Structure of the Very Neutron-Deficient Ge Region: ^{64}Ge and ^{65}Ge

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The structure of the very neutron-deficient Ge region has been investigated with use of particle-γ coincidence techniques in weak fusion-evaporation channels. Excited states up to spin $\frac{31}{2}$ have been established in ^{65}Ge, and five transitions have been assigned to the $N=Z$ nucleus ^{64}Ge. The first excited state in ^{64}Ge is at 902.1 ± 0.8 keV. The ^{65}Ge level scheme provides the first indication in this mass region of a theoretically predicted softness with respect to octupole deformation.

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In recent years, considerable progress has been made in extending the application of in-beam γ-ray spectroscopy to ever weaker fusion-evaporation channels leading to nuclei with correspondingly more extreme neutron-proton ratios. Previously inaccessible regions of the nuclear chart have been opened up for study by new particle-γ coincidence techniques. Perhaps the most dramatic example to date has been the discovery[1,2] of a new region of strong deformation ($\beta_2 \sim 0.4$) in the light Kr and Sr isotopes ($Z=36$, 38, respectively) close to $N=Z$. The extent of this deformed region and the characteristics of the surrounding transitional region are the subject of intense study, both experimentally and theoretically. Strutinsky-model calculations[3-5] of total-potential-energy surfaces indicate that these nuclei are quite soft with respect to quadrupole deformation (typically with minima for both prolate and oblate shapes) and that the deformation can change quite rapidly with particle number. Thus a rich variety of nuclear-structure features are expected in this mass region.

In this Letter we report results for two very neutron-deficient Ge isotopes ($Z=32$), which are predicted[4] to lie in the transitional region roughly midway between the spherical and strongly deformed extremes. A high-spin level scheme has been extracted for ^{65}Ge, and five γ-ray transitions have been assigned to the $N=Z$ nucleus ^{64}Ge. These isotopes were produced with cross sections (determined from activity measurements) of 13 mb and 0.4 mb, respectively, corresponding to roughly 3% and 0.2% of the calculated total fusion cross sections.

Our experiments utilized a new 4π multisegment charged-particle detector[6] designed for in-beam particle-γ and particle-γ-γ measurements in weak fusion-evaporation channels. The detector elements are phoswich scintillator telescopes [made of plastic and CaF_2(Eu)] optimized for identification of evaporation protons and alpha particles. In the initial version of the system, roughly $\frac{1}{3}$ of 4π is subtended by six telescopes, and the rest of the sphere is covered with veto detectors. For every event, the energy and type of each charged particle striking the telescopes is measured, along with the γ-ray energies and timing information. In our first application of this device,[7] high-spin states in ^{65}Ge have been studied with the reaction ^{40}Ca(^{28}Si,$2pn$), using 60–100-MeV ^{28}Si beams from the University of Pennsylvania's tandem Van de Graaff accelerator. The targets were typically 350 $\mu g/cm^2$ of ^{40}Ca evaporated onto a 30-mg/cm^2 gold backing. A group of γ rays were found to be in coincidence with two protons and no alpha particles, and with excitation functions characteristic of three-particle evaporation. These transitions, which were also observed in coincidence with neutrons, can only be produced via the $2pn$ evaporation channel leading to ^{65}Ge. The in-beam γ-ray intensities are also consistent with the production cross section determined from out-of-beam measurements of transitions in ^{65}Ga populated[8] by the β^+ decay of ^{65}Ge ($t_{1/2}=31$ s).

The ^{65}Ge-level scheme, shown in Fig. 1, was established on the basis of charged-particle–γ–γ coincidences (using one pair of Ge γ-ray detectors), charged-particle–γ-ray timing data, and angular distributions of γ rays in coincidence with a neutron detector at 0°.

