Structure of ^{80}Ge revealed by the β decay of isomeric states in ^{80}Ga: Triaxiality in the vicinity of ^{78}Ni

D. Verney,[1,*] B. Tastet,[1] K. Kolos,[1] F. Le Blanc,[1] F. Ibrahim,[1] M. Cheikh Mhamed,[1] E. Cottereau,[1] P. V. Cuong,[2] F. Didierjean,[3] G. Duchêne,[3] S. Essabaa,[1] M. Ferraton,[1] S. Franchoo,[1] L. H. Khiem,[2] C. Lau,[1] J.-F. Le Du,[1] I. Matea,[1] B. Mouginot,[1] M. Niikura,[1,†] B. Roussière,[1] I. Stefan,[1] D. Testov,[1,4] and J.-C. Thomas[5]

[1]*Institut de Physique Nucléaire, CNRS/IN2P3 and Université Paris Sud, Orsay, France*

[2]*Center for Nuclear Physics, Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam*

[3]*Institut Pluridisciplinaire Hubert Curien, CNRS/IN2P3 and Université de Strasbourg, Strasbourg, France*

[4]*Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia*

[5]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Caen, France*

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The decays of two long-lived low-lying isomeric states of ^{80}Ga were studied at the PARRNe mass separator of the ALTO ISOL facility. Over the 75 γ rays previously attributed to the ^{80}Ga decay, the decay time of 67 individual β-delayed γ activities were measured. This allowed the determination of the decay time of these two recently reported long-lived—actually β-decaying—states as well as to partially disentangle the two decay schemes. Thanks to the relatively high spin difference between these two ^{80}Ga isomers spin assignments of the daughter ^{80}Ge states could be further constrained rendering the comparison with calculations easier. From this comparison it appears that the suspected maximum of collectivity at $Z = 32$ along the $N = 50$ line should express itself through the coexistence of spherical and collective γ-soft structures.

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I. INTRODUCTION

The present study of the γ-ray deexcitation following the β decay of ^{80}Ga is part of a systematic study of the decays of surface ionized neutron-rich Ga isotopes in the vicinity of the $N = 50$ shell closure undertaken at the ALTO ISOL facility of the Institute of Nuclear Physics (IPN), Orsay. The structure of the Ge nuclei close to $N = 50$ is of high interest as it is now well established that the effective $N = 50$ gap undergoes a local minimum at $Z = 32$ thanks to the remarkable extension of precise mass measurements to this hard-to-reach region [1,2]. While the spherical $N = 50$ shell gap apparently persists, this minimum can be associated to a maximum of quadrupole coherence, or collectivity in general, as can be inferred from both beyond mean field [3] and shell model [4] treatments. ^{80}Ge having only two neutron holes with respect to the $N = 50$ closure should exhibit interesting features susceptible to help in characterizing the nature of this collectivity. Detailed γ spectroscopy following ^{80}Ga β decay is covered only by the comprehensive study of Hoff and Fogelberg [5]. All the absolute γ-ray intensities as well as branching ratios reported in the evaluation [6] originate from this work. The authors proposed a spin (3) for the ^{80}Ga ground state (g.s.) for which $T_{1/2} = 1.676(14)$ s was adopted [6]. It was underlined in Ref. [5] that, contrary to what could be expected from the systematics of $Z < 38$ $N = 49$ odd-odd isotones which all exhibit isomerism, no evidence for the existence of a second β-decaying state in ^{80}Ga could be found. Later on a $466 - 1235 - 1083 - 659$ keV cascade attributed to the deexcitation of a high spin level populated in deep-inelastic collisions was reported [7] and confirmed in a later similar experiment [8]. This cascade was interpreted as $E2$ transitions deexciting the $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+_{\text{g.s.}}$ states in ^{80}Ge. All transitions being also observed in the ^{80}Ga β decay, the possible existence of a second β-decaying state of high spin in ^{80}Ga, typically (7^-), was then suspected [7]. The proposed (8^+) isomeric state lies at 3445.11 keV in the ^{80}Ge level scheme, its half-life has been precisely determined using fast-timing techniques to be $T_{1/2} = 2.95(6)$ ns [9] which makes it a good candidate for a seniority isomer of two-hole $(1g_{9/2})^{-2}$ single particle origin. During our investigation of the β decays of neutron-rich Ga isotopes at ALTO, preliminary results on ^{80}Ga studied in a collinear laser spectroscopy experiment performed at ISOLDE were brought to our attention by the Manchester group [10]. These results were published soon after [11] and showed unambiguously the existence of two long-lived states assigned $J = 3$ and $J = 6$ (a negative parity was assigned to those states based on shell model arguments). We felt that it could be of some interest to check if the two identified long-lived states of ^{80}Ga were actually β-decaying, to determine their half-lives (Sec. III) and also to propose two separate decay schemes for $^{80(\text{ls})}$Ga (lower spin: $J = 3$ according to [11]) and $^{80(\text{hs})}$Ga (higher spin: $J = 6$ according to [11]) (Sec. IV). New insights on the spin-parity assignment of some of the known excited states of ^{80}Ge can be inferred from the large spin difference of the mother states. A discussion about the collectivity of ^{80}Ge will be proposed in Sec. V.

II. EXPERIMENTAL PROCEDURE

^{80}Ga sources were obtained as mass separated fission products created in the interaction of the 50-MeV electron primary beam with a thick UC_x target at the PARRNe mass separator operating on-line to the ALTO ISOL installation at the Institute of Nuclear Physics (IPN), Orsay. The ion production method

*verney@ipno.in2p3.fr

†Present address: Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan.

and experimental setup were basically identical to those described in Ref. [13] where additional details can be found. We mention here only the main differences with respect to that previous experiment. The primary electron beam average intensity in the present experiment was 5 μA which amounts to approximately $\gtrsim 10^{10}$ fissions/s, in order of magnitude, inside the target container [14]. As in our previous experiment a tungsten tube was used to selectively ionize Ga, but the temperature of the tube was limited here to $\simeq 2000^{\circ}$C, which is 10% lower than in the previous experiment. In such target ion-source conditions an effective yield of 9.4×10^3 ^{80}Ga^{1+} ions per second was available at the collection point of the tape station. The other main difference with respect to our previous experiment was that the shielding of the mass separator was completed and the Rb activities coming from upstream parts of the beam line were significantly suppressed. The γ-detection system consisted of one tapered coaxial HPGe detector of the EUROGAM Phase1 type with a resolution of 2.3 keV at 1.3 MeV and one small EXOGAM CLOVER detector [15] from the prototype series (100% relative efficiency) with a typical resolution for the central signal of a single crystal of 2.0 keV at 1.3 MeV. The global photopeak efficiency at 1.3 MeV was 1.4%. The cycling of the tape motion was set to a 3-s grow in to reach approximately 75% of the equilibrium activity, followed by a 9-s decay (beam off), which corresponds to approximately 5.5 times the ^{80}Ga half-life in order to allow reasonable half-life measurements while not loosing too much beam time. Data were taken with the mass-separator set on $A = 80$ during 3.3 h, so that a total number of 1.04×10^7 of β events were recorded. Figures 1 shows the total statistics for this run which amounts to 800 tape cycles. As can be seen in this figure the spectrum is quite clean and the activity is by far dominated by the decay of ^{80}Ga.

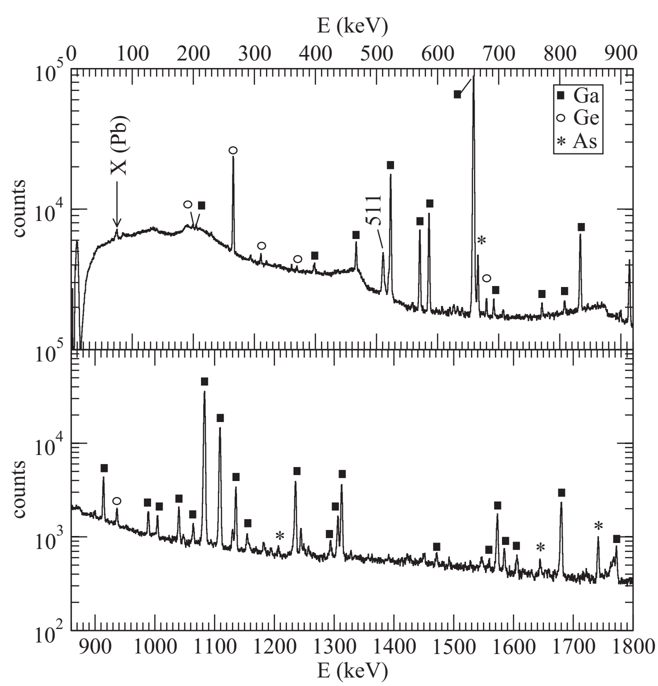

FIG. 1. β-gated γ spectrum recorded at mass 80 in the 0–1800 keV energy range.

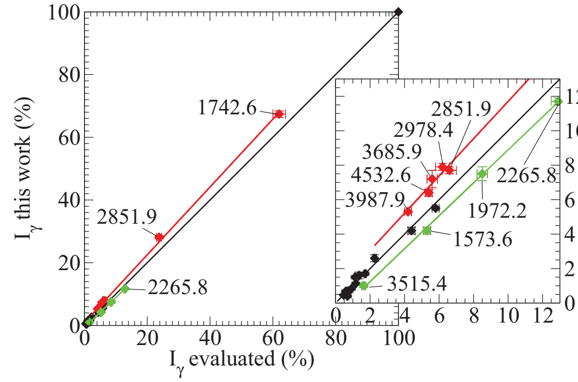

FIG. 2. (Color online) Relative γ intensities for transitions in ^{80}Ge observed in this experiment (vertical axis) vs. relative γ intensities from the evaluation [6] (horizontal axis). Symbols are in red (above diagonal) or green (below diagonal) for γ activity in clear (more than 2σ) excess or deficit, respectively, of the $^{80a+80b}$Ga source obtained in the present experiment from photofission of ^{238}U with respect to the compiled values. The last ones originate from the ^{235}U thermal neutron induced fission data of Ref. [5]. Lines are drawn only to guide the eye. Numbers close to the symbols correspond to the excitation energy, in keV, of the ^{80}Ge states from which the γ-emission originates.

