Eur. Phys. J. A **30**, 541–549 (2006)
DOI 10.1140/epja/i2006-10151-4

The European Physical Journal A

High-spin excitations of $^{84}_{35}Br_{49}$ and $^{85}_{35}Br_{50}$: Mapping the proton sub-shells towards ^{78}Ni

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Received: 25 September 2006 / Revised: 24 November 2006 /
Published online: 18 December 2006 –
Communicated by D. Schwalm

Abstract. The ^{84,85}Br nuclei have been produced as fission fragments in the fusion reaction $^{18}O + ^{208}Pb$ at 85 MeV bombarding energy and studied with the Euroball IV array. The high-spin states of the odd-odd ^{84}Br nucleus have been identified for the first time, the observed structure being built on the known 6^- isomeric state. High-spin states of ^{85}Br have been observed up to 5.4 MeV excitation energy and spin $I \sim 21/2$. From angular correlation analysis, spin values have been assigned to most of the ^{85}Br excited states up to 4 MeV. None of these excited states has been found to exhibit a delayed decay having $T_{1/2} > 10$ ns. All the observed states in ^{84,85}Br can be described by various proton excitations involving at least the two sub-shells ($\pi f_{5/2}$ and $\pi p_{3/2}$) located just above the $Z = 28$ shell closure.

PACS. 21.60.Cs Shell model – 23.20.Lv γ transitions and level energies – 25.85.Ge Charged-particle-induced fission – 27.50.+e $59 \leq A \leq 89$

1 Introduction

The characterization of the $N = 50$ shell gap, particularly its evolution with a very-large neutron excess, represents currently an intense effort of the nuclear physics community (see for instance [1–7]). In this intermediate-mass region the shell model calculations suffer from a fragmentary determination of some basic inputs, *i.e.* the single-particle energies and the two-body matrix elements. For instance, the prediction of the evolution of the $N = 50$ gap at very large neutron excess needs the knowledge of the residual interaction energies for various $\pi\nu$ configurations, issued from the fp protons ($28 < Z < 38$) and the dg neutrons ($N \sim 50$) which are mainly not known at the present time. Measurements of the level structure of some moderately neutron-rich nuclei provide data which can be compared with the results of state-of-the-art shell model calculations, leading to the determination of these crucial parameters.

More precisely, the properties of the high-spin states of many isotopes ($_{37}$Rb, $_{36}$Kr, $_{35}$Br, and $_{34}$Se) located around the $N = 50$ shell closure are expected to be dominated by few-particle excitations involving the proton and neutron sub-shells of interest. Using fusion-fission reactions, we have undertaken the study of the high-spin states of these nuclei which cannot be populated via the usual fusion-evaporation reactions because of the lack of suitable stable beam-target combinations. The analysis of the ^{84}Se excitations and the comparison with the behaviour of the heavier isotones has been already published [7], pointing out a weakening of the $N = 50$ spherical shell gap when Z is decreasing from 38 to 34. As for the ^{87}Kr nucleus, a lot of new high-spin states originating from several multi-particle configurations have been discussed by analogy with the yrast states of its $N = 50$ core [8].

In this paper we report on new results obtained in the ^{84,85}Br nuclei produced in the fusion-fission reaction $^{18}O + ^{208}Pb$ at 85 MeV bombarding energy and studied with the Euroball IV array. The high-spin states of ^{84}Br,

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identified for the first time, have been built on its known 6^- isomeric state. As for the ^{85}Br level scheme, in addition to the usual analysis of the high-fold coincidences, angular correlations have been measured to assign the spin values and the existence of isomeric states has been looked for from the Ge detector timing information. The excited states observed in ^{85,84}Br are discussed in terms of both proton and neutron excitations, involving the sub-shells located close to the Fermi levels, namely $\pi f_{5/2}$, $\pi p_{3/2}$, and $\pi g_{9/2}$ as well as $\nu g_{9/2}$ and $\nu d_{5/2}$.

2 Experimental details

2.1 Reaction, γ-ray detection and analysis

The $^{18}\mathrm{O} + {}^{208}\mathrm{Pb}$ reaction was studied at 85 MeV incident energy. The beam was provided by the Vivitron accelerator of IReS (Strasbourg). A 100 mg/cm^2 target of ^{208}Pb was used to stop the recoiling nuclei. The gamma-rays were detected with the Euroball IV array [9]. The spectrometer contained 15 Cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 Clover germanium detectors located around 90° and 30 tapered single-crystal germanium detectors located at forward angles. Each Cluster detector consists of seven closely packed large-volume Ge crystals [10] and each Clover detector consists of four smaller Ge crystals [11].

The data were recorded in an event-by-event mode with the requirement that a minimum of three unsuppressed Ge detectors fired in prompt coincidence. A set of 4×10^9 three- and higher-fold events was available for a subsequent analysis. The offline analysis consisted of both multi-gated spectra and three-dimensional "cubes" built and analyzed with the Radware package [12].

