Search for enhanced octupole correlations in ^{65}Ge

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High spin states of ^{65}Ge have been investigated via the ^{40}Ca(^{28}Si,$2pn$)^{65}Ge reaction at 93 MeV beam energy. A level scheme containing 36 new transitions and 20 new levels could be established on the basis of $\gamma\gamma$ and $\gamma\gamma n$ coincidences, γ-angular distributions and γ-linear polarization measurements. The aim of the work was to study the softness with respect to octupole deformation as theoretically predicted for the lightest Ge and Se isotopes. We could definitely show that the excitation energy of the 15/2$^-$ state (i.e., the coupling of the $g_{9/2}$ neutron to the 3$^-$ octupole state in ^{64}Ge) is not strongly lowered in comparison to the neighboring Ge nuclei, but fits reasonably well into the trend of smoothly rising energy with decreasing neutron number. Consequently, it should be concluded that the lightest Ge isotopes do not display enhanced octupole correlations, at least in the energy range of $E_x \leqslant 5$ MeV.

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I. INTRODUCTION

The neutron-deficient Ge isotopes lie in the transitional region between the spherical shell model nucleus ^{56}Ni and the strongly deformed light Kr and Sr isotopes. Hence excitation modes are rather vibrational than rotational like. Because of the small quadrupole deformation of $\beta_2 \approx 0.2$ [1], transition energies within the collective bands are quite large, which yields to a competition of collective and quasiparticle states at excitation energies $E_x \sim 4$ MeV and spins $I \sim 6-8$.

In the last decade neutron-deficient Ge isotopes were extensively studied both experimentally and theoretically. Extended level schemes have been presented for ^{66,68}Ge [2–5], revealing a striking interplay of quasiparticle and collective degrees of freedom. In an impressive experiment, Ennis *et al.* [6] studied the $N=Z$ nucleus ^{64}Ge up to high angular momentum and found softness with respect to triaxiality for this nucleus. From a theoretical standpoint, the most fruitful estimation seems to be given by the EXVAM code [7], a Hartree-Fock-Bogoliubov calculation with spin and number projection before variation. This model especially accounts for the mixing of oblate and prolate shapes, which is an important feature of the mass region. Recent calculations of Petrovici *et al.* for ^{68}Ge [8–11] indicated almost pure oblate states up to angular momentum $I^\pi = 6^+$, whereas more or less deformed prolate states dominate at higher angular momentum.

In the $A \approx 70$ mass region, the only high-j single-particle orbital for both protons and neutrons is the $g_{9/2}$ ($\pi = +$). This intruder, on the one hand, gives rise to the appearance of gaps in the single-particle energies at large deformations. On the other hand, it is close to the $p_{3/2}$ orbital and the coupling between both via the $\Delta l = 3$ interaction could result in enhanced octupole correlations. From Strutinsky-type potential-energy calculations, Nazarewicz *et al.* [12,13] predict softness toward octupole correlations for nuclei with N, $Z \sim 34$, i.e., the very light Ge and Se isotopes. If these isotopes are really soft with respect to octupole deformation, one should expect an energetically lowered collective 3$^-$ ($\frac{15}{2}^-$) state in the case of an even (odd) nucleus and a negative parity band connected to the ground state band by enhanced $E1$ transitions. In this context, the $\frac{15}{2}^-$ state is regarded as the coupling of the $g_{9/2}$ particle to the 3$^-$ octupole state of the neighboring even nucleus.

^{65}Ge was studied in beam for the first time by Görres *et al.* [14]. Their level scheme, containing some 11 γ transitions, was established on the basis of charged-particle-$\gamma\gamma$ coincidences and angular distributions of γ rays in coincidence with one neutron. Above the $\frac{9}{2}^+$ isomer, they found a sequence of three γ rays with transition energies of 864, 1255, and 1356 keV and spin and parity assignments of $\frac{13}{2}^+$, $\frac{15}{2}^{(-)}$, and $\frac{19}{2}^{(-)}$, respectively. In comparison with the neighboring nuclei ^{67,69}Ge, this would indicate a strong lowering of the $\frac{15}{2}^-$ energy of about 700 keV and hence a sharp change in nuclear structure. The sudden drop of the energy was interpreted as the onset of strongly enhanced octupole correlations as expected from theory. One then would expect a lowering of the same order of magnitude for the 3$^-$ state in ^{64}Ge. Surprisingly, Ennis *et al.* [6] found the candidate 3$^-$ state in ^{64}Ge at 2.969 MeV, which is about 850 keV higher than was anticipated from the behavior of ^{65}Ge. From a very simple point of view, one might solve this striking contradiction by interchanging the 1255 and 1356 keV γ rays in ^{65}Ge. On the one hand, this seems not to disagree with the γ intensities measured by Görres *et al.* [14]; on the other hand, it leads to spin and parity assignments of $\frac{13}{2}^+, \frac{17}{2}^+$, and $\frac{19}{2}^-$ for the involved states, which is the usual yrast sequence for the heavier odd Ge isotopes. Taking this into account, the $\frac{15}{2}^-$ state could be regarded as unknown and the question of enhanced octupole correlations in ^{65}Ge demands reinvestigation. In order to clarify this crucial point, we initiated a new in-beam study of ^{65}Ge.

II. EXPERIMENTS AND ANALYSIS

This work was conducted at the tandem Van de Graaff accelerator of the University of Cologne. ^{65}Ge was populated via the reaction ^{40}Ca(^{28}Si,$2pn$)^{65}Ge at 93 MeV beam energy. The experimental cross section was 4.7% of the total

