Penning-trap-assisted study of excitations in ^{88}Br populated in β decay of ^{88}Se

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Excited levels of ^{88}Br populated in the β decay of ^{88}Se have been studied by means of $\beta\gamma$ and $\gamma\gamma$ spectroscopy methods. Neutron-rich parent ^{88}Se nuclei were produced with proton-induced fission of ^{238}U using the Ion Guide Isotope Separator On-Line (IGISOL) method and separated from contaminants using a dipole magnet and the coupled JYFLTRAP Penning trap at the Accelerator Laboratory of the University of Jyväskylä. The level scheme of ^{88}Br has been constructed and log ft values of levels were determined. The ground-state spin of ^{88}Br is now firmly determined to be 1^-. Low-energy levels in ^{88}Br were interpreted as members of the $\pi p_{3/2}(\nu d_{5/2})^3$, $\pi p_{3/2}^{-1}(\nu d_{5/2})^3$, $\pi f_{5/2}^{-1}(\nu d_{5/2})^3$, and $\pi g_{9/2}\nu g_{7/2}$ multiplets. The shell-model calculations performed in this work reproduce well the experimental results.

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I. INTRODUCTION

The present work is a continuation of our recent studies of $N = 53$ isotones; see Refs. [1–3]. The exploration of this region is motivated by the interest in elucidating the structure of the very neutron-rich nuclei, located near the astrophysical r-process path and close to ^{78}Ni, which is expected to be a doubly magic core. Of particular interest is the study of the development of collectivity close to ^{78}Ni, which may affect the r-process path by, for example, increasing nuclear binding energies. Such collective effects have been observed at $N = 52$ and $N = 53$ in our recent studies of ^{86}Se, ^{87}Se, ^{88}Br, and ^{90}Rb [1–5] and reproduced well by shell-model calculations [6]. One of the expected consequences of this collectivity is additional low-energy, low-spin levels at $N = 53$ as compared to $N = 51$ isotones, expected due to the $(\nu d_{5/2}^3)_j$, seniority-3 multiplet. Tracing this characteristic effect should provide new information on the deformation in the region.

In the study of ^{235}U fission induced by cold neutrons [2] we proposed a spin and parity (1^-) for the ground state of ^{88}Br, changing the (2^-) assignment adopted in the compilation [7]. We also reported seven low-energy, low-spin levels interpreted as members of the $\pi p_{3/2}\nu(d_{5/2})^3$ and $\pi f_{5/2}^{-1}\nu(d_{5/2})^3$ multiplets. The number of observed levels is lower than expected, when the $(\nu d_{5/2}^3)_j$ seniority-3 multiplet is considered (its presence in ^{88}Br is confirmed at higher excitation energies, where the $\pi g_{9/2}(d_{5/2})^3$ multiplet is observed [2]). The reason is probably the yrast-type population mechanism in fission, which does not reveal the non-yrast members of the two multiplets.

It is of high interest to identify the remaining members of the two multiplets and to verify the role of the $(\nu d_{5/2}^3)_j$ seniority-3 multiplet in ^{88}Br. One should also firmly determine the spin and parity of the ground-state of ^{88}Br and remove doubts about its feeding through the β decay of ^{88}Se [7].

In this article we present new results from a Penning-trap-assisted measurement of the β decay of ^{88}Se. Compared to previous β decay studies in the region, the Penning trap allows the reduction of background and removal of isobaric contaminations from the data. The experimental data for ^{88}Br were interpreted with large scale shell-model calculations, performed in this work. The experimental details are described in Sec. II and the experimental results in Sec. III. This is followed by the interpretation of the data in Sec. IV. The work is summarized in Sec. V.

II. EXPERIMENTAL DETAILS

Neutron-rich ^{88}Se ions were produced in fission induced by a 30 MeV, 8 μA proton beam irradiating a natural uranium target. Fission products were online separated with the Ion Guide Isotope Separator On-Line (IGISOL) facility [8] of the University of Jyväskylä. The fission fragments were first stopped in a helium gas cell, then extracted with the help of a sextupole ion guide (SPIG) [9] and accelerated to 30 keV. In the next step the radioactive beam was mass-separated with a 55 degree dipole magnet and sent to the radio-frequency cooler-buncher [10] from where ions were injected into the double Penning trap setup, JYFLTRAP [11]. Inside the JYFLTRAP system the isobaric beam was separated to the isotopic level using the buffer gas cooling technique [11,12]. The isobaric scan of mass $A = 88$, measured with a microchannel plate (MCP) detector located after the Penning trap, is shown in Fig. 1. The yield of trap-separated ^{88}Se was about 300 ions/s. Based on this isobaric scan, a 130 ms long purification cycle was chosen; this allowed us to achieve the mass resolving power $\frac{M}{\Delta M} \approx 30\,000$, which was sufficient to separate all contaminants in the experiment.

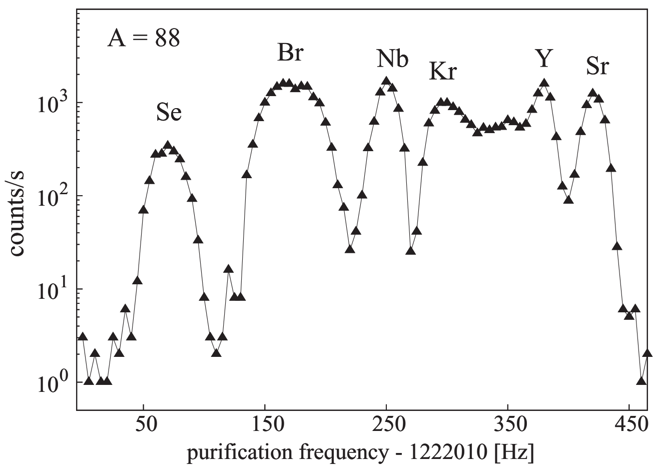

FIG. 1. Ion counts registered in the experiment using the MCP detector placed after the Penning trap. The well resolved singly charged ions from the IGISOL isobaric beam of mass $A = 88$ are marked with their element symbol.

