β and β-n decay of the neutron-rich ^{84}Ge nucleus

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The β-decay properties of the very neutron-rich ^{84}Ge nucleus were studied at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory. Several new γ-transitions and levels were added to its decay scheme and the order of the two lowest-lying levels in the daughter ^{84}As was corrected. For the first time γ radiation following β-delayed neutron emission was observed. The shell-model calculations and apparent β transition intensities were used to guide the spin assignment to the ^{84}As levels, in particular for the low-energy part of the level scheme. The new spin-parity (2^-) proposed for the ground state of ^{84}As is supported also by the systematics of $N = 51$ isotones.

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I. INTRODUCTION

Spectroscopic studies of nuclei around ^{78}Ni are informing nuclear models about the structure of ground and excited states, reflecting the evolution of proton and neutron single-particle orbitals far from stable nuclei. Extensive investigations of neutron-rich nuclei across the energy gaps at $N = 50$ and $Z = 28$ have been carried out in recent years (see, e.g., [1–13]) and demonstrate significant progress in experimental and theoretical capabilities. In particular, the investigation of nuclei with just one valence neutron outside the $N = 50$ shell helps to define the sequence of single-neutron states [14,15]. One of the effective ways to investigate the structure of $N = 51$ nuclei above ^{78}Ni is to populate them in the β^- decay of the respective $N = 52$ and $N = 53$ precursors.

The only information available to date on ^{84}Ge decay was limited to its half-life ($T_{1/2} = 942(17)$ ms) [9,16] and three β-delayed γ transitions at 43, 100, and 242 keV observed in a measurement performed at the OSIRIS facility in Studsvik [16]. In a later measurement at the ALTO facility of Orsay, ^{84}Ge was produced as decay daughter of ^{84}Ga and a partial level scheme of ^{84}As based on the same two transitions was proposed [17]. In our previous experiment at the Holifield Radioactive Ion Beam Facility (HRIBF), ^{84}Ge was also produced as the decay daughter of ^{84}Ga and two transitions, $E_\gamma = 347.1$ keV and $E_\gamma = 608.8$ keV and two levels at 589.4 and 1198.2 keV were added to the decay scheme [18].

In this work, the low-energy structure of ^{84}As$_{51}$ was studied by means of β decay of ^{84}Ge$_{52}$ and compared to shell-model calculation to guide spin assignments of observed states.

II. EXPERIMENTAL SETUP

The experiment was performed at HRIBF, Oak Ridge National Laboratory (ORNL) [19]. Details of the experimental technique are given in Refs. [9,10]. Briefly, fission fragments were produced by proton-induced fission of a ^{238}UC$_x$ target and ionized in the IRIS2 ion source. The ^{84}Ge ions were extracted from the ion source in molecular form as ^{84}GeS$^+$. Two-stage mass separation in conjunction with molecular breakup and charge exchange in a Cs-vapor cell allowed for an almost pure ^{84}Ge negative ion beam [9,20]. The beam was implanted into the tape of the moving tape collector (MTC) in the center of the detection setup at the Low-Energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) [21]. The MTC was surrounded by four HPGe clover γ-ray detectors (6% efficiency at 1.3 MeV) and two plastic scintillation counters for β-particle detection around the deposition point. Trigger-free data from all detectors were collected by a fully digital acquisition system [22–24], both during the implantation of the activity (beam on, 3 s) and when the beam was deflected away (beam off, 3 s), by an electrostatic deflector. After this period, the tape was moved for 0.36 s, transporting the implanted long-lived isobaric contaminants and daughter activities away from the measuring position, and a new cycle was started. The measurement lasted 40 min.

III. RESULTS

The β-gated γ-ray spectrum at mass 84 is presented in Fig. 1. The strongest transitions belong to the β-delayed γ ($\beta\gamma$) decay of ^{84}Ge and of its daughter ^{84}As. Transitions belonging to the known β-delayed neutron (βn) decay of ^{84}Ge can be also identified. On the basis of β-γ-γ coincidences (Fig. 2) a partial decay scheme of ^{84}Ge could be constructed; see Fig. 3.

