PHYSICAL REVIEW C VOLUME 22, NUMBER 4 OCTOBER 1980

Evidence of a spherical to prolate shape transition in the germanium nuclei

R. Lecomte, M. Irshad, S. Landsberger,* P. Paradis, and S. Monaro
Laboratoire de Physique Nucléaire, Département de Physique, Université de Montréal, Montréal, Québec, Canada
(Received 24 March 1980)

Evidence of a spherical (or oblate) to prolate shape transition around $N=40$ in even-A germanium nuclei has been obtained by measuring the static quadrupole moments of the first 2^+ excited states of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge using the reorientation effect in Coulomb excitation. The measurements yield Q_{2^+} values of $(+0.03\pm0.06)$ or $(+0.09\pm0.06)$ eb for ^{70}Ge, (-0.13 ± 0.06) eb for ^{72}Ge, (-0.25 ± 0.06) eb for ^{74}Ge, and (-0.19 ± 0.06) eb for ^{76}Ge.

[NUCLEAR REACTIONS ^{70}Ge(^{6}Li, ^{6}Li$'$), $E=10.5$ MeV; ^{72,74,76}Ge(α,α'), $E=7.0$ MeV; ^{70,72,74,76}Ge(^{16}O, ^{16}O$'$), $E=29.9$ MeV; measured $\sigma(E, E_{^{16}O'})$ deduced Q_{2^+}, $B(E2;\, 0^+\rightarrow 2^+)$. Enriched targets.]

I. INTRODUCTION

The germanium and selenium nuclei or, more generally, the nuclei around the $N=40$ region have drawn considerable attention in recent years because of the puzzling features of their low-energy spectra.[1-9] It is evident that we are dealing with a region of weakly deformed nuclei which show a large instability character. Furthermore, the probable existence of a nuclear shape transition is also inferred by these experimental studies. Theoretical calculations carried out to assess the intriguing properties of these nuclei[4,9-16] generally unveil these features without providing, however, an unequivocal picture on the type of shape transition. Indeed, an oblate to prolate shape transition around $N=40$ is predicted by several calculations,[4,11,12,16] whereas a prolate deformation is suggested by another theoretical approach.[13] Moreover, in a recent work[15] the Ge nuclei have been described as characterized by a weak transition from a spherical (^{70}Ge) to an oblate (^{72}Ge and ^{74}Ge) shape. An experimental determination of the static quadrupole moments of the first 2^+ excited states of these nuclei would provide a sensitive and significant test of their deformation properties. Recent measurements have shown that the even-A selenium isotopes ($N=40$ to $N=48$) favor a deformation of the prolate type.[17,18] The aim of the present investigation was to perform a similar experiment on the even-A germanium isotopes which span the important region from $N=38$ to $N=44$. Q_{2^+} values on some of these nuclei (^{70}Ge, ^{74}Ge, and ^{76}Ge) are reported in the literature and appear to support the existence of a spherical or oblate to prolate shape transition between ^{70}Ge ($N=38$) and ^{74}Ge ($N=42$).[19,20] However, these Q_{2^+} have been determined with large experimental errors and a lack of systematic procedures. Thus, more precise and systematical measurements were carried out to confirm (or reject) this important nuclear feature.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The measurements of Q_{2^+} and $B(E2;\, 0^+\rightarrow 2^+)$ reported herein for ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge have been performed by employing the reorientation effect in Coulomb excitation. Targets of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge were bombarded with 29.9 MeV ^{16}O and 7.0 MeV α beams or, as for ^{70}Ge, with a 10.5 MeV ^{6}Li beam. The beams were obtained from the Université de Montréal Tandem Van de Graaff accelerator and had intensities of up to 500 nA. The targets had a thickness varying from 5 to 25 μg/cm^2 and were prepared by vacuum evaporation of germanium metal on 10 or 20 μg/cm^2 thick carbon backings. The Coulomb excitation probabilities for all projectiles were measured by comparing the resolved elastic and inelastic scattered particles detected by four surface-barrier detectors placed at scattering angles of ±157.5° and ±172.5°. Typical ^{16}O and α spectra are shown in Fig. 1.

