 Mev and is non-negligible for P at 65 Mev.

The variety of effects of interference terms on angular distribution curves indicates some difficulty in arriving at conclusions concerning the participation of virtual meson states from comparisons with experiment, since modifications in assumptions regarding the nucleon-nucleon interaction produce appreciable effects at the higher energies, lack of a really quantitative agreement at the lower energies and as yet inconclusive evidence regarding the goodness of the potential used for the representation of nucleon-nucleon scattering.

Note added in proof.—The conversion of γ-ray laboratory energy to equivalent neutron laboratory energy in a scattering experiment was made in the work reported on above employing the same recoil correction as in de Swart and Marshak.[6] Soon after submission for publication it was noticed however that a complete relativistic consideration shows that with ample accuracy the γ-ray energy is the deuteron separation energy plus one half of the neutron energy. The formula is

$$h\nu = \epsilon \frac{1-(\epsilon/4Mc^2)}{1-(\epsilon/2Mc^2)} + \frac{T_{\text{lab}}{}^n/2}{1-(\epsilon/2Mc^2)},$$

where ϵ is the deuteron separation energy $\cong 2.23$ Mev and the other symbols have their usual meaning. Accordingly

$$T_{\text{lab}}{}^n = 2(h\nu-\epsilon) - (2h\nu-\epsilon)(\epsilon/2Mc^2),$$

and the correction to the main term is of the order of -0.1%. On reexamination of the data employing the change in the correction somewhat better agreement with experiment results especially at the higher energies. The γ-ray energies corresponding to 22.5, 32.8, 64.4, 107.8, 164.5, 193.9 Mev in Tables I, II, III, and IV become with the changed correction 22.2, 32.2, 62.2, 102.2, 152.2, 177.2 Mev, respectively.

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[6] J. J. De Swart and R. E. Marshak, Phys. Rev. **111**, 272 (1958). Related calculations using the Gammel-Thaler potential have been made by A. F. Nicholson and G. E. Brown, Bull. Am. Phys. Soc. Ser. II, **3**, 172 (1958) with conclusions similar to those of de Swart and Marshak.

[7] W. Czyż and J. Sawicki, Phys. Rev. **110**, 900 (1958). While no attempt has been made to check all of the terms given by these authors, it appears that the following changes should be made. In $A4$ the over-all sign should be changed and the numerical factor multiplying the second square bracket doubled. Further the coefficient of the third term in the second square bracket should be "$-\frac{4}{3}$." In $B9$ the coefficients in the second and third terms should be "2" and "$\frac{5}{8}$," respectively.