Medium-spin states of the neutron-rich ^{87,89}Br isotopes: configurations and shapes

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Medium-spin states of the neutron-rich ^{87,89}Br isotopes: configurations and shapes

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Abstract. Medium-spin excited states of the neutron-rich ^{87}Br and ^{89}Br nuclei were observed and studied for the first time. They were populated in fission of ^{235}U induced by the cold-neutron beam of the PF1B facility of the Institut Laue-Langevin, Grenoble. The measurement of γ radiation following fission has been performed using the EXILL array of Ge detectors. The observed level schemes were compared with results of large valence space shell model calculations. Both medium-spin level schemes consist of band-like structures, which can be understood as bands built on the $\pi f_{5/2}$, $\pi p_{3/2}$ and $\pi g_{9/2}$ configurations. Both nuclei have $5/2^-$ ground state spin-parity contrary to the odd-mass Br isotopes containing fewer neutrons, which have $3/2^-$ ground state spin-parity. On the basis of the properties of the $\pi g_{9/2}$ decoupled bands the deformations of the ^{87}Br and ^{89}Br fit to the systematics of nuclei in the region. ^{87}Br is close to the vibrational limit, while ^{89}Br is more rotational.

1. Introduction

Study of exotic, neutron-rich nuclei is in the forefront of the contemporary nuclear-structure research. Such investigations resulted in the observation of interesting new phenomena, like quenching of the known shell closures and formation of new ones. Thus, it is especially interesting to study neutron-rich nuclei near the shell closures. Such an interesting region is that of the nuclei near the doubly magic exotic ^{78}Ni. Besides the strength of the shell closures, the shell-model single-particle energies and residual interactions between the nucleons are also changing in these regions. Excited states of odd-mass nuclei provide important information on the single-particle energies. However, no medium-spin excited states are known for the odd-mass odd-proton nuclei with neutron number larger than 50 and proton number less than 37 near ^{78}Ni. In general, information on excited medium-spin states in this region is very scarce, due to the difficulties in finding nuclear reactions in which these states could be populated with large statistics.

Cold-neutron-induced fission of ^{235}U populates the nuclei ^{87,88,89}Br with relatively high yields, and using this reaction we can get closer to the doubly magic ^{78}Ni in studying the medium-spin states. A few low-spin excited states of ^{87}Br are known from the β decay of ^{87}Se produced by thermal neutron induced fission of ^{235}U [1]. Only tentative spins and parities could be assigned to these states on the basis of log *ft* values because the level scheme is incomplete. The ground-state spin-parity has been tentatively assigned as $5/2^-$ from β decay of this ground state to the excited levels of ^{87}Kr [2]. This assignment contradicts the previous $3/2^-$ assignment based on systematics, and raises the possibility of a deformed shape in this nucleus [3]. This provides a particular motivation to study the deformation in ^{87}Br. No excited states are known in ^{89}Br at all, and the spin-parity of the ground state is only tentatively assigned from systematics. Thus, study of medium-spin states in these nuclei looks promising in getting valuable information on this nuclear region. Therefore, we studied the excited states of the ^{87,89}Br nuclei from the cold-neutron induced fission of ^{235}U.

2. Experimental details

The experiment was performed using the PF1B cold-neutron beam of the Institut Laue-Langevin (ILL) in Grenoble [4]. The neutron beam was shaped into a 12 mm diameter pencil beam with a thermal equivalence flux of $10^8/(\mathrm{s\ cm}^2)$. Two 0.6 mg/cm^2 thick ^{235}U targets enriched to 99.7% were used. They were sandwiched between Zr and Be backings of 15 μm and 25 μm thickness, respectively, for rapid stopping of fission fragments. This enabled an almost Doppler-shift free measurement of the emitted γ rays, which were detected by the EXILL detector array [5]. It consisted of eight Compton-suppressed EXOGAM Clover detectors [6], six Compton-suppressed GASP detectors [7] and two Clover detectors of the Lohengrin spectrometer [8]. The distance between the faces of detectors and target was about 15 cm. The data were collected using a digital acquisition system with a 100 MHz clock in a triggerless mode. Altogether 15 terabytes of data were collected over the 21 day period of the experiment. During the offline analysis triggerless events, each consisting of an energy signal and the time of its registration, were arranged into coincidence events within various time windows (from 200 to 2400 ns) and sorted into 2D and 3D histograms.

