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# Coulomb excitation of $^{74}$Ge beam

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**Abstract.** $^{74}$Ge beam was Coulomb-excited on a $^{\mathrm{nat}}$Pb target. Ten $E2$ matrix elements including diagonal matrix elements for 5 low-lying states have been determined using the least-squares search code GOSIA. The expectation values of the rotational invariants $\langle Q^2 \rangle$ and $\langle \cos 3\delta \rangle$ show the small and triaxial deformation of the two lowest members of the ground-state band , while the $0_2^+$ and $2_2^+$ states are found to be almost spherical.

**PACS.** 25.70.De Coulomb excitation – 21.10.Ky Electromagnetic moments – 23.20.-g Electromagnetic transitions

## 1 Introduction

The intriguing features of the low-lying states of the even-even germanium, selenium and krypton isotopes have been discussed in a number of experimental and theoretical papers. These isotopes being located around $N = 40$ semi-closed shell show common low-lying level structure. However, previous experimental studies have reported that these nuclei have different types of deformation. The Ge isotopes have been described as characterized by the transition from a spherical shape in $^{70}$Ge to a prolate one in $^{72}$Ge and $^{74}$Ge. The nucleus $^{72}$Ge is one of a few nuclei which have the first excited state of $0^+$. From two-neutron transfer reaction and Coulomb excitation experiments [1–3], it has been proposed that the $0^+$ state is the band-head of a strongly deformed band, while the ground state has more spherical shape. The Coulomb excitation study by Kotlinski *et al.* [4] finds that the $0^+$ state is an intruder state and has a spherical structure. This is in agreement with the fact that no transition from the second $2^+$ to the second $0^+$ was seen, therefore an interpretation of the second $2^+$ state as a next band member is not realistic.

In $^{74}$Ge, several experiments [3,5–7] have been performed with two-neutron transfer reactions, a sensitive probe of the pairing degrees of freedom. On the contrary, Coulomb excitation is sensitive to deformation and low-lying states are excited with cross-sections directly related to the $E2$ matrix elements. The $2_1^+$ excited state of $^{74}$Ge has been investigated experimentally [8,9] and the $E2$ properties of other low-lying states have been studied by Lecomte *et al.* [10] by Coulomb excitation using $^4$He and $^{16}$O beams.

In the present work, the $E2$ matrix elements connecting the five observed states were extracted from the multiple Coulomb excitation of $^{74}$Ge beam using the least-squares analysis code GOSIA [11].

## 2 Experimental procedure

The 300 MeV $^{74}$Ge beam from the tandem accelerator at Japan Atomic Energy Research Institute (JAERI) was excited on a self-supporting $^{\mathrm{nat}}$Pb target of 1.7 mg/cm$^2$ thickness. The $\gamma$-ray detector array, GEMINI [12], consisting of 12 HPGe detectors with BGO anti-Compton suppressors was used to detect deexcitation $\gamma$-rays. The typical energy resolution is about 2.2 keV at 1.3 MeV $\gamma$-ray from $^{60}$Co. The Ge detectors were placed at 32°, 58°, 90°, 122° and 148° relative to the incident beam. The scattered beam ($^{74}$Ge) was detected by a newly developed position-sensitive particle detector system [13] with 4 photomultiplier tubes in combination with 2 plastic and 2 Yap Ce scintillators. It covered about 30% of total solid angle, and the positional resolution was 1.2 mm FWHM near the edge of detector and 0.5 mm at the center. The information of particle position was used for Doppler correction of $\gamma$-rays from $^{74}$Ge, simultaneously providing the impact parameter dependence of measured $\gamma$-transitions. The experimental data were recorded on magnetic tapes event by event when one HPGe detector and one particle detector gave the coincident signals. About $2\times10^8$ events were collected.

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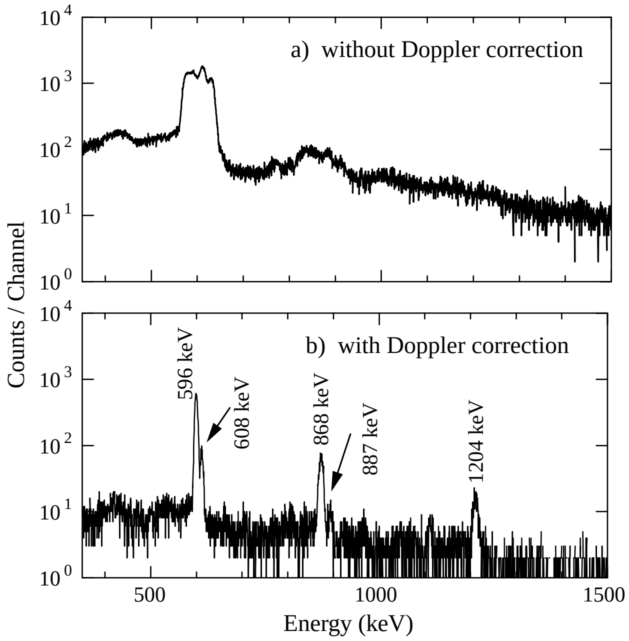


