Bromley, Bull. Am. Phys. Soc. 14, 531 (1969).
[18]D. W. Braben, L. L. Green, and J. C. Willmott, Nucl. Phys. 32, 584 (1962).
[19]D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 862ff.
[20]S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data A2, 347 (1946).
[21]E. Wernbom-Selin and S. E. Arnell, Arkiv Fysik 31, 113 (1966).
[22]J. L. Durell *et al.*, Phys. Letters 29B, 100 (1969).
[23]H. J. Maier, J. G. Pronko, and C. Rolfs, to be published.
[24]S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 16 (1955).
[25]A. J. Howard, J. P. Allen, and D. A. Bromley, Phys. Rev. 139, B1135 (1965).
[26]H. McManus and W. T. Sharp as quoted in D. A. Bromley, H. E. Gove, and A. E. Litherland, Can. J. Phys. 35, 1057 (1957).
[27]R. A. Lindgren, Ph.D. thesis, Yale University, 1969 (unpublished).
[28]K. W. Jones, A. Z. Schwarzchild, E. K. Warburton, and D. B. Fossan, Phys. Rev. 178, 1773 (1969).
[29]A. Z. Schwarzchild and E. K. Warburton, Ann. Rev. Nucl. Sci. 18, 268 (1968), and references therein.

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Inelastic Scattering of 31-MeV Alpha Particles from Zn^{64} and Zn^{66}

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The (α, α') reaction on Zn^{64} and Zn^{66} has been studied using the 31-MeV α-particle beam from the Massachusetts Institute of Technology cyclotron, with an over-all energy resolution of 80–120 keV. Angular distributions are presented, both for levels with known spin, and for levels whose spin and parity have not been previously determined. New 3^-, 4^+, and 5^- assignments are made both by comparison with levels of known spin and with the distorted-wave Born approximation. Good angular distributions are presented for the weak states at 1.81 MeV (2^+) and 2.32 MeV (4^+) in Zn^{64}. They are both out of phase with the 2^+ and 4^+ single-excitation states. The slope of the angular distribution for the 2.32-MeV (4^+) level is shallower than for the single-excitation 4^+ state, while the slopes are the same for the 2^+ states. Transition strengths in Zn^{64} and Zn^{66} are compared. Fractionation of 3^- strength in Zn^{64} has been observed, but it is smaller than that found in the calcium isotopes.

I. INTRODUCTION

The nuclear spectroscopy of the zinc isotopes has been studied by several authors.[1-9] Many levels have been found up to an excitation energy of 4.8 MeV[10]; however, spin assignments have been made only for some of the levels up to approximately 3 MeV in excitation. A comprehensive review of the available data, up to 1967, has been given by Verheul,[11] and Pancholi and Way.[12,13] We studied the inelastic α-particle scattering from Zn^{64}, Zn^{66}, Zn^{68}, and Zn^{70} with an energy resolution of 80–120 keV. This paper reports the results from Zn^{64} and Zn^{66}. The purpose of the experiment was to measure the variation in excitation strength as neutrons are added to the $1f_{5/2}$ shell and to see if the fractionation of 3^- strength observed in the region of $A = 40–48$ and $A = 90$[14,15] would also be present in the Zn isotopes. In addition, we decided to obtain more detailed angular distributions for the low-lying weaker levels, which are generally interpreted as double-excitation states.[1,2,4,5] The available data for Zn^{68} and Zn^{70} will be published at a later date. Good angular distributions are presented for some of the weaker states at high excitation energies, and new spin assignments are given for them. A comparison of transition strengths is made between levels in Zn^{64} and Zn^{66}, and with the results from other reaction experiments.

II. EXPERIMENT

We used the 31-MeV α-particle beam from the Massachusetts Institute of Technology cyclotron. The beam handling system and scattering chamber have already been described.[14,15] The scattered α particles were detected by single semiconductor counters and their signal was fed into the usual electronic counting system. The beam direction was fixed by a left-right split Faraday cup.[15] Variations in beam direction were monitored by two counters fixed on opposite sides of the beam. The beam direction was measured by left-right scattering of α particles from gold. Due to variations in the beam direction over long periods of time, we estimate the angular uncertainty to be 0.2°. The angular resolution was about 0.3°.

The targets were self-supporting metal foils, approximately 1 mg/cm^2 thick, prepared by Oak Ridge National Laboratory. The Zn^{64} target was enriched to 99.85% and the Zn^{66} to 98.8%.