More than one hundred nuclei are produced at high spin in such experiments, and this gives several thousands of γ transitions which have to be sorted out. Single-gated spectra are useless in most of the cases. The selection of one particular nucleus needs at least two energy conditions, implying that at least two transitions have to be known. The identification of transitions depopulating high-spin levels which are completely unknown is based on the fact that prompt γ-rays emitted by complementary fragments are detected in coincidence [13,14]. For the reaction used in this work, we have studied many pairs of complementary fragments with known γ-ray cascades to establish the relationship between their number of protons and neutrons [15]. The sum of the proton numbers of complementary fragments has been found to be always the atomic number of the compound nucleus, $Z = 90$. The total number of emitted neutrons (sum of the pre- and post-fission neutrons) is mainly 4, 5, and 6. This has been taken into account for identifying the γ-ray cascades of the ^{84}Br nucleus, as shown in sect. 3.1.

2.2 γ-γ angular correlations

In order to determine the spin values of excited states, the coincidence rates of two successive γ-transitions are analyzed as a function of θ, the average relative angle between the two fired detectors. The Euroball IV spectrometer has C^2_{239} combinations of 2 crystals, out of which around 2000 involve different values of relative angle within 2°. In order to keep reasonable numbers of counts, all these angles have been gathered around three average relative angles: 22°, 46°, and 75°. The coincidence rate is increasing between 0° and 90° for the dipole-quadrupole cascades, whereas it decreases for the quadrupole-quadrupole or dipole-dipole ones. More precisely, the angular-correlation functions at the three angles of interest have been calculated for several combinations of spin sequences, corresponding to typical multipole orders (see table 1). Angular correlations of transitions belonging to the yrast cascades of the fission fragments having well-known multipole orders have been analyzed and the expected values have been found in all cases.

Table 1. Values of $R(\theta)$, the angular-correlation functions normalized to the ones calculated at 75°, expected for several combinations of spin sequences.

I_1-I_2-I_3	$R(22°)$	$R(46°)$	$R(75°)$
6-4-2	1.13	1.06	1.00
5-4-3	1.06	1.03	1.00
5-4-2	0.92	0.96	1.00

2.3 Time measurements

The timing information from the germanium detectors have been used to look for isomeric states in the range 10–300 ns. During the experiment, for the purpose of time calibration, part of the data has been registered using a fast trigger signal delayed by 20 ns. This has allowed us to precisely align the timing responses of every channel to a common one displaying 0.239 ns/channel. As a result, the time spectrum summed over all the Ge detectors, without any energy condition, presents a peak having a 20 ns FWHM and extends to about 300 ns. However, it is well known that the pulses associated to low-energy γ-rays have very long rise times, which prevents us from exploiting them to measure delayed coincidences. We have studied the time resolution as a function of the transition energy: above 250 keV the time resolution has been found to be constant, FWHM = 18 ns.

In order to check all these procedures, we have built several spectra representing the difference in the times associated to two transitions, either emitted in prompt coincidence or located on both sides of a well-known isomeric state. Typical results are presented in fig. 1. The top spectra show two examples of prompt coincidences between γ-rays in several energy ranges (the 427 keV and 682 keV transitions are located above and below the 1238 keV state of ^{95}Sr, the 1223 keV and 1750 keV transitions are located above and below the 1897 keV state of ^{96}Zr), and the bottom spectra, two examples of delayed coincidences (the decay of the 556 keV isomeric state of ^{95}Sr and the one of the 1264 keV isomeric state of ^{97}Zr). The values of the slopes

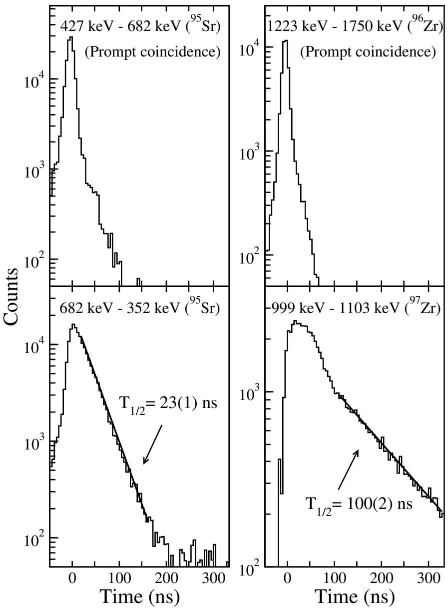

Fig. 1. Examples of time distribution between the emission of the two γ-rays showing either prompt coincidences or delayed ones corresponding to the decay of isomeric states of various nuclei produced in this experiment (see text).

measured in these cases are in perfect agreement with the known half-lives of the isomeric states, $T_{1/2} = 21.7(5)$ ns in ^{95}Sr and $T_{1/2} = 103(3)$ ns in ^{97}Zr [16].