3. Excited states of ^{87}Br and ^{89}Br

Prior to the present study a few excited states were known from neutron-induced fission of ^{235}U [1]. In order to assign new transitions to ^{87}Br and to build the medium-spin level scheme of this nucleus, we analysed the 3D γ-ray histograms created by applying a 200 ns coincidence time window and built in the Radware format [9]. The strategy we used for assigning new transitions to ^{87}Br, was based on the fact that the transitions from the complementary fission fragments are in prompt coincidence with each other. In the cold-neutron-induced fission of ^{235}U in most of the cases two or three neutrons and no protons are emitted from the primary fission fragments, leading to the secondary fission fragments of ^{147}La and ^{146}La, respectively, as complementary fission fragments of ^{87}Br. Fortunately, the level schemes of these nuclei are rather well known from previous fission experiments [10, 11].

As a first step, we have set double gates on several strong transition pairs of ^{147}La and ^{146}La. Fig. 1 shows example coincidence spectra produced this way. These spectra are expected to contain three types of γ rays:

(a) γ rays belonging to the respective complementary fission fragment nucleus, (b) γ rays belonging to the ^{87}Br nucleus, and (c) γ rays belonging to other nuclei and being accidentally in coincidence with the used gate pair. The first type of γ rays are denoted by stars in the figure. The second type of γ rays are expected to appear in all the gated spectra, while those of the third type are expected to appear only in one of them. In Fig. 1 four transitions are seen to appear in all the coincidence spectra, the 619-, 663-, 762- and 876-keV transitions. Thus, these transitions are expected to belong to the nucleus ^{87}Br. Based on the coincidence relationships between these transitions and also between the transitions which have been found to be in prompt coincidence with them, we could build the preliminary level scheme, plotted in Fig. 2. This level structure does not correspond to any known level structures belonging to the populated fission fragments. Furthermore, when setting double gates on the strong transitions of this structure, we systematically see the strong transitions of the ^{146}La and ^{147}La level schemes in the spectra. Based on these facts, we preliminarily assign the obtained level scheme to ^{87}Br. In this partial level scheme the levels correspond to states populated from prompt fission. Among the transitions belonging to the plotted level scheme only the 573 keV one was previously known, all the others are newly assigned to ^{87}Br. The newly observed level scheme forms three band-like structures labelled as Band 1, Band 2 and Band 3 in Fig. 2. The bandheads of Band 1 and Band 3 are very close to each other in energy. The difference between them is only 6.1 keV. The bandhead of Band 3 is the ground state of ^{87}Br. The previously known transitions, including the 573 keV one, feed the band head of Band 1, which thus can be considered as the previously assigned ground state. Two of the bands, Band 1 and Band 3, look like strongly coupled bands, while the third one, Band 2, looks like a weakly coupled or decoupled band. This is in a good agreement with the expectations in the case of a deformed shape. In that case two strongly coupled bands, based on the $\pi f_{5/2}$ and $\pi p_{3/2}$ configurations, and one weakly coupled band, based on the $\pi g_{9/2}$ configuration, are expected to appear at low excitation energy. Information to assist in spin-parity assignment of the newly assigned levels could be inferred from the measured angular correlation relations of the subsequent transitions in the γ-decay cascades. The eight EXOGAM

