Directional correlation of γ transitions in ^{72}Ge following the decay of ^{72}Ga

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Directional correlations of coincident gamma transitions in ^{72}Ge have been measured following the β^- decay of ^{72}Ga ($T_{1/2} = 14.1$ h), using a spectrometer consisting of a Ge(Li) and a Ge detector. The measurements were carried out for 16 gamma cascades populated in ^{72}Ge, three of which measured for the first time. The results permitted definite spin assignments to the levels at 3325 keV (3^-) and 3342 keV (2^-). In addition, several previous spin assignments to other levels in ^{72}Ge were confirmed. The multipole mixing ratios for 14 γ-ray transitions were determined from the present results.

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I. INTRODUCTION

The germanium nuclei for which both proton and neutron shell are unfilled constitute an interesting system which is subject to a variety of nuclear interactions. During the last several years, the even-A germanium nuclei have been studied extensively and although there is strong evidence that some kind of structural change takes place between light ($A \leq 70$) and heavy ($A \geq 74$) Ge nuclei, as observed for instance from the irregular variation of the many different nuclear properties as function of mass number, a simple explanation does not exist.

The level structure of ^{72}Ge has long been of special interest because this $N = 40$ semiclosed shell nucleus is one of the few known even-even nuclei to have a 0^+ first excited state and it has been argued that there may be some correlation between the anomalously low-lying first excited 0^+ state in these nuclei and the presence of a semiclosed shell with N or $Z = 40$. However, despite a large number of experimental as well as theoretical investigations which have been made in the recent years involving ^{72}Ge, its nuclear structure is still not completely understood. Many of these studies nevertheless indicate that one is dealing with a nucleus in which there is a dynamical shape coexistence involving both a weakly deformed configuration and a spherical shape.

A number of studies have been carried out in the past to determine the level structure of ^{72}Ge through β^- decay of ^{72}Ga and β^+ and electron capture (EC) decay of ^{72}As [1–3]. The most complete decay studies including extensive singles and γ-γ coincidence measurements with Ge(Li) detectors were carried out by Rester *et al.* [2, 3]. The γ-γ angular correlation measurements in the decay of ^{72}Ga were performed by Arns and Wiedenbeck [4] using NaI(Tl) detectors and by Monahan and Arns [5] using the combination of a Ge(Li) and a NaI(Tl) detector. More recently, Chen *et al.* [6] used two Ge(Li) detectors to measure the angular correlations of a few relatively strong gamma cascades. The levels of ^{72}Ge have also been studied extensively through several types of nuclear reactions. These include Coulomb excitation [7–9], (α, $2n\gamma$) [10], ($n,n'\gamma$) [11], (^{3}He,d) [12], (t,p) [13, 14], (p,t) [15], and (p,p') [16] reactions among the more recent studies. The results of all these studies produced a fairly well established level scheme of ^{72}Ge where spin and parity assignments to several levels have been made. The results are summarized in the Nuclear Data Sheets [17].

Although the angular correlations for a number of γ cascades were measured by Monahan and Arns [5], the results are ambiguous in several cases when analyzed in terms of the spin assignments to the levels due to large statistical errors. Moreover, the multipole mixing ratios of the γ-ray transitions involved were not determined explicitly by the authors. The values of some of the mixing ratios extracted from these data are given in Ref. [17]. The A_{kk} values of several γ cascades measured by Monahan and Arns [5] are in serious disagreement with the more recent results of Chen *et al.* [6] leading to conflicting conclusions regarding the spin assignments to some of the levels and the multipole mixing ratios of several γ transitions. In view of these discrepancies we decided to remeasure the angular correlations using high resolution Ge(Li) and Ge detectors and at the same time to obtain the data for a large number of γ cascades in order to better define the spins of some of the levels in ^{72}Ge and, especially, to determine the multipole mixing ratios for as many γ-ray transitions as possible. The multipole mixing ratios are important parameters which could serve to determine the relative importance of the collective and single-particle effects in any attempt to describe the level structure of the nucleus. The levels and the transitions in ^{72}Ge have been studied by measuring a total of 16 γ-ray cascades, populated from the β^- decay of ^{72}Ga, including three new cascades not measured before.