Figure 2 shows the relative intensities of the β-delayed γ rays emitted by the $^{80a+80b}$Ga source, as measured in this experiment, as a function of the evaluated values [6]. At first sight the isomeric ratio in our experiment and the one of Hoff and Fogelberg [5] appear to remain of the same order of magnitude, though the fission process and fissioning system were different [^{238}U(γ, n_f, f) vs. ^{235}U(n_{th}, f) in the latter]. Only a massive suppression of one of the two populations in the ion source could lead to a clear systematic deviation from the tabulated values. However some scattering around $X = Y$ is indeed observed and values cluster in three distinct groups. Most of the weakest transitions, especially those with $I_\gamma \lesssim 2\%$ cluster along the $X = Y$ line, partly because of lack of sensitivity of our system but also because the decay schemes of the two precursors ^{80a}Ga and ^{80b}Ga are quite fragmented and interlinked. Yet one sees clearly a group corresponding to an excess in γ activity with respect to the observations of Hoff and Fogelberg (and the evaluated table), and one with weaker intensity. Both groups deviate from the evaluated I_γ values by more than 2σ. In Fig. 2 are also reported the excitation energies of the γ-emitting state in the ^{80}Ge daughter nucleus. As will be seen in Sec. IV, all states showing a γ activity in excess are populated by the longer-lived isomer of ^{80}Ga and all those showing a γ activity in deficit by the shorter-lived isomer of ^{80}Ga (1972.2 keV is an exception and is probably simultaneously fed in both decays as explained later).

III. SEARCH FOR THE DIFFERENT ACTIVITIES

We could systematically determine the characteristic half-life of the activity of 67 of the β-delayed γ rays over the 75 originally attributed to the decay of ^{80}Ga by Hoff and Fogelberg. The average half-life of the whole observed γ activity is 1.71(2) s, a bit larger than the adopted value of

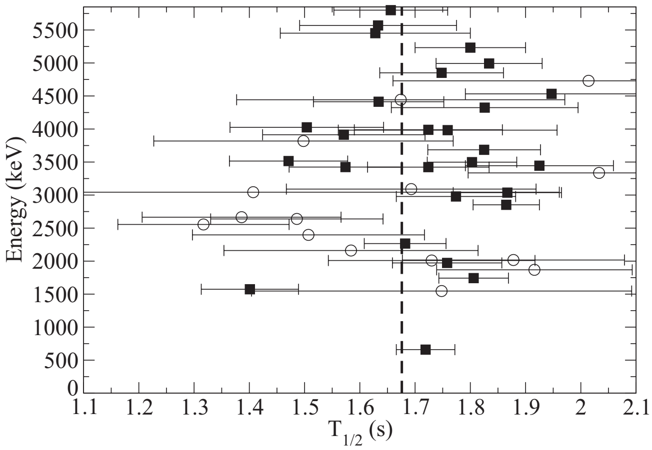

FIG. 3. Measured apparent half-life of the levels of ^{80}Ge (squares) and transitions not placed in the level scheme (circles). The adopted value $T_{1/2} = 1.676$ s [6] is represented by the dashed line.

$T_{1/2} = 1.676(14)$ s [6]. We note that $T_{1/2} = 1.697(11)$ s was proposed in a previous evaluation of $A = 80$ [17]. An apparent half-life for a given excited state in ^{80}Ge can be determined from the observed time behavior of the different γ-transitions through which it decays. For n γ transitions depopulating a given state, its apparent half-life can be obtained as the weighted average [16]:

$$\overline{T}_{1/2} = \frac{\sum_{i=1}^{n} \frac{T_{1/2}(\gamma_i)}{[\Delta T_{1/2}(\gamma_i)]^2}}{\sum_{i=1}^{n} \frac{1}{[\Delta T_{1/2}(\gamma_i)]^2}}$$

with

$$\Delta\overline{T}_{1/2} = \left[\sum_{i=1}^{n} \frac{1}{[\Delta T_{1/2}(\gamma_i)]^2}\right]^{-\frac{1}{2}}.$$

Such values are displayed in Fig. 3 as a function of the γ-ray energy. The γ transitions not placed in the level scheme are also placed in this diagram at their own energies. Values are scattered between two extremes: the shortest close to 1.3 s and the longest close to 2 s. As can be seen in Fig. 3, the adopted value $T_{1/2} = 1.676$ s is approximately situated at middistance between the extremes of the values we could determine. A higher number of points in this graph is found on the right-hand part hinting at a higher number of states populated by the longer-lived isomer. We propose to attribute to the longer-lived ^{80}Ga β-decaying state the apparent half-life measured for the (8^+) level at 3445.11 keV: $T_{1/2}^{L} = 1.925 \pm 0.134$ s. This choice appears reasonable since this level with its supposedly (8^+) nature [7] should be fed uniquely by the $J = 6$ isomer. No indirect feeding of this state has been reported [6] neither did we observe any. The presumably high spin of the state and its high excitation energy allows assuming reasonably that such an upper feeding can be indeed neglected. As can be seen in Fig. 3, most of the γ transitions characterized by the shortest apparent half-lives are unfortunately not placed in the level scheme (most of them are very weak). We however have not much choice but to propose the shortest of those values as the most probable half-life of the shorter-lived ^{80}Ga β-decaying state. This corresponds to the γ ray at 2554.95 keV with $T_{1/2}^{S} = 1.317 \pm 0.155$ s. In the following section we will check that those values are indeed consistent with all observed apparent half-lives. From the proposed (8^+) nature of the state at 3445.11 keV we propose then

$$^{80(\mathrm{hs})}\mathrm{Ga} : T_{1/2} = 1.9 \pm 0.1 \text{ s}, \quad ^{80(\mathrm{ls})}\mathrm{Ga} : T_{1/2} = 1.3 \pm 0.2 \text{ s}.$$

IV. THE ^{80a}Ga AND ^{80b}Ga DECAY SCHEMES

One can try from the individual γ-line half-life determination obtained here to propose two separate decay schemes for the ^{80a}Ga and ^{80b}Ga isomers. In the following hypotheses:

(i) the number of β-decaying states is limited to two (no intermediate activity between the two extremes determined here);
(ii) the spins of the two β-decaying states ^{80a}Ga and ^{80b}Ga are those determined experimentally in Ref. [11], a : $J = 3$ and b : $J = 6$ (a hypothesis consistent with the β-decay data as will be seen later);
(iii) the model dependent negative parity attribution for both states as proposed in [11] is correct; then,
  (a) the decay of a 3^- state would primarily populate the $J^\pi = 2^-, 3^-$, and 4^- states of ^{80}Ge through allowed transitions and $J^\pi = 2^+, 3^+, 4^+$ through first-forbidden nonunique (ffnu) transitions;
  (b) the decay of a 6^- state on the other hand would primarily populate the $J^\pi = 5^-, 6^-, 7^-$ and $J^\pi = 5^+, 6^+, 7^+$ states of ^{80}Ge through allowed and ffnu transitions respectively.

In the conventionally expected (Raman-Gove) log ft range there is no overlap possible between the spin range attainable by the decays of the two isomers except via first-forbidden unique (ffu) transitions. In that last case one could imagine 4^+ states fed simultaneously by a ffnu transition from the $J = 3$ isomer and a ffu transition from the $J = 6$ isomer and 5^+ states the other way. But there is at least an order of magnitude expected in the branching ratio between ffnu and ffu transitions and the different sources of uncertainties in the individual γ-line half-life determination should normally prevent from reaching such a sensitivity. Then, by analyzing the γ-ray time behaviors observed in our experiment as the result from the contributions of the direct feeding from the two isomers and the indirect feeding from the depopulation of higher lying ^{80}Ge states one should be able to assign each level to one of the two decay schemes. Deviations from this general rule would originate from unobserved indirect feedings or strong structure effects.

In the following we will propose a quantity suitable to help in assessing the belonging of the excited states of ^{80}Ge to one of the two decay schemes. For that purpose we express the *apparent* decay constant λ_A of a given state in ^{80}Ge as

$$\lambda_A = \frac{Br}{Br + F}[X\lambda_S + Y\lambda_L] + \frac{F}{Br + F}\lambda_F, \qquad (1)$$

where

(i) $\lambda_A = \ln 2/T_{1/2}^{A}$ and we use the $T_{1/2}^{A}$ values introduced in the previous section and presented in Fig. 3;

(ii) $\lambda_S = \ln 2/T^S_{1/2}$ and $\lambda_L = ln2/T^L_{1/2}$ are the decay constants of the shorter lived and longer lived ^{80}Ga isomers, respectively, with the $T^{(L,S)}_{1/2}$ values determined in the previous section;

(iii) $Br \equiv I_{\beta^-}$ the direct feeding of the level (per 100 decays) which is separated here into two possible contributions: XBr the contribution from the shorter lived ^{80}Ga isomer and $YBr \equiv (1-X)Br$ the one from the longer lived isomer;

(iv) correspondingly F is the indirect feeding of the level per 100 decays, $F = \sum_{i=1}^{n} F_i$ for n individual transitions to the level, where F_i is the absolute intensity of the feeding transition per 100 decays; with this notation, $Br + F$ is the absolute total decay of a given state per 100 decays;

(v) at last, $\lambda_F = \ln 2/T^F_{1/2}$ is the apparent decay constant associated with the indirect feeding, $T^F_{1/2}$ was taken as the weighted average:

$$\overline{T}^F_{1/2} = \frac{\sum_{i=1}^{n} F_i \frac{T_{1/2}(\gamma_i)}{[\Delta T_{1/2}(\gamma_i)]^2}}{\sum_{i=1}^{n} \frac{F_i}{[\Delta T_{1/2}(\gamma_i)]^2}}$$

with

$$\Delta\overline{T}^F_{1/2} = \left[\sum_{i=1}^{n} \frac{F_i}{[\Delta T_{1/2}(\gamma_i)]^2}\right]^{-\frac{1}{2}}$$

for n γ transitions feeding a given state.

