PHYSICAL REVIEW C VOLUME 16, NUMBER 6 DECEMBER 1977

High-spin states in ^{64}Zn[†]

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(Received 22 June 1977)

Levels in ^{64}Zn have been investigated via the ^{51}V(^{16}O,$p2n$) reaction with $E_{^{16}O}=36-46$ MeV, and via the ^{59}Co(^{7}Li,$2n$) reaction with $E_{^{7}Li}=18$ MeV. Measurements were made of γ-ray singles and γ-γ coincidence spectra, of γ-ray angular distributions, and of Doppler broadening of γ-ray lines. Level energies, decay modes, spins and parities, γ-ray branching ratios, γ-ray radiative admixtures, and lifetimes were extracted. Lifetimes of levels were also determined by the Doppler-shift recoil-distance technique. There is a strongly excited band with the highest member observed being a 6^+ state at 3994 keV. There is some evidence for a second even-parity band and for an odd-parity band.

[NUCLEAR REACTIONS ^{51}V(^{16}O,$p2n$) $E=36-46$ MeV; ^{59}Co(^{7}Li,$2n$) $E=18$ MeV; measured $E_\gamma, I_\gamma, \gamma(\theta), \Delta E_\gamma(\tau)$. ^{64}Zn deduced levels, J, π, δ, γ branching, lifetimes.]

I. INTRODUCTION

As part of a program to systematically study higher-spin states of even mass nuclei in the $A\approx 70$ range, we have investigated the γ rays of ^{64}Zn resulting from the heavy-ion reactions ^{51}V(^{16}O,$p2n$) and ^{59}Co(^{7}Li,$2n$). We have obtained energies, decay modes, spins and parities, γ-ray branching ratios and lifetimes of ^{64}Zn levels from γ-ray angular distribution measurements, and Doppler-shift recoil-distance measurements.

High-spin states of ^{64}Zn have also been investigated by Bruandet *et al.*[1] and Neal, Sawa, and Chagnon,[2] who have suggested level schemes and spins and parities. Lifetime measurements of many of the lower-spin states of ^{64}Zn have been made by Charvet *et al.*[3] Investigations of ^{64}Zn level structure have been carried out through (p,t) reactions,[4,5] $(p,p'\gamma)$ reactions,[6] and (p,γ) reaction analog resonance studies.[7] An early report of our present work has been published elsewhere.[8]

II. EXPERIMENTAL PROCEDURE

A target of 1.0-mg/cm^2 ^{51}V on a thick Pt backing and a thick target of ^{51}V were bombarded with ^{16}O ions extracted from the ORNL EN tandem Van de Graaff accelerator. Singles γ-ray spectra were measured for ^{16}O projectile energies between 36 and 46 MeV in 2-MeV steps. Yield curves deduced from these spectra aided in establishing the best projectile energy for optimizing the ^{51}V(^{16}O,$p2n$)^{64}Zn reaction: 46 MeV was the optimum energy, and subsequent measurements were made at this energy.

Coincidence measurements were made with two large volume Ge(Li) detectors placed at 90° and 270° with respect to the beam direction and 5 cm from the target. The angular distributions of the γ rays were measured with a large volume Ge(Li) detector 23 cm from the target and placed at 0, 45, and 90° relative to the incident beam direction. A second Ge(Li) detector was placed at 270° as a monitor. A ^{226}Ra source was placed at the target position to determine the magnitude of the correction for the target not being at the exact center of rotation of the table. As a further check, the angular distributions of the 328.5-keV $2^+\rightarrow 0^+$ γ ray of ^{194}Pt and the 355.8-keV $2^+\rightarrow 0^+$ γ ray of ^{196}Pt produced by Coulomb excitation of the backing were measured. These agreed within experimental error with calculated values.

Singles γ-ray spectra taken at 0° relative to the beam direction were analyzed by the Doppler-shift attenuation method to determine lifetimes of levels in ^{64}Zn. One spectrum was obtained with a thick ^{51}V target, so that the recoil nuclei came to rest in the target. Another spectrum was obtained with a 1.0-mg/cm^2 ^{51}V target with a thick Pt backing, so that the recoil nuclei were slowed partly in V and partly in Pt.

An experiment to measure lifetimes of states was carried out using the Doppler-shift recoil-distance apparatus described in Ref. 9. The apparatus consists of two coaxial cylinders: one attached to the beam line and terminated in a conical projection over which a 0.95-mg/cm^2 vanadium foil was stretched, and a second having a copper end plate (the stopper) coated with about 40 μm of Pb. The second cylinder slides on the first to vary the relative target-stopper separation which can be measured with a Boeckler micrometer to a precision of about 1 μm. The movable stopper was set at distances of 56 to 1270 μm from the target. The γ rays were detected by a large Ge(Li) detector placed at 0° relative to the beam direction.

A target of 25-mg/cm^2 ^{59}Co on a 0.013-cm Ni backing was bombarded with 18-MeV ^{7}Li ions to produce ^{64}Zn by the ^{59}Co(^{7}Li, 2n)^{64}Zn reaction. Angular distribution and lifetime measurements for this reaction were made in the same way as for the ^{51}V(^{16}O, $p2n$) reaction.