**Fig. 1.** The $\gamma$-ray spectrum from $^{\mathrm{nat}}$Pb($^{74}$Ge,$^{74}$Ge$'$) at $E = 300$ MeV, a) without Doppler correction and b) with Doppler correction, at a scattering angle between $\theta_{\mathrm{lab}} = 110.0°$ to $160.0°$.

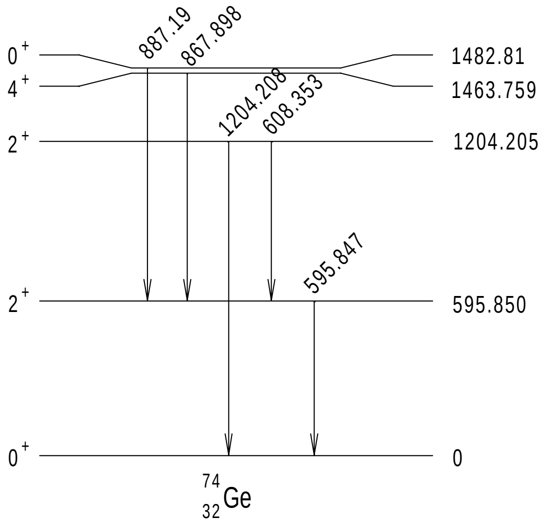


**Fig. 2.** Partial level scheme of $^{74}$Ge below 2 MeV. The energy of levels and $\gamma$-rays are taken from ref. [14].

In fig. 1, the Doppler correction of $\gamma$-ray spectrum is shown. The energy resolution for 596 keV transition has been improved from 20 keV to 5 keV FWHM. The $\gamma$-ray intensities were then used as an input to the least-squares search code GOSIA to determine the $E2$ matrix elements. Five $\gamma$-rays in fig. 2 were included in the fitting routine. The lifetime, branching ratio and mixing ratio ($E2/M1$) data from other works [14] were included in this analysis.

GOSIA constructs the standard $\chi^2$ function built of measured $\gamma$-yields from all experiments and scattering angle slices as well as from the known spectroscopic data

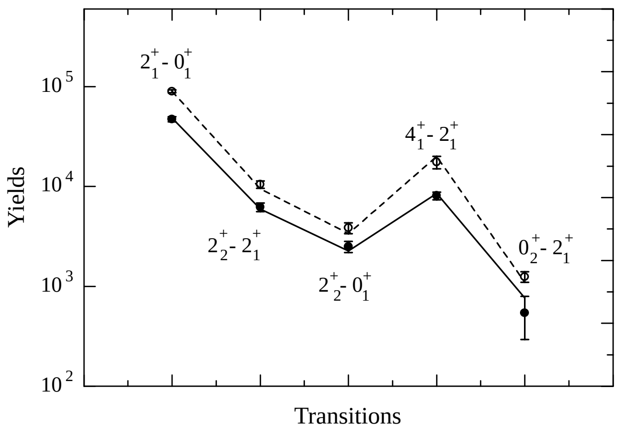


**Fig. 3.** Two data sets —scattered angle $\theta = 117°$(open circles), $\theta = 144°$(closed circles)— are shown for one Ge detector($\theta = 90°$, $\phi = 90°$). The fitting values are connecteded by the dashed and the solid line, respectively.