The ratios $R_{\exp}=d\sigma_{\mathrm{inel}}/d\sigma_{\mathrm{el}}$ were extracted from the data after the contributions of the isotopic impurities were subtracted from the spectra. The subtractions were made using the Oak Ridge isotopic analysis given in Table I.

The possible presence of contaminants which could contribute elastic scattering peaks under the Ge inelastic peaks was checked by bombarding the Ge targets with a 3 MeV proton beam. The elements present in these targets were observed by PIXE methods and techniques developed in this laboratory.[21] The analysis of the x-ray spectra showed that the ^{72,74,76}Ge targets were free of impurities which could have affected the ^{4}He and ^{16}O data (elements from K to Fe and Cu,

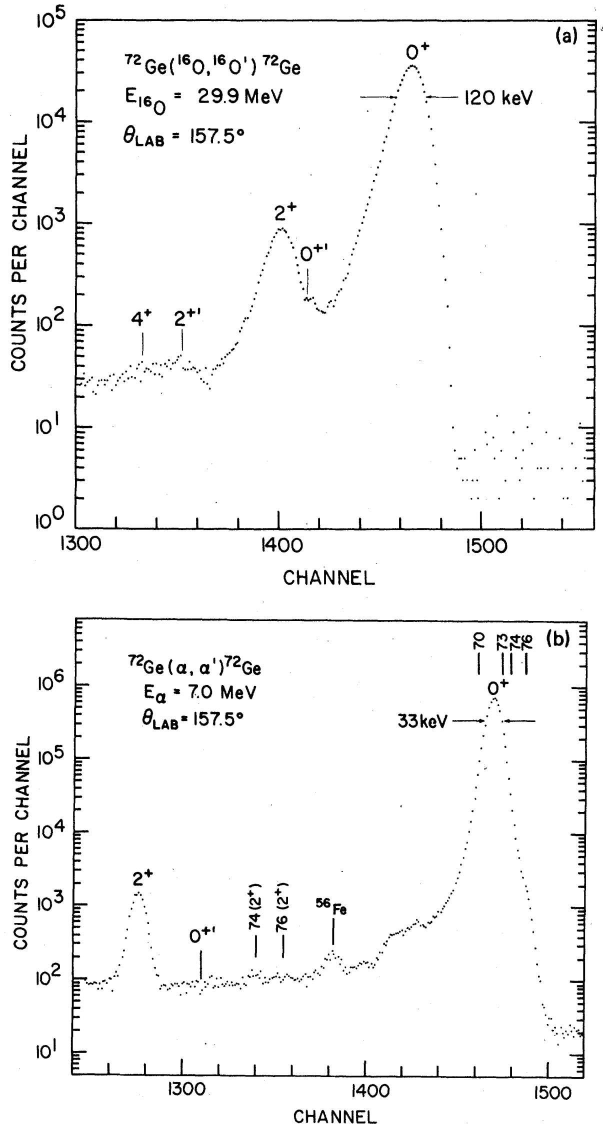

FIG. 1. (a) The ^{16}O(29.9 MeV) spectrum from ^{72}Ge at a scattering angle θ_{lab} =157.5°. (b) The α (7.0 MeV) spectrum of ^{72}Ge at a scattering angle θ_{lab} =157.5°

Zn, and Ga, respectively). However, a large amount of calcium in the ^{70}Ge target made impossible the analysis of its α spectra and for this reason the measurements on this isotope were carried out with a ^{6}Li beam.

TABLE I. Isotope composition of targets in percent. All material was obtained from Oak Ridge Separated Isotopes Divisions.

