Proton Angular Distributions from $Zn^{64,66,67,68}(d,p)$ Reactions*

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Angular distributions and Q values were determined for proton groups from (d,p) reactions with isotopically enriched targets of Zn^{64}, Zn^{66}, Zn^{67}, and Zn^{68}. The incident deuteron energy was 10 Mev. The angular distributions were fitted by Butler curves, from which values of l_n were determined, where $l_n\hbar$ is the orbital angular momentum of the captured neutron. The fits were only fair, presumably because the Butler theory cannot be expected to give good fits at $Z=30$ without modification. In addition, several peaks are evidently superpositions of closely spaced, unresolved groups with different l_n. Well-resolved empirical distributions which appear to correspond to $l_n=0$, 1, 2, 3, and 4 were observed; these serve to indicate in which direction the Butler curves should be shifted, thus increasing confidence in the correctness of the values of l_n which were assigned. For $Zn^{64}(d,p)$ we find $Q=5.71$ Mev with $l_n=1$ and 3, $Q=4.89$ Mev with $l_n=1$ and 3 or 4, $Q=4.43$ Mev with $l_n=2$, $Q=3.86$ Mev with $l_n=0$, and $Q=3.31$ Mev with $l_n=$perhaps 2 and 4. For $Zn^{66}(d,p)$ the results were $Q=4.76$ Mev with $l_n=1$ and 3, $Q=4.38$ Mev with $l_n=1$ and 3 or 4, $Q=3.85$ Mev with $l_n=2$, and $Q=3.15$ Mev with l_n uncertain. For $Zn^{67}(d,p)$ we find $Q=8.01$ Mev with $l_n=3$, $Q=6.90$ Mev with $l_n=1$, $Q=6.13$ Mev with l_n unknown, and $Q=4.52$ Mev with $l_n=$perhaps 1 and 3. For $Zn^{68}(d,p)$ the results were $Q=4.22$ Mev with $l_n=1$, $Q=3.78$ Mev with $l_n=4$, and $Q=3.40$ with $l_n=2$.

THIS paper summarizes a series of experiments to determine Q values and proton angular distributions from (d,p) reactions with isotopically enriched zinc targets. The 10-Mev external beam from the Washington University cyclotron was used. A low-resolution detection system was employed which included a proportional counter telescope and an arrangement of remotely controlled aluminum absorber stacks of variable thickness, for range measurements and energy determinations. The general features of the experimental apparatus were described in an earlier paper.[1]

Four different isotopically enriched samples[2] of ZnO were available, of which the major constituents were Zn^{64}, Zn^{66}, Zn^{67}, and Zn^{68}, respectively. Target thicknesses of 4.0 to 5.0 mg/cm^2 were used. The experimental results are summarized in Table I, in which are listed the Q values, l_n values, and the relative maximum intensities of the different proton groups, each measured at the peak of the angular distribution curve for the group. The l_n values were determined by comparison of the angular distributions with curves computed from the theoretical cross section derived by Butler.[3] Table I also gives suggested spins and parities for levels in the odd-A residual nuclei Zn^{65}, Zn^{67}, and Zn^{69}, based on speculations about the various nucleon configurations in terms of shell structure and an extreme single-particle point of view. In this connection we are especially indebted to Raz[4] for his suggestions and comments.

In the reactions studied, the 35th, 37th, 38th, or 39th neutron is being added to form the residual nucleus. The neutron configuration of a zinc nucleus consists of a core of definitely filled shells, including $1s$, $1p$, $1d$, $2s$, and $1f_{7/2}$, to which are added from 7 to 11 neutrons variously occupying $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, and $1g_{9/2}$ single-particle levels. In earlier work on (d,p) reactions with chromium,[1] iron,[5] and nickel,[6] we have found $l_n=1$ for the angular distribution of every observable proton group (except one) from isotopically enriched targets of Cr^{52}, Cr^{53}, Fe^{56}, Fe^{57}, Ni^{60}, Ni^{61}, and Ni^{62}. This suggests that neutron capture into $2p_{3/2}$ and $2p_{1/2}$ single-particle levels plays a major role when neutron number N is from 29 to 35, and one might expect indications of capture into $f_{5/2}$ and $g_{9/2}$ orbitals to occur among the zinc isotopes. This is found to be the case. As discussed below, however, we also find that angular distributions for which $l_n=1$ and having substantial cross sections continue to occur frequently for low-lying levels formed in all the $Zn(d,p)$ reactions. Thus the $p_{3/2}$ and $p_{1/2}$ single-particle orbitals continue to be important for N from 35 to 39. This suggests that in many instances the $f_{5/2}$ shell is being filled by twos, in such a way as to permit the appearance of a single hole in one of the p shells. A pairing energy which is sufficiently higher in the f shell than in the p shells could make this possible. Moreover we find several examples of $l_n=2$ and one of $l_n=0$ distributions, which may imply similar hole formation in the $d_{3/2}$ or $s_{1/2}$ shells, and thus account for the appearance of excited states having even parity.

