Photoejection of High-Energy Nucleons from Nuclei and the Quasi-Deuteron Model. I. Cross Sections and Angular Distributions*

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Experiments are described on the photoproduction of high energy neutron-proton pairs from complex nuclei. The results provide further confirmation and some clarification of the quasi-deuteron model of Levinger.

In these experiments targets of D, Li, and O are bombarded by a 340-Mev bremsstrahlung beam. In one set of measurements, intended to check the kinematical features of the model, we have observed the angular spread of the $n-p$ coincidences which arises from the momentum distribution of nucleons in the complex nuclei. These observations were preliminary to the main group of measurements, which consisted in a direct comparison of the cross sections and angular distributions of quasi-deuteron disintegrations for Li and O to those from D for 260-Mev photons. (A more limited group of measurements are reported for 200-Mev photons.)

The results of these observations indicate that the quasi-deuteron photodisintegration proceeds through the same mechanisms as are responsible for the photodisintegrations of free deuterons at the energies investigated. However, a quantitative understanding of the data, especially for the cross-section ratios, required an analysis of the effects of scattering of the emerging nucleons in the target nuclei. Qualitative arguments concerning these effects are given herein; the more quantitative discussion is postponed to a future communication.

INTRODUCTION

EARLY experiments[1,2] on the photoejection of high-energy protons from complex nuclei led to the proposal, by Levinger,[3] of a quasi-deuteron model for the high-energy nuclear photoeffect. According to Levinger's model, the photon is pictured as interacting with two nucleons in the nucleus; the ejection of high-energy nucleons is thus caused, at least in part, by the same processes as lead to the photodisintegration of the deuteron. However, the kinematics of the quasi-deuteron photodisintegration are modified by the internal motion of the nucleons in the nucleus.

Subsequent measurements of the energy and angular distributions of the high-energy photoprotons[4–7] tended to confirm the Levinger model, although a number of discrepancies appeared to exist between the experimental results and the theoretical predictions.[7] Convincing evidence for the quasi-deuteron model was supplied by the observation, by Barton and Smith[8] and by our group,[9] of neutrons, in coincidence with the photoprotons from lithium and carbon, with the kinematical relationships appropriate to the photodisintegration of the deuteron. These events were observed in sufficient number to account for the major portion (if not all) of the photodisintegrations which yield high-energy nucleons.

Following the initial measurements, which established the validity of the quasi-deuteron model, we have undertaken a series of experiments with the dual purpose of further elucidating the nature of the quasi-deuteron disintegration mechanism and of exploring the possible usefulness of this photodisintegration process as a tool for the investigation of nuclear structure—in particular, the momentum distributions of nucleons in complex nuclei. With these ends in mind, the following measurements have been undertaken:

1. The angular and energy dependence of the cross section for the quasi-deuteron photodisintegration as compared to the free deuteron photoeffect;
2. The angular distributions (spread) of the neutrons in coincidence with protons emitted at various angles and energies;
3. Dependence of the processes under investigation on atomic number;
4. The possible photoemission of proton-proton pairs.

This paper consists of two parts. First is a fuller report on preliminary experiments which we feel establish the validity of the quasi-deuteron model. The second part is a report on results concerning the mechanisms of the quasi-deuteron photodisintegration. The latter part is based mainly on the results obtained under item 1, although some data under items 2 and 3 are required in the interpretation, and they will be given when needed. Subsequent publications will deal with the interpretation of these data; one will concern the distribution of nuclear momenta in complex nuclei (from item 2) and a second will deal with the effects of nuclear size on the

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[1] D. Walker, Phys. Rev. **81**, 634 (1951).

[2] C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951).

[3] J. S. Levinger, Phys. Rev. **84**, 43 (1951).

[4] J. C. Keck, Phys. Rev. **85**, 410 (1952).

[5] J. W. Rosengren and J. M. Dudley, Phys. Rev. **89**, 603 (1953).

[6] J. W. Weil and B. D. McDaniel, Phys. Rev. **92**, 391 (1953).

[7] Feld, Godbole, Odian, Scherb, Stein, and Wattenberg, Phys. Rev. **94**, 1000 (1954).

[8] M. Q. Barton and J. H. Smith, Phys. Rev. **95**, 573 (1954).

