Photodisintegration of the Deuteron by 95-Mev Bremsstrahlung*†

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Photoprotons produced by irradiating deuterium gas with betatron x-rays have been detected with stacks of unsupported Ilford emulsions. The differential cross section was determined for photon energies between 20 and 65 Mev and for seven angles of proton emission. The observed angular distributions are well fitted by $f(\theta)=(\alpha+\sin^2\theta)(1+2\beta\cos\theta)$. The experimental results for angular distribution and total cross section have been compared with theoretical predictions assuming a purely central force. Striking departures from the central force theory are observed as the photon energy increases from 20 Mev.

INTRODUCTION

In order to formulate a satisfactory theoretical treatment of the photodisintegration of the deuteron, one requires an understanding of the interaction between the photon and the deuteron and also an adequate understanding of the interaction between the neutron and the proton. At low energies, $h\nu \lesssim 10$ Mev, the de Broglie wavelength of the particles is large compared to the range of the nuclear force, and rather simple assumptions suffice to describe the neutron-proton interaction.[1] In this low-energy range the considerable amount of experimental data which is available[2] is in excellent agreement with the theory.[3] While giving little information regarding the nuclear force law, this agreement indicates that the interaction of the deuteron with the electromagnetic field is understood rather well. As the photon energy is increased to a value above 10 Mev, but below 150 Mev, a region of intermediate energies is reached where the detailed nature of the force becomes experimentally important but where certain simplifications can still be made. These are that free mesonic effects can be neglected and that relativistic effects are still small. Within this intermediate energy region experimental data may yield valuable, and perhaps unambiguous, information regarding the nature of the neutron-proton interaction. This paper describes an experiment in the region $h\nu=20$ Mev to $h\nu=95$ Mev which was carried out as part of a comprehensive investigation of the problem at this laboratory. This program was initiated with an experiment for photon energies up to 22 Mev[4] and has been continued up to energies of 300 Mev.[5,6]

Detailed theoretical calculations of total cross section and angular distribution have been made for $10 \lesssim h\nu \lesssim 150$ Mev by Marshall and Guth[7] and Schiff[8] with the assumption of purely central nuclear forces and various shapes of the potential well. The most significant of these shapes are the so-called long-tailed types, i.e., the exponential and the Yukawa, or the Hulthén approximation to the Yukawa. They have also considered the effect of exchange forces, particularizing to the 50 percent Majorana and 50 percent ordinary interaction, which seems indicated by high-energy scattering experiments. The total cross section calculated in this way is predominantly due to the electric dipole transition and is relatively insensitive to the type of long-tailed potential chosen. The predicted angular distributions have the form of $\sin^2\theta$ (from the electric dipole effect) with a fore-aft asymmetry due to interference between electric dipole and electric quadrupole transitions. The effects of magnetic quadrupole and magnetic dipole transitions are predicted to be very small. For energies near 20 Mev the angular distribution of the emitted protons may be written

$$f(\theta)=a+b\sin^2\theta(1+2\beta\cos\theta),$$

where a is due to the magnetic dipole effect and is therefore quite small, and where the term in parentheses is perhaps more familiar as a retardation term with $\beta=v/c$ of the protons.

There have been several previous experiments performed at energies near 20 Mev, of which four will be mentioned here: (1) Barnes *et al.*,[9] using gamma rays with energies from 4 to 17.6 Mev, detected the protons with an ionization chamber and determined total cross sections; (2) Waffler and Younis[10] detected protons in deuterium-loaded photographic emulsions using the Li gammas (14.8 and 17.6 Mev); (3) Fuller[4] detected protons in nuclear emulsions using a gas target and a

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[1] H. A. Bethe and R. Peierls, Proc. Roy. Soc. (London) **A149**, 176 (1935).

[2] See, e.g., E. Segrè, *Experimental Nuclear Physics* (J. Wiley and Sons, Inc., New York, 1953), Vol. 1; and O. R. Frisch, *Progress in Nuclear Physics* (Pergamon Press Ltd., London, 1952), Vol. 2.

[3] See, e.g., J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[4] E. G. Fuller, Phys. Rev. **79**, 303 (1950).

[5] E. A. Whalin, Phys. Rev. **95**, 1362 (1954).

[6] Schriever, Whalin, and Hanson, Phys. Rev. **94**, 763 (1954).