II. EXPERIMENTAL

The radioactive sources of ^{72}Ga were prepared by neutron irradiation of 99.9% pure gallium oxide in the IEA-R1 research reactor at São Paulo. Approximately 5 mg of Ga_2O_3 were irradiated in a thermal neutron flux of $\sim 5 \times 10^{12}$ neutrons/cm^2 s for a period of 5 min. The radioactive source contained some ^{70}Ga ($T_{1/2} = 21$ min), in addition to ^{72}Ga ($T_{1/2} = 14.1$ h), formed during the irradiation of natural Ga_2O_3 with thermal neutrons. A waiting period of approximately 2–3 h was therefore allowed before starting the angular correlation measurements to permit decay of ^{70}Ga. The source with an activity of ~ 20 μCi was transferred to a lucite container and mounted at the center of the gamma spectrometer for measurements. The source dimension was approximately 2.5 × 2.5 mm.

The angular correlation spectrometer consisted of a fixed Ge detector with a volume of 89 cm^3 and a movable Ge(Li) detector with a volume of 45 cm^3. The electronic setup for the measurement of γ-γ coincidence spectra was a usual low-noise fast coincidence system coupled with a 4096-channel pulse height analyzer. The γ-γ coincidences were measured at angles of 90°, 120°, 150°, and 180°. The angular position of the movable detector was changed every 90 min and the resulting coincidence spectrum observed through the Ge detector was routed to a preassigned 1024 channel subgroup of the multichannel analyzer memory for each angular position. Each radioactive source was counted for a period of 12 h after which it was replaced by a freshly prepared source containing approximately the same initial activity. A total of 70 sources were used for the entire experiment.

The photopeak at 834 keV observed through the Ge(Li) detector was selected by the single channel analyzer (SCA) and served as the gating transition in the γ-γ coincidence measurements for all the γ cascades studied. An additional gate placed adjacent to the main gate on the higher energy side served to determine the effects of Compton scattered radiation of higher-energy γ rays included in the window setting. The intensities of coincident γ rays were determined from the Ge detector spectra recorded at various angles between the two detectors and corrected for the source decay during the measurements, the effects of Compton scattered radiation at higher energy, and chance coincidences. The chance coincidences were determined in a separate experiment by introducing a delay of 1 μs in the signal pulses from one of the detectors before reaching the coincidence unit and recording the coincidence spectrum. The corrected photopeak areas were normalized at 90° and least square fitted to the polynomial $W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$ to determine the angular correlation coefficients A_{kk}.

III. RESULTS

The direct γ-ray spectrum in the decay of ^{72}Ga obtained with the Ge detector is shown in Fig. 1(a). The γ-γ coincidence spectrum obtained with the 834 keV gate is shown in Fig. 1(b). The coincidence spectrum presented here is the result of only a partial measurement and has not been corrected for Compton contribution and accidentals. Partial results of the γ-γ coincidence spectrum obtained from the gate setting adjacent to the main 834 keV gate is shown in Fig. 1(c). The angular correlation coefficients A_{kk} obtained from the present measurements for various γ cascades are given in Table I. The A_{kk} val-

