Experimental study of ^{84}Ga β decay: Evidence for a rapid onset of collectivity in the vicinity of ^{78}Ni

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γ-rays following the β and β-n decays of the very neutron rich $^{84}_{31}$Ga$_{53}$ produced by the photofission of ^{238}U have been studied at the newly built ISOL facility of IPN Orsay: ALTO. Two activities were observed and assigned to two β-decaying states: ^{84}Ga^{g}, $I^{\pi} = (0^{-})$ and ^{84}Ga^{m}, $I^{\pi} = (3^{-}, 4^{-})$. Excitation energies of the 2^{+}_{1} and 4^{+}_{1} states of $^{84}_{32}$Ge$_{52}$ were measured at $E(2^{+}_{1}) = 624.3$ keV and $E(4^{+}_{1}) = 1670.1$ keV. Comparison with HFB + GCM calculations allows to establish the collective character of this nucleus. The excitation energy of the $1/2^{+}_{1}$ state in $^{83}_{32}$Ga$_{51}$ known to carry a large part of the neutron $3s_{1/2}$ strength was measured at 247.8 keV. Altogether these data allow to confirm the new single particle state ordering which appears immediately after the double $Z = 28$ and $N = 50$ shell closure and to designate ^{78}Ni as a fragile and easily polarized doubly-magic core.

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I. INTRODUCTION

Considerable efforts have been recently deployed in order to experimentally reach the region in the immediate vicinity of ^{78}Ni to assess the doubly magic character of this very neutron rich nucleus. One of the most interesting questions related to the persistence of the $Z = 28$ and $N = 50$ shell gaps far from stability is whether ^{78}Ni can be considered as an inert core (a good core) for the nuclear shell model. This is not only crucial for the development of nuclear shell model calculations in this exotic region but also for the underlying physical picture this model carries: Doubly magic nuclei are considered literally as the supporting pillars of the common understanding of nuclear structure. More technically, this question can be put in terms of *polarizability* of the doubly magic core: How fast can the residual interaction between valence nucleons attenuate or even erase the magic character of a core? The most spectacular example of polarization effects is that of ^{80}Zr, which in spite of its well known rotational character, is effective as a core when a sufficient number of nucleons are present in the valence space ([1] and references therein). The evidence for a strong $Z = 28$ proton core polarization has been repeatedly pointed out recently in the very neutron rich Ni and Zn isotopes: ^{70}Ni [2] and ^{80}Zn [3]. A similar feature for the $N = 50$ neutron core toward ^{78}Ni has not been observed or discussed with such clarity though first evidence of it can be found in the observation of the mean square charge radius evolutions of $_{38}$Sr [4], $_{37}$Rb [5], and $_{36}$Kr [6] isotopes. Nuclear structure data for nuclei situated beyond the $N = 50$ shell closure with $Z < 36$ is critically required to address this question properly.

In this paper we report on the study of γ-rays following the β and β-n decays of $^{84}_{31}$Ga$_{53}$. Prior to this publication, elements on β decays in masses 83, 84, and 85 were reported separately by groups from Orsay [7], ISOLDE-CERN [8], and HRIBF-Oak Ridge [9,10]. The new data presented here, when added and properly compared to the previous ones, allow to provide for the first time a consistent interpretation of the whole corpus of existing data, as will be shown in Sec. III B. Conclusions can be drawn if (and only if) this network of experimental facts is considered as a whole, pointing toward the first experimental indications on the dynamics which develops in the mostly unknown valence space opened just above ^{78}Ni.

II. EXPERIMENTAL CONDITIONS

^{84}Ga isotopes were produced using photonuclear reactions at the on-line PARRNe mass-separator operating within the ALTO facility [11]. The fission fragments were produced in the interaction of the 50-MeV electron beam delivered by the ALTO linear accelerator with a thick target containing 72 g of uranium in a standard UC$_x$ form. The oven was connected to a W ionizer heated up to $\simeq 2200^{\circ}$C which selectively ionizes alkalies but also elements with particularly low first ionization potentials such as Ga and In. The ions were accelerated through 30 kV and magnetically mass separated before being implanted on to a Al-coated mylar tape close to the detection setup. This particular configuration with Z-selection insured by the source, the intrinsic selectivity provided by the photonuclear mechanisms themselves and the A-selection achieved by the mass separator ($A/\Delta A \simeq 1500$) allowed to obtain a pure beam of ^{84}Ga^{+1} ions. The suppression of neutron deficient isotopes with photofission facilitates the production of a radioactive beam without isobaric contamination allowing sensitive measurements to be made far from stability. Even though a W tube was used, with a modest ionization efficiency for Ga of 0.7%, it is still possible to study ^{84}Ga due to the absence of ^{84}Rb. These measurements were performed during a test run dedicated to safety measurements scheduled in the different phases of the ALTO commissioning. For this reason the electron beam intensity was limited to just 1 μA instead of the nominal 10 μA. At this primary intensity, the fission rate inside the target is estimated to be 10^{10}/s [11] and the yield of ^{84}Ga ions measured at the tape station was

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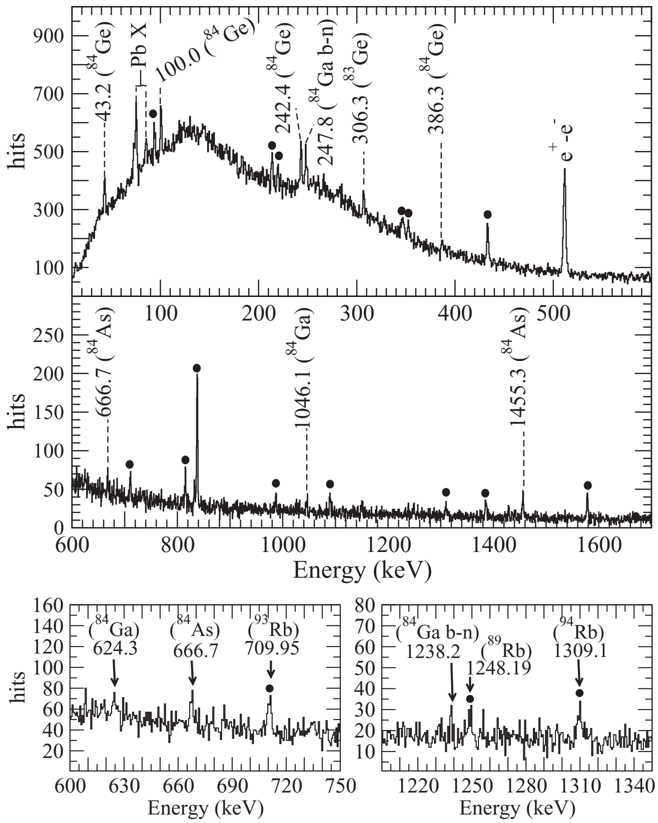