[9] Myers, Odian, Stein, and Wattenberg, Phys. Rev. **95**, 576 (1954).

observations (item 3). Preliminary results relating to item 4 have already been published.[10]

All of these investigations were performed using, as a photon source, the 340-Mev bremsstrahlung beam from the Massachusetts Institute of Technology synchrotron.[7]

THEORETICAL CONSIDERATIONS

In comparing the energy and angular distributions of the photodisintegration of the quasi-deuterons in complex nuclei with those of the free deuteron, it is expected that information may be obtained concerning differences between the processes responsible for the two phenomena. Such differences might be expected to arise, mainly, from two causes. In the first place, the distributions, both in space and in their relative momenta, of the two nucleons comprising the quasi-deuteron will be different from the corresponding distributions in the free deuteron. Secondly, the neutron and proton of the quasi-deuteron may be in a relative singlet S-state, or a P-state, as well as in the triplet S-state which is characteristic of the free deuteron.

The experimental evidence on the photodisintegration of the free deuteron is now fairly complete over a range extending from threshold to $\sim$450-Mev photon energy. In the low-energy range,[11] extending to $\sim$10 Mev above threshold, the process is predominantly electric dipole absorption (except very close to threshold) with a characteristic $\sin^2\theta$ angular distribution; all of its features are well understood in terms of the conventional theories of the neutron-proton forces. Schiff[12] and Marshall and Guth[13] have extended the low-energy calculations to photon energies of $\sim$100 Mev, assuming that the nucleon-nucleon forces are describable by the same type of potential as is required at low energies. Their calculations predict a cross section which decreases rapidly and monotonically with increasing photon energy, and which has an angular distribution which remains predominantly $\sin^2\theta$. The observed cross section shows marked deviations from this theory, even at the relatively low photon energy of $\sim$20 Mev,[14] mainly in that the angular distribution exhibits an appreciable isotropic term together with a marked asymmetry about 90°. At somewhat higher energies,[15–19] these deviations become much more marked, both in the values of the cross section (considerably higher than predicted) and in the angular distributions.

In his original calculations on the quasi-deuteron process,[3] Levinger assumed the results of Schiff[12] and Marshall and Guth[13] for the free-deuteron cross section. At the same time, in order to simplify the computations, he neglected any possible difference between the singlet and triplet n-p cross sections. The result of this computation was

$$\sigma = 6.4(NZ/A)\sigma_D{}^{\text{th}}, \tag{1}$$

where σ is the cross section for n-p production from the complex nucleus of atomic number Z and atomic weight A, $N=A-Z$, and $\sigma_D{}^{\text{th}}$ is the above-mentioned theoretical free-deuteron photodisintegration cross section. Levinger also computed the energy and angular distributions of the resulting photoprotons assuming a $\sin^2\theta$ angular distribution for the photodisintegration process and an incident bremsstrahlung photon spectrum.

As first pointed out by Rosengren and Dudley,[5] the main discrepancies between the observations on the high-energy photoprotons and the predictions of Levinger are greatly reduced by the simple expedients of substituting the observed[15–19] σ_D for $\sigma_D{}^{\text{th}}$ in Eq. (1) and using the observed angular distributions instead of the assumed $\sin^2\theta$ distribution for the free-deuteron process.

However, in so altering the Levinger theory to fit the observations, it must be recognized that considerable violence is being done to certain of the assumptions employed in obtaining Eq. (1). It is inherent in the Levinger calculation that the high momenta associated with the process under consideration reflect the presence of such high momentum components in the wave function of the original free deuteron or quasi-deuteron. Indeed, it is the sparsity of these high momentum components which accounts for the rapid falling-off of $\sigma_D{}^{\text{th}}$ with photon energy. The coefficient (6.4) of Eq. (1) is essentially a measure of the excess of high momenta in quasi-deuterons as compared to that in free deuterons. This ratio is computed on the basis of a Fermi-gas model for the nuclear momentum distribution in complex nuclei, assuming a nuclear radius of $1.4A^{\frac{1}{3}}\times10^{-13}$ cm.