From Eq. (1), one obtains the following expression for the fraction of the direct feeding to a state in ^{80}Ge, coming from the lower-spin ^{80}Ga isomer, as a function of the different half-life values:

$$X = \frac{1}{R}\frac{1/T^F_{1/2} - 1/T^A_{1/2}}{1/T^L_{1/2} - 1/T^S_{1/2}} + \frac{1/T^L_{1/2} - 1/T^F_{1/2}}{1/T^L_{1/2} - 1/T^S_{1/2}}, \qquad (2)$$

where $R = Br/(Br + F)$ is the proportion of the direct feeding contribution in the total (direct+indirect) feeding of the state. X is then used to try to attribute each of the ^{80}Ge levels to one of the two decay schemes. Levels with values close to $X = 0$ are considered as good candidates to the decay scheme of the longer-lived $J = 6$ ^{80}Ga isomer and close to $X = 1$ to the decay scheme of the shorter-lived $J = 3$ isomer. The X values could be deduced from the $T^A_{1/2}$ measured from our data for all the known levels of ^{80}Ge except the one at 5338.2 keV which decays by two weak high-energy transitions with too low statistics in our spectra. The X values are reported in Fig. 4 which can be readily compared to Fig. 3. The tips of the error bars in Fig. 4 actually correspond to the extreme values of X compatible with the uncertainties on the four periods $T^{(S,L,A,F)}_{1/2}$ involved in its determination (so they must be understood as the most likely X range). The smallest X ranges are mechanically obtained when no indirect feeding is observed, in which case all terms in $T^F_{1/2}$ simply drop. Most of the levels present X ranges compatible with 0 or 1 exclusively, and we propose to attribute them to one of the two level schemes. It shows that the half-life values $T^{(L,S)}_{1/2}$ proposed for the two ^{80}Ga isomers in the previous section are indeed compatible with the 30 values of $T^A_{1/2}$ determined

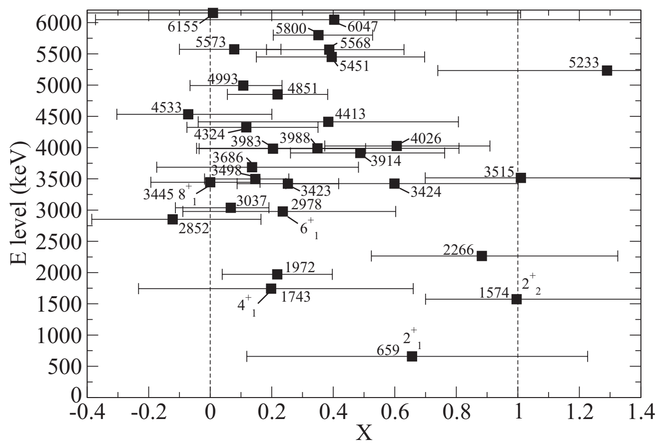

FIG. 4. X, the fraction of the feeding to ^{80}Ge states from the lower-spin ^{80}Ge isomer, as given by Eq. (2), sorted as a function of the energy level in ^{80}Ge on the ordinate axis.

independently from the 67 individual β-delayed γ activities. The only levels which present an ambiguous behavior are those located at 3913.7 keV, 5451.3 keV, 5568.0 keV, and 5800.5 keV because their X range excludes both the 0 and 1 limits and the X-central values are close to 0.5, and the level at 6155.3 keV for which the apparent half-life determination is poor and the X range encompasses both 0 and 1 limits. We will propose no decay-scheme attribution for those five levels nor for the level at 5338.2 keV as explained above.

We have used the I_γ as obtained from our data and rescaled the Br values from Ref. [6] to equilibrate the feeding (direct+indirect) and decay of the considered levels. We have checked that a direct use of I_γ and Br from the evaluation brings only minor differences. We have found only two noticeable exceptions: one for the 2^+_1 level at 659.1 keV and one for the level with no spin assignment at 2851.9 keV. As can be seen in Fig 4, the X value for the 2^+_1 level significantly deviates from the expected limit of 1. The total observed feeding γ-intensity to this level was measured to be $F = 67.6(19)\%$ very close to the value which can be calculated from Ref. [6] 64.5(16)%. We determine $T^F_{1/2} = 1.763(7)$ s, very close to, and compatible with the apparent half-life of the level $T^A_{1/2} = 1.719(53)$ s. It suggests that the contribution from the direct feeding is small. Actually a perfect agreement is found if a reduced value of $Br \simeq 5\%$ is taken instead of the tabulated 13(4)%. Unfortunately the uncertainties on X are too large to allow a precise re-evaluation of the direct branching to this state: taking into account the full uncertainties on the $T_{1/2}$ determinations would actually give $Br = 5^{+9}_{-5}\%$. This however tends to indicate that the yield of the $J = 3$ ^{80}Ga isomer was somewhat lower in our experiment than in the one of Hoff and Fogelberg. It confirms the observation made earlier with Fig. 2: the balance of the long- and short-lived γ activities are a bit different in the two works because of the different production modes of ^{80}Ga. The situation for the level at 2851.9 keV sheds even more light on this. This level attracts the most fragmented γ strength of the level scheme with 11 transitions contributing to the indirect feeding. The total observed feeding γ intensity to this level was measured to be $F = 23.3(5)\%$ and the total decay 35.8(8)% to be compared with 20.7(4)% and 23.7(7)% in the literature. This in our case would suggest $Br = 12.5(13)\%$ instead of the 3.0(9)% tabulated. When used in the calculation of X, the numbers from the literature lead to the anomalous value of $X = -1.1$. However it does not change the level-scheme attribution: this state must belong to the decay of the longer-lived ^{80}Ga isomer. No other strong deviation with respect to the values in the literature is observed. For that reason and because the measurement of the absolute γ intensities would have necessitated a direct measurement of the isomeric ratio and absolute ion counting (impossible or difficult with our experimental setup), we will not propose new branching ratios.

At last we mention the somewhat puzzling case of the state at 1742.6 keV which is assigned to (4^+) in the literature. There is no obvious reason to doubt the 4^+ assignment made to this state as it is well established in the $E2$ cascade deexciting the 8^+ isomeric state in ^{80}Ge. The total γ indirect contribution is found equal to 43(1)% in our case versus 38.7(8)% in the literature but the intensity of the decay transition at 1083.5 keV is 52.6(8)% in our case versus 48.4(2)% in the literature, in both cases a direct feeding of this state of 9.5(20)% allows to equilibrate the activity. With an X value close to 0 and following our method this level should be attributed to the decay scheme of the $J = 6$ isomer, but the log ft of 6.4 is not in the unique forbiddenness conventional range. This is however compatible with the fact that this $J = 6$ ^{80}Ga isomer apparently also decays directly to the 8^+ state through a $(\Delta J = 2, \Delta\pi = -)$ β transition with a very low log ft. If we turn to the example of the β-decay of ^{78}Ga to the even-even neighbor nucleus ^{78}Ge [18] we see a rather strong feeding with log $ft = 6.5$ from a recently determined $J^\pi = 2^-$ g.s. [19] to the well-established 4_1^+ state, which is also somewhat low for a $(\Delta J = 2, \Delta\pi = -)$ β transition (for that reason ^{78}Ga g.s. has long been assigned to $J = 3$). In any case, the fact that the higher-spin isomer feeds both $J = 4$ and $J = 8$ states in ^{80}Ge is an argument in favor for its $J = 6$ attribution made in Ref. [11]. The origin of these odd log ft values is difficult to identify. It is unlikely, but not impossible, that the Pandemonium contribution remains important at an excitation energy as high as 3.4 MeV in ^{80}Ge. Structure effects can also be at stake. Be that as it may, log ft values must certainly be taken with great caution in absolute value, they are however quite useful in relative values and one fact cannot be ignored: if the lower-spin ^{80}Ga isomer has $J^\pi = 3^-$ it should have a direct contribution to the 4^+ state at 1742.6 keV at least one order of magnitude higher than the 6^- isomer which is not compatible with our period measurements. However it should be pointed out that the β decay of the 2^- g.s. [19] of ^{78}Ga does (but weakly) feed the 0_2^+ state in ^{78}Ge [18] while in case of the ^{80}Ga decay there is strictly no evidence for the population of 0^+ excited states. This was already correctly pointed out by Hoff and Fogelberg (3.3 in [5]) as no strong peaking of a $0-2-0$ cascade is observed in γ-γ coincidence measurements at 180°. This is consistent with the increase by one unit of angular momentum between the ^{78}Ga g.s. and the lower-spin isomer in ^{80}Ga and is an argument in favor of the spin attribution of $J = 3$ made to this state in [11] provided the spin determination of ^{78}Ga is also correct.

Though log ft evaluations are extremely difficult for all the reasons just given, data we have in our possession are already sufficient for our needs. We can indeed propose the following empirical rule relying on the previous ^{80}Ge excited state spin assignments of Ref. [5] and those corresponding to the $E2$ cascades deexciting the 8^+ seniority isomer [7,8]: states belonging to the $^{80(\mathrm{hs})}$Ga decay will be supposed to have $J \geqslant 4$ and states belonging to the $^{80(\mathrm{ls})}$Ga decay, $1 \leqslant J \leqslant 3$. Following this empirical rule we propose the partial decay schemes of the two ^{80}Ga long-lived states displayed in Fig. 5.

V. DISCUSSION

A. Context

The structure of ^{80}Ge, situated at the "critical" $Z = 32$ number close to $N = 50$, is of particular interest. As mentioned in the introduction a local minimum in the effective (correlated) $N = 50$ gap, defined as $\Delta = S_{2n}(N = 52) - S_{2n}(N = 50)$, has been found. It has a strong influence on the nuclear structure nearby as best exemplified by the energy behavior of the core-breaking 1p-1h yrast states in the $N = 50$ even isotones down to $Z = 32$ [21,22]. Recent beyond mean field *and* shell model calculations do account for this minimum [3,4]. The underlying microscopic mechanism responsible for it—though necessarily contained in those calculations—is not yet established and one may wonder if it contains some generality.