FIG. 1. Upper part: β-gated γ-spectrum recorded at mass 84 (0 keV to 1700 keV). Peaks marked with dots correspond to the decay of $^{89-96}$Rb isotopes stopped within the mass separator (see text). Lower part: Zoom of the spectrum for the 600–750 keV and 1200–1350 keV energy ranges.

of the order of a few tens per second and in agreement with the predicted yields [12]. The γ-detection system consisted of one coaxial large volume HPGe detector (70% relative efficiency) with a resolution of 2.3 keV at 1.3 MeV and one small EXOGAM CLOVER detector [13] 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. These two detectors were placed in a 180° geometry close to collection point onto the tape. In this configuration a total photopeak efficiency of 3% at 1.3 MeV was achieved. This collection point was surrounded by a tube-shaped plastic scintillator for β detection ($\epsilon_\beta \simeq$ 30–50%). In an experiment with an isobaric-pure beam, the tape cycling is used to help in the identification of unknown new lines which are expected to appear in the spectra by analyzing their time dependence. The evacuation of the activities of the daughter nuclei was not an issue in this experiment because the precursor population was very weak and because the difference between the half-life of ^{84}Ga and its β and β-n descendants was large enough. Then, the tape sequence was formed by a 9 s build-up phase followed by a 1 s decay time, evacuation of the source and repetition *ad libitum*.

The β-gated γ-spectrum which was recorded with the separator field set to $A = 84$ is shown in Fig. 1. γ-lines belonging to the decay of neutron-rich Rb isotopes with mass ranging from 89 to 96 have been identified in the spectra (dots in Fig. 1). The Rb isotopes which are strongly favored in both the fission process and the ionization mechanism ($\epsilon_i \simeq 80\%$) were stopped within the separator chamber which was intentionally not shielded to allow the simultaneous safety measurements with the required conditions. The activity of the Rb isotopes was such that the associated γ lines could appear as random coincidences with β events. Despite this difficult experimental environment, the γ lines characterizing the activity of the β daughters : ^{84}Ge [$T_{1/2} = 947(11)$ ms] and ^{84}As [$T_{1/2} = 4.5(2)$ s] are clearly visible establishing that ^{84}Ga was successfully collected onto the tape.

III. RESULTS AND DISCUSSION

A. Line identifications

We confirm the existence of two γ-rays in the decay of ^{84}Ga, one at 624.3(7) keV and the other at 1046.1(7) keV (see Fig. 1), both already observed at ISOLDE-CERN having a fast decaying component [8] and at the HRIBF-Oak Ridge [10]. At ISOLDE, γ spectra were recorded during an experiment primarily dedicated to the production of neutron-rich Cu isotopes using the selective laser ion-source RILIS [15]. The ionization tube connected to the ^{238}U target was made in Nb raised to high temperature in a similar way as in our experiment, allowing substantial surface ionization of Ga. Spectra obtained at ISOLDE at $A = 85$ show the presence of the 624.3-keV peak coming from the β-n decay of ^{85}Ga. Then the 624.3-keV peak necessarily corresponds to a transition in ^{84}Ge, most probably the $2_1^+ \rightarrow 0_{\rm g.s.}^+$ as proposed in Ref. [10]. The β-n channel is known to be widely open in the decay of ^{84}Ga: A probability of $P_n = 70 \pm 15\%$ is reported in Ref. [14] and a smaller value (unpublished) has been obtained recently from experiments at Oak Ridge, $P_n = 47 \pm 10\%$ [9]. Then γ-rays from transitions in ^{83}Ge and its $A = 83$ daughters must be present in the spectra. The 306.3 keV line from the decay of ^{83}Ge ($I_\gamma = 100$ relative intensity) and the 1238.2 keV line already attributed to the β decay of ^{83}Ga [7] are indeed visible in our spectra. We also confirm the existence of a peak at 247.8(3) keV which was previously reported in the β and β-n decays of ^{83}Ga and ^{84}Ga, respectively [10] and attributed to the transition $1/2_1^+ \rightarrow 5/2_{\rm g.s.}^+$ in ^{83}Ge. In the ISOLDE data, this peak was very close to the 248.0-keV line originating from the decay of the neutron deficient ^{84}Rb isomeric state ($T_{1/2} =$ 20.26 m) thus contaminated. Such isobaric contamination is not possible at ALTO due to the photofission based production mechanism. This is illustrated by the clear absence of the 463.6-keV line (^{84}Rb^m β-decay, $I_\gamma = 36.1\%$) and of the 881.6-keV line (^{84}Rbβ-decay, $I_\gamma = 69\%$) from our spectra, as can be seen in Fig. 2. The peak observed at 247.8 keV in our data set was the most intense of the spectrum and was determined to have a half-life of $T_{1/2} = 76 \pm 48$ ms (see Fig. 3), which is compatible with the previously measured ^{84}Ga half-life $T_{1/2} = 85 \pm 10$ ms [14]. This allows (in spite of the large error due to low statistics) to attribute the 247.8-keV peak to the ^{84}Ga activity and not to that of the longer-lived β and β-n daughters. This 247.8-keV transition was observed with a very low branching ratio ($\simeq$0.5%) in the ^{83}Ga