With respect to the previous works, we have added several new transitions and states to the level scheme of ^{84}As. On the basis of β-γ-γ coincidences (see Table I) we have inverted the order of the known 100- and 43-keV transitions and we

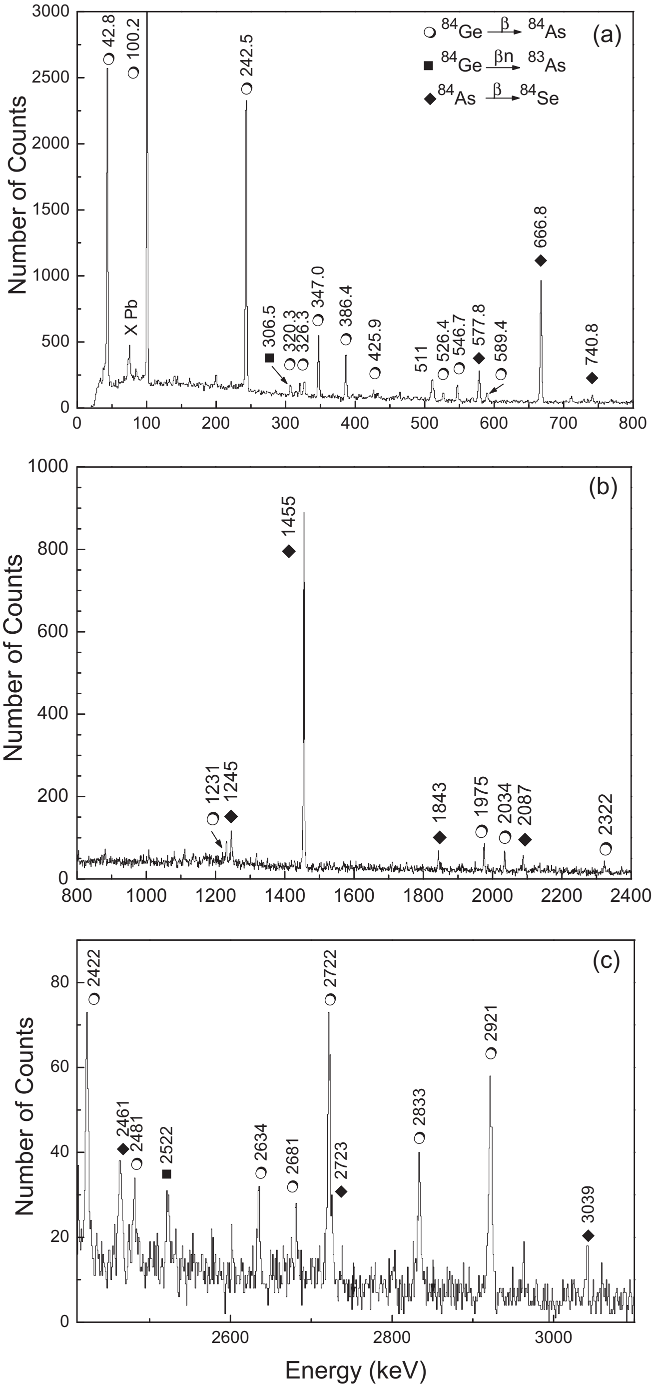

FIG. 1. Portions of the β-gated γ-ray spectrum at mass 84: 0–800 (a), 800–2400 (b), and 2400–3200 keV (c).

could not confirm the 609-keV line [18] as belonging to ^{84}Ge decay. As far as the β-delayed neutron branch is concerned, population of the first excited state in ^{83}As [28] was observed for the first time; see Table I. All the identified and assigned transitions, with the respective relative intensities, including tentative assignments on the basis of weak coincidences, are summarized in Table I.