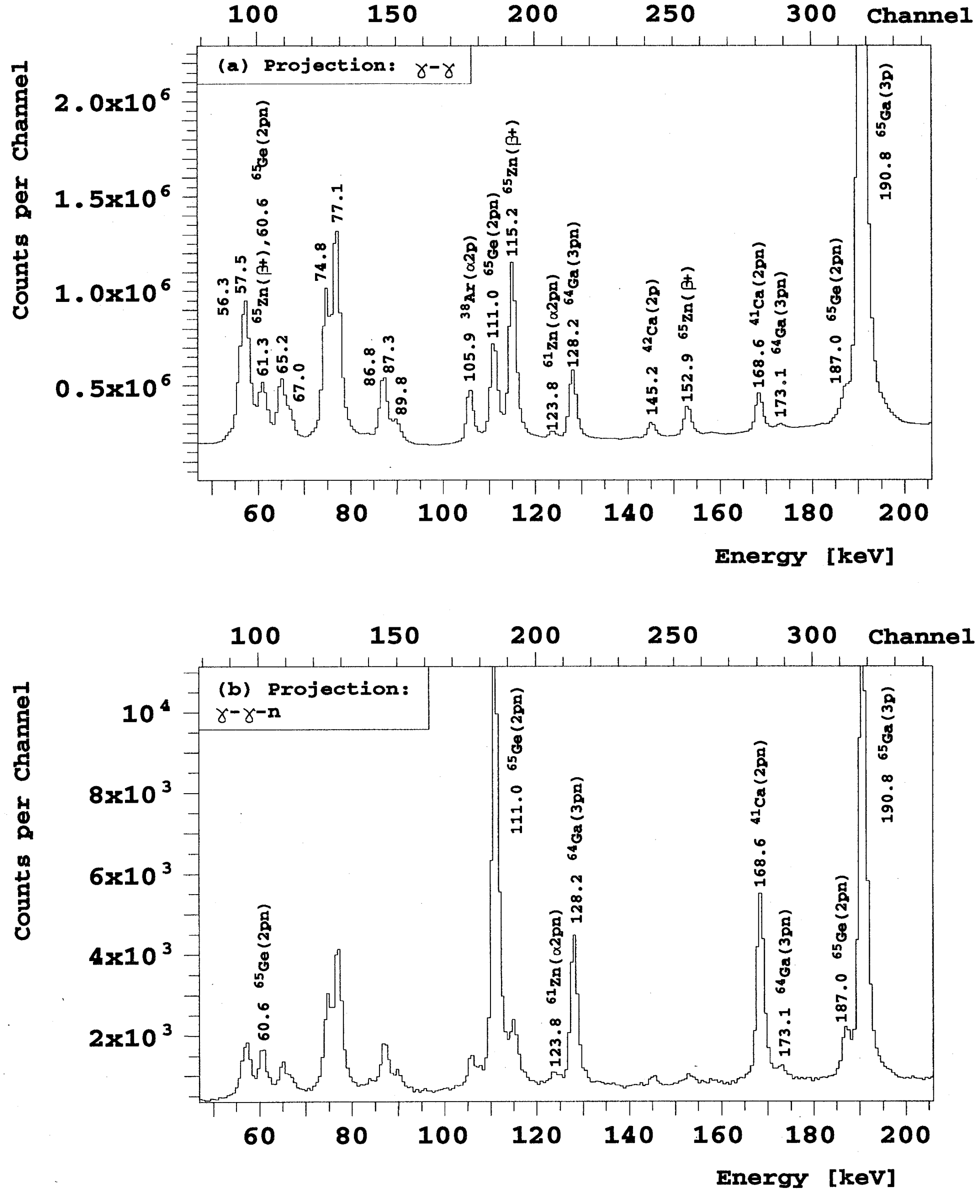


FIG. 1. Partial spectrum of γ rays projected from the (a) $\gamma\gamma$ and (b) $\gamma\gamma n$ matrix. In the lower energy range (50–90 keV), Ta and Bi x rays are labeled with their energies in keV.

fusion-evaporation cross section. Highly enriched (99.96%) ^{40}Ca targets of about 1 mg/cm^2 were used, backed by a 89 mg/cm^2 Bi-In-Cu layer to stop the beam and the recoil products. We performed $\gamma\gamma$ and $\gamma\gamma n$ coincidence measurements with the OSIRIS ring spectrometer, consisting of six Compton-suppressed Ge detectors at 90° to the beam direction. The Ge detectors typically had a resolution of 2.2 keV at 1.33 MeV and relative efficiencies between 20% and 23%. Because of the weak relative population of ^{65}Ge, we used a four segmented neutron detector mounted at 0° to the beam direction to clean up the spectra and enhance the lines of interest. Within a measuring time of 148 h, 340×10^6 $\gamma\gamma$ and 974×10^3 $\gamma\gamma n$ events were stored on magnetic tape and off-line sorted into 4096×4096 channel matrices using a prompt coincidence time gate of 40 ns.

Figures 1(a) and 1(b) show a part of the (a) $\gamma\gamma$ and (b) $\gamma\gamma n$ matrix projections. It is clearly seen that γ rays coinciding with one neutron [e.g., 111.0 keV ^{65}Ge $(2pn)$, 128.2 keV ^{64}Ga $(3pn)$, 168.6 keV ^{41}Ca $(2pn)$] are strongly enhanced in the $\gamma\gamma n$ projection. The 168.6 keV γ ray results from the ^{16}O (^{28}Si, $2pn$) ^{41}Ca reaction which is caused by the unavoidable oxidation of the Ca target.

An example of the $\gamma\gamma$ and $\gamma\gamma n$ coincidence data is given in Figs. 2(a) and 2(b). In the upper part, a spectrum of γ rays in coincidence with the 111.0 keV ground state transition of ^{65}Ge is shown, in the lower part, the same spectrum, but additionally neutron gated. Besides the well-known yrast transitions, several other γ rays are clearly visible.

In order to get multipolarities of γ rays belonging to ^{65}Ge, we performed γ-angular distributions and γ-linear polarization measurements. Angular distribution measurements were carried out via the reaction ^{40}Ca (^{28}Si,$2pn$)^{65}Ge at 93 MeV. We used three Ge detectors, which were fixed on a revolving platform with the vertical rotation axis. By turning