The four reactions are discussed individually and in somewhat greater detail in the paragraphs which follow.

$Zn^{64}(d,p)Zn^{65}$

Zn^{65} is known to have an excited state at 0.86 Mev from threshold measurements[7] on the $Cu^{65}(p,n)$ re-

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[1] A. J. Elwyn and F. B. Shull, Phys. Rev. **111**, 925 (1958).

[2] Obtained on loan through courtesy of the Isotopes Division of the U. S. Atomic Energy Commission.

[3] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1952).

[4] B. J. Raz (private communication).

[5] C. E. McFarland, Ph.D. thesis, Washington University, 1955 (unpublished).

[6] A. J. Elwyn, Ph.D. thesis, Washington University, 1956 (unpublished).

[7] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 807(A) (1954).

TABLE I. Q values, excitation energies (E), l_n values, relative maximum intensities (I_{max}), and suggested spins and parities of residual nuclei for four $Zn(d,p)$ reactions. The maximum intensities are to an arbitrary scale, and account has been taken of different target compositions and thicknesses, so that yields can be compared between different reactions. The maximum intensities were measured at the peak of the angular distribution for each proton group. The suggested spins are highly tentative and are based on simple single-particle shell model considerations.

Q (in Mev)	E (in Mev)	l_n	I_{max}	Suggested spin of final nucleus
		$Zn^{64}(d,p)Zn^{65}$		
5.71±0.06	0	3	460	5/2−
	(?)	1	1144	3/2−
4.89±0.07	0.82?	1	680	1/2−
	0.82?	4(3)	410	9/2+(7/2−)
4.43±0.09	1.28	2	746	3/2+
3.86±0.09	1.85	0	795(10°) (1600 est. at 0°)	1/2+
3.31	2.40	?	350	?
		$Zn^{66}(d,p)Zn^{67}$		
4.76±0.07	0	3	290	5/2−
	0.092?	1	730	3/2−
4.38±0.09	0.38?	1	580	1/2−
	0.38?	4(3)	350	9/2+(7/2−)
3.85±0.09	0.88	2	680	3/2+
3.15±0.11	1.61	?	?	?
		$Zn^{67}(d,p)Zn^{68}$		
8.01±0.07	0	3	15	0+
6.90±0.07	1.11	1	40	
6.13±0.12	1.88	?	low	
4.52±0.10	3.49?	1?	355	
	3.49?	3?	170	
		$Zn^{68}(d,p)Zn^{69}$		
4.22±0.07	0	1	997	1/2−
3.78±0.09	0.44	4	617	9/2+
3.40±0.08	0.82	2	1171	3/2+

action. It probably has other excited levels near the ground state, in view of gamma rays with energies 0.052, 0.092, and 0.114 Mev observed by Crosemann[8] in the beta decay of 15-min Ga^{65}. Ga^{65} also has an