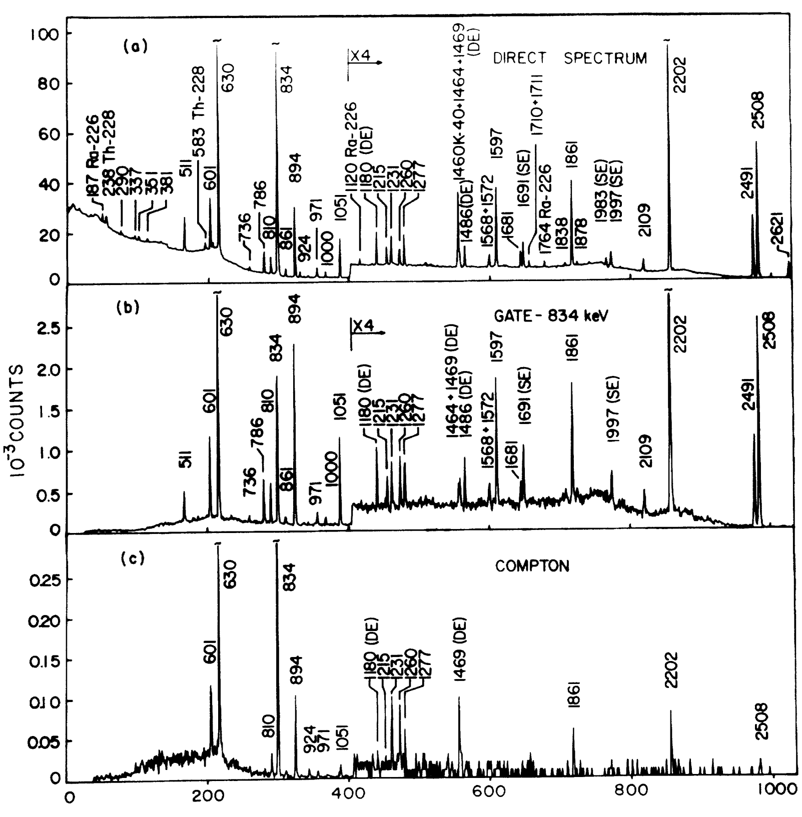

FIG. 1. Direct γ-ray spectrum in the decay of ^{72}Ga observed with the Ge detector 2.5 h after the end of irradiation (a), γ-ray spectrum in coincidence with photopeak 834 keV (b), and γ-ray spectrum in coincidence with the gate adjacent to the 834 keV photopeak (Compton contribution) (c).

ues reported here have already been corrected for the finite solid-angle effects of the detectors. The solid-angle correction factors were determined by numerical calculations [18] for the Ge detector and taken from the tables of Camp and Van Lehn [19] for the Ge(Li) detector. The A_{kk} values for the γ cascades measured by Monahan and Arns [5] and Chen *et al.* [6] are also included in this table for comparison. The multipole mixing ratios $\delta(E2/M1)$ for the γ-ray transitions together with the spin sequence considered most consistent with the observed angular correlation data and decay properties [1–3] as well as with the results of other previous studies [17] are presented in Table II. The value of mixing ratio in each case was determined from the usual χ^2 analysis as a function of δ for the mixed transition. The convention of Krane and Steffen [20] was adopted for the definition of mixing ratio. The multipole mixing ratios obtained in this study are compared with those of Monahan and Arns [5] and Chen *et al.* [6].

The parametric plots for some of the relevant spin sequences are shown in Fig. 2. The corrected values of the

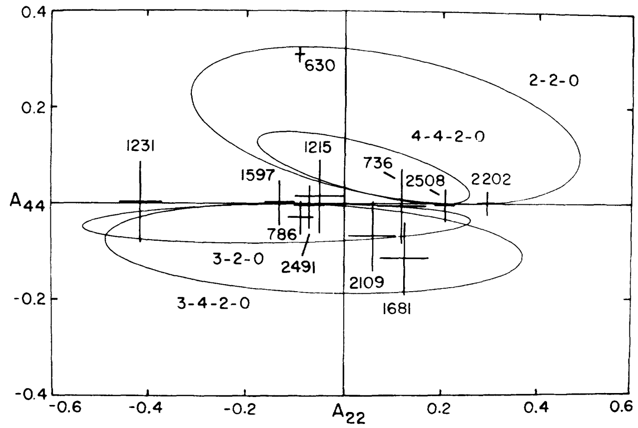

FIG. 2. Parametric plots for some of the relevant spin sequences for direct cascades and skip cascades involving the 894 keV intermediate transition. The experimental (A_{22}, A_{44}) points are shown with error bars.

TABLE I. Results of directional correlation measurements of transitions in ^{72}Ge.