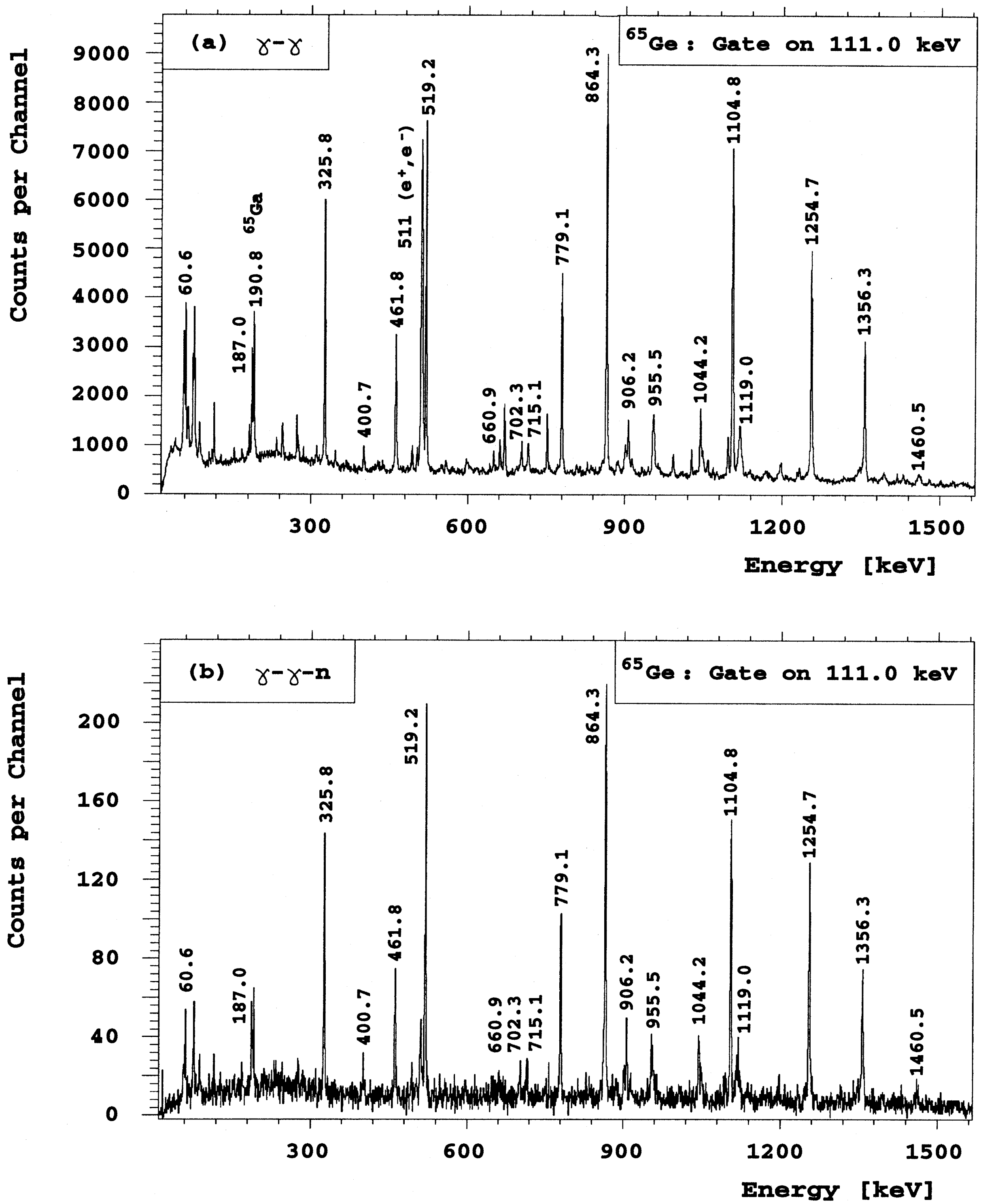


FIG. 2. (a) Spectrum of γ rays in ^{65}Ge gated with the 111.0 keV $\frac{5}{2}^- \rightarrow \frac{3}{2}^-$ transition and (b) same spectrum neutron gated.

the platform around the target chamber, we obtained angular distributions consisting of six different angles for each of the Ge detectors. For the energy and relative efficiency calibration, we used a ^{226}Ra source placed at the target position. Corrections for dead time of the detectors and incident beam current were performed by adjusting the measured intensities to the A_2/A_0 and A_4/A_0 coefficients of some well-known γ rays (i.e., 1096.2 keV $E2$ ^{65}Ga, 1027.0 keV $E2$ ^{65}Ga, 1197.2 keV $E1$ ^{62}Zn, 641.8 keV $E1$ ^{64}Zn). Finally, the three angular distributions were normalized on the 55° intensity, leading to only one angular distribution containing 13 different angles between 0° and 155° with respect to the beam

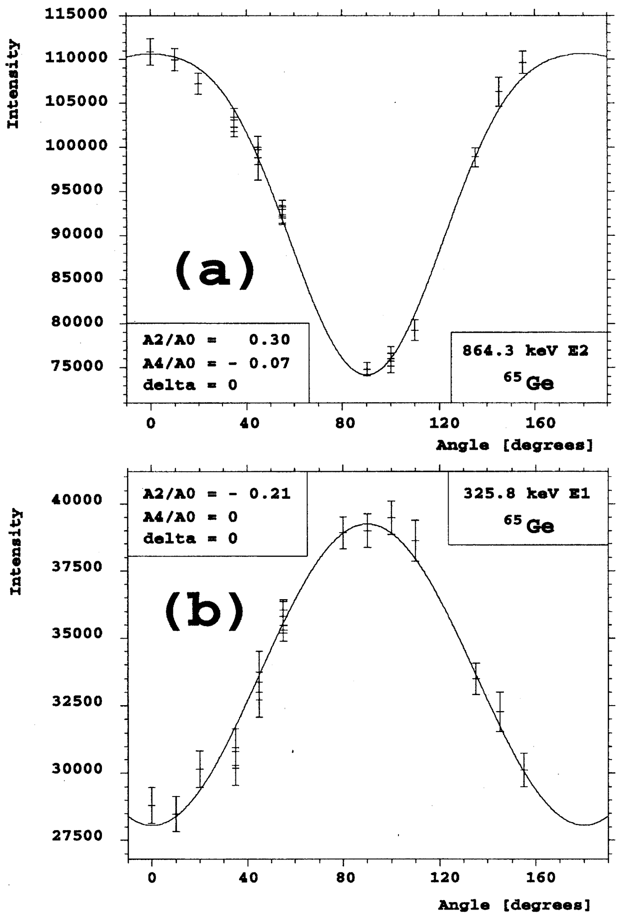


FIG. 3. Angular distribution of the (a) 864.3 keV and (b) 325.8 keV γ rays.

direction. The 125° single spectrum was used to determine the relative intensities of γ rays. As an example for the quality of the data, Figs. 3(a) and 3(b) show the angular distributions of the 864.3 keV $\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$ and 325.8 keV $\frac{9}{2}^+ \rightarrow \frac{7}{2}^-$ γ rays.

