High-spin states in $N = 50$ ^{85}Br and ^{87}Rb nuclei

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The level structures of the $N = 50$ ^{85}Br and ^{87}Rb isotopes have been studied in the fission of the compound system formed in three different heavy-ion-induced reactions. In ^{87}Rb many states above the previously known $9/2^+$ isomer have been established. The coupling of the odd proton occupying the $g_{9/2}$ orbital to the yrast states in the ^{86}Kr core can account for the first excited states above the isomer in ^{87}Rb. A comparison with the first excited states above the $9/2^+$ state in ^{85}Kr and ^{89}Y reveals similarities in the coupling. At higher excitations similar behavior to ^{89}Y is observed, indicating a possible presence of neutron-core excitations. In ^{85}Br several states up to $\sim$5 MeV excitation energy have been established. Two states at $\sim$2 MeV excitation energy are candidates for the $9/2^+$ state originating from the odd proton occupying the $g_{9/2}$ orbital. The experimental results for both isotopes are compared with predictions of the shell model.

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I. INTRODUCTION

The spectroscopic study of high-spin states of $^{85}_{35}$Br$_{50}$ and $^{87}_{37}$Rb$_{50}$ is very interesting because both isotopes have a closed neutron shell that is expected to break at higher spins and excitation energies. Moreover, both isotopes lie close to the semidoubly magic nuclide $^{88}_{38}$Sr$_{50}$. Hence, their level structure is of particular interest because of the relatively limited number of configurations available for excitations. The properties of high-spin states in both nuclei are expected to be dominated by few-particle excitations, whereas collective excitations should have a minor influence.

The ^{87}Rb isotope has only one proton less than ^{88}Sr. Its three states below 1 MeV excitation energy are of single-particle character generated mainly by excitations of the $1p_{3/2}$, $1p_{1/2}$, and $0f_{5/2}$ proton orbitals coupled to an even-even core combining the characteristics of the neighboring A and $A + 2$ nuclei [1]. An isomer with spin $9/2^+$ originating from the odd proton occupying the $g_{9/2}$ orbital has been identified and its single-particle character established [1]. However, there is no spectroscopic information for high-spin states above this isomer [2]. Conversely, a wealth of spectroscopic information for states above the $9/2^+$ state has been available for ^{85}Kr [3,4] and ^{89}Y [5–7]. The ^{85}Kr and ^{87}Rb nuclei are one neutron hole and proton particle from ^{86}Kr, respectively, whereas ^{87}Rb and ^{89}Y are one proton hole and proton particle from ^{88}Sr, respectively. Therefore, the level schemes of both these nuclei are expected to be similar to that of ^{87}Rb. Of particular interest is the observation of neutron particle-hole excitations ($\nu g_{9/2}^{-1} d_{5/2}$) that become important, in addition to pure proton excitations, above 4 MeV in the neighboring ^{86}Kr [4] and ^{89}Y [5,6], from breaking of the closed neutron core. The same neutron core excitations come into play at around 5 MeV excitation in heavier $N = 50$ nuclei, such as ^{93}Tc, ^{94}Ru, and ^{95}Rh [8,9]. It is, therefore, interesting to look for the same excitations in the $N = 50$ ^{87}Rb and ^{85}Br isotones.

The ^{85}Br$_{50}$ isotone has three protons less than ^{88}Sr. The available spectroscopic information for this isotone, being more neutron rich than ^{87}Rb, is even more limited. The known information on ^{85}Br is summarized in Ref. [3]. The ground and first excited states were identified as the $1p_{3/2}$ and $0f_{5/2}$ proton-quasihole states (relative to the ^{86}Kr core) with spins $3/2^-$ and $5/2^-$, respectively. Some additional low-spin states are also known.

The limited information on high-spin states for ^{85}Br and ^{87}Rb is mainly because of the difficulty to study these isotopes as evaporation residues in heavy-ion fusion reactions. Because of their proximity to the line of stability, these nuclei cannot be populated with stable beam-target combinations in such a reaction. ^{87}Rb has been studied via α-induced reactions [1], which bring a limited amount of angular momentum in the evaporation residue. An alternative way to study these neutron-rich nuclei is the prompt γ-ray spectroscopy of fission fragments following fusion-evaporation reactions of much heavier nuclei. Such methods have been successfully used to obtain information on high-spin states of nuclei near the line of stability [10]. Because of their proximity to the line of stability, ^{85}Br and ^{87}Rb are expected to be populated as fission fragments in such reactions. In the present work new states in ^{87}Rb, built above the the $9/2^+$ isomer, and excited states in ^{85}Br, up to 5 MeV in energy, have been identified by prompt γ-ray spectroscopy of fragments following the fission in heavy-ion-induced reactions.

Preliminary results from the present work for ^{87}Rb were previously reported in Ref. [11]. While this manuscript was in preparation concurrent results on ^{85}Br and ^{87}Rb were published independently in Ref. [12]. The two isotopes were studied in Ref. [12] as products of deep-inelastic processes in heavy-ion multinucleon transfer reactions. The study of these isotopes as fission fragments in the present work makes the two studies complementary to each other. A detailed comparison between the results in Ref. [12] and the present work is included in Sec. III C.

II. EXPERIMENTS

The 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory and the Gammasphere array were used to populate compound nuclei and for subsequent γ-ray spectroscopy. In the first experiment Gammasphere was comprised of 92 Compton-suppressed large volume HPGe detectors, while in the second and third experiments the number of Ge detectors was 100.

In the first experiment a ^{197}Pb compound nucleus (CN) was formed in the ^{24}Mg + ^{173}Yb reaction at 134.5 MeV. The target consisted of 1 mg/cm^2 isotopically enriched ^{173}Yb, evaporated on a 7 mg/cm^2 gold backing (reactions of the beam in the backing produce a ^{221}Pa CN). In the second experiment a ^{199}Tl CN was formed in the ^{23}Na + ^{176}Yb reaction at a beam energy of 129 MeV. The target consisted of approximately 1 mg/cm^2 isotopically enriched ^{176}Yb on a 10 mg/cm^2 Au backing (reactions of the beam in the backing produce a ^{220}Th CN). In the third experiment the ^{226}Th CN was populated in the ^{18}O + ^{208}Pb reaction at 91 MeV and the target was 45 mg/cm^2 in areal density.