The energy spread of the beam hitting the target was about 50 keV. The over-all energy resolution, including target thickness, counter resolution, and the beam energy spread ranged from 80–120 keV.

The cross sections for the excited states were measured with respect to the elastic scattering peak in each spectrum. The areas under the inelastic peaks were calculated either by a least-squares computer program or in some cases, manually. The elastic scattering cross sections were measured with respect to the fixed monitor counters. Due to uncertainties in beam charge collection and target thickness, we normalized the relative elastic scattering cross sections to an absolute cross-section measurement in the following way. In a separate run the elastic scattering from Zn^{64} and Zn^{66} was measured with the 7.8-MeV proton beam. The run was kept short to minimize variations in beam direction. Variations in beam charge collection efficiency were minimized by requiring that the ratio of the current-integrator reading to the fixed monitor counters remain constant. Measurements were made at small angles where the proton elastic scattering cross section follows the Rutherford formula. Immediately following the proton scattering we measured the α-particle scattering from Zn^{64} and Zn^{66}. The ratio of the measured proton elastic scattering to the calculated Rutherford cross section calibrates the integrator. This calibration was then used to compute the Zn^{64} and Zn^{66} absolute cross sections. The uncertainty in this procedure is estimated to be about 10%.

The error in the elastic cross section for one angle relative to another (the relative error) is estimated at about 3%. The largest contributors to the error in the inelastic scattering are the uncertainties in background subtraction and sometimes in the peak unfolding procedure. Data will be plotted without error bars if the relative errors are less than 8%.

The excitation energies were determined from the positions of the elastic peaks and the well-known first excited states with an uncertainty of ±30 keV for states below 5 MeV. Above an excitation of 5 MeV, where the peak locations are not as well defined, the error is ±45 keV.

III. THEORETICAL ANALYSIS

We calculated the elastic scattering angular distributions with the optical model using a Woods-Saxon potential of the form $V(r) = -(V+iW)/\{1+e^{(r-R)/a}\}$ and a Coulomb potential of a uniformly charged sphere of radius R.

The inelastic scattering was calculated in the distorted-wave Born approximation (DWBA). We used a collective form factor to describe the nuclear interaction between the α particle and the target nucleus.[16] The Coulomb-excitation contribution to the inelastic scattering was included by

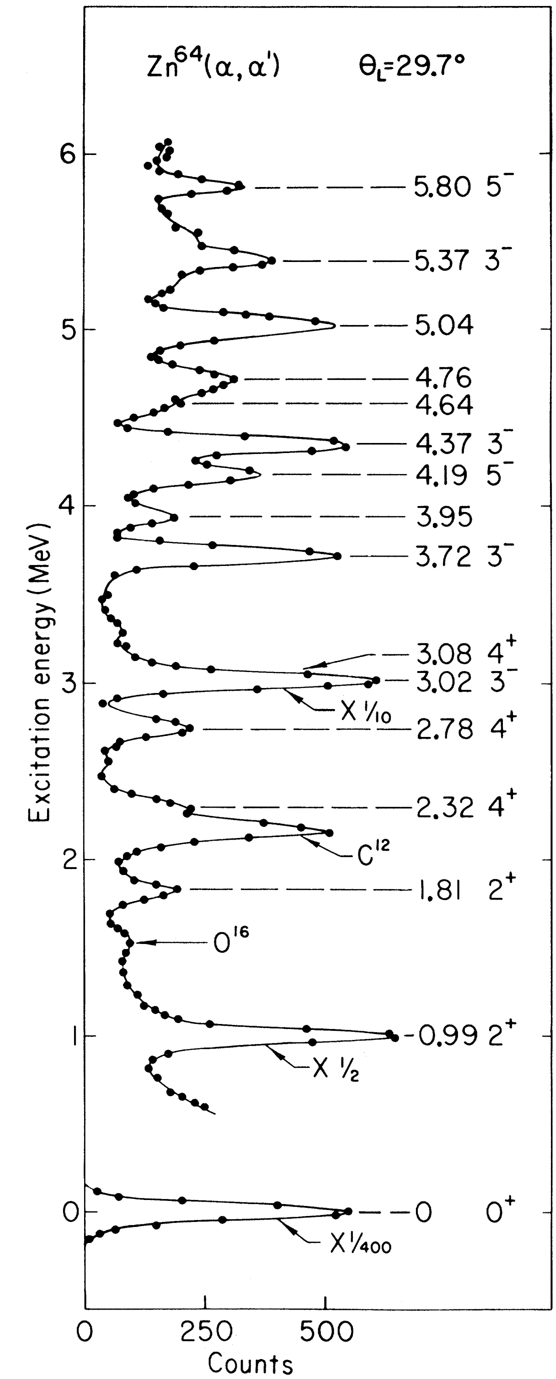

FIG 1. Spectrum of scattered α particles from Zn^{64}. The solid line merely guides the eye.