Energy level (keV)	γ cascade (keV)	A_{22}	A_{44}
1464	630-834	−0.095(10)	0.308(16)
		−0.002(09)	0.311(12)[a]
		−0.075(12)	0.225(18)[b]
1728	894-834	0.116(15)	0.023(23)
		0.125(05)	−0.005(07)[a]
		0.046(16)	−0.012(13)[b]
2065	601-(630)-834	0.029(18)	0.009(32)
		0.047(06)	−0.020(08)[a]
		0.045(50)	−0.092(75)[b]
	1231-834	−0.418(45)	0.002(80)
		−0.50 (13)	-0.16(19)[b]
2464	736-(894)-834	0.117(50)	−0.005(78)
	1000-(630)-834	−0.022(40)	0.012(62)
		−0.19 (17)	−0.22(25)[b]
2515	786-(894)-834	−0.090(25)	0.030(35)
		−0.165(43)	−0.076(66)[b]
	1051-(630)-834	0.072(17)	−0.004(25)
		0.064(06)	−0.006(08)[a]
		−0.039(55)	−0.069(84)[b]
	1681-834	0.123(50)	−0.113(75)
2943	1215-(894)-834	−0.051(50)	0.016(76)
		−0.28(19)	−0.06(28)[b]
	2109-834	0.057(48)	−0.068(74)
3036	2202-834	0.291(16)	0.001(24)
		0.283(28)	0.002(42)[b]
3325	1597-(894)-834	−0.133(30)	0.002(45)
		−0.182(50)	0.081(76)[b]
	1861-(630)-834	−0.017(22)	0.005(35)
		0.058(91)	0.14(14)[b]
	2491-834	−0.074(30)	−0.004(45)
		0.040(32)	−0.003(49)[b]
3342	2508-834	0.206(20)	−0.001(35)
		0.181(21)	−0.057(33)[b]

[a]Value from Ref. [6].
[b]Value from Ref. [5].

TABLE II. Multipole mixing ratios of gamma transitions in ^{72}Ge.

Energy level (keV)	Transition (keV)	I_i^π-I_f^π	Mixing ratios δ (this work)	Mixing ratios δ (previous work)
1464	630	$2^+ \to 2^+$	32.6±5.7	-10.3 ± 1.3 [a]
				≥60 or ≤ -60 [b]
1728	894	$4^+ \to 2^+$		
2065	601	$3^+ \to 2^+$	0.08±0.02	$-42\pm^{\infty}_{18}$ [a]
			or 4.0±0.6	
	1231	$3^+ \to 2^+$	−0.53±0.10	$-2.0\pm^{15}_{25}$ [b]
2464	736	$4^+ \to 4^+$	−1.6±0.2	
	1000	$4^+ \to 2^+$		
2515	786	$3^- \to 4^+$	0.05±0.01	0.02±0.05 [b]
	1051	$3^- \to 2^+$	−0.29±0.02	−0.31±0.05 [a]
				−0.01±0.16 [b]
	1681	$3^- \to 2^+$	0.29±0.05	
2943	1215	$3^- \to 4^+$	−0.10±0.01	>0 [b]
	2109	$3^- \to 2^+$	0.17±0.02	
3036	2202	$2^- \to 2^+$	−0.06±0.01	−0.05±0.04 [b]
3325	1861	$3^- \to 2^+$	0.21±0.01	
	1597	$3^- \to 4^+$	−0.01±0.03	0.05±0.06 [b]
	2491	$3^- \to 2^+$	0.00±0.02	0.15±0.04 [b]
3342	2508	$2^- \to 2^+$	0.06±0.05	0.09±0.05 [b]

[a] Value from Ref. [6] (the signs of mixing ratios have been changed to be consistent with the present sign convention).

[b] Value from Ref. [17]. (δ values extracted from the angular correlation data of Ref. [5].)

A_{kk} coefficients with associated errors are displayed as (A_{22}, A_{44}) points in these plots. A partial level scheme of ^{72}Ge taken from Nuclear Data Sheets [17] is shown in Fig. 3. Only the γ-ray transitions of interest in the present study are shown. The spin assignments deduced from the present investigation are included in this figure.

The ground state of ^{72}Ge is 0^+ as for all even-even nuclei and the levels at 691 and 834 keV have well established spin and parity assignments of 0^+ and 2^+, respectively, from most of the previous studies [17]. Since all of the γ cascades studied in this work involved the 834 keV γ ray as the lowest $2^+ \to 0^+$ transition, the spin assignment to most of the upper levels could be determined in a rather straightforward manner. The results of individual cascades and spin assignment to the levels are discussed below.

