Experimental study of β and β-n decay of the neutron-rich $N = 54$ isotope ^{87}As

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The β-decay properties of neutron-rich ^{87}As produced in the proton-induced fission of ^{238}U were studied at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. The low-energy excited states in $N = 53$ ^{87}Se and $N = 52$ ^{86}Se were identified through β-γ and β-delayed neutron-γ decay of ^{87}As, respectively. The experimental systematics of low-energy levels of $N = 53$ isotones, $Z = 34$ ^{87}Se, and $Z = 32$ ^{85}Ge, and along with an analysis of shell-model calculations, allow us to discuss the main features of excited states expected for the next $N = 53$ isotone, ^{83}Zn.

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I. INTRODUCTION

Nuclei in the vicinity of ^{78}Ni offer the possibility to investigate the evolution of single-particle states in very neutron-rich nuclei having few protons and several neutrons added to the ^{78}Ni core. Here we present a continuation of our decay studies of such nuclei and focus our attention on the evolution of neutron levels north east of ^{78}Ni.

The study of excited states in the $N = 50 + 1$ isotones with even Z was used to probe neutron single-particle states. Previous investigations of excited states for the neutron-rich $N = 51$ isotones (^{83}Ge, ^{85}Se) by means of both transfer reactions and decay spectroscopy [1–3] revealed a reduction of the energy difference between the first $1/2^+$ excited level and the $5/2^+$ ground state with decreasing atomic number. In $N = 51$ isotones, with one neutron outside the core, the dominating component of the wave function is given by the neutron single-particle orbital; hence their ground state has $I^\pi = 5/2^+$ ($\nu d_{5/2}$) and their first excited state has $I^\pi = 1/2^+$ ($\nu s_{1/2}$). The ground-state spin-parity for the $N = 51$ ^{81}Zn, the closest $N = 51$ isotope to ^{78}Ni studied experimentally, was determined to be $5/2^+$ on the basis of the β-feeding pattern [5]. The $\nu s_{1/2}$-$\nu d_{5/2}$ level crossing postulated in Ref. [4] was ruled out through more detailed β-γ decay study of ^{81}Zn [5,6].

It was shown [7] that the properties of neutron states in $N = 53$ isotones are different from those in $N = 51$ nuclei. The two extra valence neutrons occupying the $\nu d_{5/2}$ orbital open a new range of possible mixed configurations at low excitation energy. Also, the signatures of the onset of collectivity have been predicted [8] and reported for $N = 52$ and $N = 54$ isotones close to ^{87}As [9].

Here, we present new information on the levels in $N = 53$ ^{87}Se and $N = 52$ ^{86}Se populated in the β-γ and β-n-γ decay of the $N = 53$ ^{87}As isotope. The half-life of ^{87}As as obtained from this data set was previously reported in Ref. [10].

II. EXPERIMENTAL SETUP

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) by means of the online mass separation technique [11]. A 54 MeV proton beam of 10–12 μA average intensity from the ORIC cyclotron impinged on a high-temperature ^{238}UC$_x$ target. The fission fragments were thermalized and ionized in the IRIS2 ion source. Ions of the isotope of interest ^{87}As were extracted in molecular form as ^{87}As S$^+$ molecules [10,12] and separated using the first-stage mass separation dipole ($m/\Delta m \approx 1000$) set for mass $A = 87 + 32$. After passing through the Cs-vapor charge-exchange cell, the molecular bond was broken and the negatively charged ion beam was transported through the high-resolution magnet ($m/\Delta m \approx 10000$) that was set for $A = 87$. This combination of molecular ion beam extraction, followed by two stages of mass selection with charge exchange, resulted in an almost pure ^{87}As beam [11–13]. The beam was directed to the Low-Energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) [14] where it was deposited on the tape of a moving tape collector (MTC) in the center of the detection setup. This consisted of four HPGe clover γ-ray detectors (6% efficiency at 1.3 MeV) and two plastic scintillation counters for β-particle detection surrounding the activity-deposition point. The triggerless data from all detectors were collected by a fully digital acquisition system [15,16] both during the implantation of the activity (beam on, 1.5 s) and while the beam was deflected away (beam off, 1.5 s) by electrostatic plates placed after the high-resolution mass separator. After the period of 3 s, the tape was moved, transporting the implanted long-lived isobaric contaminants and daughter activities away from the measuring position, and a new cycle was started. This beam-on and beam-off time structure helped to enhance the ^{87}As ($T_{1/2} = 0.56$ s [10]) with respect to the longer-lived daughter activities.