3 Experimental results

3.1 High-spin states of ^{84}Br

Very few excited states were known in ^{84}Br prior to this work [16]. Two long-lived isomeric states had been identified from their β-decays. The total β-decay energies and the spin values of the most populated states in the daughter nucleus measured in the two decays, added to the fact that there is no internal isomeric transition, lead to the following result [17]: The 6^- state ($T_{1/2} = 6.0$ min) lies at 320(100) keV excitation energy above the 2^- ground state ($T_{1/2} = 31.8$ min). In order to identify the completely unknown transitions depopulating yrast states of ^{84}Br, we have first looked into spectra gated only by the first transitions of its main complementary fragment ^{137}Cs (5n channel) [16]. Besides the γ-rays known in ^{83}Br [16] and ^{85}Br (this work and [18]), new transitions are observed and can be assigned to ^{84}Br. We have, in a second time, analyzed spectra in double coincidence with one transition of ^{137}Cs and one new transition, or with two new transitions of ^{84}Br. Examples of double-gated spectra are given in figs. 2 and 3. The coincidence relationships have been carefully analyzed in order to build the level scheme shown in fig. 4. All the transitions assigned to ^{84}Br are given in table 2.

The most intense transition, 530 keV, has been placed just above the 6^- long-lived state, since only the yrast states are populated in the fusion-fission reaction. Two

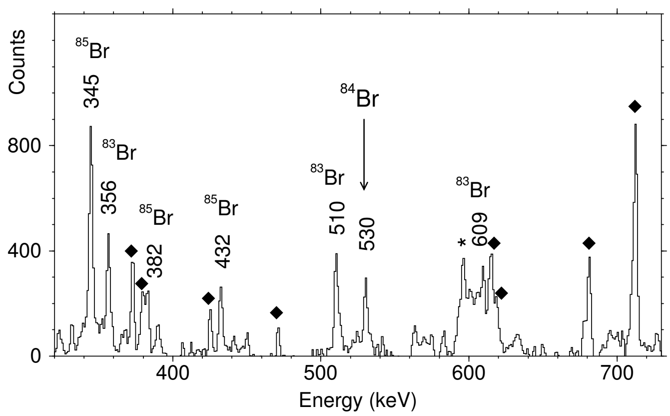

Fig. 2. Spectrum of γ-rays in double coincidence with the 1185 keV and 487 keV transitions of ^{137}Cs showing yrast transitions of ^{137}Cs (marked with filled diamonds) as well as transitions of its complementary fragments, ^{83}Br and ^{85}Br. The new 530 keV transition is assigned to ^{84}Br. The line marked with a star is a contaminant.

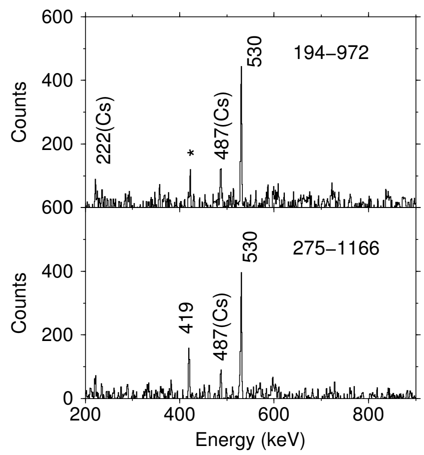

Fig. 3. Spectra of γ-rays in double coincidence with transitions newly identified in ^{84}Br. The line marked with a star is a contaminant.

Table 2. Properties of the transitions assigned to ^{84}Br which have been observed in this experiment.

$E_\gamma^{(a)}$ (keV)	$I_\gamma^{(a)}$	$J_i^\pi \rightarrow J_f^\pi$	E_i	E_f
194.1(2)	46(12)	$(8^+) \rightarrow (7^+)$	1696	1502
274.8(3)	24(6)	$(9^-) \rightarrow (8^-)$	1971	1696
419.5(3)	10(3)	$(10^-) \rightarrow (9^-)$	2390	1971
529.9(2)	100(15)	$(7^-) \rightarrow 6^-$	530	0
694.4(4)	9(3)	$(10^-) \rightarrow (8^-)$	2390	1696
726(1)	weak	$(9^+) \rightarrow (8^+)$	2422	1696
971.5(3)	36(9)	$(7^+) \rightarrow (7^-)$	1502	530
1165.9(3)	36(9)	$(8^-) \rightarrow (7^-)$	1696	530
1441.2(4)	18(5)	$(9^-) \rightarrow (7^-)$	1971	530
1501.6(4)	36(9)	$(7^+) \rightarrow 6^-$	1501	0

(a) The number in parenthesis is the error in the last digit.