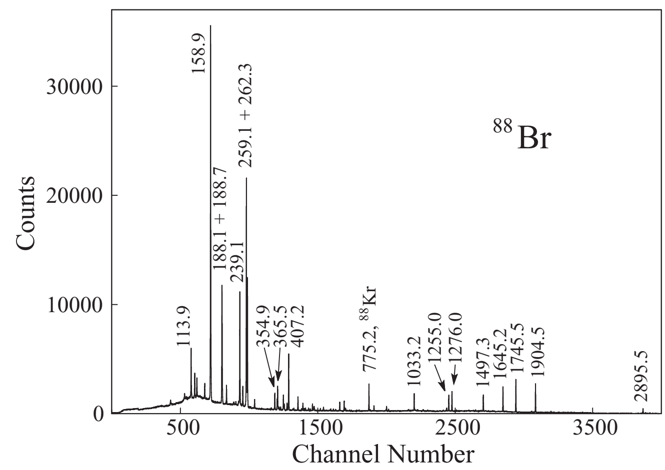

FIG. 3. A β-gated, singles γ-ray spectrum obtained in the present experiment. Energies of γ lines are labeled in keV. A nonlinear, constant-peak-width energy calibration was applied to enhance the low-energy part of the spectrum, where the density of lines is high.

For decay measurements, the monoisotopic ion samples released from JYFLTRAP were transported to the spectroscopy setup located after the trap (see Fig. 2). The purifed beam was implanted into a movable tape at the collection point. The tape was moved every 5 s to remove unwanted long-lived decay products. Our γ spectrometer consisted of five broad-energy germanium (BE-Ge) detectors, used to register low energy γ radiation, two large germanium detectors with relative effciency of 70% to register high-energy γ radiation, and a β counter. The energy resolution of the BE-Ge detectors was about 0.4 keV at 5.6 keV and 1.8 keV at 1332 keV. The germanium detectors were mounted in an octagonal geometry around the implantation point, as shown in Fig. 2. Data were collected in triggerless mode using Digital Gamma Finder cards.

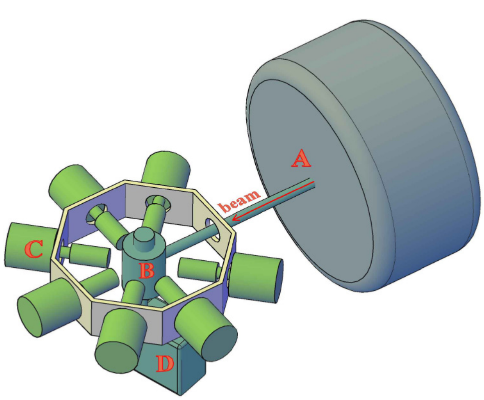

FIG. 2. Schematic view of the experimental setup. The monoisotopic ion samples released from JYFLTRAP (A) are implanted in the middle of a spectroscopic array consisting of a β counter (B) and seven Ge detectors (C). The moving tape collector device (D) is operating the implantation tape and removing unwanted long-lived decay products from the center of the setup.

III. RESULTS

A. β -decay scheme of ^{88}Se

Figure 3 shows a β-gated, singles-γ spectrum measured in our experiment. All the γ lines marked in the spectrum were assigned to ^{88}Br, except the 775.2-keV transition which belongs to its daughter nucleus, ^{88}Kr.

In the present work we confirm and extend the low-spin scheme of excited levels in ^{88}Br, reported in the prompt-γ measurement of ^{235}U fission induced by neutrons [2]. Compared to the previous β-decay measurement [13], we found 15 new levels and 44 new γ transitions populated following the β decay of ^{88}Se. All the observed lines are listed in Table I with their relative intensities, obtained from a singles-γ spectrum (not β-gated).

The scheme of excited levels in ^{88}Br obtained in this work, which is presented in Fig. 4, has been constructed based on $\gamma\gamma$ coincidences sorted within a 600 ns time window. Figure 5 shows examples of coincidence spectra. In Fig. 5(a) we show a γ spectrum gated on the 354.9-keV line, corresponding to γ decay of the new 628.2-keV level. An arrow in this spectrum marks the 272.8-keV energy. As in our recent paper [2], we do not observe any direct decay from the 272.8-keV level to the ground state. Therefore we reject the 272.8-keV transition proposed in Ref. [13]. As observed before in Refs. [2,15] the 272.8-keV level decays exclusively to the 158.9-keV level by the 113.9-keV transition, seen in Fig. 5(a) as a pronounced line.

We confirm the 158.9-, 259.1-, 272.8-, 285.5-, 407.2-, 1904.5-, and 3154.6-keV levels observed previously [13] where the authors also reported an excited level at 566.0 keV, decaying by two γ transitions, 293.3- and 566.0-keV. There is no evidence in our data supporting the 566.0-keV excited level in ^{88}Br. The 111.0-, 113.9-, 126.5-, 158.9-, 259.1-, and 285.5-keV transitions reported in prompt fission [2] are also observed in the present work.

TABLE I. Energies E_γ, relative intensities, I_γ, internal conversion coefficients, and total transition intensities per 100 decays, as observed in the β^- decay of the ^{88}Se ground state.

E_γ (keV)	I_γ (rel.)	Internal conversion coefficient	I_{tot} per 100 decays
73.6(1)	0.8(2)	1.49 [a]	0.38(5)
74.2(1)	0.6(2)	1.46 [a]	0.28(5)
100.2(1)	1.8(3)	0.49 [a]	0.51(6)
103.4(2)	0.7(1)	0.44 [a]	0.19(2)
111.2(1)	0.9(3)	0.56(10) [b]	0.27(6)
113.9(1)	9.2(6)	0.08(1) [c]	1.91(14)
121.6(1)	6.5(4)	0.25 [a]	1.56(13)
126.5(1)	4.9(4)	0.21 [a]	1.14(10)
144.6(1)	5.2(4)	0.13 [a]	1.13(12)
158.9(1)	100(2)	0.054(10) [b]	20.2(1.4)
188.1(1)	25.0(10)	5.32×10^{-2} [a]	5.05(21)
188.7(1)	16.8(10)	5.25×10^{-2} [a]	3.36(20)
200.6(1)	4.9(4)	4.3×10^{-2} [a]	0.97(9)
221.6(1)	1.2(2)	3.04×10^{-2} [a]	0.24(4)
239.1(1)	23.5(16)	2.36×10^{-2} [a]	4.61(32)
248.2(1)	4.8(4)	2.09×10^{-2} [a]	0.94(9)
259.1(1)	81.1(20)	1.80×10^{-2} [a]	15.82(93)
262.3(1)	43.5(12)	1.72×10^{-2} [a]	8.45(50)
285.5(1)	3.8(3)	1.32×10^{-2} [a]	0.73(8)
354.9(1)	6.7(4)		1.28(11)
363.6(1)	2.2(8)		0.42(15)
365.5(1)	9.5(5)		1.83(13)
374.2(2)	0.43(30)		0.08(4)
386.7(1)	8.1(5)		1.56(12)
390.0(1)	3.4(4)		0.66(8)
400.6(1)	1.9(4)		0.36(7)
407.2(1)	32.8(12)		6.29(40)
443.8(1)	7.0(4)		1.34(11)
463.9(1)	12.6(5)		2.41(16)
469.0(1)	1.6(3)		0.31(5)
474.3(1)	1.5(3)		0.29(7)
487.4(1)	2.2(3)		0.42(6)
504.2(1)	4.2(4)		0.81(8)
538.8(1)	2.0(4)		0.38(7)
552.7(1)	3.1(4)		0.59(8)
597.9(1)	2.0(4)		0.38(8)
609.2(1)	1.0(4)		0.19(7)
628.2(1)	7.3(4)		1.40(11)
649.3(1)	8.6(5)		1.65(13)
656.5(1)	3.0(4)		0.57(8)
712.3(1)	1.4(4)		0.27(7)
871.5(2)	4.2(6)		0.81(12)
1033.2(1)	26.0(11)		5.00(34)
1240.9(2)	1.4(4)		0.27(7)
1255.1(1)	21.8(11)		4.18(30)
1276.3(1)	29.7(15)		5.70(41)
1497.3(1)	32.3(17)		6.19(46)
1645.2(1)	47.6(23)		9.13(66)
1745.5(1)	63.8(32)		12.24(90)
1904.5(1)	61.4(32)		11.78(88)
2034.7(2)	5.3(5)		1.02(11)
2895.5(2)	24.7(7)		4.74(28)
2921.7(2)	4.8(4)		0.92(9)
2965.8(2)	4.6(4)		0.88(8)
2994.6(2)	3.4(4)		0.65(7)

