Coulomb-excitation studies of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge

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The characteristics of the low-lying levels of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge have been investigated via multiple Coulomb excitation effected by bombarding isotopically enriched thick targets with 36 to 42 MeV ^{16}O ions. These measurements allowed the excitation of the 2^+, $2^{+\prime}$, $0^{+\prime}$, and 4^+ levels in all nuclei. The $E2$ transition values of the γ rays deexciting the $2^{+\prime}$ and 4^+ levels to the 2^+ states are compared with those recently measured in ^{66}Ge and ^{68}Ge. A close inspection of this set of data clearly reveals a change of nuclear properties between $N = 38$ and $N = 40$. This is in agreement with the possible existence of a shape transition around $N = 40$.

[NUCLEAR REACTIONS ^{70,72,74,76}Ge(^{16}O, ^{16}O$'\gamma$), E=36 to 42 MeV; measured I_γ, E_γ; deduced $B(E\lambda)$, $B(M1)$, J, $T_{1/2}$. Enriched targets.]

I. INTRODUCTION

The low-energy spectra of the doubly even Se, Ge, and Zn nuclei have been extensively investigated in the past years.[1] Clearly, these nuclei belong to a region of weak deformation and have a large instability character emphasized by the possible existence of a structural change around $N = 40$. However, even though the hypothesis of a shape transition is very pertinent, different shapes are predicted by different models.[1] To have a clear understanding of the deformation properties of nuclei, Q_{2^+} and $B(E2)$ measurements are essential and are being carried out on a number of isotopes in this mass region at this laboratory.[2-4] The motivation of the present study was to measure by multiple Coulomb excitation the reduced transition probabilities of the γ rays deexciting the low-lying levels belonging to the one- and two-phonon states of all the available even-A stable

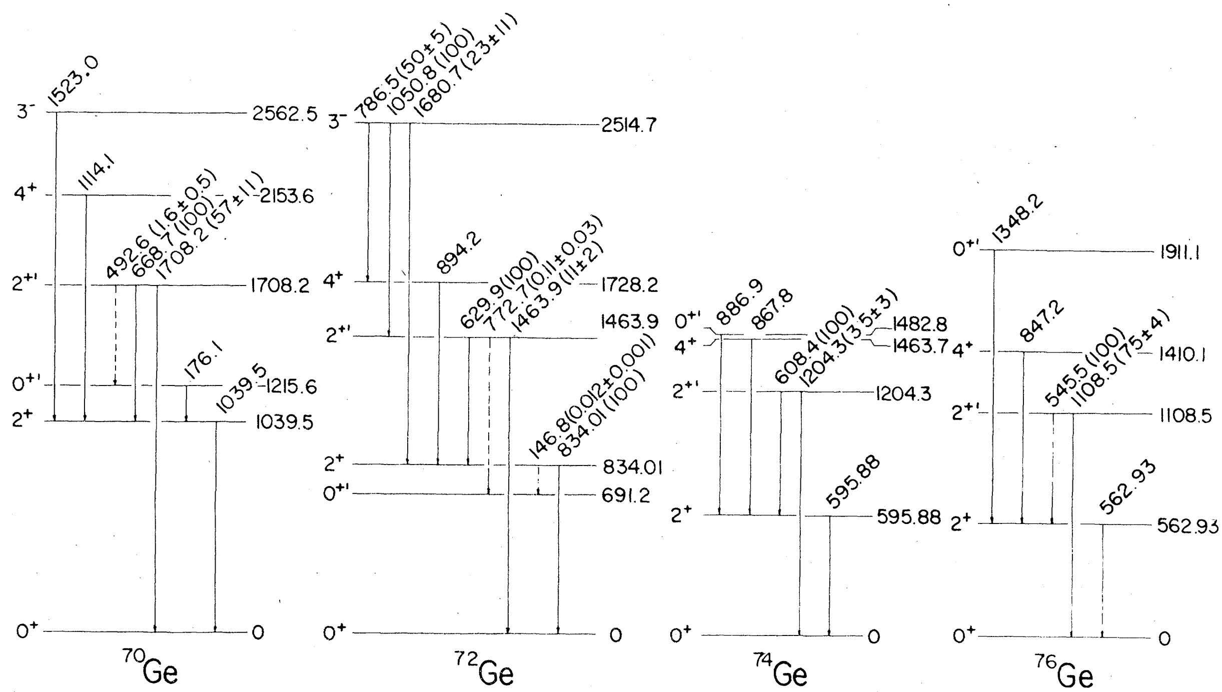

FIG. 1. Level schemes of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge deduced from the present Coulomb excitation measurements. The energy and intensity values of the $2^{+\prime} \to 0^{+\prime}$ transition in ^{70}Ge have been taken from Hinrichsen *et al.*, Nucl. Phys. A123, 250 (1969), whereas the energy and intensity values of the $2^{+\prime} \to 0^{+\prime}$ and $2^+ \to 0^{+\prime}$ transitions in ^{72}Ge have been taken from Refs. 10 and 11. The energies (and intensities) of the other transitions have been measured in this work with a precision going from ±0.1 to ±0.5 keV.

