Experimental study of the β decay of the very neutron-rich nucleus ^{85}Ge

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The β-decay properties of the very neutron-rich nucleus ^{85}Ge, produced in the proton-induced fission of ^{238}U, were studied at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. The level scheme of $^{85}_{33}$As$_{52}$ populated in ^{85}Ge $\beta\gamma$ decay was reconstructed and compared to shell-model calculations. The investigation of the systematics of low-energy levels in $N = 52$ isotones together with shell-model analysis allowed us to provide an estimate of the low-energy structure of the more exotic $N = 52$ isotone ^{81}Cu.

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I. INTRODUCTION

It has been predicted by various calculations [1–4] that a large excess of neutrons may significantly modify the shell structure with respect to the structure observed close to the β-stability line. β-decay studies in the vicinity of the very exotic nucleus $^{78}_{28}$Ni$_{50}$, which is located significantly farther away from the stability path than any other doubly magic nucleus on the neutron-rich side, are particularly well suited for testing such predictions. Moreover, other calculations predict deformation in $_{34}$Se and $_{32}$Ge nuclei with four neutrons beyond the $N = 50$ shell closure [5]. Further theoretical efforts tested with new experimental data are required. The starting point can be the study of excited states in $N = 52$ isotones with odd Z, which are good candidates to probe proton single-particle states. Our recent experimental data on the excited states in $^{83}_{31}$Ga$_{52}$ suggest a different ordering of the low-lying levels than predicted by the shell model [6]. The next $N = 52$ isotone is ^{85}As.

The first spectroscopic information on the β-decay ^{85}Ge $\to$ ^{85}As was obtained at the OSIRIS facility in Studsvik [7], where the half-life of ^{85}Ge [$T_{1/2} = 580(50)$ ms] was measured and two γ transitions of 102 and 116 keV were identified. Our later experiments confirmed these two lines and assigned a few more transitions in ^{85}As at energies of 206, 268, and 396 keV [8–11]. Furthermore, the more precise half-life $T_{1/2} = 494(8)$ ms obtained from this data set [8] is in agreement with the previous results $T_{1/2} = 580(50)$ ms [7] and $T_{1/2} = 535(47)$ ms [12]. In this work, the partial decay scheme of ^{85}Ge is presented for the first time with several new γ transitions included.

II. EXPERIMENTAL SETUP

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. Fission fragments were produced by proton-induced fission of ^{238}U on a UC$_x$ target [13] and subsequently ionized in a hot-plasma ion source to form a radioactive ion beam for experiments. The nuclei of interest, ^{85}Ge, were produced in the target, combined with sulfur, and then extracted from the ion source as molecular ions, ^{85}GeS$^+$. The purified ^{85}GeS$^+$ was selected after two stages of mass separation with a Cs-vapor cell in between to break up the molecule [14]. In the first stage of mass selection, a dipole magnet with mass resolution of $m/\Delta m \approx 1000$ separated all singly charged positive ions with $A = 117$ $(85 + 32)$ from other products. The $A = 117$ beam was then passed through a low-density Cs-vapor cell where the ^{85}GeS$^+$ molecular ion broke up and ^{85}Ge$^+$ ions were formed. The $A = 85$ ions were then selected using a high-resolution dipole magnet with mass resolution of $m/\Delta m \approx 10\,000$. This process resulted in an almost pure ^{85}Ge beam (some contamination of ^{85}As was present).

This beam was implanted into the tape of the moving tape collector (MTC) positioned in the center of the detection setup at the Low-energy Radioactive Ion Beam Spectroscopy Station [15,16]. An electrostatic deflector periodically deflected the beam away from the implantation point. The MTC periodically removed the implanted activity to avoid accumulation of long-lived contaminants and daughter activities. The measurement was structured in three phases: a 1.5-s period for the accumulation of the activity (beam-on), a 1.5-s period when beam was deflected away (beam-off), and a 0.36-s transport time to remove the radioactivity out of the detection setup. The detection setup consisted of four high-purity germanium clover γ-ray detectors (6% efficiency at 1.3 MeV) and two plastic scintillation counters for β-particle detection surrounding the beamline at the activity-deposition point. Trigger-free data from all detectors were collected by a fully digital acquisition system based on the XIA Pixie-16

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Rev. D modules with a 100 MHz clock synchronized across all modules [17–19].