**Table 1.** Present matrix elements $\langle I_{\mathrm{i}}||E2||I_{\mathrm{f}}\rangle$ and quadruple moments $(e \cdot b)$, and previous results in $^{74}$Ge.

| $I_{\mathrm{i}} \rightarrow I_{\mathrm{f}}$ | Present | Lecomte *et al.*$^{(a)}$ |
|---|---|---|
| $2_1^+ \rightarrow 0_1^+$ | $+0.551 \pm 0.0020$ | $0.55 \pm 0.0027$ |
| $2_2^+ \rightarrow 0_1^+$ | $+0.058 \pm 0.010$ | $\|0.081 \pm 0.014\|$ |
| $2_2^+ \rightarrow 2_1^+$ | $+0.50 \pm 0.04$ | $\|0.71 \pm 0.07\|$ |
| $4_1^+ \rightarrow 2_1^+$ | $+0.85 \pm 0.025$ | $\|0.77 \pm 0.04\|$ |
| $4_1^+ \rightarrow 2_2^+$ | $+0.05 \pm 0.25$ | — |
| $0_2^+ \rightarrow 2_1^+$ | $+0.14 \pm 0.04$ | $\| < 0.2\|$ |
| $0_2^+ \rightarrow 2_2^+$ | $+0.00 \pm 0.11$ | — |
| $Q_{2_1^+}$ | $-0.19 \pm 0.02$ | $-0.25 \pm 0.06$ |
| $Q_{2_2^+}$ | $+0.26 \pm 0.06$ | — |

$^{(a)}$ Coulomb excitation experiment using $^{16}$O, taken from ref. [10] and the matrix elements are calculated from $B(E2)$ values.

treated in the same way as $\gamma$-yields, not as fixed values. Normalization of different data sets is done by the code and is possible because in different data sets excitation pattern differs very strongly, thus absolute intensities are not necessary. It was possible to derive all the $E2$ matrix elements connecting the 5 low-lying states of $^{74}$Ge. The result of the least-squares fit reproduced well the $\gamma$-ray intensities (see fig. 3) and level lifetimes. Totally 10 $E2$ reduced matrix elements were determined, including 3 diagonal matrix elements. The obtained values are listed in table 1 which also shows previous results [10]. The uniqueness of the result of least-squares fit was confirmed by using many sets of starting values for the unknown matrix elements. Resulting $B(E2)$ and static moments, compared with the theoretical predictions, are shown in table 2. The errors quoted in both tables include cross-correlation errors calculated by constructing the probability distribution in the space of fitted parameters and

**Table 2.** Summary of experimental $B(E2)10^{-2}(e\cdot b)^2$, quadruple moments $(e\cdot b)$ and $B(M1)10^{-2}(\mu_N{}^2)$ values, and comparison with theoretical calculations.

| | $I_\mathrm{i} \to I_\mathrm{f}$ | Present | BET-RPA$^{(a)}$ | IBM$^{(b)}$ | $B(E2)_\mathrm{exp}/B(E2)_\mathrm{W.u.}$ |
|---|---|---|---|---|---|
| $B(E2)$ | $2_1^+ \to 0_1^+$ | $6.04 \pm 0.04$ | 5.94 | 7.39 | 34.0 |
| | $2_2^+ \to 0_1^+$ | $0.07 \pm 0.03$ | 0.030 | 0.22 | 0.4 |
| | $2_2^+ \to 2_1^+$ | $5.1 \pm 0.8$ | 7.98 | 9.67 | 29 |
| | $4_1^+ \to 2_1^+$ | $8.0 \pm 0.5$ | 8.97 | 10.48 | 45 |
| | $4_1^+ \to 2_2^+$ | $0.03^{+1.0}_{-0.03}$ | — | — | 0.17 |
| | $0_2^+ \to 2_1^+$ | $1.8 \pm 1.3$ | 3.94 | 0.24 | 10 |
| | $0_2^+ \to 2_2^+$ | $0.0^{+1.2}_{-0.0}$ | 1.10 | 0.06 | 0.0 |
| $Q$ | $2_1^+$ | $-0.19 \pm 0.02$ | $-0.18$ | $-0.245$ | |
| | $2_2^+$ | $0.26 \pm 0.06$ | — | — | |
| $B(M1)$ | $2_2^+ \to 2_1^+$ | $0.14 \pm 0.07$ | — | — | |

$^{(a)}$ The boson expansion technique coupled with random phase approximation [16].
$^{(b)}$ The interacting boson model plus configuration mixing [17].

requesting the total probability to be equal to the confidence limit chosen, *i.e.* 68.3% (for details see ref. [11]).

## 3 Results and discussion

Table 1 shows the matrix elements derived from the least-squares fit. The previous study by Lecomte *et al.* [10] left ambiguity about the sign of the interference term $P_3$ ($= M_{0_12_1}\ M_{0_12_2}\ M_{2_12_2}$, where, for example, $M_{0_12_1}$ is the reduced matrix element between the first $0^+$state and first $2^+$ state). In the present study, the sign of the interference term is determined to be positive. The present matrix elements are consistent with the available data [10].