III. RESULTS

A. Level scheme

Representative singles γ-ray spectra are shown in Figs. 1 and 2 for the ^{51}V(^{16}O, $p2n$) reaction and the ^{59}Co(^{7}Li, 2n) reaction, respectively. The results of γ-γ coincidence measurements were used to identify those γ rays belonging to ^{64}Zn and to construct a level scheme, which is shown in Fig. 3. The γ-ray energies were calibrated with a ^{226}Ra standard source, and the estimated error on the energies is ±0.4 keV. Relative γ-ray intensities obtained from the singles spectra were used to establish the order of the cascades. Those for the ^{51}V(^{16}O, $p2n$) reaction at $E_{^{16}\text{O}} = 46$ MeV are shown in parentheses in this figure.

B. Lifetime measurements

The mean lifetimes of a number of states in ^{64}Zn were measured by the Doppler-shift attenuation method following the ^{51}V(^{16}O, $p2n$)^{64}Zn and ^{59}Co(^{7}Li, 2n)^{64}Zn reactions. This method, described in the review article by Schwarzchild and Warburton,[10] is based on the fact that γ rays emitted by a recoiling nucleus will be Doppler shifted with respect to γ rays emitted by a nucleus which has come to rest. As the recoil nucleus is slowed in the target or backing, γ rays will be emitted with a range of Doppler-shifted energies, and the shape of the γ-ray photopeak will depend, among other things, on the lifetime of the state.

The computer code DOPCO[11] was used to calculate a Doppler broadened photopeak, with inputs being the projectile mass and energy, the mass of the recoil nucleus, the Q value of the reaction, the reaction cross section as a function of bombarding energy, the stopping power of the recoil nucleus in the stopping medium, and the detector angle and dimensions. A correction for feeding

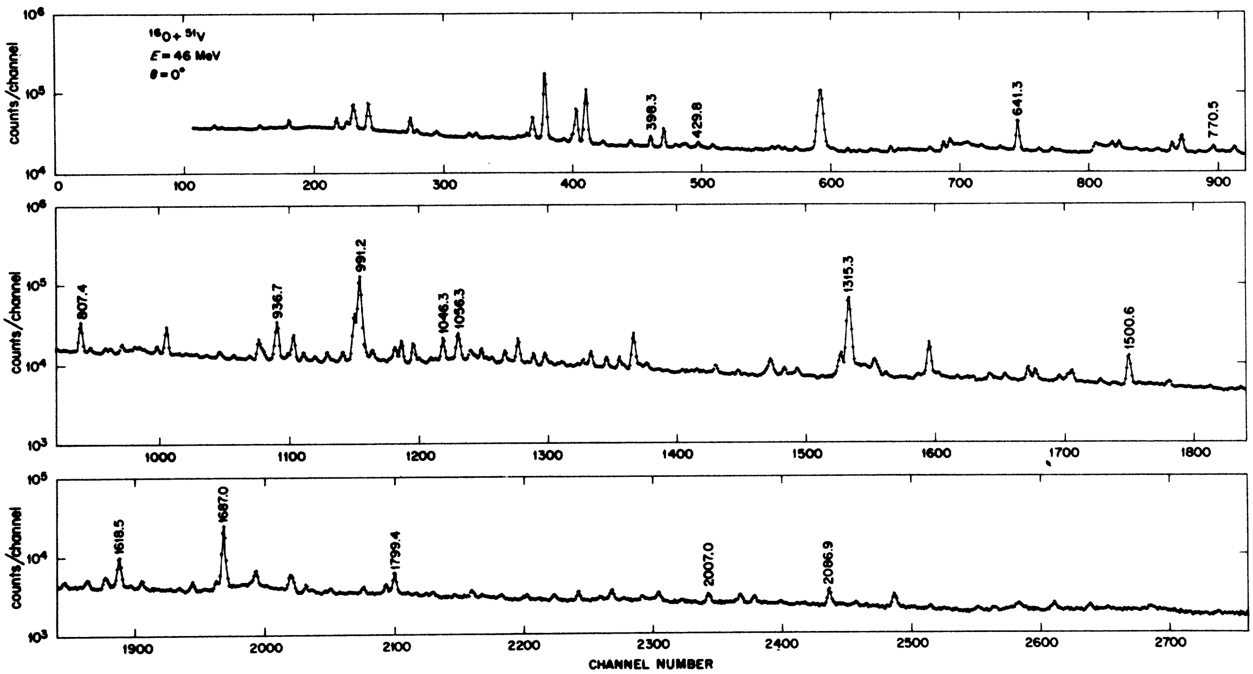

FIG. 1. Singles γ-ray spectrum resulting from bombardment of a ^{51}V target with 46-MeV ^{16}O ions. Only peaks assigned to ^{64}Zn are marked.

