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The Long-Range Protons from the Disintegration of Carbon by Deuterons and a Study of the Competing Reactions*

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The excitation curves for the reaction $C^{12}(d,p)C^{13}$ have been determined at the three laboratory angles of 0°, 90°, and 150° for the range of deuteron energies 0.78 to 1.55 Mev. Resonances were observed at 0.91, 1.16, 1.30, and 1.435 Mev corresponding to resonances found previously for the competing $C^{12}(d,p)^*C^{13}$ and $C^{12}(d,n)N^{13}$. In addition, a resonance was observed for the long-range proton group at 1.13 Mev.

The angular distributions of the long-range proton group have been determined for eight energies of bombardment and have been converted to center of mass coordinates. These angular distributions have been analyzed in terms of the Legendre polynomials and show no terms higher than the fourth order to within the experimental error of about three percent.

The intensities, positions, widths, and angular distributions of the resonances are discussed.

The excitation curves show the effects of large amounts of interference between states. The 1.30-Mev resonance is exhibited at 0° as an "anti-resonance," while the 1.435-Mev resonance shows a shift of maximum yield of about ten kev for the excitation curves at 0° and 150°.

I. INTRODUCTION

RECENTLY, carefully determined excitation curves have been obtained in this laboratory,[1,2] and at several other laboratories,[3,4] for the production of gamma-rays and neutrons when C^{12} is bombarded by deuterons. These radiations occur according to the reactions:[2,5,6]

$$C^{12}+H^2\rightarrow {}^*N^{14}\rightarrow {}^*C^{13}+H^1-0.37\text{ Mev}$$
$${}^*C^{13}\rightarrow C^{13}+\gamma(3.1\text{ Mev}), \tag{1}$$

$$C^{12}+H^2\rightarrow {}^*N^{14}\rightarrow N^{13}+n^1-0.281\text{ Mev}$$
$$N^{13}\rightarrow C^{13}+\beta^++\eta+1.20\text{ Mev}. \tag{2}$$

In addition, the neutron angular distributions have been determined at a number of bombarding energies.

The present report describes experiments that have been performed to investigate the excitation curves for the production of the long-range protons which leave C^{13} in its ground state according to the scheme:[6]

$$C^{12}+H^2\rightarrow {}^*N^{14}\rightarrow C^{13}+H^1+2.73\text{ Mev}. \tag{3}$$

Also the angular distributions of these protons have been determined at certain energies of bombardment.

It was hoped that a comparison of reactions (2) and (3) would be instructive as to the nature of the excited states of N^{14} and the validity of considering the emissions from the excited states as competing processes. Because of the identity of the spins of neutrons and protons and because of the assumed identity of the parities and spins of C^{13} and N^{13}, it would appear that no differences in the general features of yield and angular distributions could be anticipated, and that such differences as might appear would be accounted for by the penetration of the Coulomb and the centrifugal barriers by the particles. Also it appeared possible to determine the angular momentum quantum number and the parity of the resonant states by means of the angular distributions.

It was reported in reference 1 that the strong gamma-ray resonance of width 5.5 kev observed at 1.435-Mev deuteron bombarding energy does not appear with measurable intensity for the neutron reaction. Thus an investigation of this energy region for reaction (3) appeared of particular interest.

II. APPARATUS AND EXPERIMENTAL TECHNIQUES

To count the long-range protons of reaction (3) at various angles, a special target chamber was constructed. The chamber was formed of a brass cylinder 18 cm inside diameter and nine cm high. One-half inch diameter holes were drilled every 15° on one side of the cylinder, from 0° to 150°, where the 0° hole was in the direction of the deuteron beam. The holes were covered with aluminum foils of about six cm air equivalence. The target was on the axis of the cylinder and at the height of the exit holes and was carried by a ball bearing support so that it could be rotated by an external magnet to calibrated angles. Deuterons accelerated by the Rice Institute Van de Graaff generator were magnetically analyzed and collimated with apertures onto a small spot on thin carbon targets. The thin carbon targets were prepared by cracking benzene vapor on silver foils of about four cm air equivalence. The thickness of the silver foils was sufficient to stop the deuterons, but allowed the protons emitted in the forward direction to pass through and be detected.