1. Structure of ^{80}Ge

γ softness has long been suspected in the stable and light $N = 48$ nuclei (see, e.g., [20]). In fact many of the quantities $[E(2^+), B(E2), R_{42}$, etc.] usually used as indicators of collectivity show irregularities in their systematics at $N = 48$ for the even-even nuclei with $Z, N < 38, 50$. Sizable asymmetry is found for ground states of stable Ge and Se isotopes from an extensive analysis of the experimentally available $E2$ matrix elements [23]. As pointed out in [13], from comparison with beyond mean field calculations, γ softness is likely to be maintained much further away from stability along the $Z = 32$ line, $N = 50$ offering nothing but a parenthesis of rigidity. The interacting boson model description of this region has been found satisfactory [24,25] and in particular, Ge isotopes are thought to exhibit properties compatible with the $E(5)$ dynamical symmetry, that is between spherical vibrator and complete γ softness. At last, the 8^+ isomer most likely corresponds to a spherical two-neutron hole $(1g_{9/2})^{-2}$ configuration, hence coexistence between collective and spherical structures is also to be expected. In particular, due to the proximity of the $N = 50$ shell closure, competing noncollective or less collective states of marked quasiparticle nature (four protons qp and two neutron qp in the case of ^{80}Ge) may also appear as it is the case in the $N = 48$ isotone ^{84}Kr [26]. The recent development of residual interactions suitable to describe this region makes the shell model a tool of choice to describe simultaneously the potentially competing collective and qp structures, and provides a natural description of the former in terms of particle configurations (provided the valence space used in the calculation does contain all necessary degrees of freedom).

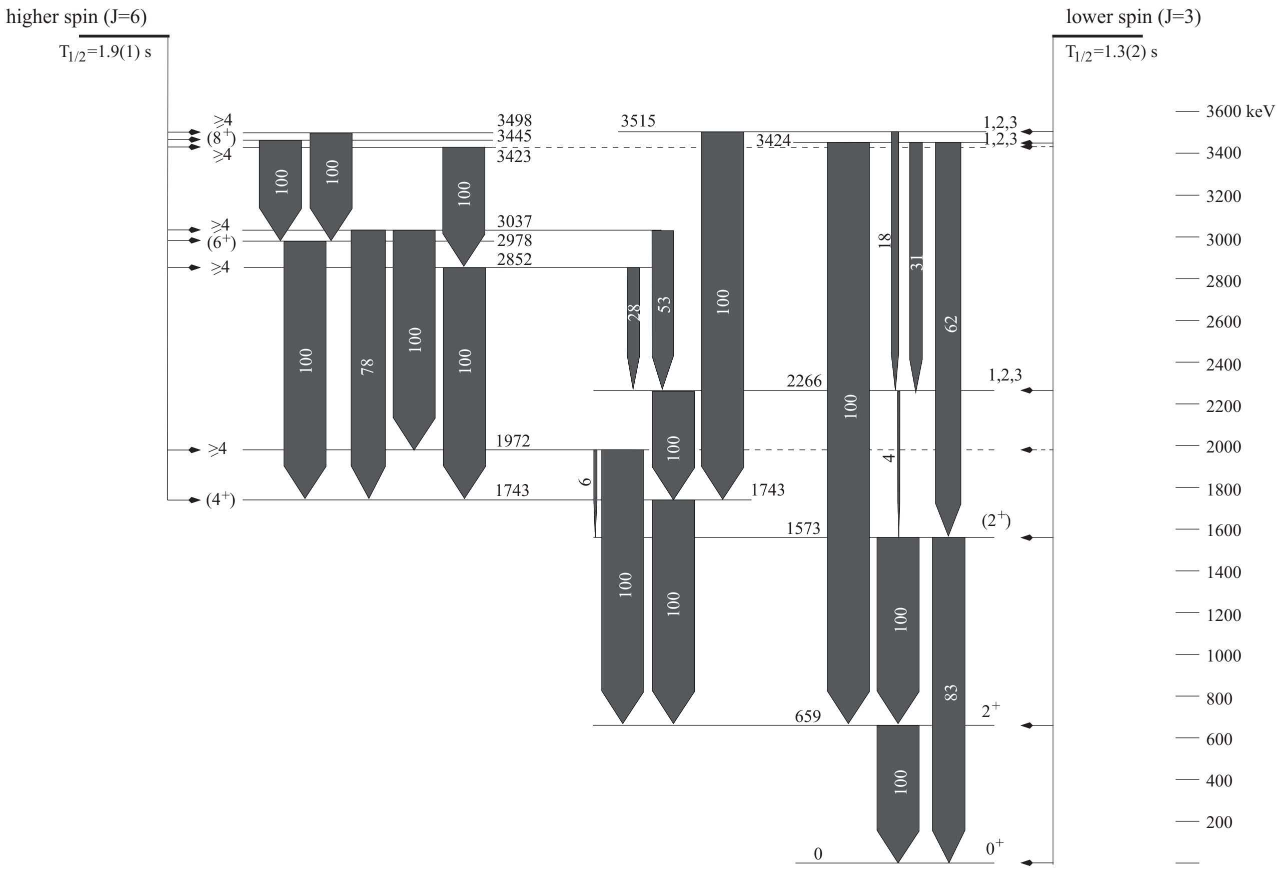

FIG. 5. Proposed decay schemes for the two ^{80}Ga β-decaying states following the discussion of Sec. IV, up to 3600 keV excitation energy. On the left hand side are displayed the levels fed directly by the β decay of the longer-lived isomer ($J = 6$), on the right hand side those fed directly by the β decay of the shorter-lived isomer ($J = 3$). Transitions displayed in the middle are those connecting the two decay schemes.

2. *Regional considerations*

Turning now to the $Z = 32$ and $N = 48$ systematics, represented in the left and right hand parts, respectively, of Fig. 6, one sees two very different pictures. This is somewhat expectable as in the Ge series the structure is dominated by the progressive filling of the neutron $g_{9/2}$ orbit while in the $N = 48$ series, protons are distributed among the $f_{5/2}$, p orbits and the structure evolution reflects roughnesses in the occupation evolution, as for instance the subshell closures $Z = 38, 40$. The evolution of the structure of the Ge isotopes is very regular as a function of the neutron number: main $2^+_1, 4^+_1, 6^+_1, 8^+_1$ g.s. bands exist, 8^+_1 states appearing as a real members of these bands, being connected to the 6^+_1 states by collective $E2$ transitions and well separated in energy from them. Aside from these g.s. bands one finds clear sequences of the type $2^+_2, 3^+_1, 4^+_2$ which look quite similar to quasi-γ bands and the presence of $3^+_1, 4^+_2$ states is well documented. In contrast, the 8^+_1 state in the $N = 48$ isotones has clearly not a collective origin, being dominated by a two neutron $g_{9/2}$ hole configuration, it is connected to the main g.s. band by weak $E2$ transitions and located close to the 6^+_1 state, leading to isomerism. One does not expect much collectivity in $^{86}Sr_{48}$ and $^{88}Zr_{48}$ due to the well-known stabilizing properties of the 38, 40 proton numbers. Collectivity however develops further below $Z = 38$ and band structures are already identified in ^{84}Kr (see, e.g., [28] and references therein). The structure is less clear than in the $Z = 32$ case as for instance no 3^+_1 state is firmly established. In ^{84}Kr the level at 2345.46 keV (with the evaluated 4^+_2 assignment, reported in the right hand part of Fig. 6) was thought to be actually a doublet of two levels at 2344.3 keV and 2345.6 keV from the results of a $(n, n'\gamma)$ experiment [38], the 2344.3 keV level being the missing 3^+_1 state (an option ruled out by the evaluators). Going towards $Z = 32$ there is no reason for a quasi-γ band structure not to reappear as it is so well established in the lighter Ge isotopes, unless a very drastic change occurs in the Ge series between $N = 46$ and $N = 48$. At last we mention that a 0^+_2 state is expected in ^{80}Ge, probably as low as 1 MeV if we follow the energy trends of the known 0^+_2 states from both $Z = 32$ and $N = 48$ systematics. Maybe it is even closer to the 2^+_1 state which would explain its non observation through $0^+_2 - 2^+_1 - 0^+_{\mathrm{g.s.}}$ coincidences already discussed earlier.

B. Theoretical approach

In this discussion we have used the recently developed sets of empirically modified two-body interaction JUN45 [29] and JJ4B [30]. A comparison of the results obtained with those two interactions has already been provided in Ref. [31] for the even-even Ge isotopes with $70 \leqslant A \leqslant 76$, and in Ref. [32]

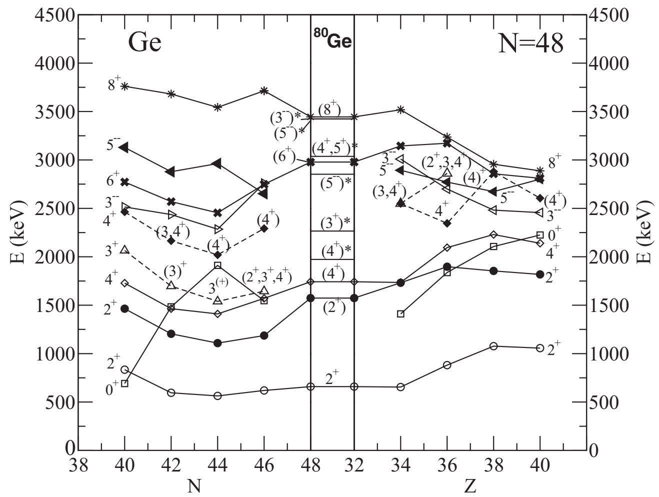

FIG. 6. The ^{80}Ge experimental level scheme placed in the Ge (left-hand part) and $N = 48$ (right-hand part) systematics. J^{π} assignments for ^{80}Ge proposed in Sec. V C are accompanied by a star, the others are taken from previous works and evaluations, as quoted elsewhere in this paper. Only the energy of the 8^+ state in ^{76}Ge is taken from an unpublished work [36].

for $A = 82$. Calculations were performed here using the m-scheme shell model code ANTOINE [33,34]. The calculated level schemes are reported in Fig. 7.