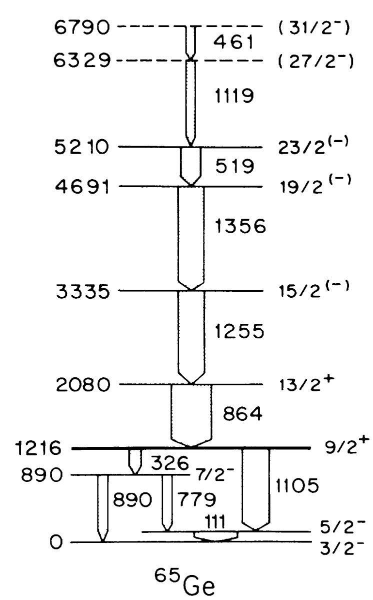

FIG. 1. Energy-level scheme for ^{65}Ge. Energies are in kiloelectronvolts. The $\frac{9}{2}^+$ state at 1216 keV is isomeric.

Several of the transitions in Fig. 1 have been previously assigned to ^{65}Ge in an unpublished Ph.D. thesis[9]; however, the reported level scheme[8,9] can be ruled out, in particular on the basis of our γ-ray timing data, which reflect the location of an isomeric transition in the cascade. The valence nucleons outside the ^{56}Ni core ($N=Z=28$) are expected to fill the closely spaced $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ levels, and the more highly excited $1g_{9/2}$. Low-lying $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ states are observed in odd-mass nuclei throughout the region, along with isomeric $\frac{9}{2}^+ \rightarrow \frac{5}{2}^-$ $M2$ decays. The ^{65}Ge $J^\pi = \frac{3}{2}^-$ ground state[10] is fed primarily by a 111-keV γ ray with a nearly isotropic angular distribution, consistent with a $\Delta J = 1$ $E2/M1$ transition with a mixing ratio[11] $\delta = -0.25 \pm 0.04$. This defines the location of the expected $\frac{5}{2}^-$ level; the $\frac{1}{2}^-$ state (which has not been observed) is expected to be only weakly populated as it is nonyrast. The charged-particle–γ timing data reveal the presence of an isomeric state at 1216 keV with $t_{1/2} = 7 \pm 1$ ns, which decays via a stretched quadrupole transition to the $\frac{5}{2}^-$ level. The lifetime makes an $E2$ assignment improbable, and strongly favors identification of the 1216-keV state with the expected $\frac{9}{2}^+$ isomer. The excitation energy and the reduced transition probability [$B(M2) = 0.11 \pm 0.02$ Weisskopf units (W.u.)] are consistent with the systematics of the $\nu g_{9/2}$ states known throughout this mass region. Above the isomer, an $E2$ assignment is required for the 864-keV stretched quadrupole (and similarly for the 519- and 461-keV transitions) by the absence of a measurable lifetime ($t_{1/2} \lesssim 2$ ns). The 1255-keV transition, with a mixing ratio consistent with zero, is ascribed to an $E1$ decay from a $\frac{15}{2}^{(-)}$ level at 3335 keV. The parity assignments for the $J = \frac{15}{2}$ and $\frac{19}{2}$ states are not rigorous, but are clearly favored by a detailed consideration of the decay pattern of the γ cascade, the observed and expected yrast states, and the systematics of heavier odd-A Ge isotopes.[12]

Excited states in ^{64}Ge were populated via $p2n$ evaporation following fusion of ^{40}Ca with ^{27}Al. The γ-ray transitions[13,14] in ^{64}Ga and ^{64}Zn, fed by β^+ decay of ^{64}Ge and ^{64}Ga, respectively, were observed with a beam-chopper system. From these measurements, the $p2n$ yield (^{64}Ge) was found to be smaller than the $2pn$ yield (^{64}Ga) by a factor of 65 ± 10, corresponding to a peak ^{64}Ge production cross section of roughly 0.4 mb. To increase further the channel selectivity for in-beam measurements, charged-particle–neutron–γ coincidences were measured, by use of a large-volume liquid-scintillator detector ($40 \times 76 \times 30$ cm^3 thick), directly coupled to a single 20-cm-diam hemispherical photomultiplier (Hamamatsu R1408). The front face of the detector was located 41 cm downstream from the target at 0°. A clean n-γ discrimination was obtained by measurement of the time of flight relative to the charged-particle detectors. A 102-MeV ^{40}Ca beam was used on a gold-backed 400-μg/cm^2 ^{27}Al target, to minimize target contaminants and to enhance the kinematic focusing of the neutrons, resulting in a measured single-neutron detection efficiency of about 10%.

