Experimental study of the β-γ and β-$n\gamma$ decay of the neutron-rich nucleus ^{85}Ga

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The β-decay properties of neutron-rich ^{85}Ga produced in proton-induced fission of ^{238}U were studied at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. Data consisted of $\beta-\gamma$ and $\beta-\gamma-\gamma$ coincidences were collected at the Low-energy Radioactive Ion Beam Spectroscopy Station after high-resolution on-line mass separation. For the first time, the excited states in the $N = 53$ isotone ^{85}Ge were established from β-delayed γ decay of ^{85}Ga. The level scheme of the $N = 52$ isotone ^{84}Ge was improved and includes now 0^+, 2^+, $(2)^+$, 4^+, and $(0)^+$ states populated in the β-delayed-neutron-γ decay of ^{85}Ga. Advanced shell-model calculations were used to analyze experimental data on ^{85}Ge and ^{84}Ge.

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I. INTRODUCTION

Nuclei near doubly magic ^{78}Ni with their large neutron-to-proton ratios have been investigated extensively in recent years both theoretically and experimentally. In the region of nuclei beyond $N = 50$, the evolution of single-particle levels as a function of the increasing neutron number is particularly interesting. Previous studies of the excited levels in ^{83}Ge and ^{85}Se [1–3] at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) revealed a continuous reduction of the energy difference between the $1/2^+$ excited state and $5/2^+$ ground state with decreasing atomic number for the neutron-rich $N = 51$ isotones. This observation suggested an emergence of a new subshell closure at $N = 58$ [3] related to the close proximity of neutron orbitals $\nu 3s_{1/2}$ and $\nu 2d_{5/2}$ beyond $N = 50$. However, shell-model analysis of $N = 51$ ^{81}Zn [4] suggested that the respective $\nu 3s_{1/2}$ orbital might be returning towards higher energies in ^{81}Zn and ^{79}Ni. The properties of neutron $2d_{5/2}$ and $3s_{1/2}$ orbitals should be further investigated in order to verify potential new subshell closure in neutron-rich nuclei beyond ^{78}Ni.

The sequence of the excited states can be different for the $N = 53$ isotones. By filling the $\nu 2d_{5/2}$ orbital $5/2^+$ and $3/2^+$ states can be produced. It was observed in $N = 53$ ^{95}Mo [5] that the seniority $v = 1$; $I = j - 1$, $3/2^+$ state lies very close to the seniority $v = 1$; $I = j$, $5/2^+$ state.

In order to inspect the level properties beyond $N = 50$, we extended our investigations towards more neutron-rich isotopes and measured the β-delayed γ (β-γ) and β-delayed-neutron-γ (β-n-γ) decay of ^{85}Ga. An earlier HRIBF study with a postaccelerated ^{85}Ga beam had provided the first information on its β-decay properties through the observation of one β-n-γ transition at 624 keV and the tentative assignment of a γ transition at 321 keV [3] as de-excitation in ^{85}Ge. This limited information resulted from low counting statistics of only ~2000 collected ions. Several thousand ions of ^{85}Ga were collected in a RIKEN experiment [6], but no β-γ spectroscopic information was provided.

In this work we present a more detailed investigation of ^{85}Ga β-γ and β-n-γ decay. Its β-decay half-life of 93(7) ms was reported in our recent publication [7].

II. EXPERIMENTAL TECHNIQUE

The experiment was performed at the Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) [8] at the HRIBF [9]. The ^{85}Ga ions were produced in the fission of ^{238}U induced by 54-MeV protons. After being extracted from the ion source as positively charged ions, the fission products went through two stages of mass separation, consisting of a low resolution magnet ($m/\Delta m \approx 1000$) and a subsequent high-resolution magnet ($m/\Delta m \approx 10\,000$) [7,10]. The radioactive beam of almost pure ^{85}Ga was deposited on the Moving Tape Collector (MTC) in the center of the detection setup at the LeRIBSS. An electrostatic "kicker" periodically deflected the beam away from the implantation point. The MTC periodically removed the implanted activity to suppress long-lived isobaric contaminants and daughter activities. The measurement was structured in order to measure its growth while implanting the ions on the MTC and its decay while the beam was deflected away. The cycle chosen was 4 s implantation, 2 s decay, and 0.36 s transporting-away time.