[7] J. F. Marshall and E. Guth, Phys. Rev. **78**, 738 (1950).

[8] L. I. Schiff, Phys. Rev. **78**, 733 (1950).

[9] C. A. Barnes *et al.*, Phys. Rev. **86**, 359 (1952).

[10] H. Waffler and S. Younis, Helv. Phys. Acta **24**, 483 (1951).

22-Mev betatron; and (4) Halpern and Weinstock[11] used 22-Mev bremsstrahlung with ZnS proton detectors. If the results of these experiments are compared with the central force theory, it is seen that the total cross section is in good agreement for a long-tailed potential, $r_0=1.74\times10^{-13}$ cm and about 50 percent charge exchange. The measured angular distributions show the characteristic $\sin^2\theta$ form; the forward shift of the peak due to the retardation term is observed, although its magnitude is subject to large experimental error. However, the value of the isotropic component observed is far too large to be explained by purely central forces.

Therefore, it is seen that as the photon energy reaches about 20 Mev, the central force theory seems to become inadequate to explain the observations, and the departures from the theory are experimentally most evident in the angular distributions of the emitted particles.

EXPERIMENTAL PROCEDURE

The source of photons was the Illinois 300-Mev betatron operated at 95 Mev. The operating energy was determined from the integrator setting which was calibrated on the basis of field measurements at the position of the electron target. The value of 95 Mev is believed accurate to ±2 percent. The photon beam was collimated by means of a tapered lead primary collimator chosen to give a one-inch beam at the deuterium target, 3.4 meters from the betatron target. A secondary lead collimator, 0.8 inch in diameter, placed 2 meters from the betatron target, was used to aid in cleaning up the beam. The photon yield was measured with an 8-inch flat Cu ionization chamber which had been calorimetrically calibrated.[12] It was necessary to extrapolate this calibration from 150 Mev to 100 Mev; this extrapolation appeared to permit little variation and the calibration was felt to be accurate to ±3 percent. However, recent work[13] seems to indicate an error in the calibration at 150 Mev; this error causes the 100-Mev calibration to be in error by 10 percent. The error is in a direction such as to increase the cross sections by 10 percent. Further work is being done to check this point; the present results have not been corrected for this possible error.

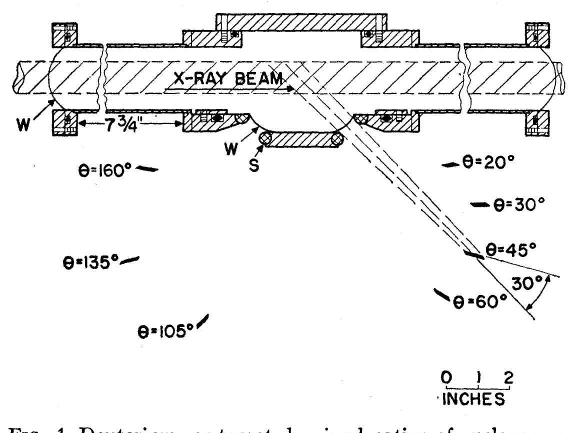

FIG. 1. Deuterium gas target showing location of nuclear emulsions. W is the 7-mil Mylar window held by an O-ring seal. S represents the slit-defining tungsten rods. The scanned portion of the emulsion stacks is represented by the solid black area. θ is the angle between the direction of the x-ray beam and the central ray to the emulsion stack. The emulsions are inclined at 30° to this central ray. (Note $\theta=45°$ position.)

Since it was desired to detect protons which had been produced by photons with energies as low as 20 Mev it was necessary to use a target with rather low self-absorption. Therefore, a deuterium gas (150 psi) target was used with a tungsten slit system to define the volume of the source of photoprotons. Figure 1 is a plan view of the target showing the positions of the emulsion stacks. The slit edges are defined by $\frac{3}{8}$-inch tungsten rod; the large value of Z, density and radius of curvature make slit edge corrections negligible. The window through which the protons must pass is of 7-mil "Mylar" DuPont polyester film. When the film is stretched into place by the pressure of the gas the window is only 0.02 g/cm^2 of CH_2. The target chamber was first evacuated, then flushed with hydrogen before filling with deuterium gas through a liquid-nitrogen cold trap. During the exposures the chamber and a 12-in. calibrated Bourdon gauge were sealed off from the remainder of the system. In order to reduce proton scattering, the entire target assembly, including emulsion stacks, was kept in a helium atmosphere.