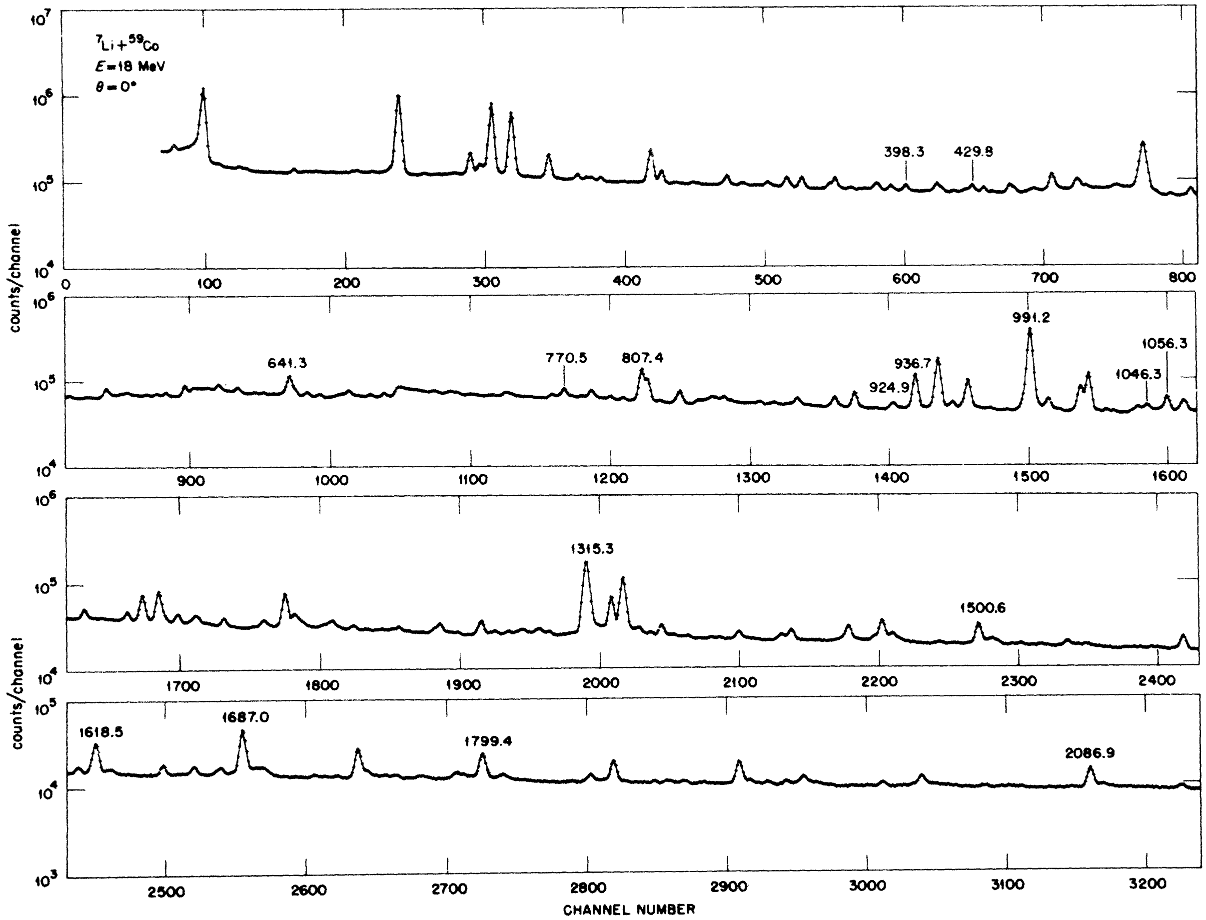

FIG. 2. Singles γ-ray spectrum resulting from bombardment of a ^{59}Co target with 18-MeV ^{7}Li ions. Only peaks assigned to ^{64}Zn are marked.

from higher levels was included when their lifetimes were known. This correction was made for all of the γ-ray transitions shown in Fig. 3 except the 924.9- and the 1618.5-keV transitions, so all the levels except those at 2999.0 and 2306.6 keV were corrected for feeding. It is possible, of course, that there was other feeding via transitions which were not observed. The stopping power of the recoil nucleus in the stopping medium was calculated using the results of Brown and Moak.[12]

For each γ ray, the photopeak shape was calculated for a series of mean lives, and these shapes were compared with the experimental peak shape. For the comparison, each calculated peak was normalized to have the same area as the experimental peak with its background subtracted. An example of an experimental photopeak and three calculated peaks is shown in Fig. 4. That the calculations show more of a dip between the shifted and unshifted parts of the peak than do the experimental data is thought to be due to the fact that DOPCO does not include changes in direction due to multiple scattering by the recoil nuclei as they slow down.

The mean life was found to be very sensitive to the amount of long-lived feeding from higher levels and also to the way in which the background under the experimental peak was chosen. The errors shown on the lifetime measurements in Table I include contributions from these effects, as well as estimates of how well the experimental photopeak was fitted.

A second method, the Doppler-shift recoil-distance technique,[9,10,13] was also used to measure the lifetimes of several states. The projectile beam impinged on a target thin enough to permit the residual nuclei to recoil freely into a vacuum, with a component of velocity v along the beam direction. By placing a metal stopper at a distance D from the target, the excited nuclei decaying in flight (i.e., in a time $t<D/v$) would emit Doppler-shifted γ rays, while the excited nuclei decaying