The detection setup consisted of four HPGe clover γ-ray detectors, two plastics scintillation counters for β-particle detection surrounding the beam line at the activity-deposition point. The photopeak efficiency for the γ array was 34% at 81 keV and 6% at 1.3 MeV. Trigger-free data from all detection channels were collected by means of an entirely digital data acquisition system [11,12].

III. RESULTS

The analysis of the β-gated γ-ray spectrum allowed us to firmly assign several new transitions at 107, 365, 472, 596, 788, 796, and 2241 keV to the β-γ decay of ^{85}Ga (see Fig. 1). On the basis of β-γ and β-γ-γ coincidences, a partial level scheme of ^{85}Ge was built; see Figs. 1–3. The half-life analysis of the most intense transition at 107 keV yielded 84(8) ms, which is consistent with the value for the 624-keV transition [99(6) ms], indicating that the 107-keV transition belongs to the β-γ decay of ^{85}Ga (see Fig. 1 in [7]). We adopted the weighted average of 93(7) ms as the ^{85}Ga half-life [7]. The tentatively reported 321-keV line [3] was not observed in the present work with much better statistics and therefore its assignment to the decay of ^{85}Ga is now rejected.

So far, only two excited states in the $N = 52$ ^{84}Ge were reported [3,14]. Transitions observed at 624.3(7) and 1046.1(7) keV [14] and at 623.9(6) and 765.1(8) keV [3] were assigned to the β-γ decay of ^{84}Ga. In both studies, the γ lines were interpreted as the $E2$ de-excitations of the 4^+-2^+-0^+ ground state band in ^{84}Ge. In order to explain their data, Lebois *et al.* proposed the existence of two close-lying β-decaying states in ^{84}Ga and suggested the spin-parity assignments of $I_1^\pi = (0^-)$ and $I_2^\pi = (3^-, 4^-)$ [14]. However, Winger *et al.* [3] firmly identified the 1046-keV line as a transition in ^{83}Ge following the ^{83}Ga→^{83}Ge β decay. No evidence for isomeric decay of ^{84}Ga was found in [3].

A substantial β-n decay branch can be expected in ^{85}Ga decay since a large energy window of $Q_{\beta n} = Q_\beta - S_n = 10.01(30)$ MeV [15] is available for this decay mode. Such a large $Q_{\beta n}$ value should enable the population of several excited states in the βn daughter nucleus ^{84}Ge. In our data five transitions were observed at 624, 764, 805, 858, 1224, and 1388 keV and assigned to the β-n-γ decay branch. This assignment is based on the fact that the 764-, 805-, and 1224-keV lines are in coincidence with the 624 keV unambiguously representing the 2^+ to 0^+ transition (see Fig. 2), while the 1388-keV line matches the sum energy of the 624- and 764-keV transitions. As expected, the 1046-keV transition was not observed [3]. No evidence for additional transitions in ^{84}Ge was found. Deduced γ-ray intensities and the energies of the excitation levels observed are summarized in Table I.