TABLE I. Coulomb excitation results from the thick-target yield measurements.

	E_γ (keV)	$J_i \to J_f$	$B(E\lambda; J_i \to J_f)$ $(10^{-2}\ e^2 b^\lambda)$	δ [a]	$B(M1; J_i \to J_f)$ $(e\hbar/2Mc^2)$	$B(E\lambda)/B(E\lambda)_{\text{S.P.}}$ [b]	$\frac{B(E2; J_i \to 2^+)}{B(E2: 2^+ \to 0^+)}$	$\beta_{J_i J_f}$ [b]	$T_{1/2}$ (ps)
^{70}Ge	1039.5	$2^+ \to 0^+$	3.57 ±0.06			20.8		0.226	1.31±0.02
	176.1	$0^{+\prime} \to 2^+$	6.0 ±1.5			35.0	1.7 ±0.4	0.207	$(5.6^{+1.9}_{-1.0})\times 10^3$
	492.2	$2^{+\prime} \to 0^{+\prime}$	0.36 ±0.31 [c]			2.1		0.072	
	668.7	$2^{+\prime} \to 2^+$	5.0 ±1.9	$+6^{+10}_{-3}$	$(4^{+13}_{-3})\times 10^{-4}$	29.2	1.4 ±0.5	0.188	$5.4^{+5.9}_{-1.8}$
	1708.2	$2^{+\prime} \to 0^+$	0.026±0.020			0.16		0.020	
	1114.1	$4^+ \to 2^+$	1.9 ±0.4			11.1	0.53±0.11	0.116	1.7 ±0.3
		$3^- \to 0^+$	0.6 ±0.4			21.3		0.225	
^{72}Ge	834.01	$2^+ \to 0^+$	4.18 ±0.06			23.5		0.240	
	142.8	$2^+ \to 0^{+\prime}$	4.1 ±0.3 [d]			23.0		0.239	3.35±0.05
	629.9	$2^{+\prime} \to 2^+$	11.4 ±1.3	-5^{+3}_{-1}	$(1.3^{+6.3}_{-0.4})\times 10^{-3}$	64.1	2.5 ±0.3	0.281	
	772.7	$2^{+\prime} \to 0^{+\prime}$	0.005±0.002 [d]			0.028		0.008	$4.5^{+0.8}_{-0.6}$
	1463.9	$2^{+\prime} \to 0^+$	0.019±0.008			0.11		0.016	
	894.2	$4^+ \to 2^+$	6.40 ±0.67			36.0	1.44±0.15	0.210	1.5 ±0.2
		$3^- \to 0^+$	0.73 ±0.16			23.7		0.238	
^{74}Ge	595.88	$2^+ \to 0^+$	6.09 ±0.06			33.1		0.285	12.37±0.12
	608.4	$2^{+\prime} \to 2^+$	10 ±2	-3 ± 1	$(2.9^{+3.2}_{-1.2})\times 10^{-3}$	54.2	1.7 ±0.3	0.260	
	1204.3	$2^{+\prime} \to 0^+$	0.13 ±0.05			0.67		0.042	$4.9^{+1.6}_{-1.0}$
	867.8	$4^+ \to 2^+$	6.67 ±0.64			36.1	1.09±0.10	0.211	$1.72^{+0.18}_{-0.15}$
	886.9	$0^{+\prime} \to 2^+$	<4.0 [e]			<22	<0.65	<0.16	<2.6
^{76}Ge	562.93	$2^+ \to 0^+$	5.56 ±0.06			28.9		0.267	18.00±0.19
	545.5	$2^{+\prime} \to 2^+$	7.4 ±0.9	-3.5 ± 1.5	$(1.3^{+2.1}_{-0.6})\times 10^{-3}$	38.7	1.34±0.17	0.218	
	1108.4	$2^{+\prime} \to 0^+$	0.17 ±0.03			0.89		0.047	$8.8^{+1.5}_{-1.1}$
	847.2	$4^+ \to 2^+$	7.3 ±1.3			38.2	1.3 ±0.2	0.216	$1.77^{+0.38}_{-0.27}$
	1348.2	$0^{+\prime} \to 2^+$	<1.7 [e]			<7.3	<0.32	<0.11	<0.9

[a] The δ values have been taken from Chung *et al.*, Phys. Rev. C 2, 139 (1970).
[b] For the calculation of $B(E2)_{\text{S.P.}}$ and $\beta_{J_i J_f}$ see Ref. 2.
[c] See caption of Fig. 1.
[d] See caption of Fig. 1 and text.
[e] The presence of impurities in these photopeaks did not allow a more precise determination of $B(E2)$.