Sufficient emulsion thickness was provided at each observation angle to stop protons which were produced by 50-Mev photons. This thickness was obtained by building stacks of 1-inch$\times$3-inch, Ilford G-5, 600-micron, unsupported emulsions. The bottom member of each stack was an Ilford plate. Since a 50-Mev photon produces a more energetic proton in the forward direction, four emulsions per stack were required at $\theta=20°$ and 30°, three per stack at 45° and 60°, and two per stack at 105°, 135°, and 160°. The position of the emulsions in a stack with respect to one another was determined by x-ray index dots formed prior to exposure to the photoprotons. The emulsions were shielded from light by $\frac{1}{2}$-mil Al foil.

Two data runs were made, one for about four hours betatron time (exposure$=5.82\times10^8$ ergs), and one for about two hours betatron time (exposure$=2.86\times10^8$ ergs). During the four-hour run the 30° observation point was used and not the 20°, while the reverse was true for the two-hour run. It was necessary to divide each exposure at these two most forward angles between two stacks of emulsions to avoid excessive background fogging. Two background runs were made; the first was made with 150 psi of H_2 in the target; the purpose of this run was to determine whether neutrons

[11] J. Halpern and E. V. Weinstock, Phys. Rev. 91, 934 (1953).
[12] D. W. Kerst and P. D. Edwards, Rev. Sci. Instr. 24, 490 (1953).
[13] A. O. Hanson and J. E. Leiss, University of Illinois Physics Research Laboratory Report (unpublished).

TABLE I. Differential cross sections as calculated from the observed numbers of protons at different angles in the laboratory system. The cross sections have been corrected for background and scanning efficiency and are expressed in the center-of-mass system. The units are microbarns per steradian. N_p is the number of protons from which each cross section was computed. $\langle h\nu' \rangle_{Av}$ (Mev, center of mass) is the computed mean photon energy to which each cross section is assigned. The energy bins are nominal since, for experimental reasons, the bins are not exactly the same for each angle.

Photon energy bin (Mev)	18°			28.6°			44°			59.4°			104.6°			134.4°			159°		
	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$	$\frac{d\sigma}{d\Omega}$	N_p	$\langle h\nu' \rangle_{Av}$
15–20							36.1	481	17.8												
17.5–20										54.0	154	18.8	68.5	95	19.3						
20–25				19.3	202	22.7	28.7	393	22.5	43.8	211	22.2	40.4	120	22.8	18.3	234	22.8	9.3	135	22.8
25–30	11.0	115	26.7	17.2	144	27.2	26.1	286	27.0	36.8	142	26.9	26.1	167	27.6	14.0	165	27.6	6.4	198	27.1
30–40	9.2	144	33.4	12.9	180	33.4	19.8	326	33.4	24.4	279	33.4	23.9	217	34.1	11.0	164	34.0	5.3	216	34.4
40–50	9.1	105	43.0	12.0	122	42.7	14.2	179	43.0	15.5	129	43.1	15.4	104	43.4	8.3	92	43.2	4.6	133	43.3
50–95	5.6	160	66.5	6.2	155	64.0	8.1	249	64.0	10.2	210	64.0	8.2	137	63.0	4.3	115	62.0	3.8	265	66.0

produced in the betatron shield scattered many protons from the target gas. This was found not to be the case, hence (n,D) scattering was not considered to be an appreciable source of background tracks. The second background run was made with a target pressure of 15 psi H_2.

In order to facilitate the microscopic scanning of the top emulsion of each stack, swath defining lines were photographically placed upon the surfaces of these emulsions. These lines were 400 microns apart, 8 to 15 microns wide, and about 15 microns deep; they served to define the swaths and considerably shortened the scanning time. Due to the shallow penetration of the lines it was possible to look beneath them and thus no area was lost.

The emulsions were fastened to glass supports and developed following in general the method described by Stiller *et al.*[14] Following a suggestion of G. Bernardini, the plates were slightly underdeveloped to suppress electron background. The resulting processed plates were quite clear and essentially no emulsion area was lost due to bubble formation or peeling. Distortions were present but were an insignificant source of error in the range measurements.