About 2.3×10^9 triples, 10^{10} and 2.5×10^9 quadruples were collected in the first, second and third experiments, respectively. Symmetrized, three-dimensional cubes were constructed in all cases to investigate the coincidence relationships between the γ rays.

III. EXPERIMENTAL RESULTS

A. Levels and transitions in ^{87}Rb

The existing information [2] on the structure of ^{87}Rb has been obtained from decay measurements [13,14], Coulomb excitation [15], particle transfer reactions [16–19], neutron, proton and α-particle scattering [1,20,21], and, more recently, in a nuclear resonance fluorescence experiment [22]. The present work is a γ ray spectroscopic study of ^{87}Rb produced as a fission fragment in fusion-evaporation reactions of heavy nuclei.

The level scheme of ^{87}Rb deduced in the present work is shown in Fig. 1. The quality of the data obtained in our experiments can be seen in the gated spectra in Fig. 2. Most of the transitions assigned here to ^{87}Rb are present in the spectrum in Fig. 2(b). Transitions of complementary fragments $^{104-106}$Ru [23] in the ^{199}Tl(CN) experiment [see Fig. 2(b)] are in coincidence in our data with transitions assigned to ^{87}Rb, a fact that further supports the assignments in the present work. In the ^{197}Pb(CN) experiment the transitions assigned to ^{87}Rb are seen mostly in coincidence with transitions belonging to ^{126,128}Xe—the complementary fragment with respect to the ^{221}Pa compound nucleus that is formed from fusion reactions of the beam with the gold backing, whereas transitions from the complementary [with respect to ^{197}Pb(CN)] Rh fragments

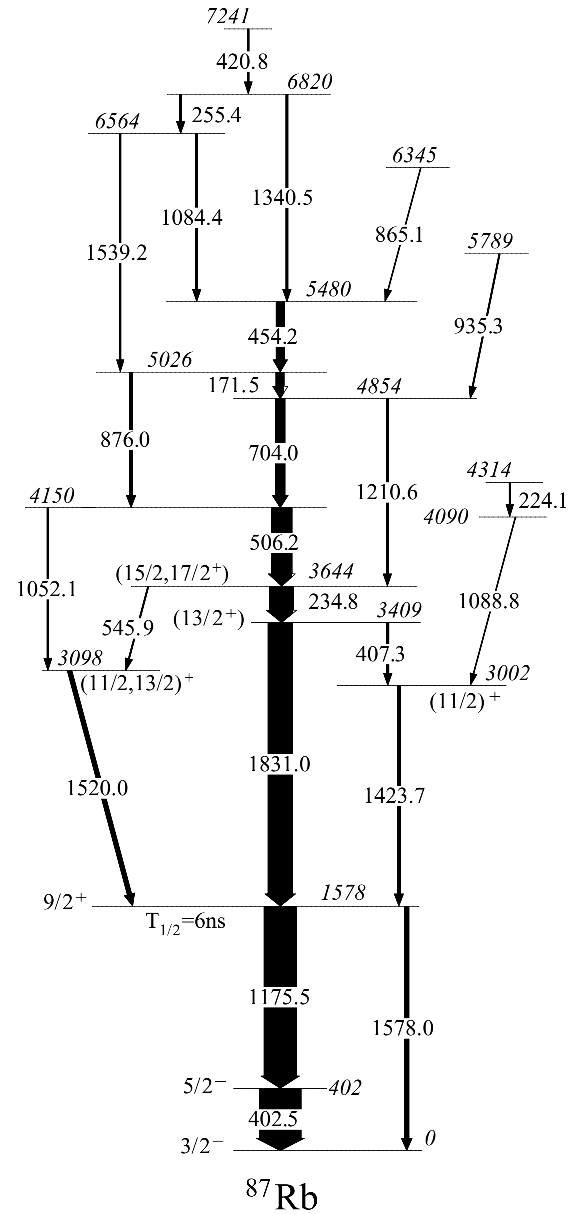

FIG. 1. Level scheme assigned to ^{87}Rb in the present work. Transition and excitation energies are given in keV. The widths of the arrows are representative of the relative intensity of the transitions.

(mostly ^{105}Rh) are weaker. The transitions in Fig. 1 and their intensities (relative to the intensity of the 402.5-keV transition), as obtained from the ^{199}Tl(CN) experiment, are listed in Table I. The relative intensities of the three lowest transitions (402.5-, 1175.5-, and 1578.0-keV transitions) were obtained from a double gate on known transitions of the ^{106}Ru complementary fragment [24].

For the previously known [1,2] $9/2^+$ isomer at 1577.9(3)-keV excitation energy an $l = 4$ value was established [2] in (^{3}He,*d*) [18] and (d,^{3}He) [19] reactions. A total of 22 new transitions have been observed above the isomer, extending the previously known level scheme up to ~7.2 MeV excitation energy. The short half-life (6 ns [1]) of this isomer

