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$E2$-$M1$ Admixtures of Transitions in ^{68}Zn

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Directional correlations were carried out with a NaI-Ge(Li) detector arrangement on three $2^+ \rightarrow 2^+$ cascades in ^{68}Zn. The data yield the following δ values: −1.46(14), −0.14(4), and +0.29(5) for the 806-, 1261-, and 1745-keV transitions to the first excited 2^+ level. The first two results confirm recent values from (n, γ) work but not the earlier ones from radioactivity studies. A new 2822-keV transition was observed from a level at that energy.

INTRODUCTION

Information on $E2$-$M1$ admixtures is particularly useful in establishing the character of excited nuclear states as indicated by a recent survey.[1] For example, the very large (typically >99%) $E2$ strengths of the transitions from the 2^+ member of the γ-vibrational band to the 2^+ first excited state were important in helping establish the quadrupole vibrational character of the states in deformed nuclei. In more spherical nuclei, the $E2$ admixtures in transitions from the $2'^+$ and higher excited 2^+ states to the lower 2^+ states have been useful in identifying whether these states are candidates for two- and three-phonon quadrupole vibrational states. In the decay of ^{68}Ga to ^{68}Zn, four excited 2^+ states are observed.[2] The $E2/M1$ mixing ratios for transitions to the first 2^+ level from the second 2^+ level, which occurs in the two-phonon range, and the third 2^+ level have been measured by γ-$\gamma(\theta)$ techniques following radioactive decay[3-5] and following neutron capture.[6] For the $2'^+ \rightarrow 2^+$ transition the δ values obtained by the two techniques differ over a factor of 2 in magnitude, as well as in sign, and for the $2''^+ \rightarrow 2^+$ transition the δ values differ a factor of 10 to indicate predominantly $E2$ in one case and predominantly $M1$ in the other. To clarify this question of the magnitudes of the δ values in these transitions in $^{68}_{30}Zn$ for which Z is near the magic number 28, we have carried out careful γ-$\gamma(\theta)$ measurements with a NaI-Ge(Li) detector arrangement. Our data verify

TABLE I. Directional correlation results for transitions in ^{68}Zn. The errors in the last numerals are given in parentheses, in general.

γ-γ cascade Energy (keV)	I^π	A_2 / A_4	δ from A_2 [a] / $\lvert\delta\rvert$ from A_4	δ from (n, γ) (Ref. 6)	δ from γ-$\gamma(\theta)$
806-1077	2^+-2^+-0^+	0.369(25)	−1.46(14)	−1.45(15)	$+4^{+3}_{-2}$ [b]
		0.234(34)	1.6(5)		
1261-1077	2^+-2^+-0^+	0.345(22)	−0.14(4)	$-(0.21^{+0.06}_{-0.04})$	−2.25 [c] (30)
		0.005(35)	≤0.37		−1.8 [d] (2)
1745-1077	2^+-2^+-0^+	0.028(34)	+0.29(5)		
		0.070(50)	0.52(27)		
578-1077	0^+-2^+-0^+	0.351(54)	0.358 [e]		
		1.161(76)	1.143 [e]		

[a] Sign convention of Ref. 8.
[b] Reference 4.
[c] Reference 5.
[d] Reference 3.
[e] Theoretical A_2 and A_4 values for 0-2-0 cascade.

the results from (n,γ) studies and in addition show that the $2'''^{+}\rightarrow 2^{+}$ transition is predominantly $M1$.

EXPERIMENTAL PROCEDURES AND RESULTS

For the directional correlation measurements, a NaI-Ge(Li) detector system was employed. Two coincidence spectra were taken simultaneously with the two analog-to-digital converters of a 4096-channel ND 161 system.[7] Gate settings in the NaI spectrum were on the 1077-keV photopeak and on 1300-1800-keV region. The latter choice was made to improve the statistics on the 1745-1077-keV cascade. Data were recorded at 90, 135, and 180°. Since there are no background contributions in either gate only the usual corrections for decentering of the source, chance coincidences, the background in the coincidence spectra, and the finite solid angle of the detectors had to be made. A check on the measurements is provided by the 0-2-0, 578-1077-keV cascade. The results for this cascade agree very nicely with the unique theoretical values.

The directional correlation results are given in Table I along with the mixing ratios, δ, in the convention of Krane and Steffen[8] where

$$\mathrm{sgn}\,\delta_{I\rightarrow I'}=\mathrm{sgn}\frac{\langle I'||E2||I\rangle}{\langle I'||M1||I\rangle}\ .$$

Also given in Table I are the previous results.

The γ-ray spectrum was carefully measured to search for a reported[2] 2338-keV transition but not seen in more recent work[9] and to search for other possible weak transitions. Our data verify the work of Carter *et al.*[2] and the revealed one new

TABLE II. Energies and relative γ intensities from the decay of ^{68}Ga.