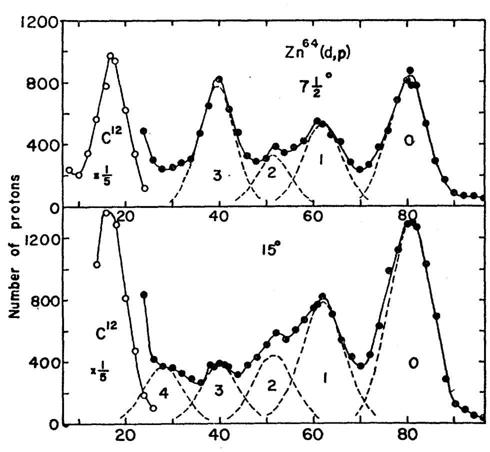

FIG. 1. Proton spectra from $Zn^{64}(d,p)Zn^{65}$ at angles of 7.5° and 15°. Each foil of the variable aluminum absorber was 1.72 mg/cm² thick. Q values are 5.71, 4.89, 4.43, 3.86, and 3.31 Mev, respectively, for groups 0, 1, 2, 3, and 4.

[8] B. Crosemann, Phys. Rev. 93, 1034 (1954).

8-min isomeric activity, but all of the gamma rays listed above decay with a 15-min period, while no 8-min gamma rays were found. The possibility exists that one of the three gamma rays occurs as a transition from the 15-min to the 8-min level in Ga^{65}. Hence information concerning energies of one or more excited levels within 200 kev of the ground state in Zn^{65} is inconclusive, but the existence of such levels seems certain. We would be unable to resolve levels with such close spacing with our apparatus.

The isotopic composition of the target material was 93.12% Zn^{64}, 6.29% Zn^{66}, 0.16% Zn^{67}, 0.43% Zn^{68}, and 0.01% Zn^{70}. In preparing proton spectra such as those shown in Fig. 1, a correction for the effect of Zn^{66} was

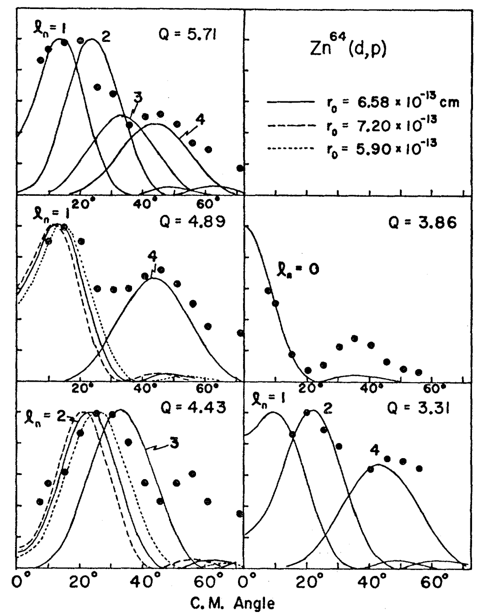

FIG. 2. Angular distributions of proton groups from $Zn^{64}(d,p)Zn^{65}$. The curves were calculated from the Butler theoretical cross section, and each is arbitrarily normalized to unity at the peak. See Table I for comparison of actual peak intensities for the different groups. The solid curve in each picture is for a Butler radius parameter r_0 equal to the Gamow radius $(1.7+1.22A^{\frac{1}{3}})\times10^{-13}$ cm.

subtracted from each. The angular distributions for the five proton groups which were found are pictured in Fig. 2.

The angular distribution for the ground-state reaction ($Q=5.71$ Mev) appears to be a mixture of $l_n=1$ with either $l_n=3$ or $l_n=4$. The hump at about 45° is best fitted with a Butler curve for $l_n=4$. On the other hand, $l_n=3$ would be more consistent with the predictions of the shell model. Presumably the two lowest levels have the odd neutron in an $f_{5/2}$ and a $p_{3/2}$ orbit, respectively, reflecting the close spacing of these orbitals in this region of neutron number. A preference for $5/2^-$ rather than $3/2^-$ for the ground state is not strong, and the spins might be reversed. Way, King, *et al.*[9] chose $5/2^-$ because the *ft* product is rather large for the positron decay of Zn^{65}, which suggests that this is an *l*-forbidden transition. We have listed $l_n=3$ for the ground state in Table I to be consistent with this conclusion.

We find the binding energy of the last neutron in Zn^{65} to be $E_n=Q+2.23=7.94$ Mev. This may be compared with values of $E_n=7.92$ Mev found by Harvey,[10] also from the (d,p) reaction, and of $E_n=8.14$ Mev computed from the masses[11] of Zn^{64} and Cu^{65} together with the energy release in the beta decay of Zn^{65}.