The detection was accomplished by a proportional

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[1] Bonner, Evans, Harris, and Phillips, Phys. Rev. 75, 1401 (1949).

[2] Bonner, Evans, and Hill, Phys. Rev. 75, 1398 (1949).

[3] Bailey, Freier, and Williams, Phys. Rev. 73, 274 (1948).

[4] Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. 75, 1147 (1949).

[5] Seigbahn and Slatis, Arkiv. f. Mat. Astr. O. Fys. 32A, No. 9 (1945); Lyman, Phys. Rev. 55, 123 (1939); Townsend, Proc. Roy. Soc. A177, 357 (1941); Hornyak, Dougherty, and Lauritsen, Phys. Rev. 74, 1727 (1948).

[6] Buechner, Strait, Sperduto, and Malm, Phys. Rev. 76, 1543 (1949).

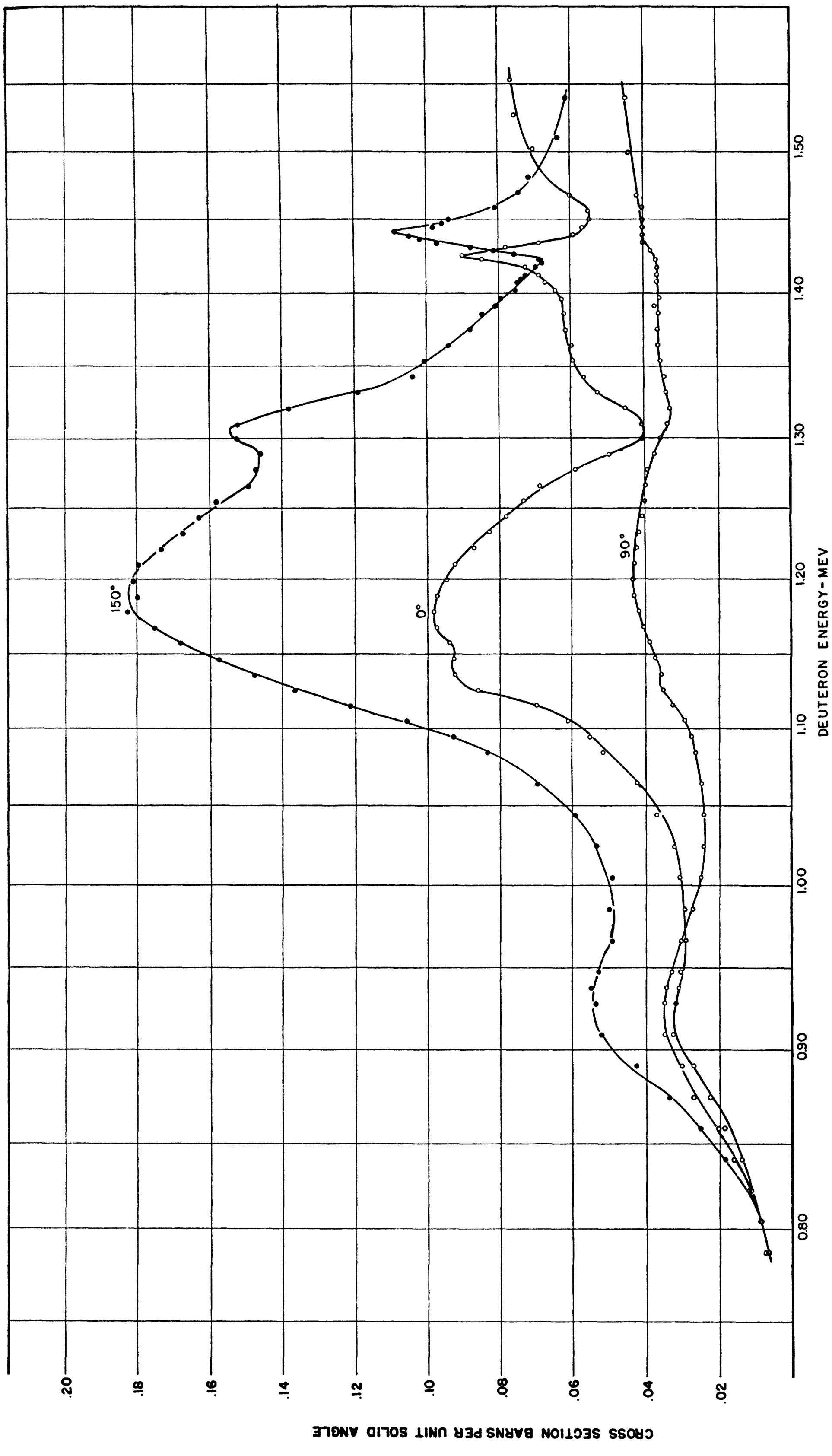

Fig. 1. The experimentally determined excitation curves for the production of long-range protons as a function of bombarding deuteron energy. The curves marked 0°, 90°, and 150° are cross sections determined at these laboratory angles.