To measure the γ-linear polarization, we used the Compton polarimeter POLALI. The spectrometer characteristics are described in detail in [27]; therefore, only a brief survey is given here. The polarimeter consists of five HP Ge detectors. A central scatterer with a relative efficiency of 3.9%, situated in a horizontal plane at 90° to the beam direction, is surrounded by four Ge detectors with relative efficiencies of about 28%, two of them mounted parallel and the other perpendicular to the scattering plane. γ radiation emitted from the target enters the scatterer via a Pb collimator. By recording the coincident energy signals of the scatterer and Ge detectors, one obtains a discrete line spectrum for each of the scatterer-Ge detector pairs. The experimental asymmetry A of the Compton-scattered γ radiation is given by

$$A(E_\gamma) = \frac{a(E_\gamma)N_\perp - N_\parallel}{a(E_\gamma)N_\perp + N_\parallel},$$

where $N_\perp$ and $N_\parallel$ are the counts of the Ge detectors perpendicular and parallel to the scattering plane and a (E_γ) is an energy-dependent geometrical correction factor. The linear polarization P (90°) is given by the quotient of the experimental asymmetry A and the polarization sensitivity Q of the polarimeter:

$$P(90°) = A(E_\gamma)/Q(E_\gamma).$$

The γ-linear polarization was obtained from the reaction ^{40}Ca(^{31}P,αpn)^{65}Ge at 115 MeV. For this reaction, linear polarization data were already present from a former measurement of ^{67}Ge. Although in the ^{31}P$\rightarrow$^{40}Ca reaction ^{65}Ge is not as strongly populated as in the ^{28}Si$\rightarrow$^{40}Ca reaction (a rough estimation leads to a relative cross section of about 2% of the total fusion-evaporation cross section), it was possible to extract γ-linear polarization data for the strongest γ rays of ^{65}Ge. An example of the linear polarization data is shown in Fig. 4 where the γ spectrum of the intensities $[a(E_\gamma)N_\perp - N_\parallel]$ from the ^{31}P$\rightarrow$^{40}Ca reaction is plotted in the energy range between 730 and 1030 keV. The small relative cross section of ^{65}Ge can be seen by the small peak height of the 864.3 keV γ ray ($\frac{13}{2}^+ \rightarrow \frac{9}{2}^+, E2$).

In Table I the angular distribution coefficients A_2/A_0 and A_4/A_0, attenuation coefficients α_2 and α_4, and mixing ratios δ are listed. The theoretical and experimental linear polarization P (90°) of γ rays is given in Table II. Table III contains the relative intensities of the ^{65}Ge γ rays as measured with the 125° detector.

III. LEVEL SCHEME OF ^{65}Ge

The level scheme of ^{65}Ge, presented in Fig. 5, is based on $\gamma\gamma$ coincidences, angular distributions, and linear polarization data as well as γ-ray intensities.

Various papers about the β^+ decay of ^{65}Ge have been published in the past [15–17]. From that, the spin and parity of the ground state are known to be $I^\pi = \frac{3}{2}^-$. The ground state is fed primarily by a 111.0 keV γ ray. Because of its low energy, angular distribution and polarization data are not available from our work, but the reported angular distribution data of Ref. [14] are consistent with a $\Delta I = 1$ $M1$ transition with an $E2$ admixture of $\delta = -0.25 \pm 0.04$. Thus the spin and parity of the 111 keV level should be $I^\pi = \frac{5}{2}^-$. Further, we observed other low spin levels of negative parity at 605 and 890 keV excitation energy, the latter one already having been established in Ref. [14]. It decays via the 890.1 and 779.1 keV γ rays into the ground state and 111 keV levels. A small decay branch via the 285.6 keV γ ray feeds the previously unknown state at 605 keV. Our angular distribution data confirm the $I^\pi = \frac{7}{2}^-$ assignment for the 890 keV level. Spin and parity of the 605 keV level can only be $I^\pi = \frac{5}{2}^-$ as a result of the $\Delta I = 1$ $M1/E2$ angular distribution of the 604.5 keV γ ray.

In accordance with Ref. [14], the $\frac{9}{2}^+$ level is observed at 1216 keV. It is depopulated by the 1104.8 keV $M2$ and 325.8 and 60.6 keV $E1$ transitions. Görres *et al.* [14] measured a lifetime of $t_{1/2} = 7 \pm 1 ns$ for the $\frac{9}{2}^+$ isomer. The $\frac{9}{2}^+$ state is fed by the yrast cascade with transition energies of 864.3, 1356.3, and 1254.7 keV and relative intensities of 100 ± 0.6, 63.5 ± 0.9, and 51.2 ± 0.7. Thus, in contradiction to the level scheme of Ref. [14], the 1356.3 keV γ ray can only be placed below the 1254.7 keV γ ray. In addition, this

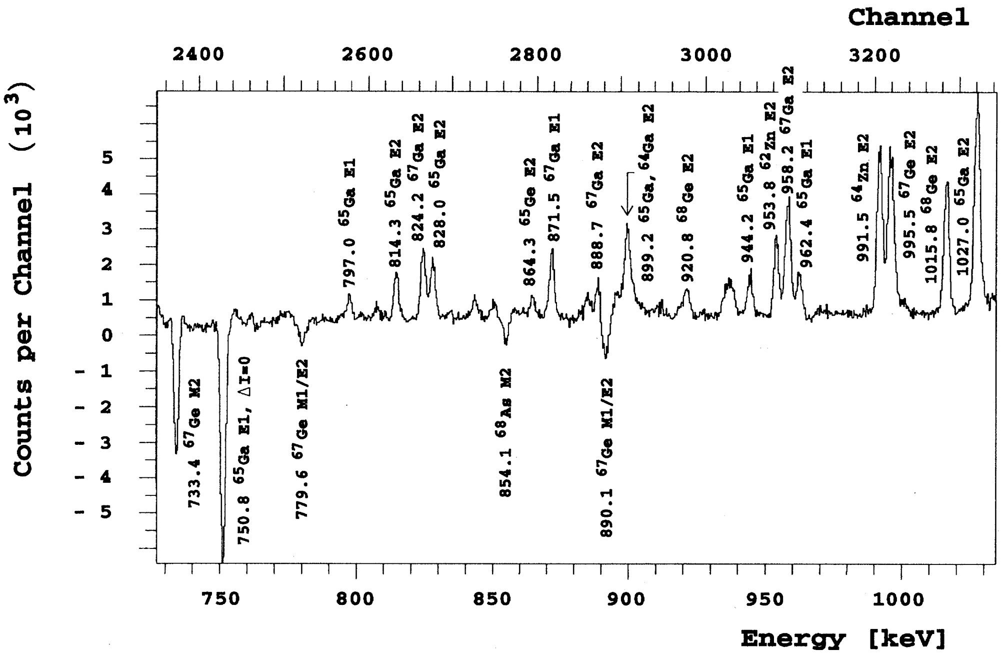


FIG. 4. Partial γ spectrum of the intensities with $[a(E_\gamma)N_\perp - N_\parallel]$ from the reaction ^{31}P$\rightarrow$^{40}Ca at 115 MeV beam energy measured with the Compton polarimeter POLALI (see text).