The angular distribution for the second proton group ($Q=4.89$ Mev) resembles that for the ground-state group, but its secondary maximum is more pronounced. What appears from a best fit with Butler theory to be a mixture of $l_n=4$ with $l_n=1$ may well be a mixture of $l_n=3$ and $l_n=1$ instead. This suggests two closely spaced and unresolved levels with excitation energies near 0.82 Mev in Zn^{65}. This excitation energy agrees fairly well with the figure 0.86 Mev obtained from the $Cu^{65}(p,n)Zn^{65}$ reaction. It is suggested that one of these states might involve an odd neutron in a $p_{1/2}$ orbital. The other level might have an odd neutron in a $g_{9/2}$ level (if $l_n=4$) or a single hole in the previously filled $f_{7/2}$ shell, formed by promoting an $f_{7/2}$ neutron to the $f_{5/2}$ shell (if $l_n=3$).

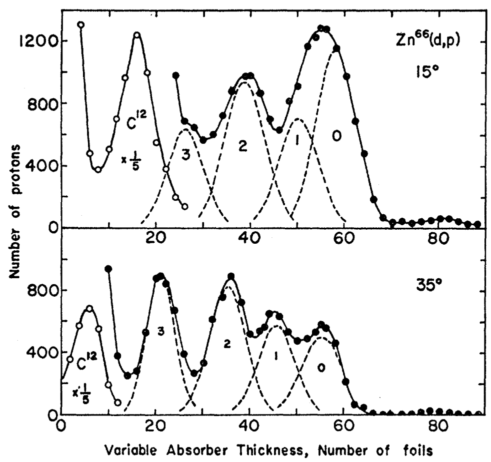

FIG. 3. Proton spectra from $Zn^{66}(d,p)Zn^{67}$ at angles of 15° and 35°. Q values are 4.76, 4.38, 3.85, and 3.15 Mev, respectively, for groups 0, 1, 2, and 3.

The third and fourth proton groups ($Q=4.43$ and 3.86 Mev) have angular distributions which are best fitted by $l_n=2$ and $l_n=0$, respectively. The situation here resembles that found in $Ca^{40,42}(d,p)Ca^{41,43}$ by Bockelman, Buechner, *et al.*,[12,13] where levels with $l_n=2$ and $l_n=0$ were found at excitation energies of 2.014 and 2.677 Mev, respectively, in Ca^{41} and at 0.991 and 1.957 Mev, respectively, in Ca^{43}. Raz[4] is of the opinion that these levels, as well as the similar ones in Zn^{65}, can be interpreted as single-hole levels formed by promoting a $d_{3/2}$ or an $s_{1/2}$ neutron from the core to the $f_{5/2}$ shell at the same time that another neutron is being captured into the $f_{5/2}$ shell. Similar levels with $l_n=2$ are also found in $Zn^{66}(d,p)Zn^{67}$ and in $Zn^{68}(d,p)Zn^{69}$ (see Table I).

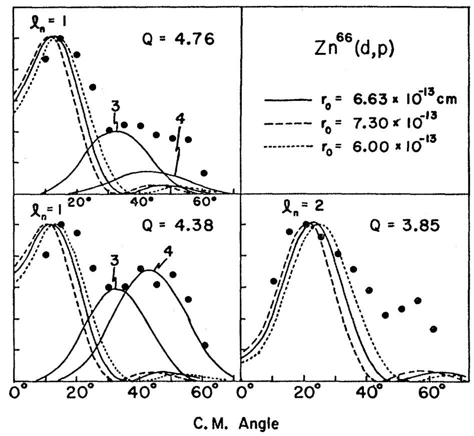

FIG. 4. Angular distributions of proton groups from $Zn^{66}(d,p)Zn^{67}$. See also the caption for Fig. 2.

A fifth proton group ($Q=3.31$ Mev) is clearly resolved at larger angles, but overlaps strongly with the $C^{12}(d,p)$ ground-state group at small angles. Its angular distribution cannot be easily determined, and our best attempts lead to a distribution which is not obviously identifiable with any particular value of l_n.

