Low-Energy Protons Produced in the Deuteron Bombardment of Nuclei*

E. W. HAMBURGER,† B. L. COHEN, AND R. E. PRICE
University of Pittsburgh, Pittsburgh, Pennsylvania
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When nuclei are bombarded by fast deuterons a continuous spectrum of protons is observed at energies corresponding to $Q<-2.2$ Mev. The shape and angular distribution of this continuum were studied for several targets, from Li to Au, with 14.8-Mev deuterons. The angular distributions are strongly peaked at or close to 0° for light elements; for heavy elements the peak broadens and moves to $\sim$50°. The energy spectra shows a peak which, with increasing angle moves to lower energies for light elements, and moves to higher energies for heavy elements. All features of the results are explained using a semiclassical theory in which the deuteron is broken up in the external field of the nucleus. The breakup occurs at or near the nuclear surface for light elements, but quite far out from it in heavy elements. Observed cross sections are far larger than theoretical predictions for either Coulomb or nuclear breakup.

I. INTRODUCTION

THE spectra of protons produced in the bombardment of light nuclei with 15-Mev deuterons show discrete groups corresponding to energy levels of the final nucleus, and a superimposed continuum at low energies.[1–6] Since the high-energy limit of the continuum always corresponds to $Q=-2.2$ Mev, it has been suggested that it is due to the breakup of the deuteron.[7] This interpretation was confirmed when a survey of (d,p) reactions in heavier nuclei[8] showed that a broad group appears at approximately the same energy for all target nuclei studied from Cu to Au. The purpose of the present work was to study the continuum in more detail for both heavy and light target nuclei.

The breakup of deuterons on very light nuclei ($A\leq 4$) has been studied previously at bombarding energies up to $\sim$6 Mev.[9,10] Aschenbrenner[11] examined the low-energy proton spectra from several heavy nuclei bombarded by 15-Mev deuterons, and Cohen and Falk[12] studied the neutron spectra from several light nuclei bombarded by a similar beam. Theoretical work on the electric breakup of the deuteron has been published by Mullin and Guth,[13,14] and several authors have considered diffraction splitting.[15]

II. EXPERIMENTAL PROCEDURE

The deuteron beam from the University of Pittsburgh cyclotron was magnetically focused and analyzed[16] before striking the target. The deuteron energy was 14.80±0.15 Mev with an energy spread of $\sim$50 kev. The targets were metallic foils of natural isotopic abundance (except the lithium target, enriched to 99.3% in Li^6) and with thicknesses of a few milligrams per square centimeter. The reaction products were selected by a magnetic analyzer which could rotate about the target, and were detected by a CsI(Tl) scintillation crystal in the focal plane of the analyzer. The amplified output of the scintillator was fed to a pulse-height analyzer. A thin aluminum foil in front of the crystal greatly degraded the energy of alpha and He^3 particles, so that the pulses due to protons were over twice as high as those due to other particles. There was, therefore, no difficulty in distinguishing protons from other particles. At energies below $\sim$5 Mev, however, the gamma-ray background made proton counting difficult. The over-all resolution for protons was determined by the width of the crystal ($\sim$10 mm) and was $\sim$150 kev full width at half maximum.

The proton spectrum was swept across the crystal by diminishing the magnetic field in constant steps. The field was determined by the dial reading of the potentiometer controlling the magnet coil current. From time to time the dial reading was checked against the more precise measurement of a proton resonance fluxmeter. The proton energy was then found from the calibration

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† Now at Departamento de Fisica, Faculdade de Filosofia, Ciencias e Letras, Universidade de Sao Paulo, Sao Paulo, Brazil.
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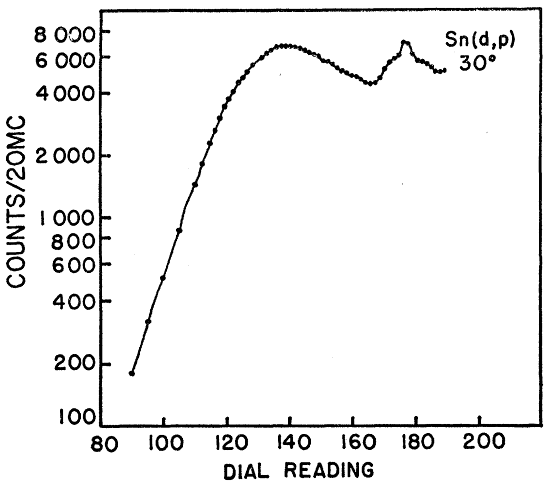

FIG. 1. Raw data from a typical run.

curve[6] of energy vs proton magnetic resonance frequency. The energy scales are estimated to be internally consistent within ±100 kev, and the error between two spectra or in the absolute energy should not exceed 200 kev.