arrangement is strongly supported by the observed second decay branch from the 3436 keV level into the 2080 keV level via the 400.7 and 955.5 keV γ rays. The angular distributions and linear polarization data revealed unambiguously the $E2$ nature of the 864.3 and 1356.3 keV γ rays and the $E1$ nature of the 1254.7 keV γ ray, respectively. Hence spin and parities of the yrast level sequence are $\frac{13}{2}^+$, $\frac{17}{2}^+$, and $\frac{19}{2}^-$, respectively, and not $\frac{13}{2}^+$, $\frac{15}{2}^-$, and $\frac{19}{2}^-$, as suggested in Ref. [14]. Some other, most probably positive parity states, have been observed at 2122, 2837, 3036, and 3738 keV excitation energies. Most of the depopulating γ rays were contaminated or rather weak in intensity. Thus angular distributions could not be analyzed, except for the 715.1 keV γ ray. Tentative spins and parities of these states are based on systematics. This will be discussed in Sec. IV.

In addition to the positive parity decay branches, the $\frac{19}{2}^-$ level at 4691 keV is depopulated via a considerable amount of negative parity states into the ground state. Spins and parities of the levels within the γ-ray cascades 462.8, 1655.1 (502.7, 1615.2 keV, respectively), 1418.1, and 1155.2 keV are most likely $\frac{15}{2}^-$, $\frac{11}{2}^-$, and $\frac{7}{2}^-$ since the ground state has $I^\pi = \frac{3}{2}^-$. Otherwise, at least two $M2$ transitions must be taken into account which should change parity and, hence, leads to a long lifetime of the initial level. This we could

TABLE I. Angular distribution coefficients A_2/A_0 and A_4/A_0, attenuation coefficients α_2 and α_4, and mixing ratios δ for the ^{65}Ge γ rays.

E_γ [keV]	I_i	I_f	A_2/A_0	A_4/A_0	α_2	α_4	δ
604.5	$\frac{5}{2}^-$	$\frac{3}{2}^-$	-0.31 ± 0.04	0.07 ± 0.01	0.50 ± 0.06	0.13 ± 0.04	$-2.35^{+0.57}_{-0.44}$
779.1	$\frac{7}{2}^-$	$\frac{5}{2}^-$	-0.37 ± 0.01	0.10 ± 0.02	0.55 ± 0.04	0.17 ± 0.03	$-2.58^{+0.17}_{-0.19}$
890.1	$\frac{7}{2}^-$	$\frac{3}{2}^-$	0.27 ± 0.03	-0.06 ± 0.04	0.53 ± 0.07	0.15 ± 0.05	0
1104.8	$\frac{9}{2}^+$	$\frac{5}{2}^-$	0.28 ± 0.01	-0.08 ± 0.01	0.63 ± 0.04	0.25 ± 0.04	-0.02 ± 0.01
325.8	$\frac{9}{2}^+$	$\frac{7}{2}^-$	-0.21 ± 0.01	0	0.63 ± 0.05	0.25 ± 0.05	0
864.3	$\frac{13}{2}^+$	$\frac{9}{2}^+$	0.30 ± 0.01	-0.07 ± 0.01	0.68 ± 0.02	0.30 ± 0.02	0
715.1	$(\frac{13}{2}^+)$	$(\frac{11}{2}^+)$	0.50 ± 0.02	0.06 ± 0.01	0.70 ± 0.05	0.33 ± 0.07	$0.66^{+0.09}_{-0.06}$
1356.3	$\frac{17}{2}^+$	$\frac{13}{2}^+$	0.30 ± 0.01	-0.06 ± 0.01	0.71 ± 0.02	0.35 ± 0.03	0
660.9	$(\frac{17}{2}^-)$	$(\frac{15}{2}^-)$	<0				
1254.7	$\frac{19}{2}^-$	$\frac{17}{2}^+$	-0.22 ± 0.01	0	0.74 ± 0.08	0.40 ± 0.12	0
187.0	$\frac{19}{2}^-$	$(\frac{17}{2}^-)$	<0				
461.8	$(\frac{21}{2}^-)$	$\frac{19}{2}^-$	-0.26 ± 0.03	2×10^{-4}	0.75 ± 0.05	0.40 ± 0.08	-0.03 ± 0.01
519.2	$\frac{23}{2}^-$	$\frac{19}{2}^-$	0.30 ± 0.02	-0.07 ± 0.02	0.75 ± 0.03	0.40 ± 0.03	0