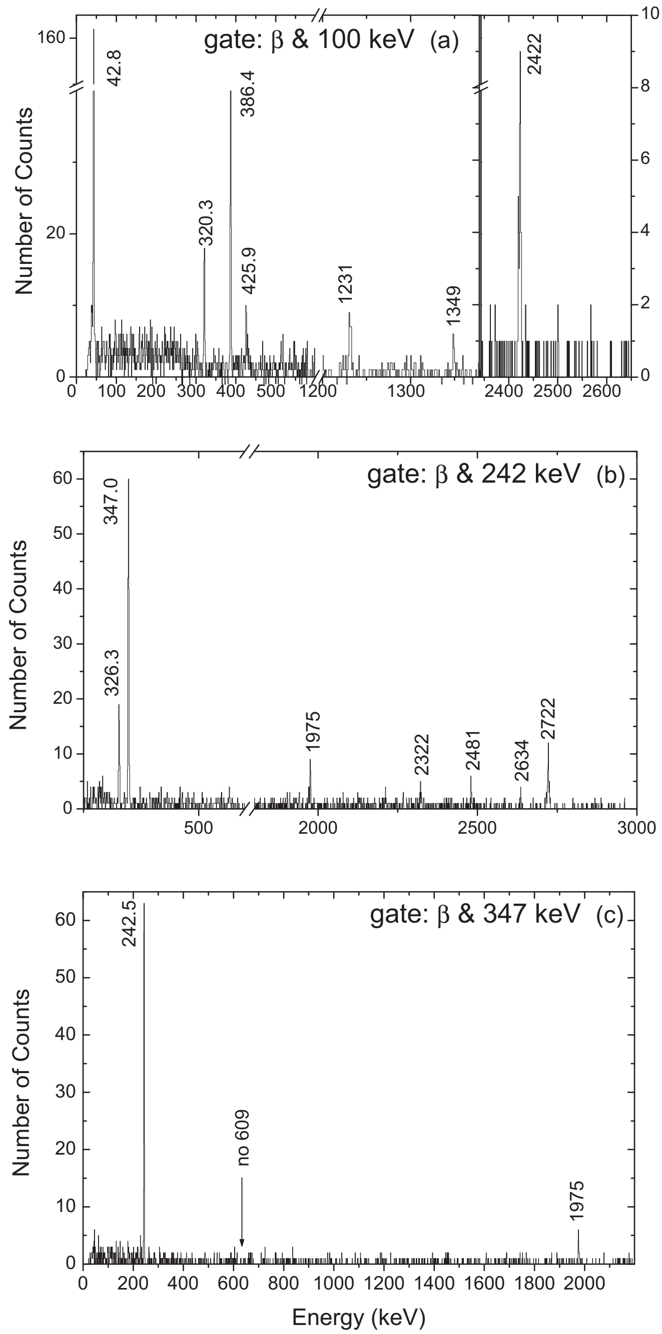

FIG. 2. The β-gated γ-ray spectra in coincidence with the 100- (a), 242- (b), and 347-keV (c) transitions.

For tentative spin-parity (I^{π}) assignments for the low-lying excited states in ^{84}As we considered that no positive-parity state can be expected at low excitation energies and that multipolarities larger than 1 will give rise to measurable lifetimes ($\sim$1 μs or larger) for transitions with low energy ($\leqslant$100 keV) [29]. Even considering the correction factors to the lifetimes from systematics [30,31], the $l > 1$ multipolarity would make the lifetime long enough to be isomeric and observed in our experiment. Since no isomers were observed in our data, this points towards $M1$ character for the two lowest-lying transitions at 43 and 100 keV.