In attempting to explain the observations on the quasi-deuteron, it is necessary, first, to understand the free-deuteron photodisintegration process at high energies. A reasonable explanation of the behavior of σ_D has been suggested by Wilson,[20] based on the assumption that the photodisintegration of the deuteron at high energies is essentially a meson-connected process. Qualitatively, we may understand the process as follows: In the region of the meson production threshold ($\sim$150 Mev) and above, the cross section for meson production by the nucleons in the deuteron is considerably greater than $\sigma_D{}^{\text{th}}$. If a meson is produced from a nucleon in the deuteron, it may either be emitted or reabsorbed by the two-nucleon system; in the latter case its energy is shared as kinetic energy of recoil of the nucleons. If the meson production process occurs when the two nucleons are relatively far apart (say further than the range of

[10] Weinstein, Odian, Stein, and Wattenberg, Phys. Rev. **99**, 1621 (1955).
[11] G. L. Squires, in *Progress in Nuclear Physics* (Academic Press, Inc., New York, 1952), Vol. 2, p. 89.
[12] L. I. Schiff, Phys. Rev. **78**, 733 (1950).
[13] J. F. Marshall and E. Guth, Phys. Rev. **78**, 738 (1950).
[14] J. Halpern and E. V. Weinstock, Phys. Rev. **91**, 934 (1953).
[15] W. S. Gilbert and J. W. Rosengren, Phys. Rev. **88**, 901 (1952).
[16] Keck, Littauer, O'Neill, Perry, and Woodward, Phys. Rev. **93**, 827 (1954).
[17] Schreiver, Whalin, and Hanson, Phys. Rev. **98**, 763(A) (1954).
[18] E. A. Whalin, Jr., Phys. Rev. **95**, 1362 (1954).
[19] L. Allen, Jr., Phys. Rev. **98**, 705 (1955).
[20] R. R. Wilson, Phys. Rev. **86**, 125 (1952).

nuclear forces, $\sim\hbar/\mu c$) the meson will escape. If, on the other hand, the two nucleons are closer together than $\sim\hbar/\mu c$, phase space arguments indicate that the reabsorption process will be greatly favored, at least for photon energies not too far above the meson threshold (say $E_\gamma \lesssim 300$ Mev). A quantitative treatment of the photodisintegration of the free deuteron, based on these ideas, together with a specific ($J=\frac{3}{2}^+$, $T=\frac{3}{2}$ resonance) model for the meson production process has been given by Austern[21] and by Feld.[22]

For the quasi-deuteron process, this model now provides a natural and simple justification for the interpretation of Rosengren and Dudley. Furthermore, at least for those processes in which the quasi-deuteron is initially in a $^3S_1$ state, we have

$$\sigma(^3S)=\alpha(NZ/A)\sigma_D, \tag{2}$$

where α is the ratio for the probability that the neutron and proton in a complex nucleus will be separated by a distance less than $\sim\hbar/\mu c$ as compared to the same probability in the free deuteron.[23] The angular distribution for this process will be the same as that observed for the free deuteron. We note, furthermore, that this model no longer requires that the high momenta of the disintegration products shall be originally present in the quasi-deuteron. The momentum distribution of the nucleons in the complex nucleus is reflected mainly in a "smearing-out" of the kinematics.[24,25]

We are, however, still left with a number of important questions. The quasi-deuteron, unlike the free deuteron, can exist in a variety of initial angular momentum states (e.g., $^1S_0$, $^1P_1$, $^3P_{0,1,2}$, etc.) and while the simple model[21,22] indicates that the meson-connected disintegrations from these states may be smaller than from the $^3S_1$, there is no reliable experimental evidence on this point. Furthermore, we do not know to what extent the nature of the process may be influenced by the presence of other nucleons. Finally, the observed cross section and angular distribution from complex nuclei will certainly be influenced by the interaction (scattering) of the nucleons on their way out of the nucleus.

Two sets of experiments are described in this article. The first group, of a preliminary nature, represent only semiquantitative checks on the quasi-deuteron model. The second set of measurements were performed to study the quasi-deuteron process as a function of angle and energy by a direct comparison with the photodisintegration of the deuteron.

A. Preliminary Experiment

1. Experimental Method

The neutron-proton pair was detected by means of a coincidence between a proton telescope and a liquid scintillation neutron counter placed at angles to one another appropriate to the photodisintegration of a free deuteron. Although the synchrotron emits a bremsstrahlung spectrum, photons of a specific energy, as determined by the energy and angle settings of the proton telescope, are singled out in these observations.

