The High Energy Charged Particles from Targets Bombarded by 190-Mev Deuterons*

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An investigation has been made of the angle and energy distributions of the high energy charged particles which emerge from beryllium, carbon, and uranium nuclei bombarded by 190-Mev deuterons. The results indicate that the yields can be explained as primarily due to two kinds of processes; nucleon-nucleon interactions, and stripping. Under this assumption, the total stripping cross section has been determined to be 0.35±0.03 barn for the lighter elements and 2.6±0.4 barns for uranium. These values suggest an $A^{\frac{2}{3}}$ dependence for this cross section.

I. INTRODUCTION

THE principal features of the inelastic processes which can be expected to occur, when nuclei are bombarded by high energy deuterons, have been described by the mechanisms of Bohr,[1] Serber,[2] Dancoff,[3] Goldberger,[4] Chew and Goldberger,[5] and Butler.[6] These features concern the various secondary particles whose angular and energy distributions are characteristic of the process which produces them. For deuterons whose incident energy is high, compared to the binding energy, it is convenient to consider a very loosely bound neutron-proton system. The effects to be described are then merely the results of high energy collisions of nucleons with the nucleus, modified by the relationship of the incident deuteron's constituent nucleons to each other.

When the incident nucleons have energy less than, roughly, 30 to 40 Mev (corresponding to an incident deuteron energy of less than 70 to 80 Mev, since the total energy is shared equally, on the average), the compound nucleus of Bohr describes one process. In this model, the mean free path of either incident nucleon within the nucleus is so short that its energy is quickly shared with other constituents of the nucleus, so that it is immediately captured. The resulting excited nucleus decays slowly, either by quantum emission, or, when sufficient energy becomes concentrated properly, by particle emission. These secondary particles will carry off most of the excitation energy, neutron emission being favored over charged particle emission because of the Coulomb barrier of the nucleus. The energy distribution will be, roughly, a decaying exponential, with substantially no particles carrying more than about 10 Mev. The angular distribution of these particles will be essentially isotropic.

When the incident deuteron has energy less than about 50 Mev, a particular process which we shall call Butler stripping is important. Since in the deuteron the nucleon separation is large and the binding energy low, just one of the incident nucleons may interact with the surface of the target nucleus. If its momentum is proper, it will be bound into the nucleus to form one particular state of a new nuclide, which may then decay to its ground state. The other nucleon, passing by, must conserve energy, parity, and angular momentum. This means that it may carry energy greater than its initial energy by the amount of the binding energy of the captured nucleon. Further, this "secondary" nucleon, instead of carrying just the momentum it had at the time of capture, will, in addition, possess additional angular momentum so that the conservation laws are satisfied. The resulting angular distribution is just a sum over those angular momentum states which are acceptable. Only a few of these are important, since the magnitude of each contribution is roughly inversely proportional to the angular momentum. The particles, then, are emitted in a pronounced forward direction, but the peak may be displaced from the axis of symmetry.

At higher deuteron energies, the Butler stripping becomes, in the limit, Serber stripping. In this mechanism the collision is "fast," so that the "secondary" particle, the nucleon which passes by, feels no reaction. In terms of the Butler theory, so many angular momenta are accepted that interference between them washes out the effect. The secondary's final momentum is the result of the motion of the deuteron center of mass and its motion with respect to the center of mass at the moment the other nucleon is stripped off by the edge of the nucleus. The resulting angular distribution is sharply forward, maximum in the direction of the axis of symmetry, with a half-width of about $3(\epsilon_d/T_d)^{\frac{1}{2}}$. The distribution of energies is centered around half the incident deuteron energy and has a half-width of about $2(T_d\epsilon_d)^{\frac{1}{2}}$, where ϵ_d is the deuteron binding energy, and T_d is the

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[2] R. Serber, Phys. Rev. 72, 1008 (1947).
[3] S. M. Dancoff, Phys. Rev. 72, 1017 (1947).
[4] M. L. Goldberger, Phys. Rev. 72, 1269 (1948).
[5] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).
[6] S. T. Butler, Phys. Rev. 80, 1095 (1950).

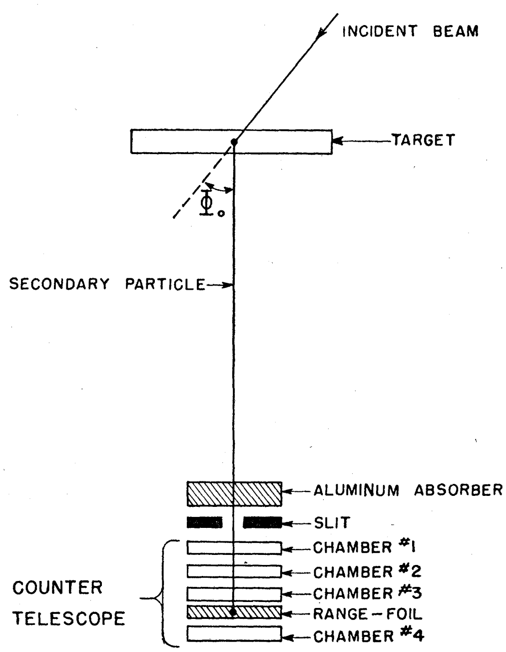

FIG. 1. Schematic diagram of the four chamber proportional counter telescope.

incident deuteron kinetic energy. The cross section for this process is proportional to the target nuclear radius.

Another effect which may occur is the "field stripping" described by Dancoff. It is the action of the Coulomb field of the target nucleus upon the incident deuteron. When the energy is low, this amounts to an orientation of the deuteron (because of Coulomb repulsion on the proton), which accounts in part for the high cross section for deuteron reactions. When the energy is sufficiently high, the transverse electric field seen by the moving deuteron may cause it to split up. The angular distribution from this process is narrower than that of the Serber stripping by a factor of two, but the total effect is predicted to be as important for heavy elements, since the cross section goes like the square of the charge of the target nucleus.

When the incident nucleon energy is as high as 90 Mev, the nucleus becomes somewhat transparent, because the nucleon-nucleon cross section decreases with energy. This makes the mean free path for nucleons in nuclear matter the order of the radius of the nucleus, so that if a collision occurs, one or more fast secondary particles may be emitted. The angular and energy distributions of the "knock-on" secondaries will depend upon the model chosen for the nucleus, but at least partial correlation is expected with the direction and energy of the incident nucleons, so that the secondaries will be emitted mainly forward, with energies equal to that of the incident nucleons, or less.