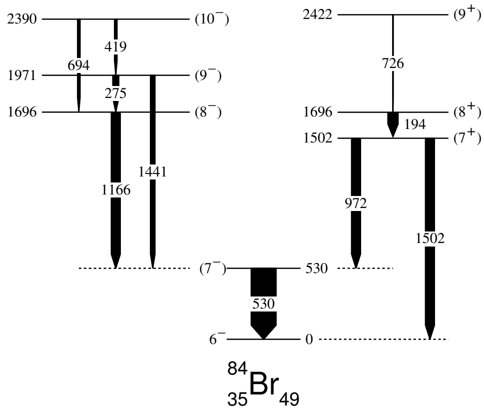

Fig. 4. Level scheme of ^{84}Br obtained in this work. The observed structures are built upon the 6^- long-lived state ($T_{1/2} = 6.0\,$min) lying at 320(100) keV excitation energy above the 2^- ground state ($T_{1/2} = 31.8\,$min).

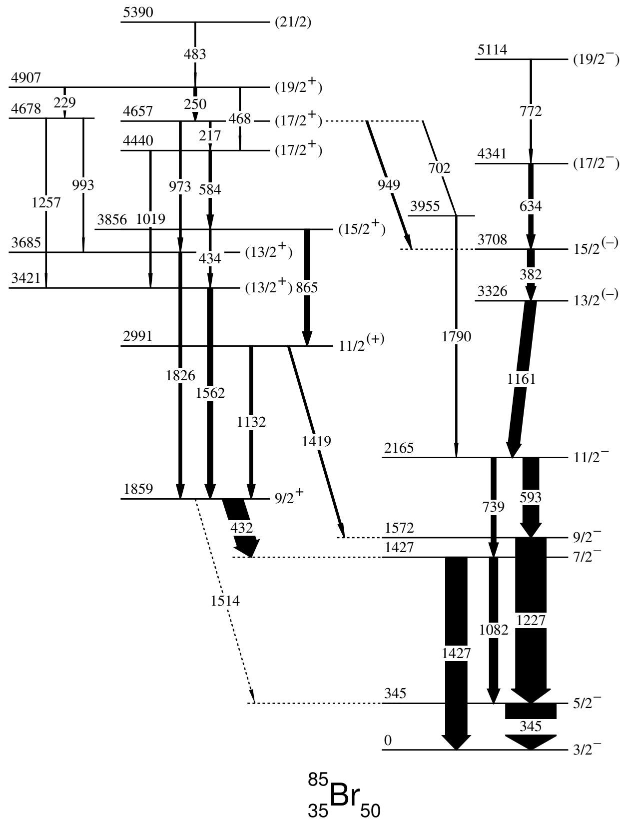

Fig. 5. Level scheme of ^{85}Br obtained in this work.

cascades of γ-rays have been observed in coincidence with the 530 keV transition, leading to two branches which are quite separate even though each of them contains a level located at the same excitation energy.

The statistics of the ^{84}Br data are unfortunately too low to perform γ-ray angular-correlation analysis. Hence the spin assignments, reported in fig. 4 and table 2, are based i) on the assumption that spin values increase with excitation energy, ii) on the requirement to satisfy all the parallel decay paths, iii) on the analogy with the level structure of neighbouring nuclei, this will be discussed in sect. 4.2.

3.2 Level scheme of ^{85}Br

The study of the high-spin states of ^{85}Br has been recently published. Using the same technique as ours, prompt γ-ray spectroscopy of fragments following fission induced by heavy ions, the authors of ref. [18] have obtained a level scheme extending up to 4.91 MeV excitation energy and spin $I = (19/2, 21/2)$, all the spin values being tentatively assigned from comparison with results of shell model calculations and with the systematics of the heavier isotones. The main issue of their work is related to the identification of the $9/2^+$ state expected around 2 MeV. In this mass region, such a state, coming from the promotion of the odd proton to the $\pi g_{9/2}$ sub-shell, is generally isomeric because of the hindrance of its γ-decay, either an $M2$ transition towards the $5/2^-$ state lying at lower excitation energy, issued from the $\pi f_{5/2}$ sub-shell, or low-energy $E1$ transitions towards negative-parity states coming from excitations among the $\pi f_{5/2}$ and $\pi p_{3/2}$ sub-shells. In ^{87}Rb$_{50}$, the $9/2^+$ state, located at 1578 keV, has $T_{1/2} = 6\,$ns and in ^{83}Br, the $9/2^+$ state, located at 1092 keV, has $T_{1/2} = 4.1\,$ns [16]. The authors of ref. [18] have found that the 1860 keV level could be a possible short-lived isomer as the intensity observed to feed this level is well larger than the intensity of its decay. Hence they propose this state as the best candidate for a $9/2^+$ isomer.

With two new transitions, the level scheme of ^{85}Br obtained in our work extends now above 5 MeV excitation energy. Whereas the energies of the states located below 5 MeV are in agreement with those of the previous work, the branching ratios of their de-excitation have been found to be different in several cases. Our level scheme is shown in fig. 5 as it will be useful to discuss the intensity of γ-rays, the spin assignments, particularly the identification of the $9/2^+$ state.