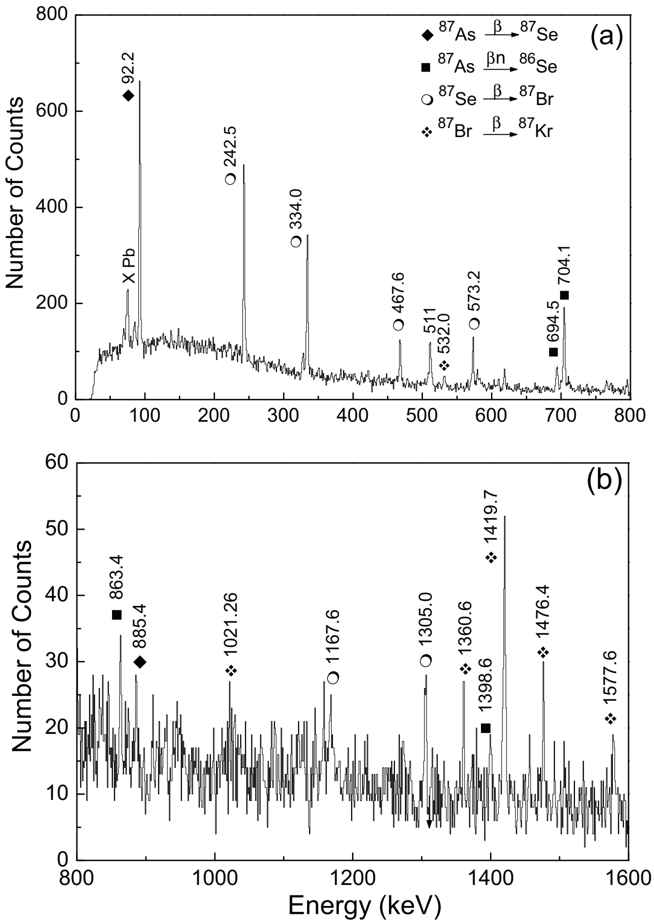

FIG. 1. Portions of the β-gated γ-ray spectrum from 0 to 800 keV (a) and from 800 to 1600 keV (b) obtained at mass $A = 87$. The strongest transitions belonging to the $\beta\gamma$ and β-$n\gamma$ decay of ^{87}As are labeled.

III. RESULTS

The experimental knowledge on excited states in ^{87}Se originates from two recent works. A 92-keV transition was assigned to the $\beta\gamma$-decay branch of ^{87}As and used for β-decay lifetime determination [10]. This low-energy transition in ^{87}Se was confirmed shortly after by analysis of ^{248}Cm fission data where three γ transitions at 91.9(2), 744.6(2), and 886.2(2) keV were identified [9].

A substantial β-n decay branch $^{87}\text{As} \rightarrow ^{86}\text{Se}$ can be expected due to the large energy window for β-n emission ($Q_{\beta n} = Q_\beta(^{87}\text{As}) - S_n(^{87}\text{Se}) = 6.814(4)$ MeV [17]). In ^{86}Se, only the high-spin yrast states up to $I = 7$ were reported recently [18,19].

The analysis of the β-gated γ energy spectrum yielded new γ-transitions belonging to the $\beta\gamma$ and β-$n\gamma$ decay branches of ^{87}As and respective daughter activities (Fig. 1). The $\beta\gamma$ spectrum obtained in coincidence with the 92-keV transition in ^{87}Se, see Figs. 2(a) and 2(b), allowed us to construct the level scheme given in Fig. 3. The proposed spin and parity assignments for the low-energy states are mostly based on the systematics and are discussed in Sec. IV.

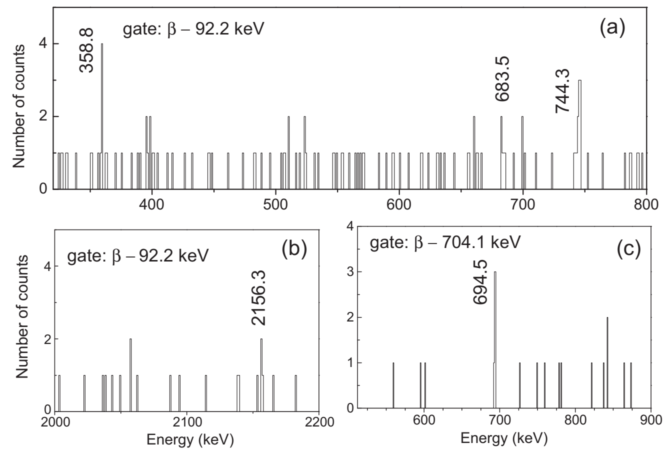

FIG. 2. The β-gated γ-ray spectra in coincidence with the 92-keV (a,b) and 704-keV (c) transitions. The 92-keV γ and 704-keV lines correspond to the β-γ decay and β-n-γ decay of ^{87}As, respectively.