adding a term b_l/r^{l+1}, to the form factor.[16] This contribution is negligible for angular momentum transfers larger than $l=3$. Since only a finite number of partial waves are available in the computer program, the effect of Coulomb excitation is not properly calculated at small angles.[16] A more detailed discussion of these points has been given in Ref. 15.

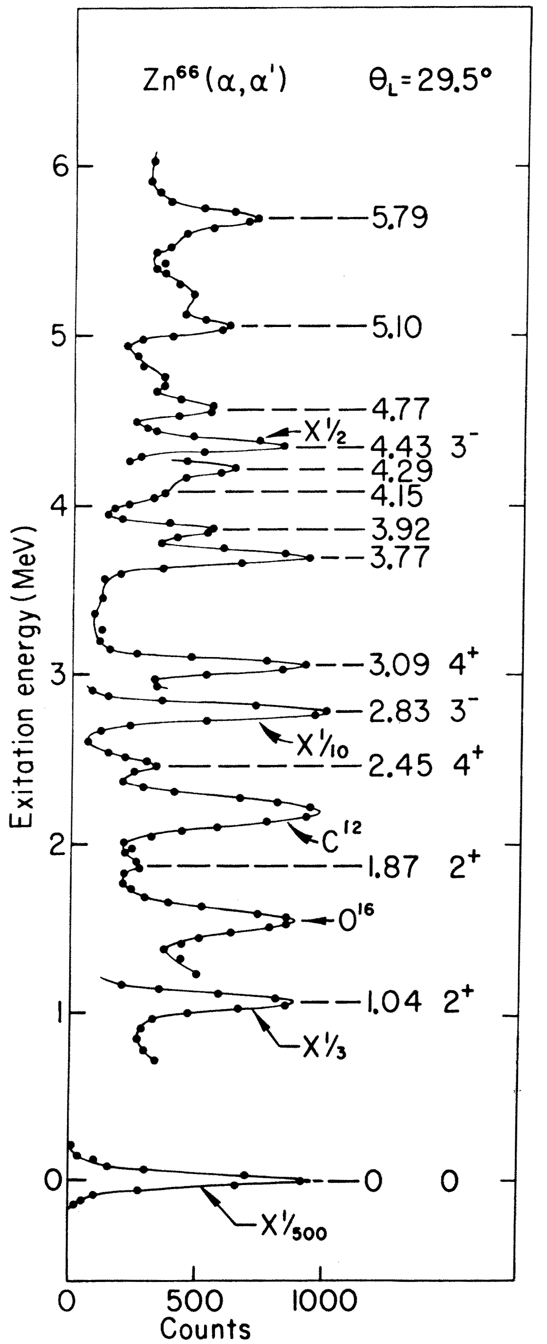

FIG. 2. Spectrum of scattered α particles from Zn^{66}. The solid line merely guides the eye.

Values of $(\beta_l R)^2$, which are proportional to the cross sections, were extracted by normalizing the DWBA calculations to the experimental angular distributions at the forward diffraction peaks. The uncertainties in $(\beta_l R)^2$ depend on the quality of the fit.

IV. EXPERIMENTAL RESULTS

Representative energy spectra for Zn^{64} and Zn^{66} are shown in Fig. 1 and Fig. 2. Figure 3 presents the elastic scattering angular distributions together with the optical-model calculations. The optical-model parameters for Zn^{66} were determined by allowing V, W, R, and a to vary until a best least-squares fit was achieved, whereas for Zn^{64}, a two-parameter search was made, with V and W fixed at the values found in the Zn^{66} search. The resulting parameters are given in the legend to Fig. 3.