	Isotopes				
Target	70	72	73	74	76
70	98.45	0.57	0.23	0.61	0.14
72	0.75	97.85	0.41	0.80	0.19
74	0.26	0.49	0.20	98.90	0.15
76	1.30	2.00	0.63	3.25	92.82

To derive the Q_{2^+} and $B(E2;\ 0^+ \rightarrow 2^+)$ values of the first 2^+ excited states of the even-A Ge nuclei, the experimental cross section ratios R_{exp}, which are given in Table II, were fitted with the computer code of Winther and de Boer.[22] All the other reduced matrix elements $\mathfrak{M}_{rs}$ of the quadrupole operator were also inserted in the program. These matrix elements were obtained from $B(E2)$ values determined by Coulomb excitation measurements (thick target yield method) performed in this laboratory.[23] The energy levels and the reduced matrix elements included in the analysis are shown in Fig. 2. The final results are summarized in Table III together with values of Q_{2^+} measured by other groups.

III. DISCUSSION

As usual two values of Q_{2^+} are shown in Table III since it is impossible with the experimental techniques employed here to distinguish between constructive and destructive interference from the $2^{+\prime}$ states. However, constructive interference for prolate deformation ($Q_{2^+} < 0$) is strongly favored for nuclei belonging to this mass region.[24-28] Thus the smaller Q_{2^+} values are chosen as the more probable for ^{72}Ge, ^{74}Ge, and ^{76}Ge which then can be considered as moderately deformed prolate spheroids. Indeed, Q_{2^+} values consistent with zero (destructive interference) are not expected for these nuclei, characterized by several experimental and theoretical data as having a structure intermediate between a rotator and a vibrator.[17] In the case of ^{70}Ge the choice is less evident since the Q_{2^+} is positive both for constructive and destructive interference. It is clear, however, that even without digressing on the possible choice of interference sign, both Q_{2^+}

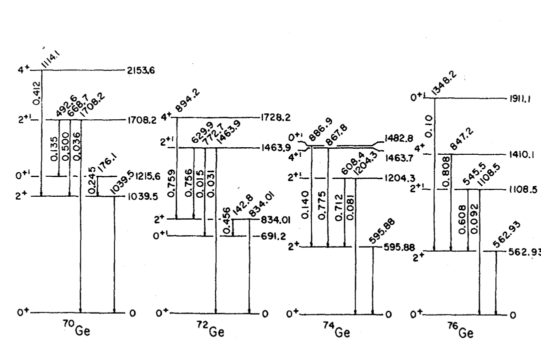

FIG. 2. Energy levels and reduced matrix elements of ^{70}Ge, ^{72}Ge, ^{74}Ge, and ^{76}Ge included in the analysis (See Ref. 23). The δ values of the $2^{+\prime} \rightarrow 2^+$ transitions have been taken from K. C. Chung *et al.*, Phys. Rev. C 2, 139 (1970).

TABLE II. Values of the experimental and least-square fitted ratios.

Isotope	Beam energy (MeV)	Lab angle (deg)	$R_{exp}\times10^3$ [a]	$R_{fit}\times10^3$ [b]
70	10.5 (^{6}Li)	157.5	1.878 (0.69)	1.879
	29.9 (^{16}O)	157.5	11.96 (0.77)	11.97
		172.5	12.14 (1.23)	12.10
72	7.0 (α)	157.5	1.975 (0.87)	1.950
		172.5	1.981 (0.72)	1.998
	29.9 (^{16}O)	157.5	23.70 (0.87)	23.68
		172.5	24.35 (0.77)	24.19
74	7.0 (α)	157.5	5.640 (0.45)	5.635
		172.5	5.832 (0.51)	5.841
	29.9 (^{16}O)	157.5	67.48 (0.79)	67.70
		172.5	69.63 (1.17)	69.32
76	7.0 (α)	157.5	5.687 (0.68)	5.697
		172.5	5.935 (1.11)	5.917
	29.9 (^{16}O)	157.5	70.20 (0.57)	69.88
		172.5	71.10 (0.71)	71.72

[a] The experimental errors for R_{exp} are statistical only and are quoted in percent.
[b] The fitted ratios are those obtained for positive value of $P_3 = M_{02} \cdot M_{22} \cdot M_{02}$, except for ^{70}Ge, where the fitted ratios were obtained for the negative value.