The partial level scheme of $^{74}$Ge, already known from previous experiments [14], is shown in fig. 2. A closely spaced $0^+$, $2^+$, $4^+$ triplet appears at around twice the energy of the $2_1^+$ state. It has been viewed as a typical vibrational triplet. The present $B(E2)$ values are compared with theoretical calculations in table 2. The $B(E2, 2_1^+ \to 0_1^+)$ and $B(E2, 4_1^+ \to 2_1^+)$ are enhanced about 40 times relative to the Weisskopf (W.u.) estimate. The $B(E2, 2_2^+ \to 0_1^+)$ is 0.4 W.u., while pure vibrational model prohibits such coupling. $B(E2, 4_1^+ \to 2_1^+)/B(E2, 2_1^+ \to 0_1^+)$, $B(E2, 2_2^+ \to 2_1^+)/B(E2, 2_1^+ \to 0_1^+)$ and $B(E2, 0_2^+ \to 2_1^+)/B(E2, 2_1^+ \to 0_1^+)$ are 1.3, 0.84 and 0.30, respectively; in disagreement with the vibrational model, predicting the ratio of 2 for all of them. In spite of the fact that level energies of $0_2^+$, $2_2^+$ and $4_1^+$ states support a vibrational character, we conclude that $B(E2)$ values and their ratios do not justify such an interpretation. For $^{72}$Ge, the strong $B(E2, 2_2^+ \to 2_1^+)$ and $B(E2, 4_2^+ \to 2_2^+)$ point out that the $2_2^+$ state is highly collective and might be interpreted as being the band-head of the rotational band as suggested by B. Kotlinski [4]. The value obtained in the present work is not very much different, implying similar interpretation. The pattern of $E2$ matrix elements conclusively proves that first $2^+$ and $4^+$ states belong to the rotational ground-state band, second $0^+$ state is an intruder almost spherical state, while second $2^+$ level could be interpreted as a band-head of the $\gamma$-vibrational band. To further confirm this interpretation the quadrupole sum-rules technique, comprehensively presented in ref. [15] was applied. This approach allows to model-independently reproduce the shape of charge distribution assuming the complete set of $E2$ matrix elements for the amenable structure is measured. Following GOSIA analysis, the rotational invariants, $\langle Q^2\rangle$ and $\langle \cos 3\delta\rangle$ have

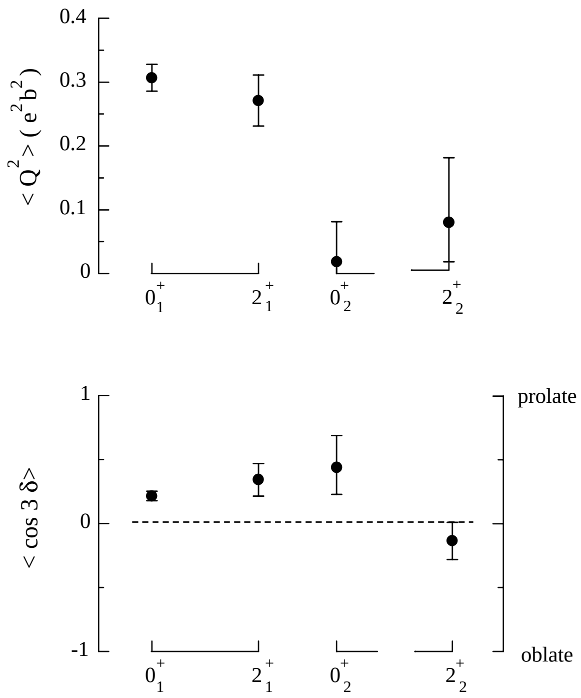


**Fig. 4.** Centroids for the magnitude and asymmetry of the intrinsic frame $E2$ properties of the low-lying states of $^{74}$Ge.

been calculated using the code SIGMA [11]. They have been derived using the experimental $E2$ matrix elements and their centroids are presented in fig. 4. B. Kotlinski *et. al*. strongly suggested that the $0_2^+$ state of $^{72}$Ge has a spherical shape [4]. In $^{74}$Ge, the $0_2^+$ state turned out to be also spherical as seen from the centroid $\langle Q^2 \rangle$ value. No result could be obtained for the $4^+$ state, since no data about matrix elements to the higher, unobserved states, could be included.