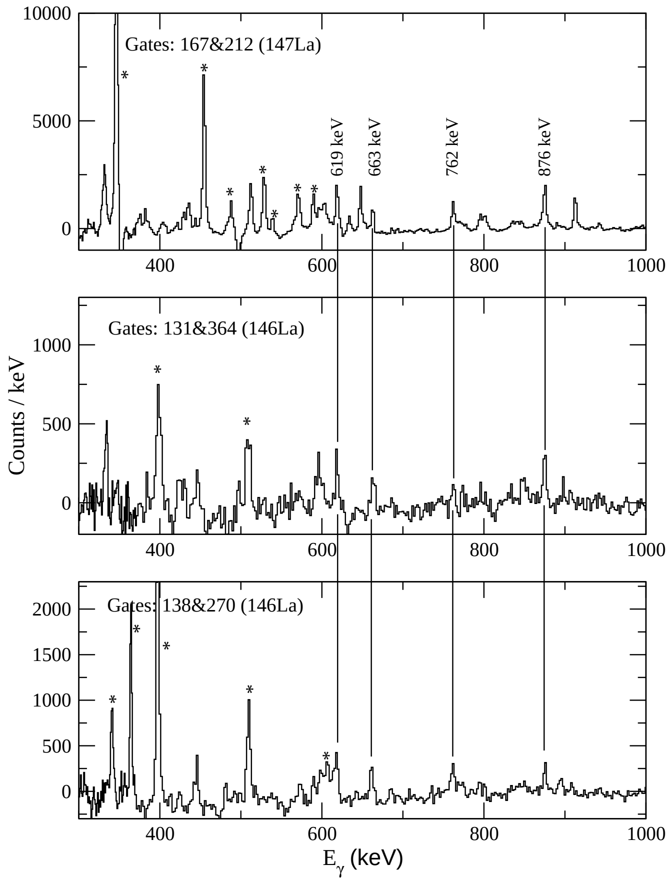

Figure 1. Coincidence spectra obtained by double gating on strong transitions of ^{146}La and ^{147}La, the complementary fission fragments of ^{87}Br. Stars denote the transitions in the respective complementary fission fragment.

clover detectors were mounted in the EXILL spectrometer in one plane perpendicular to the beam direction in an octagonal geometry.

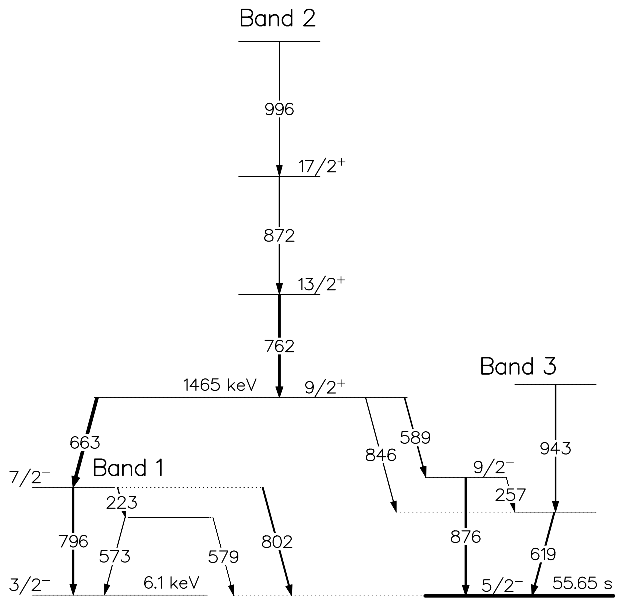

Figure 2. Preliminary partial level scheme of ^{87}Br observed in the present experiment.