III. RESULTS

The strongest transitions presented in the β-gated γ-ray spectrum at mass 85 (see Fig. 1) belong to the β or βn decay of ^{85}Ge.

The weaker lines correspond to the daughters' activities in the mass $A = 85$ chain [20]. There are a few γ lines observed and marked with star symbols, which are unassigned. The half-life and β-γ-γ coincidence analysis did not provide evidence for their belonging to ^{85}Ge decay or any of the daughter activities.

The analysis of the β-γ (see Fig. 1) and β-γ-γ (see Fig. 2) data confirmed all five lines previously identified [7–11] and added several new transitions to the β decay of ^{85}Ge. The transitions observed and assigned to the decay of ^{85}Ge are summarized in Table I together with their intensities. Relative γ intensities ($I^{\rm rel}_{\gamma+\rm CE}$) were determined with respect to the 268-keV line. For $I^{\rm rel}_{\gamma+\rm CE}$ of the weakest transitions, β-γ-γ coincidences were used. The partial decay scheme of ^{85}Ge is proposed here for the first time (see Fig. 3). A transition at 345 keV, which was observed in the coincidence spectrum, was added tentatively, because a line at the same energy was reported as following ^{85}Se $\rightarrow$ ^{85}Br decay [20].

A substantial β-n-decay branch is present in ^{85}Ge decay owing to the large energy window of $Q_{\beta n} = 4659(5)$ keV available for this channel [20]. Its probability was recently measured, $P_n = 17.2(18)\%$ [22]. In our data four γ transitions in ^{84}As were observed at 42.7, 100.1, 242.5, and 347.1 keV [23]. The 100.1-keV line is a doublet with the 102.0-keV line in ^{85}As. The intensity of the 102.0-keV transition reported in Table I is corrected for the intensity of the 100.1-keV line, which is estimated from the β-γ-γ coincidence spectrum to be about 2.4% of the sum of the intensities of the 102.0- and 100.1-keV lines.

Apparent β feeding I_β(rel) was calculated by normalizing the relative γ intensity to the sum of all observed intensities feeding the ground state (g.s.) (102.0, 218.3, 267.8, 500.9, 745.4, 979.0 keV) and corrected for $P_n = 17.2(18)\%$ [22]. Our experiment was not sensitive to direct β transitions to the ground state of ^{85}As. Taking a typical value of $\sim$6.5 for the log(ft) of a first-forbidden transition between the ($3/2^+$) and ($5/2^-$) ground states, we obtain an estimation of $I_\beta \sim 5\%$. Therefore, we list our β intensities as *apparent*, i.e., without taking into account this relatively small g.s.-to-g.s. β feeding.

IV. DISCUSSION

The parent nucleus ^{85}Ge ($Z = 32$, $N = 53$) has a positive-parity ground state with $I^\pi_{\rm g.s.} = (3/2^+, 5/2^+)$ [11]. Systematics of $N = 53$ isotones [24], together with shell-model (SM) calculations [25], favor the ($3/2^+$) assignment over ($5/2^+$). A tentative value for I^π of the ground state, and the first excited state of the daughter nucleus ^{85}As can be estimated on the basis of systematics of the $N = 52$ isotones ^{83}Ga [6,26] and ^{87}Br [27].