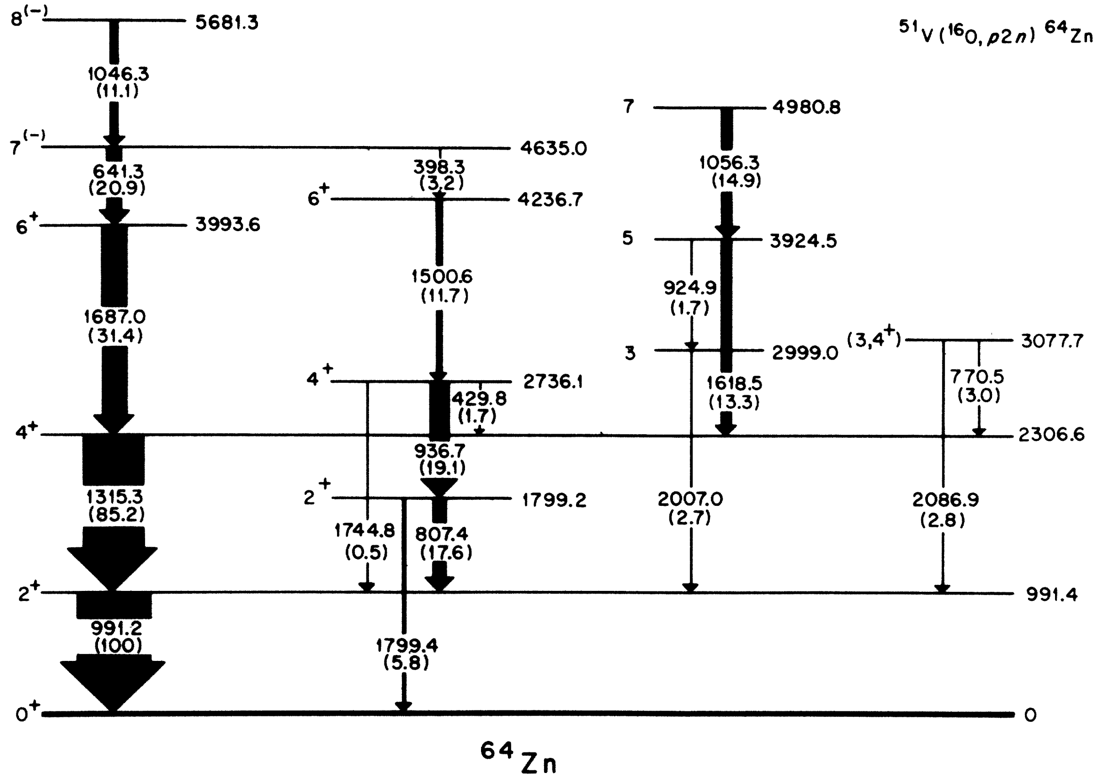

FIG. 3. Levels and transitions of ^{64}Zn. γ-ray energies were calibrated with a ^{226}Ra standard source, and the estimated error on the energies is ±0.4 keV. The number in parentheses with each γ ray gives its relative intensity for bombardment of ^{51}V with 46-MeV ^{16}O ions. The approximate uncertainty is ±6% for relative intensities greater than 20, ±15% for intensities between 5 and 20, and ±30% for intensities less than 5. The basis for the spin-parity assignments is discussed in Sec. III D.

after being stopped (i.e., in a time $t > D/v$) would emit unshifted γ rays. The γ rays at $\theta = 0°$ from nuclei which decay in flight have energies given by

$$E = E_0[1 + (v/c)] \tag{1}$$

while those decaying at rest have energy E_0. The intensities of the Doppler-shifted peak I_s and the unshifted peak I_0 are given by

$$\begin{aligned} I_s &= N[1 - \exp(-D/v\tau)], \\ I_0 &= N \exp(-D/v\tau), \end{aligned} \tag{2}$$

where N is the total number of reaction-produced γ rays and τ is the mean life of the initial state.

Therefore, a measurement of the ratio

$$R = I_0/(I_0 + I_s) = \exp(-D/v\tau) \tag{3}$$

as a function of D gives the mean life, as v can be determined from the γ-ray spectrum using Eq. (1).

A number of corrections, which have been described in the literature,[9,13] were applied to this zero-order description. These include the effects of velocity and distance distributions for the recoiling ions, feeding from higher-lying levels when the lifetimes are known, attenuation of the γ-ray angular distribution, relativistic solid-angle effects, variation of detector efficiency with energy, and effects of finite detector solid-angle and finite extension of the source.

The recoil velocity imparted to the ^{64}Zn nuclei was determined to be $v/c = 0.012 \pm 0.001$ from the difference in energies of the shifted and unshifted peaks. The computer code FILIP2[14] was used to compute the ratio $R = I_0/(I_0 + I_s)$ for each stopper distance, to apply the corrections mentioned above, and to perform a least-squares fit to Eq. (3) to determine the mean lifetime τ. The result of such a fit for the 641.3-keV γ ray is shown in Fig. 5.

The lifetimes of the 398.3- and 641.3-keV γ rays were determined by this method. The uncertainties given in Table I for the lifetimes of these γ rays include contributions from the corrections to the zero-order theory as well as contributions from uncertainties in I_0 and I_s.

Our lifetime results are given in Table I. We find good agreement with the results of Charvet *et al.*[3] and Bruandet *et al.*[1]

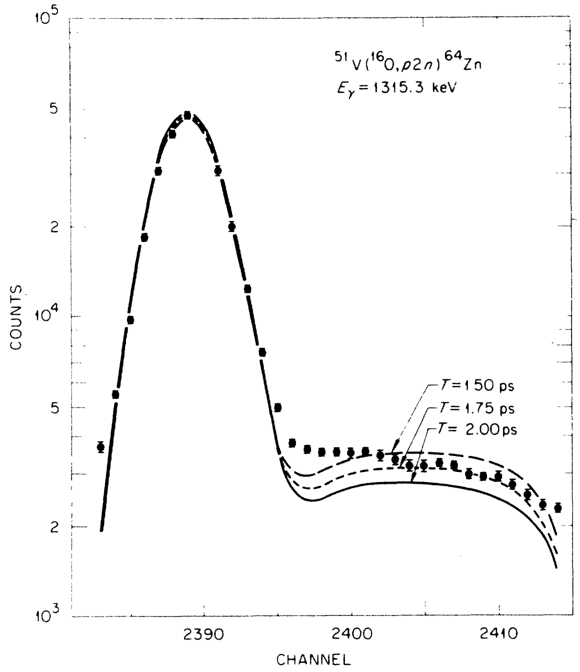

FIG. 4. The Doppler-broadened 1315.3-keV γ-ray peak observed at 0° to the ^{16}O beam in the ^{51}V(^{16}O,$p2n$)^{64}Zn reaction at $E_{^{16}O} = 46$ MeV. Theoretical curves for three different mean lives are shown.