Chew and Goldberger have described a process by which deuterons, tritons, etc., may be produced. The nucleons within the nucleus are in motion, and when an incident nucleon penetrates, there is some probability that a pair may result in such a momentum relationship that, say, a deuteron is formed. If the total energy is high, so that the mean free path is long, this "pick-up" deuteron may escape as a secondary. Three-particle pick-up will result in a triton or He^3 secondary. These "pick-up" particles will be emitted strongly forward, and they will be peaked around some energy which gives the best compromise between the formation probability, which involves the internal nucleon momentum distribution, and the escape probability.

High energy fission can also occur when heavy nuclei are bombarded by nucleons. The secondary nucleons, mainly neutrons are emitted isotropically and with energy less than 10 Mev.

The aim of the present work was an investigation of the high energy charged secondary particles (proton energy >26 Mev, deuteron energy >35 Mev) from bombardment of beryllium, carbon, and uranium nuclei by 190-Mev deuterons. The information to be gained includes (a) the relative importance of the deuteron's binding energy in collisions with nuclei, (b) a measurement of the cross section for stripping, and (c) evidence for the existence of Dancoff field stripping.

II. EXPERIMENTAL METHOD

Consider an inelastic scattering process, defined to be one in which the particles emitted at a given mean angle Φ_0 include a more or less broad spectrum of energies. In such a case, the connection between the observation and the differential scattering cross section is given by

$$C(\Phi_0, T_0, T_0')=\int\int\int J(T')N\frac{d^2\sigma}{d\Omega dT}(\Phi, T, T') \times P(T, \Omega)d\Omega dTdT'. \quad (1)$$

$C(\Phi_0, T_0, T_0')$ = number of counts observed in the detector, when it is set to accept particles of mean energy T_0 at mean angle Φ_0, when particles of mean energy T_0' are bombarding the target.

$J(T')$ = number of incident particles whose energies lie between T' and $T'+dT'$. The integration is over all T'. $\int J(T')dT'=I$ = total number of particles incident upon the target. The beam particles are assumed to be independent of each other.

N = number of target nuclei per cm^2 in the beam direction and is assumed to be constant.

$\frac{d^2\sigma}{d\Omega dT}(\Phi, T, T')$ = differential scattering cross section in the laboratory system for producing particles of energy T at angle Φ when the target nuclei are bombarded with particles of energy T'.

$P(T, \Omega)$ = detector resolution probability function which describes how efficiently a particle of energy T emitted into a solid angle Ω will be detected.

If it is assumed that (a) the number of target nuclei remains constant, approximately, during bombardment; (b) the incident beam particles are independent of each other; (c) the spread in energy of the incident beam particles is small compared to the nominal beam energy T_0'; (d) the differential scattering cross section varies only slowly over the range of incident beam particle energies and over the range of angles and energies accepted by the emitted-particle detecting system; and (e) the integral of the detector resolution function can be determined in terms of the accepted solid angle $\Delta\Omega_0$ and the accepted energy width $\Delta T(T_0)$, Eq. (1) can be written

$$C(\Phi_0, T_0, T_0')=I(T_0')N\frac{d^2\sigma}{d\Omega dT}(\Phi_0, T_0', T_0) \times\Delta\Omega_0\Delta T(T_0). \quad (2)$$

For the purposes of the present experiment, it was sufficient to detect charged particles without trying to discriminate between them. It was already known that the secondary charged particles would be mainly protons, with some deuterons, and the numbers of other kinds of charged particles would be negligibly small, due to the small cross section for their production. Equation (1), generalized, becomes, in such a case,

$$C(\Phi_0, T_0^j, T_0')=\sum_j \int\int\int J(T')N\frac{d^2\sigma^j}{d\Omega dT^j} \times(\Phi, T^j, T')P(T^j, \Omega)d\Omega dT^j dT', \quad (3)$$

where the sum is over the j different kinds of secondaries. $d^2\sigma^j/d\Omega dT^j$ is the differential cross section for producing a type j secondary particle of energy T^j at angle Φ, when the incident energy is T'. Under suitable approximations, as explained, (3) becomes

$$C(\Phi_0, T_0^j, T_0')=I(T_0')N\Delta\Omega_0\sum_j \frac{d^2\sigma^j}{d\Omega dT^j} \times(\Phi_0, T_0^j, T_0')\Delta T(T_0^j). \quad (4)$$

In the present investigation, the emitted charged particles were detected by a differential-range measuring device. These charged secondaries, in order to be counted were required to traverse the first three chambers of a proportional counter telescope (in coincidence) and stop in a thin range foil before reaching the fourth chamber (anticoincidence) (see Fig. 1). The secondary particle energies are measured by varying the thicknesses of aluminum absorbing foils placed in front of the counter telescope and applying the range-energy relationship.

Consider a specific proton which has been produced by a (d,p) reaction exactly at the midpoint of the target. Suppose this proton, moving at an angle Φ_0 (in the laboratory system) to the original beam direction, has energy just sufficient to carry it through (a) the remaining target thickness, (b) the air path between the target and the counter telescope, (c) the aluminum absorber, (d) the first three chambers of the telescope, and (e) exactly half the range-foil thickness.

Such a path defines a specific proton energy T_0. However, both the converter and the range foil have finite thicknesses, and even monoenergetic particles straggle in range. For this problem, we will assume that the final resolution of the detector is given by the fold function

$$P(T)=\int_{-\infty}^{\infty} p_c(T-E)\int_{-\infty}^{\infty} p_b(K)p_a(E-K)dKdE, \quad (5)$$

where $p_a(T)$ is a function which describes the effect of finite target thickness, $p_b(T)$ is a function which describes the effect of finite range foil thickness, and $p_c(T)$ is a function which describes the effect of range straggling.

An example of the fold is shown in Fig. 2 for a mean proton energy $T_0\approx 155.7$ Mev. The fold was done graphically. While the detector resolution is 4 Mev wide at half-maximum, the integral of the resolution function is a bite in energy only about 1.5 Mev wide. The fold also indicated that the best resolution for a given counting intensity was to be obtained by making the range foil and target of equal range.

The lower limit to the energies of the secondary particles which can be detected is set by the minimum range which each particle must have in order to just reach the range foil in the detector. This minimum energy is 26 Mev for protons and 35 Mev for deuterons.