$Zn^{66}(d,p)Zn^{67}$

Zn^{67} is known[9] to have excited states at 0.092, 0.182, 0.388, and 0.88 Mev in consequence of numerous investigations of the beta decays of Cu^{67} and Ga^{67}. The ground state spin is known to be $5/2^-$, and the four excited states have been assigned the spins $3/2^-$, $5/2^-$, $3/2^-$, and either $3/2^-$ or $5/2^-$, respectively. We could not expect to resolve the three lowest levels, but were able to distinguish a level at about 0.38 Mev.

The isotopic composition of the target material was 93.79% Zn^{66}, 2.57% Zn^{64}, 1.60% Zn^{67}, 2.00% Zn^{68}, and 0.05% Zn^{70}. No correction for the less abundant isotopes was made in the proton spectra such as those pictured in Fig. 3.

The angular distributions shown in Fig. 4 for the first three of the four proton groups are very similar to those for the first three groups from $Zn^{64}(d,p)$, and thus

[9] *Nuclear Level Schemes*, $A=40$—$A=92$, compiled by Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

[10] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

[11] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).

[12] C. K. Bockelman and W. W. Buechner, Phys. Rev. **107**, 1366 (1957).

[13] Bockelman, Braams, Browne, Buechner, Sharp, and Sperduto, Phys. Rev. **107**, 176 (1957).

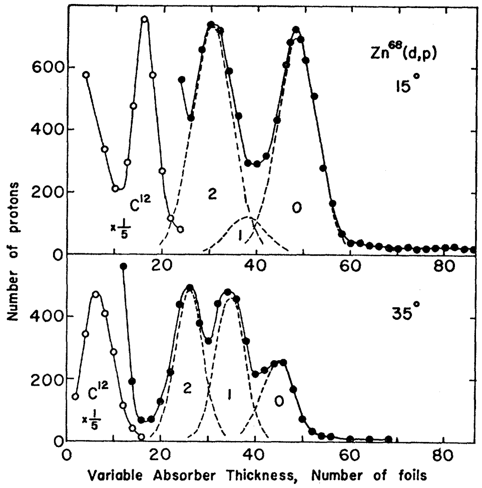

FIG. 5. Proton spectra from $Zn^{68}(d,p)Zn^{69}$ at angles of 15° and 35°. Q values are 4.22, 3.78, and 3.40 Mev, respectively, for groups 0, 1, and 2.

our interpretation of the resulting states in Zn^{67} is correspondingly similar to the one invoked for that reaction. We regard the ground state group ($Q=4.76$ Mev) as an overlap of at least two, one with $l_n=1$ and the other with $l_n=3$. The $l_n=3$ must belong to the ground-state group, in view of the $5/2^-$ spin of Zn^{67}. We associate the $l_n=1$ with the 0.092-Mev level, with the odd neutron going into a $p_{3/2}$ orbital. We are unable to resolve the 0.182-Mev level, and if its spin assignment of $5/2^-$ is correct, its angular distribution would merge with that from the ground-state reaction.

The binding energy of the last neutron in Zn^{67} comes out to be $E_n=6.99$ Mev. This may be compared with values of 7.00 Mev from a measurement of the $Zn^{67}(\gamma,n)$ threshold by Sher, Halpern, and Mann[14] and of 7.50 Mev computed from mass measurements[11] for Zn^{66} and Zn^{67}.

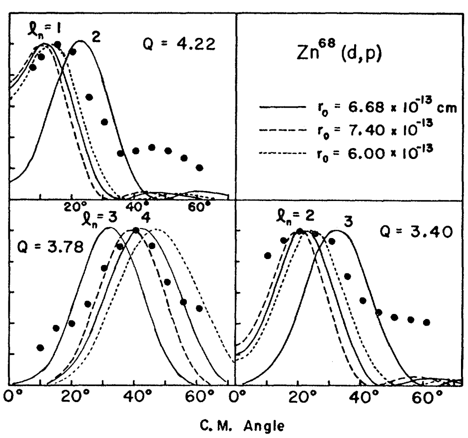

FIG. 6. Angular distributions of proton groups from $Zn^{68}(d,p)Zn^{69}$. See also the caption for Fig. 2.