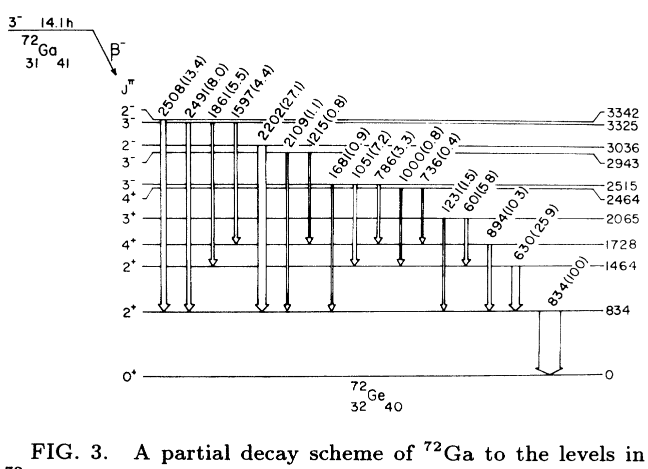

FIG. 3. A partial decay scheme of ^{72}Ga to the levels in ^{72}Ge.

A spin and parity of 2^+ is well known for the 1464 keV level [17]. The angular correlation result of the 630-834 keV cascade is in excellent agreement with the 2-2-0 spin sequence (see Fig. 2). The present value of A_{22} coefficient, however, differs considerably from that obtained by Chen *et al.* [6]. Since the above γ cascade is quite strong and in view of the fact that their measurements were also performed with two Ge(Li) detectors, this discrepancy is quite surprising. While the value of the multipole mixing ratio of the 630 keV γ transition obtained in both measurements is quite large indicating a predominantly quadrupole character of the transition, the phase of the mixing ratio differ. The positive sign of the mixing ratio obtained in this work is consistent with most of the previous determinations as can be seen in Ref. [21] where angular distribution and correlation data from literature are analyzed in terms of consistent choice of the phase relationship between $E2$ and $M1$ matrix elements. The A_{kk} values obtained by Monahan and Arns [5] for this cascade do not intersect the (A_{22}, A_{44}) ellipse with 2-2-0 spin sequence for any possible choice of mixing ratio even after considering the experimental errors of several standard deviations in these coefficients. This might indicate possible interference from some of the unresolved γ cascades since one of the detectors used in their measurements consisted of a NaI(Tl) crystal.

According to most of the previous studies [17] the spin and parity of the 1728 keV level is 4^+. This assignment is also consistent with the level systematics of the neighboring even-A germanium isotopes. Our result for the 894-834 keV cascade is in excellent agreement with the A_{kk} coefficients expected for a 4-2-0 spin sequence with both 894 keV and 834 keV γ transitions as $E2$. Theoretically expected coefficients for this spin sequence are $A_{22} = 0.102$, $A_{44} = 0.009$. The A_{22} value obtained by Chen *et al.* [6] for this case is much higher (more than three standard deviations) compared to the theoretical value. The A_{22} value obtained by Monahan and Arns [5] is incompatible with the 4-2-0 sequence unless a highly unlikely possibility of an octupole admixture in the 894 keV γ ray is admitted. The authors in fact do not rule out the possibility of some interference in this cascade measurement. Since this γ cascade serves well as a check of the internal consistency of other cascades measured from the same gate it should be emphasized at this point that the possible interferences from Compton scattered γ rays, even in the measurements carried out with the Ge or Ge(Li) detectors, must be very carefully determined and properly taken into account.

The spin and parity of the 2065 keV level is firmly established [1–6, 12] as 3^+. The present angular correlation results of the 1231-834 keV and 601-(630)-834 keV cascades de-exciting this level agree with those of previous measurements [5, 6] as well as with the above spin assignment.

A spin and parity of 4^+ has been assigned to the 2464 keV level [17], mainly based on the results of (p, t) reaction work [15]. Earlier angular correlation results [5] for the 1000-(630)-834 keV cascade contain large statistical uncertainty and allow any one of the possible spin values 2, 3, or 4 for the above level. Assuming a 4^+ assignment and using the value of the multipole mixing ratio $\delta(630) = 32.6$ determined in the present work, we calculated the expected A_{kk} values for the 4-2-2-0 spin sequence as $A_{22} = -0.0217$ and $A_{44} = 0.0026$. Here the 1000 keV γ ray was assumed to be of pure multipolarity $E2$. The present experimental A_{kk} values for the 1000-(630)-834 keV cascade are in excellent agreement with the calculated results (see Table I) thus providing a direct confirmation of the 4^+ spin assignment. The angular correlation result of an additional cascade 736-(894)-834 de-exciting the same level measured in this work is also consistent with this spin assignment.