The observed coincidences with the known 704-keV transition in ^{86}Se, see Fig. 2(c), identified a 694.5-keV line depopulating the 1398.6-keV state. This 1398.6-keV level also de-excites through a direct transition to the ^{86}Se ground state; see Fig. 1(b). The transition at 863 keV seen in the β-γ spectrum (Fig. 1) is known as the 4^+ to 2^+ transition in ^{86}Se [18–20]. The 695- and 1399-keV γ lines were added to the level schemes proposed in Refs. [18,19] following Ref. [20] and this work. Previously the spins and parities of the 704.1- and 1567.4-keV levels were firmly assigned on the basis of angular correlations, to be 2^+ and 4^+, respectively [19]. We tentatively assign $I^\pi = (2^+)$ to the 1399-keV excited state in ^{86}Se since this level is not present in the high-spin sequence of states populated in spontaneous fission of ^{248}Cm [18,19], but it is observed in the β-n decay of ^{87}As (this work) and in β decay of ^{86}As [20].

The relative intensities for the γ-ray transitions in the β-γ and β-n-γ decay of ^{87}As are listed in Table I.

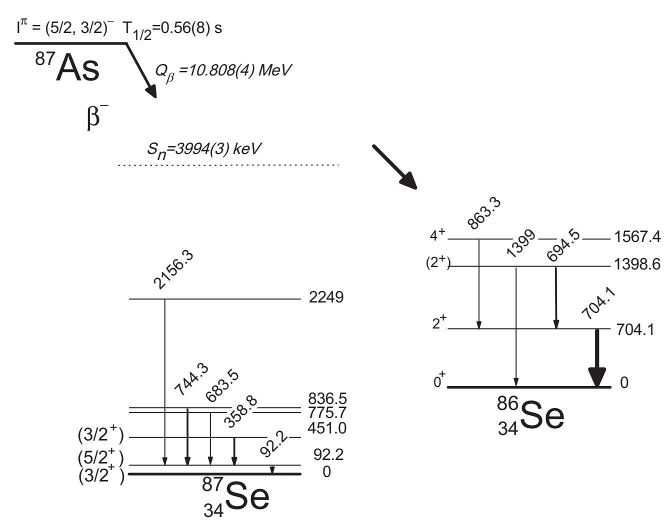

FIG. 3. Partial experimental decay scheme of ^{87}As. The Q_β and S_n energies are taken from Ref. [17]. See text for details.

TABLE I. Relative γ-ray intensities ($I_{\rm rel}$) for the β and βn decays of ^{87}As normalized to the 704-keV transition.

$E_{\rm level}$ (keV)	E_γ (keV)	$I_{\rm rel}$	^{87}As decay channel
92.2(3)	92.2(3)	93.7(5.2)[b]	β
451.0(5)	358.8(5)	1.5(0.3)[a]	β
775.7(5)	683.5(5)	2.4(0.5)[a]	β
836.5(5)	744.5(5)	5.6(0.4)	β
2249(1)	2156(1)	3.5(1.2)[a]	β
704.1(3)	704.1(3)	100.0(9.0)	βn
1398.6(5)	694.5(5)	18.0(8.0)	βn
1567.4(5)	863.3(5)	12.0(1.0)	βn
1398.6(5)	1399(1)	14.9(1.2)	βn

[a]The intensities are taken from β-γ and β-γ-γ coincidence spectra.
[b]$\alpha_{\rm tot}$ ($M1$) = 0.13 is included in $I_{\rm rel}$ calculation [21].