[a] A mean theoretical value for $M1$ and $E2$ multipolarity.
[b] Reference [15].
[c] Reference [2].

In the spectrum gated on the 259.1-keV line, shown in Fig. 5(b), there are 121.6- and 363.6-keV lines. This observation indicates the presence of a 26.2-keV transition linking the 285.7- and 259.5-keV levels, as already proposed in our previous work [2]. The 26.2-keV transition is not seen in the spectrum, probably due to high conversion at this γ energy. An estimated lower limit for the total conversion coefficient is 6. This value compared to theoretical values of 4.1, 5.2, and 108.8 for $E1$, $M1$, and $E2$ transitions, respectively, suggests an $M1 + E2$ multipolarity for the 26.2-keV decay.

New levels in ^{88}Br found in this work at 188.1, 188.7, 262.3, 427.2, 628.2, 663.1, 649.1, 815.4, 871.5, 914.7, 966.1, 2267.0, and 3109.9 keV are supported by the evidence in Figs. 5(c) and 5(d), where we show γ spectra gated on the 188-keV doublet and the 262.3-keV line. All lines seen in these spectra are new. In the spectrum shown in Fig. 5(c) we observe the 73.6-, 74.2-, 239.1- and 474.3-keV lines, corresponding to decays from the 262.3-, 427.4- and 663.0-keV levels, respectively. In Fig. 5(d) there are 365.5-, 386.7-, 1255.1- and 1276.3-keV lines which form two cascades depopulating the 1904.5-keV level and defining two new levels at 628.2 and 649.3 keV. Apart from that, one sees there the 400.6- and 552.7-keV decays from the respective 663.0- and 815.4-keV levels.

Interestingly, we could also observe the 111.0-keV line (clearly resolved in the singles spectrum from the 113.9-keV line) corresponding to the decay of the 5.1 μs isomer at 270.0 keV in ^{88}Br [15]. The half-life obtained from fitting the corresponding time-decay spectrum of the 111.3-keV line is 5.1(9) μs. This value clearly confirms the isomer in the data, which is probably populated indirectly, via γ cascades.

B. The direct feeding of the ground state of ^{88}Br

In Ref. [13] authors estimated β feeding to the ground-state of the ^{88}Br nucleus as no more than 38%. Later Lin *et al.* reported a value of 20.5% [16], while in a recent compilation [7] an upper limit of 3% only is given. This situation requires clarification.

The direct feeding of the ground state in β decay can be estimated from intensities of a pair of selected γ rays from the decay of mother and daughter nuclei under radioactive equilibrium, as proposed in Ref. [16]. Figure 6 illustrate schematically this idea for the the case of ^{88}Br. The ground state of ^{88}Br is fed both by direct β decays (I_β) and by γ-ray cascades (I_γ), part of which go via 158.9-keV transition ($I_{158.9}$). In the ^{88}Kr daughter nucleus the ground state is fed directly in β decay (I_β) and by γ-ray cascades, mostly by the 775.2-keV transition ($I_{775.2}$).

The direct β feeding in β decay to the ground state of ^{88}Br can be expressed as

$$F_{gs} = 1 - (I_A)_{gs} \tag{1}$$

where $(I_A)_{gs}$ is a sum of absolute intensities of all γ lines feeding the ground state.

Under radioactive equilibrium, the total feeding of both ground states in ^{88}Br and ^{88}Kr is equal, leading to the relation $\frac{(I_A)_{158.9}}{(I_A)_{775.2}} = \frac{(I_R)_{158.9}}{(I_R)_{775.2}}$, where (I_A) and (I_R) are absolute and relative intensities of the pair of selected γ rays, here 158.9 and 775.2 keV. On the other hand, the ratio of the absolute intensity