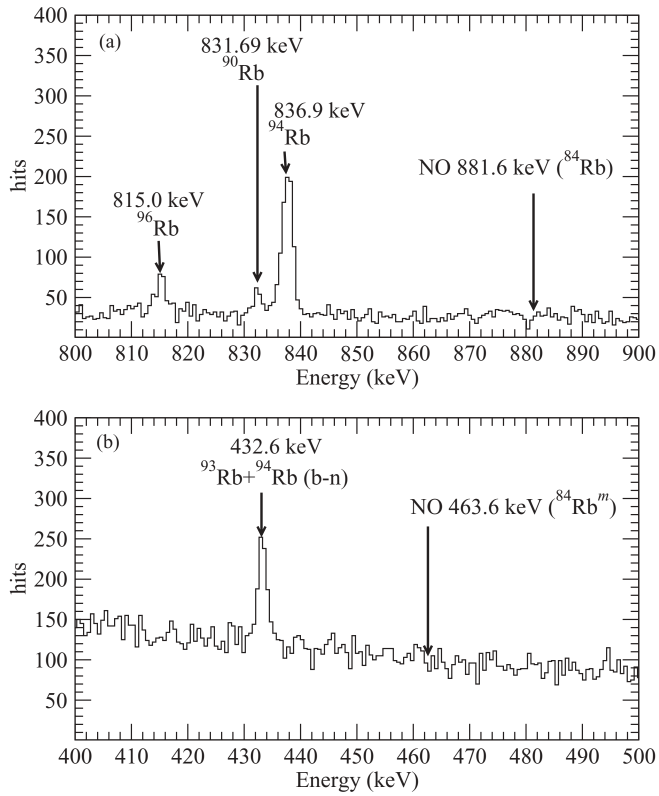

FIG. 2. Parts of the β-gated γ spectrum with mass separator set to $A = 84$: (a) from 800 keV to 900 keV and (b) from 400 keV to 500 keV. γ-rays fed in the decays of neutron-rich Rb isotopes appear as random coincidence with β events (due to their high activity caught into the separator: see text). There is, however, strictly no contribution of the neutron-deficient ^{84}Rb isotope for which lines among the strongest would have been observed at 463.6 keV and 881.6 keV (β decay of ^{84}Rb^{m} with $I_\gamma = 36.1\%$ and ^{84}Rb with $I_\gamma = 69\%$, respectively) showing that ^{84}Rb was *not* produced during this experiment.

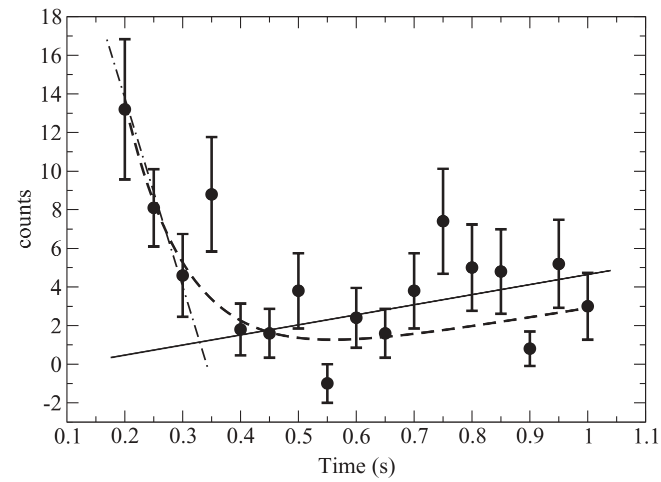

FIG. 3. Number of events in the 248-keV peak (background subtracted) per time bin of 0.1 s during the 1-s decay time of the tape cycle. The time behavior was assumed to be the superposition of a fast (exponential) decay component plus a slow (approximated as linear) build-up component. The former represents the decay of the ^{84}Ga source while the latter takes into account the activity of the daughter nuclei. The fit was then applied to the function $f(\Delta t) = I \cdot \exp(-\lambda \cdot \Delta t) + A \cdot \Delta t + B$ where I stands for the ^{84}Ga population at equilibrium with the beam after the 9-s build-up phase of the tape cycle, λ has the usual meaning of the decay constant and $\Delta t = 0.1$ s, value of the time bin. I, λ, A, and B were treated as free parameters leading to the result $T_{1/2} = 76 \pm 48$ ms (with $R^2 = 0.6$). The resulting function $f(\Delta t)$ is represented by the dashed curve. The dash dotted line and the continuous line were added only to guide the eye.

β decay [10]: This is coherent with its non observation in our previous experiment on mass 83 due to low statistics as already mentioned in Ref. [7]. The two γ lines at 100.0 keV and 242.4 keV attributed to the decay of ^{84}Ge [16] are also clearly observed in our spectra. They correspond to transitions between states of ^{84}As as well as two others (previously not reported in literature) at 42.7(3) keV and 386.0(5) keV, observed in coincidence with the one at 100.0 keV. Transitions in ^{84}As are to be discussed in a forthcoming paper. The list of the γ-rays attributed to the decays of the ^{84}Ga population and its β and β-n daughter populations are reported in Table I. All attributions can be considered as certain insofar as they are in good agreement with results obtained elsewhere with different production and identification techniques *except* the line at 1046 keV, for which a detailed analysis of the γ-activity balance is necessary and discussed in the following subsection.

B. γ-activity analysis

Assuming a unique origin, i.e., a unique β-decaying state in ^{84}Ga which would be simultaneously at the origin of (i) the feeding of the transition $2_1^+ \rightarrow 0_{\text{g.s.}}^+$ at 624.3 keV in ^{84}Ge, (ii) the creation of a population of ^{84}Ge which in turn decays through the 100.0 keV and 242.4 keV transitions in ^{84}As, and (iii) the feeding of the $1/2_1^+ \rightarrow 5/2_{\text{g.s.}}^+$ in ^{83}Ge, a

TABLE I. Summary of the main γ lines ($E_\gamma \leqslant 1700$ keV) observed in the ^{84}Ga β and β-n decays in this experiment. Line intensities are given relative to the peak at 247.8 keV ($I_{248} \equiv 100$). Attributions (mother nucleus and decay channel) are given in the third column. The fourth column contains references for the attributions, "t.w." stands for this work.