values of ^{70}Ge suggest a different structure for this nucleus. In fact, ^{70}Ge could be considered as almost spherical (constructive interference) or as a moderately deformed oblate spheroid (destructive interference). This is in agreement with the overall evolution of the intrinsic deformation parameter γ calculated with the use of the sum-rule method of Kumar.[29] These γ values (for the 2^+ state) are 31.9° (constructive interference) or 32.3° (destructive interference) for ^{70}Ge, 27.5° for ^{72}Ge, 26.4° for ^{74}Ge, and 26.9° for ^{76}Ge. This soft spherical (or oblate) to prolate shape transition around $N=40$ is clearly displayed by some theoretical calculations.[4,11,12,16] This result, however, totally disagrees with the conclusions of the theoretical approach of Kumar[15] which represents, so far, the only attempt to calculate specifically the Q_{2^+} in some Ge nuclei as ^{70}Ge (+0.15 eb), ^{72}Ge (+0.23 eb), and ^{74}Ge (+0.24 eb). Only the Q_{2^+} of ^{70}Ge is in fair agreement with the experimental value given by destructive interference, whereas a sign disagreement occurs for ^{72}Ge and ^{74}Ge. Thus the predicted spherical to oblate shape transition at $N=40$ (Ref. 15) is not borne out by the present experimental results. It should be mentioned that, using the same prescriptions, strong oblate deformation was suggested also for ^{74}Se and ^{76}Se.[30] This is, however, in complete disagreement with recent results[17,18] which clearly favor a prolate deformation for

TABLE III. Summary of results for the $B(E2{:}\ 0^+ \rightarrow 2^+)$ and Q_{2^+} values for the even-A germanium nuclei.

Isotope	P_3 [a]	$B(E2{:}0^+\rightarrow2^+)$ e^2b^2	Q_2 (eb) Present work [b]	Ref. 19	Ref. 20
70	+	0.179 ± 0.003	+0.03 ± 0.06	+0.003 ± 0.10	
	−	0.178 ± 0.003	+0.09 ± 0.06		
72	+	0.208 ± 0.003	−0.13 ± 0.06		
	−	0.208 ± 0.003	−0.05 ± 0.06		
74	+	0.305 ± 0.003	−0.25 ± 0.06		−0.25 ± 0.10
	−	0.304 ± 0.003	−0.05 ± 0.06		−0.17 ± 0.10
76	+	0.278 ± 0.003	−0.19 ± 0.06	−0.18 ± 0.14	−0.15 ± 0.10
	−	0.277 ± 0.003	−0.03 ± 0.06	+0.05 ± 0.14	−0.05 ± 0.10

[a] $P_3 = M_{02} \cdot M_{22} \cdot M_{02}$; P_3 positive corresponds to constructive interference.
[b] For the calculation of the errors and applicable corrections of Q_{2^+} see Refs. 17 and 18.

these nuclei.

The presently measured Q_{2^+} represent 8% (or 24%), 31%, 50%, and 31% of the rotational value. This shows that the maximum deformation is reached at $N=42$ (^{74}Ge) as expected in nuclei of this mass region. Then the deformation seems to be decreasing with an increasing of the neutron number. This trend is also suggested by the nuclear properties of ^{78}Ge (Refs. 8, 9) and it is different from that evinced in the selenium nuclei, which do not show significant variations in their deformation properties with mass number.[17,18]

This work was supported by the National Research Council of Canada.

*Present address: Département de Génie Nucléaire, Ecole Polytechnique, Casier postal 6079, Succ. "A," Montréal, Québec H3C 3A7, Canada.