The spin and parity of the 2515 keV level is known [17] to be 3^-. The present results of the 786-(894)-834 and 1051-(630)-834 keV cascades agree with those of earlier measurements [5, 6] and also with the above spin assignment. An additional cascade 1681-834 keV has been measured in this work and the results clearly indicate a 3-2-0 spin sequence (see Fig. 3). The last result is therefore an independent confirmation of the spin assignment of the level.

The level at 2943 keV has been assigned [17] a spin and parity of 3^-. The previous [5] as well as the present angular correlation results of the 1215-(894)-834 keV cascade support this spin assignment. The results of an additional γ cascade at 2109-834 keV measured in this work are quite unambiguous (see Fig. 2) and confirm the spin of the level as 3.

The spin of the level at 3036 keV is known [1–5] to be 2 and the parity is negative [22, 23]. The present angular correlation results for the 2202-834 keV cascade are quite unambiguous indicating the 2-2-0 spin sequence (Fig. 2). The 2202 keV transition is predominantly dipole in character in accord with the negative parity of the level.

The spin assignments to the levels at 3325 and 3342 keV are believed to be 3 and 2, respectively [17], and the parities of both the levels are negative [2, 22]. Angular correlation results of Monahan and Arns [5] indicated a spin of 2 or 3 for the 3325 keV level and 3 for the 3342 keV level. The results of the present study for the 2491-834, 1597-(894)-834, and 2508-834 keV cascades deexciting these two levels very clearly establish the spin of the levels at 3325 and 3342 keV as 3 and 2, respectively.

IV. DISCUSSION

Since the ^{72}Ge nucleus is only four protons away from the closed shell of 28 protons and has the closed neutron subshell N=40, it is quite reasonable to ascribe collective features to this nucleus and assume that the excited states arise as a result of surface vibrations. Some of the properties of the low-lying states of ^{72}Ge in fact conform to the predictions which follow from the considerations of a simple vibrational model [3, 4].

The one aspect of the low-lying states of ^{72}Ge which is in serious conflict with the vibrational picture is the presence of a 0^+ level as the first excited state. It is possible that this state can be explained from the shell model in terms of the excitation from the ground-state configuration of a pair of neutrons to $g_{9/2}$ orbits or of a pair of protons to $p_{1/2}$ orbits. A similar interpretation has been given [24] for the (0^+) first excited state of ^{90}Zr with N=50 (closed neutron major shell) and $Z = 40$ (closed proton subshell).

In a recent heavy ion Coulomb excitation study of ^{72}Ge Kotlinski *et al.* [9] determined a large number of $E2$ matrix elements coupling the low-lying states and observed that the states 0_1^+, 2_1^+, 4_1^+, and 6_1^+ are connected by large $B(E2)$ values with enhancement factors ranging from 24 to 37 as compared to single particle value. The authors therefore suggested a rotational band interpretation for these states. Furthermore the 2_2^+ and 4_2^+ states at 1464 and 2464 keV, respectively, were also found to be highly collective and were interpreted as the members of another rotational band based on the 2_2^+ bandhead, the so called "gamma band." The authors, however, found no evidence for any rotational band based on the 0_2^+ state observed at 691 keV in this nucleus and concluded that this state probably has a spherical shape and can be treated as an "intruder" state perturbing a triaxial quadrupole deformed collective rotational structure.

