Deuteron Disintegration by Au, Rh, Cu, and C from 8 to 15 MeV*

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Deuteron disintegration by Au, Rh, Cu, and C has been studied with a *p-n* correlation technique. In all targets, the neutrons tend to go predominantly in the forward direction. For heavier targets and lower deuteron energies, the protons are emitted predominantly on the same side of the beam as the neutrons and at larger angles (although there is a small secondary peak on the opposite side of the beam), while for lighter targets and higher deuteron energies, they are emitted predominantly on the opposite side of the beam from the neutrons. From this it is surmised that the former behavior characterizes a breakup by the Coulomb force, while the latter behavior characterizes a breakup by the nuclear force; this conclusion is supported by theoretical estimates. From the energy sharing between neutrons and protons, the average radius at which breakup occurs is determined; as expected, it is much larger for Coulomb than for nuclear breakup, but in all cases it is more than twice as large as the usual "nuclear radius."

INTRODUCTION

THE breakup of a deuteron into a neutron and a proton due to its interaction with a heavy nucleus was first proposed by Oppenheimer[1] and has since been studied both theoretically and experimentally by a great many authors. Some older experimental work[2–6] was based on observations of a single breakup particle, either the neutron or the proton, but in a more recent work by Udo[7] they were both detected in coincidence while the proton energy was measured. In this paper, we report on a study of the latter type in which, in addition, both the neutron and proton energies are simultaneously determined

The deuteron breakup process is of interest because it can be calculated theoretically in detail with a sufficient effort in numerical computation and reasonable approximations. Since the breakup is due to a combination of the Coulomb and nuclear fields, the latter usually being represented by an optical-model potential, and since the Coulomb field is accurately known, this affords a tool for studying the optical-model potential. Moreover, since the breakup generally occurs at relatively large distances from the nucleus, it gives information on that potential in a region that is not readily accessible to study by other methods.

EXPERIMENTAL

Figure 1 schematically represents the experimental setup. The neutrons from (d,pn) events are detected by a 2-in. diam×1-in. thick Pilot "B" organic scintillator viewed by an Amperex 56 AVP photomultiplier tube. The protons from these events are detected by a fully depleted, 1000-μ thick surface barrier detector, and their energies are measured directly from the pulse-amplitude information in the usual way. Neutron energies are determined from a time-of-flight measurement. The start pulse for the time–to–pulse-height converter (TPHC) is derived from an amplitude discriminator whose level is set to trigger at $\frac{1}{10}$ of the amplitude of the pulse height of the Compton edge from the 660-keV γ ray from Cs^{137}. The stop pulse is supplied by a time pickoff unit in the proton leg. A 110-nsec resolving-time coincidence is required between an event in the proton detector and an event that triggered a second amplitude discriminator on the neutron detector set at 2.5 times the level of the lower discriminator. This added coincidence reduces the count rate of the TPHC by allowing consideration of only time-correlated events in the two detectors. The difference in the discriminator settings reduces the time slewing inherent in amplitude discrimination. The output of the TPHC is amplified and supplied to one side of a two-dimensional pulse-height analyzer. The 110-nsec coincidence also opens a linear gate in the proton energy leg which greatly reduces the dead time in the multichannel analyzer. Various delays to ensure proper timing are indicated.

The beam intensity (times the effective target

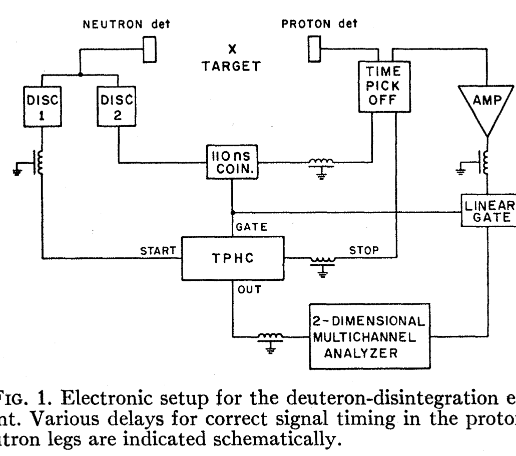

FIG. 1. Electronic setup for the deuteron-disintegration experiment. Various delays for correct signal timing in the proton and neutron legs are indicated schematically.

* Supported by the National Science Foundation.
[1] J. R. Oppenheimer, Phys. Rev. **47**, 845 (1935).
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[3] B. L. Cohen and C. E. Falk, Phys. Rev. **84**, 173 (1951).
[4] F. A. Aschenbrenner, Phys. Rev. **48**, 657 (1955).
[5] B. L. Cohen *et al.*, Phys Rev. **118**, 499 (1959).
[6] E. W. Hamburger, B. L. Cohen, and R. E. Price, Phys. Rev. **121**, 1143 (1961).
[7] F. Udo, University of Amsterdam report, 1964 (unpublished).

thickness) is monitored by a surface-barrier detector counting elastic-scattering events at a fixed angle of 30°.