The proton telescope consisted of two plastic scintillators. The first plastic scintillator measured dE/dx and the second the energy E. Both plastic scintillators were five inches in diameter and $\frac{1}{2}$ inch thick. Four-inch diameter holes in brass defined the solid angle of the telescope. Minimum pulse heights were set in both detectors to select a certain energy spread of protons. This method has been described in detail previously.[7] By an appropriate choice of biases and of the thickness of absorber in front of the telescope, the telescope could be set to detect protons of a predetermined energy E_p with an energy spread ΔE_p. Most electrons and π mesons were excluded by the pulse height requirements in both crystals. However, the requirement of a coincidence with neutrons should remove all electrons and π^- events in the coincidence measurements. With the bias held constant, the energy interval ΔE_p is different for each proton energy (absorber thickness). In practice, ΔE_p was between 20 and 25 Mev. ΔE_p was determined experimentally in a separate experiment.

In this preliminary experiment, the neutron counter was a ten-centimeter diameter by 30-centimeter long hollow plastic cylinder filled with cyclohexylbenzene containing terphenyl. The bias was set so that neutrons with energies less than about 15 Mev would not be observed. The neutron detector and its efficiency are discussed in detail in a separate article,[26] in which the electronic circuitry employed is also described.

Neutron-proton coincidences from deuterium were observed in order to study the angular resolution and efficiency of the neutron counter. Since the deuterium was in the form of heavy water, a light-water subtraction was necessary. The water samples were contained in thin-walled, almost identical plastic cells. In addition, measurements were made with a lithium target. Unfortunately, in this set of measurements, the lithium sample was in the form of a cylinder 10 cm long and 10 cm in diameter. This bulky sample had the effect of changing the experimental resolution of the apparatus as well as of scattering some of the outgoing particles.

The geometry employed is shown in Fig. 1.

[21] N. Austern, Phys. Rev. **100**, 1522 (1955).

[22] B. T. Feld, Nuovo cimento **2**, Suppl. 1, 145 (1955).

[23] A simple computation, based on a nuclear density corresponding to a radius of $1.2A^{\frac{1}{3}}\times10^{-13}$ cm and a Hulthén wave function for the deuteron, gives $\alpha\approx3.8$.

[24] A quantitative discussion of the modified kinematics will be given in a later paper reporting on the momentum of nucleons in various nuclei.

[25] *Note added in proof.*—K. G. Dedrick [Phys. Rev. **100**, 58 (1955)] has reported detailed numerical calculations based on the Levinger model and assuming completely uncorrelated nucleons in which specific account is taken of the nucleon motions and interactions within the nucleus. However, since the numerical results reported are for photon energies below 125 Mev and include electric dipole and quadrupole absorption only, we have not been able to apply these calculations to the interpretation of our observations.

[26] Christie, Feld, Odian, Stein, and Wattenberg, Rev. Sci. Instr. (to be published).

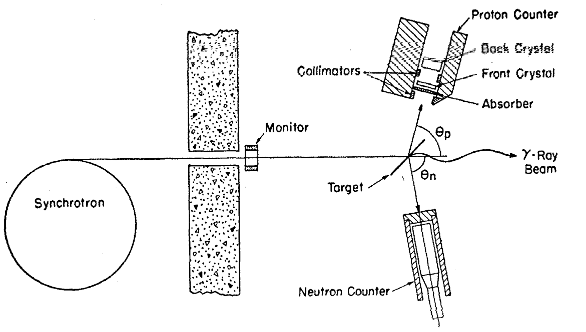

FIG. 1. Experimental geometry for preliminary measurements. θ_n is varied in the experiment.

2. *Results*

For the measurements at photon energies of about 250 Mev, the proton counter was set to observe 125-Mev protons at an angle of 76° to the beam. For the measurements at photon energies of about 140 Mev, the proton counter was set at an energy of about 70 Mev and at 78° to the beam. Both angles and energies were chosen to correspond to a free deuteron center-of-mass angle of 90°.

The neutron-proton coincidences were measured as a function of neutron angle (with the proton counter held fixed in energy and angle). The results are shown in Figs. 2 and 3. The D_2O and H_2O samples were cycled at each setting of the neutron angle. The neutron angles were cycled by frequently returning to the neutron angle of 76° for the 250-Mev runs and 78° for the 140-Mev runs.

The observed spread in the neutron angles for deuterium (Figs. 2 and 3) can be accounted for by the geometry and finite size of beam, targets, and detectors. The neutron-proton coincidence curves from lithium and oxygen (obtained from the H_2O target measurements) are in semiquantitative agreement with the predictions of the quasi-deuteron model. These curves are expected to be broader than those from deuterium because of the initial momentum of the nucleons in the nucleus. When one changes the photon energy from 250 to 140 Mev, the momentum acquired by the neutron through the photon absorption is reduced, while the initial momentum of the nucleons, which must be added to the acquired neutron momentum, remains constant. Therefore, the spread in neutron angles for Li and O should increase, as observed, in going from $E_\gamma = 250$ to $E_\gamma = 140$ Mev.