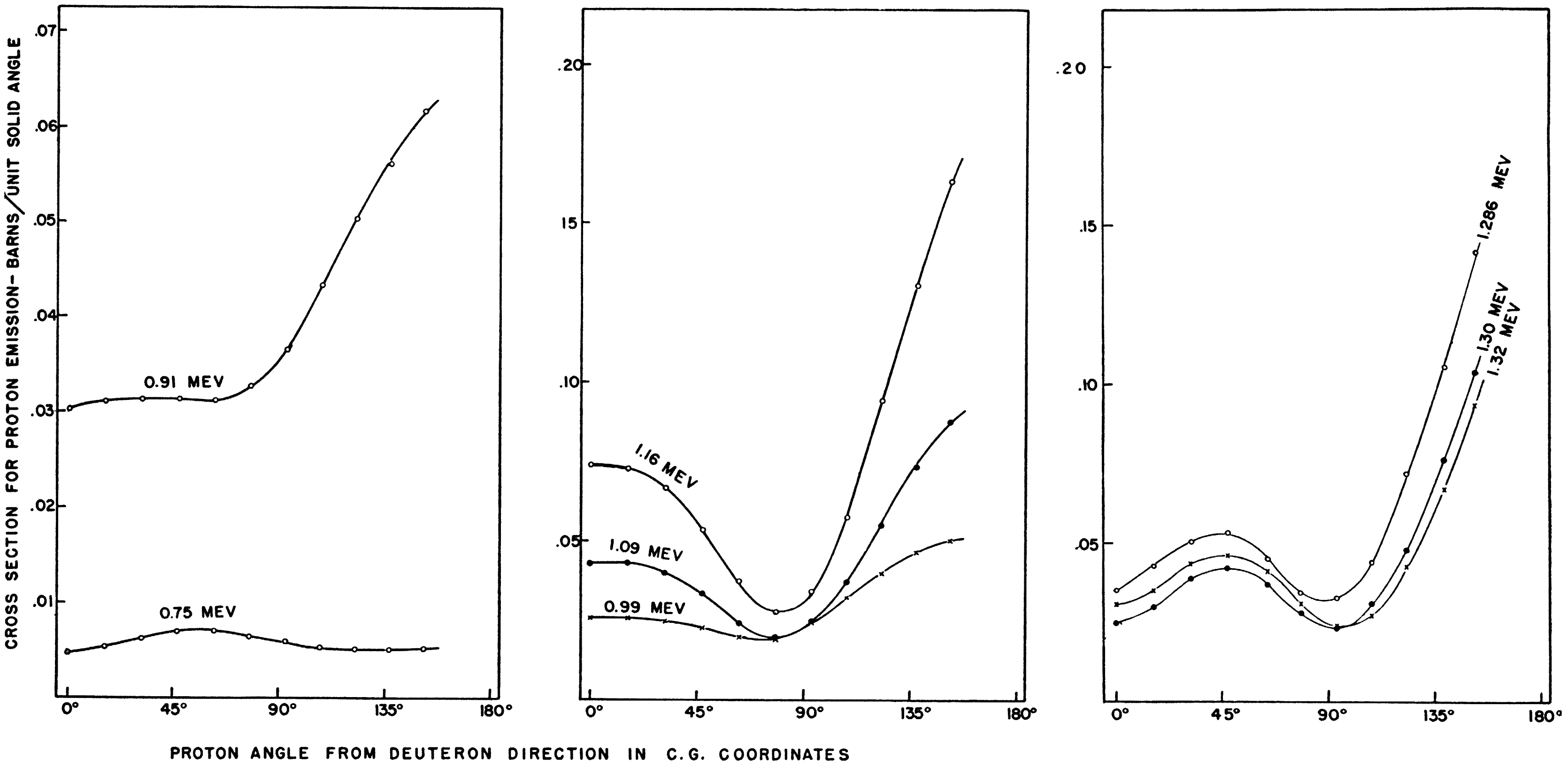

FIG. 2. The angular distribution of the long-range protons in center of mass coordinates for the deuteron bombarding energies indicated.

counter of standard design, which had a thin aluminum window for entrance of the protons. Absorbing foils were placed between the counter aperture and the target chamber exit holes so that the protons would be within a few cm of the end of their range when detected. This procedure prevented protons from the $O^{16}(d,p)$ reaction from being counted. These O^{16} protons would otherwise be a considerable source of error, since the exposure of the target to the beam produced a layer of oxygen. The pulses were amplified by a linear amplifier and were recorded with a scale of 64 circuit. In obtaining data, several foils of different thicknesses were used. Each datum point so obtained was always within a few percent of the others. The solid angle subtended by the counter window was 1.064×10^{-3} steradian.

The thicknesses of the targets were obtained[1] by comparison with reaction (2). The protons were counted at 0° at 1.30 Mev bombarding energy, and the positrons from the N^{13} remaining at the end of the bombardment were counted for several half-lives. Excitation curves were obtained with this apparatus for the laboratory angles of 0°, 90°, and 150°. These data are shown in Fig. 1, and are to be compared with Fig. 1 of reference 1, which shows the excitation curves for reactions (1) and (2). The resonance for reaction (3) at 1.435 Mev has been observed with thinner targets than those used in obtaining the data in Fig. 1. This resonance appears to have about the same width of 5.5 kev as reported for the gamma-ray resonance.[1]

The angular distributions shown in Fig. 2 were obtained by observing the proton yield at several stabilized bombarding energies. These data have been corrected for the center of mass motion, which changes the angle of emission and the solid angle of observation. The curves of Fig. 2 are to be compared with similar curves for reaction (2) as shown by Fig. 4 of reference 1.

III. DISCUSSION OF THE ANGULAR DISTRIBUTIONS

The angular distribution functions for reactions (2) and (3) have been expanded in the Legendre polynomials. These expansions were performed by evaluating the integrals

$$I_n=\int_{-1}^{+1}\sigma(E,\,\cos\theta)P_n(\cos\theta)d(\cos\theta),$$

so that for the expansion $\sigma(E,\,\cos\theta)=\sum A_n(E)P_n(\cos\theta)$ the coefficients A_n are given by $A_n(E)=\frac{1}{2}(2n+1)I_n$. The coefficients A_n, as functions of the deuteron energy E, are shown in Fig. 3 for reaction (2) and Fig. 4 for reaction (3). It is noted that no angular functions of order higher than four are necessary to describe the angular distributions analyzed. Coefficients that contributed less than the estimated experimental errors of ten percent for the neutrons and three percent for the protons were neglected.