The raw data from a typical run are shown in Fig. 1. The data processing consisted of substituting the dial reading abscissa scale with an energy scale and dividing the observed number of counts by the energy to obtain a number proportional to the differential cross section per unit energy interval. The absolute cross-section scales were computed from the target thicknesses and detector solid angle.[6]

At small angles, there was a background of low-energy protons due to slit edge scattering; it was minimized by appropriate adjustment of antiscattering slits.[5,6] Previous experience had shown that the slit edge scattered counts were very sensitive to the beam position. The effect was therefore monitored by comparing the counting rates when the beam was focused on the right and on the left side of the target. It is estimated that at most 15% of the cross sections presented in this paper, at the forward scattering angles, is due to this background. At larger scattering angles the background is much less.

Another possible source of error is target contamination. However, the systematic variation of the measured cross section with atomic number shows that the impurities in the targets were small. For example, if appreciable quantities of carbon or oxygen existed in the heavy targets the observed spectra at large angles would show more low-energy particles. The only contaminant group which did appear in several targets is the recoil proton group due to hydrogen.

Relative cross sections are estimated to be good within ±15% for the same target within ±20% for different targets. Absolute cross sections are probably accurate within ±30%.

All data, except that for lithium in Fig. 3, are presented in the laboratory system of reference. The laboratory system coincides with the center-of-mass system for heavy elements. For aluminum, on the other hand, the energy in the entrance channel (in the c.m. system) is 13.8 Mev and a proton group corresponding to a c.m. energy of 8 Mev has laboratory

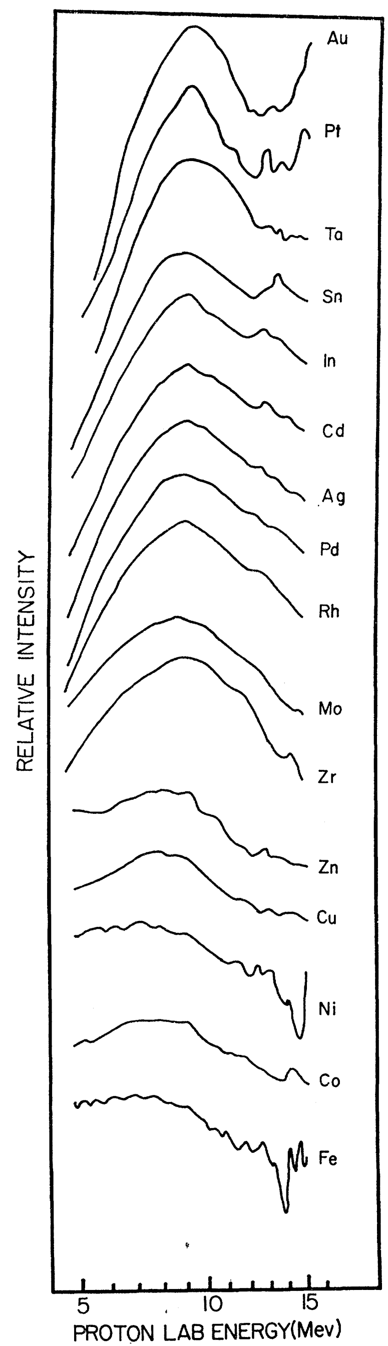

FIG. 2. Spectra of low-energy protons from bombardment of 16 elements with 14.8-Mev deuterons at $\theta_{lab}=30°$. Data from reference 8.

energies of 9.1 Mev at $\theta_{lab}=12°$ ($\theta_{c.m.}\cong 13°$), 9.0 Mev at $\theta_{lab}=29°$ ($\theta_{c.m.}\cong 31°$) and 8.2 Mev at $\theta_{lab}=85°$ ($\theta_{c.m.}\cong 39°$).

III. RESULTS

Figure 2 shows the spectra, obtained previously,[8] of low-energy protons produced at $\theta_{lab}=30°$ by deuteron bombardment of 16 elements. Figures 3 to 8 show the spectra from 6 elements at several angles.

The general features of the spectra of Fig. 2 are the following: All spectra show a broad maximum for E_p between 5 and 9 Mev. The maximum has a flat top for the lighter elements, extending from 5 to 9 Mev for $_{26}$Fe, but becomes more sharply peaked as Z increases: thus for $_{26}$Fe the cross section is constant to within 20% from 5 to 9 Mev while for $_{40}$Zr this region extends only from 8 to 10.5 Mev and for $_{79}$Au it goes from 8.2 to 10.0 Mev. The peak also shifts toward higher energies with increasing Z. However, from Zr to Au no appreciable shift seems to occur; we return to this later.