1. Intrinsic shape determination within a pure shell model approach

In recent literature addressing collectivity development within the shell model, the analysis of the wave function in terms of intrinsic shape and motion generally relies on (i) relationships between certain quantities [energy and $B(E2)$ ratios, quadrupole moments] derived from the static axial and triaxial (Davydov-Filippov) rotor models, and (ii) potential energy surfaces from beyond mean field techniques. The main drawback is that (i) shapes are—most of the time—not static, (ii) without projecting on the angular momentum and restoring the particle number, a simple inspection of potential energy surfaces can be misleading. It is possible nevertheless to have a more general transcription of the shell model wave functions to intrinsic shapes and motions without relying on (i) and (ii) by using the *model-independent* n-body moments $P^{(n)}$ introduced by Kumar [27]. The diagonal matrix elements $P_s^{(n)} = \langle s \| P^{(n)} \| s\rangle$, with $|s\rangle$ the shell model eigenvectors J_i^{π}, were calculated up to $n = 6$. Calculation of the diagonal matrix elements $P_s^{(n)}$ involves summation over diagonal and nondiagonal $E2$ matrix elements between s and all possible intermediate states obtained from the shell model calculations. Here we have limited the sums to the subset $\{0^+_{1-4}, 1^+_1, 2^+_{1-5}, 3^+_{1,2}, 4^+_{1-4}, 5^+_1, 6^+_{1,2}, 8^+_{1,2}\}$. A strictly exact equivalence between the shell model $E2$ properties calculated in the laboratory frame and those in the intrinsic frame would have been obtained this way by exhausting the full $E2$ strength function. Care has been taken to include the main $E2$ transitions to the lowest lying states up to 8^+_1, in that way reasonable convergence criteria [27] are already achieved. Then the Kumar relations for the equivalent ellipsoid are applied, allowing to get without any loss of generality: the axial deformation parameter β_s, the asymmetry angle γ_s, and their fluctuations for each individual state s considered. Standard effective charges were used, $e_p = 1.5\ e$ and $e_n = 0.5\ e$ as the charge naturally cancels out in the derivation of these quantities. The $B(E2)$ values (reported in Fig. 7) are also already in quite reasonable agreement with the experimentally available ones [35] with such effective charges. The results are displayed in Fig. 8 in a β-γ sextant representation.

2. ^{80}Ge collectivity from shell model results

Though the lower parts of the level schemes exhibit apparent similarities between the two calculations (Fig. 7), one understands now that the structures described are in fact different. From the right-hand part of Fig. 7 (JJ4B calculations) one recognizes easily a band-like sequence very similar to what can be expected in a γ-soft situation, that is not too far from the O(6) limit of IBM: the $4^+_1, 2^+_2$ states would correspond to the $\tau = 2$ multiplet and the $6^+_1, 4^+_2, 3^+_1, 0^+_2$ states to $\tau = 3$. In addition, states are easily sorted as a function of the strongest $E(2)$ transitions in band-like systems. The $E2$ sequence decaying towards the g.s. has approximately the shape of a main g.s. band in a γ-soft rotor picture, even if the $B(E2)$ ratios are not exactly those expected in the pure O(6) limit. In Fig. 8(b), all the states which are strongly connected by $E2$ transitions are indeed located in a kind of γ pocket. As expected the 8^+_1 state is much less collective and does not belong to this γ pocket having the same $\gamma_{\rm rms}$ value as the $0^+_{\rm g.s.}$ and 2^+_1 state but with much lower $\beta_{\rm rms}$. What is obtained with the JUN45 interaction [left-hand side of Fig. 7 and Fig. 8(a)] is actually quite different. A pseudo-g.s. band is also present but, unlike with JJ4B, it ceases to be Yrast already at $J^{\pi} = 4^+$. In Fig. 8(a) it forms a sequence of states with very small $\gamma_{\rm rms}$, parallel to the β axis, starting at what can be considered as a quasispherical 6^+_2 state, with continuous increase of the axial deformation as the spin decreases. This is characteristic of quasiparticle (qp) states, in that case six qp (as the inspection of the wave functions also reveals, see later). A band system develops on top of the 2^+_2 and 3^+_1 states which exhibits features typical of quasi-γ bands. The states forming this system are all situated in a relatively well-defined region in the β-γ sextant centered around $\beta_{\rm rms} \simeq 0.135$ and $\gamma_{\rm rms} \simeq 34^{\circ}$. The 8^+_1 state presents very similar properties to the one calculated with JJ4B. At last, we note that the states which present the largest $\gamma_{\rm rms}$ values, $3^+_1, 4^+_1$, and 5^+_1 with JUN45 and $3^+_1, 4^+_2$, and 5^+_1 with JJ4B, can be considered as rigidly asymmetric according to Kumar's prescription on $P^{(6)}$ moments. As there is no way experimentally to access such high-order momentum (very complete multiple Coulomb excitation could do but to our knowledge there exists no example in the literature), we will not claim for the discovery of permanent low energy triaxial shape—claim found more often than necessary in recent literature. We note that according to the fourth-order momentum prescription, none of the calculated levels show significant β softness.

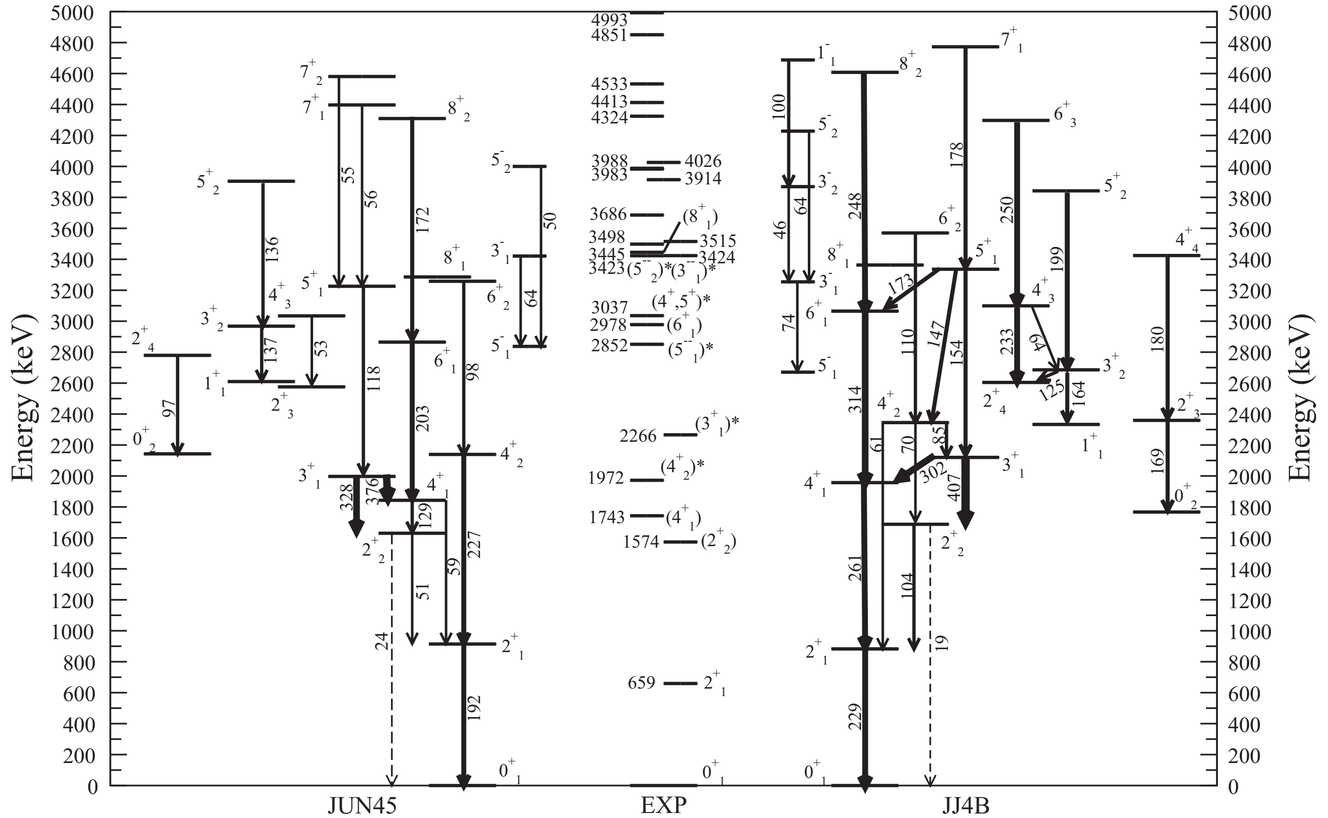

FIG. 7. Central part: ^{80}Ge experimental levels (up to 5 MeV). Those attributed to the higher-spin β-decay scheme are shifted to the left and those attributed to the lower-spin β-decay scheme to the right. Unless specified, the former are proposed ($J \geqslant 4$) and the latter ($1 \leqslant J \leqslant 3$) according to the discussion of Sec. IV. J^π adopted by the evaluator are reported when available, those which are proposed after the discussion of Sec. V C are accompanied by a star. Levels with uncertain decay-scheme assignment (3914 and 4026 keV in this energy span) are left in the middle. On the left (right) side is displayed the calculated level scheme using JUN45 (JJ4B) residual interaction, sorted in band-like structures according to their major $E2$ connections. Numbers close to the transition arrows are the $B(E2)$ values in e^2fm^4. Apart from the $2_2^+ \to 0_1^+$ transitions, only $E2$ transitions with $B(E2) > 50e^2$fm^4 are reported here for the sake of clarity.

3. Microscopic origin of the collective features

An analysis of the wave function is provided graphically in Fig. 9 in terms of proton configuration distribution of the $0^+_{\text{g.s.}}$, $2^+_{1,2}$, 3^+_1, $4^+_{1,2}$, $6^+_{1,2}$ states. Calculations where also done for the closed shell neutron neighbor ^{82}Ge in order to illustrate the influence of the neutron-hole pair. Three important remarks are in order:

(i) The general effect of the neutron pair suppression is to spread out the distribution which is perfectly expectable as the nucleus gains immediately some collectivity when opening the neutron shell. Some states keep a somewhat clear memory of the closed shell configuration: for instance the 2_2^+ and 3_1^+ states. These are incidentally two states belonging very clearly to the triaxial system whatever the interaction. The first conclusion is that most of the triaxial collectivity is of pure proton origin.