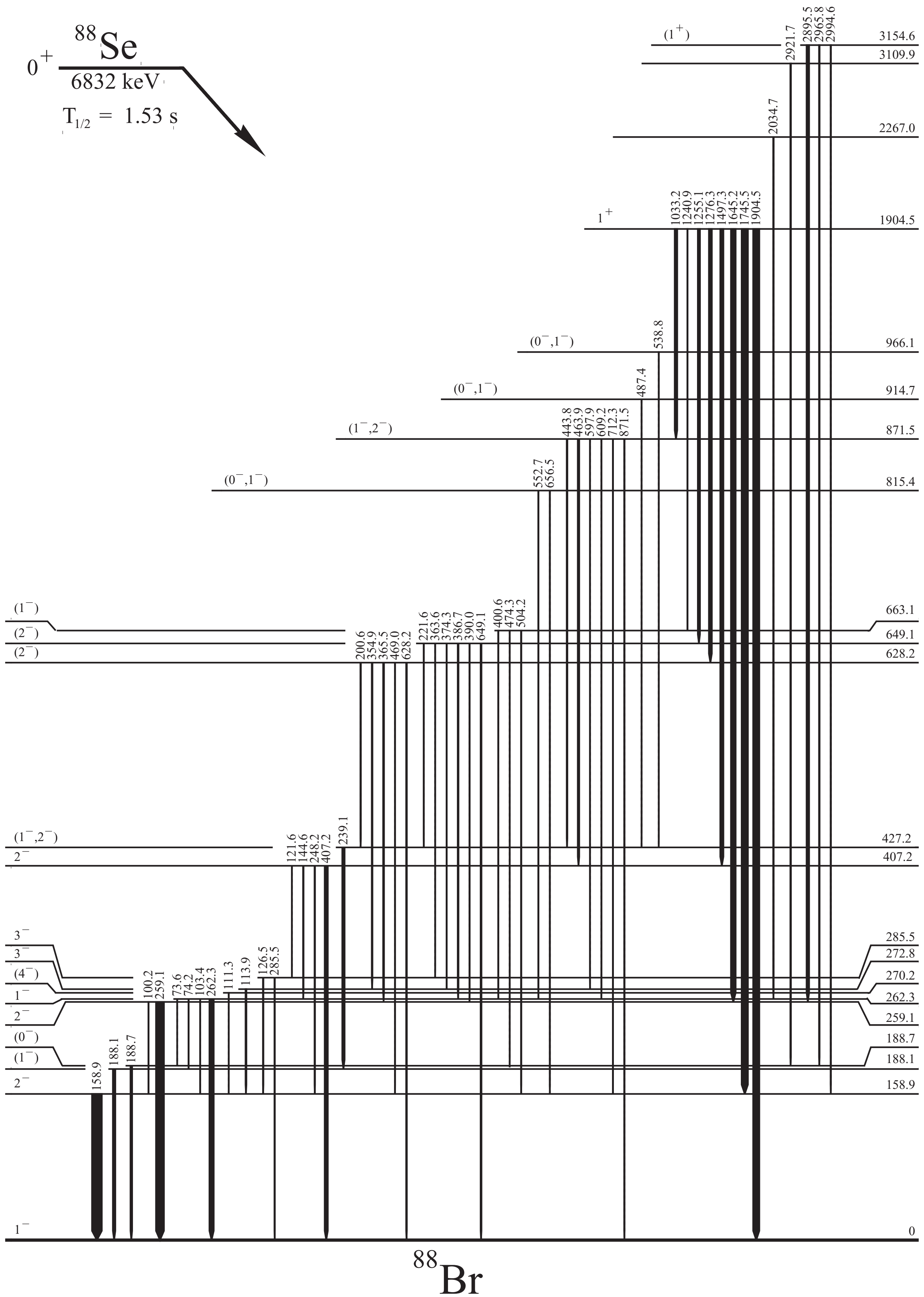

FIG. 4. A β-decay scheme of ^{88}Se, as observed in the present work. $T_{1/2}$ and Q_β values are taken from [14].

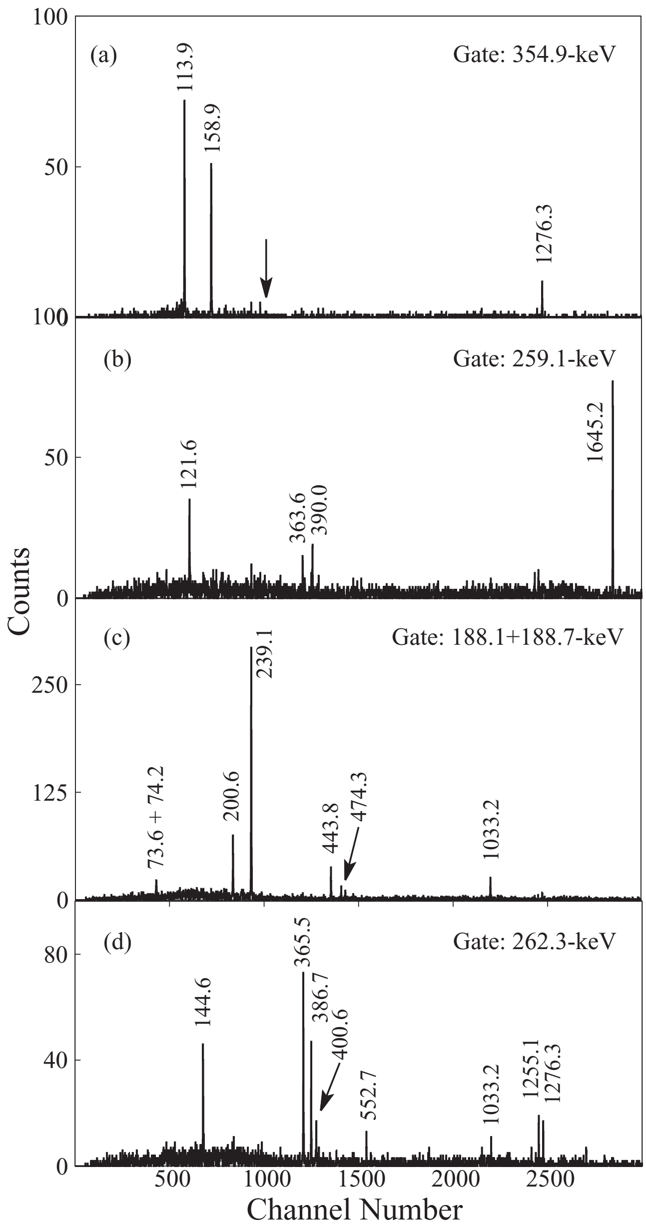

FIG. 5. Examples of β- and γ-gated spectra, obtained in this work. Peaks are labeled in keV. The arrow in panel (a) marks the position of the 272.8-keV energy.

of 158.9-keV line $[(I_A)_{158.9}]$ to the absolute intensities of all lines feeding the ground state of ^{88}Br $[(I_A)_{gs}]$ is equal to the ratio of their relative intensities, $\frac{(I_A)_{158.9}}{(I_A)_{gs}} = \frac{(I_R)_{158.9}}{(I_R)_{gs}}$. Thus, formula (1) reads now

$$F_{gs} = 1 - \frac{(I_R)_{158.9}}{(I_R)_{775.2}} \frac{(I_R)_{gs}(I_A)_{775.2}}{(I_R)_{158.9}}. \quad (2)$$

Formula (2) is similar to the formula proposed by Lin *et al.* [16]:

$$F_{gs} = 1 - \frac{(A_P)_{\rm Se}}{(A_P)_{\rm Br}} \frac{\epsilon_{\rm Br}}{\epsilon_{\rm Se}} \frac{(I_A)_{\rm Br}}{(I_R)_{\rm Se}}, \quad (3)$$