The two-dimensional display of the data consists of proton energy and time difference between proton and neutron flight time on the respective axes. Each run is analyzed by summing the events along the locus of points corresponding to

$$E_p+E_n=E_i-E_{\text{be}}-E_r, \tag{1}$$

where E_i is the initial bombarding energy, E_r is the target nucleus recoil energy, E_{be} is the binding energy of the deuteron, and E_p, E_n is the energy of the proton and neutron, respectively The total number of events obtained in this fashion was normalized by the beam monitor to obtain absolute cross sections.

In general, the kinematic locus defined by Eq. (1) is easy to observe because the ratio of true events to background is quite large. For those special angles at which the neutron detector is nearly behind the proton detector, the breakup kinematic locus was masked by another effect. Elastically scattered dueterons from the target that strike the proton detector tend to disintegrate in the latter. The neutrons from such events are then detected in the neutron detector. The time resolution of the apparatus, 2.5 nsec, is only capable of resolving the two neutron groups at relatively low neutron energy. This effect has been subtracted from the data presented here.

Further difficulty was encountered with the Cu data. The deuteron breakup kinematic locus was lost in a

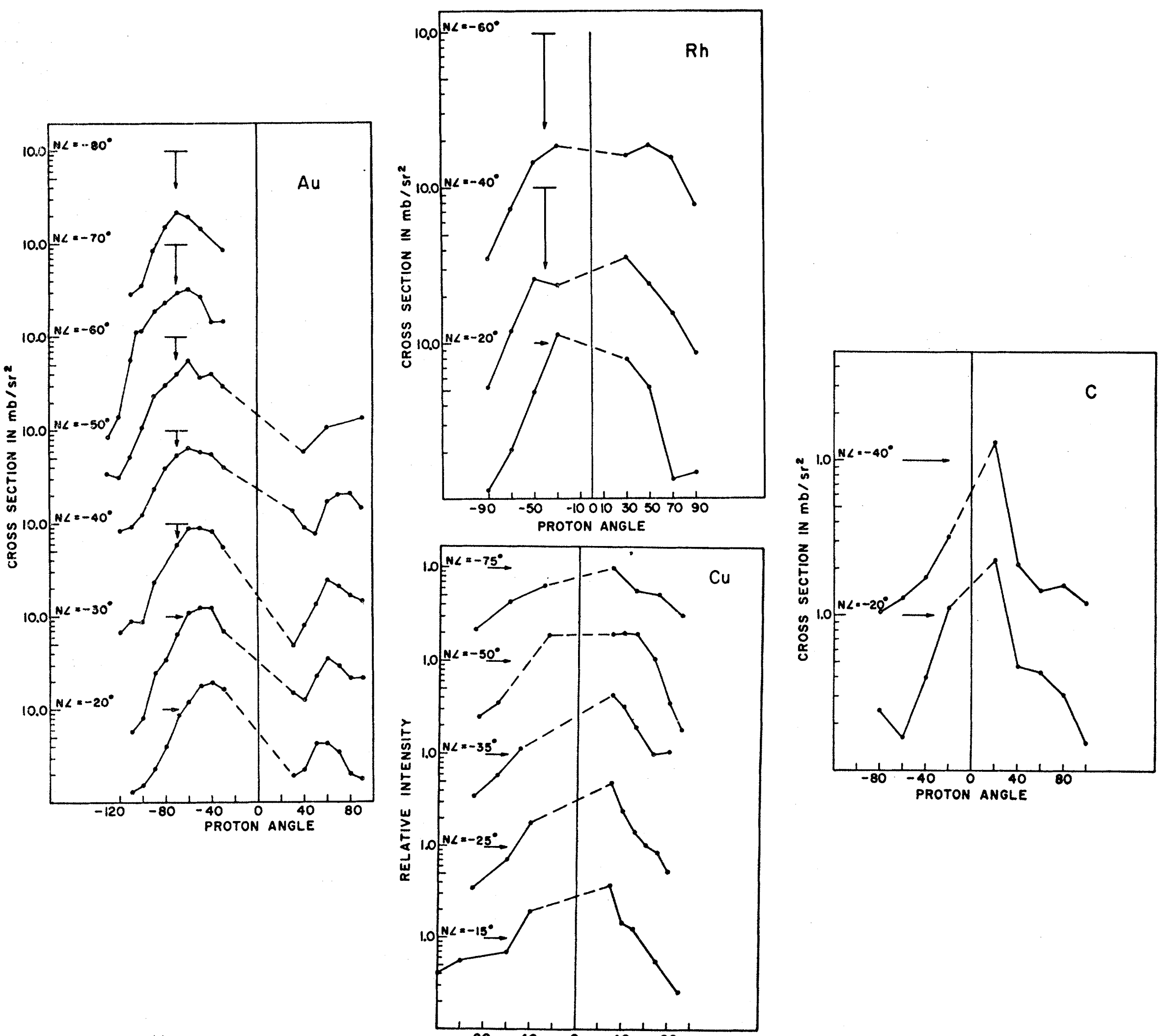

FIG. 2. Proton angular distributions for Au, Rh, Cu, and C at 12-MeV for various neutron angles. Negative proton angles correspond to the neutron and proton detector in the same side of the incident beam. The beam direction is designated by a vertical line at 0°. The scale on the ordinate to be used for each curve is indicated with an arrow. The neutron angle for each curve is also indicated by the arrow.

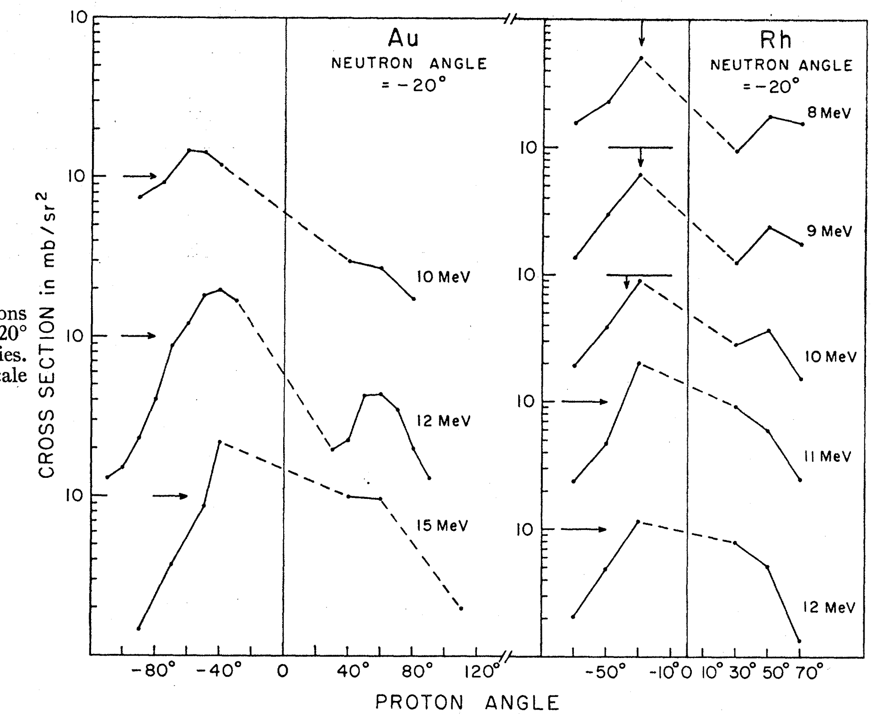

FIG. 3. Proton angular distributions for Au and Rh at neutron angle of −20° and at various incident deuteron energies. The arrows indicate the ordinate scale and the energy for each curve.