(ii) The $0^+_{\text{g.s.}}$ and 2_1^+ states in ^{80}Ge are essentially made of pairs of protons in the $f_{5/2}$, $p_{3/2}$ orbits accompanied by a two neutron-hole $g_{9/2}^{-2}$ pair with limited diffusion in the deeper p orbits. They can be identified with the states of quasi-particle character mentioned earlier. Such configurations are found again, though in slightly lower proportion, only in the 4_2^+ and 6_2^+ states calculated with JUN45. It was noticed earlier that the 2_1^+, 4_2^+, and 6_2^+ states calculated with JUN45 were situated on a line parallel to the β axis in the β-γ sextant and had moderate γ values (6_2^+ should be considered as quasispherical). These states are dominated by pairing components of the interaction.

(iii) All states which are clearly triaxial are dominated by the proton $f_{5/2}^3 p_{3/2}^1$ configuration, accompanied by other minor components of the type $f_{5/2}^3 p_{1/2}^1$, $f_{5/2}^2 p_{3/2}^1 p_{1/2}^1$, that is systematically with at least a broken proton pair with one proton promoted from the $f_{5/2}$ to p orbits. These states are dominated by quadrupole components of the interaction which connect $\Delta\ell = 2$ orbits.

Concluding this subsection, the situation from the shell model point of view is clear: the structure of ^{80}Ge is the result of the subtle balance between pairing and quadrupole terms of the interaction each of which governing two coexisting systems respectively: one of the (so-called here) qp-type and one of the collective triaxial type. The main difference between the two calculations is simply in the relative position in energy

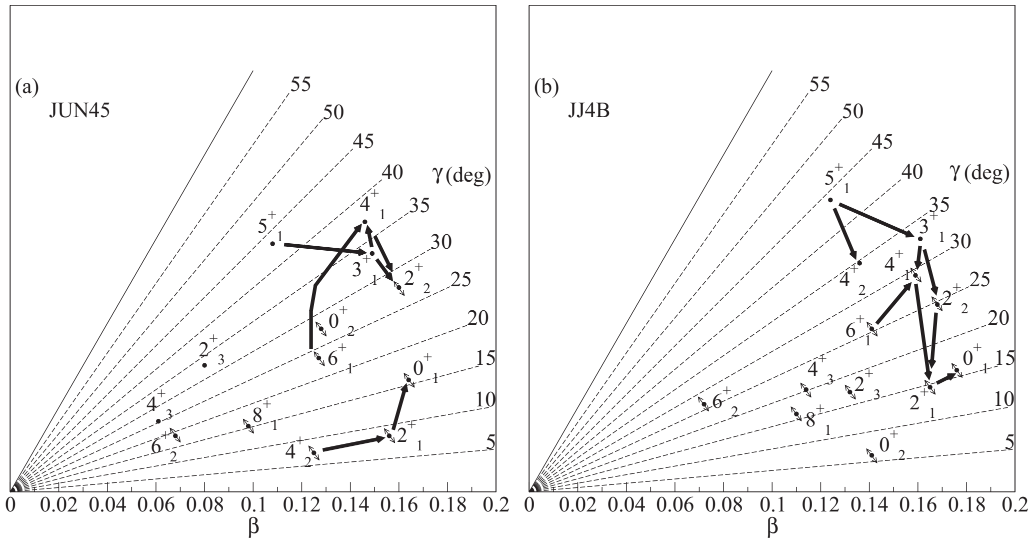

FIG. 8. Centroids of the *intrinsic* deformation parameters β_s and γ_s in polar representation for states $s = 0^+_{1-3}, 2^+_{1-3}, 3^+_1, 4^+_{1-3}, 5^+_1, 6^+_{1,2}, 8^+_1$ in ^{80}Ge. Values correspond to the shell model wave-functions obtained using the (a) JUN45 and (b) JJ4B sets of residual interaction parameters, through the evaluation of the Kumar operators with $E2$ matrix elements (see text). States which are γ-soft according to the value of the width $\sigma(\cos 3\gamma)$ as defined by Eq. (11) in Ref. [27] are marked with thin double arrows. The main $E2$ transitions connecting the states are represented by thick black arrows.

of these two systems: the qp-type is favored in energy using JUN45 while it is the collective triaxial type using JJ4B. Quite independently from the details of the interactions (a simple pairing plus quadrupole interaction would give the same) the reason for this difference is easy to find: the effective single particle energy separation between $f_{5/2}$ and $p_{3/2}$ in ^{79}Cu is about 1 MeV with JUN45 while it is only 390 keV with JJ4B, and proton quadrupole collectivity is obviously much more easily triggered in the last case. A more systematic study of triaxial collectivity and its microscopic origin in this mass region, e.g., in the framework of the shell model, is certainly called for, but it was felt that it fell beyond the scope of this work.

C. Discussion of the two decay schemes

In the following we use the very limited spin determination from the preceding section in combination with the results from shell model calculations and arguments from $Z = 32$, $N = 48$ systematics to try to propose a structure interpretation for ^{80}Ge, consistent with the experimental observations.

1. 1573.6 keV level

As suspected by Hoff and Fogelberg this level is likely to correspond to the 2^+_2 state. It definitely belongs to the lower-spin state decay scheme and has similar decay properties as the firmly established 2^+_2 state of the $Z = 32$ and $N = 48$ neighbors ^{78}Ge and ^{82}Se, with a strong transition to the ground state bypassing the 2^+_1 state. It is reproduced in both calculations, with good agreement in energy, as the second excited state. And, as it can be seen in Fig. 8, this state is clearly γ-soft with $\gamma_{\rm rms} \simeq 25$–$28^\circ$ in both calculations. Considering the results from JJ4B, it has properties compatible with those of a 2^+_γ band-head of a γ band.

2. 1742.6 keV level

From Fig. 4, this level can be attributed to the higher-spin state decay scheme. As mentioned earlier there is no reason to doubt this is the 4^+_1 state as it appears in the $E2$ cascade fed by the 8^+_1 isomer. It appears also in the main $E2$ sequence in the JJ4B calculation but not in the JUN45 calculation.

3. 1972.2 keV level

This is one of the few examples for which the shorter-lived isomer ratio coefficient X is simultaneously well determined while its range does not encompass any of the two limits 0 or 1. In the diagram of Fig. 4 the X range for this state is clearly on the side of small values but not strictly compatible with 0. This favors an attribution of this level to the higher-spin isomer decay and $J \geqslant 4$ but does not rule out completely a contribution from the lower-spin isomer decay. In addition, as seen in Fig. 2, it belongs to the deficit I_γ group, which apparently contains only levels of the shorter-lived isomer decay. Such ambiguous behavior is expected from $J = 4, 5$ states, as mentioned earlier. The only naturally occurring calculated counterpart would then be the 4^+_2 state. Experimentally this state deexcites mainly towards the 2^+_1 state but has also a minor connection to the state at 1573.6 keV (see Fig. 5) proposed as the (2^+_2) state in the preceding paragraph. This is consistent with the calculated $B(E2)$ of the transitions deexciting the 4^+_2 state with JJ4B and the 4^+_1 state with JUN45. In fact, considering their experimental decay properties, it seems that the structure of the 4^+_1 and 4^+_2 states, as obtained from the JUN45 calculation, are just energetically inverted. A 4^+ assignment to this 1972.2 keV level is also consistent with the $N = 48$ systematics: the well established 4^+_2 state in ^{84}Kr$_{48}$ exhibits quite similar decay properties (see [28]). At last, this state was also populated in deep inelastic collisions [36].

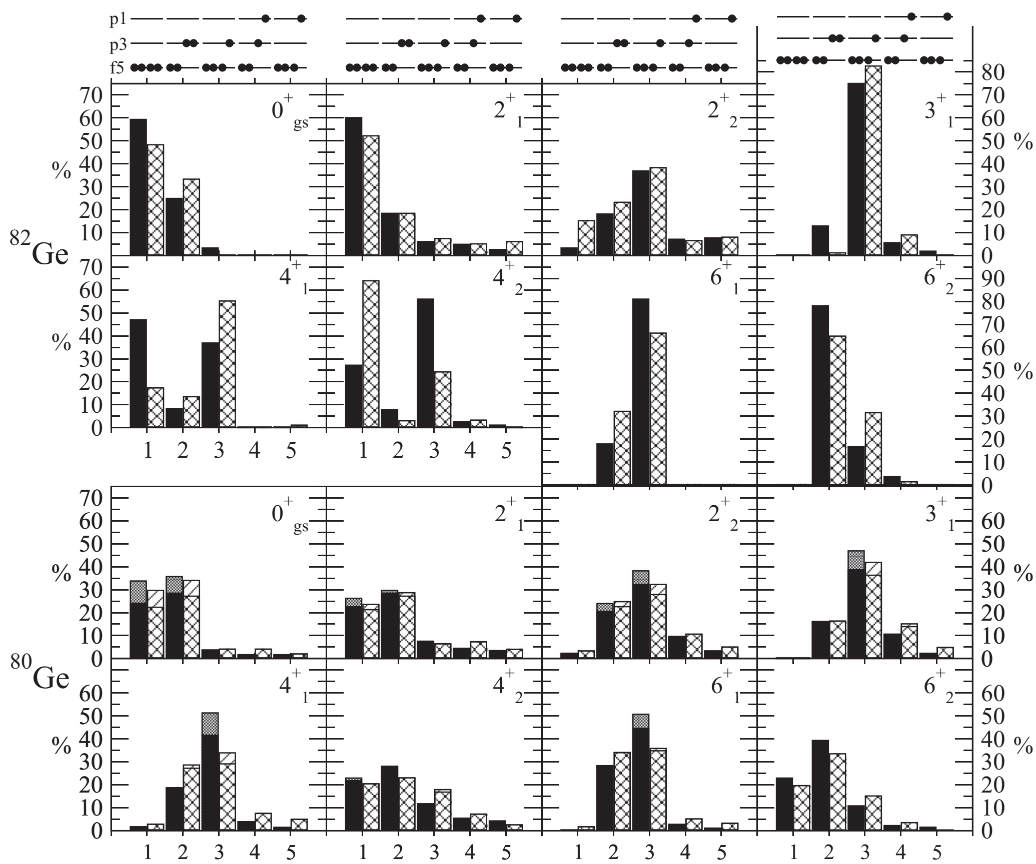

FIG. 9. Proton configuration distribution of the wave-functions of the $0^+_{\mathrm{g.s.}}$, $2^+_{1,2}$, 3^+_1, $4^+_{1,2}$, $6^+_{1,2}$ states in ^{82}Ge (top) and ^{80}Ge (bottom). The value of a given component of the wave function, in percent, is represented with plain color (black and gray) bars for shell model results obtained with the JUN45 interaction and hatched (doubly and simply) bars for those obtained with the JJ4B interaction. Only the five leading components are represented here: configuration $1 = \pi f^4_{5/2}$, configuration $2 = \pi(f^2_{5/2}p^2_{3/2})$, configuration $3 = \pi(f^3_{5/2}p^1_{3/2})$, configuration $4 = \pi(f^2_{5/2}p^1_{3/2}p^1_{1/2})$, and configuration $5 = \pi(f^3_{5/2}p^1_{1/2})$ as illustrated schematically in the uppermost part of the figure. For ^{80}Ge, the fraction of a given proton configuration coupled to a simple two hole $\nu g^{-2}_{9/2}$ configuration is represented with full black bars and gray bars on top of the previous when the hole pair is promoted to the deeper neutron orbits $\nu p^{-2}_{1/2}$, $p^{-2}_{3/2}$, $f^{-2}_{5/2}$, for JUN45 calculation results. The equivalent is crossed-hatched and simply hatched respectively for JJ4B results.