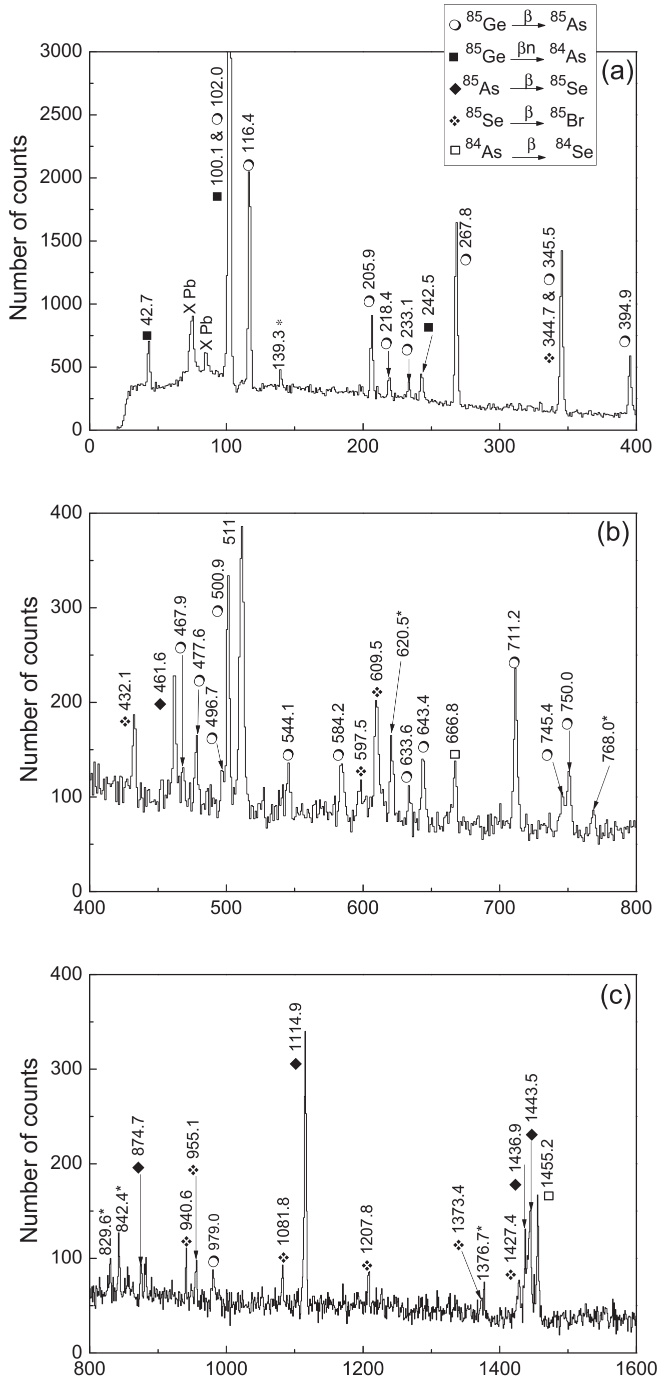

FIG. 1. Portions of the β-gated γ-ray spectrum obtained at mass $A = 85$ collected during both beam-on and beam-off periods: 0–400 keV (a), 400–800 keV (b), 800–1600 keV (c). The strongest transitions belong to the ^{85}Ge $\rightarrow$ ^{85}As β decay and ^{85}Ge $\rightarrow$ ^{84}As βn decay. The weaker transitions correspond to decays in the daughters, ^{85}As, ^{84}As, and ^{85}Se [20]. Six lines marked with a star are unassigned.

For ^{83}Ga, the assignment $I^\pi_{\rm g.s.} = (5/2^-)$ was made on the basis of information about absolute β feeding [26]. Two γ transitions in ^{83}Ga de-exciting levels at 218 and 109 keV in cascade were registered in later studies and identified as of $M1$ character. The level ordering was suggested to be