Energy (keV)	Rel. int.	Attribution	Refs.
42.7(3)	81(3)	^{84}Ge β	t.w.
100.0(3)	79(5)	^{84}Ge β	[16]
242.4(3)	92(7)	^{84}Ge β	[16]
247.8(3)	**100**	^{84}Ga β-n	[10]
306.3(3)	78(6)	^{83}Ge β	[17]
386.0(5)	53(5)	^{84}Ge β	t.w.
624.3(7)	38(5)	^{84}Ga β	[8,10]
666.7(7)	50(6)	^{84}As β	[18]
1046.1(7)		^{84}Ga β-n	[10]
	42(6)	^{84}Ga β	t.w.
1238.2(7)	30(5)	^{83}Ga β[a]	[7]
1455.3(7)	83(9)	^{84}As β	[18]

[a]Fed in the ^{84}Ga β-n decay in the present experiment.

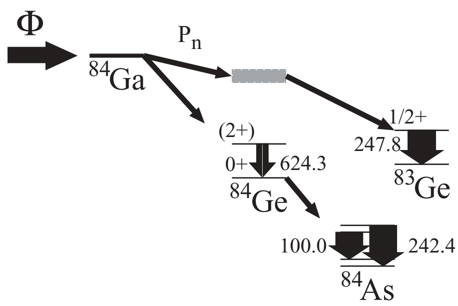

FIG. 4. Decay paths in the hypothesis of a unique β-decaying state in ^{84}Ga.

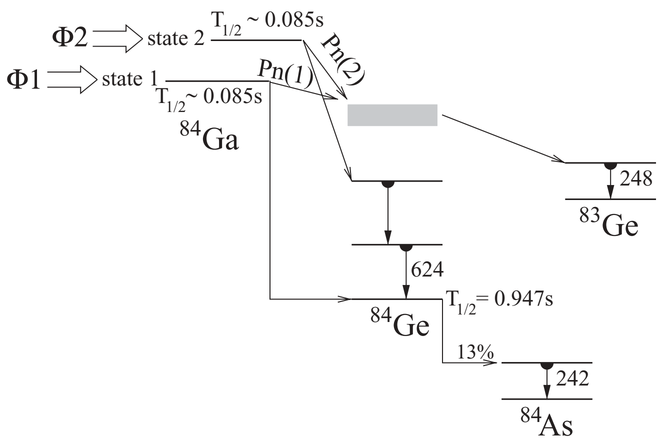

FIG. 5. Decay paths in the hypothesis of two β-decaying states in ^{84}Ga. State 1 is assumed to be of low-spin value (probably $I = 0$) and state 2 of "high"-spin value (probably $I \geqslant 3$, see text). Branching ratio to the 242-keV transition in ^{84}As is from Ref. [16].

clear unbalance in the γ activities of the different members of the $A = 83$, 84 isobaric chains is observed. This activity unbalance can be put in quantitative terms: In the hypothesis of a unique β-decaying state in ^{84}Ga, one ends up with a decay pattern such as represented in Fig. 4. Then one can calculate an effective feeding Φ of the ^{84}Ga population from the observed intensity of the 247.8-keV transition in ^{83}Ge and the P_n value. From the obtained Φ value, the expected 242.4-keV peak intensity, I_{242}, of the transition in ^{84}As can be deduced. With $P_n = 70 \pm 15\%$ from Ref. [14] one finds $I_{242} = 5 \pm 2$ and with $P_n = 47 \pm 10\%$ from [9] one finds $I_{242} = 13 \pm 6$. Both results are to be compared to $I_{242} = 92 \pm 7$ effectively observed in our experiment (see Table I). In addition, it should be noted that the 624.3-keV and the 247.8-keV transitions are seen to be fed equally in the data from ISOLDE [8] while the intensity ratio in our experiment is $I_{624}/I_{248} \simeq 38/100$ (see Table I). Furthermore, in the ISOLDE $A = 84$ spectra, one clearly observes the feeding of the 866 keV transitions which was already attributed to the $(7/2^+_1) \rightarrow 5/2^+_{\text{g.s.}}$ transitions in ^{83}Ge [7] but not observed at all in the present experiment. Such feeding can only originate from the β-n decay of a state with $I \geqslant 3$ in ^{84}Ga.

The only way to account simultaneously for both the clear γ-activity unbalance observed in our spectra *and* the results from ISOLDE is to assume the existence of *two* β-decaying states in ^{84}Ga: One with very low spin, dominant at ALTO, which would feed primarily the ^{83}Ge$1/2^+$ state and the ^{84}Ge ground state through the β-*n* and β channels, respectively, and a second, much largely produced at ISOLDE, of spin $I \geqslant 3$. This situation is represented in a pictorial way in Fig. 5 where it is assumed, for simplicity, that the β branch of the low-spin state (state 1) feeds directly the ^{84}Ge ground state and that the β branch of the "high"-spin state (state 2) contributes to 100% to the 624-keV $2^+ \rightarrow 0^+\gamma$-transition in ^{84}Ge.[1] Then one ends up with a closed system of four equations and four unknowns: Φ_1 and Φ_2, the effective yields in number of nuclei per second produced in low-spin state (state 1) and "high"-spin state (state 2), respectively, and $P_n(1)$ and $P_n(2)$, the β-delayed neutron emission probability of the low-spin state (state 1) and the "high"-spin state (state 2), respectively. This system can then be solved exactly by using the measured values of the relative γ-peak intensities I_γ for $E_\gamma = 242.4$ keV, $E_\gamma = 247.8$ keV, and $E_\gamma = 624.3$ keV as reported in Table I and the total β-delayed neutron emission probability P_n, equal to the sum of those of the two β-decaying states $P_n = P_n(1) + P_n(2)$. Since there is a substantial difference between the P_n values available from Refs. [14] with $P_n = 70 \pm 15\%$ and [9] with $P_n = 47 \pm 10\%$, all quantities were calculated as a function of P_n ranging between those two values and plotted in Fig. 6. The relative contributions to the 248-keV peak originating from the two β-decaying states in ^{84}Ga is also given in part (c) of the figure from which it is clearly seen that the system becomes insolvable for $P_n \gtrsim 72.5\%$. It is also interesting to note from Fig. 6(b) that, within the hypothesis mentioned above, the effective yield for the "high"-spin state Φ_2 is much lower (approximately one order of magnitude) than the one of the low-spin state Φ_1 for *any* total value of P_n. This is coherent with the assumption made above: The low-spin state production is dominant at ALTO (while this is probably not the case at ISOLDE).