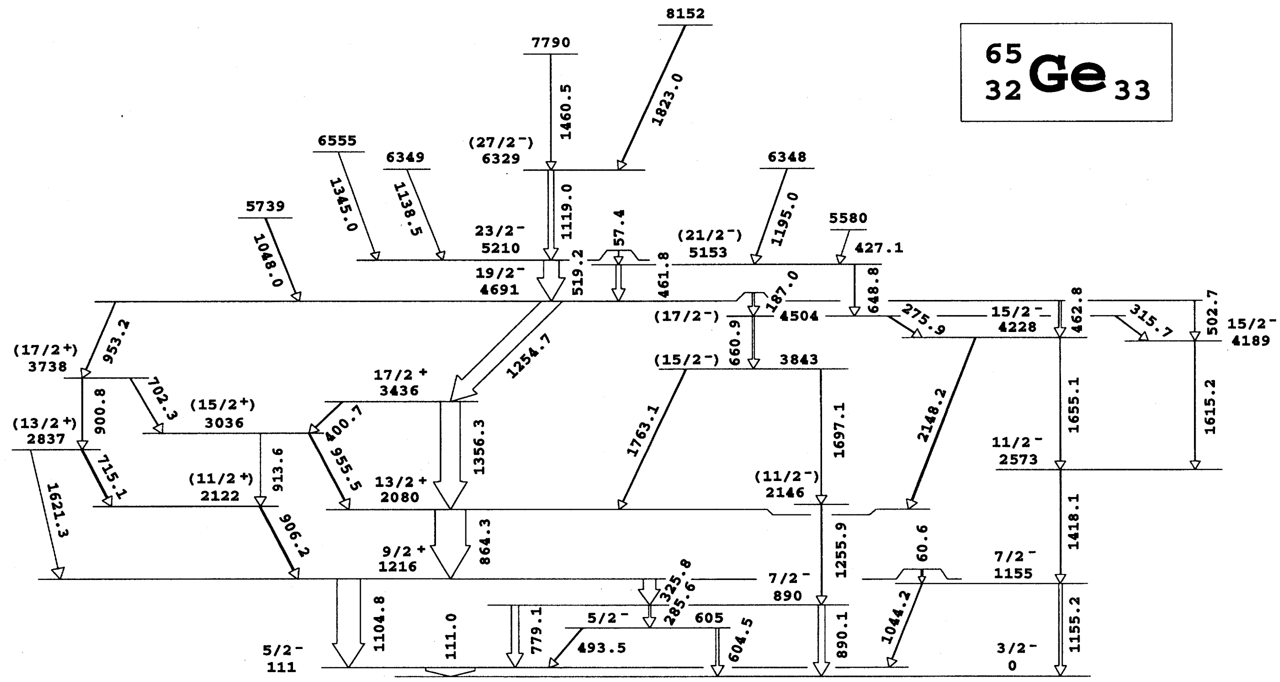


FIG. 5. Level scheme of ^{65}Ge as populated in the ^{40}Ca(^{28}Si,$2pn$) ^{65}Ge reaction. The γ-ray intensities are proportional to the widths of the arrows.

exclude with regard to the prompt coincidence condition (see Sec. II). The γ-ray cascade of 187.0, 660.9, 1697.1, and 1255.9 keV (1763.1 keV, respectively) in coincidence with the 519.2 and 461.8 keV γ rays along with the γ transitions depopulating the 890 keV level established the levels at 2146, 3843, and 4504 keV. γ-ray intensities were too weak for a proper analysis of the corresponding angular distributions. Nevertheless, the intensity of the 187.0 and 660.9 keV γ rays apparently was maximal at 90°. Thus we assume a $\Delta I = 1$ dipole character for both γ rays and spin and parity assignments of $I^{\pi} = (\frac{15}{2}^{-})$ and $(\frac{17}{2}^{-})$ for the 3843 and 4504 keV states, respectively.

The $\frac{19}{2}^{-}$ state is fed by the $E2$ transition of 519.2 keV, leading to the $I^{\pi} = \frac{23}{2}^{-}$ assignment for the 5210 keV level, and by a parallel cascade via the 57.4 and 461.8 keV γ rays. In disagreement with Ref. [14], the 461.8 keV γ ray is definitely not coincident with the 519.2 keV γ ray (this does not hold for the 462.8 keV γ ray). Consequently, both transitions have to be placed parallel to each other. The analysis of the 461.8 keV γ-ray angular distribution was aggravated by a contaminating 460.3 keV γ ray of ^{41}Ca, but is consistent with a pure $\Delta I = 1$ dipole transition. Thus an $I^{\pi} = (\frac{21}{2}^{-})$ assignment is most likely for the level at 5153 keV. This is additionally supported by a similar configuration in the neighboring nucleus ^{67}Ge [18]. The $\frac{23}{2}^{-}$ state at 5210 keV is populated by the 1119.0, 1460.5, and 1823.0 keV γ rays. Unfortunately, these γ rays were strongly Doppler broadened, which made it impossible to extract angular distributions. According to the systematics of the odd Ge isotopes, we propose $I^{\pi} = (\frac{27}{2}^{-})$ for the 6329 keV level.

IV. DISCUSSION

The valence nucleons outside the ^{56}Ni core are expected to fill the closely spaced $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$ negative parity orbitals and the $1g_{9/2}$ intruder orbital with positive parity. Thus it is reasonable to consider the $\frac{3}{2}^{-}$ ground state and the 111 keV $I^{\pi} = \frac{5}{2}^{-}$ state as single-particle states where the unpaired neutron occupies preferably the $p_{3/2}$ and $f_{5/2}$ orbital, respectively. The $\frac{5}{2}^{-}$ state at 605 keV and the $\frac{7}{2}^{-}$ states at 890 and 1155 keV may be regarded as collective excitation modes of the ground state, which is corroborated by the large $E2$ components of the depopulating 604.5 keV (85% $E2$) and 779.1 keV (87% $E2$) γ rays. In a very simplified picture,

TABLE II. Theoretical and experimental linear polarization $P(90°)$ for the ^{65}Ge γ rays.

E_{γ} [keV]	I_i	I_f	$P\,(90°)_{\mathrm{theor}}$	$P\,(90°)_{\mathrm{expt}}$	Multipol.
1104.8	$\frac{9}{2}^{+}$	$\frac{5}{2}^{-}$	-0.48 ± 0.01	-0.41 ± 0.10	$M2$
325.8	$\frac{9}{2}^{+}$	$\frac{7}{2}^{-}$	0.29 ± 0.01	0.28 ± 0.05	$E1$
864.3	$\frac{13}{2}^{+}$	$\frac{9}{2}^{+}$	0.49 ± 0.01	0.52 ± 0.05	$E2$
1356.3	$\frac{17}{2}^{+}$	$\frac{13}{2}^{+}$	0.50 ± 0.01	0.45 ± 0.10	$E2$
1254.7	$\frac{19}{2}^{-}$	$\frac{17}{2}^{+}$	0.30 ± 0.01	0.33 ± 0.06	$E1$

TABLE III. Relative intensities of the ^{65}Ge γ rays as measured with the 125° detector normalized on the 864.3 keV γ ray (100 ± 0.6).