Regarding the incident deuteron as two essentially independent nucleons, the processes which will be observed in this experiment are the result of the incident proton interactions with the nucleus to yield (a) knock-on protons or (b) pick-up deuterons, and the incident neutron interactions with the nucleus to yield (a) stripped protons, (b) knock-on protons, and (c) pick-up deuterons. While the incident neutron interacts only with subnuclear protons to yield an observable particle (protons of energy >26 Mev, deuterons of

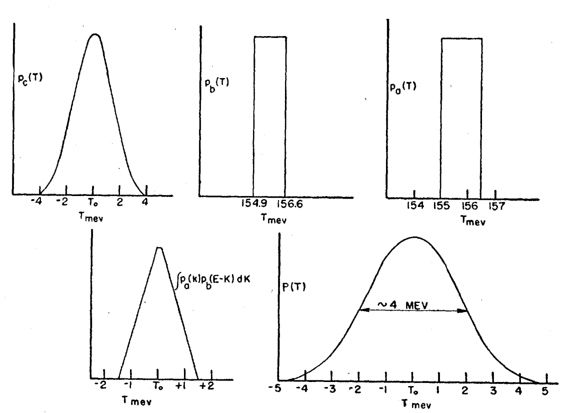

FIG. 2. The energy resolution of the detector, as the fold of the several detector functions. The fold was integrated graphically.

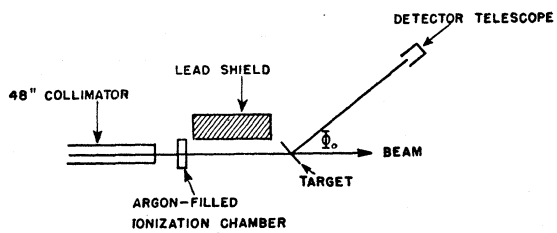

FIG. 3. Schematic diagram of the experimental arrangement.

energy >35 Mev), the incident proton can interact with either neutrons or protons. The counts observed when the detector is set at some mean angle Φ_0, and for particles of mean energy $T_0{}^j$, will be

$$C=IN\Delta\Omega_0\{\Sigma_p\Delta T_p+\Sigma_d\Delta T_d\}, \quad (6)$$

where

$$\Sigma_p=\frac{1}{A}\left\{(A-Z)\frac{d^2\sigma(p,n)}{d\Omega dT}+Z\frac{d^2\sigma(p,p)}{d\Omega dT}+Z\frac{d^2\sigma(n,p)}{d\Omega dT}\right\}+\frac{d^2\sigma(d,p)}{d\Omega dT},$$

$$\Sigma_d=\frac{1}{A}\left\{(A-Z)\frac{d^2\sigma(p,d)}{d\Omega dT}+Z\frac{d^2\sigma(n,d)}{d\Omega dT}\right\},$$

ΔT_p= energy bite taken by range foil for protons,

ΔT_d= energy bite taken by range foil for deuterons.

III. APPLICATION OF EXPERIMENTAL METHOD

A. General Procedure

The experimental arrangement is shown in Fig. 3. The collimated external deuteron beam of the 184-inch cyclotron was monitored by an argon-filled ionization chamber whose collected charge was integrated electronically. The targets were thin and larger in lateral extent than the beam. They were placed in the beam and the emitted charged secondary particles were detected by a proportional counter telescope. This detector was shielded with lead from any particles which might have scattered either from the mouth of the collimator or from the ionization chamber. The number of incident deuterons was determined from the charge collected in the ionization chamber, and the number of secondaries produced at mean angle Φ_0 into the solid angle defined by the slit was determined from the counts in the telescope. The range of each particle measured its energy. The effects of the air path of the incident beam and the general cyclotron background were removed by using no target on alternate runs. The target-blank difference thus measured the intensity of secondary particles which came from the target.

B. Beam and Alignment

The source of deuterons for the experiment was the full energy circulating beam from the 184-inch synchrocyclotron. These deuterons were multiply scattered[7] into the magnetic deflector channel and steered into a shielded enclosure where the experiment was carried out (Fig. 4). The beam pulse obtained this way is of about 40 microseconds duration, with a repetition rate of about 60 pulses per second. The deuteron energy is fixed by the path through the magnetic deflector channel and the steering magnet. This energy was determined from the curvature in the magnetic field and from the range in aluminum and corresponds to approximately 190 Mev. The variation in energy is thought to be less than ±2 percent.

The beam was collimated by means of a four-foot brass plug so that it was about $\frac{1}{2}$ inch in diameter when it emerged from the shielding. The position and spread of this beam were measured by the blackening produced on x-ray films placed at several points along the beam path. The surface of the table which supported the apparatus was then oriented parallel to the plane containing the beam, target, and detector. The table was also adjusted so that fiducial marks inscribed for the purpose fell along the beam path as defined by the films. The alignment was checked frequently by means of films to insure that it was correct at each angular setting of the detector. The alignment is thought to be accurate to $\pm\frac{1}{2}$ degree.

In order to insure that the counts varied linearly with the number of deuterons incident, as indicated by Eq. (6), the beam intensity was adjusted so that the real coincidence counting rate per unit of collected charge was constant as a function of beam intensity. The beam intensity was always chosen so that the singles rate in any one chamber was about one count per beam pulse, since at this counting rate the number of accidental triple coincidences is negligible, as was shown by the beam plateau.

C. Beam Monitor

The deuteron beam was monitored with an argon-filled ionization chamber, whose multiplication factor for 190-Mev deuterons as determined by comparison with a Faraday cup, was 1525 charges collected per deuteron. The charge collected by the ionization chamber was placed on a low leakage condenser connected to the input grid of an integrating electrometer. The electrometer was of the 100 percent feedback type, and drove a continuous recorder which recycled itself after reaching a predetermined voltage. The recording circuit automatically calibrated itself periodically against a standard cell.

The condenser used was calibrated by means of an impedance bridge against a standard condenser whose capacitance is known to about 0.1 percent. The monitor system is believed to be accurate to ±2 percent.