background of lower-energy (*d,pn*) events. The breakup protons were clearly resolved at high proton energy; thus Fig. 2 shows relative cross sections rather than absolute cross sections for Cu.

RESULTS AND DISCUSSION

Figure 2 shows proton angular distributions for Au, Rh, Cu, and C taken at 12-MeV incident deuteron energy for various neutron angles. Generally speaking, the neutrons are strongly forward peaked for all targets, and the cross section increases with increasing *Z*. The maximum in the proton angular distributions from Au moves to large angles as the neutron angle is increased. Except for a small secondary peak corresponding to neutrons and protons emerging on opposite sides of the beam, the Au distributions show that the neutrons and protons come predominantly on the same side of the beam. This is in qualitative agreement with a Coulomb breakup model calculation of Ketchum and Austern,[8] which predicts a secondary peak in the angular distributions for protons and neutrons coming on opposite sides of the beam. This indicates that an important part of the breakup process for Au at 12 MeV is from the Coulomb interaction.

The Rh distribution is fairly symmetric about the beam direction. The Cu distribution is peaked for neutrons and protons emerging on opposite sides of the beam, and this behavior is more enhanced in the C data.

Since the Coulomb effect is very much smaller in carbon than in the other nuclei, one might conclude that the emergence of the neutron and proton on opposite sides of the beam is characteristic of a breakup due to nuclear rather than Coulomb interactions. This type of behavior was also predicted theoretically by Austern[9] for cases where the nuclear interaction is dominant. Since the "same side" versus "opposite side" behavior of the angular distributions for Cu and Rh are intermediate between that for C and Au, one may conclude that both nuclear and Coulomb interactions are important in deuteron breakup on those nuclei.