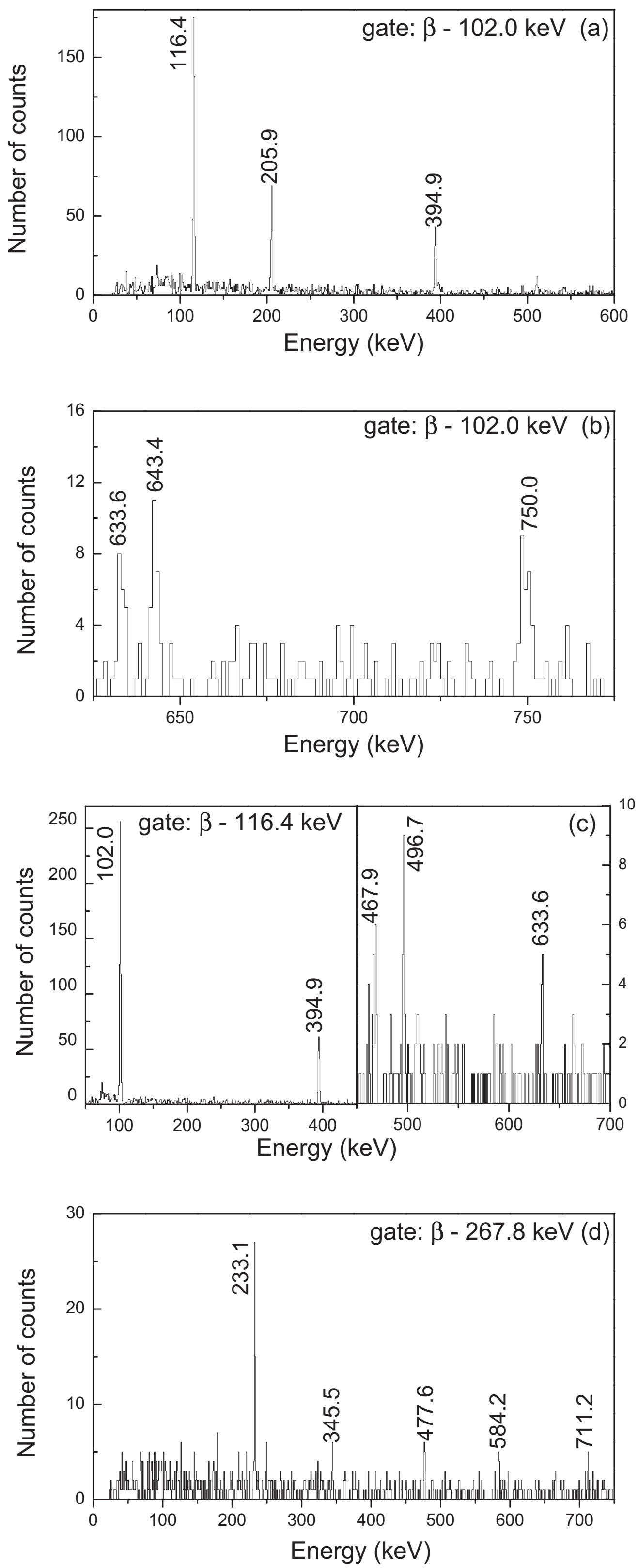

FIG. 2. The β-gated γ-ray spectra in coincidence with the 102-keV transition (a),(b), 116-keV (c), and 268-keV (d), which belong to the ^{85}Ge $\rightarrow$ ^{85}As β decay.

$I^\pi = (1/2)^-$, $(3/2)^-$, and $(5/2)^-$ for the 218-keV, 109-keV, and ground state, respectively [6]. Spin/parity $(5/2^-)$ was assigned to the ^{87}Br ground state [27]. The recent assessment of ^{87}Br states by the Evaluated Nuclear Structure Data File (ENSDF) evaluators [28], based primarily on Refs. [27,29], follows the $(5/2^-)$ g.s. assignment and lists (1/2, 3/2, 5/2) possibilities for the spins of all known levels, from the 243-, 334-, and 573-keV states up to the 3987-keV state; compare Fig. 4(a).