D. Targets

The beryllium, carbon, and uranium foil targets used in the experiment were all thin (~700 mg per cm²) and

[7] C. E. Leith, Phys. Rev. 78, 89 (1950).

cut from stock materials. These foils were mounted on a carriage which could be driven from a remote position. This arrangement made it simple to change targets with a minimum loss of running time, and a single no-target run sufficed to determine the background subtracted from all three targets for any one angle and energy determination. The targets were about 2 inches square, larger in lateral dimensions than the beam. This was checked photographically for the minimum and maximum angular positions of the target. The target carriage rotated upon a mount which also contained the detector telescope, and the target surface was at all times perpendicular to the line joining the target and the detector. The target thicknesses were made as nearly equal as possible, so that a change of target had a negligible effect upon the resolving power of the apparatus.

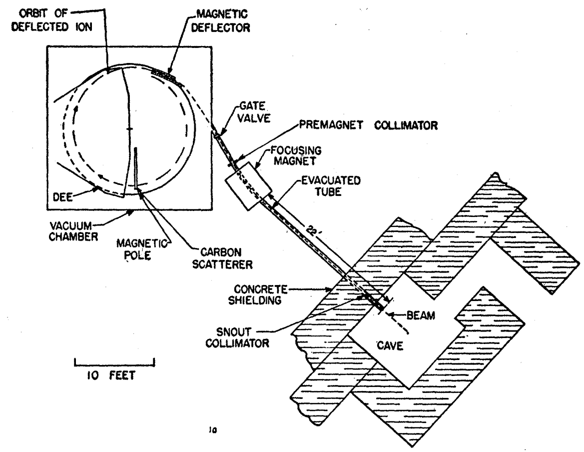

FIG. 4. Schematic diagram of cyclotron and shielded enclosure.

E. Absorber Correction

At the deuteron energy used in this experiment, the absorbers used to measure the emitted particle energies are so thick (up to several g/cm^2) that some particles which would otherwise pass through are removed by Rutherford scattering and nuclear absorption. The loss was ascertained as a function of aluminum absorber thickness by making an integral range determination using protons. The maximum correction used was of the order of 25 percent. An auxiliary experiment showed that the attenuation cross section for deuterons in aluminum is approximately twice that for protons.

F. Detector

In order to reduce the number of accidental coincidences due to background from the cyclotron and to define more sharply the direction from which the particles come, the detector consisted of a four-chamber proportional counter telescope, in front of which was placed a lead slit. The slit, two inches thick, had an opening one inch square which, at a distance of 30 inches from the target, defined the solid angle $\Delta\Omega_0$. The number of particles which have stopped in the range foil is then the number which traverse the first three chambers in coincidence, minus the number which traverse all four chambers in coincidence. In order to test that the counting rate varied linearly with solid angle as predicted by Eq. (6), a determination of counting rate was made as a function of the reciprocal of the square of the distance between the target and the slit. The dependence was found to be linear.

Each chamber of the telescope consisted of a multiwire, parallel-plate proportional counter, whose dimensions were 3 inches by 3 inches by $1\frac{1}{2}$ inches. The counter wires were made of 0.003-inch nickel, supported under spring tension by Teflon bars between brass frames. The spacing between wires was $\frac{3}{4}$ inch. The chamber volumes were defined by 0.0005-inch aluminum foils which were fastened across the brass frames. All the components were cleaned with chemicals and then rinsed with water. All four chambers were then mounted into a gas-tight box which was designed in such a way as to allow the range foil to be inserted between the third and fourth chambers from outside the box. A thin aluminum window allowed the particles to enter the telescope, and the electrical connections were brought out through Kovar seals in the roof of the box. After assembly, the box and its components were outgassed, flushed, and then filled with a mixture of 96 percent argon and 4 percent CO_2 to a pressure of one atmosphere.

The chambers were operated at about 2300 volts and the linear amplifier gains were adjusted so that the largest pulses were not quite overloading. Under these conditions, the typical plateau obtained by plotting the real coincidence rate against the discriminator bias setting on the first three chambers was adequate.

To test whether the fourth chamber was large enough in lateral dimensions to accept most of the particles from the one inch slit, the real coincidence rate was determined as a function of the amount of counter area open. This was done by putting a very thick shield in front of the fourth chamber and withdrawing it vertically. The main portion of the particles accepted by the slit lay well within the 3-inch by 3-inch face of the fourth chamber. The requirements placed on the detection system were found to be rather stringent, in that the telescope was required to detect charged particles over an extremely wide range of energies and hence, over an extremely wide range of ionization losses. In fact, the method of counting which was used introduces spurious counts which are the result of imperfect counting of particles in the fourth chamber and nuclear attenuation of particles in the range foil. The efficiency of the fourth chamber is less than unity because (a) particles which have energy sufficient to enter the fourth chamber may have been scattered enough to be missed, (b) the energy loss in the fourth chamber, being statistical, may fluctuate enough so that some particles

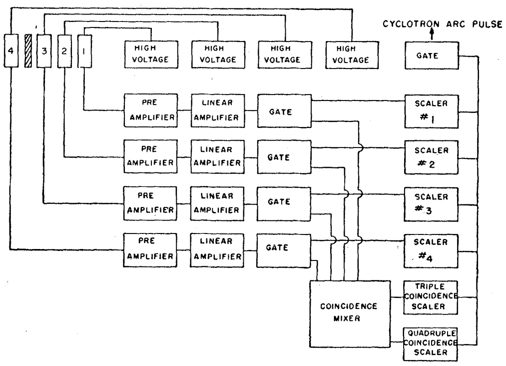

FIG. 5. Block diagram of the electronics associated with the detector.

are not counted, (c) the pulse from the fourth chamber may be delayed sufficiently (longer electron collection time in the counter, or electronic circuit delays) for some particles to be missed.

The range-foil material was tantalum, chosen because it was available in foil form in a variety of thicknesses, and because a material of high atomic weight was needed to give the most stopping power for the least nuclear absorption. The fourth chamber was large enough so that multiple scattering did not cause appreciable losses.

Correction runs were made for each experimental point to take account of the spurious events which the detector recorded because of its mode of operation. The correction to the data amounted to about 40 percent, at maximum, resulting in rather poor statistics for the real events at small angles.

G. Electronics

A block diagram of the electronic circuits associated with the operation of the counter telescope is shown in Fig. 5. Pulses from the first three chambers generated 2 microsecond gates, and pulses from the fourth chamber generated 3 microsecond gates which overlapped the others in time. The time delay in pulses from the fourth chamber relative to the pulses from the first three chambers was measured by the quadrupole coincidence rate, varying the delay on the gate from the fourth chamber. A small but finite contribution was missed, which was a contributing factor in making the fourth chamber efficiency less than unity. This jitter is believed to be the result not only of variation in ion collection time in the counter chambers, but also the effect of the response of the coincidence mixer circuits.