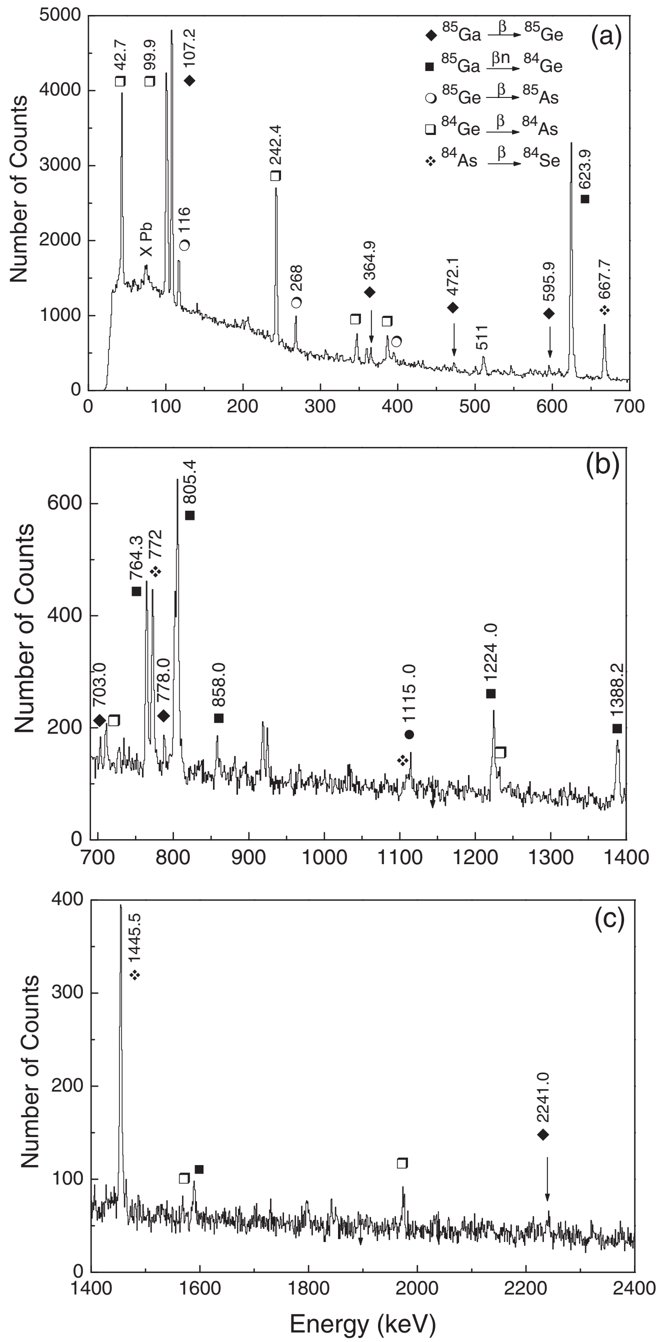

FIG. 1. The β-gated γ-ray spectrum obtained at mass $A = 85$. The strongest transitions belong to the β decay of ^{85}Ga→^{85}Ge and βn decay of ^{85}Ga→^{84}Ge. The weaker transitions belong to the daughter activities ^{85}Ge $T_{1/2} = 0.56(5)$ s, ^{84}Ge $T_{1/2} = 0.954(14)$ s, and ^{84}As $T_{1/2} = 4.2(5)$ s [13].

IV. DISCUSSION

A. β decay of ^{85}Ga

Ground-state spin and parity of odd-A, $Z = 31$ Ga isotopes were determined to be $3/2^-$ for neutron numbers $N \leqslant 50$ with the only exception of $N = 42$ ^{73}Ga [16]. A $5/2^-$ ground state was identified experimentally at and beyond the $N = 50$ shell closure in ^{81}Ga [4,16] and ^{83}Ga [3]. This configuration

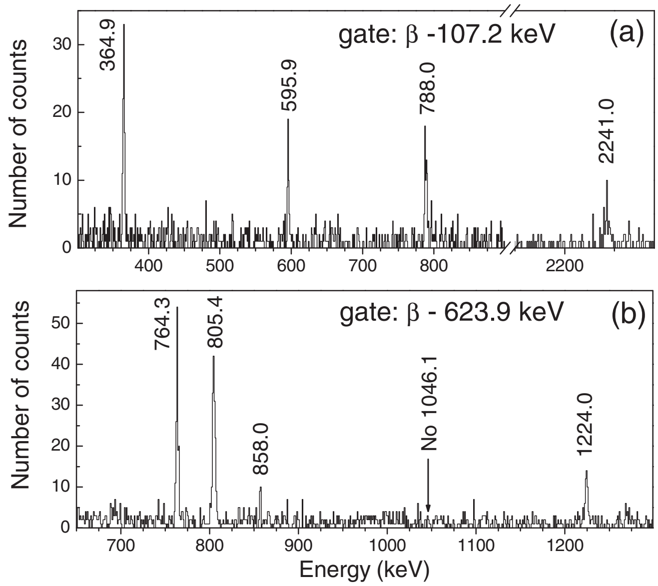

FIG. 2. The β-gated γ-ray spectra in coincidence with the 107-keV (a) and 624-keV (b) transitions. The 107-keV γ and 624-keV lines correspond to the β-γ decay and β-n-γ decay of ^{85}Ga, respectively.

change was explained as the effect of the inversion between $\pi f_{5/2}$ and $\pi p_{3/2}$ single-particle states with increased neutron number, in analogy to what has been observed in the $Z = 29$ Cu isotopes [17–19]. Thus, we consider the spin and parity $I^{\pi} = (5/2^-)$ for the ground state of $N = 54$ ^{85}Ga.