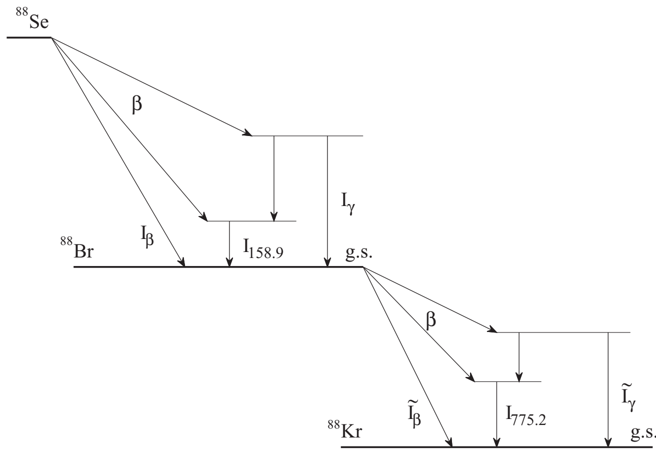

FIG. 6. Scheme of the idea of direct β feeding in β decay proposed by Lin *et al.* [16].

where $(A_P)_{\rm Se}$ and $(A_P)_{\rm Br}$ are the peak areas for the selected pair of selenium and bromium γ rays, $\epsilon_{\rm Br}$ and $\epsilon_{\rm Se}$ are their relative detection efficiencies, $(I_A)_{\rm Br}$ is the absolute intensity of the selected bromium decay γray $[(I_A)_{775.2}$ in formula (2)], and $(I_R)_{\rm Se}$ is the ratio of the relative intensity of selected selenium γ ray to the relative intensities of all lines feeding the ground state of ^{88}Br.

Using formula (3) and the results reported in Ref. [13], Lin *et al.* have calculated β-feeding of the ground-state in ^{88}Br to be 20.5%. This result has to be corrected because (i) the decay scheme presented in Ref. [13] is incomplete and (ii) formula (3) is an approximation of the exact formula (2). While deriving formula (3) from formula (2) one assumes that $\frac{(A_P)_{\rm Se}}{\epsilon_{\rm Se}} = (I_R)_{775.2}$ and $\frac{(A_P)_{\rm Br}}{\epsilon_{\rm Br}} = (I_R)_{158.2}$, where $(A_P)_{\rm Se}$ and $(A_P)_{\rm Br}$ represent γ intensities only.

We used movable tape, which removed long-lived decay products. Therefore there was no radioactive equilibrium in our measurement and we have to use the $\frac{(A_P)_{\rm Se}\epsilon_{\rm Br}}{(A_P)_{\rm Br}\epsilon_{\rm Se}} = 0.299$ value of Ref. [16], which we, however, corrected for the internal conversion of the 158.9- and 775.2-keV lines, obtaining the ratio 0.315. The total conversion coefficient for the 158.9-keV line was derived from the K-conversion coefficient measured in Ref. [15]. Taking the ratio 0.315, the total intensity of the 775.2-keV line, $(I_A)_{\rm Br} = (I_A)_{775.2} = 0.625$ as reported in [17], and the $(I_R)_{\rm Se}$ calculated using our new excitation scheme of ^{88}Br, we determined the ground-state feeding of ^{88}Br to be 26(9)%.

We also made another estimation of the ground-state feeding using the intensity of the 1904.5-keV transition of 11.78 per 100 decays [13] as a reference. This allows one to calculate total intensities per 100 decays of other transitions in ^{88}Br, using relative γ intensities and total conversion coefficients listed in Table I. Intensities per 100 decays of transitions populating the ground state in ^{88}Br sum up to 76(2)%. Considering that the β-n branching in the decay of ^{88}Se is 0.7% [7], we calculated the direct ground-state feeding in β decay of 24(3)%. This value is consistent with the result obtained above. The two values are derived from the same dataset and are not independent. Therefore calculating their

TABLE II. β feeding and log ft values of levels populated in the β^- decay of the ground-state of ^{88}Se as observed in this work. For further information concerning feeding of the ground state in ^{88}Br, see Sec. III B.

E_{level} (keV)	β feeding (%)	log ft	I^π
0.0	26(9)	5.5(2)	1^-
158.9	2.2(33)		2^-
188.1	0.0(9)		(1^-)
188.7	0.2(7)		(0^-)
259.1	0.0(21)		2^-
262.3	3.2(15)	6.3(2)	1^-
270.2	0.26(10)	7.4(2)	(4^-)
272.8	0.02(2)		3^-
285.5	0.01(1)		3^-
407.2	1.3(14)	6.8(3)	2^-
427.3	1.3(8)	6.7(3)	$(1^-,2^-)$
628.2	0.1(11)		(2^-)
649.1	0.4(9)		(2^-)
663.0	1.2(3)	6.6(1)	(1^-)
815.4	1.2(2)	6.1(1)	$(0^-,1^-)$
871.5	0.4(9)		$(1^-,2^-)$
914.7	0.4(1)	7.0(1)	$(0^-,1^-)$
966.1	0.4(1)	7.0(1)	$(0^-,1^-)$
1904.5	54.5(40)	4.5(1)	1^+
2267.0	1.0(1)	6.1(1)	
3109.9	0.9(1)	5.8(1)	
3154.6	6.3(5)	4.9(1)	(1^+)

average is not justified. Taking a more cautions approach, we adopt the 26(9)% value.

We note that the upper limit of 3% for the feeding to the ground-state of ^{88}Br reported in the compilation [7] was used to support the (2^-) spin and parity adopted for this level. Considering the new feeding obtained in this work, as will be discussed in the next section, this spin should be changed.

C. Spin and parity assignments for levels in ^{88}Br

Using the total intensities per 100 decays of γ transitions, we estimated the population of levels in ^{88}Br following the β decay of ^{88}Se, as shown in Table II. These values were then used to calculate log ft values, computed using the code provided by NNDC [18]. The resulting log ft, shown in Table II, were used together with the observed intensity branchings to propose spins and parities of excited states in ^{88}Br, as described below.

The 1904.5-keV level is the most strongly populated state following the β decay of the 0^+ ground state of ^{88}Se. The log $ft = 4.51$ indicates an allowed character of the β decay to this level, consistent with the $0^+ \rightarrow 1^+$, Gamow-Teller transition, only. This allows an assignment of spin and parity 1^+ to the 1904.5-keV level, in accord with the previous assignment [7].