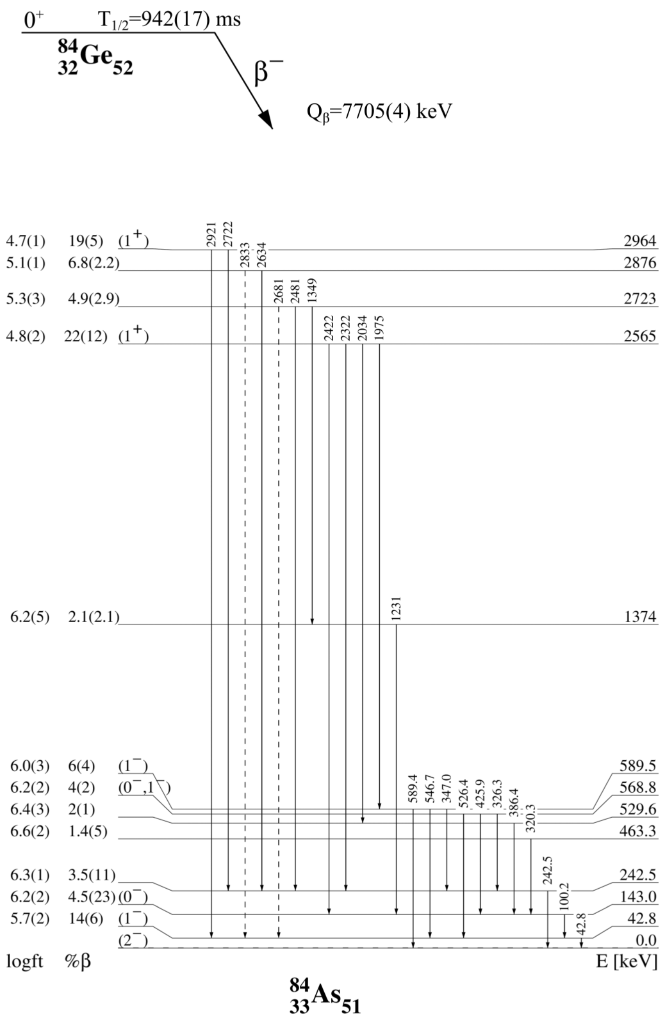

FIG. 3. Partial decay scheme of ^{84}Ge as obtained in this work. Dashed transitions were tentatively assigned on the basis of very weak β-γ coincidence with 43 keV. The Q_β energy and $T_{1/2}$ are taken from Refs. [25] and [9], respectively.

Since high-resolution γ-ray detectors (like HPGe) have low detection efficiency, in particular for high-energy direct transitions de-exciting high-lying states in the daughter nucleus, and since the total γ intensity is usually highly fragmented, a portion of the β strength will go undetected. It will therefore be assigned to lower-lying states (the so-called pandemonium effect [32]) and only apparent β feeding, and consequently $\log(ft)$, can be calculated. Apparent β feedings were calculated by normalizing the relative γ intensities to the sum of all intensities feeding the ground state (43, 242, and 589 keV) and considering the 10% branching for β-delayed neutron emission [33]. Apparent $\log(ft)$ values were estimated, see Fig. 3, and used for guidance in the tentative spin-parity assignment. For this we considered only those levels with apparent β-feeding larger than 4%. At excitation energies above 2.5 MeV, positive-parity states can be expected and feeding by Gamow-Teller transitions becomes possible. Considering the larger apparent β feeding for the 2565- and 2964-keV states and lower apparent log(ft), $I^\pi = (1^+)$ can be assumed, suggesting the observed β transitions as $0^+ \rightarrow 1^+$ GT transformations; see Fig. 3.

TABLE I. Relative γ-ray intensities (I_{rel}) for the $\beta\gamma$ and βn-decays of ^{84}Ge normalized to the 42.8-keV transition.