The top emulsion of each stack was surface scanned to locate the proton tracks; the coordinates of each track were recorded and the projected range measured with a calibrated eyepiece reticle. If the track stopped, the depth at stopping was measured with the fine focus; but if the track passed through the emulsion, the exit coordinates were measured. In order to follow the proton track through successive emulsions in the stack, the lower plates were placed on oversized glass slides, and, using Canada balsam as a bond, were adjusted so that the coordinates of the index dots were the same as those of the upper emulsion. Scanning efficiency was 98 percent to 99 percent and scanning rate was about 5 tracks per scanner hour, including all measurements.

ANALYSIS OF OBSERVATIONS

Microscope readings were converted to proton ranges by using the measured emulsion shrinkage factors. Ranges were converted to proton energies by using the range-energy curve of Wilkins[15] which was corrected for energy losses by using the curves of Aaron.[16] In making these corrections it was assumed that the proton originated at the center of the x-ray beam. A numerical integration showed that this approximation introduced an error of 0.5 Mev for the associated mean photon energy in the worst case. The associated photon energy and the conversions to the center-of-mass system were obtained from the dynamical relations which have been plotted[17] and tabulated[18] for such use.

In principle, all tracks which entered the surface of the top emulsion were accepted, since uncollimated tracks should appear on the background plates also and thus be subtracted. In practice, it was observed that certain generous selection criteria could be used with impunity. With these criteria, backgrounds were 1 percent to 5 percent. The distribution of proton entry angles corresponded satisfactorily to that expected from consideration of the geometry.

The numbers of protons were grouped according to their energies and converted into differential cross sections by a straightforward calculation which involved certain approximations. These approximations were computed to introduce an error of less than 1 percent. The cross section so calculated corresponds to a mean value for a range of photon energies. In order to compute the mean photon energy to which the calculated cross section is to be assigned, it was necessary to assume an energy dependence for the cross section. In first approximation the dependence was taken to be that calculated by Marshall and Guth; then, if necessary, this was corrected for the experimentally observed dependence. The calculated cross section also corresponds to a mean value for the range of θ which is permitted by the slit system, about $\pm 5°$. The mean value of θ was taken to be the central value; this

[14] Stiller, Shapiro, and O'Dell, Rev. Sci. Instr. **25**, 340 (1954).

[15] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report, G/R **664**, 1951 (unpublished).

[16] W. A. Aaron, University of California Radiation Laboratory-1325, 1951 (unpublished).

[17] M. Weiner, National Bureau of Standards Circular, 515, 1951 (unpublished).

[18] J. Malmberg and L. J. Koester, *Tables of Nuclear Reaction Kinematics at Relativistic Energies* (University of Illinois, Urbana, 1953).

approximation is in error by about 1° in the worst case.

When one considers all sources of error in the computation of absolute values for the differential cross section, but neglects the statistical uncertainty in the numbers of protons, a probable error of 8 percent is assigned to the differential cross sections at all energies except the highest, where an error of about 14 percent is assigned. The greater uncertainty for the highest energies (65 Mev) is due to the large size of the bin of photon energies (50 to 95 Mev). These errors do not include the possible error due to ion chamber calibration which was previously mentioned and which could increase the cross sections by 10 percent.

OBSERVATIONS

The differential cross sections calculated from the observed number of protons are tabulated in Table I. These cross sections have also been plotted *versus* $h\nu'$, center-of-mass photon energy; two such plots are shown in Fig. 2. For those angles of observation near 90° the observed values are in agreement with the predictions of central force theory, and hence the total cross sections will roughly agree also. However, as evidenced in Fig. 2, there is a striking departure from theory for angles near 0° and 180°.