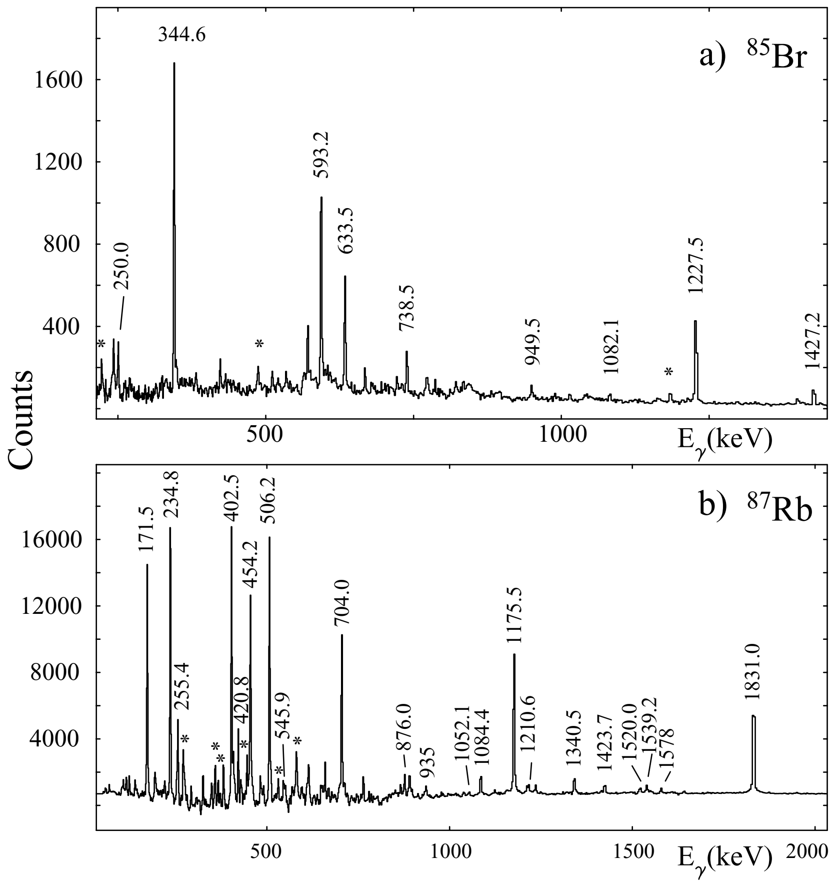

FIG. 2. Spectra of transitions assigned to ^{85}Br and ^{87}Rb in the present work. The energies of the transitions are in keV. (a) ^{85}Br spectrum, from the ^{226}Th(CN) experiment, double-gated on the 382.2- and 1160.6-keV transitions. Transitions associated with the complementary ^{137}Cs isotope [23] are indicated by asterisks. (b) ^{87}Rb spectrum, from the ^{199}Tl(CN) experiment. Sum of all possible combinations of double gates of the 171.5-, 234.8-, 402.5-, 506.2-, and 704.0-keV transitions. Transitions associated with the complementary Ru isotopes [24] are indicated by asterisks. Unlabelled peaks in both spectra are most likely contaminants.

together with the backed targets used in both experiments permitted the observation and confirmation of the 402.5- and 1175.5-keV transitions that deexcite this isomer toward the ground state. Moreover, a weak 1578.0-keV transition seen in coincidence with all the transitions above the $9/2^+$ isomer implies the presence of a previously unknown $E3$ transition between the isomer and the ground state. In the literature an off-yrast 1578.05(5)-keV state has been reported [2] with an assignment of $1/2^-$ or $3/2^-$ that populates the $5/2^-$ and ground states via the 1175.40(8)- and 1578.03(14)-keV transitions,

TABLE I. Energies and intensities of γ-ray transitions assigned to ^{85}Br and ^{87}Rb in the present work.

Energy[a] (keV)	Intensity (%)	Energy[a] (keV)	Intensity (%)	Energy[a] (keV)	Intensity (%)	Energy[a] (keV)	Intensity (%)
				^{87}Rb			
171.5	22(6)	224.1	<2	234.8	55(8)	255.4	5(2)
402.5	≡100	407.3	5(1)	420.8	5(2)	454.2	20(3)
506.2	48(5)	545.9	3(1)	704.0	22(6)	865.1	2.5(5)
876.0	7(2)	935.3	2.5(8)	1052.1	4(1)	1084.4	6(2)
1088.8	2.2(7)	1175.5	77(9)	1210.6	5(2)	1340.5	5(2)
1423.7	8(2)	1520.0	11(3)	1539.2	3(1)	1578.0	11(3)
1831.0	57(9)						
				^{85}Br			
217.3	8(2)	229.0	7(2)	250.0	24(5)	344.6	≡100
382.2	31(6)	432.5	46(8)	434.6	17(4)	467.3	3(1)
584.0	14(4)	593.2	54(8)	633.5	24(4)	702.0	<3
738.5	25(4)	864.5	12(3)	949.5	5(2)	972.4	8(3)
992.8	5(2)	1018.8	12(3)	1082.1	19(3)	1132.1	15(3)
1160.6	55(7)	1227.5	75(9)	1257.0	8(2)	1419.3	5(2)
1427.2	49(6)	1514.8	<3	1562.3	42(7)	1790.7	4(1)
1826.2	20(3)						

[a]The uncertainties on the γ-ray energies vary from 0.2 to 0.5 keV for the strong transitions and from 0.6 to 1 keV for the weakest ones.

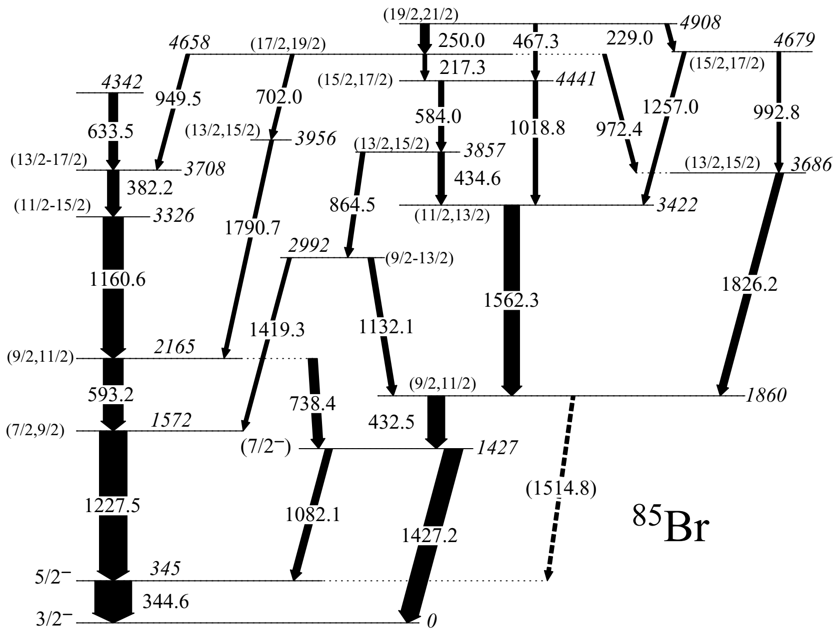

FIG. 3. Level scheme assigned to ^{85}Br in the present work. Transition and excitation energies are given in keV. The widths of the arrows are representative of the relative intensity of the transitions.

respectively. For this level, an $l = 1$ value was reported [2] from a $(d, ^3\mathrm{He})$ [16] reaction. Experimentally the resolution for the excitation energy of the levels observed in the present work cannot distinguish between a 1578.05- and a 1577.9-keV state, and the branching ratios out of both states seem equal within errors. However, it is highly unlikely that such an off-yrast state (1578.05-keV, $1/2^-,3/2^-$) would be populated in the fission of the compound nuclei in this experiment. Moreover, the sequence of transitions above the 1578-keV state observed in the present work strongly favors a $9/2^+$ assignment for this state (see discussion below).