IV. RESULTS AND DISCUSSION

A. Presentation of Data

By the method indicated, the number of particles which stopped in the range foil per microampere of incident deuteron beam has been determined as a function of energy at laboratory angles of 7.5°, 10°, 15°, 20°, and 45°.

A set of composite curves, derived from both theory and experiment, with which to compare these points has been obtained by means of Eq. (6). The values used for the nucleon-nucleon differential cross sections $d^2\sigma(n,p)/d\Omega dT$, $d^2\sigma(p,n)/d\Omega dT$, and $d^2\sigma(n,d)/d\Omega dT$, were taken from the experiments of Hadley and York,[8] and Hoffmann and Strauch.[9] For the uranium target, the results of Hoffmann and Strauch were extrapolated from lead. As a first approximation, the differential cross section for producing protons by protons, $d^2\sigma(p,p)/d\Omega dT$, has been taken equal to that for producing protons by neutrons, $d^2\sigma(n,p)/d\Omega dT$, which has been verified in the case of scattering from hydrogen. The differential cross section for deuteron pick-up by protons $d^2\sigma(p,d)/d\Omega dT$ has been assumed equal to that for neutrons, $d^2\sigma(n,d)/d\Omega dT$. Finally, the shape of the stripping cross section, $d^2\sigma(d,p)/d\Omega dT$, has been computed from the theory of Serber and normalized to fit the observed points. This theory predicts the differential cross section to be

$$\frac{d^2\sigma(d,p)}{d\Omega dT}=\frac{CT_0^{\frac{1}{2}}}{[\frac{1}{2}\epsilon_d+T_1+T_0-2(T_1T_0)^{\frac{1}{2}}\cos\Phi_0]^2}, \quad (7)$$

where T_1 is one-half the incident deuteron kinetic energy, ϵ_d is the deuteron binding energy, Φ_0 is the angle between the beam direction and the emergent nucleon, and T_0 is the kinetic energy of the emergent nucleon.

An example of the construction of a resultant composite yield curve is shown in Fig. 6. The variation of the composite curves with angle is shown in Fig. 7 for the case of carbon.

Figures 8, 9, and 10 show the data, together with the appropriate composite curves. In these figures the composite curves have been corrected for absorber attenuation. The data have been normalized to counts per microcoulomb of incident deuterons and has been corrected for cyclotron background and detector effciency. The ranges of aluminum used in the experiment have been converted to energies on the proton scale by means of the curves of Aron *et al.*,[10] for both protons and deuterons which the counter telescope detected, so that a single energy scale suffices for both kinds of particles. The standard deviations shown are due to counting statistics only. The energy resolution of the detector for each point was determined by a graphical integration of Eq. (5), using the appropriate parameters at each energy.

B. Results

By fitting curves of the shape given by Eq. (6) to the experimental points at each angle, centered around 90

[8] J. Hadley and H. York, Phys. Rev. **80**, 345 (1950).
[9] K. Strauch and J. A. Hoffmann, Phys. Rev. **86**, 563 (1952).
[10] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663 (unpublished).

Mev, values of the proportionality constant C in Eq. (7) were determined. This enabled the total cross section for stripping to be computed by integrating Eq. (7). In view of the fact that stripping has a relatively small dependence upon atomic weight, the beryllium and carbon targets give the same cross sections, within the accuracy of the experiment. For this reason the cross sections determined from these two elements have been lumped together and averaged. The results are given in Table I. The weighted averages are:

beryllium or carbon $(0.35\pm 0.03)\times 10^{-24}$ cm^2,
uranium $(2.6\pm 0.4)\times 10^{-24}$ cm^2.

The standard deviations were computed from external consistency by assigning a standard deviation to the proportionality constant which was consistent with those attributed to the experimental points. It is felt that this procedure is justified, since the constant cannot be varied over wider limits and still have the composite curve fit the data so well.

In addition to the data shown, the charged particle yield was investigated as a function of energy in preliminary experiments at laboratory angles of 90° and 135°. The yields were low and dropped off rapidly with increasing energy and angle.

C. Conclusions

From the comparison of the experimental points and the composite curves, it can be said that the assumed interactions are indeed the principal collision mechanisms, at least to a first approximation. It is, of course, to be expected that the deuteron can be considered as a system of two independent nucleons, since the binding energy ($\sim$2.2 Mev) is small compared to the total kinetic energy ($\sim$190 Mev).

Beryllium and carbon were chosen as target nuclei in the hope that the loose neutron in beryllium might produce a large effect, compared to a nucleus with a closed structure, like carbon. No such effect was observed.

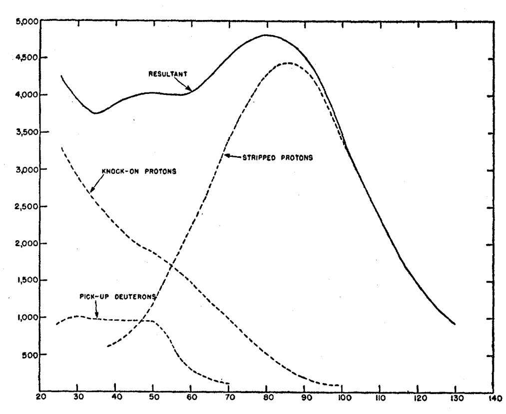

FIG. 6. Example of the construction of a composite yield curve from its components. The case shown is for the carbon target at $\Phi=10°$.

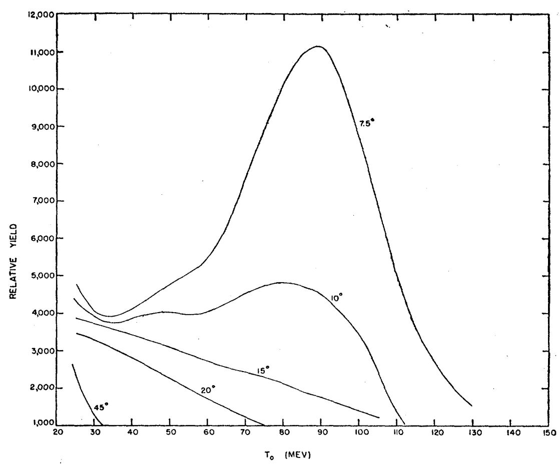

FIG. 7. A complete set of composite curves for the angles investigated experimentally. The case shown is for the carbon target.