Assuming similar behavior in ^{85}As as observed in ^{83}Ga, we propose $M1$ character for the 102.0- and 116.4-keV transitions. This is consistent with the fact that the γ rays are in prompt coincidence with β particles. For both transitions, multipolarity $E2$ or larger would give rise to a measurable lifetime ($\sim$1 μs) [30], which was not observed in the data. Assuming $I^\pi_{\rm g.s.} = (5/2^-)$ and keeping in mind the systematic behavior described above, we propose $I^\pi = (3/2^-)$ for the first excited state at $E^* = 102.0$ keV.

The 116.4- and 218.3-keV transitions depopulate the 218.3-keV level to the first excited and ground states, respectively. Assuming $M1$ character for the 116.4-keV and $E2$ for the 218.3-keV transitions, the calculated ratio of their intensities would be about 4 [30,31], which is consistent with the experimental intensity ratio $I_\gamma(116.4\ \text{keV})/I_\gamma(218.3\ \text{keV}) = 8(1)$. This points towards a spin difference of 2 between the 218-keV level and ground state, suggesting $I^\pi = (1/2^-)$ for the 218.3-keV state.

These low-lying negative-parity and low-spin states will be fed in the β decay of ^{85}Ge by first-forbidden transitions. Apparent log(ft) values for decay to these levels range from 5.8(1) to 7.5(1) (Table I; Fig. 3), confirming such picture. Positive-parity states that could be populated by allowed Gamow-Teller transitions are expected to occur at higher excitation energies according to the shell model (SM).

Shell-model calculations were performed using the NUSHELLX code [32] with the N3LO (Next-to-Next-to-Next-to-Leading Order) nucleon-nucleon interaction [33] and valence space containing all active orbitals above the ^{78}Ni core, as described in Ref. [6]. The ^{85}As level scheme (up to 1 MeV) predicted by the SM is compared with the experimental data in Fig. 3. The sequences of the calculated levels is in fair agreement with the ones arising from experiment. Below 1 MeV, three groups of levels are predicted by the SM in the range 0–100, 350–450, and 700–1000 keV corresponding to the levels observed in experiment.

Only excited states of negative parity are present in the shell-model calculations, which suggest that the lowest-energy part of the ^{85}As level scheme is fed by first-forbidden β transitions, which is consistent with experimental data. The first group of excited states with positive parity is expected at $\sim$3.3 MeV. Its population by Gamow-Teller β transitions was not observed in the experiment.

To comprehend the evolution of the level structure in $N = 52$ isotones, the SM calculations were extended to the neighboring ^{81}Cu, ^{83}Ga, ^{85}As, and ^{87}Br nuclei; see Fig. 4(b). The number of levels predicted in the calculations for $^{83}_{31}$Ga, $^{85}_{33}$As, and $^{87}_{35}$Br are in good agreement with the experimental data at low excitation energies, although its order is not in agreement with experimental systematics. A similar picture is expected

TABLE I. Relative ($I^{\text{rel}}_{\gamma+\text{CE}}$) γ-ray intensities for the β decay of ^{85}Ge normalized to the 267.8 keV transition. Energy values expressed in keV. E_f is the energy of the final level. I_β(rel) represent the apparent β-feeding determined from $I^{\text{rel}}_{\gamma+\text{CE}}$. Apparent log(ft) determined from I_β(rel) is also given.