C. Angular distributions

The angular distribution coefficients $A_2 = a_2/a_0$ and $A_4 = a_4/a_0$ were extracted from the equation

$$W(\theta) = a_0 + a_2 g_2 P_2(\cos\theta) + a_4 g_4 P_4(\cos\theta), \qquad (4)$$

where the corrections for the finite solid angle subtended by the Ge(Li) detector were calculated to be $g_2 = 0.99$ and $g_4 = 0.97$, and $W(\theta)$ is the normalized γ-ray intensity at angle θ with respect to the beam direction. The angular distribution results obtained from both reactions are summarized in Table II. In several instances, the γ-ray peak in the spectrum from one of the reactions contained an impurity γ ray, and its angular distribution could not be obtained from that reaction.

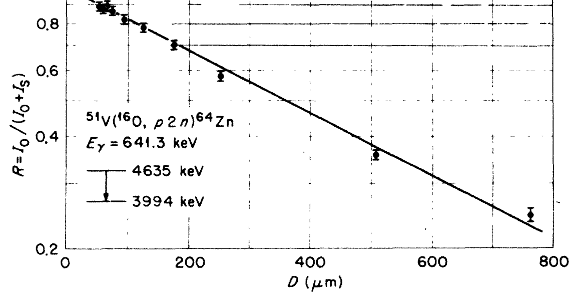

FIG. 5. The ratio of the unshifted to the sum of the unshifted plus shifted γ-ray intensities as a function of target-stopper separation for the 641.3-keV transition in ^{64}Zn.

TABLE I. Mean lifetimes of γ rays from ^{64}Zn. Lifetimes of the 398.3- and 641.3-keV γ rays were determined by the recoil-distance method. Those of the other γ rays were determined by the Doppler-shift attenuation method.

Level (keV)	E_γ (keV)	This work τ (ps)	Other work τ (ps)
1799.2	807.4	3 ±2	$2.6^{+0.8}_{-0.5}$ [a]
	1799.4	3 ±2	$2.6^{+0.8}_{-0.5}$ [a]
2306.6	1315.3	1.4 ±0.8	$0.63^{+0.14}_{-0.10}$ [a]
2736.1	429.8	5 ±3	
	936.7	2.5 ±1.0	$3.0^{+1.2}_{-0.7}$ [a]
2999.0	2007.0	0.11±0.05	
3077.7	770.5	1.4 ±0.4	$2.0^{+1.5}_{-0.8}$ [a]
	2086.9	1.5 ±0.5	$2.5^{+1.4}_{-0.8}$ [a]
3924.5	924.9	< 2.5	
3993.6	1687.0	0.22±0.05	
4236.7	1500.6	1.8 ±0.3	
4635.0	398.3	152 ±19	
	641.3	143 ±14	130±15 [b]
4980.8	1056.3	1.9 ±0.6	
5681.3	1046.3	1.4 ±0.3	

[a] Reference 3. [b] Reference 1.

The dependence of the theoretical angular distribution coefficients on the physical parameters is given by Yamazaki[15] as

$$a_k = \alpha_k(J_i)B_k(J_i)[F_k(J_f L_1 L_1 J_i) + 2\delta F_k(J_f L_1 L_2 J_i) + \delta^2 F_k(J_f L_2 L_2 J_i)], \qquad (5)$$

where $\delta = \langle J_f \| L_2 \| J_i\rangle / \langle J_f \| L_1 \| J_i\rangle$ is the multipole mixing ratio defined for emission radiation in the phase convention of Biedenharn and Rose,[16] and where $L_2 = L_1 + 1$. $B_k(J_i)$ is the coefficient for a system of nuclei completely aligned in a plane perpendicular to the beam direction, and $\alpha_k(J_i)$ is the attenuation of the alignment. The assumption is made that the population of magnetic substates of the radiating level can be described by a Gaussian function involving only one parameter, so $\alpha_4(J_i)$ is uniquely related to $\alpha_2(J_i)$.

For possible values of the initial and final spins, this parameter $\alpha_2(J_i)$ and the multipole mixing ratio δ were changed in steps, and a goodness-of-fit index χ^2 was calculated at each step, where

$$\chi^2 = [A_{2\,\mathrm{exp}} - A_{2\,\mathrm{cal}}(J,\delta,\alpha)]^2/\epsilon_{A_2}^{\,2} + [A_{4\,\mathrm{exp}} - A_{4\,\mathrm{cal}}(J,\delta,\alpha)]^2/\epsilon_{A_4}^{\,2} \qquad (6)$$

TABLE II. Angular distribution results from the ^{51}V(^{16}O,$p2n$)^{64}Zn reaction with $E_{^{16}\mathrm{O}} = 46$ MeV, and from the ^{59}Co(^{7}Li,$2n$)^{64}Zn reaction with $E_{^{7}\mathrm{Li}} = 18$ MeV.