The 28 detector pairs provided three different relative angles: 0°, 45° and 90° taking into account the symmetries. More details on the technique are reported in Ref. [5]. In order to derive the angular correlation relations, 3D γ-γ-angle matrices were created and analysed using the program developed in Ref. [12]. The observed angular correlations of the two lowest transitions in Band 2, i.e. the 762 keV and 872 keV transitions, are consistent with stretched quadrupole character for both of them. This indicates that Band 2 is an E2 band, probably corresponding to a weakly coupled or decoupled configuration. This assumption is confirmed by the fact that no cross-over transitions have been observed in this band. Both Band 1 and Band 3 look like ΔI=1 bands with quadrupole cross-over transitions. This assumption is also confirmed by the angular correlations observed for the 796 keV - 663 keV cascade in Band 1 and for the 876 keV - 589 keV cascade in Band 3. The observed angular correlations in the first cascade are consistent with the stretched quadrupole character of the 796 keV transition and stretched dipole character of the 663 keV transition. In Band 3, the observed angular correlations are consistent with the stretched quadrupole character for the 876 keV transition and either ΔI=0 dipole or stretched quadrupole character of the 589 keV transition. If the 589-keV transition were a stretched quadrupole then the ground-state spin would be $4\hbar$ less than that of the bandhead state of Band 2. However, in this case the 802 keV transition, feeding the ground state, would have a ΔI=3 character. This is unlikely taking into account that the 802-keV state is decaying also by quadrupole and dipole transitions. Thus, we assign a ΔI=0 dipole character to the 589-keV transition.

Similarly to ^{87}Br we could also build a preliminary level scheme of ^{89}Br, and the two level schemes were found to be very similar to each other. The levels in ^{89}Br are also grouped into three bands, which have similar characters to the ones in ^{87}Br.

4. Configurations and deformations of the observed bands

Using the derived multipole characters of the transitions together with information on the level schemes of neighbouring odd-proton nuclei and comparison with the results of shell-model calculations, we could tentatively assign spin-parity values to the observed levels. A decoupled band based on the $\pi g_{9/2}$ configuration is expected to appear at relatively low energy for both nuclei with a band-head spin-parity of $9/2^+$ from the deformed Nilsson scheme and also from the comparison with the level scheme of neighbouring odd-proton nuclei. In the case of ^{87}Br we can compare the level scheme with that of ^{89}Rb. In ^{89}Rb this bandhead is at about 1200 keV excitation energy. In ^{87}Br the bandhead energy of Band 2 is close to this. Based on

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these arguments we tentatively assign $\pi g_{9/2}$ configuration to Band 2 and $9/2^+$ spin-parity to its bandhead level. Assuming that spin values increase with increasing energy, and taking into account the observed multipole characters in Band 1 and Band 3, we can assign spin values of 3/2 to the bandhead of Band 1 and 5/2 to the bandhead of Band 3. Thus the ground-state spin of ^{87}Br is 5/2 in agreement with the value derived by Porquet et al. [2]. Considering the expected configurations and the determined bandhead spins, we can tentatively assign $\pi p_{3/2}$ and $\pi f_{5/2}$ configurations to Band 1 and Band 3, respectively. Therefore, the bandhead spin-parities are $3/2^-$ and $5/2^-$.

Similar tentative configurations and bandhead spin-parities could be derived for the bands in ^{89}Br. Thus, in both nuclei the ground state is the $5/2^-$ bandhead of the $\pi f_{5/2}$ band, while the first excited state is the $3/2^-$ bandhead of the $\pi p_{3/2}$ band. The two bandheads are close to each other, and the difference between their energies seems to increase with increasing neutron number.

In order to verify the suggested spin-parities and configurations, we compared them with preliminary results of the contemporary shell model calculations using a large valence space including 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. The model and the parameters of the calculations are the same as used in Ref. [13]. The compared experimental and calculated level energies and spin-parities, as well as single-particle configurations are plotted in Fig. 3 for both nuclei. It can be seen in the figure that the tentative experimental spin-parities and configurations are rather well reproduced by the calculations. This good agreement supports the proposed assignments. The level energies are also relatively well reproduced for the low-lying states. There are, however, larger differences between the experimental and calculated level energies at the highest-spin levels of the $\pi g_{9/2}$ bands. This might be due to a larger experimental collectivity than predicted by the calculations. If the $\pi g_{9/2}$ bands are decoupled