The data inferred from the present work were compared to the available model predictions. Boson expansion technique coupled to the random phase approximation (BET-RPA) was used to describe many properties of $^{74}$Ge by K.J. Weeks *et al*. [16]. This approach reproduces well the energy levels of $^{74}$Ge and other Ge stable isotopes. The calculated $B(E2; 2_1^+ \rightarrow 0_1^+)$, $B(E2; 4_1^+ \rightarrow 2_1^+)$ and $Q_{2_1^+}$ agree with the present experimental data, while $B(E2)$ values related to the $2_2^+$ and $0_2^+$ states do not. The calculation of Interacting Boson Model plus Configuration Mixing (IBM) was performed for $^{68}$Ge to $^{76}$Ge by P.D. Duval *et al*. [17]. This model also reproduces the energy levels of $^{74}$Ge. The agreement between experimental and theoretical values for $B(E2)$ and $Q_{2_1^+}$ is good, except for those connected to the $2_2^+$ state.

## 4 Conclusion

The Coulomb excitation experiment of $^{74}$Ge beam was performed with $^{\mathrm{nat}}$Pb target. Ten $E2$ matrix elements including 3 diagonal matrix elements for 5 low-lying states have been determined using the least-squares search code GOSIA. The theoretical $B(E2)$ values based on BET-RPA and IBM are generally consistent with the present experimental data, with the exception of $B(E2, 2_2^+ \rightarrow 2_1^+)$.

The most important conclusion of this work is that the sequence of levels observed cannot, as would seem obvious just from the energies, be interpreted as vibrational. The measurement proves that while the lowest $0^+$, $2^+$ and $4^+$ form a rotational band, the second $0^+$ is an intruder spherical band. Similar conclusions were drawn from the analysis of Coulomb excitation of $^{72}$Ge.

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## References

1. G. Gneuss, W. Greiner, Nucl. Phys. A **171**, 449 (1978).
2. K. Kumar, J. Phys. G **4**, 849 (1978).
3. R. Lecomte, G. Kajrys, S. Landsberger, P. Paradis, S. Monaro, Phys. Rev. C **25**, 2812 (1982).
4. B.Kotlinski, T. Czosnyka, D. Cline, J. Srebrny, C.Y. Wu, Nucl. Phys. A **519**, 646 (1990).
5. G. Rotbard, M. Vergnes, G. La Rana, J. Vernotte, J. Kalifa, G. Berrier, F. Guilbault, R. Tamisier, J.F.A. Van Hienen, Phys. Rev. C **16**, 1825 (1977).
6. D. Ardouin, B. Renaud, K. Kumar, F. Guilbault, P. Avignon, R. Seltz, M. Vergnes, G. Rotbard, Phys. Rev. C **18**, 1987 (1978).
7. C. Lebrun, F. Guildbault, D. Ardouin, E.R. Flynn, D.L. Hanson, S.D. Orbesen, R. Rotbard, M. Vergnes, Phys. Rev. C **19**, 1224 (1979).
8. D.W. Grissmer, R. Beyer, R.P. Scharenberg, G. Schilling, J.A. Thomson, J.W. Tippie, Nucl. Phys. A **196**, 216 (1972).
9. R. Lecomte, M. Irshad, S. Landsberger, P. Paradis, S. Monaro, Phys. Rev. C **22**, 1530 (1980).
10. R. Lecomte, M. Irshad, S. Landsberger, G. Kajrys, P. Paradis, S. Monaro, Phys. Rev. C **22**, 2420 (1980).
11. T. Czosnyka, D. Cline, L. Hasselgren, C.Y. Wu, Nucl. Phys. A **458**, 123 (1986).
12. K. Furuno, M. Oshima, T. Komatsubara, K. Furutaka, T. Hayakawa, M. Kidera, Y. Hatsukawa, M. Matsuda, S. Mitarai, T. Shizuma, T. Saitoh, N. Hashimoto, H. Kusakari, M. Sugawara, T. Morikawa, Nucl. Instrum. Methods Phys. Res. A **421**, 211 (1999).
13. Y. Toh, M. Oshima, T. Hayakawa, Y. Hatsukawa, J. Katakura, M. Matsuda, H. Iimura, H. Kusakari, D. Nishimiya, M. Sugawara, Y.H. Zhang, submitted to Nucl. Instrum. Methods Phys. Res. A.
14. A. R. Farhan, Nucl. Data Sheets **74**, 529 (1995).
15. D. Cline, Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986).
16. K.J. Weeks, T. Tamura, T. Udagawa, Phys. Rev. C **24**, 703 (1981).
17. P.D. Duval, D. Goutte, M. Vergnes, Phys. Lett. B **124**, 297 (1983).