It was somewhat surprising to find the spread from lithium larger than that from oxygen. However, a subsequent analysis showed that this probably arose from the bulkiness of the lithium target combined with the excessively large solid angles subtended by the detectors. On the basis of these analyses, appropriate changes were made in the apparatus and targets in the later experiments. Much more understandable curves were obtained in the later experiments which employed this effect to study the momentum of nucleons in various nuclei.

B. The Angular Dependence of the Photo-Disintegration of the Quasi-Deuteron

1. *Method*

Revisions in the targets, apparatus, and geometry were made on the basis of our experience in the preliminary measurement. A rectangular lithium target was made which more closely resembled the water targets. Thicker plastic scintillators were obtained for the back detector of the proton telescope so that all π^+'s and electrons could be discriminated against on the basis of pulse height in both crystals. The collimator in the telescope was changed to one with a three-inch diameter hole to improve the angular resolution. The ΔE_p employed were reduced and kept between 12 and 16 Mev. The targets were set at angles such as to minimize the geometrical angular spread.

It was desired to compare the total number of neutron-proton coincidences from Li and O to those from deuterium as a function of proton angle and

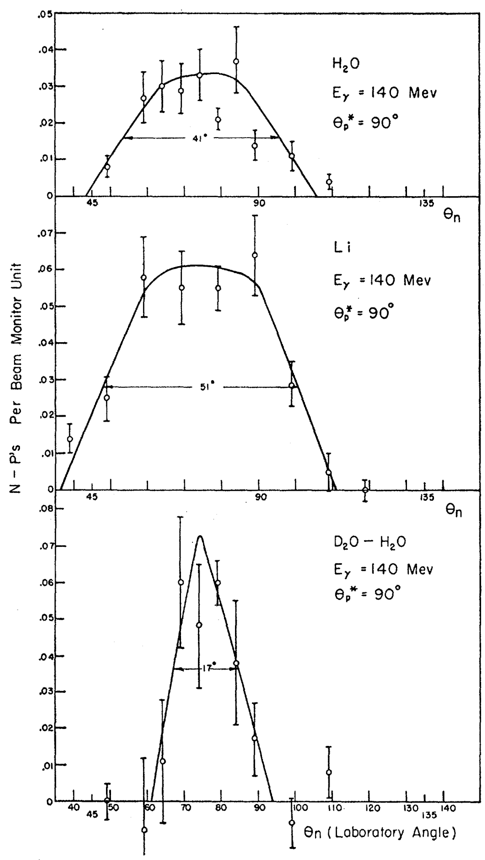

FIG. 2. Variation of neutron-proton coincidences with neutron angle. Gamma-ray energy is 140 Mev.

energy. (The center-of-mass angle for a free deuteron disintegration is determined by the proton detector.) To determine the total number of *n-p* coincidences, one would have to integrate curves of the type shown in Figs. 2 and 3, keeping in mind that there is also a spread in the vertical direction. (The x-ray and the proton lay in the horizontal plane.) At angles other than 90° in the c.m. system, the vertical spread could be appreciably different from the horizontal spread, since our scheme observes quasi-deuterons whose center-of-mass motion is in the horizontal plane.

If one desired to perform this integration, an exact knowledge of the angular resolution of the neutron detector would also be required. To avoid the necessity of this integration, a large neutron detector was con-

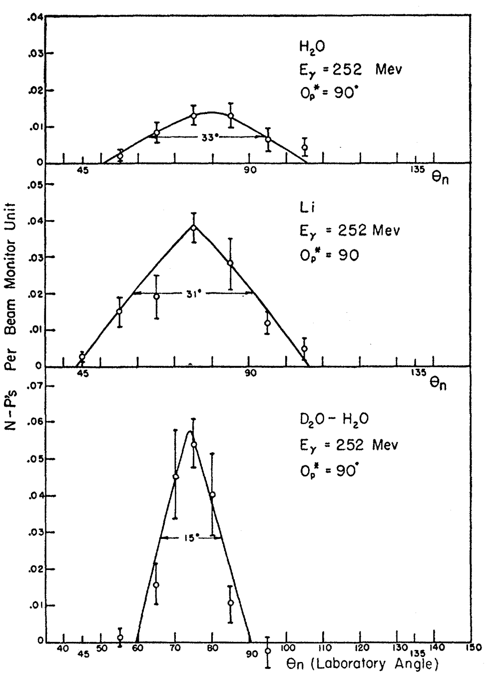

FIG. 3. Variation of neutron-proton coincidences with neutron angle. Gamma-ray energy is 252 Mev.