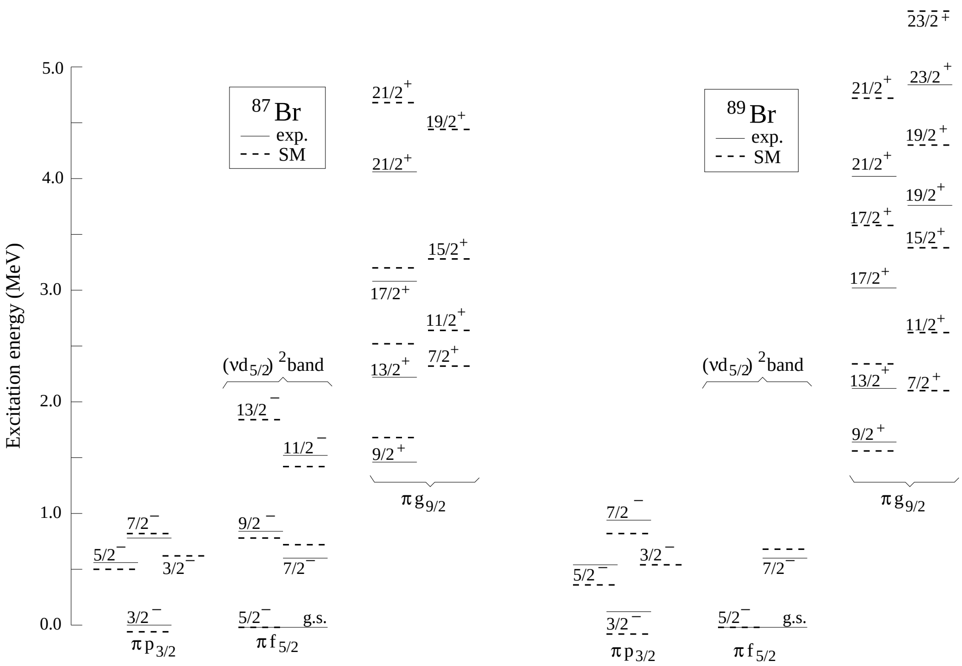

Figure 3. Comparison of the observed medium-spin level scheme of ^{87}Br and ^{89}Br with the results of large-scale shell model calculations.

bands, the energy ratios of the third and second levels relative to the bandheads play the same role as the E_{4+}/E_{2+} ratios in the even-even nuclei, i.e. they provide information about the deformation of the nucleus. These values are 2.1 and 2.5 for ^{87}Br and ^{89}Br, respectively, which are close to the E_{4+}/E_{2+} ratios of the neighbouring even-even nuclei, and indicate that ^{87}Br is close to the vibrational limit, while ^{89}Br is more rotational.

5. Conclusion

Medium-spin excited states of the neutron-rich ^{87}Br and ^{89}Br nuclei have been studied by means of in-beam γ spectroscopy of fission fragments of the ^{235}U, using the EXILL Ge detector array. The fission has been induced by the cold-neutron beam of the PF1B facility of the Institut Laue-Langevin, Grenoble. Preliminary level schemes were built for both nuclei. The observed excited states in both nuclei form three band-like structures. Angular correlation information from the experiment combined with systematics of the neighbouring odd-proton nuclei enabled tentative spin-parity assignments to the new levels and configuration assignments to the bands. They can be understood as bands built on the $\pi f_{5/2}$, $\pi p_{3/2}$ and $\pi g_{9/2}$ configurations. These assignments have been confirmed by the preliminary results of the contemporary shell model calculations using a large valence space. Both nuclei have $5/2^-$ ground state spin-parity contrary to the odd-mass Br isotopes containing fewer neutrons, which have $3/2^-$ ground state spin-parity. Properties of the $\pi g_{9/2}$ decoupled bands indicate that the deformations of the ^{87}Br and ^{89}Br fit to the systematics of nuclei in the region. The nucleus ^{87}Br is close to the vibrational limit, while ^{89}Br is more rotational.

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