E_{level}	E_γ	E_f	Coincidence	$I^{\text{rel}}_{\gamma+\text{CE}}$	I_β(rel)	log(ft)
			β-decay channel			
102.0	102.0(2)	0	116.4, 205.9, 305.4, 394.9, 399, 467.9, 496.7, 544.1, 633.6, 643.4, 750.0, 1681, 1757	248(20)[a]	22(5)	5.8(1)
218.4	116.4(2)	102.0	102.0, 394.9, 467.9,	76(6)[a]	6(2)	6.3(2)
			496.7, 633.6	76(6)[a]	6(2)	6.3(2)
	218.4(5)	0	394.9, 467.9, 496.7,	9(1)		
			633.6	9(1)		
267.8	267.8(2)	0	233.1, 345.5, 477.6, 584.2, 711.2, 1324 1947	100(8)	9(2)	6.1(1)
307.9	205.9(2)	102.0	102.0, 305.4, 467.9, 544.1	33(4)	4(1)	6.5(1)
500.9	233.1(5)	267.8	267.8	6(1)	7(1)	6.2(1)
	399(1)[c]	102.0	102.0			
	500.9(2)	0		27(3)		
613.3	394.9(2)	218.4	102.0, 116.4, 218.4, 467.9	45(4)	9(1)	6.1(1)
	345.5(5)[c]	267.8	267.8, 467.9,			
	305.4(5)[b]	307.9	102.0, 205.9, 467.9	4(1)		
715.1	496.7(8)	218.4	102.0, 116.4, 218.4	4(1)	0.8(3)	7.1(2)
745.4	643.5(5)	102.0	102.0	12(2)	6(1)	6.2(1)
	477.6(5)	267.8	267.8	8(1)		
	745.4(5)	0		11(2)		
852.0	633.7(5)	218.3	102.0, 116.4, 218.4	4(1)	8(1)	6.1(1)
	544.1(5)	307.8	102.0, 205.9	8(2)		
	584.2(5)	267.8	267.8	12(2)		
	750.1 (5)	102.0	102.0	13(2)		
979	711.2(5)	267.8	267.8	27(3)	8(1)	6.0(1)
	979.0(5)	0		12(3)		
1081.2	467.9(8)	613.3	102.0, 116.4, 205.9, 218.4, 267.8, 305.4, 345.5, 394.9	4(1)	0.9(2)	7.0(1)
1592	1324(1)[b]	267.8	267.8	1.1(2)	0.22(4)	7.5(1)
1783	1681(1)[b]	102.0	102.0	1.9(3)	0.39(8)	7.2(1)
1859	1757(1)[b]	102.0	102.0	1.8(2)	0.36(6)	7.2(1)
2215	1947(1)[b]	267.8	267.8	0.8(1)	0.17(3)	7.4(1)
			β-n-decay channel			
42.7	42.7(5)	0	100.1	45(4)[a]	7.9(9)	
142.8	100.1(5)	42.7	42.7	6(1)[a]	1.2(3)	
242.5	242.5(5)	0	347.1	15(2)	2.9(4)	
589.6	347.1(8)	242.5	242.5	0.4(1)	0.07(2)	

[a] α_{tot} $(M1) = 0.0855(23)$ for $E_\gamma = 102$ keV, $\alpha_{\text{tot}}[M1 = 0.0589(16)]$ for $E_\gamma = 116$ keV, $\alpha_{\text{tot}}(M1) = 0.896(24)$ for $E_\gamma = 43$ keV are included in the calculation.
[b] Only seen in coincidence spectra.
[c] Tentatively assigned on the basis of very weak coincidences and therefore its intensity is not included in the balance.

for the next $N = 52$ isotone $^{81}_{29}$Cu. The lower-energy portion of the ^{81}Cu level scheme predicted by the SM seems to agree with the observed smooth trend visible in the experimental data, suggesting that for ^{81}Cu, $I^\pi_{\text{g.s.}} = (5/2^-)$. A cascade of two $M1$ transitions is therefore expected in the low-energy part of the ^{81}Cu level scheme.

An investigation of the wave function for all low-energy $5/2^-$, $3/2^-$, and $1/2^-$ states in ^{87}Br, ^{85}As, ^{83}Ga, and ^{81}Cu shows