Now, one must come back to the case of the 1046.1-keV peak which is observed at mass 84 with the same intensity as the 624.3-keV peak, but not observed at mass 85 nor at mass 83. There are only four possible origins for this ray: (i) the β decay or (ii) β-*n* decay of the low-spin state in ^{84}Ga or (iii) the β decay or (iv) β-*n* decay of the "high"-spin state in ^{84}Ga. (i) β decay from the low-spin state: In that situation the 1046.1-keV transition would connect a second 2^+ state to the ground state in ^{84}Ge, it should then have been observed in the β-*n* decay of ^{85}Ga in the ISOLDE spectra, just like the 624.3-keV line, and this not the case. (ii) β-*n* decay from the low-spin state: In that situation and considering that no 1046.1-keV peak was observed in the ^{83}Ga decay experiment [7], the 1046.1-keV transition should connect a second $1/2^+$ state to the ground state in ^{83}Ge and would have been observed in the $A = 84$ spectra of the present experiment with a similar intensity as the 247.8-keV β-*n* peak,

[1]This *does not* mean that a 100% branching ratio to the 2^+ state is assumed but that the $2^+_1 \rightarrow 0^+_{\text{g.s.}}$ transition has $I_\gamma = 100$ in β decay.

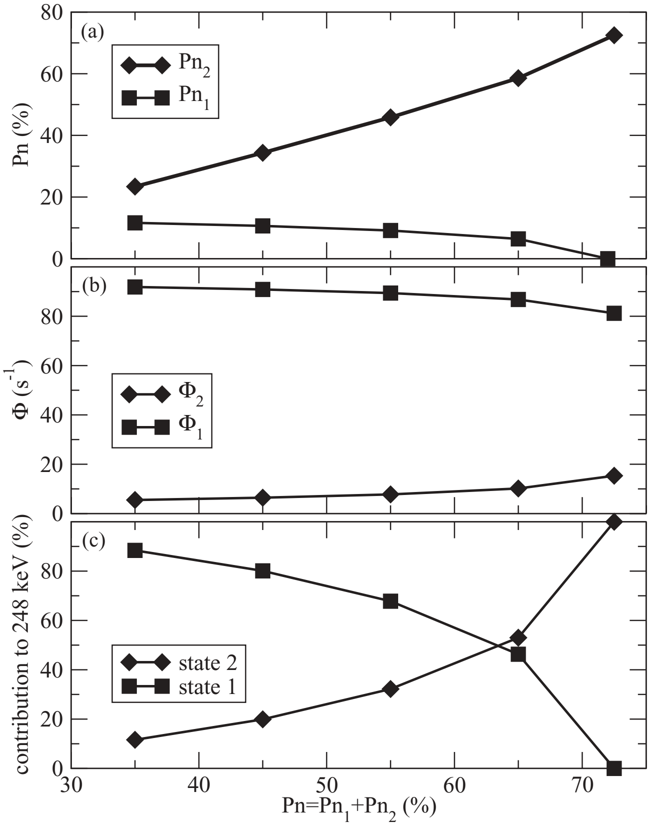

FIG. 6. (a) β-delayed neutron emission probabilities of state 1 (low spin) and 2 (“high”spin), (b) effective yields (number of collected nuclei per second) for state 1 (Φ_1) and state 2 (Φ_2) and (c) relative contribution to the 248-keV transition from β-n decay of states 1 and 2. All quantities were determined from the measured relative intensities I_γ of the transitions at 242.4 keV, 247.8 keV, and 624.3 keV as reported in Table I, in the framework of the two β-decaying states hypothesis of Fig. 5 and reported as a function of the total β-n probability $P_n = P_n(1) + P_n(2)$.

this again, is not the case. (iv) β-n decay from the “high”-spin state: In that situation and considering that no 1046.1-keV peak was observed in the ^{83}Ga decay experiment [7], the 1046.1-keV transition should connect a state with $I^\pi \geqslant 9/2^+$ to the $5/2^+$ ground state of ^{83}Ge and would be connected to the $7/2^+$ state at 866 keV in ^{83}Ge through a 799-keV transition which would have been visible in the ISOLDE spectra. Again, this is not the case. In the end, considering all data presently available, the only remaining possibility is (iii): The 1046.1-keV transition is fed by the β decay of the “high”-spin state in ^{84}Ga. Therefore the 1046.1-keV peak belongs to the ^{84}Ge level scheme. Furthermore, since this 1046.1-keV peak is observed at mass 84 and not mass 85, the only remaining possibility is that it corresponds to the γ-decay of a ^{84}Ge excited state of spin higher than 2 (which in turn cannot be fed in the ^{85}Ga β-n decay). Furthermore, it has the same relative intensity as the 624.3 keV peak (see Table I), we propose then to attribute this 1046.1 keV peak to $4_1^+ \rightarrow 2_1^+$ transition in ^{84}Ge.