IV. DISCUSSION

The $N = 54$ isotone ^{87}As has five protons outside the closed $Z = 28$ shell. These protons are distributed among fpg orbitals, generating a negative-parity ground state in $Z = 33$ ^{87}As. For ^{87}As, with $\nu g_{9/2}$ orbital fully occupied, we expect the $\pi f_{5/2}$ state below $\pi p_{3/2}$. This is analogous to ^{85}Ga [7] and to the chain of copper isotopes (^{71,73,75,77}Cu), where the crossing of the $\pi f_{5/2}$ state below $\pi p_{3/2}$ occurs between ^{73}Cu and ^{75}Cu [22–24]. The $(5/2)^-$ assignment for the ground state of ^{87}As is consistent with an apparent β-n feeding of the 4^+ state in ^{86}Se. This $I^\pi = 4^+$ state can be fed by neutrons emitted with angular momentum $l = 1$ through the intermediate $I = 7/2^-$ and $5/2^-$ states in ^{87}Se populated in the Gamow-Teller decay of ^{87}As. However, the $(3/2)^-$ assignment for the ground state of ^{87}As cannot be ruled out, and hence we tentatively assign $I^\pi = (5/2,3/2)^-$ to the ^{87}As ground state; see Fig. 3.

The low-energy excited states in the $N = 53$ isotone ^{87}Se are expected to have positive parity from the level systematics of $N = 53$ $^{85}_{32}$Ge [7] and $^{89}_{36}$Kr [25] isotones. The recent study of the yrast structure in this nucleus by Rząca-Urban *et al.* [9] tentatively assigns $(3/2^+)$ and $(5/2^+)$ to the ground state and first excited state in ^{87}Se, respectively. The population of the same levels in the β decay of either the $5/2^-$ or $3/2^-$ ground state of ^{87}As is possible through *first-forbidden* β transitions. Such a scenario is not uncommon in this region of the chart of nuclei, in particular in the case of the β decay of ^{85}Ga to $^{85}_{53}$Ge [7].

Comparing the level structure of the $N = 53$ ^{87}Se (see Fig. 3) and ^{85}Ge [7], we propose $I^\pi = (3/2^+)$ for the 451-keV excited state in ^{87}Se. No candidate level could be identified for the $1/2^+$ state dominated by the $\nu s_{1/2}$ orbital. According to β-decay selection rules, we do not expect a substantial direct feeding of such $1/2^+$ level from a $5/2^-$ ^{87}As ground state, while the first-forbidden β transition between the alternative ground state $J^\pi = 3/2^-$ and $1/2^+$ could occur. The $\nu s_{1/2}$ state in ^{87}Se can be populated in β-n decay of ^{88}As, similarly to the $1/2^+$ level in ^{85}Ge$_{53}$ fed in the β-n decay of ^{86}Ga [26], but not populated in $\beta\gamma$ decay of ^{85}Ga [7].

We have performed shell-model (SM) calculations of the $N = 53$ isotones ^{87}Se, ^{85}Ge, and ^{83}Zn with residual interaction derived from N3LO chiral interactions [27,28] and a valence space containing all active orbitals outside the ^{78}Ni core (see Refs. [29,31] for details). The results are compared to experimental data, where available, in Fig. 4. The similarity