[14] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).

The second proton group ($Q=4.38$ Mev) is apparently also an overlap of two unresolved groups, one with $l_n=3$ or 4, the other with $l_n=1$, and is quite similar in this respect to the second group from $Zn^{64}(d,p)$. Again it is suggested that one level may have spin $1/2^-$, with its odd neutron in a $2p_{1/2}$ shell. The other level could be $7/2^-$ because of a single hole in the $f_{7/2}$ shell (if $l_n=3$) or might be $9/2^+$, with the odd neutron in the $g_{9/2}$ shell (if $l_n=4$).

The third group ($Q=3.85$ Mev) seems to be principally $l_n=2$ and again it is suggested that this may be the result of a single hole in the $d_{3/2}$ shell caused by promotion to the $f_{5/2}$ shell of one neutron while a second is being captured also in the $f_{5/2}$ shell to form a pair.

A fourth group ($Q=3.15$ Mev) suffers interference at small angles from the $C^{12}(d,p)$ reaction, and no conclusions concerning l_n can be drawn.

$Zn^{68}(d,p)Zn^{69}$

This reaction is discussed ahead of the $Zn^{67}(d,p)$ reaction because of the residual nucleus is odd A and thus one might expect some similarity with the two preceding cases. The isotopic composition of the zinc in this target was 95.47% Zn^{68}, 1.19% Zn^{64}, 1.83% Zn^{66}, 1.40% Zn^{67}, and 0.11% Zn^{70}. No corrections for the effects of the less abundant isotopes were made in the proton spectra such as those displayed in Fig. 5. Three principal proton groups were observed, and the corresponding angular distributions are shown in Fig. 6.

The angular distribution for the ground state group ($Q=4.22$ Mev) lies between Butler curves for $l_n=1$ and $l_n=2$. We favor the choice $l_n=1$ because the beta decay of Zn^{69} is allowed, which leads us to expect the Zn^{69} parity to be odd, the same as that assumed for the daughter Ga^{69}. Moreover, it appears quite generally that our angular distributions, at least for $l_n=1$, are slightly shifted to higher angles relative to the Butler curves, especially for Q as low as 3 or 4 Mev. We believe the ground state of Zn^{69} is probably $1/2^-$, with an odd neutron in the $p_{1/2}$ shell.

The other two groups clearly indicate the presence of even parity excited states of Zn^{69}. The second proton group ($Q=3.78$ Mev) is best fitted by $l_n=4$, so that the odd neutron would appear in the $g_{9/2}$ shell. This level appears to be the 13.8-hour isomeric level at 0.436 Mev which, according to Duffield and Langer,[15] decays by an $M4$ transition to the ground state. This is consistent with our assignments of $1/2^-$ to the ground state and $9/2^+$ to the 0.44-Mev level.

The third proton angular distribution is somewhat broader than usual and may represent an overlap of two closely spaced levels. It seems certain that $l_n=2$ is correct for at least one such level, and again this may result from promotion of one neutron from $d_{3/2}$ together with capture of another, to form a pair in another orbit of higher angular momentum and pairing energy.

[15] R. B. Duffield and L. M. Langer, Phys. Rev. **89**, 854 (1953).

The binding energy of the last neutron in Zn^{69} we find to be $E_n=6.45$ Mev. If E_n is computed from the masses[11] of Zn^{68} and Ga^{69} together with the beta-decay energy for Zn^{69}, the result is $E_n=6.6$ Mev. Eby[16] obtained a figure of 6.39 Mev from the $Zn^{68}(d,p)$ reaction. If fact, all our findings with respect to this reaction are in good agreement with those of Eby for all three proton groups.

$Zn^{67}(d,p)Zn^{68}$

The isotopic abundances in the Zn^{67} target were 56% Zn^{67}, 18.7% Zn^{64}, 10.5% Zn^{66}, 8.1% Zn^{68}, and 6.7% Zn^{70}. Corrections were subtracted to eliminate the effects of Zn^{64}, Zn^{66}, and Zn^{68} from the proton spectra, such as those in Fig. 7, but nothing could be done about the Zn^{70}.