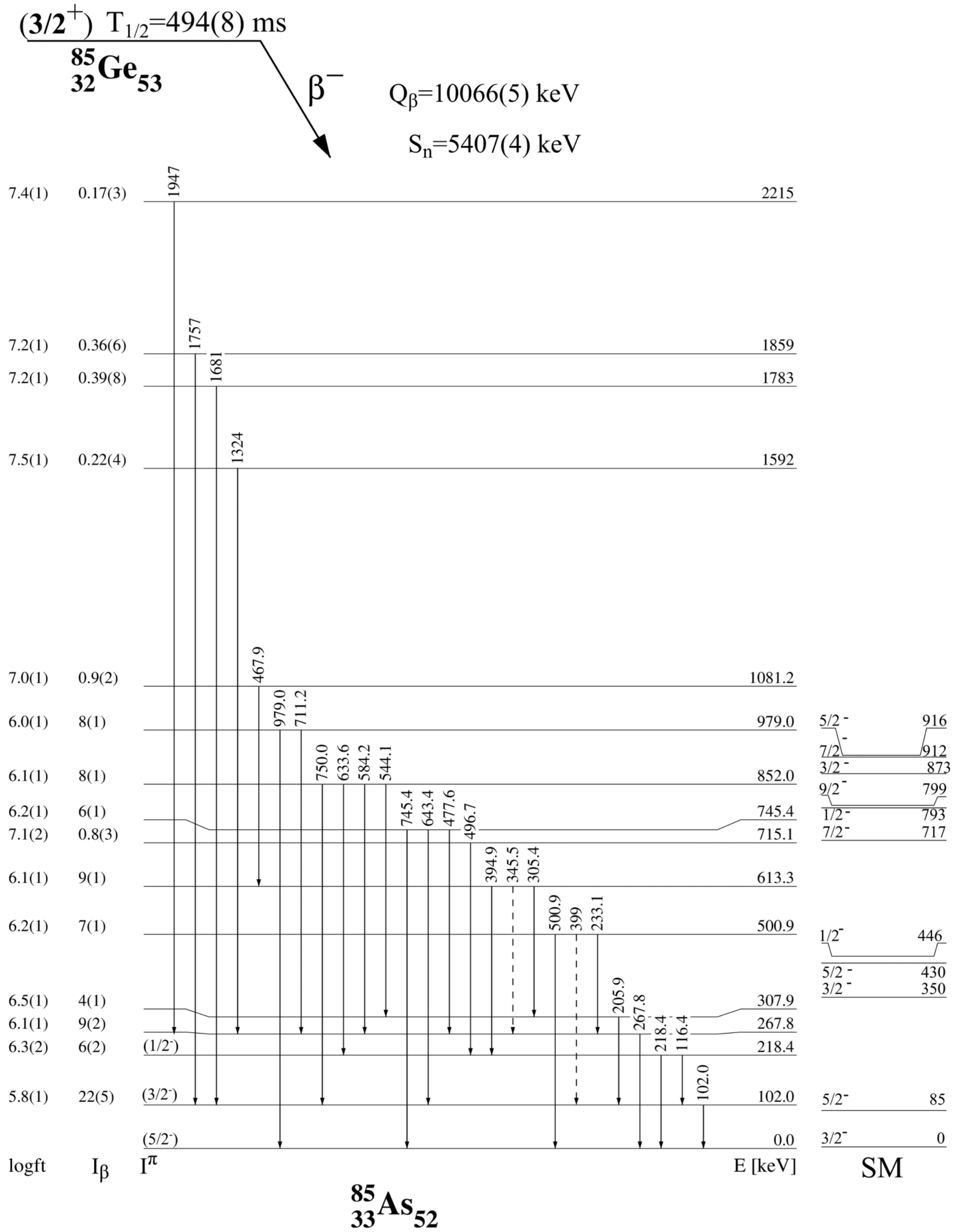

FIG. 3. Partial decay scheme of ^{85}Ge as obtained in this work. Dashed transitions were tentatively assigned on the basis of weak β-γ coincidence. The Q_β and neutron-separation S_n energy were adopted from Refs. [20,21], the half-life is taken from Ref. [8]. Listed β-feeding intensities were obtained as "apparent," i.e., assuming no direct feeding to the ^{85}As$^{g.s.}$; compare text.