Elementary arguments give some indication of the angular momenta and parity of the excited states, provided that the parity and spins of the incoming and outgoing particles are known. If the deuteron has spin 1, protons and neutrons spin $\frac{1}{2}$, and C^{12} has spin zero with even parity, and if the spins of C^{13} and N^{13} are one-half and they both have odd parity, one can calculate the allowed values of incoming and outgoing orbital angular momenta.

It has been shown[7] that when the differential cross section is expressed as $\sigma(\theta)=\sum A_nP_n(\cos\theta)$ that the coefficients A_n, with $n>2l^{\max}$, are zero; where $l^{\max}$, in this case, is the maximum orbital momentum of the incoming deuterons. Thus a finite number of total angular momentum states are indicated by the angular distributions. Analysis indicates that the coefficients A_n may show resonance or dispersion shapes in the region of a resonance. The cross section will have a general angular term of the form $P_{l_1}(\cos\theta)P_{l_2}(\cos\theta)$, which can be an odd function only if one of the outgoing angular momentum quantum numbers l_1 or l_2 are odd. This implies that if two states of opposite parity contribute to the disintegration the angular distributions will not be symmetrical about the equatorial plane in the C.M. system. Also, one might expect that when a resonant state competes in the emission of two groups of protons, or in the emission of neutrons and protons, then the cross sections will be governed by the probability of the particles penetrating the Coulomb and centrifugal barriers.

The Legendre polynomial coefficients shown in Figs. 3 and 4 have large values for the odd terms for the three first pronounced resonances: at 0.91, 1.16, and 1.30 Mev. This may be considered to indicate that the parity alternates for these states. Because of the similarity of the angular distributions and of the excitation curves in this energy region for reactions (2) and (3) it seems reasonable to assume that both reactions show resonances coming from the same states in $^*N^{14}$. The anomaly in the coefficient of the $P_2(\cos\theta)$ term in the region of the 1.16-Mev resonance shows that deuterons of at least one unit of orbital angular momentum contribute to the reaction. However, in this energy region the penetrability of *d*-deuterons is only about two percent of that of *s*-deuterons so that it seems unlikely that *d*-deuterons alone cause either of the states. Also *p*-deuterons cannot be mainly responsible for the 0.91-Mev resonance since there is no indication there of an anomaly in the term in $P_2(\cos\theta)$. These facts are most simply explained by assuming that the 0.91-Mev resonant state has a total angular momentum one unit and even parity, with the 1.16-Mev resonant state having one or two units of total angular momentum and odd parity.

The 1.30-Mev resonance shows anomalies in the Legendre polynomial coefficients up to A_4 and so indicates that *d*-deuterons, at least, are of some consequence in the formation of this state. The simplest

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[7] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).