Four proton groups could be distinguished for certain, but there appear to be others which are unresolved.

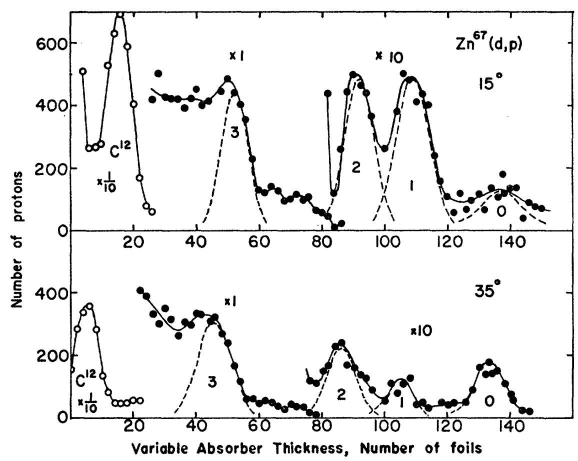

FIG. 7. Proton spectra from $Zn^{67}(d,p)Zn^{68}$ at angles of 15° and 35°. Q values are 8.01, 6.90, 6.13, and 4.52 Mev, respectively, for groups 0, 1, 2, and 3.

The angular distributions for three of the four are shown in Fig. 8. No reliable distribution was obtained for the other one ($Q=6.13$ Mev) because its presence became evident only after correction for the other zinc isotopes. The Q value is likewise unreliable.

The ground-state group ($Q=8.01$ Mev) is of very low intensity, but seems well fitted by $l_n=3$, which is consistent with the measured spin of $5/2^-$ for Zn^{67} and the assumption of 0^+ for stable Zn^{68}. The second group ($Q=6.90$ Mev) is just as clearly fitted by $l_n=1$, and again the intensity is very low. The excitation energy of 1.11 Mev for this level agrees with the figure 1.10 Mev for the energy of the gamma ray[9] which follows the beta decay of Ga^{68}. Nothing can be said for certain about l_n for the low-intensity third group, while the fourth group ($Q=4.52$ Mev) is the first to show intensity comparable with those observed in the other

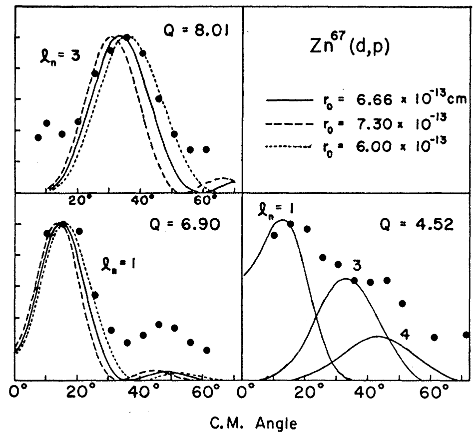

FIG. 8. Angular distributions of proton groups from $Zn^{67}(d,p)Zn^{68}$. See also the caption for Fig. 2.

three zinc reactions and seems to be an overlap of at least two groups, possibly with $l_n=1$ and $l_n=3$.

Interpretations in terms of the extreme single-particle picture are not appropriate here where the residual nucleus is even-even. It is possible that the levels of Zn^{68} might include a sequence of two-particle shell model states with spins 0^+, 2^+, and 4^+, and perhaps also a collective level with spin 2^+. We have not attempted, however, to assign specific spins to any of the three excited states which were observed.

It is interesting to note that among the four Zn(d,p) reactions we have investigated, we find what appear to be relatively clean experimental angular distributions with $l_n=0$, $l_n=1$, $l_n=3$, and $l_n=4$, plus somewhat less certain examples of $l_n=2$. In Fig. 9 are smoothed-out curves representing selected angular distributions observed in this work. They show the decided and regular shift in angular position of the maximum which characterizes the Butler theory and its variants. To be sure,