	^{51}V(^{16}O,$p2n$)^{64}Zn reaction		^{59}Co(^{7}Li,$2n$)^{64}Zn reaction	
E_γ (keV)	A_2	A_4	A_2	A_4
398.3	−0.27 ± 0.07	−0.07 ± 0.04	−0.24 ± 0.08	0.05 ± 0.06
429.8	0.14 ± 0.07	−0.09 ± 0.11		
641.3	−0.29 ± 0.04	0.04 ± 0.02		
770.5	−0.12 ± 0.08	0.01 ± 0.08	0.00 ± 0.04	−0.01 ± 0.04
807.4	−0.15 ± 0.02	−0.00 ± 0.02		
924.9			0.05 ± 0.10	−0.02 ± 0.10
936.7	0.18 ± 0.04	−0.02 ± 0.02	0.13 ± 0.02	0.00 ± 0.02
991.2	0.17 ± 0.02	−0.01 ± 0.02	0.14 ± 0.02	−0.01 ± 0.02
1046.3	0.11 ± 0.05	0.10 ± 0.04		
1056.3	0.27 ± 0.05	−0.02 ± 0.04	0.28 ± 0.02	−0.05 ± 0.02
1315.3	0.30 ± 0.02	−0.06 ± 0.02		
1500.6	0.34 ± 0.08	−0.14 ± 0.08	0.25 ± 0.05	−0.04 ± 0.03
1618.5	−0.25 ± 0.09	0.16 ± 0.06		
1687.0	0.23 ± 0.04	−0.07 ± 0.02	0.25 ± 0.03	−0.05 ± 0.02
1799.4	0.20 ± 0.08	−0.01 ± 0.05	0.12 ± 0.03	−0.03 ± 0.03
2007.0	−0.06 ± 0.10	−0.20 ± 0.10	0.05 ± 0.10	−0.09 ± 0.10
2086.7	0.22 ± 0.08	0.05 ± 0.08	0.21 ± 0.08	−0.04 ± 0.08

and ϵ_{A_k} is the uncertainty in A_k. A value of χ^2 exceeding the 1% level was taken to exclude that combination of parameters.

D. Spin-parity assignments

The preferred spin assignments are given in Fig. 3 and in Table III. These are in agreement with the spin assignments of Bruandet *et al.*[1] and Neal *et al.*[2] The basis for these is discussed below. It is assumed that the transitions observed have *E*1, *M*1, or *E*2 multipolarity. When two or more values of spin of a level were consistent with the angular distribution of the deexciting γ ray, the slope of the excitation function of that γ ray was used as supplementary information. This technique has been discussed, for example, by Taras and Haas.[17] One would expect the population of the higher-spin states to increase more rapidly than the population of the lower-spin states with projectile energy. In

TABLE III. Properties of the energy levels of ^{64}Zn.

Level (keV)	J^π	τ (ps)	E_γ (keV)	Branching ratio	δ	$\frac{\lambda}{\lambda_{\mathrm{s.p.}}}$	
1799.2	2⁺	3 ± 2	807.4	75 ± 5	−5.5 ± 4.0 or −0.8 ± 0.3		
			1799.4	25 ± 5	∞	0.22	(*E*2)
2306.6	4⁺	1.4 ± 0.8	1315.3	100	∞	9	(*E*2)
2736.1	4⁺	2.5 ± 1.0	429.8	9 ± 3	1.7 ± 0.5 or −0.2 ± 0.3		
			936.7	88 ± 3	∞	25	(*E*2)
			1744.8	2.3 ± 0.5	∞	0.03	(*E*2)
2999.0	3	0.11 ± 0.05	2007.0	100	0.03 ± 0.11 or −5 ± 2		
3077.7	(3, 4⁺)	1.4 ± 0.4	770.5	51 ± 5			
			2086.9	49 ± 5			
3924.5	5	< 2.5	924.9	14 ± 4	∞	> 4	(*E*2)
			1618.5	86 ± 4	−5.4 ± 0.7		
3993.6	6⁺	0.22 ± 0.05	1687.0	100	∞	17	(*E*2)
4236.7	6⁺	1.8 ± 0.3	1500.6	100	∞	3.9	(*E*2)
4635.0	$7^{(-)}$	145 ± 13	398.3	13 ± 2	−0.3 ± 0.3	0.8×10^{-5}	(*E*1)
			641.3	87 ± 2	−0.2 ± 0.3	1.4×10^{-5}	(*E*1)
4980.8	7	1.9 ± 0.6	1056.3	100	∞	21	
5681.3	$8^{(-)}$	1.4 ± 0.3	1046.3	100	7.5 ± 1.5	29	(*E*2)
						4×10^{-4}	(*M*1)

TABLE IV. Ratios of γ-ray intensities at $E_{^{16}O} = 46$ MeV to those at $E_{^{16}O} = 38$ MeV.