E_i [keV]	E_f [keV]	E_γ [keV]	Relative intensity
605	0	604.5±0.1	10.3±0.5
890	111	779.1±0.1	22.2±0.4
890	0	890.1±0.1	16.5±1.3
890	605	285.6±0.2	4.2±0.3
1155	0	1155.2±0.2	12.0±2.0
1155	111	1044.2±0.2	7.0±0.5
1216	111	1104.8±0.1	77.5±0.5
1216	890	325.8±0.1	38.9±0.4
2080	1216	864.3±0.1	100.0±0.6
2122	1216	906.2±0.2	10.2±1.5
2837	2122	715.1±0.2	7.9±0.4
3036	2080	955.5±0.2	13.9±1.6
3436	2080	1356.3±0.1	63.5±0.9
4504	3843	660.9±0.2	11.8±0.5
4691	3436	1254.7±0.1	51.2±0.7
4691	4504	187.0±0.2	13.5±0.4
5153	4691	461.8±0.1	15.3±2.0
5210	4691	519.2±0.1	47.8±0.4
6329	5210	1119.0±0.3	18.2±1.8

these can be thought of as an fp-shell neutron coupled to the lowest 2^+ excited state of the core. Hence the decay pattern is very similar to the light odd Ga isotopes where the lowest $\frac{5}{2}^-$ state is single-particle-like, while the second $\frac{5}{2}^-$ has a collective $E2$ transition to the lowest $\frac{3}{2}^-$ state.

The $\frac{9}{2}^+$ state at 1216 keV defines the location of the expected $\nu\, g_{9/2}$ level. The excitation energy and the reduced transition probability of $B(M2)=0.11$ W.u. are consistent with the systematics of the $g_{9/2}$ states known throughout the mass region. Beyond that, the level spacing of the yrast sequence with transition energies of 864.3, 1356.3, 1254.7, 519.2, and 1119.0 keV agrees very well with the neighboring Ge istopes. This is demonstrated in Fig. 6. It can be seen that the energies of the yrast levels track very closely among one

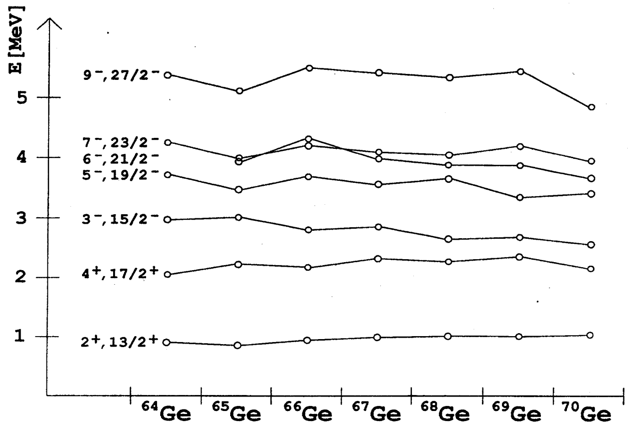


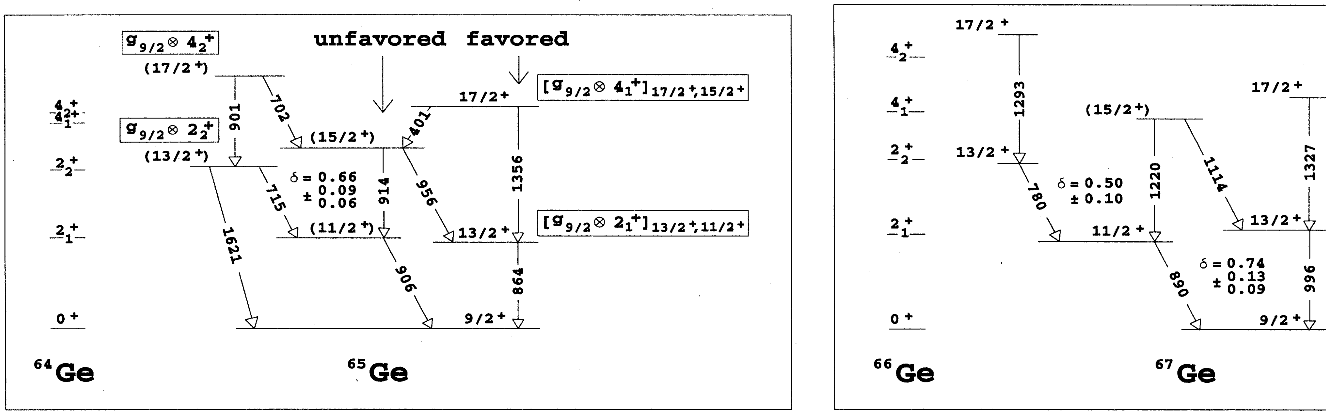
FIG. 6. Energy level systematics of the yrast states for the even and odd Ge isotopes. The energies of the odd systems are shown relative to the $I^\pi=\frac{9}{2}^+$ states.

another within the chain of Ge isotopes between ^{64}Ge and ^{70}Ge, suggesting an interpretation in the framework of the weak coupling model. For the sake of comparison, the excitation energies of levels in the odd systems are shown relative to the excitation energy of the respective $I^\pi=\frac{9}{2}^+$ states.

Referring to the question of octupole correlations, one can say the following: As pointed out in Sec. III, the strongly lowered yrast $\frac{15}{2}^-$ state at 3335 keV proposed in Ref. [14] does not exist. On the other hand, our level scheme yields three $\frac{15}{2}^-$ states at considerably higher energies of 3843, 4189, and 4228 keV. In the neighboring Ge isotopes, the $\frac{15}{2}^-$ (3^-) state is fed directly via an $E2$ transition from the $\frac{19}{2}^-$ (5^-) level and decays via an $E1$ transition into the $\frac{13}{2}^+$ (2^+) level. Hence the level at 4228 keV should be the corresponding state in ^{65}Ge since it is fed directly by the $\frac{19}{2}^-$ state (via the 462.8 keV γ ray) and decays into the $\frac{13}{2}^+$ state (via the 2148.2 keV γ ray). With respect to the $\frac{9}{2}^+$ state, this means an excitation energy of 3013 keV for the $\frac{15}{2}^-$ state, which fits very well into the trend of smoothly increasing energy with decreasing neutron number within the chain of Ge isotopes (see Fig. 6). As a consequence, it should be concluded that the very light Ge isotopes do not display softness toward octupole correlations, at least in the energy range of $E_x \leqslant 5$ MeV. On the other hand, in a recent publication of Nakatsukasa *et al.* [19] (and also in Ref. [6]) it is pointed out that an increase of the 3^- ($\frac{15}{2}^-$) octupole energy does not itself contradict the theoretical predictions of enhanced octupole correlations for the particle numbers N, $Z\approx34$. The reason is that in the $A\approx70$ mass region the 3^- excitation energy is not strongly correlated to the $B(E3,0^+\rightarrow3^-)$ transition probability. The available experimental data (see the compilation of Spear [20]) exhibit the $B(E3,0^+\rightarrow3^-)$ values 35.8, 23.6, 8.8, and 8.7 W.u. for ^{70,72,74,76}Ge. Thus the collectivity increases with decreasing neutron number, although the 3^- excitation energy remains nearly constant with a value of $\sim$2.5 MeV. Further, the $B(E3,0^+\rightarrow3^-)$ value of ^{70}Ge is one of the largest known throughout the mass region. To give a certain answer to the question whether enhanced octupole correlations play an important role in the structure of neutron-deficient Ge isotopes or not, it seems to be absolutely necessary to determine the $B(E3,0^+\rightarrow3^-)$ values for the lighter Ge istopes ^{64,66,68}Ge equally.