Though the statistics was quite limited, the asymmetry ratio obtained for the transition towards the 2^+_1 state supports a multipolarity $\lambda = 2$.

4. 2265.8 keV level

This level is one of the few belonging clearly to the lower-spin isomer decay scheme, and, according to our hypothesis in Sec. IV, can be assigned to $1 \leqslant J \leqslant 3$. It decays mainly to the 4^+_1 state with a minor branch to the (2^+_2) state. It does not attract specially large β strength hence negative parity is unlikely. The most likely theoretical counterpart is the 3^+_1 state though it appears below the 4^+_2 state in both calculations. Other close lying predicted levels with $J = 1$ or 2 must be ruled out: a 1^+ state would decay directly to the ground state via a $M1$ transition and a 2^+ state would probably populate the expected 0^+_2 revealing its presence. The two calculations consistently describe the 3^+_1 state as collective, triaxial, with $\gamma_{\mathrm{rms}} \simeq 30^\circ$ and $0.14 \leqslant \beta_{\mathrm{rms}} \leqslant 0.16$.

5. 2851.9 keV level

As seen in Fig. 4, this level definitely belongs to the higher-spin state decay scheme. This level was already discussed in Sec. IV as from our data it appears to attract much larger β strength as compared to values reported in the literature [$Br = 12.5(13)\%$ instead of the tabulated 3.0(9)%]. For that reason it is the first potential candidate to a negative parity assignment. In Fig. 5 one sees that it decays to the 4^+_1 state and to the state at 2265.8 keV tentatively assigned to (3^+) in the preceding paragraph with relative photon branchings 100 and 28, respectively. In the $N = 48$ neighbor ^{82}Se$_{48}$, a 5^- state is well established in the evaluation [37] at 2893.7 keV, probably the same which was reported by Gausemel et al. [39] at 2891.6 keV and which decays towards the 4^+_1 state and the state assigned $(3, 4^+)$ at 2548.5 keV (see Fig. 3 in [39]). Similarly a 5^- state is firmly established at 2768.6 keV in ^{84}Kr$_{48}$ which decays towards the 4^+_2 state. The 5^-_1 state is predicted by both calculations not too far in energy: 2670 keV with JJ4B and 2837 keV with JUN45 (see Fig. 7). In the end, we very tentatively propose $J^{\pi} = (5^{-})$ for this 2851.9 keV level especially because we cannot find any other simple assignment consistent with the markedly higher β feeding and because it fits relatively well with both $Z = 32$ and $N = 48$ systematics.

6. 2978.4 keV level

This is the proposed 6^{+} state of the main $E2$ sequence [7,8]. It belongs as expected to the higher-spin state decay scheme (see Fig. 4) and decays solely to the 4_1^{+} state (see Fig. 5). According to both calculations it belongs to the triaxial system (see Fig. 8) but in two different manners: as a member of the main g.s. band with the JJ4B interaction and as a member of the band-like sequence on top of the 2_{γ}^{+} with the JUN45 interaction.

7. 3036.9 keV level

The lower-spin fraction X is well determined (see Fig. 4) and very close to (and compatible with) 0. Hence this level belongs to the higher-spin state decay scheme without ambiguity. From Fig. 5 one sees that it has three photon branches: the most important being to the 4_1^{+} state and the two others towards the states at 1972.2 keV and 2265.8 keV previously assigned to (4^{+}) and (3^{+}), respectively (see Sec. V C3 and IV). There is unfortunately no easy counterpart in the even-even neighbors. In the hypothesis that our previously proposed J^{π} assignments are correct it could be a 4^{+} or 5^{+} state. An interesting theoretical counterpart could be the 5_1^{+} state calculated at 3336 keV with JJ4B, which simultaneously shows relatively strong $E2$ transitions (see Fig. 7) to the $3_1^{+}, 4_2^{+}$, and 6_1^{+} states, consistently with its belonging to the γ-soft structure. In both calculations, the 5_1^{+} state is the one which has the maximum $\gamma_{\rm rms}$ value with $\gamma_{\rm rms} \simeq 45^{\circ}$ (see Fig. 8). We propose $J^{\pi} = (4^{+}, 5^{+})$ for this level, mainly from decay considerations and relying on our previous J^{π} attributions. It would then be an additional experimentally identified member of the triaxial system.

8. 3423.0 keV level

This level has an X range very similar to the one of the level at 1972.2 keV: well determined, on the side of small values, but not strictly compatible with 0 which leads to suspect a real contribution from both isomers. It may therefore by assigned to $J = 4, 5$ as in Sec. V C3. Its direct β feeding is significantly larger than for the other neighboring levels, which makes it a potential candidate for negative parity. The only observed γ decay is toward the level at 2851.9 keV previously tentatively assigned to $J^{\pi} = (5^{-})$. Actually this 3423.0 keV level in ^{80}Ge has similar properties as the one located at 3452.3 keV in the higher-spin isomer decay scheme of the $N = 48$ neighbor ^{82}Se$_{48}$ [39] which decays only to the 2891.8 keV level that we suspect to be the analog of the ^{80}Ge 2852 keV level discussed in Sec. V C 5 above. This 3452.3 keV level in ^{82}Se is thought to be a (5^{-}) state [20,39], a possibility maintained in the evaluation. Based on this comparison (and the possible negative parity inferred from the observed direct β feeding) we tentatively propose that the 3423.0 keV level could be assigned to $J^{\pi} = (5_2^{-})$. We note that the closest calculated negative parity state is a 3^{-} state but then it would be difficult to explain why no transitions towards lower lying 2^{+} states is observed (see next subsection).

9. 3423.7 keV level

Interestingly enough, this level forms a very close doublet with the previous level, but since it decays via γ transitions of very different energies, it is clearly seen to have a very different β-delayed (apparent) half-life. As seen in Fig. 4 the lower-spin fraction X determination is poor, but the X range is compatible with 1. Hence we propose this level as a member of the low-spin state decay-scheme. A J^{π} assignment for this level based on comparisons with the shell model results is very difficult as there are several potential candidates. One thing is practically certain: it must have a low J as it deexcites toward the 2_1^{+}, 2_2^{+} states as well as toward the state at 2265.8 keV that we tentatively assigned to $J^{\pi} = (3^{+})$ in Sec. V C4. Very similar decay properties are found for the state at 2665.6 keV in the ^{78}Ge neighbor. In their study of ^{78}Ga β decay, Lewis *et al.* observed that this state attracts much higher β strength as compared to the other close-lying levels. Since the ground state of the mother nucleus ^{78}Ga is now determined to be 2^{-} [19], it would be natural to propose $J^{\pi} = 3^{-}$ for this 2665.6 keV in ^{78}Ge, assignment which could be the same for the 3423.7 keV level discussed here. However, no particularly strong direct β feeding is observed from our data, which may be due to the fact that the β activity of the lower-spin state is weaker in our mixed source. The 3_1^{-} state is predicted very close in energy at 3421 keV with the JUN45 interaction and at 3254 keV with JJ4B (see Fig. 7). In short, this 3423.7 keV level is the best candidate for a 3_1^{-} state which is expected in this energy range both from systematics and calculations.

10. 3445.1 keV level

This is the 8^{+} isomer studied in Refs. [7–9]. Its β-delayed apparent half-life was used in Sec. III to determine the half-life of the high-spin state β activity, hence the mean lower-spin fraction X is 0 identically. This 8_1^{+} state is nicely reproduced by both calculations (see Fig. 7) being calculated at 3286 keV with JUN45 and 3362 keV with JJ4B. As can be seen in Fig. 8, this level does not belong to the triaxial system and exhibits very little collectivity with low $\beta_{\rm rms}$ *and* $\gamma_{\rm rms}$ values, and there is no collective $E2$ transition to any of the calculated levels. There is little difference in the nucleon distributions in the wave functions calculated with the two interactions with, for neutrons, 100% $\nu g_{9/2}^{-2}$ (as expected), and for protons, a leading component $\pi(f_{5/2}^{2} p_{3/2}^{2})$ (42% with JJ4B and 46% with JUN45) followed by $\pi f_{5/2}^{4}$ (19% with JJ4B and 22% with JUN45).

We will not discuss further the rest of the level scheme as it becomes more and more speculative as we go higher in energy.

D. Conclusion of the discussion

It seems that the experimental situation is not too far from the description provided by shell model calculations. Both calculations have drawbacks and advantages. The main g.s. band seems correctly described using the JJ4B interaction. The problem with JUN45 is that the less collective qp-type 4^+ state appears yrast while it should not. The level at 1573.6 keV is most likely the 2_2^+ state that shell model calculations clearly describe as the band head of a (quasi-)γ-band. Two other levels at 2265.8 keV and 3036.9 keV are potential candidates to be members of this band, though we could not ascribe their spin firmly, the first being proposed (3^+) and the second (4^+, 5^+). The proposed (4_2^+) state at 1972.2 keV cannot belong to the γ band as it appears below the proposed (3_1^+) state. It is rather a member of the qp-type system predicted by both calculations (see Sec. V B).