C. Nature of the two β-decaying states of ^{84}Ga

Within the hypothesis of a decay scheme corresponding to the representation of Fig. 5, it is possible to set limits on the spin-parity values of the two β-decaying states of ^{84}Ga. The uncertainties on the relative intensities of the 624.3-keV and 1046.1-keV lines, as reported in Table I, leave room for an upper limit of the branching ratio from the ^{84}Ga low-spin state to the ^{84}Ge 2^+ state of $Br(2^+) \lesssim 0.4\%$ and correspondingly for a lower limit of the β transition to the 0^+ ground state of $Br(0^+) \gtrsim 99.6\%$. Applying a similar reasoning for the “high”-spin ^{84}Ga β-decaying state ($I \geqslant 3$, see text above), the uncertainties on the relative intensities of the 624.3-keV and 1046.1-keV lines leave room for an upper limit of the branching ratio to the ^{84}Ge 2^+ state of $Br(2^+) \lesssim 9\%$ and correspondingly for a lower limit of the β transition to the 4^+ state of $Br(4^+) \gtrsim 91\%$. If one is to try to associate some quantitative estimate of the log ft values with such branching ratios, then a few assumptions are necessary. First, considering the proton and neutron single particle states naturally available (see Sec. IV) a negative parity can be assumed for both ^{84}Ga β-decaying states: The β transitions considered in the following are then of the first-forbidden type. Second, the $T_{1/2}$ values for both β-decaying states are assumed to be equal to the one of Ref. [14]. This is certainly a good assumption for the low-spin state as revealed by the study of the β-n 248-keV peak time evolution (see Fig. 3). No half-life of the high-spin β-decaying state could be extracted from the present data due to low statistics. However considering the typical release times of the target-ion source used in our experiment, this second half-life is necessary of the same order of magnitude as the previous, probably shorter. And finally, the difference of binding energies between the ground and isomeric states has to be neglected due to the lack of experimental value for ^{84}Ga. Hence the extrapolated value $Q_\beta = 14000(718)$ keV of Ref. [19] is used, the uncertainty associated with this estimate being probably larger than the energy difference between the two β-decaying states. The calculated limits for the log ft associated with those assumptions are summarized in Table II from which it can be deduced that the most probable spin and parity for the two β-decaying states observed in ^{84}Ga are (0^-) for the low-spin state and (3^-,4^-) for the “high”-spin state. The corresponding β-decay scheme is represented in Fig. 7. No indication on the relative order in energy between the two β-decaying states can be obtained from the present

TABLE II. Summary of the log ft limiting values calculated from the branching ratios observed between the two β-decaying states of ^{84}Ga and the 0^+, 2^+, 4^+ states of ^{84}Ge. “*l.s.*” and “*h.s.*” stand for low spin and “high” spin, respectively, “1st-f. u.” and “1st-f. n.u.” stand for first-forbidden unique and nonunique, respectively.

Transition	log ft	Nature	Selection
^{84}Ga(*l.s.*) $\rightarrow$ ^{84}Ge(0^+)	$\lesssim$5.0	1st-f. n.u.	$\Delta I = 0, 1$; $\Delta\Pi = -$
^{84}Ga(*l.s.*) $\rightarrow$ ^{84}Ge(2^+)	$\gtrsim$10	1st-f. u.	$\Delta I = 2$; $\Delta\Pi = -$
^{84}Ga(*h.s.*) $\rightarrow$ ^{84}Ge(2^+)	$\gtrsim$6.0	1st-f. n.u.	$\Delta I = 0, 1$; $\Delta\Pi = -$
^{84}Ga(*h.s.*) $\rightarrow$ ^{84}Ge(4^+)	$\lesssim$4.8	1st-f. n.u.	$\Delta I = 0, 1$; $\Delta\Pi = -$

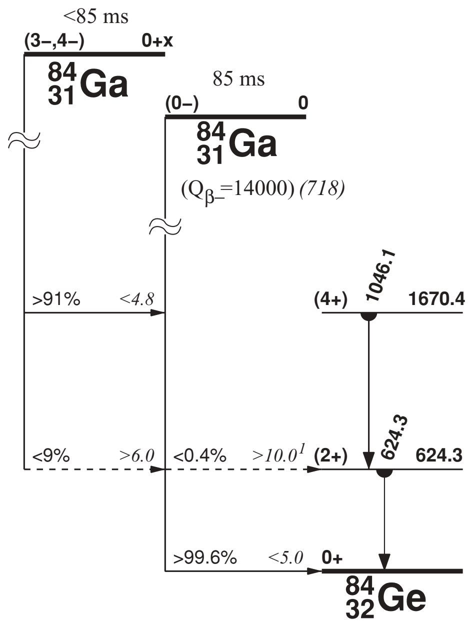

FIG. 7. Tentative decay scheme for ^{84}Ga. Only the β branch is represented.

data. However, considerations on the known relative order of the proton and neutron single-particle states in this mass region, as discussed in the following Section, would suggest that the low-spin β-decaying state could be the ground state of ^{84}Ga.

IV. INTERPRETATION

The coexistence of two close lying levels with spin difference $\Delta I \gtrsim 3$ in ^{84}Ga is easily accounted for by considering the natural valence space available for three neutrons and three protons above a ^{78}Ni core. The recent experimental breakthrough in close vicinity of ^{78}Ni [7,20,21] provides indeed a rather clear picture of the single particle level ordering in this very neutron rich region: For protons, $1f_{5/2}$ and $2p_{3/2}$ are close to each other and in this order in energy while for neutrons, $2d_{5/2}$ is the lowest closely followed by $3s_{1/2}$. Then the natural proton-neutron configuration for ^{84}Ga ground state is $(\pi 1f_{5/2})^3 \otimes (\nu 2d_{5/2})^3$. Use of the Paar model describing the proton and neutron coupling to the core vibrations [22] shows that $I^\pi = 0^-$ is the favored member of the proton-neutron multiplet which fits well with our experimental findings. The first excited configuration is either $(\pi 1f_{5/2})^3 \otimes (\nu 2d_{5/2})^2(\nu 3s_{1/2})^1$ or $(\pi 1f_{5/2})^2(\pi 2p_{3/2})^1 \otimes (\nu 2d_{5/2})^3$. The first configuration gives rise to a doublet 2^-–3^- and the second produces a state $I^\pi = 4^-$ which is energetically favored in Paar's model. The two states with $I^\pi = 3^-$ originating from each of those two configurations are likely to be connected which could push the lowest below the 4^- state. The higher spin long-lived state is then either 3^- of mixed configuration or 4^- of clean configuration $(\pi 1f_{5/2})^2(\pi 2p_{3/2})^1 \otimes (\nu 2d_{5/2})^3$. These attributions of spins and configurations, and the adequacy of the particle-core vibration coupling picture follow and complete the general trends of the nuclear structure emerging