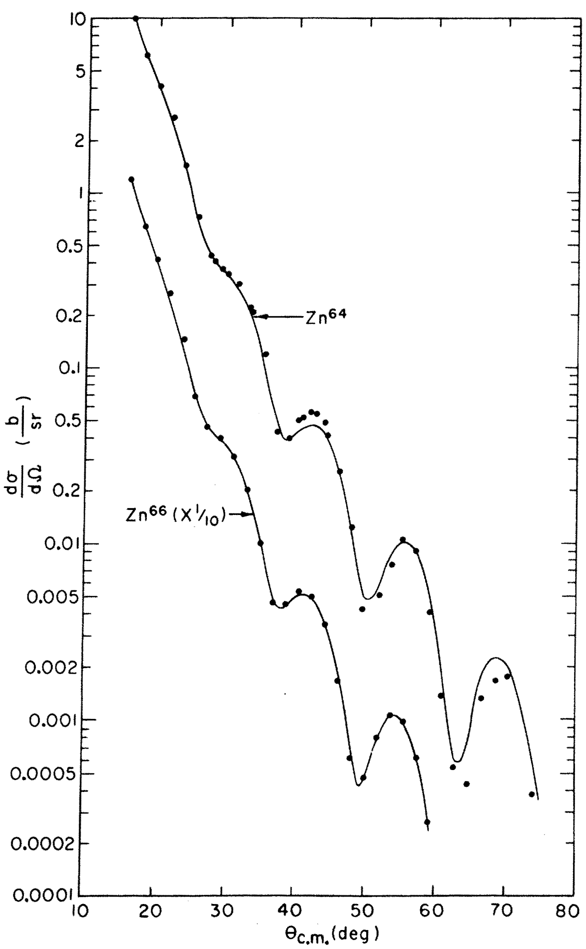

FIG. 3. Elastic scattering cross sections for 31-MeV α particles from Zn^{64} and Zn^{66}. The solid line is the optical-model fit to the data. The Zn^{64} optical-model parameters are $V=45.05$ MeV, $W=11.65$ MeV, $R=6.557$ F and $a=0.551$ F. The Zn^{66} parameters were $V=45.05$ MeV, $W=11.65$ MeV, $R=6.637$ F, and $a=0.562$ F.

The Zn^{64} inelastic angular distributions and DWBA calculations are given in Figs. 4 and 5. The odd-parity states are shown in Fig. 4 and the even-parity states in Fig. 5. The angular distributions and DWBA fits for the odd- and even-parity states in Zn^{66} are given in Figs. 6 and 7. No fit could be obtained for the 1.81- and 2.32-MeV levels in Zn^{64} and the 1.87- and 2.45-MeV levels in Zn^{66}. This point will be discussed later. In our opinion the quality of the DWBA fits is good.

Table I collects the excitation energies, spins, parities, β_l and $(\beta_l R)$ values, and transition strengths for Zn^{64} and Zn^{66}. The uncertainties in the $(\beta_l R)$ values listed in the table were estimated to be about 5%. Two transition values, G_l and $G_l^{(f)}$, are presented in the table. The first transition rate G_l, the quantity usually given in (α, α') experiments, is computed on the basis of a uniform mass distribution and is given, in Weisskopf single-particle units, by the relation

$$G_l = \frac{Z^2}{4\pi} \frac{(l+3)^2}{2l+1} \left(\frac{\beta_l R}{1.2A^{1/3}}\right)^2 .$$

Owen and Satchler have shown that the use of a uni-

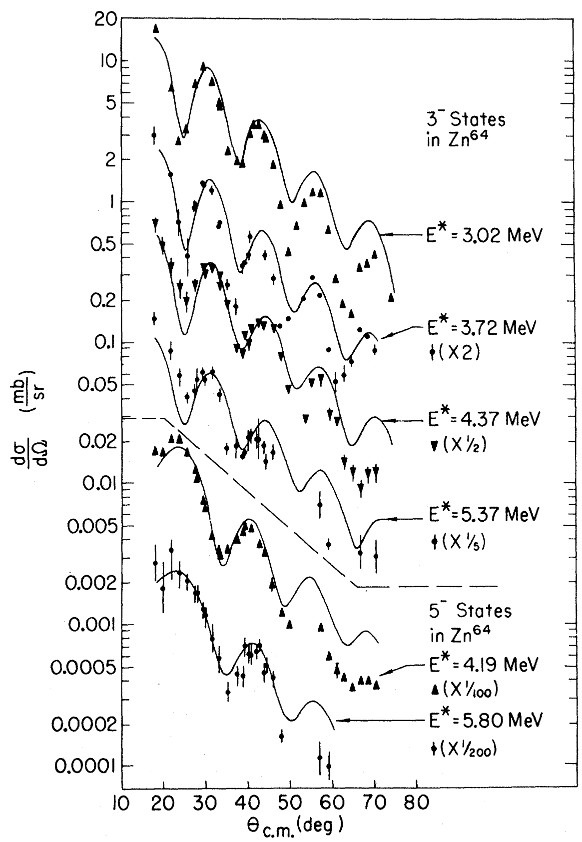

FIG. 4. Differential cross sections for the odd-parity states in Zn^{64}. The solid line is the DWBA calculation.