E_{level} (keV)	E_γ (keV)	I_{rel}	Coincidence (keV)	^{84}Ge decay channel
42.8(2)	42.8(2)	100(9)[a]	100.2, 320.3, 326.3,	$\beta\gamma$
			347.0, 386.4, 425.9,	$\beta\gamma$
			526.4, 546.7, 1231,	$\beta\gamma$
			1349, 1975, 2034,	$\beta\gamma$
			2322, 2422, 2481,	$\beta\gamma$
			2634, 2681[b], 2722,	$\beta\gamma$
			2833[b], 2921	$\beta\gamma$
143.0(2)	100.2(2)	41(3)[c]	42.8, 320.3, 326.3,	$\beta\gamma$
			347.0, 386.4, 425.9,	$\beta\gamma$
			1231, 1349, 1975,	$\beta\gamma$
			2034, 2322, 2422,	$\beta\gamma$
			2481, 2634, 2722	$\beta\gamma$
242.5(2)	242.0(2)	55(4)	326.3, 347.0, 1975,	$\beta\gamma$
			2322, 2481, 2634,	$\beta\gamma$
			2722	$\beta\gamma$
463.3(2)	320.3(2)	2.5(6)	42.8, 100.2	$\beta\gamma$
529.6(2)	386.4(2)	12(1)	42.8, 100.2, 2034	$\beta\gamma$
568.8(2)	326.3(2)	3.0(6)	242.0	$\beta\gamma$
	425.9(2)	1.1(4)	42.8, 100.2	$\beta\gamma$
	526.4(2)	2.7(3)	42.8	$\beta\gamma$
589.5(2)	347.0(2)	14(1)	242.5, 1975	$\beta\gamma$
	546.7(2)	5.4(6)	42.8, 1975	$\beta\gamma$
	589.4(2)	4.2(7)	1975	$\beta\gamma$
1374(1)	1231(1)	5.3(7)	42.8, 100.2, 1349	$\beta\gamma$
2565(1)	1975(1)	13(2)	42.8, 242.5, 347.0,	$\beta\gamma$
			546.7, 589.4	$\beta\gamma$
	2034(1)	8.7(10)	42.8, 100.2, 386.4	$\beta\gamma$
	2322(1)	5(2)	242.5	$\beta\gamma$
	2422(1)	12(1)	42.8, 100.2	$\beta\gamma$
2723(1)	1349(1)	1.6(7)	42.8, 100.2, 1231	$\beta\gamma$
	2481(1)	4.8(9)	242.5	$\beta\gamma$
	2681(1)	2.2(7)	42.8[b]	$\beta\gamma$
2876(1)	2634(1)	5.1(7)	242.5	$\beta\gamma$
	2833(1)	7(1)	42.8[b]	$\beta\gamma$
2964(1)	2722(1)	16(2)	242.5	$\beta\gamma$
	2921(1)	17(2)	42.8	$\beta\gamma$
306.4(5)	306.4(5)	5(1)		$\beta n\gamma$

[a] $\alpha_{\mathrm{tot}}(M1) = 0.96$ [26,27] is included in I_{rel} calculation.
[b] Tentative assignment on the basis of weak coincidences.
[c] $\alpha_{\mathrm{tot}}(M1) = 0.08$ [26,27] is included in I_{rel} calculation.

The 42.8- and 143.0-keV levels appear to be fed by first forbidden transitions, suggesting $I^\pi = (0^-,1^-)$; see apparent log(ft) in Fig. 3. The I^π values can be further restricted by considering also the $M1$ character of the 100.2-keV transition. No cross-over transition was observed from the 143-keV level to the ground state. If such a transition had an $M1$ character, it would be observed in the present dataset, since its lifetime would be a factor of 2 faster than the observed 100-keV transition. If it were $E2$, it would be isomeric with a half-life of about half microsecond. This points towards a spin difference of 2 between the 143-keV level and the ground