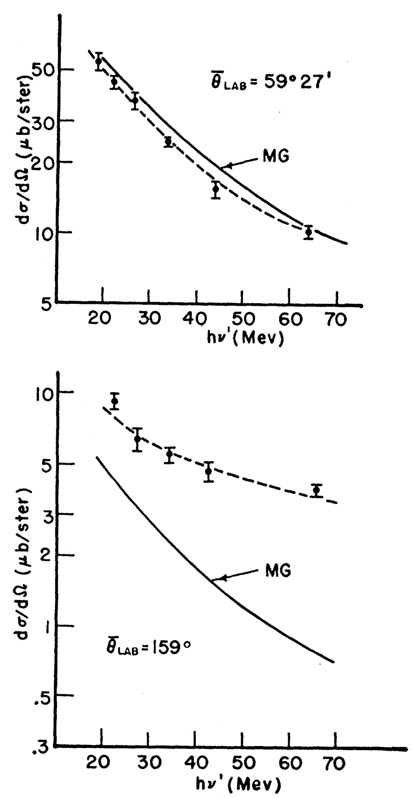

FIG. 2. Sample plots of differential cross section (center-of-mass system) *versus* $h\nu'$, the center-of-mass photon energy for a given laboratory angle of observation. The errors shown are only those due to statistics. The dotted line is a smooth curve connecting the experimental points which was used for interpolation; the solid line represents the calculations of Marshall and Guth for 50 percent charge exchange, long-tailed potential, and an effective range of 1.74×10^{-13} cm.

The differential cross sections have also been plotted *versus* θ (the angle between the incident x-ray beam and the emitted proton expressed in the center-of-mass system), and for a constant mean photon energy. Figure 3 shows samples of such plots. In many cases it was necessary to interpolate between measured values on the plots such as Fig. 2 in order to obtain values for a given energy; in such cases the smooth curves as drawn in Fig. 2 (dotted lines) were used and this smoothing is somewhat reflected in the plots of Figs. 3 and 4.

Analytic curves were fitted to the measured points of the angular distributions. The form of the fitted curves is:

$$f(\theta)=(\alpha+\sin^2\theta)(1+2\beta\cos\theta).$$

This form was chosen since it seems to fit the observations very well and may be suggestive in interpreting the data. Fitting was performed by standard methods, but it should be noted that the determination of the parameter β is dependent upon a previous determination of α. The total cross section was obtained by integrating the fitted analytic function. Figure 4 is a plot of total cross section *versus* photon energy. The experimentally determined values of α and β are also plotted in Fig. 4.

The results of this experiment can be compared with the results of Halpern and Weinstock.[11] From Fig. 4 we may extrapolate to 20 Mev and obtain:

$$\sigma_{tot}=(5.1\pm0.16)\times10^{-28}\ \text{cm}^2,\ \alpha=0.09\pm0.01,\ \beta\sim0.09.$$

Also, at 20 Mev Halpern and Weinstock obtained:

$$\sigma_{tot}=(5.4\pm20\ \text{percent})\times10^{-28}\ \text{cm}^2,\quad \alpha=0.13\pm0.04,\quad \beta\sim0.1.$$

This agreement is considered satisfactory. Further extrapolation of Fig. 4 to 17.6-Mev yields a total cross section which is some 20 percent below the previous experiments with the Li gammas.[9,12,19] This disagreement is not considered serious because of the extrapolation required. The extrapolated angular distributions appear to be in satisfactory agreement.

The results of this experiment have previously been compared with the overlapping work of Whalin at higher energies and the agreement is good. This comparison is shown in Fig. 2 of reference 5.

DISCUSSION

The total cross section is seen to agree with the calculation of Marshall and Guth up to a photon energy of about 40 Mev (Fig. 4). This agreement, as well as the fact that the angular distribution suggests a principally $\sin^2\theta$ dependence, indicates that the electric

[19] P. V. S. Hough, Phys. Rev. **80**, 1096 (1950).