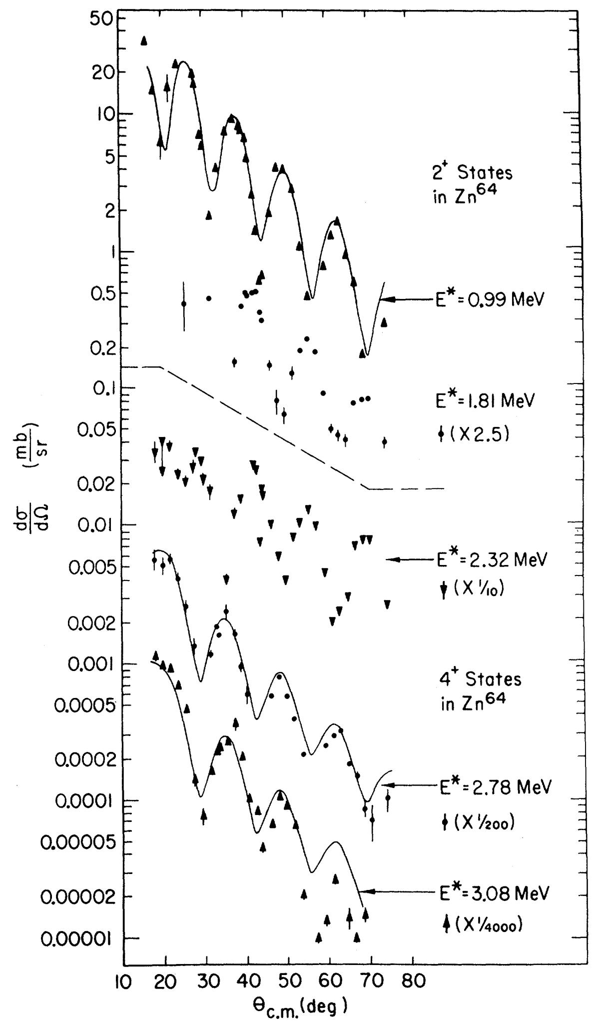

FIG. 5. Differential cross sections for the even-parity states Zn^{64}. The solid lines are the DWBA calculations. States shown without fits are treated separately in the text – Sec. V.

form charge distribution tends to underestimate the transition strength, the error becoming more serious with increasing multipolarity.[17] Hence, the second transition strength, $G_l^{(f)}$, employs a Fermi mass distribution and was computed using the tables of Bernstein,[18] where a more complete discussion of these points is given. It has been standard practice to quote the results of (α, α') experiments in terms of electromagnetic transition rates. We will, however, add the subscript IS for the isoscalar transition operator defined by Bernstein.[18]

Well-defined angular distributions were obtained for levels at 3.95 MeV in Zn^{64} and at 3.77 and 3.92 MeV in Zn^{66}, for which no good DWBA fits could be found. No spin assignments are made for these

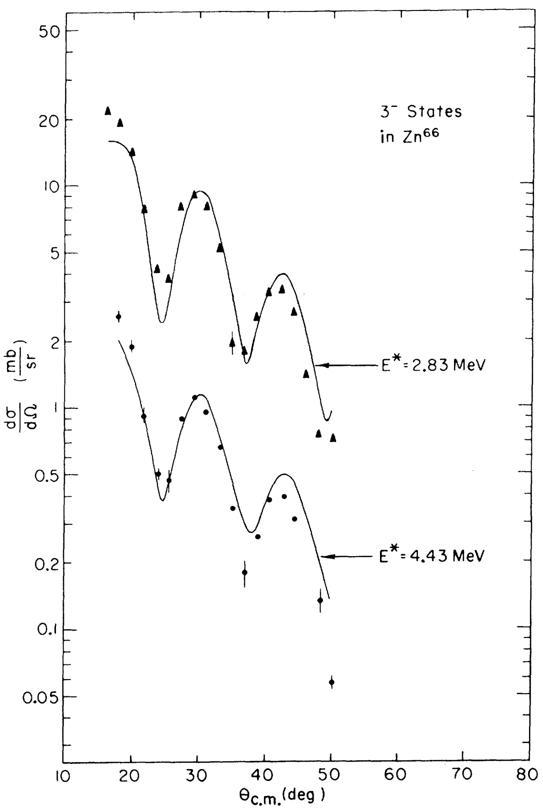

FIG. 6. Differential cross sections for the odd-parity states in Zn^{66}. The solid lines are the DWBA calculations.