All the transitions assigned to ^{85}Br are given in table 3. The relative intensity of the low-lying transitions have been measured in the spectrum in double coincidence with two transitions of ^{137}Cs (one of the complementary fragments of ^{85}Br), whereas the relative intensity of the other transitions have been measured in several spectra in double coincidence with two low-lying transitions of ^{85}Br. Our results differ from the previous ones in three points, i) all the transitions de-exciting the high-spin states have a lower intensity (for instance $I_\gamma(634) = 8\%$ instead of 24% in ref. [18]), ii) the relative emission rates measured for the de-excitation of the 4440 keV, 3856 keV, 2991 keV and 2165 keV levels are at variance, iii) no imbalance of the decay intensity has been measured which would be the indication of an isomeric state. The first feature can be explained by probable different triggering conditions which were very low in our experiment (see sect. 2.1), this favours the population of lower-spin states as compared

Table 3. Properties of the transitions assigned to ^{85}Br observed in this experiment.

$E_\gamma^{(a)}$ (keV)	$I_\gamma^{(a)}$	$J_i^\pi \rightarrow J_f^\pi$	E_i	E_f
217.0(3)	2.9(12)	$(17/2^+) \rightarrow (17/2^+)$	4657	4440
228.7(3)	1.6(8)	$(19/2^+) \rightarrow (17/2^+)$	4907	4678
249.5(2)	5.0(15)	$(19/2^+) \rightarrow (17/2^+)$	4907	4657
344.5(1)	100	$5/2^- \rightarrow 3/2^-$	345	0
382.1(2)	13(3)	$15/2^{(-)} \rightarrow 13/2^{(-)}$	3708	3326
432.0(2)	39(4)	$9/2^+ \rightarrow 7/2^-$	1859	1427
434.3(3)	3.3(13)	$(15/2^+) \rightarrow (13/2^+)$	3856	3421
468.0(4)	1.1(5)	$(19/2^+) \rightarrow (17/2^+)$	4907	4440
483(1)	weak	$(21/2) \rightarrow (19/2^+)$	5390	4907
583.9(3)	4.2(1.3)	$(17/2^+) \rightarrow (15/2^+)$	4440	3856
593.3(2)	31(3)	$11/2^- \rightarrow 15/2^-$	2165	1572
633.6(3)	8.0(24)	$(17/2^-) \rightarrow 15/2^{(-)}$	4341	3708
702(1)	weak	$(17/2^+) \rightarrow (15/2)$	4657	3955
738.6(3)	9(3)	$11/2^- \rightarrow 7/2^-$	2165	1427
772.2(5)	2(1)	$(19/2^-) \rightarrow (17/2^-)$	5114	4341
864.6(4)	9(3)	$(15/2^+) \rightarrow 11/2^{(+)}$	3856	2991
949.3(5)	3(1)	$(17/2^+) \rightarrow 15/2^{(-)}$	4657	3708
972.5(5)	2.5(10)	$(17/2^+) \rightarrow (13/2^+)$	4657	3685
993.2(5)	1.3(6)	$(17/2^+) \rightarrow (13/2^+)$	4678	3685
1018.8(3)	16(3)	$(17/2^+) \rightarrow (13/2^+)$	4440	3421
1082.1(4)	2.2(9)	$7/2^- \rightarrow 5/2^-$	1427	345
1132.2(4)	5.0(15)	$11/2^{(+)} \rightarrow 9/2^+$	2991	1859
1160.5(3)	22(3)	$13/2^{(-)} \rightarrow 11/2^-$	3326	2165
1227.3(2)	60(6)	$9/2^- \rightarrow 5/2^-$	1572	345
1257.2(5)	1.2(6)	$(17/2^+) \rightarrow (13/2^+)$	4678	3421
1419.3(5)	3(1)	$11/2^{(+)} \rightarrow 9/2^-$	2991	1572
1426.8(2)	42(4)	$7/2^- \rightarrow 3/2^-$	1427	0
1514(1)	< 1	$9/2^+ \rightarrow 5/2^-$	1859	345
1562.3(3)	10(3)	$(13/2^+) \rightarrow 9/2^+$	3421	1859
1790.0(5)	2(1)	$(15/2) \rightarrow 11/2^-$	3955	2165
1826.0(5)	5(2)	$(13/2^+) \rightarrow 9/2^+$	3685	1859

(a) The number in parenthesis is the error in the last digit.

to the higher-spin ones. On the other hand, the second feature cannot be understood and the isomerism of the 1859 keV state assumed in the previous work will be discussed in sect. 3.4.

