results being in agreement with the exact computations of Rarita and Schwinger[3]):

$$\frac{\sigma_{e,\ \mathrm{tensor}}}{\sigma_e}=\frac{1}{1+bq^2}\left\{1+\frac{5}{18}q^2\left(1+\frac{3}{5}\frac{\hbar\omega-W_1}{W_1}\right)^2\right\}, \tag{2}$$

where q is the ratio of the D component of the ground state wave function to the S component at $r=r_t$, and b is given by:

$$b=\frac{1}{9}+\frac{2}{3}\frac{(1+\alpha r_t)^2}{(\alpha r_t)^3}. \tag{3}$$

In the energy region considered, the total cross section is decreased slightly by the inclusion of tensor forces. For $r_t=2.8\times10^{-13}$ cm, the correction is less than two percent, and for $r_t=1.8\times10^{-13}$ cm, the correction is less than five percent.

The angular distribution for unpolarized γ-rays, in the center-of-mass system is given by:†

$$f(\theta)=a+\sin^2\theta(1+2\beta\cos\theta),\quad \beta=\frac{v}{c}=\left\{\frac{\hbar\omega-W_1}{Mc^2}\right\}^{\frac{1}{2}}. \tag{4}$$

The term $2\beta\cos\theta$, which is a correction of the first order in β, arises from interference between electric dipole and electric quadrupole terms and leads to a distinct asymmetry.‡ In the laboratory system the finite momentum of the incident photon will introduce a further asymmetry. The distribution corresponding to (4) can be obtained by replacing $\sin^2\theta$ by:

$$\sin^2\theta\left[1+2\beta\left(1+\frac{W_1}{\hbar\omega-W_1}\right)\cos\theta\right]. \tag{5}$$

The photoelectric part of the angular distribution (4) in the laboratory system is identical with that obtained by Sommerfeld for atomic hydrogen, because of the kinematic nature of the retardation effect which is independent of the particular atomic or nuclear system involved. It is of interest to point out that this asymmetry sets in at energies as low as 10 Mev, while qualitatively one would expect the quadrupole term to play a role around 70 Mev where $\lambda\!\!\!^{-}=r_t$.

The data obtained by Fuller[1] indicate that the total cross section decreases less rapidly with energy than that given by Eq. (1), but by fitting at 13 Mev rather than at 7 Mev as he has done, Eq. (1) is found to yield agreement within the experimental error. However, the large statistical errors in these data do not permit any definite conclusions in this respect. (The approximate expression (2) and the exact calculations of Hu and Massey[4] indicate that at energies greater than 20 Mev the cross section should fall off less rapidly than indicated by (1), because of the influence of tensor forces. In the energy range of Fuller's experiments, however, this effect should not be important.) In Fig. 1 the angular distribution (4) ($f(\theta)$), (computed for $\hbar\omega=17$ Mev) in the laboratory system, is compared with Fuller's data ($F(\theta)$) for the energy range 14.0 to 20.3 Mev. It is seen that the agreement is quite good but the experimental error is too large to justify any definite conclusions.

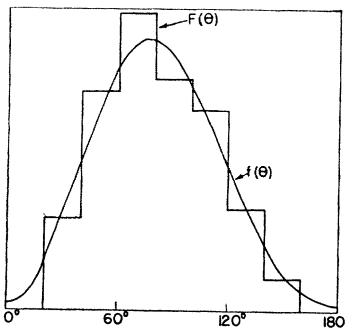

FIG. 1. Comparison of the angular distribution $f(\theta)$ with Fuller's data $F(\theta)$ in the energy range 14.0 to 20.3 Mev.

Further experiments in this energy region would certainly have considerable significance, since they would yield information on the following aspects of the N-P interaction.