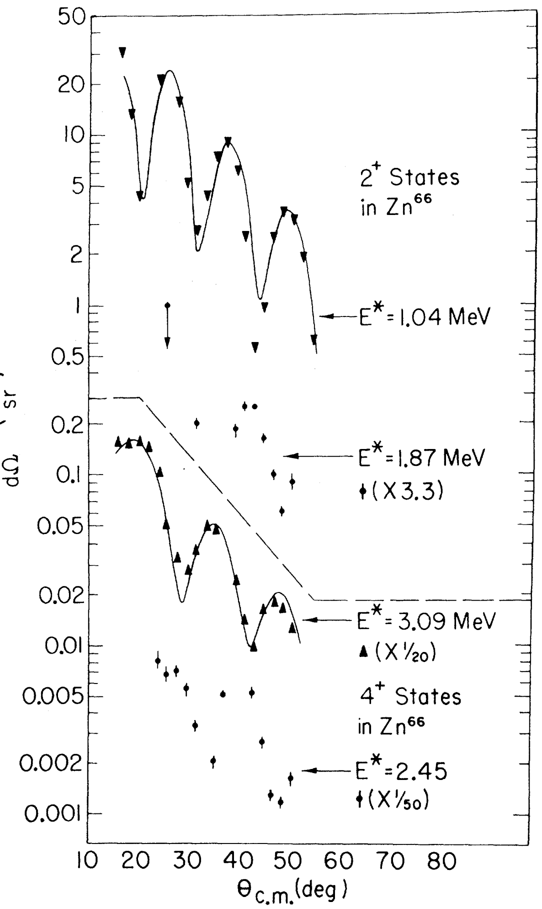

FIG. 7. Differential cross sections for the even-parity states in Zn^{66}. The solid line is the DWBA prediction. The states shown without fits are treated separately in the text – Sec. V.

levels. The angular distribution for the 3.95-MeV level is in phase with those at 2.78- and 3.08-MeV excitation. It is possible that these angular distributions are due to close lying levels which could not be separated with our energy resolution. Some other weak transitions were found for which only fragmentary angular distributions could be obtained. Their excitation energies are included, without spin assignment, in the list of levels in the table.

V. DISCUSSION

In both Zn^{64} and Zn^{66} the first 2^+ and 3^- states are the most strongly excited. Several weaker low-lying levels have also been identified.[11,12] Among the higher-lying states, a possible assignment of $J^\pi = 3^-$ was made to a state at about 4.40 MeV in Zn^{66},[5] whereas for others only very tentative spin assignments were tried. The strong 2^+ and 3^- states in Zn^{64}, mentioned above were found in this experiment at 0.99 (2^+) and 3.02 MeV (3^-), and in Zn^{66} at 1.04 (2^+) and 2.83 MeV (3^-). The DWBA gives good fits to their angular distributions. The $(\beta_2 R)$ and $(\beta_3 R)$ values, listed in the table for these states, are in good agreement with the (α, α') data – at 22[17,19] and 43 MeV,[4,20] and with the results of (p, p') measurements.[2,9] There are several Coulomb-excitation measurements for the first 2^+ states in Zn^{64} and Zn^{66}, for which the $B(E2)$ values differ among each other by as much as a factor of 2.[11,12] For comparison, we computed $B(\mathrm{IS}2)$, using a Fermi mass distribution, by the method given in Ref. 18. Our result for Zn^{64} and Zn^{66} of $(1.7 \pm 0.2) \times 10^{-49}$ cm^4 agrees with Stelson and McGowan's value of 1.7 ± 0.2 for Zn^{64} and 1.5 ± 0.1 for Zn^{66}.[21]

In Zn^{64} the levels at 3.72, 4.37, and 5.37 MeV have angular distributions whose shapes are very similar to that of the strong first 3^- state at 3.02 MeV. The same is true of the 4.43-MeV level in Zn^{66}, which is similar to the 3^- state at 2.83 MeV. Since, in addition to this identity in shape, the DWBA calculation also gives good $l = 3$ fits to these states, we are confident of our 3^- spin assignments. This confirms the tentative assignment to the 4.43-MeV level in Zn^{66} mentioned above.[5]

TABLE I. Transition rates in Zn^{64} and Zn^{66}.