Placing ^{80}Ge with spin and parity assignments proposed here in the Ge and $N = 48$ systematics (Fig. 6) deserves a few comments:

Considering the Ge systematic, one sees that going from $N = 46$ to $N = 48$ the members of the γ band rise significantly in energy: a behavior expected when approaching the $N = 50$ shell closure and which follows the energy increase initiated at $N = 44$, that is at mid distance between $N = 38$ and $N = 50$. The excitation energy of the 3_1^+ states increase between $N = 46$ and $N = 48$ is much more sudden than a simple extrapolation from $N = 44$, 46 would suggest. This means that Ge nuclei undergo a fast transition from an extreme softness at $N = 44$, in the middle of the neutron $g_{9/2}$ shell to a spherical vibrational like behavior at $N = 50$.

Considering now the $N = 48$ systematic, one sees the potential candidates for a 3^+ assignment going regularly down in energy as the proton number decreases, in a similar way as the 2_2^+ states, starting at $Z = 36$. This indicates a progressive increase of triaxial collectivity on the $N = 48$ line when approaching $Z = 32$. The question is now to know if $Z = 32$ corresponds indeed to a maximum of this collectivity as the evolution of masses would suggest. Presently available data on ^{78}Zn are too scarce to answer that question (see [40] and references therein).

Three other levels are good candidates for negative parity states: the levels at 2851.9 keV, 3423.0 keV, and 3423.7 keV for which we propose $J^\pi = (5_1^-)$, (5_2^-), and (3_1^-). The fact that the 5_1^- state is found below the 3_1^- state in excitation energy is consistent with the systematic evolution in both $Z = 32$ and $N = 48$ series (see Fig. 6): the two levels have crossed already at $N = 46$ in the Ge chain and at $Z = 34$ in the $N = 48$ series. All the levels discussed so far have natural counterparts in the calculated level scheme, except the (5_2^-). Three 5^- states appear naturally in the valence space considered here from proton-neutron couplings of the type $\pi f_{5/2}p \otimes \nu g_{9/2}$ and they should be calculated at the correct energy. The absence in the calculations of a second low lying 5^- state, for which there is a clear evidence also in the $N = 48$ neighbors ^{82}Se and ^{84}Kr, is curious. It may be the only indication we have of the presence of an intruding configuration such as $\pi f_{5/2} \otimes \nu d_{5/2}$ (across $N = 50$). But apart from this exception it is clear that the most important part of the structure of ^{80}Ge does belong to the "natural" valence space above ^{56}Ni, and the collectivity has a proton origin. The fear expressed in [29] that collectivity of nuclei close to $N = 50$ could suffer from the limited valence space seems not so well justified, at least in the specific case studied here. If problems occur they come from the proton sequence as explained in Subsection V B and $N = 50$ seems to continue acting as a strong effective closure. This confirms, in some way, the conclusions drawn from Coulomb excitation data [35].

VI. SUMMARY AND CONCLUSION

Pure ^{80}Ga beams were produced at the PARRNe mass separator of the ALTO ISOL facility, using a surface ionization ion source, and collected on a movable tape system. The decays of the ^{80}Ga sources were studied using a compact but rather conventional β and γ detection setup and data obtained in the previous similar study by Hoff and Fogelberg [5] are confirmed. The β-delayed γ activities were systematically studied and 67 individual half-lives could be determined (over the 75 γ rays previously attributed to the ^{80}Ga decay). This data is compatible with the existence of the two long-lived isomers discovered from collinear laser spectroscopy measurements [11] and proves that both of them are β-decaying states. We could determine the half-life value for each of these two isomers for the first time. The higher-spin ($J^\pi = 6^-$) isomer half-life was determined from the apparent (β-delayed) γ-activity half-life of the 8^+ state established in the ^{80}Ge level scheme from in-flight studies [7,8], it corresponds to the longer-lived β activity with $T_{1/2} = 1.9 \pm 0.1$ s. From the shortest β-delayed γ activity observed in this experiment, the lower-spin ($J^\pi = 3^-$) isomer half-life was determined to be $T_{1/2} = 1.3 \pm 0.2$ s. All other β-delayed γ activities are compatible with these two values. By analyzing the whole set of β-delayed γ activities we could determine the relative contributions from each of the $^{80(\mathrm{ls})}$Ga and $^{80(\mathrm{hs})}$Ga β decays to most of the ^{80}Ge excited states and two distinct decay schemes could be proposed for the first time.

The true question in studying ^{80}Ge is to understand what is the influence of the apparent weakness in the $N = 50$ shell gap around $Z = 32$, revealed by mass measurements, in the structure of neutron-rich nuclei nearby. The providentially large spin difference between the two ^{80}Ga β-decaying states populating different excited states in ^{80}Ge allows shedding light on this point as spin and parity of the daughter states can be further constrained. Although spin and parity determination cannot be considered as definitive from standard β-decay studies there exists in the present case a solid body of evidence allowing to understand the main features of the ^{80}Ge structure. The neutron-rich Ge isotopes, beyond $N = 40$, exhibit well developed γ bands. On the other hand the light $N = 48$ nuclei have more rigid structures, easier to interpret in terms of qp excitations, due to the proximity of the $N = 50$ shell closure. From the present study it is clear that both collective γ-soft and more spherical qp particle structures coexist in ^{80}Ge. This interpretation is supported by both careful regional considerations and properly analyzed state-of-the-art shell model results. Those last reveal that the two competing structures result from the balance between paring and quadrupole terms of the residual interaction. This confirms that the apparent weakness in the $N = 50$ shell gap around $Z = 32$ is due to beyond mean field correlations, mainly of quadrupole nature. It is clear also that the γ-softness that survives in ^{80}Ge just before the $N = 50$ shell closure has a pure proton origin, and in fact, the main features of ^{80}Ge structure in general do belong to the natural valence space above ^{56}Ni. ^{80}Ge certainly is the most collective of the light even-even $N = 48$ isotones studied so far but quadrupole coherence is not sufficient to erase the effect of the (good) $N = 50$ shell closure, contrary to the situation encountered in the $N = 28$ region [41].

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[1] J. Hakala *et al.*, Phys. Rev. Lett. **101**, 052502 (2008).
[2] S. Baruah *et al.*, Phys. Rev. Lett. **101**, 262501 (2008).
[3] M. Bender, G. F. Bertsch, and P.-H. Heenen, Phys. Rev. C **78**, 054312 (2008).
[4] K. Sieja and F. Nowacki, Phys. Rev. C **85**, 051301(R) (2012).
[5] P. Hoff and B. Fogelberg, Nucl. Phys. A **368**, 210 (1981).
[6] B. Singh, Nucl. Data Sheets **105**, 223 (2005).
[7] A. Makishima, M. Asai, T. Ishii, I. Hossain, M. Ogawa, S. Ichikawa, and M. Ishii, Phys. Rev. C **59**, R2331 (1999).
[8] Zs. Podolyák *et al.*, Int. Jour. Mod. Phys. E **13**, 123 (2004).
[9] H. Mach *et al.*, J. Phys. G: Nucl. Part. Phys. **31**, S1421 (2005).
[10] T. Procter and J. Billowes (private communication, 2010).
[11] B. Cheal *et al.*, Phys. Rev. C **82**, 051302(R) (2010).
[12] K.-L. Kratz, V. Harms, A. Wöhr, and P. Möller, Phys. Rev. C **38**, 278 (1988).
[13] M. Lebois *et al.*, Phys. Rev. C **80**, 044308 (2009).
[14] F. Ibrahim *et al.*, Nucl. Phys. A **787**, 110c (2007).
[15] F. Azaiez and W. Korten, Nucl. Phys. News **7**, 21 (1997).
[16] P. R. Bevington and D. K. Robinson, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 2002).
[17] B. Singh, Nucl. Data Sheets **66**, 623 (1992).
[18] D. A. Lewis, J. C. Hill, F. K. Wohn, and M. L. Gartner, Phys. Rev. C **22**, 2178 (1980).
[19] E. Mané *et al.*, Phys. Rev. C **84**, 024303 (2011).
[20] J. V. Kratz *et al.*, Nucl. Phys. A **250**, 13 (1975).
[21] A. Prévost *et al.*, Eur. Phys. J. A **22**, 391 (2004).
[22] T. Rząca-Urban, W. Urban, J. L. Durell, A. G. Smith, and I. Ahmad, Phys. Rev. C **76**, 027302 (2007).
[23] W. Andrejtscheff and P. Petkov, Phys. Lett. B **329**, 1 (1994).
[24] A. R. Subber, Turk. J. Phys. **35**, 43 (2011).
[25] N. Turkan *et al.*, Math. Comp. Appl. **15**, 428 (2010).
[26] H. Rotter *et al.*, Nucl. Phys. A **514**, 401 (1990).
[27] K. Kumar, Phys. Rev. Lett. **28**, 249 (1972).
[28] D. Abriola *et al.*, Nucl. Data Sheets **110**, 2815 (2009).
[29] M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, Phys. Rev. C **80**, 064323 (2009).
[30] B. A. Brown, private communication, as first used in D. Verney *et al.* Phys. Rev. C **76**, 054312 (2007).
[31] S. J. Q. Robinson, L. Zamick, and Y. Y. Sharon, Phys. Rev. C **83**, 027302 (2011).
[32] A. Gade *et al.*, Phys. Rev. C **81**, 064326 (2010).
[33] E. Caurier *et al.*, Rev. Mod. Phys. **77**, 427 (2005).
[34] E. Caurier and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).
[35] H. Iwasaki *et al.*, Phys. Rev. C **78**, 021304(R) (2008).
[36] T. Faul, PhD thesis, Université de Strasbourg, 2007 (unpublished).
[37] J. K. Tuli, Nucl. Data Sheets **98**, 209 (2003).
[38] S. A. Hamada *et al.*, J. Phys. G: Nucl. Phys. **13**, 1143 (1987).
[39] H. Gausemel, K. A. Mezilev, B. Fogelberg, P. Hoff, H. Mach, and E. Ramström, Phys. Rev. C **70**, 037301 (2004).
[40] C. J. Gross *et al.*, Acta Phys. Pol. **40**, 447 (2009).
[41] B. Bastin *et al.*, Phys. Rev. Lett. **99**, 022503 (2007).