With respect to the magnitude of the stripping cross section, the values 0.35 barn and 2.6 barns are much larger than the values of 0.12 barn and 0.43 barn which are to be expected from the Serber stripping theory for beryllium and uranium, respectively. Further, this theory predicts an $A^{\frac{1}{3}}$ dependence for the total stripping cross section. However, the values determined in this experiment indicate an $A^{\frac{2}{3}}$ dependence, shown in Fig. 11. This discrepancy in magnitude and dependence is not wholly unexpected, in view of the fact that the Serber theory does not include the large contribution to stripping which must result from the transparency of nuclear matter. For example, if the projected deuteron separation is such as to allow both nucleons of the deuteron to fall within the area defined by the nuclear diameter, it would be possible for one nucleon to be removed by collision, while the other passed through the transparent nucleus. For such collisions, the stripping cross section would more closely approximate the geometrical cross section, and a dependence faster than $A^{\frac{1}{3}}$ would result. Of course, the nucleus is not perfectly transparent, and the diameters of the heavy nuclei are of the order of several mean free paths for the nucleons with which we are concerned. This means that the shape of the differential cross section which was used to fit the data is certainly not correct. However, the shape cannot differ too much from the form used, and still permit a good fit to the data. The accuracy of the experiment does not permit a more detailed description of this enlarged differential stripping cross section.

The large cross section for uranium can be used to explain qualitatively the results of Helmholtz *et al.*,[11] in observing the angular distribution of neutrons from deuterons bombarding uranium targets. Their angular distribution fitted the shape predicted by the Serber theory alone. Now the Dancoff cross section for electric

[11] Helmholz, McMillan, and Sewell, Phys. Rev. **72**, 1003 (1947).

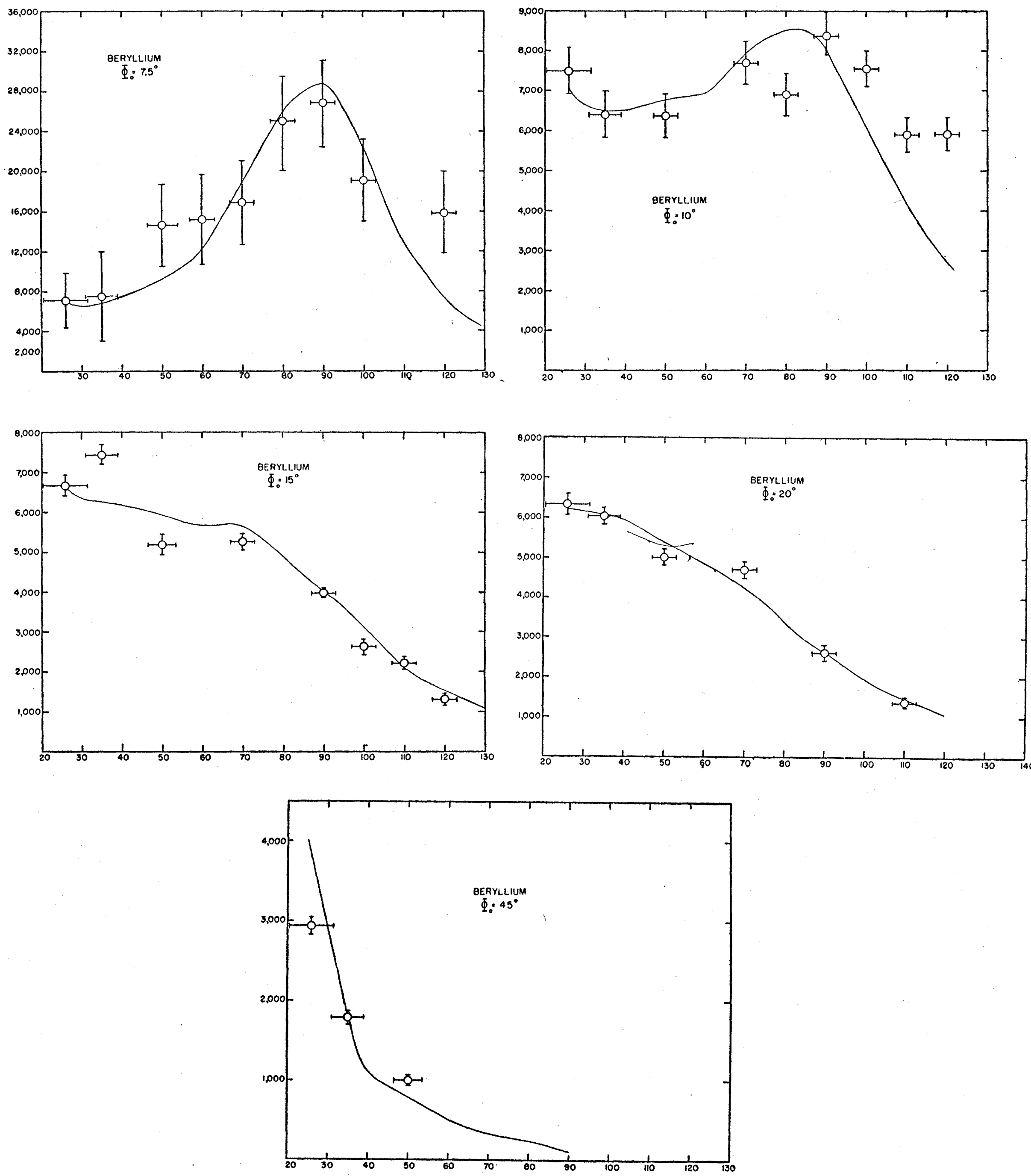

FIG. 8. The energy distributions of secondary charged particles from a thin beryllium target at laboratory angles of 7.5°, 10°, 15°, 20°, and 45°. The abscissas are in Mev on the proton energy scale. The ordinates are in number of counts detected per microcoulomb of incident deuterons.