The levels at 3002 and 3098 keV were previously established in a (p, p') reaction [21] to be of positive parity. In the present work transitions between these levels and the $9/2^+$ isomer have been observed. Moreover, for these two levels, an $l = 5$ value was reported [21], in excellent agreement with the spin assignments proposed in the present work. The 3409-, 3644-, and 4150-keV levels reported here have similar (within 2–3 keV) excitation energies to the 3411,- 3647-, and 4153-keV levels, respectively, observed in Ref. [21]. For the 4153-keV level an $l = 2$ value was reported, which makes it highly unlikely to be the same level as the 4150-keV level observed in the present work expected to be a high-spin $(I \geqslant 13/2)$ state. For the 3411- and 3647-keV levels no l value was obtained in Ref. [21]. The 3411-keV level could be the same state as the 3409-keV level reported here. The 3644-keV level would require an $l = 7$ excitation in (p, p') to correspond to the 3647-keV state in the present work.

Spin and parity assignments of all levels of ^{87}Rb reported in this work are difficult to deduce experimentally because of the lack of directional correlation information for the fission products. However, based on comparison with experimental and theoretical results on the first excited states in ^{85}Kr [3,4] and ^{89}Y [5–7] and with shell-model calculations [25], spin and parity assignments for four levels above the isomer are suggested (see discussion below).

While this manuscript was in preparation concurrent results on ^{87}Rb were published independently in Ref. [12]. Generally, there is excellent agreement between the two studies of ^{87}Rb. The discussion below includes a detailed comparison of the two studies.

B. Levels and transitions in ^{85}Br

The existing information [3] on the structure of ^{85}Br has been obtained in β-decay measurements [26] and single-proton pickup reactions [27,28].

^{85}Br was weakly populated in the ^{197}Pb(CN) and ^{199}Tl(CN) experiments. However, it was populated more strongly in the ^{226}Th(CN) experiment. Four previously known transitions of ^{85}Br [3] (344.6-, 432.5-, 1082.1-, and 1427.2-keV) were observed in coincidence with known lines of ^{137}Cs [23], which is the complementary fragment to ^{85}Br in the four-neutron fission channel of ^{226}Th. Several new transitions were observed in coincidence with the known lines of ^{137}Cs and in coincidence with the four previously known transitions of ^{85}Br. Some of the transitions assigned to ^{85}Br are present in the spectrum in Fig. 2(a). The level scheme of ^{85}Br deduced in the present work is shown in Fig. 3. The intensities of the transitions in Fig. 3 (relative to the intensity of the 344.6-keV transition) are summarized in Table I. The relative intensities of the lowest 344.6- and 1427.2-keV transitions were obtained from a double gate on known transitions of the ^{137}Cs complementary fragment [23].

As in the case of ^{87}Rb, spin and parity assignments of all levels of ^{85}Br reported in this work are difficult to support experimentally. However, based on comparison with the results of shell-model calculations [25] and with the systematics of the heavier $N = 50$ odd-mass isotones, tentative assignments for the levels in Fig. 3 can be made. The 1427- and 1860-keV levels were observed in the β decay of ^{85}Se [26], but no spin-parity assignments were made. In the latest evaluation for ^{85}Br [3], three possible spins ($1/2^-$, 3/2, and 5/2) are suggested for the 1427-keV level, whereas this state was assumed to have a ($7/2^-$) assignment in Ref. [25], where it was assumed to be one of the two $7/2^-$ states (at 1239- and 1886-keV excitation energies) predicted by the calculations. The $7/2^-$ assignment has been adopted here as more probable for the 1427-keV state. The calculations [25] predict a $9/2^-$ state at 1299-keV energies and a $9/2^+$ state at 2020-keV excitation energies. The experimentally observed 1572-, 1860-, and 2165-keV states are all candidates for these two states, with the latter two lying close to the 2020-keV excitation energy predicted by the calculation. In the present work lifetimes can not be determined for the levels observed. However, the intensity observed to feed the 1860-keV level (sum of intensities of the 1132.1-, 1562.3-, and 1826.2-keV transitions in Table I) is significantly larger than the intensity observed for the transitions (432.5- and 1514.8-keV transitions) that decay out of this level, indicating that this state could be a possible short-lived isomer. Hence, the 1860-keV level is considered here as the best candidate for the $9/2^+$ isomer, although this assignment cannot be excluded for the 2165-keV state. The 1572-keV state lies too low in excitation energy to be the $9/2^+$ state (see systematics of the $9/2^+$ states in the discussion below); a $9/2^-$ assignment is more probable. There are no predictions reported for states with higher spins than 9/2 [25]. At higher excitation energies, a tentative assignment to the spin of some of the levels can be made, as seen in Fig. 3, based on the assumption that the spins of the levels increase with increasing excitation energy.

C. Comparison with concurrent work from Ref. [12]

While this manuscript was in preparation, concurrent results on ^{85}Br and ^{87}Rb were published independently in Ref. [12]. The present work confirms independently the assignment of most of the transitions of Ref. [12] to ^{85}Br and ^{87}Rb. In this section we perform a comparison between the present work and the results of Ref. [12], discussing in detail significant differences.

There is excellent agreement between the ^{87}Rb level scheme proposed in the present work and that in Ref. [12]. Additional transitions are observed in the present study, whereas the spin-parity assignments in Ref. [12] are more robust, because they are supported by angular distribution ratios from oriented states. The assignment of $17/2^{(+)}$ to the 4151-keV level of ^{87}Rb in Ref. [12] suggests a $13/2^{(+)}$ assignment for the 3098-keV level observed in the present work. The 3098-keV level may have been weakly populated in Ref. [12] because two peaks at energies $\sim$1050 keV and $\sim$1520 keV (the 3098-keV level is feeded and depopulated by a 1052- and a 1520-keV transitions, respectively, in Fig. 1) are present in the spectrum in the lower part of Fig. 1 in Ref. [12].