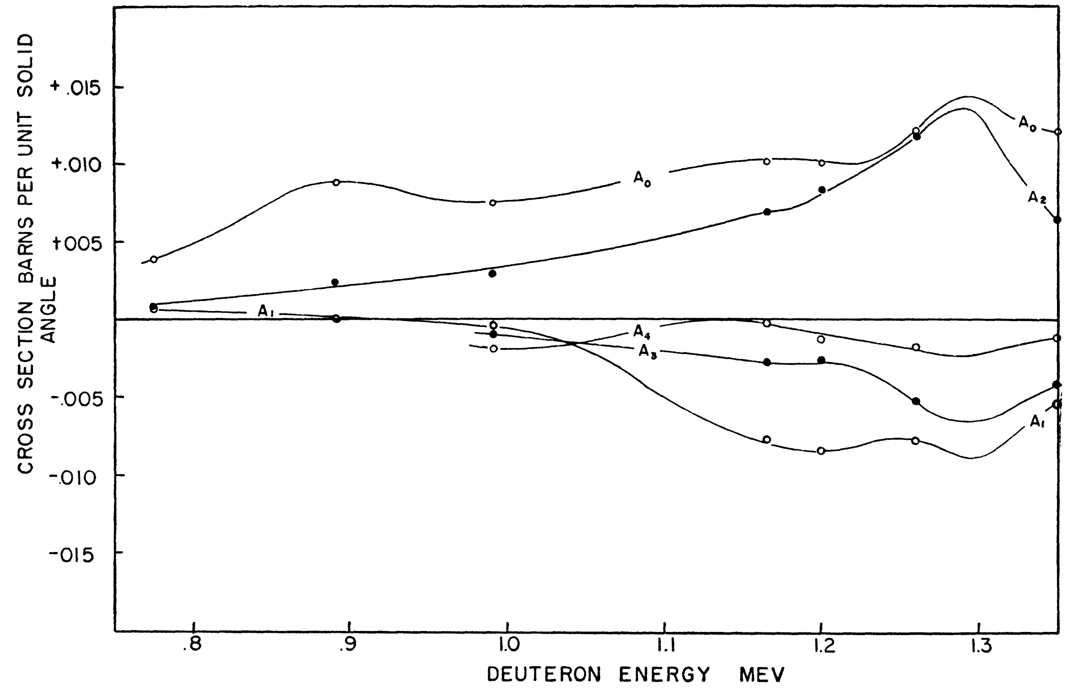

FIG. 3. The coefficients $A_n(E)$ in the expansion $\sigma_{\text{neutron}}(E, \cos\theta)=\Sigma_n A_n(E)P_n(\cos\theta)$ plotted as a function of the bombarding deuteron energy.

explanation of these facts is that the state in $^*N^{14}$ showing the 1.30-Mev resonance is of even parity and has one or two units of total angular momentum.

IV. THE INTENSITIES OF THE RESONANCES

The cross sections of the three reactions can be compared at the resonances by estimating each cross section above the background due to the overlapping resonances. The assignments of total angular momentum and parity for the first three large resonances of reactions (2) and (3) can be checked by comparison of the ratio of the total cross sections at resonance to the ratio of the penetrabilities of the two types of particles. The proton penetrabilities have been obtained from the curves of Christy and Latter,[8] and the neutron penetration of the centrifugal barrier has been calculated by the simple formulas of Weisskopf:[9]

$$P_1=x^2/(1+x^2)(p\text{ neutrons}),$$
$$P_2=x^4/(9+3x^2+x^4)(d\text{ neutrons}),$$

where $kR=x$, $R=e^2/2mc^2(1^{\frac{1}{3}}+13^{\frac{1}{3}})$ in this case, $k=\mu v/\hbar$, μ is the reduces mass, and v is the C.M. velocity. Since several outgoing angular momenta are important (as is witnessed by the complexity of the angular distributions), it was not possible to ascertain how to combine the penetrabilities. However, the intensity and penetrability ratios were found to be equal to within a factor of two when the lowest outgoing orbital angular momenta allowed were used. The approximate equality of these ratios may be taken to indicate that the nuclear part of the probability for long-range proton emission and neutron emission is nearly equal; or that the assignments of parity and angular momenta to the states, though far from certain, do not contradict the available data.

If reaction (1) is compared with reaction (3) in the same way for these three states, the agreement is not good. The intensity ratio of the short-range protons to long-range protons for these resonances in about unity. However, the ratio of the penetrabilities is very small (about 10^{-2} to 10^{-3}). Thus the short range protons are about one hundred times more intense than would be expected under the assumptions. It is perhaps significant that the disagreement is so large. This must mean that some mechanism other than that described by the simple assumptions is operating. A likely possibility is that the excited state in C^{13} formed by reaction (1) does not have the same parity and angular momentum as the ground state; and the short-range protons are emitted with less orbital angular momentum than the ground-state group has. However, at 0.91 Mev if s low energy protons are emitted (the most favorable case) and the high energy protons are p, the penetrability ratio disagrees with the intensity ratio by a factor of about fifteen. The same is true for the other resonances.

It is instructive to compare the rate of rise of the cross sections of the 0.91-Mev resonance for reactions (1) and (2). If these are the same levels, the ratio of the factor of rise should be the same as the ratio of the factor of rise of the penetrabilities since there appear to

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[8] Christy and Latter, Rev. Mod. Phys. 20, 185 (1948).