3.3 Spin values of the excited states of ^{85}Br

In order to determine the spin values of the ^{85}Br states, we have analyzed several γ-γ angular correlations. The experimental results obtained for the strongest transitions emitted by ^{85}Br are given in table 4. As compared to the calculated values reported in sect. 2.2, the measured values indicate that the transitions of the three couples, 1427-432, 345-1227, and 1227-593, have different multipole orders, whereas the transitions of the two couples, 593-1161 and 1161-382, have the same order (dipole or quadrupole). As quadrupole transitions with low energy are less likely in such a semi-magic nucleus, the 432 keV transition is assigned to be dipole and thus the 1427 keV transition to be quadrupole. Moreover, taking into account that the 345 keV transition is known to be $M1$ [16], a quadrupole character can be assigned to the 1227 keV transition and a dipole one to the 593 keV, 1161 keV, and 382 keV transitions. The electric or magnetic character of all these transitions can be now assigned from the lack or the existence of several linking transitions between excited states. First of all, a magnetic character for the 1427 keV transition would lead to a $I^\pi = 7/2^+$ value for the 1427 keV state, which should be only linked to the 345 keV state as an $M2$ transition of 1427 keV cannot compete with an $E1$ transition of 1082 keV. Therefore, the $I^\pi = 7/2^-$ value is assigned to the 1427 keV state. The same holds for the 1572 keV state which only decays to the $5/2^-$ state. A positive-parity state would also decay to the 1427 keV state with an $E1$ transition of 145 keV which is not observed. The 1227 keV transition is then assigned as an $E2$ transition, leading to $I^\pi = 9/2^-$ for the 1572 keV state. As for the 1859 keV state, the relative intensity of the 432 keV and 1514 keV γ-rays excludes a negative parity, as an $E2$ transition of 1514 keV would be well favoured as compared to an $M1$ transition of 432 keV. Then, the 1859 keV level is unambiguously the $I^\pi = 9/2^+$ state which is expected in ^{85}Br from the promotion of the odd proton to the $\pi g_{9/2}$ sub-shell.

Table 4. Coincidence rates between γ-rays as a function of their relative angle of detection, divided by the ones obtained around 75°.

E_γ-E_γ	$R(22°)^{(a)}$	$R(46°)^{(a)}$	$R(75°)^{(a)}$
1427-432	0.93(6)	0.92(4)	1.00(4)
345-1227	0.94(5)	0.98(3)	1.00(4)
1227-593	0.95(5)	0.97(4)	1.00(4)
593-1161	1.07(6)	1.06(4)	1.00(4)
1161-382	1.08(6)	1.05(4)	1.00(4)

(a) The number in parenthesis is the error in the last digit.

For the higher-energy states, we have chosen spin values increasing ($\Delta I = 1$ or 2) with excitation energy and satisfying all the parallel decay paths, that are given in fig. 5 and table 3.

3.4 Search for isomeric states in ^{85}Br

We have looked for isomeric states in the range $T_{1/2} =$ 10–300 ns using the time distribution between two transitions emitted by ^{85}Br, or one transition emitted by ^{85}Br and one by ^{137}Cs. None of the excited states of ^{85}Br measured in this work has been found to be isomeric. The two spectra, presented in fig. 6, show the case of the 1859 keV state. They only display prompt components, meaning that $T_{1/2}(1859\,\text{keV}) < 10$ ns, which is the intrinsic limit of the experimental method.

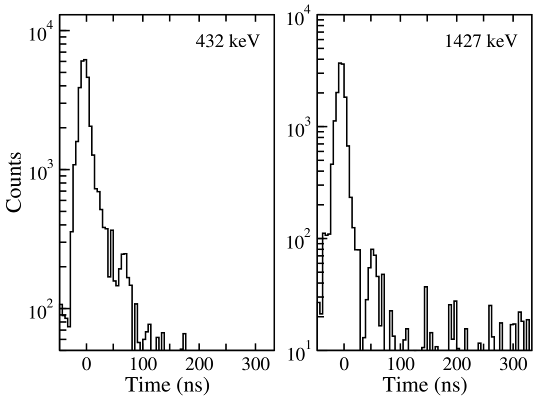

Fig. 6. Time distribution between the emission of the 1185 keV γ-ray (^{137}Cs) and one transition de-exciting the 1859 keV state of ^{85}Br (432 keV and 1427 keV γ-rays). These prompt coincidences lead to $T_{1/2}(1859\,\text{keV}) < 10$ ns (see text).

Thus, another explanation has to be found to understand the intensity imbalance measured for the 1859 keV state in the previous work. It is worth pointing out that the 432 keV transition which de-excites the 1859 keV state is a member of a doublet, and the second member (the 434 keV transition, in coincidence with the 432 keV one), partly de-excites the 3856 keV state. The relative emission rate measured for the de-excitation of the 3856 keV level in the present work ($I(434)/I(864) \sim 0.4$) is very different from the previous result ($I(434)/I(864) = 1.4$). An overvaluation of the 434 keV component in the previous work would induce a too low intensity for the 432 keV transition.