The sharpening of the peak occurs principally on the low-energy side, which is very flat for the light elements and drops to very low values for the heavy elements. It may be worthwhile to point out that this sharpening would not be so obvious on a linear plot.

The aluminum and lithium cross sections of Figs. 3 and 4 are large at forward angles and decrease rapidly at larger angles. At the same time the peak for aluminum shifts in energy from ~8.5 Mev at 12° to ~5 Mev at 61°. For copper (Fig. 5) the same comments hold except that the variation of both the peak intensity and the peak energy with angle is slower. For zirconium (Fig. 6) the cross section is almost constant at forward angles, having a peak at ~30°, and decreases toward larger angles. The peak energy shift is again less than in copper. Cadmium (Fig. 7) has a minimum in the forward direction and a maximum at 30°. The position of the peak energy does not shift with angle. Finally platinum (Fig. 8) has a maximum at 60° and the peak shifts toward higher energies with increasing angle.

The general features of the spectra of Figs. 4 to 8 are summarized in Figs. 9, 10, and 11. The lithium data are not included because the large correction due to the center-of-mass motion makes the comparison with the other data difficult. Figure 9 shows the peak differential cross section (in millibarns per steradian-Mev) as a function of scattering angles for the five elements studied. The shift of the peak in the angular distribution from 0° for small Z to ~50° for Pt and Au is clearly visible. Figure 10 shows the proton energy at the peak as a function of angle. Here one sees the downward shift of the energy for the light elements, the constancy for cadmium and the upward shift for platinum. In Fig. 10 we see that the absence of any energy shift of the peak when Z varies from 40 to 80, observed in Fig. 2, is a peculiarity of the angle 30°. At other angles a shift does occur. As an indication of this shift, the energy of

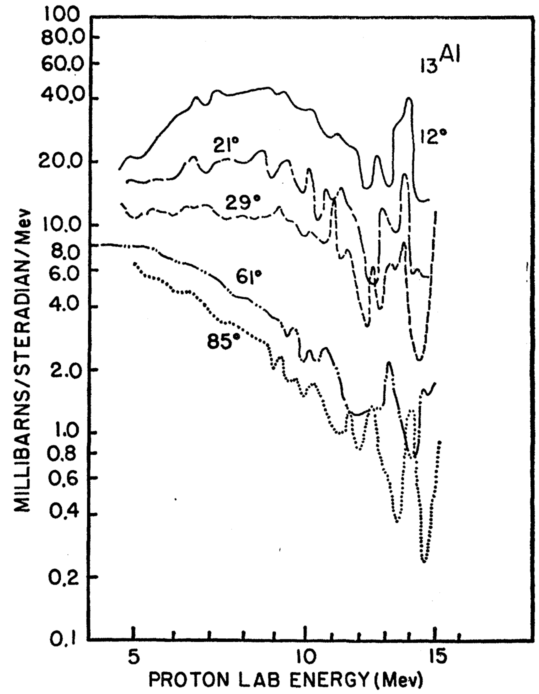

FIG. 4. Spectra of protons from bombardment of aluminum with 14.8-Mev deuterons, at several angles.

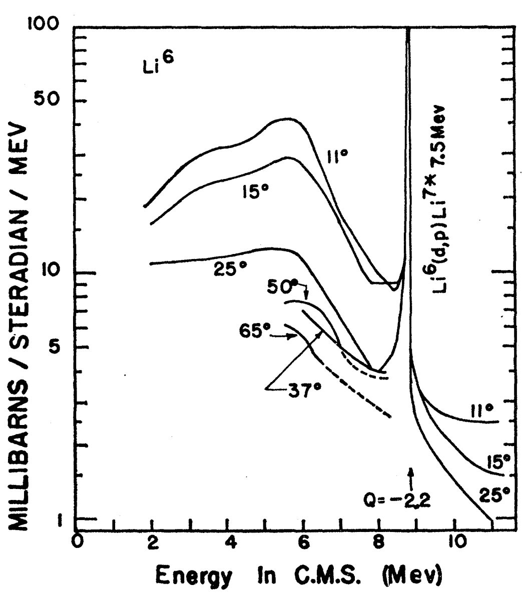

FIG. 3. Proton spectra from the bombardment of Li^6 with 14.8-Mev deuterons. The deuteron c.m. energy is 11.1 Mev. The abscissa is the total kinetic energy in the c.m. system and the cross section is also given in the c.m. system. The angles labeling the curves are laboratory angles; corresponding c.m. angles are, approximately: 13°, 19°, 32°, 47°, 63°, and 80°. At 50° and 65° a point was measured at 8.2 Mev but no data were taken between 7 and 8 Mev, where the curves are dashed. These data were taken in the course of another experiment (reference 6) using nuclear emulsions to detect the analyzed particles. The resolution was ~60 kev; no narrow groups were found at energies below that of the Li^7 7.5 new level, but broad levels may exist.