The 26(9)% β feeding and the resulting log $ft = 5.5(2)$ of the ground state in ^{88}Br exclude spin $I = 2$ or higher for this level. The 0^+ spin and parity is excluded by the isospin selection rule and the 1^+ solution would likely require a lower log ft. We also note that no positive-parity states are expected at low excitations in ^{88}Br [2]. Of the remaining 0^- and 1^- solutions, we choose the latter, considering the 8.7% branch following the β decay of the ground state of ^{88}Br to the 2^+ level in ^{88}Kr [19]. The present 1^- spin and parity assignment to the ground state in ^{88}Br confirms the (1^-) spin and parity solution, proposed in our fission study [2].

The 272.8- and 285.5-keV levels are populated following the induced fission of ^{235}U in Ref. [2], where they were assigned spins and parities of (3^-). A very weak β feedings of 0.02(2)% and 0.01(1)% to the 272.8- and 285.5-keV levels, found in this work, support these spin assignments.

The prompt character and the low-energy of the 158.9-keV decay, connecting the 158.9-keV level and the ground state, suggests a $\Delta I = 1$, $M1 + E2$ multipolarity. For this energy, an $E1$ character is less likely as it would be rather slow in a nucleus where no octupole correlations are expected. Moreover, no positive-parity levels are predicted at such low excitation energies in ^{88}Br [2]. The $M1 + E2$ multipolarity of the 158.9-keV line is consistent with the 1^- or 2^- spin and parity assignment to the 158.9-keV level. The 272.8- and 285.5-keV levels are linked with the 158.9-keV state, through the 113.9- and 126.5-keV decays. Taking into account their mixed dipole-quadrupole nature as the most probable and the spin 3^- assigned to the 272.8- and 285.5-keV levels we reject the 1^- hypothesis for the 158.9-keV state. Summarizing, we attribute a spin and parity of 2^- to the 158.9-keV level which is consistent with β feeding of 2.2(33)% to this state as it is observed in this work.

Strong transitions from the 259.1- and 262.3-keV levels to the ground state and low-energy decays to the 158.9-keV level limit the spin values of the 259.1- and 262.3-keV excitations to the 0^-, 1^-, or 2^-. Spin 0^- and 1^- for the 259.1-keV level can be rejected because of the 26.2-keV, prompt link with the 285.5-keV level ($I^\pi = 3^-$), which may have only $M1 + E2$ multipolarity. The level at 262.3 keV was not seen in induced fission of ^{235}U [2], but it is populated in the β decay of ^{88}Se. It means that this state has a non-yrast nature, and spin and parity $I^\pi = 1^-$ or 0^- are the most likely solutions for it. We note that the low-energy 103.4-keV transition, which links the 262.3- and 158.9-keV levels, probably has a mixed dipole-quadrupole character, and in view of it a spin hypothesis 0^- is not a possible solution for the 262.3-keV state. Considering the observations discussed above and log ft value of 6.3 of the 262.3-keV level, we propose spin and parity $I^\pi = 2^-$ for the 259.1-keV level and $I^\pi = 1^-$ for the 262.3-keV one.

Taking into account the 121.6-keV, low-energy prompt γ decay of the 407.2-keV level to the 3^-, 285.5-keV level and the strong 407.2-keV decay to the ground state, we propose spin and parity 2^- or 3^- for the 407.2-keV level. This is consistent with the lower limit of 6.8 for the log ft of this level. However, spin 3^- is unlikely, considering the strong 1497.3-keV decay of the 1^+, 1904.5-keV level to the 407.2-keV level. One may note that $M2$ multipolarity of the 1497.3-keV transition would be coherent only with a long lifetime of the 1904.5-keV excitation, which is not observed. Therefore we assign spin and parity 2^- to the 407.2-keV state.

Decay patterns of the 628.2- and 649.1-keV states are similar to the decay pattern of the 407.2-keV level. Both states decay via prompt γ-rays to the 1^- ground state, 1^- state at

262.3 keV and to the 3^- states at 272.3 keV or 285 keV. Because of this we tentatively propose spin and parity (2^-) for both 628.2- and 649.2-keV levels.

Low-lying 188.1- and 188.7-keV levels were not seen among excitations in ^{88}Br populated in fission [2]. This suggests their non-yrast nature and spins lower than $I = 2$. Both states are fed by the low-energy γ transitions, which decays from the 262.3-keV level. Considering the low energies of these lines, the $M1 + E2$ characters are the most probable for them, which indicates negative parities for both discussed levels. One can agree that two states lying so close to each other should most likely have different spins and therefore one of them should have spin $I^\pi = 0^-$, and the second one $I^\pi = 1^-$. Taking into account the value of the β feeding of 0.2 (7)% to the 188.7-keV level and 0.0(9)% to the 188.7-keV state, we tentatively suggest to assign spin values 0^- and 1^- to the 188.7- and 188.1-keV levels, respectively.

Rather strong β feeding of 6.3(5)% to the 3154.6-keV state and the resulting $\log ft = 4.9$ of this level suggests a tentative spin and parity (1^+) for the 3154.6-keV state.

Tentative spin and parity assignments to other levels, shown in Fig. 4 and listed in Table II were proposed, based on their decay branchings and $\log ft$ values.

IV. DISCUSSION

A. General remarks

As discussed in our previous work [2] the low-spin structure of ^{88}Br, which is expected to be similar to that of ^{86}Br [20,21], should be dominated by two overlapping proton-neutron $(\pi p_{3/2},\nu d_{5/2})_j$ and $(\pi f_{5/2}^{-1},\nu d_{5/2})_j$ multiplets with spin j ranging from 1^- to 4^- and from 0^- to 5^-, respectively. However, there may be differences between the two nuclei due to the seniority-3, $(\nu d_{5/2}^3)_j$ multiplet at $N = 53$, which is expected to generate additional low-energy, low-spin levels in ^{88}Br as compared to ^{86}Br.

Higher-energy levels can be formed by the promotion of the odd proton to the $g_{9/2}$ orbital, which produces the $(\pi g_{9/2},\nu d_{5/2})_j$ multiplet with 2^+ and 7^+ members at the endings of the multiplet. Next, when the odd neutron is promoted to the $g_{7/2}$ orbital the $(\pi g_{9/2},\nu g_{7/2})_j$ multiplet is formed with spin range 1^+ to 8^+. We note that the 1^+ member of the $(\pi g_{9/2},\nu g_{7/2})_j$ multiplet, strongly populated in β decay, is reported in a number of rubidium, yttrium, and bromium nuclei [21–25].