Figure 3 shows the proton angular distributions at various beam energies for Au and Rh at a fixed neutron angle of −20°. It seems reasonable to expect the relative importance of the Coulomb interaction to increase with increasing *Z*, and with decreasing bombarding energy.

This effect is clearly evident from Fig. 3 in that the results for Au at 15 MeV are similar to those for Rh at 12 MeV, and the results for Au at 12 MeV are similar to those for Rh at 9 MeV. In both cases, there is a clear progression in which emission of the proton on the same side of the beam as the neutron is enhanced and the most probable angle is increased as the bombarding energy is lowered.

No statistical error bars have been shown in Fig. 2 or 3 since other sources of error were probably much larger. Absolute cross sections can be considered good to within 20%; the largest contribution of error here is

[8] H. B. Ketchum, thesis, University of Pittsburgh, 1960 (unpublished).

[9] N. Austern (private communication).

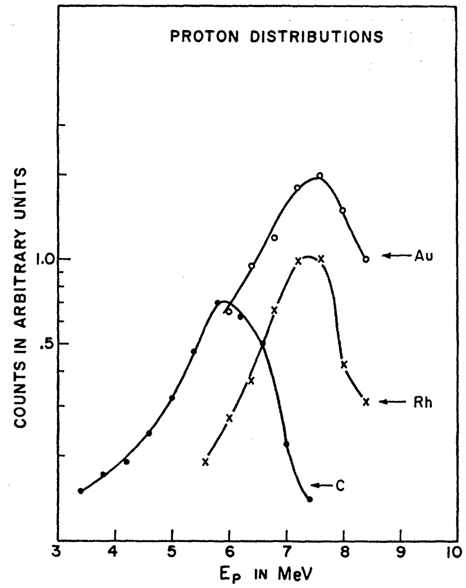

FIG. 4. Typical proton energy distributions for Au, Rh, and C for neutron angle of −20° and proton angle of −50°. The incident deuteron energy is 12 MeV.

in the efficiency of the neutron detector. Errors in relative cross sections are approximately 10%. The major source of error in this case is in the day-to-day normalization with the monitor.

Hamburger *et al.*[6] show that the most probable radius r_b at which the breakup occurs is given by

$$r_b = Ze^2/[2E_p' - (E_i - E_{\text{be}})], \quad (2)$$

where E_p' is the energy at the peak of the proton spectrum. Typical spectra are shown in Fig. 4. Table I shows various values of E_p' and r_b for different Z and E_i, for proton and neutron angle of −50° and −20°, respectively. Since the angular dependence of the proton spectra was small, the angles for Fig. 4 and the calculations in Table I were chosen for convenience. A modification of Eq. (2) was made for C to include the nuclear interaction by adding the optical-model potential to the Coulomb potential. The results gave $r_b = (2.2 \rightarrow 3.0)A^{1/3}$ for C at 12 MeV. A range of values for r_b is given for C because in this region the sum of the nuclear and Coulomb potentials are varying very slowly, so that the same value of E_p' is obtained from any value of r_b chosen within this range.

TABLE I. Calculated values for most probable breakup radius r_b for different incident deuteron energies E_i.

	Rh			Au	
E_i (MeV)	E_p (MeV)	$r_b/A^{1/3}$ (F)	E_i (MeV)	E_p (MeV)	$r_b/A^{1/3}$ (F)
8.0	4.0	6.3	10.0	5.4	3.9
9.0	5.0	3.8	12.0	7.6	3.6
10.0	6.0	3.3	15.0	10.4	2.4
11.0	6.8	2.9			
12.0	7.4	2.7			

It is clear from these results that the breakup generally occurs far outside of what is generally considered to be "the nuclear radius," and that this distance becomes larger for heavier nuclei and for lower energy. Since the nuclear potential falls off much more rapidly than the Coulomb potential at large radii, this explains why Coulomb breakup becomes relatively more important in the latter cases.

It is interesting to note from Table I that in cases where $r_b/A^{1/3}$ is the same for Rh and Au (at different incident energies), the angular distributions are similar. This would indicate that the interaction depends on the ratio of r_b to the nuclear radius.

A quantitative determination of the relative importance of Coulomb and nuclear interactions in the deuteron breakup process is clearly beyond the scope of this work, if indeed it has a definite meaning in view of the fact that the processes are coherent. However, it does seem evident from these results that these two processes lead to rather different types of angular correlations, and by exploiting this difference, one can qualitatively trace the shift from a predominant nuclear interaction for lower Z and higher E_i, to a predominant Coulomb interaction for higher Z and lower E_i.