[1]J. Barrette, M. Barrette, G. Lamoureux, S. Monaro, and S. Markiza, Nucl. Phys. A235, 154 (1974).
[2]J. V. Kratz, H. Franz, N. Kaffrell, and G. Hermann, Nucl. Phys. A250, 13 (1975).
[3]K. E. G. Löbner, G. Dannhäuser, D. J. Donahue, O. Häusser, R. L. Hershberger, R. Lutter, W. Klinger, and W. Witthuhn, Z. Phys. A 274, 251 (1975).
[4]D. Ardouin, R. Tamisier, M. Vergnes, G. Rotbard, J. Kalifa, G. Berrier, and B. Grammaticos, Phys. Rev. C 12, 1745 (1975).
[5]M. Borsaru, D. W. Gebbie, J. Nurzynski, C. L. Hollas, L. O. Barbopoulos, and A. R. Quinton, Nucl. Phys. A284, 379 (1977).
[6]K. P. Lieb and J. J. Kolata, Phys. Rev. C 15, 939 (1977).
[7]M. Vergnes, G. Rotbard, F. Guilbaut, D. Ardouin, C. Lebrun, E. R. Flynn, D. L. Hanson, and S. D. Orbesen, Phys. Lett. 72B, 447 (1978).
[8]J. F. Mateja, L. R. Medsker, H. T. Fortune, R. Middleton, G. E. Moore, M. E. Cobern, S. Mordechai, J. D. Zumbro, and C. P. Browne, Phys. Rev. C 17, 2047 (1978).
[9]D. Ardouin, B. Remaud, K. Kumar, F. Guilbaut, P. Avignon, R. Seltz, M. Vergnes, and G. Rotbard, Phys. Rev. C 18, 2739 (1978).
[10]J. K. Parikh, Phys. Rev. C 5, 153 (1972).
[11]T. S. Sandhu and M. L. Rustgi, Phys. Rev. C 12, 666 (1975).
[12]M. Didong, H. Müther, K. Goeke, and A. Faessler, Phys. Rev. C 14, 1189 (1976).
[13]Y. Tanaka and T. Tomoda, Prog. Theor. Phys. 50, 121 (1973).
[14]F. Sakata, S. Iwasaki, T. Marumori, and K. Takada, Z. Phys. A 286, 195 (1978).
[15]K. Kumar, J. Phys. G 4, 849 (1978).
[16]M. Girod and B. Grammaticos, Inst. Phys. Conf. Ser. No. 49, 225 (1979).
[17]R. Lecomte, P. Paradis, J. Barrette, M. Barrette, G. Lamoureux, and S. Monaro, Nucl. Phys. A284, 123 (1977).
[18]R. Lecomte, S. Landsberger, P. Paradis, and S. Monaro, Phys. Rev. C 18, 2801 (1978).
[19]J. J. Simpson, U. Smilansky, and D. Ashery, Nucl. Phys. A138, 529 (1969).
[20]D. W. Grissmer, R. Beyer, R. P. Scharenberg, G. Schilling, J. A. Thomson, and J. W. Tippie, Nucl. Phys. A196, 216 (1972).
[21]R. Lecomte, P. Paradis, S. Monaro, M. Barrette, G. Lamoureux, and H. A. Ménard, Nucl. Instrum. 150, 289 (1978).
[22]A. Winther and J. de Boer, in *Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, N. Y., 1966).
[23]R. Lecomte, M. Irshad, S. Landsberger, P. Paradis, and S. Monaro (unpublished).
[24]A. Christy and O. Häusser, Nucl. Data Tables A11, 281 (1972).
[25]R. D. Larsen, J. A. Thomson, R. G. Kerr, R. P. Scharenberg, and W. R. Lutz, Nucl. Phys. A195, 119 (1972).
[26]C. Fahlander, L. Hasselgren, J. E. Thun, A. Bockisch, A. M. Kleinfeld, A. Gelberg, and K. P. Lieb, Phys. Lett. 60B, 347 (1976).
[27]T. Tamura, Phys. Lett. 28B, 90 (1968).
[28]V. I. Isakov and I. Kh. Leinberg, Zh. Eskp. Teor. Fiz. Pis'ma Red. 9, 698 (1969) [JETP Lett. 9, 438 (1969)].
[29]K. Kumar, in *The Electromagnetic Interactions in Nuclear Physics*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1974).
[30]B. Renaud and K. Kumar, Inst. Phys. Conf. Ser. No. 49, 232 (1979).