TABLE I. Absolute cross sections.

Element	Al^{13}	Cu^{29}	Zr^{40}	Cd^{48}	Pt^{78}
Angle	12°	12°	29°	29°	60°
$d\sigma/d\Omega$ (mb/sr)	260	205	150	92	50
σ (mb)	630	550	400	370	380

the peak (and of the half maxima) at the angle where the cross section is largest is plotted vs atomic number in Fig. 11. It is seen that the energy increases slowly with A.

The absolute cross sections, integrated over energy at the peak of the angular distribution, are given in Table I (third line). An approximate value for the total cross section was also estimated from the data of the third line and from the angular distributions shown in Fig. 9. The values are given in the fourth line of Table I; they are probably accurate within 30%.

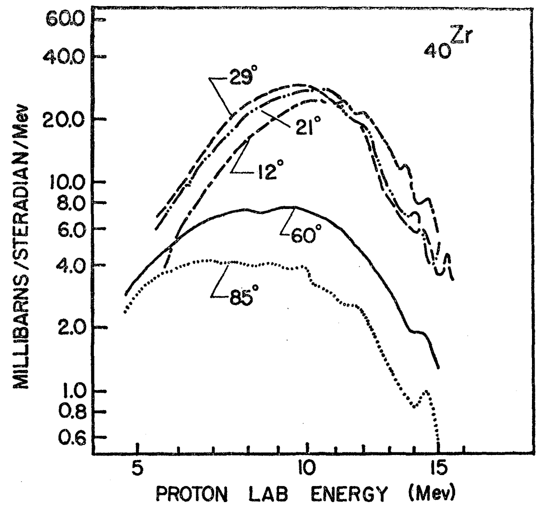

FIG. 6. Spectra of protons from bombardment of zirconium with 14.8-Mev deuterons, at several angles.

IV. DISCUSSION

The regularity of the results, the very slow variation with atomic number (much slower than would be expected if a Coulomb barrier penetration were involved), and the apparent change in character at $Q\sim-2.2$ Mev indicate that the process involved is a breakup of the deuteron in the external field of the nucleus. We therefore adopt this model and attempt to use it to achieve a quantitative understanding of the experimental results. It should be remarked before we proceed that we are initially evading the question of whether the breakup is due to nuclear or electrical forces; most results of our model are independent of this detail.

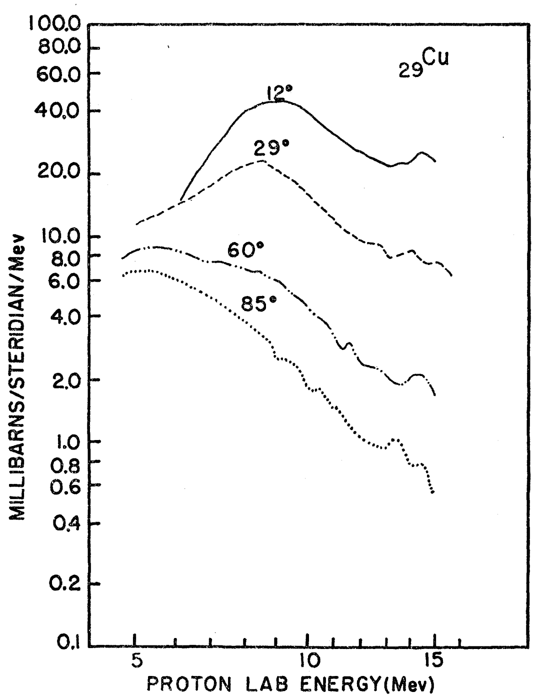

FIG. 5. Spectra of protons from bombardment of copper with 14.8-Mev deuterons, at several angles.

In any deuteron breakup model, the expression for the proton energy spectrum depends on (a) phase space factors, (b) the internal motion in the deuteron before breakup, and (c) Coulomb effects. Since a calculation including all three effects becomes complex and obscures qualitative understanding, we consider first the case where (a) and (b) are dominant and (c) may be neglected (light elements), and second the case where (c) is dominant and (a) and (b) may be considered as perturbations (heavy elements).