	E^* (MeV)	J^π	β_l	$\beta_l R$	G_l [a]	$G_l^{(f)}$ [b]
Zn^{64}	0.99	2^+	0.19	1.2	24.	26.
	1.81	2^+				
	2.32	4^+				
	2.78	4^+	0.053	0.35	2.0	3.3
	3.02	3^-	0.20	1.3	27.0	35.
	3.08	4^+	0.084	0.55	5.1	3.3
	3.72	3^-	0.057	0.37	2.2	2.8
	3.95					
	4.19	5^-	0.074	0.48	4.3	9.4
	4.37	3^-	0.059	0.39	2.4	3.1
	4.64					
	5.04					
	5.37	3^-	0.044	0.29	1.3	1.7
	5.80	5^-	0.042	0.28	1.4	3.2
Zn^{66}	1.04	2^+	0.19	1.3	24.	26.
	1.87	2^+				
	2.45	4^+				
	2.83	3^-	0.19	1.3	23.	30.
	3.09	4^+	0.075	0.50	4.2	6.8
	3.77					
	3.92					
	4.15					
	4.43	3^-	0.072	0.48	3.6	4.5
	4.54					
	4.77					
	4.91					
	5.10					
	5.37					
	5.50					
	5.69					
	5.79					

[a] G_l is the transition strength in Weisskopf single-particle units.
[b] $G_l^{(f)}$ is discussed in Sec. IV.

New 4^+ and 5^- states are identified on the basis of good DWBA fits. The 5^- states were seen in Zn^{64} at 4.19 and 5.80 MeV. The 4^+ states were found at 2.78 and 3.08 MeV in Zn^{64} and at 3.09 MeV in Zn^{66}. It is worth noting that the 4^+ transition strengths are somewhat higher (approximately 30%) than in most other nuclei.[18] Johnson and Jones[9] assigned a spin of 2^+ to a level at 2.73 MeV in their $Zn^{64}(p, p')$ work. Since our excitation energies are generally about 30 keV higher than theirs, it is likely that this is the same state to which we assign a spin of 4^+. In view of the quality of our DWBA fits, we assign unambiguously $J^\pi = 4^+$ to this state.

From the table we see that the transition strengths to the first 2^+ states in Zn^{64} and Zn^{66} are equal, while the strength of the first 3^- state is somewhat less in Zn^{66} than in Zn^{64}. The sum of the strengths of the higher-lying 3^- states in Zn^{64} is 22% of the first 3^--state strength. This fractionation of strength is smaller than that measured in Zr^{90}, Mo^{92}, and in the calcium isotopes.[14,15] Only two 3^- states were identified in Zn^{66}. The ratio of the transition strengths of the second to the first 3^- state in Zn^{66} is 16%, while the total 3^- strength is 86% of that in Zn^{64}. The fact that fewer higher-lying states were identified in Zn^{66} may be due to its higher level density.

The levels at 1.81 and 2.32 MeV in Zn^{64} and at 1.87 and 2.45 MeV in Zn^{66} were seen in many reaction experiments,[1,12] and their spins and parities are known.[8,11,12] In both nuclei, the lower state has $J^\pi = 2^+$ and the higher state $J^\pi = 4^+$. From previous inelastic α scattering data, most of which covered only a small angular region, these levels were considered to be two-phonon states.[4-6] We extended our measurements over a larger angular range. Our angular distributions for these states are exactly out of phase with the single-excitation 2^+ and 4^+ states (Figs. 5 and 7). This supports the