The $(5/2^-)$ assignment for the ^{85gs}Ga is also supported by good agreement between the experimental half-life and its calculated value [7]. The microscopic calculations using the energy density functional DF3a and Continuum Quasiparticle Random Phase Approximation (CQRPA) [20–24] including both Gamow-Teller and first-forbidden (ff) β transitions were found to follow closely the experimental half-lives of nuclei near ^{78}Ni [7,25]. These calculations yielded $T_{1/2} = 119$ ms in a good agreement with the experimental value of 93(7) ms [7]. For a $3/2^-$ ground state, the same model predicts a much longer half-life, $T_{1/2} = 246$ ms.

The level energy systematics in the $N = 51$ isotones shows rather regular behavior: the first $(3/2^+)$ excited state decreases in energy with respect to the $5/2^+$ ground state while going from $\sim$2 MeV in ^{91}Zr to $\sim$1 MeV in ^{83}Ge. If we look at the systematics of $N = 53$ isotones, the trend is not as smooth; see Fig. 4. The energy difference between the ground state and first excited state is much lower (<260 keV). While going from ^{93}Zr to ^{85}Ge an inversion between $5/2^+$ and $3/2^+$ spins happens at $^{89}_{36}$Kr [26], where the first $(5/2^+)$ excited state lies at only 29 keV. As far as the next isotone (^{87}Se) is concerned, it is known that the first observed excited state is at 92 keV [25]. Tentative spin/parity assignments of $(3/2^+)$ and $(5/2^+)$ for the ^{87}Se ground state and first excited state, respectively, were recently made [27].

TABLE I. Relative γ-ray intensities (I_{rel}) for the β and βn decays of ^{85}Ga normalized to the 623.9-keV transition.

E_{level} (keV)	E_{γ} (keV)	I_{rel}	^{85}Ga decay channel
107.2	107.2(1)	30.3(6.8)	β
472.1	364.9(1)	3.71(0.77)	β
472.1	472.1(1)	2.05(0.23)	β
703.1	595.9(1)	3.7(1.2)	β
703.1	703.1(1)	1.26(0.45)	β
895.2	788.0(1)	2.26(0.61)	β
903.0	796.0(1)	0.41(0.12)	β
2348.2	2241.0(1)	3.4(1.2)	β
623.9	623.9(1)	100.0(18.0)	βn
1388.2	764.3(1)	13.4(2.7)	βn
1388.2	1388.2(1)	8.13(1.58)	βn
1429.3	805.4(1)	20.8(4.2)	βn
1847.9	1224.0(1)	10.0(2.4)	βn
2287.0	858.0(1)	2.3(6)	βn

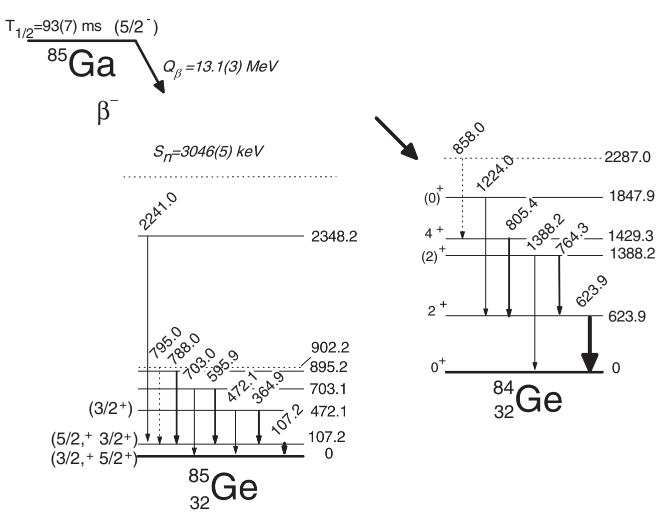

FIG. 3. Partial experimental decay scheme of ^{85}Ga. The Q_{β} and S_n energies are taken from [15]. See text for details.