In the first case, the phase space factors are proportional to $(E_p)^{\frac{1}{2}}$ (for the proton) and $(E_d-2.2\text{ Mev}-E_p)^{\frac{1}{2}}$ (for the neutron), where E_d and E_p are the deuteron and proton energies, respectively. The deuteron internal motion factor is $(K^2+\gamma^2)^{-2}$, where $\mathbf{K}=\frac{1}{2}\mathbf{K}_d-\mathbf{K}_p$ ($\hbar\mathbf{K}_d$ and $\hbar\mathbf{K}_p$ are the deuteron and proton momenta) and the deuteron wave function is taken as $r^{-1}\exp(-\gamma r)$ with $\gamma=0.23\times10^{13}\text{ cm}^{-1}$. The results obtained for this case are shown in Fig. 12. The cross section is larger at 0° where the peak is at $E_p=7$ Mev. At larger angles, the peak shifts to lower energies, going to 2 Mev at 90°.

These properties agree qualitatively with those observed for light elements (see Figs. 3 and 4). However, neither the anisotropy nor the peak energy shift observed are as large as in Fig. 12. It will be seen that these discrepancies can be explained by Coulomb effects.

In the second case, where Coulomb effects are considered dominant, we consider a "point" deuteron. As it approaches the nucleus, its kinetic energy is converted to Coulomb energy (E_c) to the extent,

$$E_c(r)=Ze^2/r. \qquad (1)$$

After breakup (at $r=R$), the proton energy is increased by the Coulomb energy, so that the average final proton

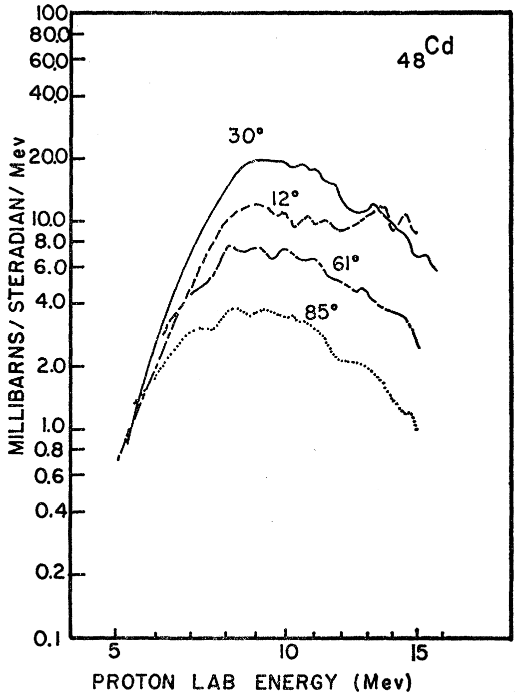

FIG. 7. Spectra of protons from bombardment of cadmium with 14.8-Mev deuterons, at several angles.

energy is

$$E_p=\tfrac{1}{2}(E_d-E_c-2.2\text{ Mev})+E_c=6.3\text{ Mev}+\tfrac{1}{2}E_c. \quad (2)$$

From (2) it is apparent that the peak in the proton energy spectrum must be well above 6.3 Mev; since it is energetically restricted to be below 12.6 Mev and neutron phase space considerations lower this limit by at least ~1 Mev, the peak in the energy spectrum can move only from ~8 Mev to 11 Mev as the atomic number increases from 30 to 90. This explains a striking feature of the experimental data, the fact that the peak shifts with atomic number more slowly than would be expected if a Coulomb barrier penetration were involved.

If we accept the quantitative validity of this model at the angles where the intensities are largest, we can calculate the distances from the nucleus at which breakup occurs; these are listed in Table II (line 4). They are somewhat larger than the compound nucleus interaction radius (line 5), but this difference is substantially decreased if the "point" deuteron is replaced by an actual deuteron and the polarization of its orientation in the Coulomb field is taken into account. The values in Table II then refer to the position of the proton which is further from the nucleus than the center of mass of the deuteron by as much as 1 fermi. Thus, the breakup occurs near the nuclear surface for $_{29}$Cu, but still quite far out from it for $_{78}$Pt.

Our simple model can also explain, at least semi-quantitatively, the angle of maximum intensity. It results, essentially, from Rutherford scattering. We assume that the breakup occurs at the classical distance

TABLE II. Classical calculations were done to obtain E_c (the Coulomb energy of the deuteron at breakup), $R(E_c)$ (the distance of the deuteron from the center of the nucleus at breakup) and θ(calc) (the calculated angle of maximum intensity). These were calculated using E_p, the observed peak energy of the protons. A comparison with 1.5 $A^{\frac{1}{3}}$ and the observed angle of maximum intensity is shown.