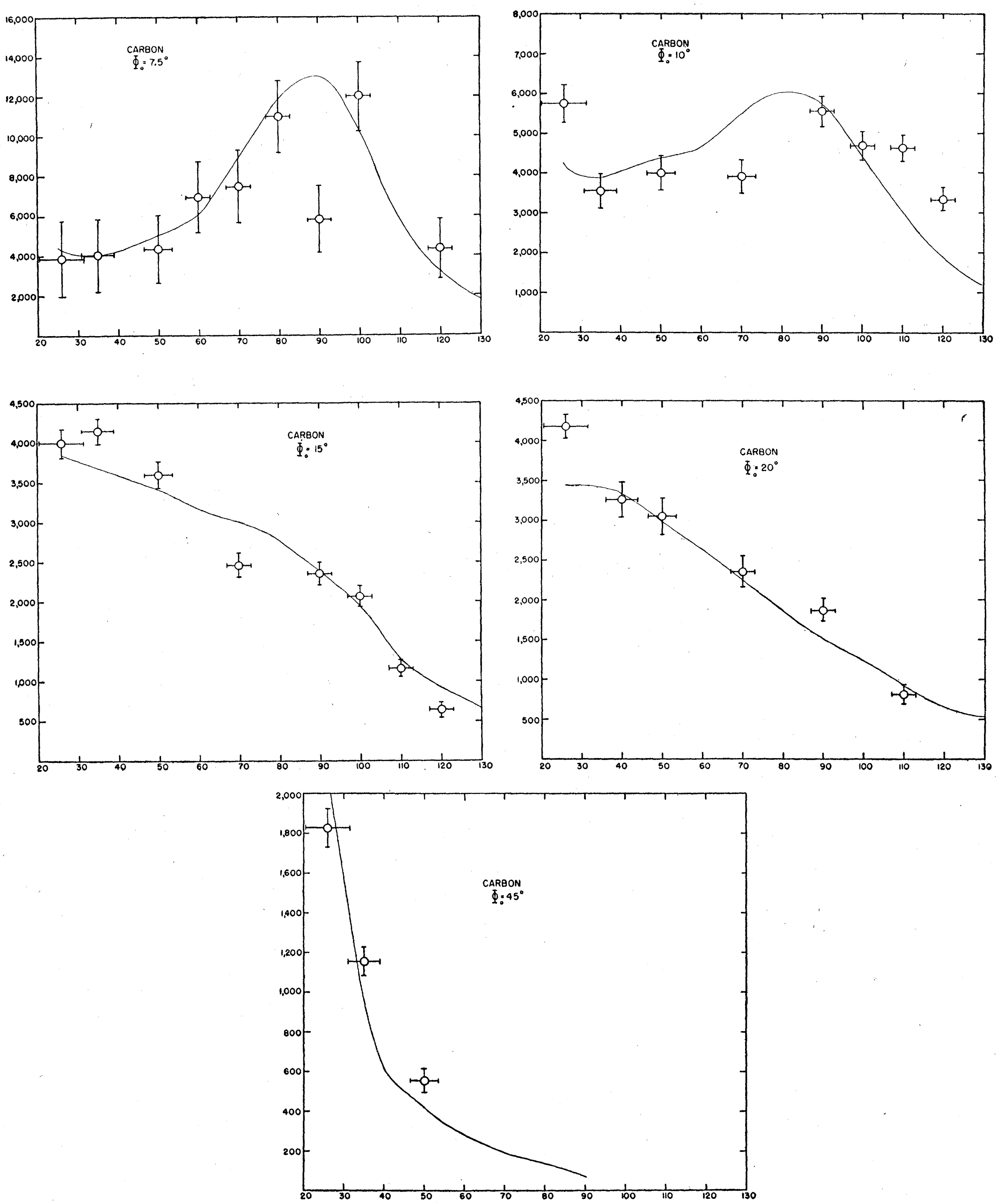

FIG. 9. The energy distributions of secondary charged particles from a thin carbon target at laboratory angles of 7.5°, 10°, 15°, 20°, and 45°. The abscissas are in Mev on the proton energy scale. The ordinates are in number of counts detected per microcoulomb of incident deuterons.