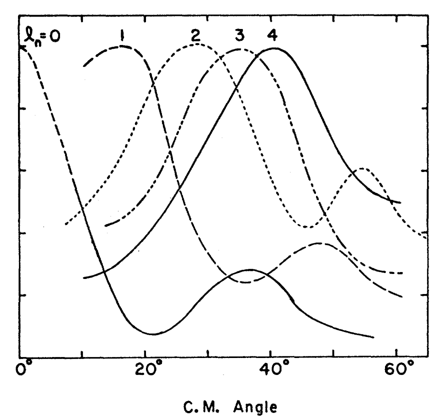

FIG. 9. Smoothed-out curves for selected experimental angular distributions from Figs. 2, 6, and 8. The $l_n=0$ and $l_n=2$ curves are for $Q=3.86$ Mev and 4.43 Mev in $Zn^{64}(d,p)$. The $l_n=1$ and $l_n=3$ curves are for $Q=6.90$ and 8.01 Mev in $Zn^{67}(d,p)$. The $l_n=4$ curve is for $Q=3.78$ Mev in $Zn^{68}(d,p)$. These particular distributions were selected in the belief that they are relatively free of unresolved contributions having different l_n.

[16] F. S. Eby, Phys. Rev. **96**, 1355 (1954).

our empirical curves are for rather disparate Q values, but we have found,[1,5,6] for $l_n=1$ at least, that the position of the maximum appears to be rather insensitive to the magnitude of Q, for 10-Mev incident deuteron energy.

Comparison of empirical angular distributions with theoretical curves becomes somewhat unreliable as a method for determining l_n for moderate or high values of Z, because a complete theoretical treatment of the problem, which omits no factor of importance and from which differential cross sections can be computed without elaborate computational aids, is not available. The Butler derivation, in particular, contains several simplifying assumptions whose validity is especially questionable as Z becomes fairly large. The behavior of the empirical distributions as shown in Fig. 9 encourages us to believe that our assignments of l_n are meaningful.

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(p,α) Reactions Induced by 23-Mev Protons

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The (p,α) reactions induced by 23-Mev protons in targets of a wide range of atomic number were studied by observing the outgoing alpha particles. Alpha-particle energy distributions and absolute differential cross sections were measured at 30, 60, 90, 120, and 150 degrees. For targets of atomic number $\lesssim 50$, the energy spectra and angular distributions indicate that most of the alpha particles are produced in compound nucleus reactions; however, there is evidence that the Coulomb barriers of the excited compound nuclei are somewhat lower than those of ground state nuclei. The alpha particles from the heaviest elements and the high-energy parts of the spectra from lighter targets are strongly forward peaked and are produced by direct interaction reactions. Total (p,α) cross sections vary from 175 mb for Al to 3.8 mb for Pt.

INTRODUCTION

THE properties of particles emitted in nuclear reactions are influenced by the nuclear processes involved in the reactions. If the energy level spacings of the residual nuclei are smaller than the energy resolution of the instruments used to study the emitted particles, the observed energy distributions are smoothly varying. The statistical theory of nuclear reactions predicts particles emitted from compound nucleus reactions to have energy distributions that are Maxwellian and characterized by the temperatures of the residual nuclei; in the case of charged particles, these energy distributions are altered by the Coulomb barrier, which is usually thought to be a function of nuclear size.

A number of studies of (p,α) reactions have been reported;[1–14] however, these have all used targets of light nuclei, and most have dealt with the ground state or low-energy excited levels of the residual nuclei.

In the work reported here, a survey of (p,α) reactions induced by 23-Mev protons was made by observing the outgoing alpha particles from targets of a wide range of atomic number. Energy distributions and absolute differential cross sections were determined at several angles to the proton beam.

EXPERIMENTAL

The energy-analyzed external 23-Mev proton beam of the ORNL 86-in. cyclotron was used for these experiments. The beam was collimated and passed through thin foils of the targets being studied and into a Faraday cup which monitored the beam. The outgoing alpha particles were observed through holes located in the wall of the 11-in. diameter scattering chamber at angles of 30, 60, 90, 120, and 150 deg from the proton beam.

The particles were detected by a proportional counter—scintillation counter telescope. The scintillation counter consisted of a 0.1-in. thick CsI(Tl) crystal and a Dumont 6291 photomultiplier tube. Energy distributions were determined by pulse height analysis of the scintillation counter pulses; a coincidence gate on the 20-channel pulse height analyzer was triggered with proportional counter pulses which passed an integral

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