1. Target	$_{29}$Cu	$_{40}$Zr	$_{48}$Cd	$_{78}$Pt
2. E_p at peak (Fig. 10) (Mev)	9.0	9.6	9.5	10.6
3. E_c (Mev) from (2)	5.4	6.6	6.5	8.6
4. $R(E_c)$ (f) from (2)	7.7	8.7	10.6	12.9
5. 1.5 $A^{\frac{1}{3}}$ (f)	6.0	6.7	7.3	8.7
6. θ (calculated)	26°	32°	32°	44°
7. θ (observed)	10°	30°	35°	50°

of closest approach, q, which is related to the angle of deflection $\theta=\theta_p+\theta_d$ by

$$q=\frac{Ze^2}{2E_p}(1+\csc\tfrac{1}{4}\theta_p)=\frac{Ze^2}{2E_d}(1+\csc\tfrac{1}{4}\theta_d). \quad (3)$$

The results are quite insensitive to the accurate validity of this assumption. If we now set q equal to R extracted from (2) (or line 4 of Table II), we find the values of θ given in line 6 of Table II. Comparing them with the observed angles of maximum intensity (line 7), it is seen that the agreement is quite good except for $_{29}$Cu. This may perhaps be explained by the fact that the interaction in the lighter elements occurs at the nuclear surface rather than far out from it as in the heavy elements.

The internal motion in the deuteron has been neglected so far in the discussion for the heavy elements.

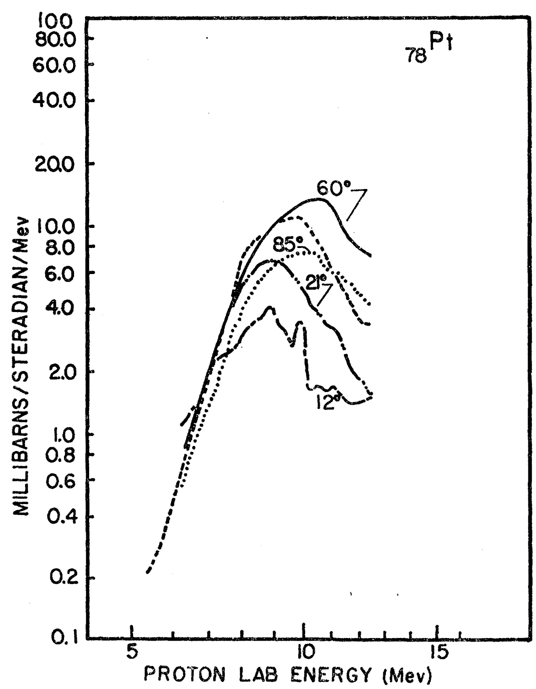

FIG. 8. Spectra of protons from bombardment of platinum with 14.8-Mev deuterons, at several angles.

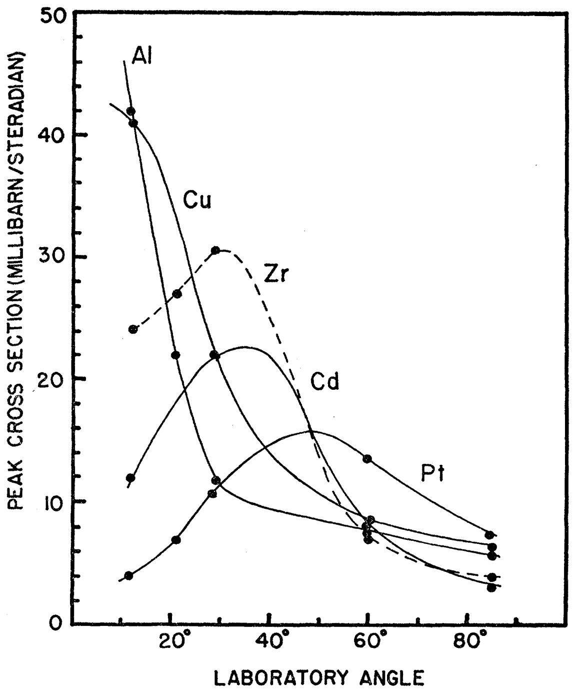

FIG. 9. Peak cross sections as a function of angle. The curves are freely drawn through the experimental points.

It will tend to produce spectral shapes qualitatively similar to those of Fig. 12 except that the forward direction must be replaced by the direction of maximum intensity (line 7 of Table II), because of the deflection in the Coulomb field.

The data of Aschenbrenner[11] can be interpreted using our model. Besides obtaining spectra for several heavy elements, he studied the variation of the spectrum with deuteron energy for a tantalum target. The energy of the peak decreases linearly with E_d, as predicted by Eq. (2), except that the coefficient of E_d is $\sim$0.7 rather than 0.5. Furthermore, he finds that the low-energy cutoff of the spectra is approximately independent of the incident energy. This can be explained by our model if we assume that the deuteron must penetrate at least to a radius R' in order to breakup. Then the proton will have at least the Coulomb energy corresponding to R' and the cutoff energy will be independent of the incident energy but will vary with Z. The value of R' found from the experimental cutoff energies is $R'\simeq 1.1\, A^{\frac{1}{3}}$.