Energy (keV)	Relative intensity: Vaughan *et al.* (Ref. 9)	Carter *et al.* (Ref. 2)	Present work
578.4(3)	0.7(1)	1.1(2)	1.00(12)
805.9(1)	2.2(2)	2.8(2)	2.95(12)
1077.4(1)	100	100	100
1261.3(1)	3.1(2)	2.9(2)	3.00(7)
1744.8(2)	0.5(1)	0.28(4)	0.30(4)
1883.2(1)	4.8(3)	4.1(4)	4.33(12)
2338.0(4)	<0.1	0.04(2)	0.050(6)
2822(1)			0.015(2)

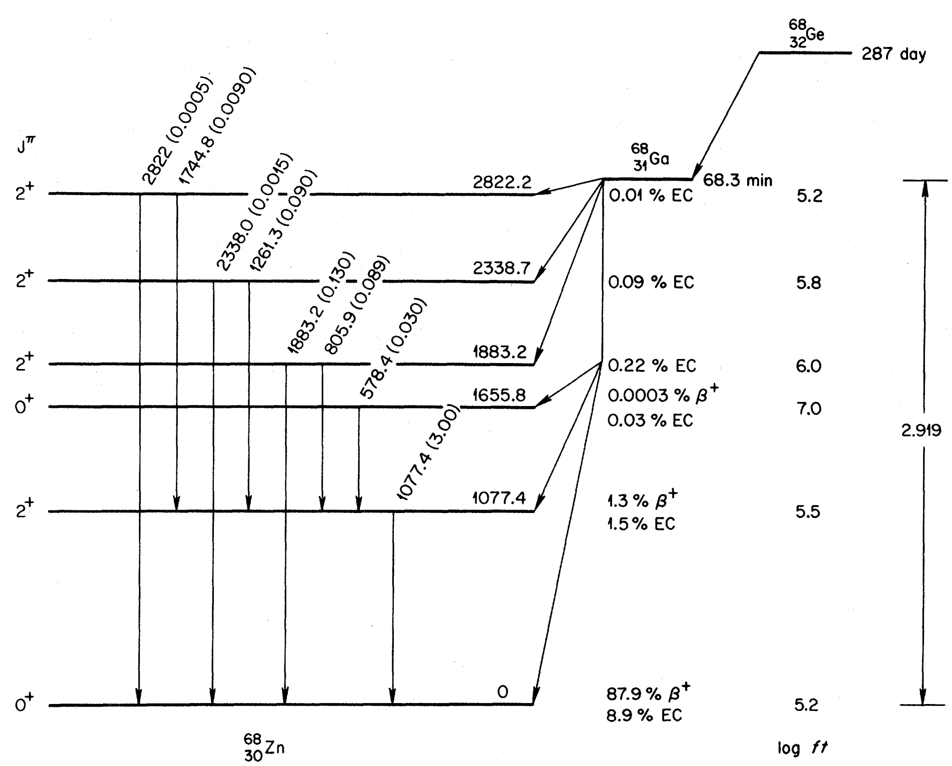

FIG. 1. Decay scheme of ^{68}Ge based on the present work. The β^+ intensity was determined from the annihilation radiation intensity [Carter *et al.* (Ref. 2)] and ϵ/β^+ ratios taken from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

transition at 2822 keV, which is also reported in (n, γ) work.[6]

The γ-ray intensities were measured with a 50-cm^3 Ge(Li) detector, which had a 10% efficiency and a resolution of 2.5 keV at 1.3 MeV. Two separate runs were made and the average results are given in Table II together with earlier results. Runs were taken at different source-to-detector distances to check for sum peaks.

DISCUSSION

Since the transitions to the first 2^+ level are all quite weak in radioactive decay and there is also strong 511-keV annihilation radiation, γ-$\gamma(\theta)$ measurements with NaI detectors are difficult in this case. In the (n, γ) work, this is not the situation. Our work verifies the (n, γ) results for the first two correlations. The δ value for the $2'^+ \to 2^+$, 806-keV transition is somewhat smaller than those for similar transitions in neighboring nuclei,[10] but still shows collective enhancement of the $E2$ component. This enhancement is seen when one notes that the value of δ calculated for single-particle $E2$ and $M1$ transition probabilities for the 806-keV transition is 0.02. So when collective effects are not present to enhance the $E2$ and/or retard the $M1$ strengths, the $M1$ strengths totally dominate. On the other hand, the δ values for the transitions from the third and fourth 2^+ levels are much smaller than for the 806-keV transition to suggest less collective character for these transitions but they are still 5 to 7 times the single-particle estimates of 0.03 and 0.04 for these two cases. One also notes that these two δ values have the opposite sign to provide a further test for any future microscopic calculations.

The decay scheme based on our measurements is given in Fig. 1. Our γ-ray intensities agree nicely with those of Carter *et al.*[2] The 2338.0-keV transition is verified and a new transition of 2822 keV is observed and depopulates a level of that energy.

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