The proposed level scheme of ^{85}Br in the present work is much more extensive than the one reported in Ref. [12]. However, there are differences in the proposed sequence of the transitions common in both studies and the 296.9-keV transition assigned to ^{85}Br in Ref. [12] is not observed in the present data. No trace of the weak 296.9-keV transition was observed in the double gates in our data. A 864.5-keV transition feeds a cascade to the 1572-keV level, but it was placed at higher excitations (above the 1419.3-keV transition). Moreover, the ordering of the 593.2- and 1160.6-keV transitions has been reversed in Fig. 3 compared to the ^{85}Br level scheme in Ref. [12]. To support the sequence of transitions assigned to ^{85}Br in Fig. 3, two additional spectra are shown in Fig. 4. In these spectra, double gates are placed on transitions from the two different decay paths of the 2165-keV level: the strong path, in Fig. 4(a), involves the 593.2- and 1227.5-keV transitions, whereas the weak path, resulting in fewer counts in the spectrum in Fig. 4(b), involves the 738.5- and 1427.2-keV transitions. The three transitions feeding in cascade the 2165-kev level in Fig. 3 are clearly observed in both spectra with similar intensity ratios between them. Moreover, in the lower spectrum, the 593.2- and 1227.5-keV transitions are not present, supporting the placement of both transitions below the 2165-keV level in Fig. 3. The weak 949.5-keV transition that was placed above the 3708-keV level in Fig. 3 can be clearly observed only in the double gate on the strong path, whereas it lies below detection limits in the weak-path gate. A peak of energy at $\sim$950 keV is present in the spectrum in the upper part of Fig. 2 in Ref. [12], supporting the assignment of the 949.5-keV transition to ^{85}Br.

The experimental results in Ref. [12] suggest that the 1227.5-keV transition is of quadrupole character and the 593.2-keV transitions is dipole in nature, whereas the 432.5- and 1427.2-keV transitions were not observed in Ref. [12]. That could be an indication that the 1572-keV level is a $9/2^-$ state, and the 2165-keV level is a 11/2 state, leaving again the 1860-keV level as the best candidate for the $9/2^+$ isomer. However, this scenario remains still tentative, until at least the multipolarities of the 432.5- and 1427.2-keV transitions are determined or lifetime measurements are performed in this nucleus. Hence, even with the additional experimental information provided in Ref. [12] on the multipolarities of the strong transitions assigned to ^{85}Br, both levels (1860 and 2165 keV) remain possible candidates for the $9/2^+$ isomer.

IV. DISCUSSION

Although both nuclei have a closed $N = 50$ shell and differ by only two protons, the differences in the structures of ^{87}Rb and ^{85}Br, displayed in Figs. 1 and 3, respectively, start at very low excitation energies and spins. The structure in ^{85}Br with two extra proton holes in the (fp) shell is “richer,” because there are more ways to generate states by coupling the protons in these orbitals. On the other hand, the structure of ^{87}Rb appears more similar to those in the neighboring odd-mass ^{85}Kr [4] and ^{89}Y [5,6] isotopes, as discussed below. The proposed configurations discussed below are summarized in Table II.

The systematics of the $9/2^+$ states, which originate from the odd proton occupying the $g_{9/2}$ orbital, in the odd-mass $N = 48$ and $N = 50$ Br, Rb, Y, and Nb isotopes is shown in Fig. 5. In Nb isotopes the $g_{9/2}$ orbital forms the ground state, whereas in the lighter isotopes the location of the $9/2^+$ state shifts gradually to higher excitations as the $g_{9/2}$ orbital moves away from the Fermi surface. For the wave function of the $9/2^+$ state in ^{87}Rb, an 85% component from the $(g_{9/2} \otimes 0^+)$ coupling and a 14% component from the $(g_{9/2} \otimes 2^+)$ coupling was estimated [1] using the particle-anharmonic core coupling model and the