(a) Percentage mixture. Rarita and Schwinger and Hu and Massey have shown that the magnitude of the isotropic term in Eq. (2) is very sensitive to the choice of mixture. (For zero percent charge exchange $a=0.4$ at 17.5 Mev, while for mixtures near 50-50, $a=0.02$ including magnetic dipole contributions.) Furthermore the asymmetry in the angular distribution will be greater for pure ordinary forces than that given by (4).

(b) Range of the N-P interaction. Since the magnitude of the total cross section (for intermediate energies) depends only on the triplet well radius and on the deuteron binding energy, measurements of total cross sections should give a good indication of the range of the N-P interaction.

A more complete treatment including the influence of the shape of the interaction potential and a more detailed analysis of the effect of tensor forces is in preparation.

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† This expression is rigorously correct for zero-range N-P interaction, but for energies up to 20 Mev it is an excellent approximation for both square-well and Hulthen potentials.

‡ There is some confusion about this asymmetry in the literature. A. Pais [Kgl. Danske Vid. Sels. Math.-fys. Medd. Bind 20, No. 17 (1943)] and J. M. Jauch [Phys. Rev. **69**, 276 (1946)] conclude that there can be no interference between terms corresponding to final states of different parity because such states correspond to different isotopic spin functions. However, L. Rosenfeld [*Nuclear Forces* (Interscience Publishers, Inc., New York, 1949), Vol. I, p. 47] and others have shown that the inclusion of isotopic spin and the assumption that proton and neutron are simply different states of the same nucleon leads to the same results in any physical processes as the assumption that proton and neutron are distinct particles. We wish to thank Dr. L. L. Foldy for an illuminating discussion of this isotopic spin formalism.

[1] E. G. Fuller, Phys. Rev. **76**, 576 (1949).

[2] W. Hepner and R. Peierls, Proc. Roy. Soc. **A181**, 43 (1942).

[3] W. Rarita and J. Schwinger, Phys. Rev. **59**, 436, 556 (1941).

[4] Tsi-Ming Hu and H. S. W. Massey, Proc. Roy. Soc. **A196**, 135 (1949).

High Energy Photo-Disintegration of the Deuteron

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COMPUTATIONS of total cross sections and angular distributions for the photo-disintegration process have been carried out for square-well radii of 1.8 and 2.8×10^{-13} cm in the energy range 20–100 Mev, and for zero radius in the range 20–300 Mev on the following assumptions.

(a) The electromagnetic interaction is represented by $\mathbf{E}\cdot\mathbf{r}$ (rather than $\mathbf{A}\cdot\mathbf{v}$) and $\boldsymbol{\mu}\cdot\mathbf{H}$ for electric and magnetic dipole

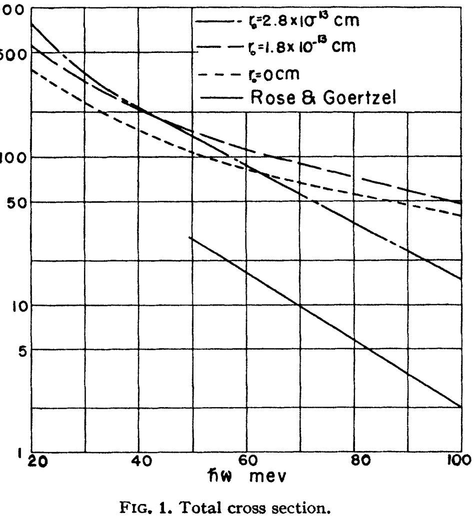

FIG. 1. Total cross section.