Gamma-ray spectra gated on various combinations of evaporated particles are shown in Fig. 2, where several of the known lines in the $2pn$ and $3pn$ channels have been labeled. These lines feed through into the $1pn$-γ spectrum because of events in which one or two of the protons are lost in the dead areas between the detectors. (The $3pn$ feedthrough would be more than an order of magnitude larger if the veto detectors covering $\frac{2}{3}$ of 4π were turned off.) However, such lines are always at least equally visible in the higher-multiplicity spectrum, thus allowing a straightforward identification of the charged-particle component of the evaporation. Candidates for $1pxn$ lines can be identified by subtraction of the feedthrough contributions to the $1pn$-γ spectrum, resulting in the spectrum at the bottom of Fig. 2. A constant times the $2pn$-γ spectrum has been subtracted in order to eliminate the strong $2pn$ lines[15]; feedthrough from α-related channels has been similarly subtracted. In this procedure, the higher-multiplicity channels are oversubtracted, resulting in negative peaks, for example for the

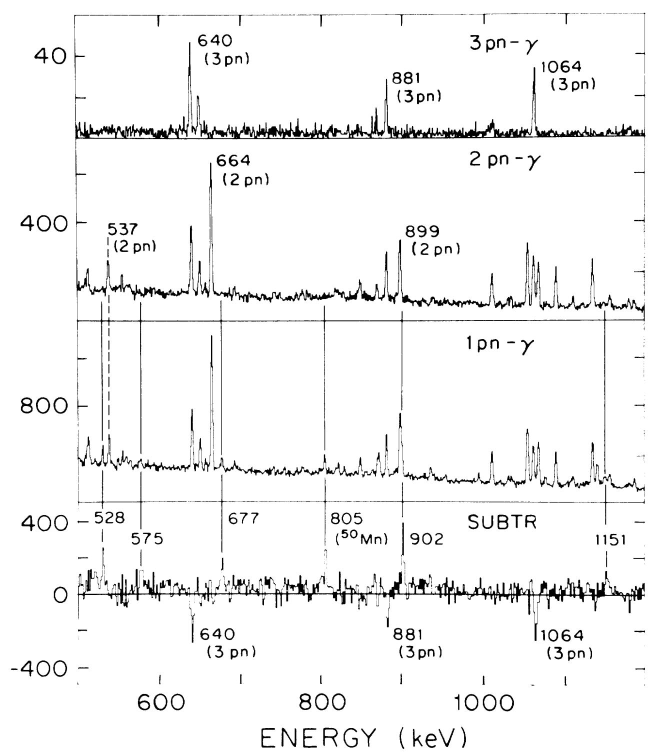

FIG. 2. γ-ray spectra in coincidence with a neutron plus various combinations of charged particles, for 102-MeV ^{40}Ca on ^{27}Al; energies are in kiloelectronvolts. The bottom curve is a subtracted spectrum (see text); it has been compressed by adding adjacent channels in pairs. The 805-keV transition is from the reaction ^{12}C(^{40}Ca,pn)^{50}Mn.

$3pn$ transitions. The labeled positive peaks exhibit the proper $1pxn$ signature; e.g., the 528-keV transition is clearly present in $1pn$-γ and absent in $2pn$-γ. The strong 902-keV peak is only partially resolved from a known $2pn$ line at 899 keV.