structed which could be made to subtend solid angles sufficiently great to include all the neutrons in coincidence with the observed protons. This detector thus performs the desired integration for us. The large neutron detector is shown schematically in Fig. 4. Its uniformity and efficiency are described in detail in a separate article.[26] Its bias was set to avoid observing neutrons with energies less than 15 Mev.

To be certain that this detector was observing all neutrons in coincidence with the protons, a special set of measurements was made in which the distance of the large neutron counter from the target was varied. This is equivalent to varying the solid angle of the counter. The results of the test are shown in Fig. 5. The fact that the *n-p* coincidence rate is flat beyond a certain solid

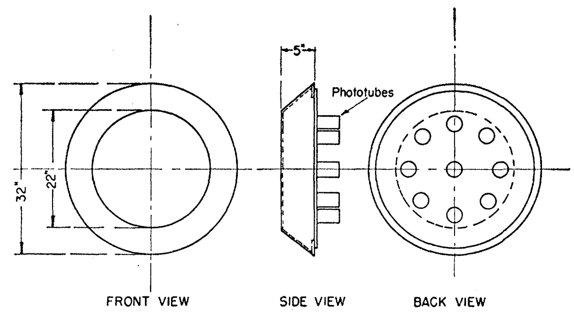

FIG. 4. Large neutron counter used to integrate over neutron angles.

angle indicates that all neutrons in coincidence with protons are being observed at the larger solid angles. For the measurements on Li and O, we employed a solid angle larger than 0.3π which, from the data of Fig. 5, appears to be safely on the plateau. For the measurements on deuterium, the counter was moved back so that the neutrons would be spread across the counter in the same way as they were spread from Li and O. Thus, for each angle and energy setting of the proton detector, it was necessary to set the large neutron detector at only one (neutron) angle.

2. *Measurements and Results*

The purpose of these measurements was to compare the cross section for the production of *n-p* coincidences from Li and O to that of deuterium. For such processes the differential cross section is given by an expression of the form

$$\frac{d\sigma}{d\omega}=\frac{\text{(counts per monitor unit)}}{\epsilon FNA\ \text{(flux per monitor unit)}},\tag{3}$$

where ϵ is the over-all efficiency including solid angles; F is a factor that would correct to the center of mass and take account of the energy spread; N is the number of atoms/cm²; and A is the effective area of the target. If one takes ratios of cross sections, say of Li to O, then the factors ϵ, F, A, and flux per monitor unit cancel out in the ratio. However, rather than compare cross sections

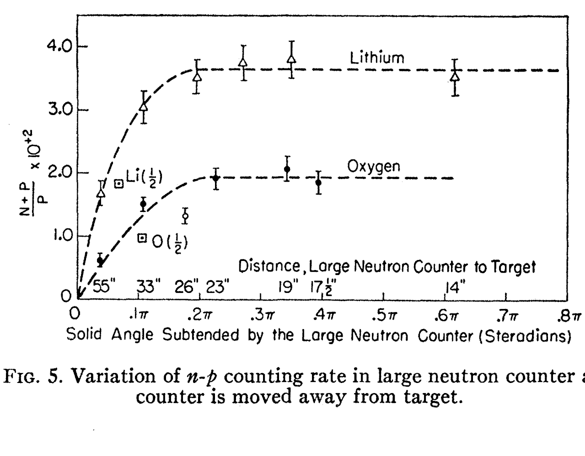

FIG. 5. Variation of *n-p* counting rate in large neutron counter as counter is moved away from target.

TABLE I. Summary of data[a] for H_2O and D_2O. $E_\gamma = 260$ Mev; $\theta_P^* = 90°$; $\theta_P = \theta_N = \theta_{\text{lab}} = 76°$; $E_P = 129$ Mev; $E_N = 129$ Mev.