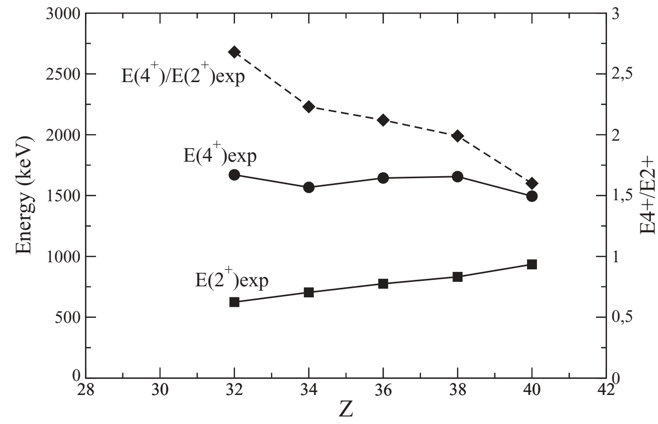

FIG. 8. Experimental systematics of the energies of the first 2^+ and 4^+ states and ratio $E(4_1^+)/E(2_1^+)$ for the proton-deficient even-even $N = 52$ isotones (last stable isotone has $Z = 40$).

in the region close to ^{78}Ni in terms of dominant single particle states and dynamics.

This latter aspect is of particular interest here. As can be seen from Fig. 8 there is an increase of the experimental $E(4_1^+)/E(2_1^+)$ values for the $N = 52$ isotones from stability ($Z = 40$) toward neutron excess. The inclusion of the new value at $Z = 32$ obtained in the present work reveals some acceleration in this tendency (similar to the one between $Z = 40$ and 38) which should, most generally speaking, be interpreted as a sudden increase of collectivity. If one now considers the $E(4_1^+)/E(2_1^+)$ ratio systematics for the isotopic chain of Ge (filled diamonds in Fig. 9), one sees that the $E(4_1^+)/E(2_1^+)$ ratio regains approximately the same value in ^{84}Ge, after the $N = 50$ shell closure, as it had, just before, in ^{80}Ge. The general picture which emerges then is that everything happens as if the $N = 50$ shell closure offered nothing but a local parenthesis of rigidity against the general tendency to softness of the neutron-rich Ge nuclei. Special softness against collectivity for neutron-rich Ge nuclei is a well-known fact which has long been pointed out closer to

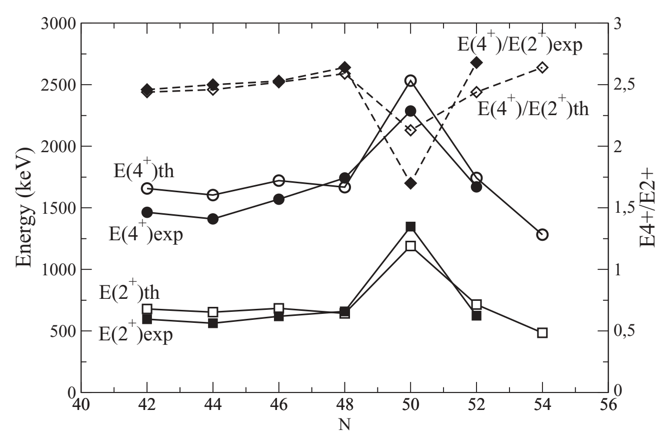

FIG. 9. Calculated (open symbols) vs experimental (filled symbols) systematics of the energies of the first 2^+ and 4^+ states and ratio $E(4_1^+)/E(2_1^+)$ for the neutron-rich even-even Ge isotopes up to mass 86 (last stable isotope has $N = 44$).

stability. The systematic study of their structure from stability toward $N = 50$ show that these nuclei exhibit most of the usual features characterizing transitional nuclei with coexistence of permanent deformation, rotation, γ softness, and vibrations [23] for which a global theoretical description is generally difficult. In order to understand better the nature of this collectivity, and its quick onset just around $N = 50$, Hartree-Fock-Bogoliubov (HFB) calculations were performed [24] using the Gogny-D1S effective interaction [25,26]. Numerical methods and codes used were those described in Ref. [27]. Rotational and vibrational degrees of freedom in the triaxial plane were described within the beyond mean-field approach developed by the group of CEA Bruyères-le-Châtel and based on the generator coordinate method under gaussian overlap approximation (GCM + GOA) [28]. As can be seen in Fig. 9, the resulting energy values for the first 2^+ and 4^+ excited states are in very good agreement with the experimental ones, as are the ratios $E(4_1^+)/E(2_1^+)$.

It is well known that those ratios constitute not all but one piece of evidence for collectivity. It is then interesting to compare also the results from GCM + GOA calculations with recently measured [30] reduced electric quadrupole transition probability $B(E2)\uparrow$ for neutron-rich Ge isotopes. Such comparison is made in Fig. 10 where it is seen, again, that the agreement is remarkable, especially knowing that no effective charge is introduced in such calculations. It is striking to consider that even the structure of the singly-magic nucleus ^{82}Ge is well reproduced in this approach while, in general, the GCM basis is too tight to reproduce rigid singly-magic nuclei. The fact that the collective basis in the GCM calculations is well suited simply means that quadrupole coherence dominates the structure of ^{82}Ge. This fact is also coherent with the recent discovery of a local minimum at $Z = 32$ in the $N = 50$ shell gap from mass measurements [31]. As can be seen in the Fig. 4 of Ref. [31], both the location of the minimum and the size of the gap is reproduced by self-consistent mean-field calculation *exclusively* when beyond mean-field correlations are included. In shell-model