4 Discussion

4.1 Excited states of $^{85}_{35}$Br$_{50}$

The configurations of the first excited states of the light $N = 50$ isotones are mainly due to the four *proton* sub-shells located between $Z = 28$ and $Z = 50$, which are successively $\pi f_{5/2}$, $\pi p_{3/2}$, $\pi p_{1/2}$, and $\pi g_{9/2}$. The two first sub-shells are obviously involved in the $3/2^-$ ground state and the $5/2^-$ first-excited state of ^{85}Br, its odd proton being located in one of the two sub-shells, $\pi p_{3/2}$ or $\pi f_{5/2}$, close in energy. Shell model calculations of the level schemes of several $N = 50$ isotones have been performed many years ago [19]. At that time, as only states having low-spin values were known in ^{85}Br, the calculated states have been limited to $I \leq 9/2$. A comparison with the low-lying experimental states has been already done in ref. [18]. In order to go further, we discuss the high-spin states observed in this work by analogy with the various excitations known in the two neighbouring even-even nuclei.

It is well known that the 2_1^+ and 4_1^+ states of $^{86}_{36}$Kr ($^{84}_{34}$Se), at 1565 (1454) keV and 2250 (2121) keV, respectively, involve the re-orientation of the proton angular momenta in the fp sub-shells which are not completely filled. In ^{85}Br, the three states with negative parity observed above 1 MeV can be explained similarly, the maximum spin corresponding to the $[\pi f_{5/2}\text{-}\pi p_{3/2}]^{+7}$ configuration is $11/2^-$. Then the promotion of one pair into the $\pi p_{1/2}$ sub-shell leads to a maximum spin $I^\pi = 13/2^-$ ($[\pi f_{5/2}\text{-}\pi p_{3/2}]^{+5}[\pi p_{1/2}]^{+2}$ configuration). This could correspond to the excited state located at 3326 keV. It is worth pointing out that $I^\pi = 13/2^-$ is the maximum spin achievable from the re-orientation of the angular momenta in the fp sub-shells.

The configuration of the $9/2^+$ level at 1859 keV, $[\pi f_{5/2}\text{-}\pi p_{3/2}]^{+6} \otimes [\pi g_{9/2}]^{+1}$, can be viewed as the coupling of a $^{84}_{34}$Se core and a proton in the $\pi g_{9/2}$ sub-shell. The excited states located above the 1859 keV level are expected to be due to the core excitation, such as the re-orientation of the angular momenta of two protons in the fp sub-shells giving rise to the 2_1^+ and 4_1^+ states of ^{84}Se. The maximum spin of such a configuration involving one broken pair is $17/2^+$. In ^{84}Se, the break of two proton pairs within the fp sub-shells leads to a 6^+ state, which has been tentatively identified at 3370 keV [7]. One can remark that the highest excited state of ^{85}Br identified in the present work lies at around 3.5 MeV above the $9/2^+$ state. Therefore, all the excited states, located above the 1859 keV and connected to the $9/2^+$ state, can be interpreted as the coupling of one proton in the $\pi g_{9/2}$ sub-shell and one broken pair within the $\pi f_{5/2}\text{-}\pi p_{3/2}$ sub-shells ($I_{max} = 17/2^+$) or two broken pairs giving $I_{max} = 21/2^+$.

Figure 7 sums up the evolution of these states issued from proton excitations in ^{85}Br as well as in ^{84}Se and ^{86}Kr.

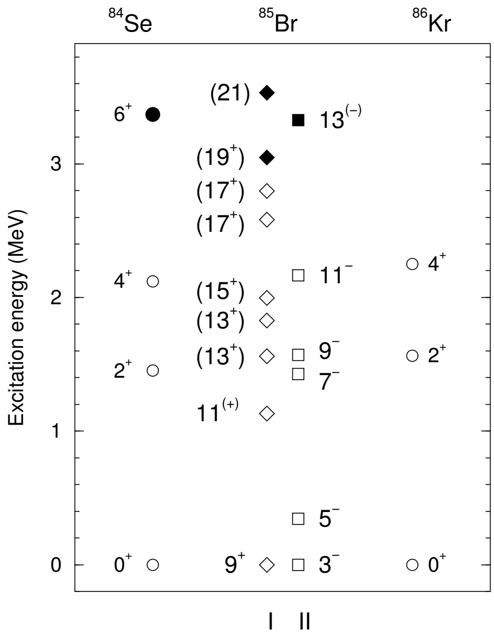

Fig. 7. Excitation energies of the ^{85}Br states from proton excitations compared to those of its two even-even neighbours. The structure noted I is built on the $9/2^+$ state, the one noted II is built on the $3/2^-$ state (all the states of ^{85}Br are labelled by $2I^\pi$). The states issued from the breaking of one proton pair within the $\pi f_{5/2}\text{-}\pi p_{3/2}$ sub-shells are drawn with empty symbols and those issued from the breaking of two proton pairs are drawn with filled symbols.