Run[b]	Prot / MH_2O	Prot / MD_2O	ΔP / M	$N-P$ / MH_2O	$N-P$ / MD_2O	$\Delta(N-P)$ / M	$\Delta(N-P)$ / P	$N-P$ / PH_2O	$N-P$ / PD_2O
1	7.112	7.964	0.852	0.042	0.140	0.098	0.115	0.0060	0.0176
2	7.553	8.521	0.968	0.048	0.143	0.095	0.098	0.0064	0.0168
3	7.021	8.078	1.057	0.049	0.157	0.108	0.102	0.0070	0.0194
4	7.753	8.520	0.767	0.048	0.148	0.100	0.130	0.0061	0.0174
Av	7.360	8.271	0.91	0.047	0.147	0.100	0.110	0.0064	0.0178
Correction of 0.02 H_2O[c]			0.15			0.001			
Corrected av value:		Prot/MD_2 = 1.06			$N-P/MD_2$ = 0.101				

[a] Large conuter far away (51 in.).
[b] Each run corresponds to about 2000 monitor units.
[c] The correction of 0.02 H_2O is to correct for the H_2O cell having a thickness that is 0.98 of the thickness of the D_2O cell.

per atom, it appears to be more meaningful to compare cross sections per nucleon in the nucleus. For such a comparison, the ratio reduces very simply to

$$\frac{(d\sigma/d\omega)_{\text{Li}}}{(d\sigma/d\omega)_{\text{D}}} = \frac{[\text{counts per } M/(\text{g cm}^{-2})]_{\text{Li}}}{[\text{counts per } M/(\text{g cm}^{-2})]_{\text{D}}}, \tag{4}$$

where M stands for monitor unit.

In order to illustrate the kind of consistency that was obtained in one of the most reliable sets of identical measurements, and the corrections applied, a summary of the data taken at 76° to the beam is shown in Tables I and II. It will be noted that the H_2O-D_2O subtraction involves a difference of two large numbers for the proton rates. For the n-p coincidence, the situation is somewhat better. The columns $(N-P)/P$ are used to check on the reliability of the electronics and the stability of the neutron counter.

The average corrected values obtained from such summaries are then divided by the g/cm² of target in the beam; from these numbers the ratios of cross sections (per nucleon) are obtained from expression (4). The ratios obtained for 260-Mev photons are plotted against the (free deuteron) center-of-mass angle in Fig. 6. The Li/D ratios are essentially independent of angle. The O/D ratio seems lower at the smaller angles. Within the statistical accuracy of the experiment, however, it appears that the quasi-deuteron process has the same angular distribution as the photodisintegration of the deuteron for 260-Mev photons.

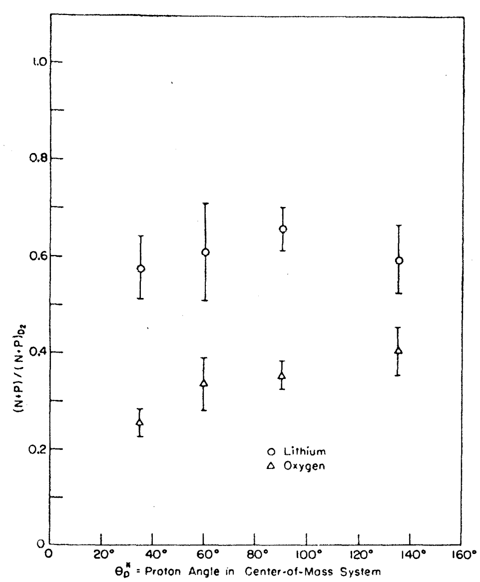

FIG. 6. Angular distribution of photoneutron proton pairs from lithium and oxygen relative to deuterium. $E_\gamma = 260$ Mev.

The fact that the Li/D ratio has a value of 0.65, while the O/D ratio is 0.35 is understandable on the basis of a separate measurement (to be described in a subsequent communication), in which targets ranging from lithium to lead were studied. These measurements showed that the difference between 0.65 and 0.35 arises from the greater attenuation of the nucleons on traversing the larger nucleus.