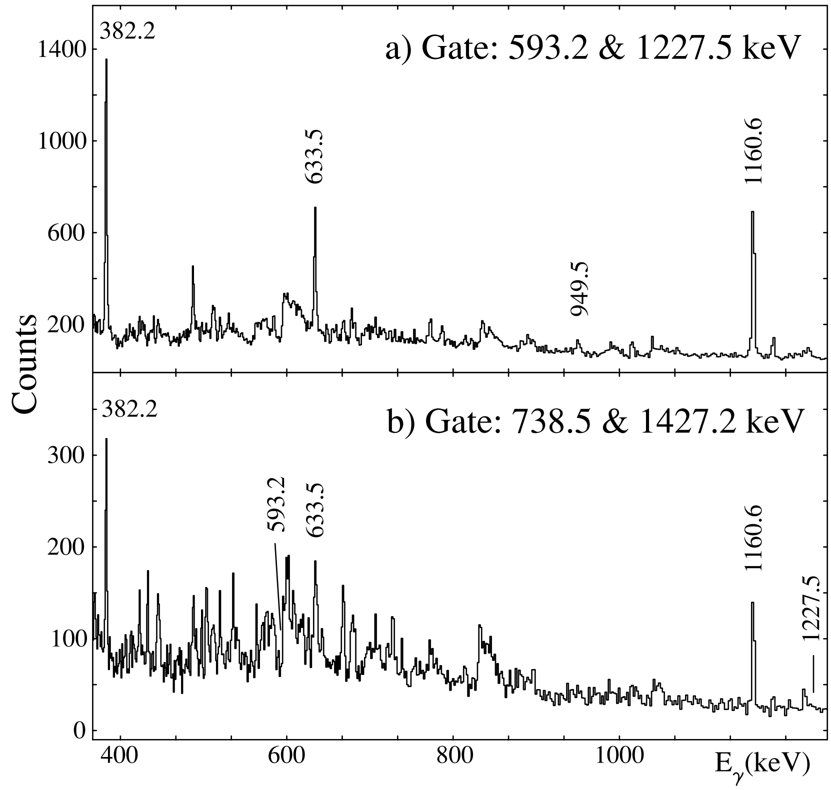

FIG. 4. Double-gated spectra on ^{85}Br transitions belonging to the two different paths of deexcitation out of the 2165-keV level in Fig. 3. The data are from the ^{226}Th(CN) experiment and the energies of the transitions are in keV. (a) Double gate between the 593.2- and 1227.5-keV transitions. (b) Double gate between the 738.5- and 1427.2-keV transitions. In both spectra the transitions above the 2165-keV level in Fig. 3 are indicated. The statistics are much better in (a), because the 593.2- and 1227.5-keV transitions are much stronger than the 738.5- and 1427.2-keV transitions. The weak 949.5-keV transition in Fig. 3 is statistically significant only in (a). The absence of the 593.2- and 1227.5-keV transitions in (b) is indicated.

known levels of the adjacent even-even Kr and Sr core nuclei. The 3^- states in the cores are at a much higher excitation than the $9/2^+$ isomer of ^{87}Rb (~3.1 MeV in ^{86}Kr and ~2.7 MeV in ^{88}Sr). If there is an admixture of the $p_{3/2} \otimes 3^-$ configuration in the $9/2^+_1$ state this is probably very small. However, because a weak $E3$ transition is observed from the $9/2^+$ isomer to the ground state, such an admixture is probable. For ^{85}Br, it is not yet clear whether the 1860- or the 2165-keV level is the $\pi g_{9/2}$ state. From the systematics in Fig. 5 an excitation energy of ~2 MeV can be extrapolated for the $9/2^+$ isomer; hence, both 1860- and 2165-keV levels fit the systematics and are included in Fig. 5.

TABLE II. Main configurations of high-spin states in ^{85}Br and ^{87}Rb relative to the ^{86}Kr core.

E_x (keV)	I^π	Suggested configuration(s)
	^{87}Rb	
1578	$\frac{9}{2}^+$	$\pi g_{9/2}$
3002	$(\frac{11}{2})^+$	$\pi g_{9/2} \otimes 2^+$
3409	$(\frac{13}{2}^+)$	$\pi g_{9/2} \otimes 2^+$
3644	$(\frac{15}{2}, \frac{17}{2}^+)$	$\pi g_{9/2} \otimes 4^+$
4000–6500		$\pi g_{9/2} \otimes [5^-, 6^-, 7^-$ and/or $\nu g_{9/2}^{-1} d_{5/2}]$
6500–7241		possible $[\pi f_{5/2}^{-1} g_{9/2}^2] \otimes [\nu g_{9/2}^{-1} d_{5/2}]$
	^{85}Br	
1860 or 2165	$\frac{9}{2}^+$	$\pi g_{9/2}^{-1}$

The sequence of first excited states above the $9/2^+$ isomer in ^{87}Rb resembles those in the neighboring odd-mass ^{85}Kr [4] and ^{89}Y [5,6] nuclei (see Figs. 6 and 7). Indeed, the $11/2^+$ and $13/2^+$ states, formed by the coupling of a nucleon to the lowest 2^+ states of the ^{86}Kr and ^{88}Sr cores, in both ^{85}Kr and ^{89}Y resemble the sequence observed in the present work for

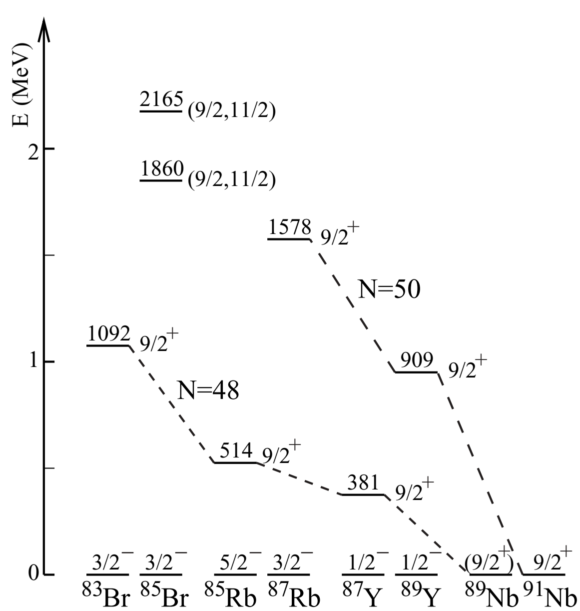

FIG. 5. Systematics of the $9/2^+$ states originating from the odd proton occupying the $g_{9/2}$ orbital in the odd-mass $N = 48$ and $N = 50$ Br [21,present work], Rb [2,24], Y [7,24], and Nb [24] isotopes.

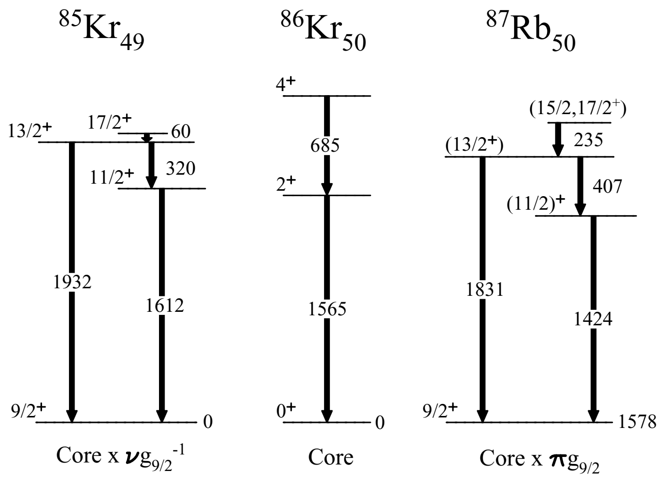

FIG. 6. Partial level schemes of $^{85}_{36}$Kr$_{49}$ [4], $^{86}_{36}$Kr$_{50}$ [4] and $^{87}_{37}$Rb$_{50}$ (present work). Transition and excitation energies are given in keV.