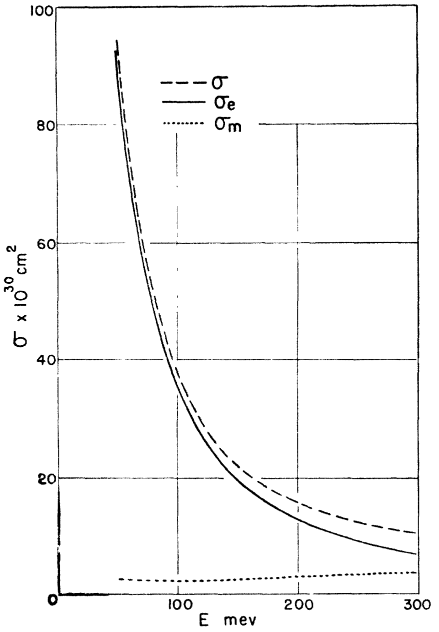

FIG. 2. Zero-range cross sections including all multipoles.

transitions, respectively, and by equivalent expressions for higher poles.[†]

(b) The wells for the triplet and singlet states are assumed to have the same radius ($r_0=r_t=r_s$). This assumption is probably a fair approximation for energies up to 100 Mev.

(c) A 50-50 mixture of ordinary and Majorana forces is assumed for both triplet and singlet states and the outgoing nucleon is consequently free, by hypothesis, for transitions to states of odd parity.[‡] For final states of even parity the effect of binding is included. The results of these computations are as follows:

I. Total cross section.—Total cross sections for the three radii are shown in Fig. 1 in the energy range 20–100 Mev. (The total cross sections obtained by Rose and Goertzel are also shown in the energy range 50–100 Mev.) It is found that only a few multipoles (electric and magnetic dipole and quadrupole) need be considered, and even at 100 Mev the electric dipole contribution accounts for more than 90 percent of the total cross section for all radii considered. The values of the total cross section at this energy are $\sigma_{\mathrm{tot}}=15.0$, 48.0, 40.0×10^{-30} cm² for $r_0=2.8$, 1.8, and zero, respectively. Interference between initial and final state wave functions is quite important, $\sigma(2.8)$ being smaller than $\sigma(0)$ because of *destructive* interference, while $\sigma(1.8)$ (1.8×10^{-13} cm is now considered the best value of r_t) is larger than $\sigma(0)$ because of constructive interference. Binding in the even states decreases the importance of magnetic dipole and electric quadrupole contributions considerably. For example, at 100 Mev electric quadrupole transitions ($^3S-{}^3D$) account for only two percent of the cross section for $r_0=2.8$ and for four percent for $r_0=1.8$. The value of $\sigma(2.8)$ at 100 Mev is eight times larger than that obtained by Rose and Goertzel for the same radius. Figure 2 shows the total cross section including all multipoles for $r_0=0$ and for energies from 50–300 Mev. Electric and magnetic contributions are shown separately, and it can be seen that while magnetic contributions are unimportant at 100 Mev they become increasingly significant at higher energies.

II. Angular distribution.—The angular distribution of the photo-protons ($f(\theta)$) at 100 Mev for $r_0=2.8\times10^{-13}$ cm (in the energy region considered, the angular distribution is not very sensitive to the choice of r_0) and a 50-50 mixture is shown in Fig. 3 along with Rose and Goertzel's result ($F(\theta)$) for a 100–0 mixture. As can be seen, there is a slight asymmetry in the forward direction because of interference between electric dipole and quadrupole terms. This asymmetry is not very great, however, because binding in the D state reduces the quadrupole cross section. The asymmetry would be very pronounced for a 100–0 mixture, as indicated by the Rose and Goertzel distribution which, however, is not exact because the effect of binding in final states is quite important.

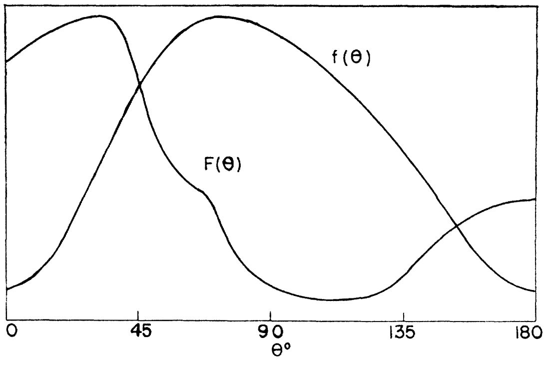

FIG. 3. Angular distribution.