Our identification of transitions in ^{64}Ge is based on their $0\alpha 1pxn$ signature in the coincidence data, on our detailed knowledge of the pn channel (leading to ^{65}Ge), and on the consistency of the in-beam intensities [which give $\sigma(2pn)/\sigma(p2n) = 78 \pm 24$] with the activity data. The $p3n$ channel is expected to be much weaker, and would peak at considerably higher beam energy. Reactions on light target contaminants were ruled out by identical measurements with carbon and oxygen targets. The five transitions assigned to ^{64}Ge are listed in Table I. On the basis of the γ-ray intensities, the 902-keV line must be the $2^+ \to 0^+$ transition (on the assumption that 0.1 meV $< E_{2^+} <$ 3 MeV), thus determining the energy of the first excited state. Similarly, the 1151-keV line is the most likely candidate for the $4^+ \to 2^+$ transition, although γ-γ coincidences and γ-ray angular distributions will be necessary to determine the level scheme in this transitional nucleus. After completion of the present work,[16] Ooi *et al.* reported[17] the assignment to ^{64}Ge of a transition at 901.6 ± 0.5 keV, using the reaction ^{12}C(^{54}Fe,$2n$) and particle-γ coincidences. This result is in good agreement with the strongest of the lines which we have observed, and the cross-bombardment information provides an important verification of the assignment.

Early calculations by Sheline[18] of single-particle energies in a deformed potential predicted a shell gap for a superdeformed shape ($\varepsilon = 0.6$) for $N \sim Z \sim 32$. However, these calculations did not include liquid-drop effects, which drive the nucleus towards a spherical shape. Strutinsky-model calculations including both shell and liquid-drop effects have *not* predicted a strongly deformed ^{64}Ge ground state. For example, Ragnarsson and Sheline[3] calculated a very soft potential-energy surface for ^{64}Ge with a spherical minimum, while Bengtsson *et al.*[4] report minima at $\varepsilon \sim 0.15$–0.20 for ^{64,66,68}Ge. In the odd Ge isotopes, the high-spin yrast states have been interpreted[19,20] as coupling of a $g_{9/2}$ neutron to the excitations of the neighboring even-even cores (e.g., in terms of weak coupling to core vibrations, or decoupled bands built on rotation of a prolate core). Figure 3 shows the systematics of the excitation energies of yrast states in ^{65,67,69}Ge (relative to the $\frac{9}{2}^+$ state) and of the corresponding core states, which are identified at the right. The new results for the ^{64}Ge $2^+ \to 0^+$ transition and the corresponding $\frac{13}{2}^+ \to \frac{9}{2}^+$ transition in ^{65}Ge fit smoothly into the pattern of slowly decreasing energies with decreasing N. (Note, however, that from a simple picture in which the collectivity is related to the number of neutron-proton pairs[22] in the N and $Z = 28$–50 shells, one would expect the 2^+ energy to be *rising* as N decreases.) The positive-parity sequence is observed in ^{67,69}Ge only up to $\frac{17}{2}^+$. The yrast states at higher spin appear to arise from coupling to the negative-parity core states with $J \geq 5$, which have been interpreted as members of a two-quasiparticle rotational band,[23] and which are strongly populated in ^{66,68}Ge. In general, the yrast states in ^{65}Ge fit smoothly into the systematics, consistent with a picture in which there is no sharp change in the nuclear structure (such as a major increase in the quadrupole deformation) out to $N = Z$. However, the $\frac{15}{2}^{(-)}$ state, which in ^{67,69}Ge follows closely the excitation energy of the 3^- core vibration, suddenly drops in energy relative to the $\frac{9}{2}^+$ by more than 700 keV in going from ^{67}Ge to ^{65}Ge. This may reflect a drop in the 3^- energy in the ^{64}Ge core (see below). The sharp increase in the $\frac{19}{2}^{(-)} \to \frac{15}{2}^{(-)}$ transition energy in ^{65}Ge is probably responsible for our nonobservation of the $\frac{17}{2}^+$ state, as the competing $\frac{19}{2}^{(-)} \to \frac{17}{2}^+$ branch should be below our sensitivity (if we assume that the structure of

TABLE I. Energies and intensities for γ-ray transitions assigned to ^{64}Ge in the present work. The identification is somewhat less certain for the transitions in parentheses because of complications from neighboring lines in other channels.