The variation of R' with $A^{\frac{1}{3}}$, suggests that these radii are determined by the requirement that the electric field have a certain value. In effect, the order of magnitude of the electric field Ze^2/r^2 necessary to breakup the deuteron is given by

$$(Ze^2/r^2)R_d \simeq 2.2 \text{ Mev}. \tag{4}$$

where $R_d\simeq 3.1$ f is the average neutron-proton distance in the deuteron. This yields $r\sim 1.0\, A^{\frac{1}{3}}$ f, in fair agreement with the experimental value.

Finally we consider the neutron spectra from deuteron breakup: For each breakup proton of energy E_p a neutron of energy

$$E_n = E_d - E_p - 2.2 \text{ Mev}, \tag{5}$$

is also emitted. Our data therefore permit predictions to be made concerning the neutron spectra in the energy range $0<E_n<7$ Mev, corresponding to $5.5<E_p<12.5$ Mev. The experimentally observed spectra will contain also neutrons from compound nucleus decay and from (d,n) stripping reactions in which nor proton is emitted. In the energy region $Q<-2.2$ Mev stripping does not seem to contribute strongly to the proton spectra from heavier targets, so that it can perhaps be neglected also in the neutron case.

For light target nuclei the spectra and angular distributions of the neutrons due to breakup should be similar to those of the protons, but shifted toward smaller energies and angles because of the Coulomb field. For heavy nuclei the maximum in the angular distribution should be at approximately half the angle of the proton maximum; the shape of the spectrum at the forward angle θ should be related to the proton spectrum at $\theta/2$ by the transformation Eq. (5).

The neutron spectra corresponding to the measured proton spectra from Al and Cu at 12° (Figs. 4 and 5) were calculated using Eq. (4); the result can be roughly (within 50% maximum deviation) represented by the expression.

$$N(E_n) \propto E_n \exp(-E_n/\epsilon), \tag{6}$$

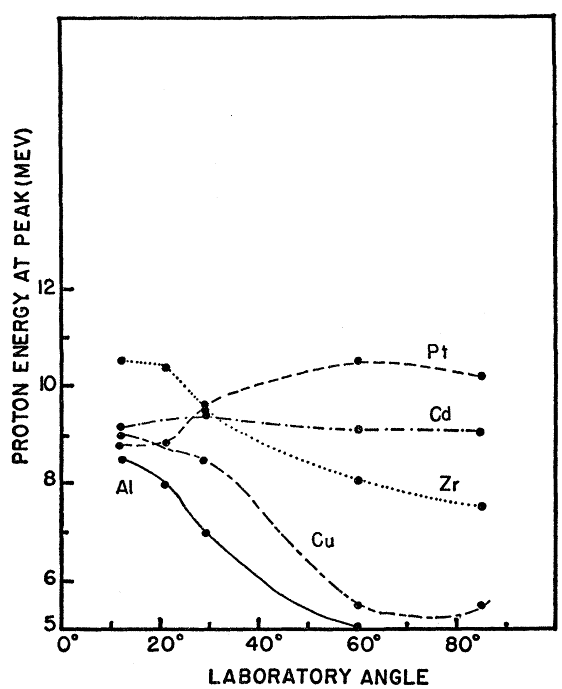

FIG. 10. Proton energy at the spectrum peak as a function of angle. For the lighter elements the peaks are broad so that their energies are not well determined.

with $\epsilon \simeq 2.0$ Mev. This is in reasonable agreement with the neutron spectrum measurements of Cohen and Falk[12] which give $\epsilon \simeq 2.5$ Mev. A detailed comparison between the two experiments is not possible, however, since the work of Cohen and Falk was done with thick targets.

It is interesting to compare the total breakup cross sections with the expected cross sections for formation of a compound nucleus.[17] These are about 600 mb, 700 mb, and 450 mb for $Z=10$, 30, and 80, respectively, as compared to measured breakup cross sections (Table I) of about 600 mb, 550 mb, and 380 mb. The deuteron breakup is thus quite comparable in probability with compound nucleus formation. As a consequence one expects that the neutron cross sections in the region $Q<-2.2$ Mev be about twice the proton cross sections, because the compound nucleus decays preferentially by slow neutron emission.