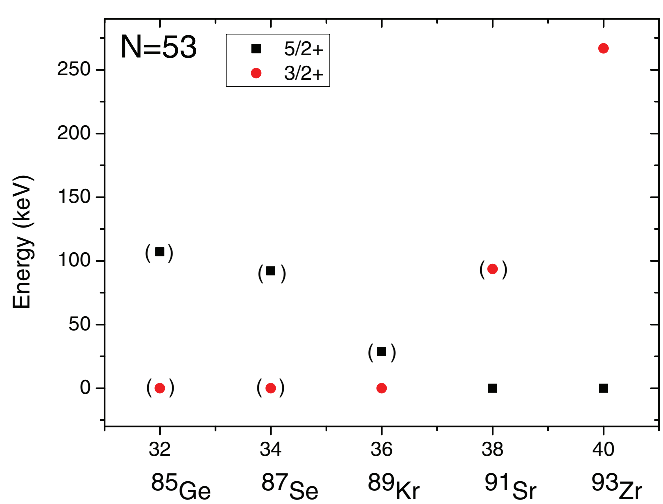

FIG. 4. (Color online) Systematics of the first $5/2^+$ and $3/2^+$ excited states of the $N = 53$ isotones. Brackets indicate tentative spin and parity assignments. See text for details.

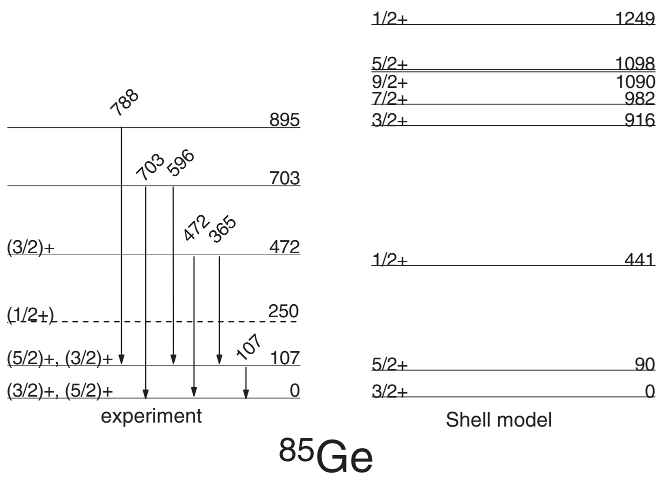

FIG. 5. Experimental and shell-model excited states in ^{85}Ge. All energies are in keV. Only positive parity was considered for low-lying levels since negative-parity states are expected from our shell-model calculations to exceed 3-MeV excitation energy. The 250-keV level is reported in [38]. See text for details.

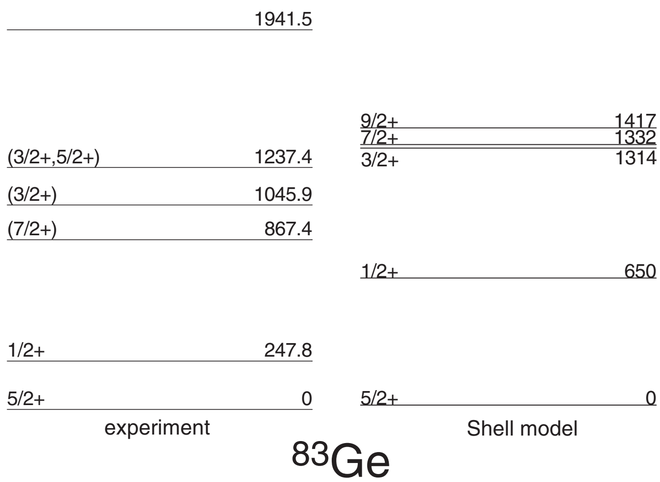

FIG. 6. Experimental [2] and shell-model states in ^{83}Ge. All energies are in keV. Only positive parity was considered for low-lying levels since negative-parity states are expected from our shell-model calculations to exceed 3-MeV excitation energy. See text for details.

In order to investigate how far along the $N = 53$ isotone chain this level inversion proceeds, we performed shell-model (SM) calculations for ^{85}Ge. We used a valence space that contains all orbitals active outside the ^{78}Ni core, the $1f_{5/2}, 2p_{3/2}, 2p_{1/2}, 1g_{9/2}$ for protons and $2d_{5/2}, 3s_{1/2}, 1g_{7/2}, 2d_{3/2}, 1h_{11/2}$ for neutrons. The effective interaction has been derived from a realistic nucleon-nucleon CD-Bonn potential, corrected empirically in its monopole part to reproduce a large set of nuclear data. More information on the interaction and its other applications in the region of neutron-rich nuclei above ^{78}Ni can be found in Refs. [28–32]. ANTOINE and NATHAN shell-model codes [33,34] have been used for the diagonalization of Hamiltonian matrices.