E_γ (keV)	J_i	$\frac{I_\gamma(46\text{ MeV})}{I_\gamma(38\text{ MeV})}$
1799.4	2	0.69 ± 0.09
807.4	2	0.81 ± 0.06
991.2	2	1.00
770.5	(3,4)	0.92 ± 0.12
936.7	4	0.96 ± 0.07
1315.3	4	1.61 ± 0.12
1618.5	5	1.84 ± 0.18
1500.6	6	1.47 ± 0.14
1687.0	6	2.26 ± 0.19
398.3	7	2.5 ± 0.4
1056.3	7	2.7 ± 0.5
641.3	7	3.2 ± 0.3
1046.3	8	12^{+17}_{-5}

Table IV is shown, for each γ ray, the ratio of the population at $E_{^{16}O} = 46$ MeV to that at $E_{^{16}O} = 38$ MeV. These ratios are average values of the slopes of the excitation functions. The general trend is an increase in the ratio with increasing spin. This supports our spin assignments.

Previous studies by Sen Gupta and van Patter[6] and by Konijan *et al.*[18] have established the spin and parity of the 991.4-keV level as 2^+, and that of the 1799.2-keV level also as 2^+. Our angular distribution results for 991.2-, 807.4-, and 1799.4-keV γ rays are consistent with these assignments.

The angular distribution of the 1315.3-keV γ ray establishes the spin of the 2306.6-keV level as 2 or 4. From its intensity ratio in Table IV, $J = 4$ is selected. From its lifetime in Table I, we calculate $\lambda/\lambda_{\text{s.p.}}(E2) = 9$ and $\lambda/\lambda_{\text{s.p.}}(M2) = 140$, where λ is the transition probability obtained from the measured lifetime, and $\lambda_{\text{s.p.}}(E2)$ and $\lambda_{\text{s.p.}}(M2)$ are the Weisskopf single-particle transition probability estimates[19] calculated with $r_0 = 1.2 \times 10^{-13}$ cm. This strongly suggests that the transition is $E2$ and the parity of the level is positive.

The angular distribution of the 1687.0-keV γ ray establishes the spin of the 3993.6-keV level as 4 or 6. From its intensity ratio, $J = 6$ is selected. From its lifetime, we calculate $\lambda/\lambda_{\text{s.p.}}(E2) = 17$ and $\lambda/\lambda_{\text{s.p.}}(M2) = 250$. This strongly suggests that the transition is $E2$ and the parity of the level is positive.

The angular distribution of the 641.3-keV γ ray establishes the spin of the 4635.0-keV level as 5 or 7. From its intensity ratio, $J = 7$ is selected.

The angular distribution of the 398.3-keV γ ray establishes the spin of the 4236.7-keV level as 6, 7, or 8. Since the 1500.6-keV γ ray and the 936.7-keV γ ray form a cascade to the 2^+ 1799.2-keV level, this indicates that the spin of the 2736.1-keV level is 4 and that of the 4236.7-keV level is 6.

From the lifetime results we calculate for the 936.7-keV γ ray $\lambda/\lambda_{\text{s.p.}}(E2) = 25$ and $\lambda/\lambda_{\text{s.p.}}(M2) = 370$, and for the 1500.6-keV γ ray, $\lambda/\lambda_{\text{s.p.}}(E2) = 3.9$ and $\lambda/\lambda_{\text{s.p.}}(M2) = 56$. This suggests that these transitions are $E2$ and that the parities of the 2736.1- and 4236.7-keV levels are positive.

The angular distribution of the 1046.3-keV γ ray establishes the spin of the 5681.3-keV level as 6 or 8. From its intensity ratio, $J = 8$ is selected. This level is assigned negative parity since no transition is observed to either the 6^+ 3993.6-keV level or to the 6^+ 4236.7-keV level. Since the 1046.3-keV transition has a value of $\delta = 7.5 \pm 1.5$, we suggest that it is an $E2$ transition and the parity of the 4635.0-keV level is negative.

The angular distribution of the 1618.5-keV γ ray establishes the spin of the 3924.5-keV level as 3 or 5. From its intensity ratio, $J = 5$ is selected.

The angular distribution of the 1056.3-keV γ ray establishes the spin of the 4980.8-keV level as 5 or 7. From its intensity ratio, $J = 7$ is selected.

The angular distribution of the 2007.0-keV γ ray is consistent with $J = 1$, 2, or 3 spin assignments for the 2999.0-keV level. The decay of the 3924.5-keV level to the 2999.0-keV level favors the $J = 3$ spin assignment.

The nuclei ^{66}Zn, ^{68}Ge, and ^{70}Ge (Refs. 20, 21, and 22) have 3^- states, typical of octupole vibrational states, at 2826, 2649, and 2563 keV, respectively. On this basis alone, we would tentatively assign our $J = 3$ state at 2999.0 keV odd parity. Bruandet *et al.*[1] and Neal *et al.*[2] identify this state as 3^-. Fodor *et al.*[7] report a 3^- state at 3002 keV from ^{63}Cu(p,γ) reaction analog resonance studies. This would imply that the $J = 5$ state at 3924.5 keV and the $J = 7$ state at 4980.8 keV also have odd parity. We find, however, that the 1618.5-keV transition has a value of $\delta = -5.4 \pm 0.7$, which would indicate an $E2$ transition. This would give the state at 3924.5 keV even parity. We do not understand this discrepancy, and so do not assign parities to these states.

The angular distribution of the 770.5-keV γ ray is consistent with a spin of 3, 4, or 5 for the 3077.7-keV level, and the angular distribution of the 2086.9-keV γ ray is consistent with a spin of 1, 2, 3, or 4 for this level. Together, these and the decay mode give $J = 3$, 4^+ for the 3077.7-keV level.