The wide divergence between these results and those reported by Rose and Goertzel both in total cross section and in angular distribution (see Figs. 1 and 3) can be traced to the large difference between the $\mathbf{A}\cdot\mathbf{v}$ and $\mathbf{E}\cdot\mathbf{r}$ "types" of interaction which are equivalent for a 100–0 mixture but not for a 50-50 mixture.

The present results indicate that the following information about the N-P interaction might be obtained from experiments on the high energy photo-disintegration of the deuteron:

(a) Since the total cross section is sensitive to the choice of radius, the magnitude of the total cross section should provide some information about the range of the N-P interaction.

(b) Since the angular distribution is very sensitive to the mixture (see Fig. 3) and relatively insensitive to the choice of radius, information could be obtained about the ratio of ordinary to exchange forces.

Consequently, it would be quite interesting to check the theoretical trend indicated by Figs. 1–3 using the various betatrons and synchrotrons spanning the range from 10–300 Mev.[¶]

A detailed report of the photo-disintegration of the deuteron, including the energy range 2.2–10 Mev is in preparation. The effects of relativity corrections, tensor forces and the long-range tail of the N-P interaction will also be discussed.[||]

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[†] It has been found [A. F. Siegert, Phys. Rev. **52**, 787 (1937); R. G. Sachs, Phys. Rev. **74**, 433 (1948); C. Møller and I. Rosenfeld, Kgl. Danske, Vid. Sels. Math.-fys. Medd. Bind 20, No. 12 (1943)] that for low energies $\mathbf{E}\cdot\mathbf{r}$ is equivalent to $\mathbf{A}\cdot\mathbf{v}$ *plus* interaction with exchange currents. It has also been shown [L. Rosenfeld, *Nuclear Forces* (Interscience Publishers, Inc., New York, 1949), Vol. II, p. 449] that at low energies the electromagnetic interaction with the magnetic moments of the nucleons is correctly given by $\boldsymbol{\mu}\cdot\mathbf{H}$. The expressions $\mathbf{E}\cdot\mathbf{r}$ and $\boldsymbol{\mu}\cdot\mathbf{H}$ are consequently correct for electric and magnetic dipole and transitions which alone play a role at low energies. For higher energies, however, there is at present no unique expression for the electromagnetic interaction. Thus, for higher poles the interaction will depend upon the details of the meson field theory assumed, but at any rate, since one has to correct $\mathbf{A}\cdot\mathbf{v}$ for exchange currents, expressions of the $\mathbf{E}\cdot\mathbf{r}$ type are probably better approximations than $\mathbf{A}\cdot\mathbf{v}$.

[‡] This problem has been treated by M. E. Rose and G. Goertzel [Phys. Rev. **72**, 749 (1947)] for ordinary N-P interaction and an electromagnetic interaction of the form $\mathbf{A}\cdot\mathbf{v}$ on the assumption that the outgoing nucleons can be treated as free for energies above 50 Mev. For ordinary forces, electromagnetic interactions of the form $\mathbf{E}\cdot\mathbf{r}$ and $\mathbf{A}\cdot\mathbf{v}$ are equivalent but for exchange forces they lead to radically different results. Rose and Goertzel's results are shown in Figs. 1 and 3, since they indicate the results to be expected for ordinary N-P interaction.

[¶] The Compton effect on the proton will be of some importance at the higher energies. However, the Compton cross section has been found to be considerably smaller than the photo-cross section [J. L. Powell, Phys. Rev. **74**, 1258 (1948); L. L. Foldy and R. G. Sachs (private communication)]. Furthermore, if an energy-sensitive detector is used the Compton particles will be eliminated automatically.

[||] According to R. S. Christian and R. Serber the high energy N-P scattering results are best fitted by long-range potentials of the Yukawa and exponential type. These potentials can be simulated by two-step square well, used previously for low energy scattering by Bohm and Richman.