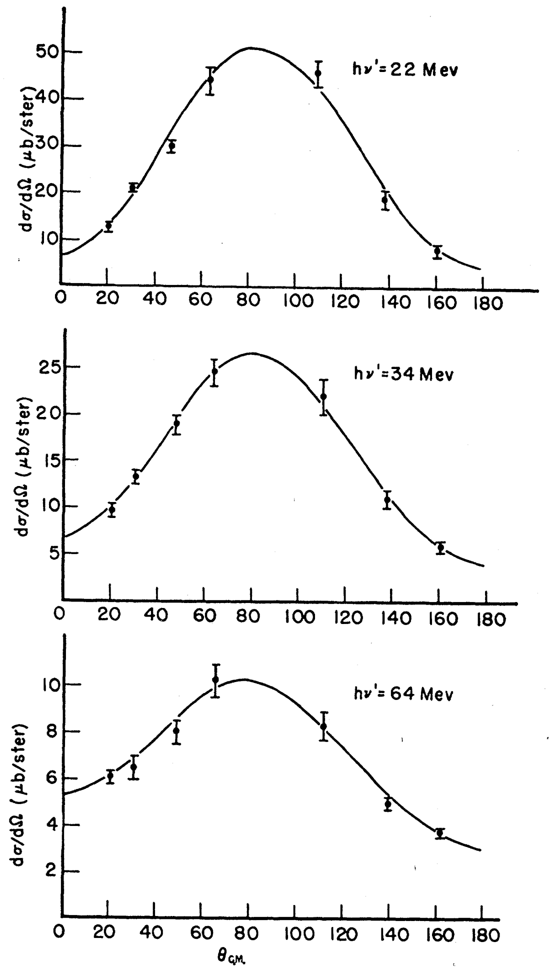

FIG. 3. Sample plots of differential cross sections (c.m.) *versus* θ (c.m.) for a constant mean photon energy. The points are the experimental points as shown in Fig. 2, except that when interpolation was necessary the dotted curve of Fig. 2 was used as a guide. Errors displayed are statistical only. The solid curve is of the form of $f(\theta)=(\alpha+\sin^2\theta)(1+2\beta\cos\theta)$ and has been fitted to the observed points.

dipole transition is dominant and confirms the exchange character (about 50 percent) of the central force interaction. However, the value of α appears inexplicable on the basis of purely central forces.

There have been a number of attempts to consider the effect of the noncentral forces[20–22] which are known to exist from the quadrupole moment of the deuteron. While these calculations are not entirely complete, they do indicate that it is difficult to explain the large value of the isotropic component by other than a strongly singular noncentral interaction. Further, these calculations do not seem to explain the energy dependence of the total cross section. Yamaguchi[23] has considered the two nucleon problem in terms of a separable, nonlocal potential which is strongly singular. On this basis he has been able to obtain the total cross section with some success. But the isotropic term is still low.

The fore-aft asymmetry is most easily interpreted as a retardation effect. In the central force calculations this effect is taken into account by considering the interference between electric dipole and electric quadrupole transitions. These calculations agree qualitatively with the observed asymmetries, but it should be noted that the value of β obtained from the data is considerably below the value predicted.

Several specific meson models have been proposed which show promise of explaining the observed cross sections not only above the meson threshold but also for energies somewhat below it.[24–26] Further calculations of this type are being done at this laboratory by I. Hodes and Y. Yamaguchi.

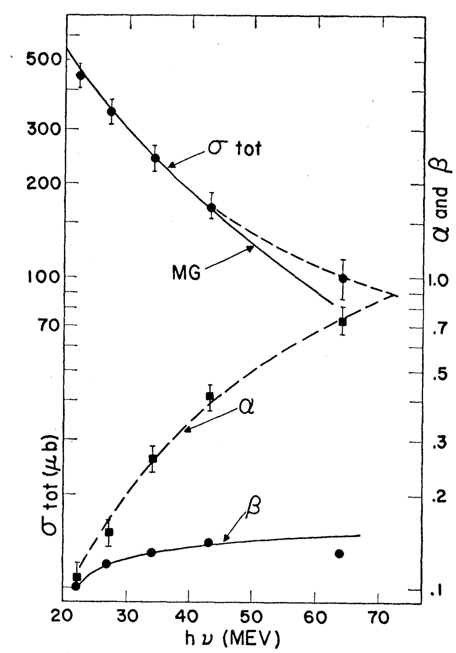

FIG. 4. Total cross section (c.m.) *versus* photon energy (c.m.). Each point represents about 1000 proton tracks. Errors are statistical plus the probable error arising from the integration of the observed angular distribution. The solid curve is that calculated by Marshall and Guth for central forces. The experimentally determined values of the angular distribution parameters are also plotted *versus* photon energy. No error in β is shown since it is not determined independently of α; however, for the plotted value of α and σ_{tot}, β is determined to within about 10 percent.

[20] W. Rarita and J. Schwinger, Phys. Rev. **59**, 556 (1951).
[21] T. Hu and H. S. W. Massey, Proc. Roy. Soc. (London) **A196**, 135 (1936).
[22] N. Austern, Phys. Rev. **85**, 283 (1952).
[23] Yoshio Yamaguchi and Yoriko Yamaguchi, Phys. Rev. **95**, 1635 (1954).
[24] R. R. Wilson, Phys. Rev. **86**, 125 (1952).
[25] Y. Nagahara and J. Fujimara, Progr. Theoret. Phys. (Japan) **8**, 49 (1952).
[26] B. Bruno and S. Depken, Arkiv Fysik **6**, 177 (1953).