^{87}Rb, suggesting $11/2^+$ and $13/2^+$ assignments for the 3002- and 3409-keV states, respectively. The coupling of the neutron $g_{9/2}$ hole to the lowest 4^+ states of the cores forms $15/2^+$ and $17/2^+$ states. The ordering of these states in ^{85}Kr and ^{89}Y is not the same, with the $17/2^+$ state in ^{85}Kr located very close to the $13/2^+$ state (see Fig. 6), whereas in ^{89}Y it is located much higher in excitation and above the $15/2^+$ state (see Fig. 7). A candidate for the $17/2^+$ state in ^{87}Rb is the 3644-keV level. However, from the sequence of transitions this level can also have a spin of 15/2; hence, the one-to-one comparison used previously for the $11/2^+$ and $13/2^+$ states cannot be applied. The 2415-keV level in Fig. 7 was taken from the literature [2] and was not observed in the present work, probably because it is an off-yrast state. It may correspond to the $7/2^+$ states observed in the heavier $N = 50$ Y, Nb, and Tc isotopes (see Fig. 7) as reported in Ref. [25]. In ^{91}Nb and ^{93}Tc the $11/2^+$ state is higher in excitation energy than the $13/2^+$ state. Hence, the decay pattern of the $13/2^+$ states, observed in the lighter ^{89}Y, ^{87}Rb, and ^{85}Kr, is not observed in ^{91}Nb and ^{93}Tc.

Above the 3644-keV level of ^{87}Rb the sequence of transitions is rather complicated and not directly comparable to the corresponding parts of the level schemes in ^{85}Kr and ^{89}Y. For the origin of the states in this region three possibilities exist: (i) they are of negative parity originating from the coupling of the $g_{9/2}$ proton to the 5^-, 6^-, and 7^- states of the core, as observed in ^{85}Kr; (ii) they are of positive parity and originate from coupling of the $g_{9/2}$ proton to the particle-hole $\nu g_{9/2}^{-1} d_{5/2}$ configuration, as observed in ^{89}Y; (iii) they are a mixture of both positive- or negative-parity states originating from the previous configurations. Because for $N = 50$ nuclei the required energy for exciting one neutron out of the closed shell is observed to be approximately 5 MeV [4,8] and in ^{85}Kr and ^{89}Y this breaking up of the core happens at 4 MeV in excitation energy, the second possibility seems more favorable for states in ^{87}Rb at excitation energies above 4 MeV. However, once the $N = 50$ shell is broken, there is an indication of a sudden and large change in the level density and in most cases the core-particle coupling picture fails to describe the excited states of the odd-mass nuclei in this mass region [22]. Hence, a calculation with a microscopic model is necessary to understand the structure of the excited states at these high excitation energies.

In Fig. 8 some of the ^{85}Br and ^{87}Rb excited states observed in the present work are compared with the results of shell-model calculations from Ref. [25]. The model space utilized in the calculations consisted of the $1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$, and

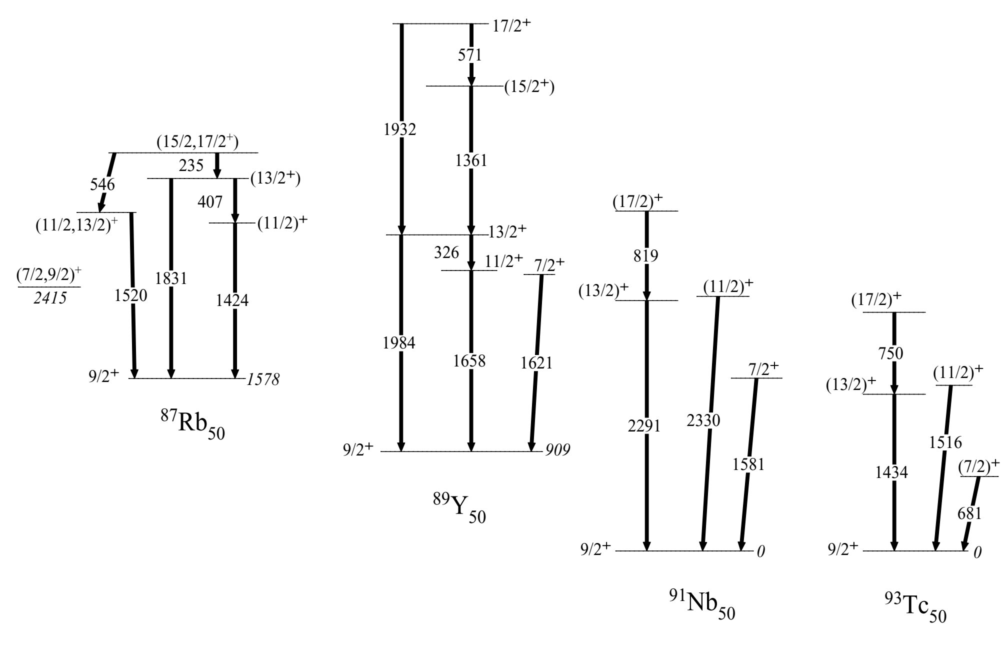

FIG. 7. Partial level schemes of the $N = 50$ odd-mass nuclei $^{87}_{37}$Rb [2,present work], $^{89}_{39}$Y [7], $^{91}_{41}$Nb [24], and $^{93}_{43}$Tc [24] showing the positive-parity states above the $9/2^+$ state. Transition and excitation energies are given in keV. The corresponding states in ^{85}Br have not been established.