E_γ (keV)[a]	$I_\gamma^{rel}(135°)$[b]
528.5	40
(575.5)	39
677.0	41
902.1	100
(1150.7)	61

[a]Energies accurate to ± 0.8 keV.

[b]γ-ray intensities normalized to the 902.1-keV yield, accurate to $\pm 20\%$ (statistical uncertainty only).

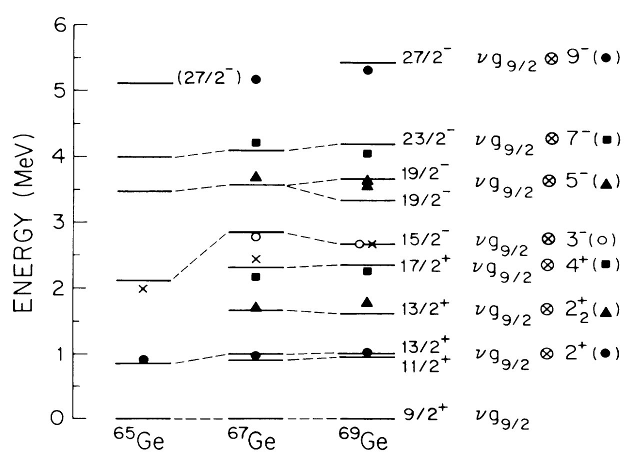

FIG. 3. Energies of yrast states relative to the $\frac{9}{2}^+$ level for ^{65}Ge (present work), ^{67}Ge (Ref. 19), and ^{69}Ge (Ref. 20). The circles, squares, and triangles represent the energies of the corresponding core excitations. The crosses represent predictions of octupole vibration energies (normalized to ^{68}Ge) based on the calculations of Ref. 21. See text for discussion.

the states is unchanged from ^{67,69}Ge).

The Strutinsky calculations of Nazarewicz *et al.*,[21] which included octupole as well as quadrupole and hexadecapole shape degrees of freedom, indicated that nuclei in the light Ge-Se region would be stable but rather soft with respect to octupole deformation, with the largest effect predicted for ^{64}Ge. The results were reported in terms of the octupole stiffness parameter C_3, determined from the curvature of the potential-energy surface as a function of β_3. In a hydrodynamic model, the octupole vibration energy is given by $\hbar\omega_3 = \hbar(C_3/B_3)^{1/2}$. Using the calculated[21] C_3 and the empirical 3^- energy for ^{68}Ge, we determined the inertial parameter B_3. The octupole vibration energies for the other Ge isotopes were then predicted from the calculated stiffness parameters,[21] and inertial parameters scaled (slightly) according to the hydrodynamic-model A dependence. The calculations (shown as crosses in Fig. 3) predict a modest decrease in the 3^- energy in ^{66}Ge (compared with an observed modest increase), followed by a sharper drop in ^{64}Ge. The predicted ^{64}Ge 3^- energy is quite consistent with the $\frac{15}{2}^{(-)}$-$\frac{9}{2}^+$ spacing observed in ^{65}Ge. We also note that the calculations of Ref. 21 show an anticorrelation between quadrupole and octupole effects. Ge is predicted to display octupole softness (rather than Sr, for example) at least partly because it is *not* strongly quadrupole deformed, and we could not have expected this behavior if the ^{64}Ge or ^{65}Ge level schemes had suggested a large increase in the quadrupole deformation at $N=Z$. Clearly, it will be interesting to perform the difficult γ-γ measurements in ^{64}Ge which are necessary to test this interpretation by directly identifying the 3^- excitation.

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