In concluding, it may be said that the details of the experimentally observed angular distributions and the observed magnitude of the total cross section above 40-Mev demonstrate the inadequacy of a theory which assumes purely central forces. Apparently further theoretical calculations are required before it is possible to describe these results in terms of present meson theories.

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Decay of Bi^{207}

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The gamma rays of 8.0-year Bi^{207} have been studied with single-crystal and coincidence scintillation spectrometers. The measured relative intensities of the 0.570-, 1.07-, and 1.77-Mev transitions are 1, 0.84 ±0.06, and 0.096 ± 0.007, respectively. Upper limits on the intensity of a 2.40-Mev and of a 1.47-Mev gamma ray of 0.05 percent and 0.2 percent (see note added in proof on page 713), respectively, of the 1.77-Mev gamma ray have been obtained. Coincidence spectrometry with the lead K x-rays indicates pure L-electron capture to the 2.34-Mev state and 2.8 ± 0.3 percent K-electron capture to the 0.570-Mev level. Other coincidence measurements agree quantitatively with the proposed decay scheme. The angular correlation of the $1.77-0.570$-Mev cascade has been measured and is also in agreement with the proposed decay scheme.

I. INTRODUCTION

THERE is considerable interest in the spins and energies of the levels in Pb^{207} since the proton number is "magic" (82) and the neutron number is "magic" minus one (125). Pryce,[1] for example, assumed the levels were states of a single excited neutron and was able to combine pairs of these neutron levels to predict the term value order in Pb^{206}. In his calculations, the energies and spins of the levels in Pb^{207} had to be assumed. Experimentally, much work has been done on these levels. They have been studied through α decay of Po^{211},[2] through β-decay of Tl^{207},[3] and from electron capture of Bi^{207}.[4–7] Levels at 0.570, 0.870, 1.64, 2.34, and 2.49 Mev have all been reported as well as other gamma radiation whose position in the suggested decay scheme was somewhat uncertain. Other levels in Pb^{207} have been found from (d,t) and (d,p) reactions on lead.[8]

In addition, an isomeric transition with a half-life of 0.84 ± 0.02 second was found following the decay of Bi^{207},[9] and from $Pb^{207}(n,n')Pb^{207m}$,[10] and gamma rays of 1.07 and 0.570 Mev were identifiable. The spin assignment $13/2\rightarrow5/2\rightarrow\frac{1}{2}$ was made for the isomeric cascade. This was based on the measured conversion coefficient of the 1.07-Mev gamma ray ($\alpha_{1.07}{}^{K}=0.096\pm0.010$) and from the angular correlation of the gamma rays in the cascade.[6]

In view of the high energies of several of the reported gamma rays, Dr. E. C. Campbell of this laboratory suggested that our 3 in. diameter by 3 in. thick NaI(Tl) crystals would be ideally suited for a quantitative study of the decay. Coincidence and single-crystal spectroscopy were performed and the angular correlation of the $1.77-0.570$-Mev cascade was also measured. A quantitatively consistent level scheme may be constructed from the results.

II. SOURCE

The source used in the experiments described below was made by a 25-Mev proton bombardment of lead in the ORNL cyclotron in November, 1952, and was taken from the same chemically separated sample used by McGowan and Campbell[6] for the previous angular correlation experiments. The same source was used for single-crystal and coincidence measurements. It consisted of 15 microliters of a solution of $Bi(NO_3)_3$ evaporated to dryness on a piece of Scotch tape. For angular correlation measurements, the source was a dilute solution of $Bi(NO_3)_3$, 25 μl in volume, enclosed in a fluorothene holder.

[1] M. H. L. Pryce, Proc. Phys. Soc. (London) A65, 773 (1952); D. Alburger and M. H. L. Pryce, Phys. Rev. 95, 1482 (1954).
[2] H. M. Neumann and I. Perlman, Phys. Rev. 81, 958 (1951).
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[4] M. A. Grace and J. R. Prescott, Phys. Rev. 84, 1059 (1951).
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[10] E. C. Campbell and M. Goodrich, Phys. Rev. 78, 640 (1950).