Several types of theoretical calculations are now available to explain not only the presence of this anomalous first excited 0^+ state in ^{72}Ge but also the observed irregularity in the A dependence of several different properties of even-Ge nuclei which indicate that some sort of structural change takes place between A=70 and A=74. Among these observables are for example: relative cross sections for the 0_2^+, 2_1^+, 2_2^+, and 4_1^+ states, observed in the (^{3}He,d) reaction in the even Ge nuclei with $N = 34$–46 [25] where a deep minimum appears at $N = 40$ for the 2^+ and 4^+ states with variations of one or two orders of magnitude. On the other hand a broad maximum is observed for the 0_2^+ state at N=40 probably indicating a different structure for this state. A similar behavior has been observed also for the (t,p) reaction cross sections [13, 26]. The energy of the lowest excited 0^+ state is lowest at N=40 where this state drops below the lowest 2^+ state to become the first excited state in ^{72}Ge. The $B(E2)$ values connecting the low-lying 2^+ and 0^+ states show a sharp change [27] at N=40. The ratio E_{4^+}/E_{2^+}, which usually serves as the indicator of nuclear deformation, is of the order of 2.1 for ^{68,70,72}Ge but rises to 2.5 for ^{74,76}Ge. Many of these features have been considered as an indication of a shape transition as well as coexistence of spherical and deformed shapes [25, 28].

The Hartree-Fock calculations [25] for even Ge isotopes show the existence of a shape transition from oblate to prolate with increasing neutron number. The ^{68}Ge is found to be an oblate rotator, while ^{76,78}Ge nuclei are prolate ones. In between, the transition proceeds gradually. In ^{72}Ge the prolate-oblate energy difference is very small, and the shape change is predicted at N=42. The static quadrupole moments of the first 2^+ excited states of ^{70,72,74,76}Ge have been measured recently using re-orientation effects in Coulomb excitation [8] and the results are in good agreement with the above calculations except that the oblate to prolate shape transition occurs at N=40.

Kumar [28] has employed the dynamic deformation model to calculate the spectra of ^{70,72,74}Ge. The calculated potential energies indicate a shape transition from a nearly spherical ^{70}Ge to an oblate transitional ^{72}Ge to an oblate deformed ^{74}Ge. The predicted spherical to oblate shape transition at N=40 is, however, not borne out by the experimental results of the quadrupole moments of the first 2^+ excited states in these nuclei [8]. Sign disagreement occurs between the experimental and theoretically calculated values of Q_{2^+} for ^{72}Ge and ^{74}Ge. The energy level spectra calculated from the dynamic deformation model are in reasonable agreement with the experimental results with the exception of 0_2^+ level in ^{72}Ge which is not reproduced. The calculations also support the hypothesis of shape coexistence [29] which asserts that the 0_2^+ states of these nuclei are considerably more deformed than their ground states.

De Vries [30] used a quasiparticle-phonon coupling model, in which two-quasiparticle excitations constructed in the $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ configuration space are coupled with the quadrupole vibrations of the ^{40}Ca or ^{56}Ni core, to calculate the energy spectra and electromagnetic properties of even Ge nuclei $^{68-76}$Ge. The spectra, except for low-lying excited 0^+ state, could be reproduced reasonably well. The author also calculated the absolute values of the multipole mixing ratios $\delta(E2/M1)$ for a few of the gamma transitions between the lowest positive parity states in these nuclei. The calculated mixing ratios are too large in most cases compared to the experimental values.

Weeks *et al.* [31] used the boson expansion technique in which collective quadrupole motion was coupled to pairing vibration in a random phase approximation to calculate several properties of the $^{68-76}$Ge nuclei. The energies of most of the positive parity states below 3 MeV are predicted reasonably well with the exception of 3_1^+ state. The 0_2^+ state in ^{72}Ge is, however, predicted at slightly too low energy compared with the experimental result. The $B(E2)$ values for transitions involving 0_1^+, 2_1^+, 4_1^+, and 6_1^+ agree well with the experimental data. On the other hand large discrepancy between theory and experiment is observed for the transitions originating from the 0_2^+ state. The calculated $B(E2;0_2^+\to 2_2^+)$ value in ^{72}Ge is smaller by a large factor. The agreement between the experiment and theory is also poor for the quadrupole moment of the 2_1^+ state Q_{2^+}. The authors conclude that the 0_2^+ state in ^{72}Ge is a mixture of mainly a pair of proton dominated quadrupole collective excitation and neutron pairing vibration.