V. CONCLUSION

The coarse features of the low-energy proton spectra from (d,p) reactions have been studied for several target nuelci as a function of angle. The protons in the energy region $Q<-2.2$ Mev are mostly due to breakup of the deuteron: stripping reactions to unbound levels of the final nucleus and protons from compound nucleus decay seem to be less important.

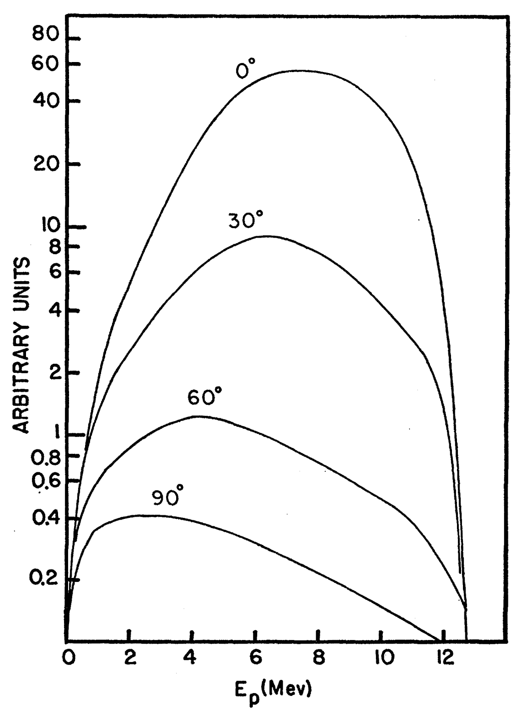

FIG. 11. The expression $(E_p)^{\frac{1}{2}}(E_d-2.2-E_p)^{\frac{1}{2}}/(K^2+\gamma^2)^2$ as a function of E_p, at several angles, $E_d=15$ Mev.

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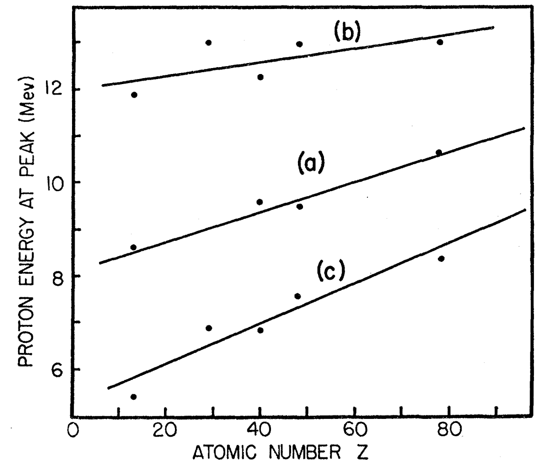

FIG. 12. (a) Proton energy at peak of spectrum at peak of angular distribution, vs atomic number Z. (b) and (c) Proton energies at half peak height at same angle as (a). For a given Z the distance between the (b) and (c) points is the full width at half maximum, Γ, of the peak. Γ decreases as Z increases. The straight lines have been drawn to show the general trend of the points.

A semiclassical model for the breakup has been proposed; it accounts qualitatively and even semiquantitatively for the observed features. In light nuclei, the breakup occurs at or near the nuclear surface, but in heavy nuclei, it occurs quite far out from the nucleus.

With regard to the question of whether the breakup is due to Coulomb or nuclear forces, it is difficult to give a conclusive answer. Consideration of the distance from the nucleus where breakup occurs indicates that it may be due to nuclear forces in light elements, and due to Coulomb forces in heavy elements. However, comparisons between our measured cross sections and theoretical predictions give cause for concern.

Theoretical estimates of electric breakup cross sections by Mullin and Guth[13] give $\sigma \lesssim 100$ mb for ${}_{12}$Mg, $\sigma \lesssim 220$ mb for ${}_{29}$Cu, and $\sigma \lesssim 170$ mb for ${}_{79}$Au; these are far smaller than the measured cross sections (Table I). On the other hand, theoretical cross sections for diffraction breakup, which is due to nuclear forces, are also much smaller than the observed cross sections. Glauber[15] estimates $\sigma \simeq 0.3\pi RR_d$ which is a maximum of $\lesssim 200$ mb for heavy elements. More complete calculations by Akhiezer and Sitenko[15] are complicated but the results are also quite small. Thus, theoretical calculations for both Coulomb and nuclear breakup yield cross sections much smaller than the observed ones. There seems to be a need for improved calculations.

A detailed experimental study of the neutron spectra produced in (d,n) reactions in the energy region $Q<-2.2$ Mev would be helpful. Besides yielding more information on the deuteron breakup mechanism, it would allow an evaluation of the importance of compound nucleus formation in deuteron-induced reactions at medium energies.