The spins and parities predicted by shell model for the ground state and the first excited state of the $N = 53$ ^{85}Ge are $3/2^+$ (0 keV) and $5/2^+$ (90 keV), respectively (see Fig. 5). The accuracy of the shell-model calculations is expected to be about 250 keV; hence it is possible that the predicted order of these first two levels is inverted. A similar sequence of $3/2^+$ and $5/2^+$ states is obtained in calculations presented in [2,4].

We therefore analyzed different scenarios for the properties of the ground state and low-energy states in ^{85}Ge assuming parities and spins of $1/2^+$, $3/2^+$, and $5/2^+$. The first excited state in the $N = 53$ ^{85}Ge, at 107 keV, has an experimental upper half-life limit of about 30 ns. The expected lifetime of the 107-keV state can be obtained following the systematics of γ-transition probabilities and their enhancement or retardation with respect to Weisskopf estimates [35] performed by Endt [36]. The respective $M1$ 107-keV transition between $3/2^+$ and $5/2^+$ levels, see Fig. 5, would have a half-life below 10 ps, even after taking into account a retardation factor of 4–20 with respect to the Weisskopf systematics (Figs. 6 and 7 in [36]). This means that the 107-keV would be a prompt $M1$ transition, with a half-life well below the detection limit of our experiment. The intensity balance of the observed γ transitions feeding the 107-keV level accounts for only about 1/3 of the intensity of the de-exciting 107-keV transition, thus allowing for direct β population of this level; see Table I. This first forbidden β transition would be connecting the initial $(5/2^-)$ with the $(3/2^+)$ or $(5/2^+)$ final state. If this first excited state at 107 keV had $I^\pi = 1/2^+$, the fast $M1$ transition to the $(3/2^+)$ ground state can occur, but strong β feeding through a first forbidden transition changing angular momentum by two units (first forbidden unique β transition, from $5/2^-$ to $1/2^+$) is very unlikely.

An $E2$ multipolarity of the 107-keV transition, i.e., the decay between $1/2^+$ and $5/2^+$ states, can be excluded. Using the expected $E2$ probability enhancement for mass $A \sim 85$ nuclei ranging 1.9–17 (see Fig. 5 in [36]), we obtain a half-life estimate between 1 μs and 100 ns. Such a half-life would be detected in our experiment. If the 107-keV transition were

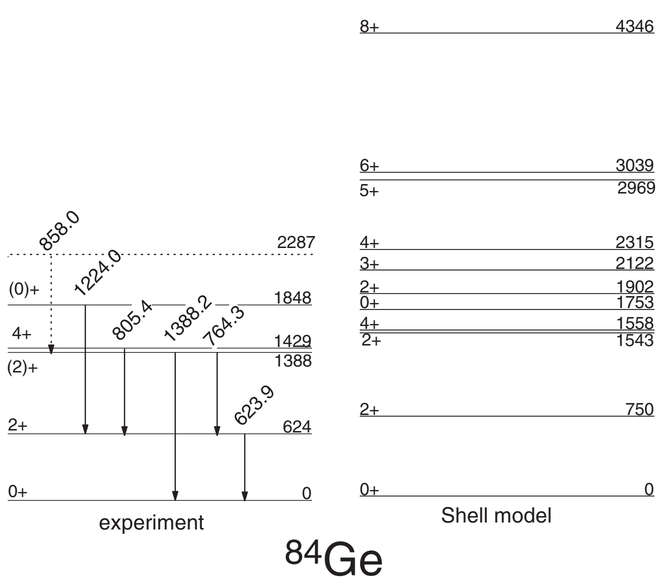

FIG. 7. Experimental and shell-model excited states in ^{84}Ge. All energies are in keV. See text for details.

among the top 10% of the fastest $E2$ transitions, see Fig. 7 in [36], its half-life might be close to our experimental upper limit of 30 ns. However, such strongly enhanced $E2$ transitions occur in mass $A = 85$ region only for $0_2{}^+ \rightarrow 2_1{}^+$ transitions in even-even nuclei [37], which supports the expectation of a half-life longer than 30 ns for a 107-keV $E2$ de-excitation. The experimental observations are in agreement with the $3/2^+$ and $5/2^+$ shell-model assignment for the ground state and first excited state at 107 keV, although the reversed assignment cannot be definitely ruled out. We consider these two options below.