We would like to point out that two other papers dealing with the fact of octupole collectivity in the $A\approx70$ mass region have ben published in the last few years. Cottle [21,22] analyzed systematically the behavior of 3^- states from the available experimental data and obtained maximum octupole softening for N and Z values equal to 40. Chuu *et al.* [23] studied the negative parity states and octupole collectivity of even Ge isotopes in the framework of the interacting boson model with enlarged model space including both collective and noncollective basis states. They found that the portions of the collective configurations in 3^- states increase when going from ^{64}Ge to ^{72}Ge and decrease from ^{72}Ge to ^{74}Ge.

Finally, we would like to discuss the nonyrast positive parity states observed in ^{65}Ge. As pointed out in Sec. III, spins and parities of these states are based on a systematical comparison with the neighboring nuclei ^{67,69}Ge. This is demonstrated in Fig. 7. In ^{67}Ge and ^{69}Ge the



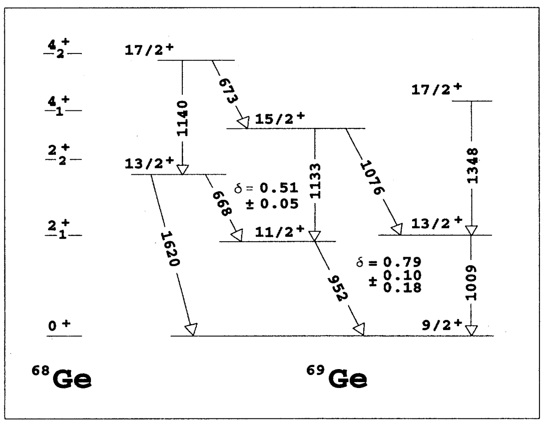


FIG. 7. Positive parity states in ^{65,67,69}Ge. The data of ^{67}Ge and ^{69}Ge are taken from Refs. [25] and [26].

positive parity level structure contains the $g_{9/2}$ favored band members with $I^\pi=\frac{9}{2}^+$, $\frac{13}{2}^+_1$, and $\frac{17}{2}^+_1$, the corresponding unfavored states with $I^\pi=\frac{11}{2}^+$ and $\frac{15}{2}^+$ and two additional states with $I^\pi=\frac{13}{2}^+_2$ and $\frac{17}{2}^+_2$. The latter two can be explained by the coupling of the $g_{9/2}$ neutron to the 2^+_2 and 4^+_2 states of the neighboring even nuclei. For the sake of comparison, the excitation energies of the 2^+_1, 2^+_2, 4^+_1, and 4^+_2 core states of the even Ge nuclei are plotted in Fig. 7 likewise. From the same excitation pattern in ^{65}Ge, we identify the states at 2122 and 3036 keV with the unfavored $g_{9/2}$ band members and the states at 2837 and 3738 keV with the second $\frac{13}{2}^+$ and $\frac{17}{2}^+$ states. The mixing ratio of the 715.1 keV γ ray ($\delta=+0.66$) in ^{65}Ge is in reasonable agreement with the mixing ratios of the corresponding γ rays in ^{67,69}Ge (see Fig. 6). In the light odd Ge nuclei, the $g_{9/2}$ bands are well decoupled. This is reflected by the relatively small deformation ($\beta_2\approx0.2$; see Ref. [1]) of the Ge isotopes in comparison to the strongly deformed Se and Kr isotopes ($\beta_2\approx0.3$–0.4). In the case of strongly coupled bands, the sign of the mixing ratio δ of the intraband transitions is often used to determine the intrinsic quadrupole moment Q_0. For instance, in ^{69}Se [24] the positive sign of δ of the $\frac{11}{2}^+\to\frac{9}{2}^+$ γ ray implied a negative sign of Q_0 and, hence, an oblate structure of the $g_{9/2}$ band. Unfortunately, this relation does not hold for the Ge isotopes where the deformation is somewhat less. Thus it would be desirable to calculate the excitation pattern of ^{65}Ge in the framework of the EXVAM code where the oblate-prolate mixing is studied in detail.

V. SUMMARY

In conclusion, we employed the ^{40}Ca(^{28}Si,$2pn$)^{65}Ge and ^{40}Ca(^{31}P,αpn)^{65}Ge reactions to measure $\gamma\gamma$ and $\gamma\gamma n$ coincidences, angular distributions, and linear polarization of γ rays. The level scheme of ^{65}Ge was extended by 36 new transitions and 20 new levels. Besides the $\frac{17}{2}^+$ state of the $g_{9/2}$ positive parity band, three $\frac{15}{2}^-$ states could be established at excitation energies of $E_x\sim4$ MeV. The structure of the yrast band appears to be consistent with the systematics of the other odd Ge isotopes and with a weak coupling of the odd $g_{9/2}$ neutron to excitations of the even-even ^{64}Ge core. In addition, we were able to identify the nonyrast positive parity states with $I^\pi=\frac{11}{2}^+$, $\frac{15}{2}^+$, and $\frac{13}{2}^+_2$, and $\frac{17}{2}^+_2$. The excitation energy of the candidate $\frac{15}{2}^-$ octupole state fits very well into the trend of smoothly rising energy with decreasing neutron number. So far, no hints for enhanced octupole correlations in ^{65}Ge could be found.

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