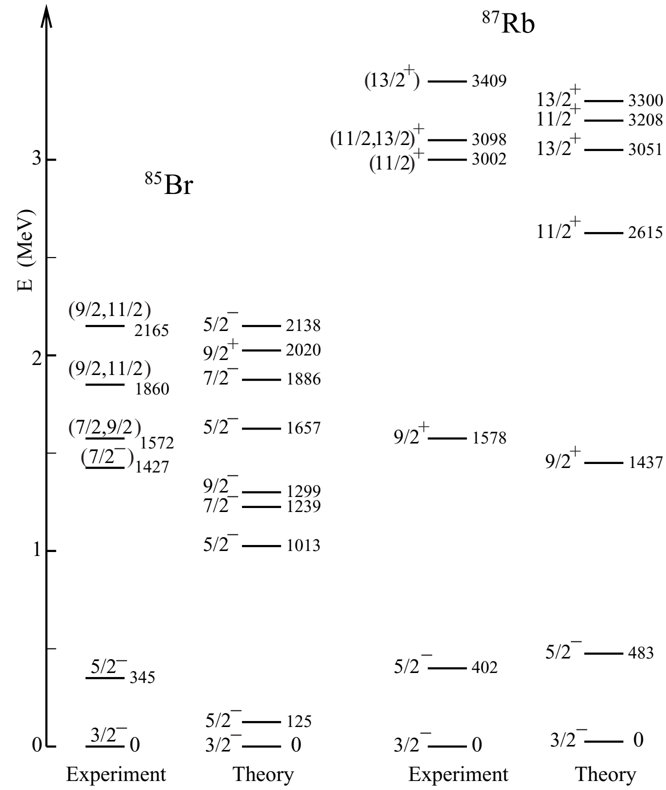

FIG. 8. Comparison of selected excited states in ^{85}Br and ^{87}Rb isotopes (present work) with the results of shell-model calculations from Ref. [25].

$0g_{9/2}$ proton orbitals. The calculation for ^{85}Br predicts the $9/2^+$ state at a 2020-keV excitation energy, which is very close to the observed 1860- and 2165-keV states. The low-spin off-yrast negative-parity states predicted in the calculation are not expected to be populated in the present experiment. The results of the calculation for ^{87}Rb are in good agreement with the observed states up to 3.5 MeV excitation energy. Two $13/2^+$ states and one $11/2^+$ state are predicted at excitation energies between 3 and 3.5 MeV, in excellent agreement with our observations. For ^{87}Rb the calculation predicts $7/2^-$ and $9/2^-$ states at excitation energies at and above ~2 MeV, respectively, much higher than the low lying $5/2^-$ state and the $3/2^-$ ground state. Not only have such excitations, far from yrast, not been observed in ^{87}Rb in the present work, but they have also not been observed in the ^{89}Y isotone [5–7].

In this mass region sequences of strong magnetic dipole transitions have been observed: above excitation energies of 7 MeV in ^{89}Y a sequence of three fast $M1$ transitions with $E_\gamma \sim 420$ keV dominates the level scheme [6]. This sequence has been suggested to be the excitation of one additional proton from the $f_{5/2}$ to the $g_{9/2}$ orbital, requiring negative parity assignments for these states. The 420.8-keV transition observed at excitation energies of ~7 MeV in ^{87}Rb may suggest a similar sequence. In the lighter odd-mass Rb isotopes, a rapid onset (near $N = 42$) and decline (near $N = 48$) of magnetic rotation has been suggested [29] with magnetic dipole rotational bands built on the $\pi(g_{9/2}) \otimes \nu[g_{9/2}(fp)^1]$ configuration and band-head excitation energies around 2–3 MeV. Because of the $N = 50$ closed shell in ^{87}Rb the phenomenon of magnetic rotation, if there, should start at higher excitation energies, after the breaking of the neutron shell. Further investigation of the high-spin states in ^{87}Rb is needed to determine whether the 420.8-keV transition is similar to the structure seen in ^{89}Y.

The results of the shell-model calculations in Ref. [12] include one 7/2 state of negative parity and two 9/2 states, of positive and negative parity, below excitation energies of 2 MeV. No candidates for the negative parity 7/2 and 9/2 states predicted by the calculations [12,25] were observed in Ref. [12], whereas the more extensive level scheme proposed in the present work includes such candidates.

In Ref. [12] the predictions of the shell-model calculation with no particle-hole excitations across the $N = 50$ core (SM1) are in much better agreement with the experimental results in ^{87}Rb up to excitation energies of ~4 MeV, whereas inclusion of excitations across the $N = 50$ core (SM2 calculation) seem necessary above this excitation energy. One would expect a similar situation for ^{85}Br. Indeed, in Fig. 9 of Ref. [12], the SM1 calculation predicts an excitation energy for the $9/2^+$ isomer of ~2 MeV, in agreement with the result of the calculations in Ref. [25] and in agreement with the candidates (1860- and 2165-keV levels) proposed for this state in the present work. Assuming that the 1860-keV level is the $9/2^+$ state, the 3422-, 3857-, and 4441-keV levels could be the $13/2^+$, $15/2^+$, and $17/2^+$ states, respectively, in excellent agreement with the SM1 calculation in Ref. [12], which predicts these levels at ~3.3, ~3.8, and ~4.5 MeV in excitation, respectively.

V. SUMMARY

In summary, high-spin states of ^{85}Br and ^{87}Rb have been observed following the fission of three hot compound nuclei formed in three different fusion-evaporation reactions. The assignment of the transitions is based on coincidences with previously known lower lying transitions, as well as with known transitions in the complementary fragments. Several states above the $9/2^+$ isomer in ^{87}Rb were established. Based on comparison to similar states in the neighboring ^{85}Kr and ^{89}Y isotopes, the first excited states above the $9/2^+$ isomer in ^{87}Rb can be understood as originating from pure proton configurations involving the coupling of the odd $g_{9/2}$ proton to the first excited states in the core. At higher excitations (above ~4 MeV) the $\nu g_{9/2}^{-1} d_{5/2}$ configuration probably comes into play, after breaking of the closed neutron shell. An additional excitation of a proton from the $f_{5/2}$ orbital to the $g_{9/2}$ orbital seems possible at even higher excitations (above ~7 MeV). Several new states were established in ^{85}Br and the previously known level scheme was extended to excitation energies of up to ~5 MeV. The states at excitation energies of 1860 and 2165 keV are both candidates for the $9/2^+$ state originating from the odd proton occupying the $g_{9/2}$ orbital and predicted by a previously published shell-model calculation [25] at excitation energy of 2020 keV. Generally, the results of the calculations are in good agreement with the states observed in the present work and helped in guiding tentative spin-parity assignments. Significant differences on the level scheme of

^{85}Br between the present results and the concurrent results published independently in Ref. [12] were discussed in detail. More experimental information, especially firm spin and parity assignments of the high-spin states reported here, as well as lifetime measurements, is needed to confirm the interpretations suggested in the present work.

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