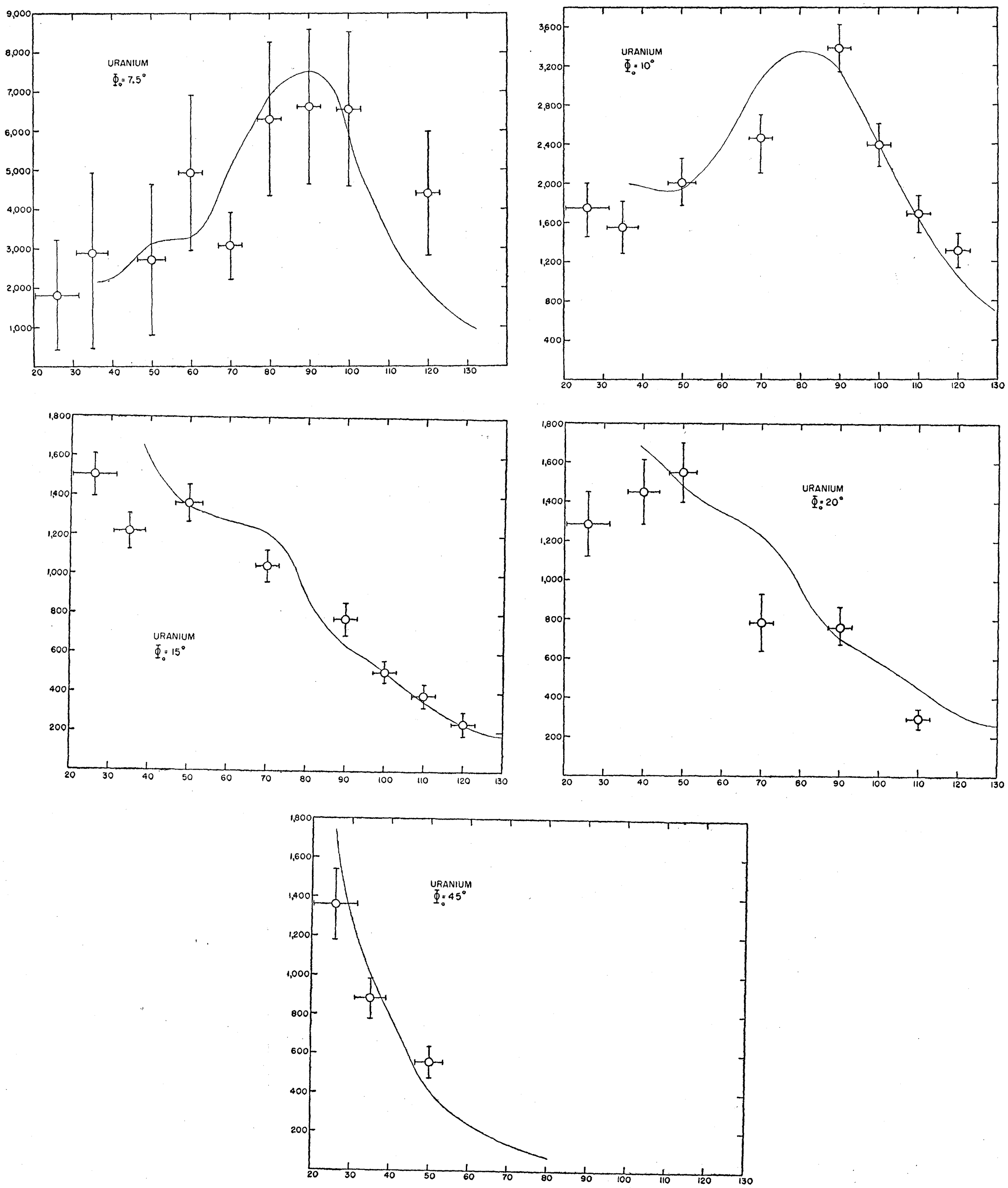

FIG. 10. The energy distributions of secondary charged particles from a thin uranium target at laboratory angles of 7.5°, 10°, 15°, 20°, and 45°. The abscissas are in Mev on the proton energy scale. The ordinates are in number of counts detected per microcoulomb of incident deuterons.

field stripping was predicted to be about 0.1 barn in uranium, compared to 0.43 barn for the Serber process. Therefore, since the angular distribution from electric stripping is much narrower than that from the Serber theory, a total angular distribution is to be expected that is somewhat narrower than was observed, corresponding to a superposition of these two effects. This was hard to understand, as long as the Serber process was the only expected one. However, comparing the 0.1 barn for electric stripping in uranium to the enlarged

TABLE I. The measured cross sections and their weighted averages.

$$\Sigma=\int\int\frac{d^2\sigma}{d\Omega dT}dTd\Omega=2\pi C\int_0^\infty\int_0^\pi\frac{T_0^{\frac{1}{2}}\sin\Phi_0 d\Phi_0 dT_0}{[\frac{1}{2}\epsilon_d+T_0+T_1-2(T_1T_0)^{\frac{1}{2}}\cos\Phi_0]^2}=\frac{4\pi^2C}{(2\epsilon_d)^{\frac{1}{2}}}.$$

Target	Angle	Σ (barns)	
Be	7.5°	0.40±0.03	
	10°	0.26±0.02	
	15°	0.34±0.01	
	20°	0.58±0.05	
			Σ_{Av}(Be or C) = (0.35±0.03) barn
C	7.5°	0.33±0.06	
	10°	0.36±0.03	
	15°	0.38±0.02	
	20°	0.64±0.07	
U	7.5°	2.9±0.8	
	10°	2.9±0.1	
	15°	1.6±0.2	Σ_{Av}(U) = (2.6±0.4) barns
	20°	4.6±0.7	

stripping cross section of 2.6 barns, with its angular distribution similar to that of Serber, the results of the neutron angular distribution measurements are quite reasonable.

The high total yield of neutrons observed by Knox[12] can also be qualitatively explained by the values of the enlarged stripping cross sections without invoking contributions from the electric stripping, which appears to be negligible in comparison.

D. Comparison with Theory

Although it was expected that the nuclear transparency should allow some contribution to stripping from the central portion of the nucleus, that contribution cannot be calculated easily. However, a few simple considerations can give some ideas concerning the quantities measured in this experiment.

Let σ_S be the Serber stripping cross section, σ_D be the Dancoff electric stripping cross section, τ_S be the transparency factor for 90-Mev nucleons near the edge of the nucleus, τ be the transparency factor for 90-Mev nucleons which pass through the main body of the nucleus, and R be the nuclear radius. The total stripping cross section can then be roughly represented by

$$\sigma=\sigma_S+\sigma_S\tau_S+(\pi R^2-\sigma_S)\tau+\sigma_D. \quad (8)$$

That is, σ_S is the cross section for the proton missing the nucleus, while the neutron hits the edge; $\sigma_S\tau_S$ is the cross section for the neutron missing the nucleus while the proton hits the edge, but traverses with probability τ_S; $(\pi R^2-\sigma_S)$ is the probability that both the incident nucleons strike the nucleus, and, when multiplied by τ, gives the cross section for the proton emission.

As a rough approximation, we can take τ_S equal to unity; it is probably somewhat larger than τ. A value for τ can be inferred from the analysis of neutron scattering made by Fernbach, Serber, and Taylor.[13] They find that the absorption cross sections for 90-Mev nucleons in beryllium and uranium are 0.55 and 0.88 of the geometric cross sections, respectively. This means that the respective transparency factors in these nuclei are 0.45 and 0.12, which lead to total stripping cross section values of approximately 0.33 barn for beryllium and approximately 1.3 barns for uranium. Comparing these with the measured values, it would seem that while the agreement in the case of beryllium is excellent, this simple mechanism does not account for the high uranium value. If, on the other hand, the theory is roughly correct, the measurement implies a nuclear transparency of about 0.6 for uranium, which is clearly in disagreement with absorption cross-section measurements. Part of the discrepancy in the uranium case can be accounted for by using a radius in Eq. (8)

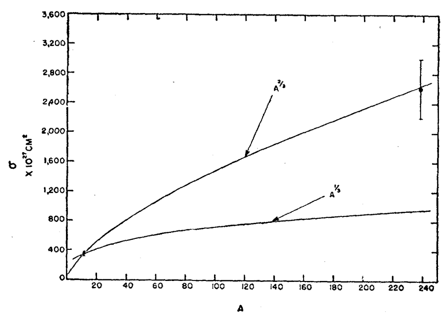

FIG. 11. The enlarged stripping cross section as a function of atomic weight.

which is enlarged to include the range of nuclear forces, as has been necessary to explain other nuclear collision processes. Probably the main reason for the disagreement is to be found in our neglect of the opaqueness of the uranium nucleus, in which case the agreement within a factor of two with the simple theory is mainly fortuitous. This is to be expected from the breakdown of the impulse approximation at the larger angles, rendering Eq. (7) invalid.

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[12] W. J. Knox, Phys. Rev. **81**, 687 (1951).

[13] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).