Ge isotopes. A precise assessment of these $B(E2)$ is cardinal in the determination of Q_{2^+} (see Ref. 5) and also provides sensitive data for testing theoretical predictions. Strangely enough complete information on these values is somewhat lacking in the even-A stable Ge isotopes. Only in ^{70}Ge and ^{72}Ge are some results available and mostly from in-beam γ ray spectroscopy measurements.[6-8]

II. EXPERIMENTAL PROCEDURE AND RESULTS

Multiple Coulomb excitation measurements were effected by bombarding thick targets of enriched ^{70}Ge (98.4%), ^{72}Ge (97.8%), ^{74}Ge (98.9%), and ^{76}Ge (92.8%) with 36 to 42 MeV ^{16}O ions. The targets were evaporated onto a thick tantalum backing and ranged in thickness between 20 to 40 mg/cm^2. The thick-target γ ray yields were measured positioning the target at 45° with respect to the incoming beam and with an 80 cm^3 Ge(Li) detector having a 2.0 keV resolution at 1.33 MeV. The detector was located at 15 cm from the target and at 55° with respect to the incident beam. The γ rays which are attributed to the even-A Ge nuclei are shown in the level schemes of Fig. 1.

From the γ ray yields the reduced $E\lambda$ transition probabilities were determined from the first- and second-order time-dependent perturbation theory of Alder *et al.*[9] To employ this method, the rate of energy loss of the ^{16}O projectiles in the target material must be known. Usually the uncertainty in this parameter is high (~10%) and thus has a large bearing on the precision of the calculated $B(E\lambda)$. To avoid this inconvenience, the very precise absolute $B(E2;\ 0^+\rightarrow 2^+)$ values of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge determined from (α,α') and $(^6\mathrm{Li},{}^6\mathrm{Li}')$ scattering experiments[5] were used to normalize the data extracted by the thick-target yield method. The final results are summarized in Table I.

The $0^{+\prime}$, $2^{+\prime}$, and 4^+ triplet of states has been detected in all the Ge isotopes with the exception of the $0^{+\prime}$ level in ^{72}Ge. This level becomes the first excited state in ^{72}Ge and it is fed by two very weak 142 and 772 keV γ rays decaying from the 2^+ and $2^{+\prime}$ state, respectively. The $B(E2)$ values of these two transitions, shown in Table I, have been calculated from the Coulomb excitation yields and the known branching ratio for decay of these two levels.[10,11] It should be remarked that the present $B(E2;\ 2^+\rightarrow 0^{+\prime})$ value is approximately 30% larger than that determined experimentally by Haight.[12]

The $B(E2;\ 0^{+\prime}\rightarrow 2^+)/B(E2; 2^+\rightarrow 0^+)$ ratio decreases sharply with an increase of the neutron number as in the Se nuclei.[2] The $0^{+\prime}$ levels in the Ge nuclei are characterized by several puzzling properties which will not be discussed here since they have been considered at length elsewhere.[1]

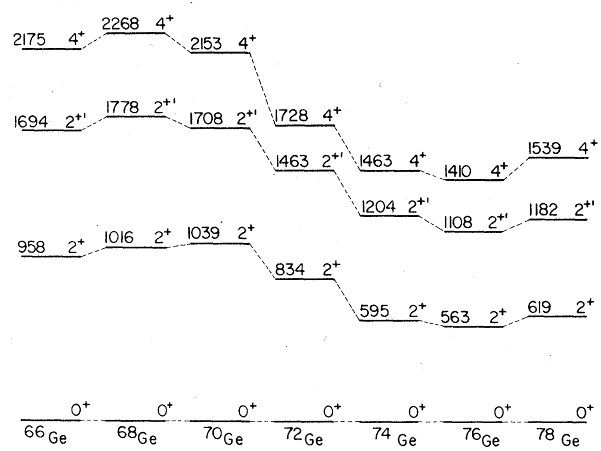

FIG. 2. Low-lying level schemes of the Ge nuclei in the mass region 66–78. Only the 0^+, 2^+, $2^{+\prime}$, and 4^+ are considered. The level schemes of ^{66}Ge and ^{68}Ge are taken from Refs. 17–19. The level scheme of ^{78}Ge is taken from Mateja *et al.*, Phys. Rev. C 17, 2047 (1978).