that the neutron wave function is dominated (70%–80%) by the $\nu d_{5/2}$ orbital component. The $\nu s_{1/2}$ orbital contributes only up to 20% to the these wave functions; compare Ref. [26]. The proton wave functions are more complex, owing to a strong competition between $\pi f_{5/2}$ and $\pi p_{3/2}$ single-particle orbital. Both components have contributions ranging from 40% to 50% in ^{87}Br, ^{85}As, and ^{83}Ga. The general similarity of the experimentally determined and calculated structures of ^{83}Ga and ^{85}As encourages the extrapolation to ^{81}Cu. One would expect that the valence proton is the main player to determine the nature of low-energy excited levels in ^{81}Cu; compare, e.g., Refs. [34–36]. This is supported by our SM calculations. The main proton component of the wave function has an amplitude of about 80%: The single proton outside the $Z = 28$ core seems to occupy either the $\pi p_{3/2}$ orbital ($3/2^-$ level) or the $\pi f_{5/2}$ orbital ($5/2^-$ level). However, the first $1/2^-$ level has a similar structure as the other heavier $N = 52$ isotones (30%–40% $\pi f_{5/2}$ and $\pi p_{3/2}$). Experimental data on the spin of the lowest-lying states in ^{81}Cu is needed to verify the inversion of the $3/2^-$ and $5/2^-$ lowest-lying state and, hence, the reliability of the SM predictions on its structure. An experiment using a total γ absorption technique might be the ultimate tool

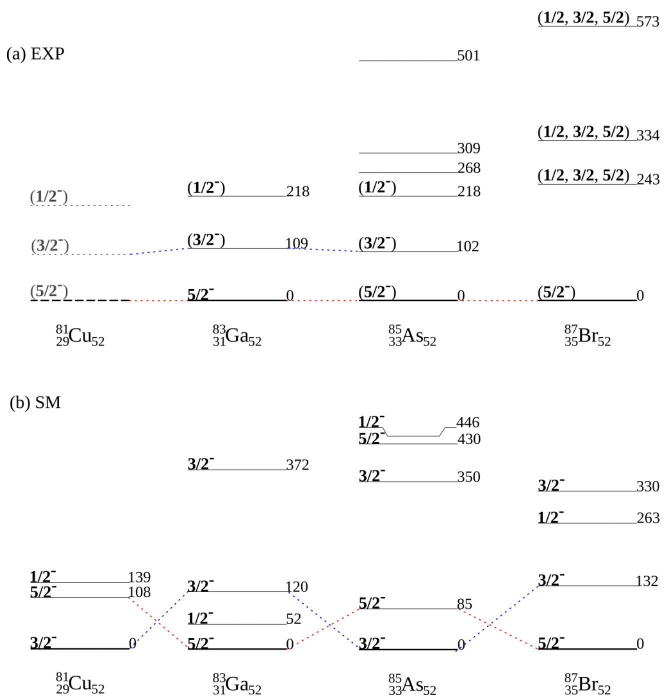

FIG. 4. Experimental (a) [6,28,29] and shell-model (SM) predictions (b) of low-energy levels in $N = 52$ isotones. The lowest-energy $5/2^-$, $3/2^-$, and $1/2^-$ states occur within the first 200–300 keV in experimental data and calculations. In panel (a) the level scheme of ^{81}Cu is predicted from systematic of heavier $N = 52$ isotones. Energies are expressed in keV.

to determine the β-feeding pattern including the g.s.-to-g.s. transition [37].

V. SUMMARY

We have investigated the β and β-n decay of ^{85}Ge produced at the HRIBF using the online mass separation technique enhanced by formation and breakup of molecular ions. The partial level scheme with several new transitions in the daughter nucleus ^{85}As was proposed for the first time. Assuming our experimental results and taking into account the systematic behavior for $N = 52$ isotones, spin and parity values were tentatively assigned to the ground and low-energy states in ^{85}As as $(5/2^-)$, $(3/2^-)$, and $(1/2^-)$, respectively. Shell-model calculations reproduced the experimental trend of the low-lying states for $N = 52$ isotones, which allowed us to suggest the main features of excited states to be expected in the very exotic nucleus ^{81}Cu.

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