[9] V. Weisskopf, Lecture at Los Alamos, Summer, 1949.

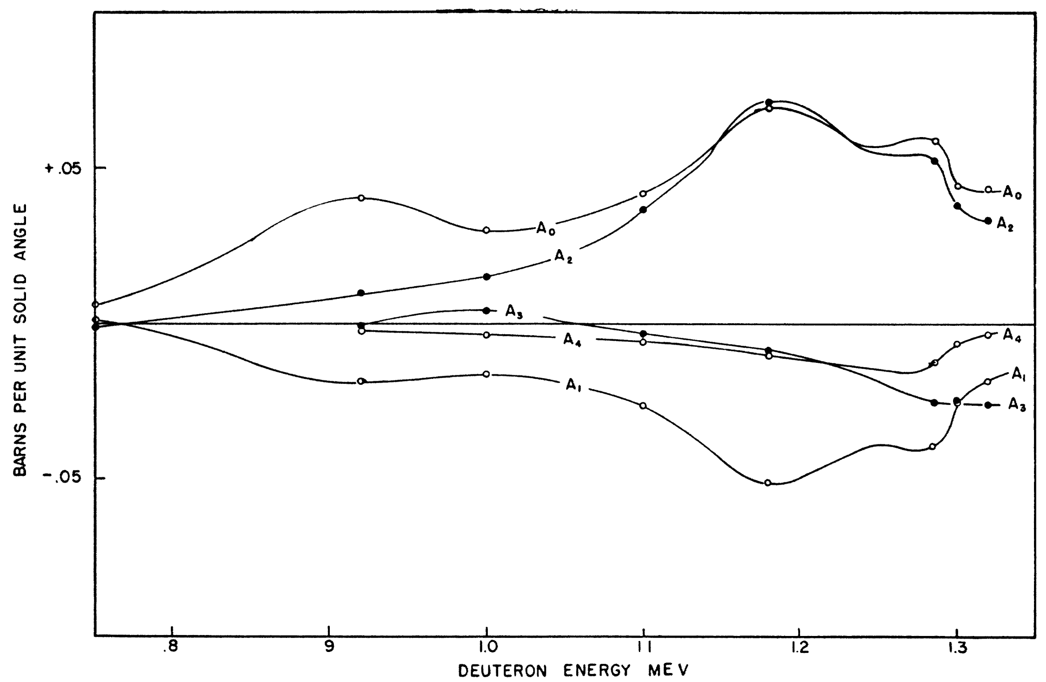

FIG. 4. The coefficients $A_n(E)$ in the expansion $\sigma_{\text{protron}}(E, \cos\theta) = \Sigma_n A_n(E) P_n(\cos\theta)$ plotted as a function of the bombarding deuteron energy.

be no resonances below. This ratio of rise of the experimental cross sections of reaction (1) to reaction (2) for the energy interval from 0.80 to 0.91 Mev is about unity. Now if *p*-particles are principally emitted by both reactions, the penetrability ratio of rise is about three, while if *s* short-range protons and *p*-neutrons are emitted, the penetrability ratio of rise is again about three. It is not obvious how the experimental cross sections could be in error by a factor of three.

V. THE POSITIONS AND WIDTHS OF THE RESONANCES

If the resonances that are shown by the three reactions are really competitive, one would expect them to coincide, except for small shifts due to the fact that the two proton groups of reactions (1) and (3) and the neutrons of reaction (2) do not have equal penetrabilities. Actually, not all the resonances have been found for all the reactions: the 1.13-Mev resonance is found only for reaction (3); the 1.435-Mev resonance only for reactions (1) and (3); however, this need not invalidate the theory of competition, but may point to unknown selection rules. However, Heydenburg, *et al.* have questioned the competition in this reaction.[4] The general similarity for the levels at 0.91, 1.16 and 1.30 for the three reactions and in particular the angular distributions for reactions (2) and (3) would lend credence to the hypothesis of competition.