Duval *et al.* [32] calculated the properties of $^{68-76}$Ge nuclei in the framework of an interacting boson model which included the configuration mixing. Such a model takes into account both collective and shell aspects of nuclear structure. The authors used the interacting boson model IBM-2 approach in which explicit distinction is made between the neutron and proton bosons. The agreement with the experimental data is only limited. The energy of 0_2^+ state in ^{72}Ge is predicted in good agreement with the experimental value. The theory, however, predicts an unobserved 2^+ state at about 1.3 MeV in ^{72}Ge. The calculated $B(E2)$ values agree in general with the experimental data except in the case of $2_2^+\to 0_2^+$ transition where the theoretical value is overestimated by a factor of 25.

A parameter-free microscopic calculation within the Hartree-Fock-Bogoliubov approximation has been carried out by Petrovici *et al.* [33] in an attempt to describe the complicated behavior of the low-lying levels of even germanium nuclei. In the case of ^{72}Ge the calculated values of $B(E2)$ for various transitions are in reasonable agreement with the experimental data with the exception of $B(E2;0_2^+\to 2_2^+)$ where the calculated value is roughly 40 times larger than the experimental result. The calculations suggest that the 0_2^+ state in this nucleus is collective and deformed and probably is the bandhead of a rotational band. The value of the quadrupole moment of the 2_1^+ state in ^{72}Ge as well as the experimentally observed transition from an oblate to prolate shape [8] in going from ^{68}Ge to ^{74}Ge is well reproduced. According to these authors, strong mixing of prolate and oblate intrinsic shapes is responsible for a complicated structure of ^{72}Ge.

It was mentioned before that the multipole mixing ratio is an important parameter intimately related to the nuclear structure, however, it is important in this context to remember that in addition to its magnitude the phase of the $E2/M1$ mixing ratio is also an important observable which has in the past not been widely used as a probe of the nuclear structure. When determined in a consistent manner the phase can be related to the intrinsic electromagnetic matrix elements and in a model-dependent way to the details of the nuclear structure [34]. The $E2/M1$ mixing ratios for some of the γ transitions in even-A Ge nuclei presented in Table III already reveal an interesting feature. The data show an almost clear tendency of phase change at N=40. The magnitude as well as the phases of the mixing ratio of $2_2^+\to 2_1^+$ transi-

TABLE III. Multipole mixing ratios of some gamma transitions in $^{66-76}$Ge.

$I_i^\pi \rightarrow I_f^\pi$	^{66}Ge[a]	^{68}Ge[b]	^{70}Ge[c]	^{72}Ge[d]	^{74}Ge[e]	^{76}Ge[f]
2_2^+-2_1^+	$-3.3\pm^{1.8}_{2.6}$	-0.15 ± 0.03	$-3.6\pm^{1.1}_{0.6}$	32.6 ± 5.7	3.4 ± 0.4	3.5 ± 1.5
3_1^+-2_2^+	-2.2 ± 0.2	0.06 ± 0.2	-0.05 ± 0.08	0.08 ± 0.02 or 4.0 ± 0.6	1.3 ± 0.4	
3_1^+-2_1^+		0.16 ± 0.08		-0.53 ± 0.10	-0.34 ± 0.05	

[a]Values from Ref. [35].
[b]Values from Ref. [36].
[c]Values from Ref. [37].
[d]Values from present work.
[e]Values from Ref. [38].
[f]Values from Ref. [39].

tions were analyzed by Krane [34] in a systematic manner for a large number of even-even nuclei in the mass range $58 \leq A \leq 152$ and it was suggested that it might be of interest in the comparison of the relative phases to determine the degree to which the phase and possibly also the magnitude of the $2_2^+ \rightarrow 2_1^+$ mixing ratios correlate with the static quadrupole moment of the 2_1^+ state Q_{2^+}. Unfortunately the quadrupole moment data is not available in many cases to draw detailed conclusions; it may be worth pointing out here that the sign of Q_{2^+} in even Ge nuclei does change at N=40 (Ref. [8]).

In the present work, angular correlations of 16 γ cascades were measured and multipole mixing ratios of 14 γ-ray transitions were determined. Although the spin and parity assignments to a number of levels are known from previous studies, the present results more conclusively confirm these assignments and firmly establish the spins of the levels at 3325 and 3342 keV as 3 and 2, respectively. The presently measured values of the multipole mixing ratios for a large number of γ-ray transitions in ^{72}Ge should stimulate new attempts for the theoretical calculations of these quantities to further elucidate the structure of this nucleus.

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