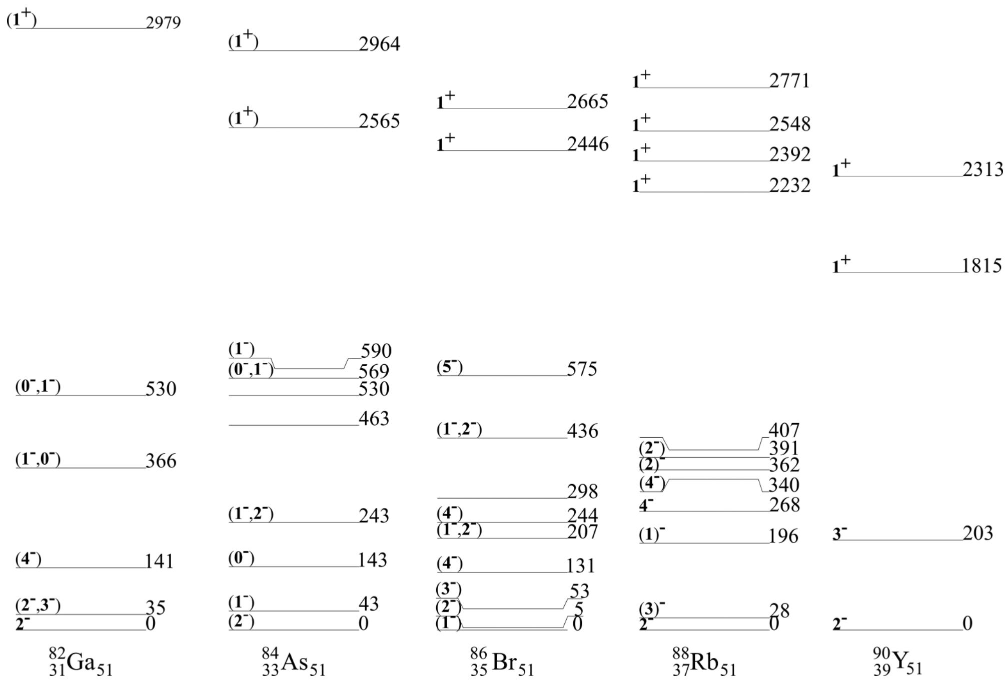

FIG. 4. Systematics of low-spin excited states in $N = 51$ isotones [11,34,37]. Energies are given in keV. Two energy scales are used for below and above 1 MeV.

state. In addition, the decay of the (1^+) states at 2565 and 2964 keV populates the 43- and 143-keV levels, respectively, while they do not decay directly to the ground state. Such behavior suggests a maximum spin change of 1. The calculated lifetimes for these transitions also suggest a dominant $E1$ character for them. The ground state of ^{84}As feeds the first (2^+) excited state in ^{84}Se with large apparent intensity [34,35]. Since the $I^\pi = (1^-)$ 42.8-keV level in ^{84}As decays to the ground state directly through an $M1$ transition, we therefore propose $I^\pi = (2^-), (1^-)$, and (0^-) for the ground state, 43- and 143-keV levels in ^{84}As, respectively. This is consistent with the systematics of I^π for the $N = 51$ isotones; see Fig. 4. The (1^-) assignment for the ^{86}Br ground state is supported by recent ^{86}Br decay data obtained using a total absorption spectroscopy technique [36]. Larger 0^+ ground-state β feeding was detected, with a smaller β intensity for the direct β population to the 2^+ state in ^{86}Kr. However, the respective 2^- state is located only 5 keV above the (1^-) ground state [37] [both the 1^- ground state and 2^- first excited state in ^{86}Br have mixed configuration $(\pi p_{3/2} \nu d_{5/2}, \pi f_{5/2} \nu d_{5/2})$].

IV. DISCUSSION

Shell model (SM) calculations for ^{84}As were performed in order to interpret its low-energy structure. The NUSHELLX code [38] was used with a model space containing all the active orbitals outside the ^{78}Ni core and single-particle energies $d_{5/2}$ (-11.3 MeV), $g_{7/2}$ (-7.6 MeV), $2d_{3/2}$ (-10.2 MeV), $s_{1/2}$ (-10.5 MeV), and $h_{11/2}$ (-6.3 MeV) for neutrons and $f_{5/2}$ (-25.3 MeV), $p_{3/2}$ (-24.8 MeV), $p_{1/2}$ (-23.6 MeV), and $g_{9/2}$ (-20.3 MeV) for protons. The N3LO residual interaction based on nucleon-nucleon forces in Refs. [39,40] was used. In Fig. 5 the results of the calculation for the lowest-lying excited states are plotted in comparison with the experimental level scheme as obtained from this work.

The level densities at low-excitation energies all are well reproduced by calculations, considering that only low spins are observed in the experiment. All low-energy states are dominated by one neutron in the $d_{5/2}$ or $s_{1/2}$ orbital coupled to protons in the $f_{5/2}$ and $p_{3/2}$ orbitals in different proportions. Below 500 keV, three groups of levels are predicted by the SM in the ranges 0–150, 220–250, and 400–500 keV. The first and second group of levels are dominated by one neutron in the orbital $d_{5/2}$ (about 90% of the neutron component of the wave function), while for the third group the $s_{1/2}$ component starts to be equal to the $d_{5/2}$. This is consistent with the results obtained for ^{83}Ge, which has a $5/2^+$ ground state and $1/2^+$ first excited state calculated at $\sim$400 keV (measured at 248 keV) [11]. In the case of ^{83}Ge low-excitation-energy states are dominated by protons in $f_{5/2}$ and neutrons in $d_{5/2}$ and $s_{1/2}$ orbitals. The investigation of the wave function from our calculations for $^{84}_{33}$As$_{51}$ shows that the addition of one proton to $^{83}_{32}$Ge$_{51}$ renders the proton $p_{3/2}$ orbital important.