3^- states have been Coulomb excited in ^{70}Ge and ^{72}Ge. In ^{72}Ge the decay mode of the 3^- level is in good agreement with that proposed by Horoshko *et al.*[13] The 3^- state in ^{70}Ge is known to deexcite essentially (~100%) to the first 2^+ excited level through a 1523 keV γ ray.[13] This transition is masked by a strong 1524 keV impurity peak. The 1524 keV peak, as well as the 437 and 1227 ones, are always present in the Coulomb excitation spectra and are due to transition deexciting levels of ^{42}Ca (^{42}Sc decay). Since the intensities of these γ rays are well known, a comparison of all the Ge Coulomb excitation spectra enabled us to determine the intensity of the $3^-\rightarrow 2^+$ 1523 keV transition. The $B(E3)/B(E3)_{\mathrm{S.P.}}$ values (see Table I) agree well with these found by Kregar and Elbek[14] and Curtis *et al.*[15] but are somewhat smaller than those determined by Kline *et al.*[16] No 3^- states were excited in ^{74}Ge and ^{76}Ge. This is not unexpected since the octupole strength in these two nuclei is fractionalized among several close by 3^- levels with poor collective characteristics.[15]

III. DISCUSSION

For clarity and comparison purposes, the behavior of the 2^+, $2^{+\prime}$, and 4^+ levels of the even-A Ge nuclei in the mass region 66–78 is shown in Fig. 2, whereas in Fig. 3 the results presented in Table I for the 2^+ and 4^+ states are displayed graphically together with similar data on ^{66}Ge and ^{68}Ge.[17-19]

Some interesting features are immediately apparent. For instance, the position of the 2^+, $2^{+\prime}$,

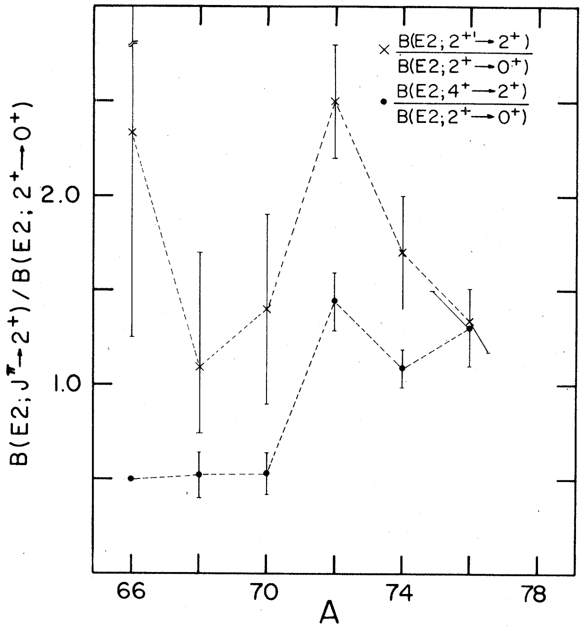

FIG. 3. Experimental values of the $B(E2; 4^+ \to 2^+)/B(E2; 2^+ \to 0^+)$ and $B(E2; 2^{+\prime} \to 2^+)/B(E2; 2^+ \to 0^+)$ ratios for the Ge nuclei. The values in ^{66}Ge and ^{68}Ge are taken from Refs. 17 and 18.

and 4^+ states does not change appreciably from ^{66}Ge to ^{70}Ge, whereas a steep decrease in energy is observable between ^{70}Ge and ^{72}Ge. These levels shift again downwards in ^{74}Ge to become fairly stable in position up to ^{78}Ge, even though there is an evident tendency in ^{78}Ge toward an energy increase. This trend has been observed also in the Se nuclei with the exception of the 2^+ state of ^{82}Se (see Refs. 2, 3) and it is probably due to the approaching of the close neutron shell $N=50$. The $B(E2;\ 4^+ \to 2^+)/B(E2;\ 2^+ \to 0^+)$ and $B(E2;\ 2^{+\prime} \to 2^+)/B(E2;\ 2^+ \to 0^+)$ ratios show also a remarkable behavior around $N=40$. The first ratio displays a sudden jump between ^{70}Ge ($N=38$) and ^{72}Ge ($N=40$) since it hovers around two distinct and approximately constant values in the mass region 66–70 (0.5) and 72–76 (~1.2), respectively. On the other hand, the value of the second ratio is decreasing going from ^{66}Ge to ^{70}Ge. This trend, however, is interrupted at $N=40$ where the $B(E2;\ 2^{+\prime} \to 2^+)/B(E2;\ 2^+ \to 0^+)$ shifts upwards to smoothly decrease again down to ^{76}Ge.

Clearly, these data reveal a change of nuclear features between ^{70}Ge and ^{72}Ge and confirm the existence of a structural change around $N=40$ evinced by Q_{2^+} measurements performed in this laboratory.[5] No similar pattern seems present in the more deformed Se nuclei[2-4,20] which are characterized by very smooth variations in the nuclear properties of their low-lying levels. However, both families of nuclei have the common feature that maximum deformation (or softness) is attained at $N=42$, although in the even-A Ge isotopes the energies of the one- and two-phonon states would favor maximum deformation at $N=44$ (^{76}Ge).

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