In our recent work concerning β decay of the ground state of ^{86}Se [21], we proposed a mechanism for population of excited levels in ^{86}Br via Gamow-Teller decay. According to the described mechanism, the Gamow-Teller decay of the $g_{7/2}$ neutron, which is admixed in the ground state of ^{86}Se, preferably populates the $(\pi g_{9/2},\nu_{7/2})_{1^+}$ configuration. The main component of the ground state configuration of ^{86}Se is the $d_{5/2}$ neutron orbital. Therefore, β decays to low-lying states are explained as the first forbidden decay of the $d_{5/2}$ neutron to the $p_{3/2}$ or $f_{5/2}$ proton. A similar scenario can be proposed in a case of decay of the ^{88}Se nucleus, which has two more neutrons.

B. Shell-model calculations

To verify the proposed interpretations we have calculated excitations in ^{88}Br using the shell model, taking the $1f_{5/2},2p_{3/2},2p_{1/2},1g_{9/2}$ orbitals for protons and the $2d_{5/2},3s_{1/2},1g_{7/2},2d_{3/2},1h_{11/2}$ orbitals for neutrons, outside the ^{78}Ni core. Similar calculations were performed previously for the odd-A, $N = 52$ and $N = 53$ isotones [1,4] as well as for ^{86,88}Br and ^{90}Rb isotopes [2,3]. The effective interaction is described in Refs. [6,26], with the proton-proton part of the interaction updated to reproduce new data in the $N = 50$ isotones [27]. The calculations have been performed using the m-scheme shell model code ANTOINE [28] and the coupled-scheme code NATHAN [29]. Full diagonalizations in the model space have been achieved.

There was a good compatibility between the experimental results and the theoretical calculations in our previous study concerning the structure of excited levels in ^{88}Br, populated via fission of ^{235}U (see Figs. 12 and 13 in Ref. [2]). In that work the shell-model calculations reproduced well the overall scale of the excitations in both ^{86}Br and ^{88}Br nuclei; however, the order of some calculated members of the low-lying multiplets was not consistent with the experimental counterparts. For example, the experimentally observed ground state of ^{86}Br has spin $I = 1^-$ whereas the shell model predicted the spin of the ground state as 4^- and, moreover, the calculated 1^- level was located 300 keV above its experimental counterpart. Because of this we fine-tuned the proton-neutron $V_{d5/2,p3/2}$ and $V_{d5/2,f5/2}$ matrix elements to obtain more accurate reproduction of these multiplets in the odd-odd ^{86}Br isotope. The shell-model calculations with the refined interaction were presented in our recent paper about experimental levels in ^{86}Br and ^{86}Kr [21], where theoretical results fit much better to the experimental data than in the previous case [2]. The same effective interactions as in ^{86}Br and ^{86}Kr have been used in the present work.

The results of the calculations are compared to the experimental data of ^{88}Br in Fig. 7. Excited states with spins 4 and 5 populated in prompt-γ work [2], which are not observed in β decay, have been added to Fig. 7. The calculation is normalized to the experiment at the 1_1^- level and reproduced properly the overall scale of observed excitations of 3.5 MeV in the discussed nucleus.

The $\pi f_{5/2}^{-1}(\nu d_{5/2})^3$, $\pi p_{3/2}(\nu d_{5/2})^3$, and $\pi p_{3/2}^{-1}(\nu d_{5/2})^3$ multiplets, including negative-parity excitations with spins from 0^- to 5^- are calculated in the energy range from 0 to 1.6 MeV. In Fig. 7, members belonging to the same multiplet are linked by lines to guide the eyes: $\pi f_{5/2}^{-1}(\nu d_{5/2})^3$–dashed line, $\pi p_{3/2}(\nu d_{5/2})^3$–solid line, and $\pi p_{3/2}^{-1}(\nu d_{5/2})^3$–dashed-dotted line. Members of these multiplets are reproduced with an average accuracy of 100 keV, which is a very good result for shell-model calculations in the studied region. The positive-parity levels as members of the $\pi g_{9/2}\nu d_{5/2}$ are calculated to lie above 1.6 MeV.

In Table III we show occupations of neutron and proton orbitals, computed in this work for levels in ^{88}Br. The dominant contribution to wave functions in ^{88}Br is around 30%. They have a more complex composition compared with those in ^{86}Br, which have the dominant contributions of about 60%.

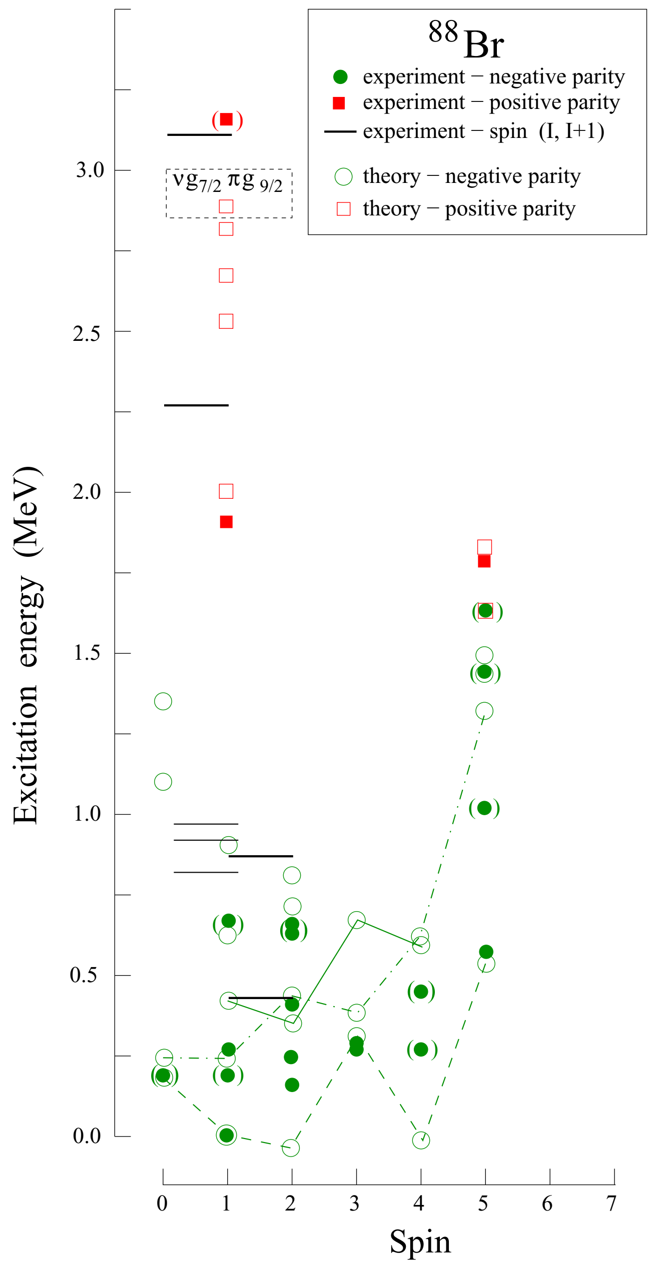

FIG. 7. Comparison of excited levels in ^{88}Br, observed in this work, to the present shell-model calculations. Calculations are normalized to the experiment at the 1_1^- level. The experimental levels with spin 4 and 5 are taken from Ref. [2].