Some measurements were also made corresponding to photon energies of about 200 Mev using a 340-Mev bremsstrahlung cutoff. The value for the ratios at 90° (in the center of mass of the free deuteron) are 0.85 ± 0.10 for Li/D and 0.57 ± 0.07 for O/D. The relative values are understandable on the same basis as described above. However, the fact that the absolute

TABLE II. Summary of data[a] for lithium and oxygen. $E_\gamma = 260$ Mev; $\theta_P^* = 90°$; $\theta_P = \theta_N = \theta_{\text{lab}} = 76°$; $E_P = 129$ Mev; $E_N = 129$ Mev.[b]

Substance	Run[b]	P/M	$(N-P)/M$	$(N-P)/P$
Li	1	5.42	0.244	0.0450
	2	5.42	0.244	0.0450
	3	6.07	0.257	0.0423
	Av	5.64	0.248	0.0441
O_2	1	7.00	0.142	0.0203
	2	7.00	0.142	0.0203
	3	7.55	0.150	0.0198
	Av	7.18	0.145	0.0201

[a] Large counter up close (10 in.).
[b] Each run corresponds to about 2000 monitor units.

values of the ratios are greater than for 260-Mev photons does not appear to be consistent with the theoretical ideas discussed above.

As a byproduct of these coincidence measurements, we obtained data on the proton emission (i.e., the proton singles rate). The ratios for the production of protons by 260-Mev photons are shown in Fig. 7. Again we have plotted cross-section ratios per nucleon in the nucleus. For lithium, the ratios seem to be independent of angle. However, for oxygen there again seems to be a rise at the backward angles. The other interesting point to note is that there does not seem to be a comparable attenuation (in escaping from the nucleus) of the protons, in that both ratios are about 1.3. This apparent direct Z dependence of the photoproton production has been observed previously by many groups.[7]

An understanding of the apparent Z dependence of the single proton ratio and its failure for the n-p coincidence ratio requires a more detailed investigation of the attenuation and the geometries involved. However, a tentative explanation can be advanced along the following lines: The attenuation arises from scattering of the nucleons inside of the target nucleus. In the case of the n-p coincidence measurements, any scattering is likely to prevent the observation of an n-p pair. In the case of single protons, scattering will also occur; however, for single protons, one must take into account those protons which are scattered into the angles of observation as well as those which are scattered out. This problem is discussed further in the projected article dealing with the A-dependence of this effect. These scattering phenomena also might provide an explanation of the backward rise of the proton counting rate from oxygen relative to deuterium.

Another possible by-product of these measurements is a determination of the differential cross section for the photodisintegration of deuterium. However, in these experiments, the heavy water-light water subtraction leads to such poor statistical accuracy that no significant conclusions can be drawn from our data.

CONCLUSIONS

The first and most obvious conclusion is that the quasi-deuteron model is a good one for photons with energies between 140 and 300 Mev. However, until a quantitative analysis of the effect of scattering on the single proton rates has been achieved, it is difficult to say whether the quasi-deuteron process can account for all the high-energy photoprotons not associated with real meson production.

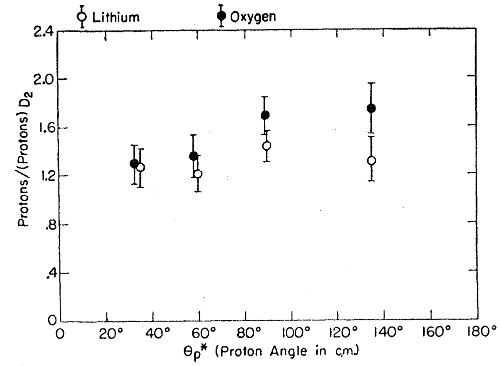

FIG. 7. Proton rates for oxygen and lithium relative to deuterium for various laboratory angles.

In that the observed kinematical relationships are close to those of a deuteron and in that the angular distribution (in the center-of-mass system) is very similar to that of a deuteron, it would appear that the major contribution to this photoprocess must come from neutron and proton pairs which are in a relative S-state.

It is very tempting to draw the more interesting conclusion, from the Li data at 260 Mev, that despite the presence of other nucleons the neutron-proton pairs are predominantly in an S-state in a complex nucleus. However, the oxygen angular distribution did vary slightly from that of the deuteron and the values of the ratios at 260 and 200 Mev do not agree. A possible explanation of these effects, especially the discrepancy in the ratios, could lie in a dependence of the ratios upon the maximum energy of the photon spectrum. This could arise from the suppression of disintegrations involving those portions of the initial momentum distribution which require photons of energies in the region of or beyond the bremsstrahlung cutoff. The validity of such an explanation could be verified by measuring the dependence of the ratios on the maximum energy of the bremsstrahlung spectrum.

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