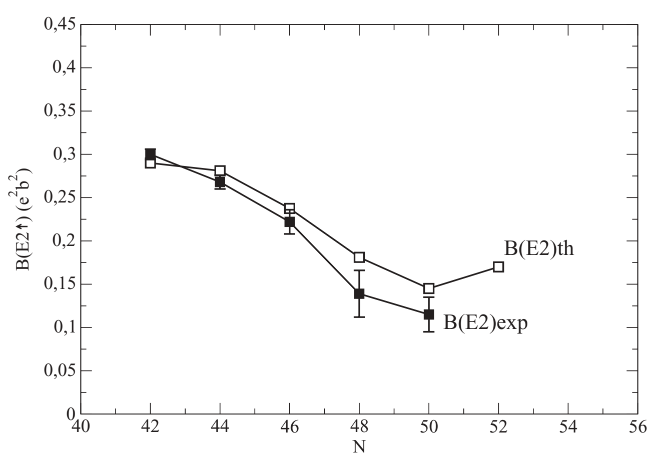

FIG. 10. Calculated (open symbols) vs experimental (filled symbols) systematics of the $B(E2)\uparrow$ for the neutron-rich even-even Ge isotopes. Experimental values for $N = 42–44$ are from the evaluation [29] and for $N = 46–50$ from Ref. [30].

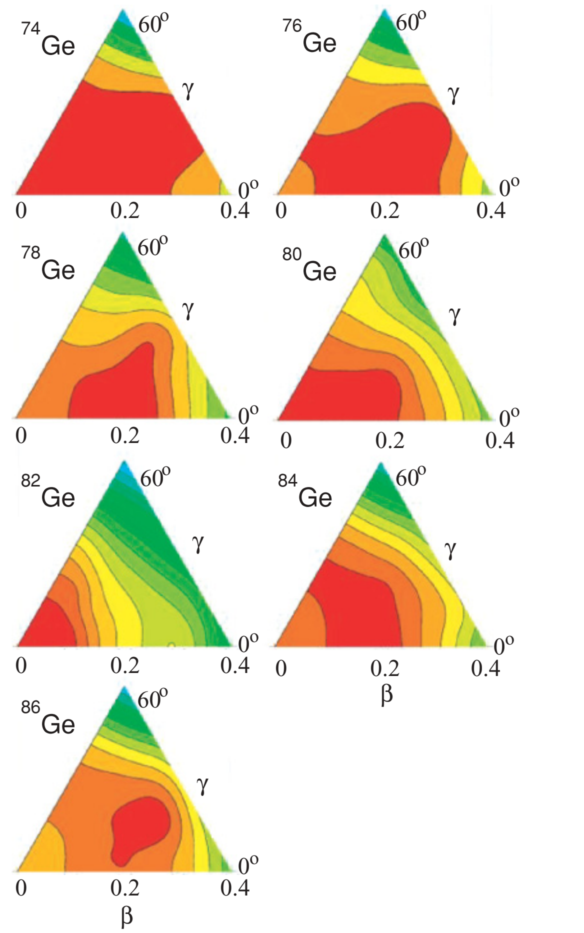

FIG. 11. (Color online) Potential energy surfaces $V(\beta, \gamma)$ calculated for $^{74-86}$Ge$_{42-54}$ obtained in constrained HFB calculations [24]. Equipotential lines are separated by 1 MeV.

language when large values of the effective charges for neutron (e_ν) or proton (e_π) are necessary to reproduce the observed $B(E2)$ one is led to invoke polarization of some kind for the neutron or proton core, respectively. The fact is that any missing correlations due the valence space truncation can contribute to polarization effects. The good agreement for both $B(E2)$ and $E(4_1^+)/E(2_1^+)$ ratios which is obtained here between experiment and beyond mean-field calculations hints for a dynamical origin to the $Z = 28$ core polarization first reported in Ref. [2] and then confirmed at $N = 50$ in Ref. [3]. From those considerations it is tempting to push the interpretation a bit further: If shell model calculations using ^{78}Ni as a core became available, then it is very likely that this core would have to be considered as polarized (not only the $Z = 28$ proton core but certainly also the $N = 50$ neutron core).

The nature of those dynamical effects can be described at least qualitatively by considering the calculated potential energy maps in the triaxial plane of Fig. 11. One clearly sees that the evolution from $N = 50$ to 52 corresponds to a transition from vibration around a spherical equilibrium shape to complete γ softness with the apparition of a shallow

γ valley. Prediction for $N = 54$ is that collectivity increases even more with a surface potential energy closer to that of a triaxial rotor, and a corresponding decrease of the calculated 2_1^+ and 4_1^+ excitation energy values associated with an increase of the $E(4_1^+)/E(2_1^+)$ ratio (see Fig. 9).

V. CONCLUSION

In conclusion, ^{84}Ga isotopes were produced on-line with the ALTO facility. In order to explain the experimental data, we propose the existence of two close lying β-decaying states in this nucleus, with proposed spin-parity assignments $I_1^\pi = 0^-$ and $I_2^\pi = 3^-, 4^-$. Such coexistence can be understood as the natural consequence of the specific single-particle relative ordering (quite different from that long known close to stability) appearing in the immediate vicinity of ^{78}Ni with close lying $1f_{5/2}$ and $2p_{3/2}$ orbits for protons and $2d_{5/2}$ and $3s_{1/2}$ for neutrons. The transition from the $1/2_1$ state in ^{83}Ge (already observed in Ref. [21]) to the 5/2 ground state was observed at 247.8 keV. This fixes the excitation of the dominant fragment of the $3s_{1/2}$ single-particle state to a higher degree of accuracy compared to previous work. In addition, the observation of the β decay of the higher spin long-lived state ($I_2^\pi = 3^-$, 4^-) allows the determination of the energies of the 2_1^+ and the—tentatively proposed—4_1^+ excited state of ^{84}Ge, hinting for an immediate restoration of collectivity just after the $N = 50$ shell closure for $Z = 32$. Up to now, the whole corpus of experimental data points toward a doubly-magic ^{78}Ni with a “doubly-polarized” core character.

ACKNOWLEDGMENTS

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