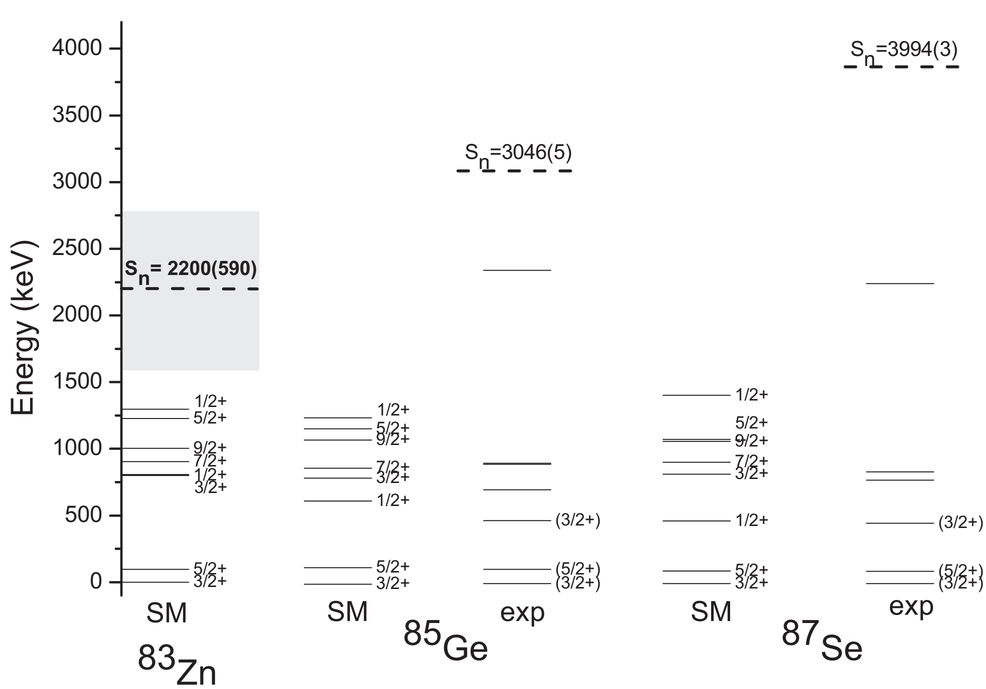

FIG. 4. Experimental and shell-model predictions of low energy excited states in even-Z, $N = 53$ isotones. Data from the present work and from Refs. [7,30]. All energies are in keV. See text for details.

of the level structure for these three isotopes points to the fact that these states are dominated by the neutron configurations, with protons acting as spectators.

The experimental level pattern in ^{85}Ge and ^{87}Se is well reproduced in the shell-model calculations. The first $5/2^+$ and $3/2^+$ states, dominated by a $\nu d_{5/2}$ orbital, are generating the ground state and first excited state within the first 100 keV. A lifetime of ~600 ps was calculated for this transition, which includes a hindrance factor of 3×10^{-3} W.u. [32–36] creating a relatively long lifetime for this $M1$ transition. The measurement of this $\tau \sim 600$ ps is well within the experimental reach of a fast-timing techniques [37] and worth measuring to verify the expected $M1$ character of the 92-keV transition. The next excited state, expected to have a large $\nu s_{1/2}$ component, is not populated in the β-decay of ^{85}Ga and ^{87}As. However, the $(3/2^+)$ state was observed at about 0.4–0.5 MeV in both ^{85}Ge and ^{87}Se. These three levels are followed by several positive-parity states around 1 MeV excitation energy. The states at the excitation energies above 4 MeV (i.e., above S_n) in ^{85}Ge and ^{87}Se are most likely populated by allowed Gamow-Teller β transitions competing with first forbidden decays. Lower β endpoint energies are compensated by larger matrix elements of allowed β transitions, creating observable β feeding to the high-energy levels, which results in population of ground and excited states in the respective β-delayed neutron daughters [38]. The intensity pattern of β-delayed γ transitions is similar in both ^{85}Ga and ^{87}As decays, with intense lines around 0.1, 0.4, and 0.7–0.8 MeV. Therefore, a similar level structure and similar γ de-excitation properties are expected for the more exotic $N = 53$ isotope ^{83}Zn; see Fig. 4. If we were to populate ^{83}Zn excited states in the β decay of ^{83}Cu, the levels fed by allowed decays are likely neutron unbound. The detection of the Gamow-Teller strength pattern in ^{83}Cu decay would require β-delayed neutron energy measurements [39,40]. The low-energy structure of ^{83}Zn could be detected either in ^{83}Cu first-forbidden β decay or in ^{84}Cu $\beta s5/2^-$ ^{87}As ground state, while the first-forbidden β transition between the alternative ground states $J^\pi = 3/2^-$ and $1/2^+$ could occur. The $\nu s_{1/2}$ state in ^{87}Se can be populated in β-n decay of ^{88}As, similarly to the $1/2^+$ level in ^{85}Ge$_{53}$ fed in the β-n decay of ^{86}Ga [26], but not populated in $\beta\gamma$ decay of ^{85}Ga [7].

V. SUMMARY

We have investigated the β and β-n decay of ^{87}As and identified new transitions in the $N = 53$ ^{87}Se and $N = 52$ ^{86}Se daughter nuclei. The ground-state configuration of ^{87}As is consistent with $5/2^-$; however, the $3/2^-$ cannot be completely ruled out by our data. The spin and parity values were tentatively assigned to the low-energy states as $(3/2^+)$, $(5/2^+)$, and $(3/2^+)$ in ^{87}Se, respectively. The comparison of the experimental decay schemes of ^{87}As → ^{87}Se and ^{85}Ga → ^{85}Ge with shell-model analysis allowed us to predict the main features of β-γ and β-neutron-γ decays of the still unknown nuclei ^{83}Cu and ^{84}Cu populating low-energy states in ^{83}Zn.

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