IV. DISCUSSION

In Table III we have summarized the level properties of ^{64}Zn. This table gives, for each level, the level energy, the spin and parity, the mean lifetime τ, the γ rays depopulating the level and their branching ratios, the multipole mixing ratio

TABLE V. Comparison of experimental and calculated $B(E2)$ values for several transitions in ^{64}Zn.

E_i (keV)	E_f (keV)	$B(E2)_{\mathrm{exp}}$ (e^2 fm^4)	$B(E2)_{\mathrm{cal}}$ [a] (e^2 fm^4)
1799.2	0	4^{+8}_{-2}	2.9 ± 1.7
2306.6	991.4	150^{+200}_{-50}	390 ± 60
2736.1	991.4	$0.5^{+0.3}_{-0.1}$	0.14 ± 0.02
2736.1	1799.2	400^{+260}_{-110}	38 ± 6
3993.6	2306.6	270^{+80}_{-50}	360 ± 60
3993.6	2736.1	< 10	18 ± 3

[a] Reference 24.

δ, and the ratio of the measured transition rate to the single-particle transition rate.

The ground-state band is observed through the 6^+ level. The $E2$ enhancements over the single-particle values are $\lambda/\lambda_{\mathrm{s.p.}} = 17$, 9, and 20 (from Ref. 3) for the 1687.0-, 1315.3-, and 991.2-keV cascade γ rays. The 4236.7-, 2736.1-, and 1799.2-keV levels may be the 6^+, 4^+, and 2^+ members of a second band. The enhancements of the $E2$ transition probabilities are $\lambda/\lambda_{\mathrm{s.p.}} = 4$ and 25 for the 1500.6- and 936.7-keV γ rays. The dissimilarity of the nucleus in this band and in the ground-state band is indicated by a lack of transitions between members of the two bands. One interband transition observed, the 1744.8-keV γ ray, has the small $E2$ transition probability $\lambda/\lambda_{\mathrm{s.p.}} = 0.03$. Transitions from the 6^+ 3993.6-keV level to the 4^+ 2736.1-keV level and from the 6^+ 4236.7-keV level to the 4^+ 2306.6-keV level were not observed. From limits on their intensities we find $\lambda/\lambda_{\mathrm{s.p.}}(E2) < 0.6$ for the former and < 0.02 for the latter. Second 2^+ and 4^+ levels are found in ^{62}Zn and ^{66}Zn (Refs. 23 and 20) but a second 6^+ level is not reported.

Recent shell-model calculations for ^{64}Zn have been made by van Hienen, Chung, and Wildenthal.[24] They treated Zn nuclei as a ^{56}Ni core with active particles in the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbitals. In Table V is a comparison of their calculated $B(E2)$ values for several transitions in these two even-parity bands with $B(E2)$ values deduced from our experimental lifetime measurements. Except for the 2736.1- to 1799.2-keV transition, the experimental and calculated transition probabilities are in agreement within experimental errors. While the large $E2$ enhancements may be taken as evidence supporting a collective nature of these bands, they are, in fact, well reproduced by these restricted shell-model calculations.

If the 2999.0-keV level is a 3^- state, the level spacing and $E2$ enhancements of the 1056.3- and 924.9-keV γ rays ($\lambda/\lambda_{\mathrm{s.p.}} = 21$ and >4, respectively) suggest that the 4980.8-, 3924.5-, and 2999.0-keV levels may be members of an odd-parity collective band. This would be similar to the band reported in ^{74}Se (Ref. 25). The energies of the 3924.5- and 4980.8-keV levels are similar to those of 5^- and 7^- levels in ^{66,68}Zn and ^{68,70}Ge (Refs. 20, 26, 21, and 22, respectively). However, there is a difference. In each of these nuclei a 6^- state is observed between the 5^- and 7^- states. Possibly in ^{64}Zn a 6^- state is very close in energy to the 4980.8-keV level, and is therefore populated very weakly.

The $E2$ enhancement of the 1046.3-keV γ ray, $\lambda/\lambda_{\mathrm{s.p.}} = 29$, suggests that the $8^{(-)}$ 5681.3-keV level may be a member of a collective band with the $7^{(-)}$ 4635.0-keV level as the bandhead.

It is interesting to note the long lifetime (145 ps) of the $7^{(-)}$ 4635.0-keV level. This level is de-excited by two $E1$ transitions, each of which is retarded by $\sim 10^5$ with respect to the single-particle estimates. A possible explanation is that this state consists of a $g_{9/2}$ proton and an $f_{5/2}$ proton totally aligned to give a 7^- state. Thus, a transition from the 4635.0-keV level to either of the even-parity bands would require a single quasiparticle transition from the $g_{9/2}$ orbital to a p or $f_{5/2}$ orbital. The change of 2 or greater in the total angular momentum of the quasiparticle would be expected to give a highly retarded $E1$ transition as observed. It should be noted that this discussion depends on the negative parity assignment to the 4635.0-keV level. This assignment is somewhat tenuous as it depends on nonobservation of γ-ray transitions. The long lifetime of this state may equally well be taken as evidence for a 7^+ assignment, in which case the $M1$ retardations are normal.

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†Research supported by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation.

*Supported in part by Oak Ridge National Laboratory as a consultant.

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