As far as positive-parity states are concerned, the same calculations predict that the lowest-lying ones are at just above 3 MeV in excitation energy. The high excitation energy of the first 1^+ states has been verified in the present data, as discussed in Sec. III.

V. SUMMARY

In an experiment at the HRIBF we have measured the β-decay properties of ^{84}Ge. Several new transitions were added to its decay scheme and the order of the two lowest-energy

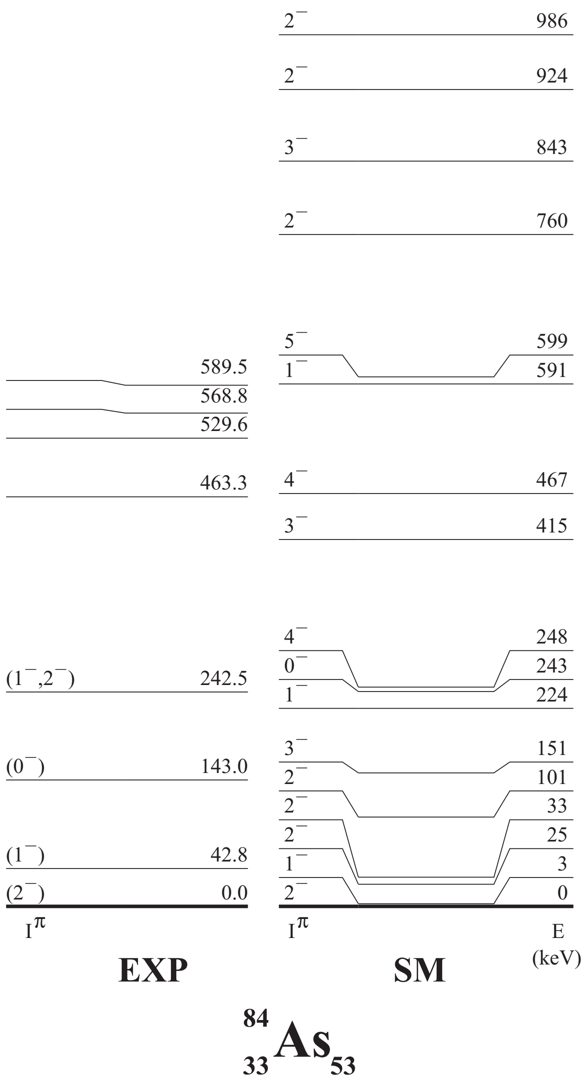

FIG. 5. Lowest-lying excited states in ^{84}As from this work (EXP) in comparison with predictions from shell- model (SM) calculations. The vertical (energy) axis is plotted to scale. See text and Fig. 3 for details.

levels in the daughter ^{84}As was corrected. The β-delayed neutron emission to the excited state in ^{83}As followed by γ emission was detected for the first time. Gamow-Teller β transitions to the (1^+) excited states above 2.5 MeV were identified for the first time, while the lower-energy section of ^{84}As level scheme is fed mostly by first forbidden β transitions. The spin-parity (2^-) was assigned as a ground-state configuration based on the observed γ intensities, β-feeding pattern, and level systematic in $N = 51$ isotones. The shell-model calculations for the lowest-lying excited states in the $N = 51$ daughter nucleus ^{84}As showed that their wave function is given predominantly by $[\nu d_{5/2},(\pi f_{5/2}, p_{3/2})]$ below 250 keV and $[(\nu d_{5/2},s_{1/2}),(\pi f_{5/2}, p_{3/2})]$ above. It also showed that adding one proton to the $Z = 32$, $N = 51$ ^{83}Ge increases the relevance of the $p_{3/2}$ orbital with respect to $f_{5/2}$.

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