The 472-keV level de-excites through two transitions: the 365-keV to the 107-keV level and the 472-keV to the ground state. The experimental intensity ratio of the 472-keV to 365-keV transition is $I_\gamma(\text{472-keV})/I_\gamma(\text{365-keV}) = 0.55(6)$. Guided by the level systematics and present shell-model predictions, we consider two options for the spin/parity of the 472-keV level: $1/2^+$ and $3/2^+$. We have calculated the lifetimes for both transitions and the intensity ratios under these two scenarios:

(i) For $I^\pi(\text{472-keV}) = 1/2^+$, $I^\pi(\text{107-keV}) = 3/2^+$, and $I^\pi(\text{g.s.}) = 5/2^+$: Assuming $M1$ (365-keV) and $E2$ (472-keV) character, we obtained lifetimes of the order of picoseconds and nanoseconds, respectively. The calculated intensity ratio between the 472-keV and the 365-keV transitions is 0.04.

(ii) For $I^\pi(\text{472-keV}) = 3/2^+$, $I^\pi(\text{107-keV}) = 3/2^+$, and $I^\pi(\text{g.s.}) = 5/2^+$. Assuming $M1$ character for both transitions, the calculated intensity ratio between the 472 keV and the 365 keV is 1.66.

(iii) For $I^\pi(\text{472-keV}) = 1/2^+$, $I^\pi(\text{107-keV}) = 5/2^+$, and $I^\pi(\text{g.s.}) = 3/2^+$. Assuming $E2$ (365-keV) and $M1$ (472-keV) character, we obtained lifetimes of the order of nanoseconds and picoseconds, respectively. The calculated intensity ratio between the 472-keV and the 365-keV transitions is 142.

(iv) For $I^\pi(\text{472-keV}) = 3/2^+$, $I^\pi(\text{107-keV}) = 5/2^+$, and $I^\pi(\text{g.s.}) = 3/2^+$. Assuming $M1$ character for both transitions, the calculated intensity ratio between the 472 keV and the 365 keV is 1.66.

On the basis of these considerations and γ-ray intensities presented in Table I, we propose $(3/2)^+$ as the most probable spin and parity for the 472-keV level.

B. Structure of the first excited states in ^{83,85}Ge

Shell model calculations for ground and excited states in ^{83}Ge and ^{85}Ge are shown in comparison to the experimental data in Figs. 5 and 6. The addition of two neutrons to the $N = 51$ ^{83}Ge reduces the energy of the first $3/2^+$ level. For ^{85}Ge, the shell model predicts two close lying $3/2^+$ and $5/2^+$ states, as detected in our experiment. The low energy of the first $1/2^+$ state in the $N = 51$ ^{83}Ge (248 keV) is overestimated by about 400 keV in shell model, similar to the calculations presented in [2]. The predicted energy of the $1/2^+$ state in ^{85}Ge is lower by ~200 keV with respect to ^{83}Ge. The corresponding $I^\pi = 1/2^+$ excited state in ^{85}Ge was not detected in this experiment for one possible candidate, since $I^\pi = 3/2^+$ assignment was made for the observed 472-keV level. A candidate for the $I^\pi = 1/2^{+85}$Ge level at 250 keV has been proposed in our recent work on ^{86}Ga β-neutron-γ decay [38].

We have also calculated the wave functions of the lowest energy $1/2^+$, $3/2^+$, and $5/2^+$ states in ^{83}Ge and ^{85}Ge. The predictions point to the ground-state configurations dominated by the $d_{5/2}$ neutrons, while the $s_{1/2}$ orbital is a main component in the lowest $I^\pi = 1/2^+$ states. As far as the protons are concerned, the $p_{3/2}$ and $f_{5/2}$ orbitals are mostly present in all the wave functions.