We note that the wave functions of the low-lying, negative-parity levels are complex but similar to each other, and this suggests the presence of collective effects in ^{88}Br, causing large configuration mixing within the $\pi f_{5/2}^{-1}(\nu d_{5/2})^3$, $\pi p_{3/2}(\nu d_{5/2})^3$, and $\pi p_{3/2}^{-1}(\nu d_{5/2})^3$ multiplets.

Table III also presents occupations for 1^+ levels, which are dominated by the $g_{9/2}$ proton orbital (numbers in bold). The 1_1^+ state, which has 7% of neutron $\nu g_{7/2}$ configuration, might correspond to the experimental 1^+ level at 1904.5 keV with β feeding of 54.5% and $\log ft = 4.5$. The 1_5^+ level, shown in a dashed-line box in Fig. 7 is a good counterpart

TABLE III. Occupation of neutron and proton orbitals, calculated in this work for levels in ^{88}Br, using the shell model.

Levels	Neutrons					Protons			
	$d_{5/2}$	$s_{1/2}$	$g_{7/2}$	$d_{3/2}$	$h_{11/2}$	$f_{5/2}$	$p_{3/2}$	$p_{1/2}$	$g_{9/2}$
0_1^-	2.55	0.20	0.06	0.12	0.07	3.93	2.25	0.56	0.25
0_2^-	2.41	0.33	0.05	0.15	0.06	3.97	2.35	0.46	0.22
1_1^-	2.56	0.17	0.05	0.13	0.07	4.69	1.63	0.45	0.23
1_2^-	2.47	0.23	0.06	0.15	0.08	4.26	2.11	0.39	0.24
1_3^-	2.46	0.26	0.06	0.16	0.06	4.51	1.82	0.44	0.24
1_4^-	2.41	0.30	0.07	0.16	0.07	4.37	1.90	0.50	0.23
2_1^-	2.58	0.17	0.05	0.14	0.07	4.69	1.63	0.45	0.23
2_2^-	2.59	0.16	0.07	0.12	0.07	4.92	1.36	0.46	0.25
2_3^-	2.49	0.25	0.06	0.13	0.07	4.08	2.22	0.46	0.24
2_4^-	2.37	0.33	0.07	0.16	0.07	4.32	1.95	0.50	0.23
3_1^-	2.55	0.15	0.06	0.16	0.08	4.66	1.67	0.44	0.23
3_2^-	2.47	0.23	0.06	0.15	0.08	3.87	2.48	0.40	0.24
3_3^-	2.51	0.23	0.06	0.13	0.07	4.47	1.89	0.39	0.25
3_4^-	2.54	0.20	0.06	0.15	0.06	4.56	1.71	0.49	0.22
4_1^-	2.56	0.16	0.05	0.15	0.07	4.72	1.63	0.42	0.23
4_2^-	2.61	0.12	0.07	0.12	0.08	4.71	1.72	0.31	0.26
4_3^-	2.50	0.22	0.06	0.16	0.07	4.67	1.69	0.43	0.22
4_4^-	2.46	0.23	0.06	0.16	0.07	4.31	2.11	0.38	0.21
5_1^-	2.59	0.12	0.06	0.15	0.08	4.47	1.67	0.42	0.24
1_1^+	2.43	0.18	0.07	0.23	0.09	3.92	1.56	0.44	**1.07**
1_2^+	2.39	0.14	0.06	0.17	0.24	4.57	1.29	0.22	**0.92**
1_3^+	2.43	0.16	0.05	0.23	0.13	4.39	1.29	0.28	**1.04**
1_4^+	2.42	0.11	0.07	0.23	0.17	4.36	1.37	0.27	**1.00**
1_5^+	**1.55**	0.26	**0.94**	0.19	0.08	4.06	1.48	0.33	**1.12**

for the experimental (1^+) excitation at 3154.6 keV with β feeding of 6.3% and $\log ft = 4.9$. This level, predicted at 3.0 MeV, is dominated (37%) by the $\pi g_{9/2} \nu g_{7/2}$ configuration, and it might be a good source of information on $g_{9/2}$ and $g_{7/2}$ orbitals.

V. SUMMARY

In summary, we have observed excited levels in odd-odd ^{88}Br, populated in the β decay of the ground state of ^{88}Se. The β feeding of the ground state of ^{88}Br has been determined to be 26(9)%, which gives $\log ft$ value of 5.5. We firmly assigned spin and parity of 1^- to the ground state of ^{88}Br, which was suggested in our previous study [2].

The low-spin excitations are identified as members of the $\pi f_{5/2}^{-1}(\nu d_{5/2})^3$, $\pi p_{3/2}(\nu d_{5/2})^3$, and $\pi p_{3/2}^{-1}(\nu d_{5/2})^3$ multiplets, similar to those observed in ^{86}Br. In the present work we support the low spin structure of excited levels up to 300 keV observed in the yrast cascade of ^{88}Br in the prompt-γ measurement of ^{235}U induced fission [2].

The large-scale, shell-model calculations, performed in this work, reproduced well the experimental results. They support the presence of collective effects in ^{88}Br, the consequence of which are additional low-energy levels with mixed structure of wave functions. Moreover, for the strongly β-fed 1^+ level at 1904.5 keV, the calculated counterpart has 7% of the neutron $\nu g_{7/2}$ configuration. This is a similar result as that obtained in ^{86}Br [21], where the 1^+_2 has 8% of the neutron $\nu g_{7/2}$ configuration, and supports the proposed scenario of a Gamow-Teller decay to the 1904.5 keV level in ^{88}Br. We stress the importance of verifying in future investigations the proposed population of levels in the $N = 53$ isotones by Gamow-Teller decays of $g_{7/2}$ neutrons.

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