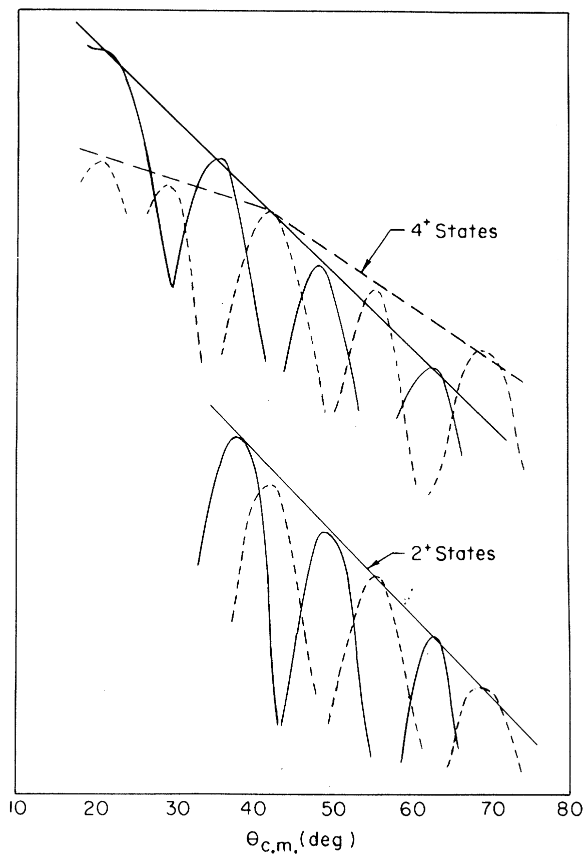

FIG. 8. Comparison of the shapes of the single- and double-excitation states. The solid curve represents the shape of the single-excitation state, while the double-excitation state is shown as a dashed line. The heavy straight lines indicate the slope of the envelopes of the curves.

contention that the excitation is mostly a two-step process.[22] In Fig. 8 we compare the slope of the experimental cross sections for single excitation to those of the double excitation. The envelope of the angular distribution of the 4^+ state at 2.32 MeV in Zn^{64} is shallower than that of the other 4^+ states, which is characteristic for a multiple-step process. However, the slope of the envelope of the 1.81-MeV (2^+) state in Zn^{64} is identical to that of the first 2^+ state. The Zn^{66} data show that the 4^+ state at 2.45 MeV is very similar in shape to the one at 2.32 MeV in Zn^{64}. There are not enough data to determine the slope of the 1.87-MeV (2^+) angular distribution. A comparison of the excitation strengths and double excitation features for all the even Zn nuclei will be reported in a forthcoming paper.[23]

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[1]M. Calderbank, E. J. Burge, V. E. Lewis, and D. A. Smith, Nucl. Phys. A105, 601 (1967).

[2]V. E. Lewis and M. Calderbank, Nucl. Phys. A117, 673 (1968).

[3]E. K. Lin, Nucl. Phys. 73, 613 (1965).

[4]H. W. Broek, T. H. Braids, J. L. Yntema, and B. Zeidman, Nucl. Phys. 38, 305 (1962).

[5]H. W. Broek, Phys. Rev. 130, 1914 (1963).

[6]H. Faraggi and J. Saudinos, Argonne National Laboratory Report No. ANL-6848, 1964 (unpublished), p. 137.

[7]H. L. Wilson and M. B. Sampson, Phys. Rev. 137, 305 (1965).

[8]A. K. Sen Gupta and D. M. Van Patter, Nucl. Phys. 50, 17 (1964).

[9]R. R. Johnson and G. D. Jones, Nucl. Phys. A122, 657 (1968).

[10]A. A. Katsunos and J. R. Huizenga, Phys. Rev. 159, 934 (1967).

[11]H. Verheul, Nucl. Data B2(3), 71 (1967).

[12]S. C. Pancholi and K. Way, Nucl. Data B2(6), 48 (1968).

[13]S. C. Pancholi and K. Way, Nucl. Data B2(6), 97 (1968).

[14]E. P. Lippincott and A. M. Bernstein, Phys. Rev. 163, 1170 (1967).

[15]E. J. Martens and A. M. Bernstein, Nucl. Phys. A117, 241 (1968).

[16]R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. 3240, 1962 (unpublished).

[17]L. W. Owen and G. R. Satchler, Nucl. Phys. 51, 155 (1964).

[18]A. M. Bernstein, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum Press, Inc., New York, 1969), Vol. III.

[19]C. B. Fulmer, J. Benveniste, and A. C. Mitchell, Phys. Rev. 165, 1218 (1968).

[20]The 43-MeV (α, α') data of Ref. 4 were presented without a DWBA analysis. The optical-model parameters for the elastic scattering were given, however, which enabled us to make the relevant DWBA calculations and to extract the ($\beta_l R$) values.

[21]P. H. Stelson and F. K. McGowan, Nucl. Phys. 32, 652 (1962).

[22]R. Johnson and G. Jones have fitted the 4^+ state at 2.32 MeV with a single-excitation DWBA calculation.

[23]N. Alpert, J. Alster, E. J. Martens, and W. Pickles, to be published.