The lowest $5/2^+$ states in both nuclei are dominated by seniority a $\nu = 1$ component (77% in $N = 51$ and 50% in $N = 53$), so that the $I = 5/2^+$ spin results mostly from the coupling of the odd neutron in the $d_{5/2}$ orbital to the proton 0^+ state. The structure of the $3/2^+$ in ^{83}Ge is dominated by the proton 2^+ coupled to the neutron $5/2^+$ (69%). The weight of this component in ^{85}Ge is reduced to only 27% while the $0^+_\pi \otimes 3/2^+_\nu$ coupling is favored (50%). The structure of the first $1/2^+$ state in both nuclei is again similar and dominated by the odd neutron in the $s_{1/2}$ orbital coupled to the proton 0^+ state, however, with a slightly more complex wave function in ^{85}Ge. One should note that another $1/2^+$ state is predicted in the shell-model calculations in ^{85}Ge at 1249 keV, which belongs to the $(d^3_{5/2})$ multiplet. The single-particle-like $1/2^+$ state appears in the calculations lower in energy due to the small size of the $d_{5/2}$-$s_{1/2}$ gap, decreasing to zero in ^{79}Ni in the presented shell-model calculations.

C. β-n decay of ^{85}Ga and the structure of ^{84}Ge

There are six γ transitions assigned in our work to the β-neutron-γ decay of ^{85}Ga. The observed γ-decay pattern is very well reproduced by the shell-model calculations predicting the 0^+, 2^+, 2^+, 4^+, and 0^+ level sequence in ^{84}Ge; see Fig. 7. The presence of a direct 1388-keV transition to the ground state competing with the 764-keV γ line, and simultaneous absence of a direct γ transition from the 1429-keV level to the 0^+ ground state is consistent with the sequence of excited states 2^+ (624 keV), 2^+ (1388 keV), and 4^+ (1429 keV). The γ transition at 1224 keV is de-exciting the 1848-keV level to the 2^+ level, not to the 4^+ and 0^+ states. This is consistent with the 0^+ assignment for the 1848-keV level; see Fig. 7.

If we compare the total relative intensities of the γ transitions in the β-γ and β-n-γ decay branches (see Table I), we notice that their ratio is roughly ~25–75%. This is consistent with the large probability for β-delayed neutron emission of $P_n = 68\%$ obtained within a microscopic DF3a+CQRPA model by Borzov [22]. This model was recently found to describe very well the βn rates [20] and β half-lives [7,25] for nuclei around ^{78}Ni. Similarly, a large $P_n = 61\%$ value is predicted for ^{85}Ga decay by Moeller [39]. Moeller predicts also a high P_{2n} branching of 10% for the ^{85}Ga precursor, which is not observed in our work. The quantitative comparison of the experimental βn rate to the theoretical predictions is not possible, since we cannot exclude the presence of unobserved direct β and βn transitions from the ground state of ^{85}Ga to the ^{85}Ge and ^{84}Ge ground states, respectively.

V. SUMMARY

The β-γ and β-n-γ decay spectroscopy of the very neutron-rich isotope ^{85}Ga was performed at the HRIBF facility at Oak

Ridge National Laboratory. Several new γ transitions were identified and assigned to its β-γ and β-n-γ decay branch. The observed level schemes and measured γ intensities, together with theoretical predictions, are consistent with the $(5/2^-)$ and $(3/2^+, 5/2^+)$ assignment for the spin and parity of the ^{85}Ga and ^{85}Ge ground states, respectively. The first $(1/2^+)$ state in both isotopes has a large $\nu s_{1/2}$ wave-function contribution. The energy of this $(1/2^+)$ state in ^{83}Ge is overestimated by about 400 keV in the present shell-model approach, similarly to other shell-model calculations [2,4]. The predicted energy of 441 keV for the first $1/2^+$ state in ^{85}Ge is close to the observed level at 472 keV. However, spin and parity of $(3/2^+)$ was deduced for the 472-keV level, and $(5/2^+, 3/2^+)$ was proposed for the 107-keV excited state in ^{85}Ge. We note that a $(1/2^+)$ level at 250 keV was observed in β-n decay of ^{86}Ge.

The level structure of $N = 52$ ^{84}Ge observed up to 2.3-MeV excitation energy in the β-n decay of ^{85}Ga allowed us to deduce the energies of 2^+, $(2)^+$, 4^+, and $(0)^+$ excited levels sequence. The energies of the 2^+ and 4^+ levels in the ground-state band are found to be 624 keV [3] and 1429 keV (this work).

The observed β-γ and β-n-γ relative branching ratios are consistent with theoretical predictions confirming an increasing role of β-n decay for neutron-rich isotopes beyond $N = 50$.

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