The shift of a resonance due to the change of the penetrability across the resonance would be a maximum in the case of reaction (1). This shift would not be greater than 25 kev for the widths of the observed resonances of reaction (1). For reactions (2) and (3) they would be very small.

The levels at 0.91, 1.16 and 1.30 Mev show no shifting within the accuracy of the determinations. The excitation curves of the three reactions investigated at this laboratory were obtained with different targets, and and simultaneous experiments would be required to decide if the levels do not coincide. One can only say that the data, to the accuracy of the experiments, indicate no displacements.

The most striking examples of the shifting of resonance position occur when particles are observed at different angles across a resonance. The 1.435-Mev resonance shows a shift of about ten kev for reaction (3) from 0° to 150°. This shift may be due largely to the "interference" of the protons from this state with the overlapping states. The shape of the level is not entirely the Breit-Wigner shape, but has some of the shape of a dispersion curve.

The experimental widths of the resonances can be estimated from Figs. 1, 3, and 4, and from the data of reference 1. Each particular resonance, when shown by the different reactions, has widths that are closely the same. The only variation in width to be expected would be due to changes in penetration of the barrier in going across a resonance. Even for reaction (1) these changes are small percentage-wise. The small magnitude of the variation of widths for the three reactions give some support to the competing reaction hypothesis.

TABLE I. Resume of the locations, widths, estimated intensities above background, probable total angular momentum of the resonances, probable angular momenta of the deuterons that contribute to and the particles that are emitted from each resonance.

Deuteron energy at resonance Mev	Total width Mev	Estimated relative total cross section (barns) above background			Probable l incoming	Probable total angular momentum and parity of $^*N^{14}$	Probable l outgoing
		γ's	neutrons	long protons			
0.91	0.200	0.12	0.08	0.36	0	1 even	1
1.13	0.030	0	0?	0.1	——	——	——
1.16	0.200	0.15	0.05	0.30	or 1/1, 3	or 1 odd/2 odd	or 0, 3/2
1.30	0.080	0.15	0.07	0.16	0, 2/2	or 1 even/2 even	or 1/1, 3
1.435	0.0055	0.3	0.01	0.2	——	——	——
1.62	0.0200	0	0.07	—	——	——	——
1.73	0.200	0.6	0.07	—	——	——	——

VI. CONCLUSIONS

The very strong similarity of excitation curves for the three reactions, and the similarity of the angular distribution up to 1.3 Mev for reactions (2) and (3) indicate competition. The widths of the resonances and their positions seem to be described well by competition of the three reactions. However, the intensity of reaction (1) with respect to reaction (2) or (3) is not at all explicable, while the ratios of intensities of reaction (2) and (3) seem well enough explained.

The total angular momenta and the parities may not be those deduced by consideration of the angular distributions and the penetrabilities, but these seem to be the simplest explanations of the experimental facts.

There are two aspects of the study that remain obscure: (*a*) What mechanism accounts for the unexpectedly large cross section for the short range protons; and (*b*) why do only the long-range protons exhibit the 1.13-Mev and the 1.435-Mev resonances, when otherwise reactions (2) and (3) are so similar;

It may be remarked on point (*a*) that the short-range protons act as if they did not need to penetrate the barrier.

The resonance at 1.13 Mev shown for the long-range protons is of low intensity so that the possibility of its occurrence for reaction (2) is not eliminated. However, the data of reference 1 shows that the neutrons do not exhibit the 1.435-Mev resonance as do the long range protons; or at most, the neutron resonance is but a few percent of the proton cross section. This is explicable for reactions (2) and (3) if the state at 1.435 Mev is of a large total angular momentum, induced by and emitting high angular momenta particles. Since the neutron penetrabilities are considerably smaller than those for the long-range protons, only the latter would strongly show the resonance. But this high angular momentum certainly would not be expected to allow the very strong resonance shown by the low energy proton group.

A tabulation of the best information on the resonances in given in Table I.

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