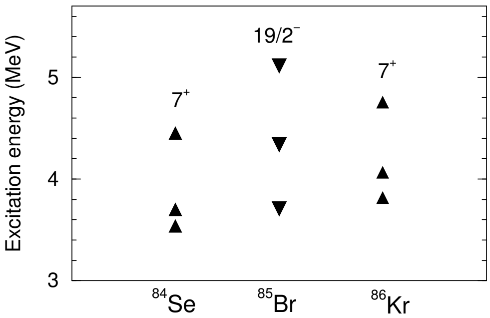

Fig. 8. Excitation energies of the ^{85}Br states from the breaking of the neutron core compared to those of its two even-even neighbours. The maximum spin value within each structure is written above the corresponding state.

In the $N = 50$ isotones, the configuration of the first *neutron-core* excitation, $\nu[g_{9/2}]^{-1} \otimes \nu[d_{5/2}]^{+1}$, gives a multiplet of states with spin values ranging from 2^+ to 7^+. This configuration has been assigned to the 5^+, 6^+, and 7^+ yrast states of ^{86}Kr and ^{84}Se [7]. Such an excitation is also expected in ^{85}Br, the maximum spin value being $19/2^-$ when the odd proton is located in the $\pi f_{5/2}$ sub-shell. The three excited levels which have been observed at 3708, 4341, and 5114 keV, can be proposed to be due to this neutron core excitation as their excitation energies are in the good range (as shown in fig. 8) and their spin values are too high for any fp sub-shell excitations. It is worth pointing out that the break of the neutron core is also expected in the structure built on the $\pi g_{9/2}$ excitation. This would lead to excited states having $I_{max} = 23/2^+$ located around 4.5 MeV above the $9/2^+$ state. Unfortunately, the statistics of our data set is too low to identify states lying at such high excitation energy.

4.2 Excited states of $^{84}_{35}Br_{49}$

In the odd-odd ^{84}Br nucleus, four configurations are expected below 2 MeV, giving four multiplets of states: $\pi p_{3/2} \otimes \nu g_{9/2}$ ($3^- \leq I^\pi \leq 6^-$), $\pi f_{5/2} \otimes \nu g_{9/2}$ ($2^- \leq I^\pi \leq 7^-$), $\pi p_{1/2} \otimes \nu g_{9/2}$ ($I^\pi = 4^-$ and 5^-), and $\pi g_{9/2} \otimes \nu g_{9/2}$ ($0^+ \leq I^\pi \leq 9^+$). Their zero-order energies deduced from the four measured single-proton energies in the ^{85}Br core ([16], this work) are given in table 5. One can notice that the third configuration cannot be involved in the states discussed in this work, as the 4^- and 5^- states, not yrast, cannot be populated in the fusion-fission reaction. Therefore it is left out in the following discussion.

When the residual proton-neutron interaction is taken into account, the relative order of the actual states depends on the nature (particle or hole) of the odd nucleons (see, for instance, ref. [20]). More precisely, when the two odd nucleons have the same character (particle-particle or hole-hole), the energies of the two states having the extreme spin values are the most lowered by the residual interaction. On the contrary, when the two odd nucleons have opposite characters (particle-hole configurations), the states with medium spin values are the most lowered in energy.

Table 5. Configurations expected in $^{86}_{37}$Rb and $^{84}_{35}$Br: the zero-order energy deduced from the proton energies in the respective $N = 50$ cores and spins of the states favoured in energy thanks to the proton-neutron residual interaction.

	$E_{\pi\nu}$ (keV) (zero order)	Configuration	Favoured states
^{86}Rb	0	$[\pi p_{3/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$	3^-, 6^-
	402	$[\pi f_{5/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$	2^-, 7^-
	845	$[\pi p_{1/2}]^{1} \otimes [\nu g_{9/2}]^{-1}$	4^-, 5^-
	1578	$[\pi g_{9/2}]^{+1} \otimes [\nu g_{9/2}]^{-1}$	6^+, 7^+
^{84}Br	0	$[\pi p_{3/2}]^{+1} \otimes [\nu g_{9/2}]^{-1}$	4^-, 5^-
	345	$[\pi f_{5/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$	2^-, 7^-
	1192	$[\pi p_{1/2}]^{1} \otimes [\nu g_{9/2}]^{-1}$	4^-, 5^-
	1859	$[\pi g_{9/2}]^{+1} \otimes [\nu g_{9/2}]^{-1}$	6^+, 7^+

Whereas the odd neutron of ^{84}Br is obviously $[\nu g_{9/2}]^{-1}$, the nature of the odd proton depends on its sub-shell. To determine it, we can start with the simpler case of the neighbouring isotone, $^{86}_{37}$Rb. Taking into account the position of the proton Fermi level among the sub-shells for $Z = 37$, one can deduce that the $\pi p_{3/2}$ and the $\pi f_{5/2}$ excitations are of hole type, wheras the $\pi g_{9/2}$ excitation is of particle type. The spins of the ^{86}Rb states favoured in energy thanks to the proton-neutron residual interaction are given in the first part of table 5. The experimental results [21] are in good agrement with such simple arguments. The $[\pi f_{5/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$ configuration gives the 2^- ground state, the 7^- being at 780 keV. The 6^- and 3^- states, from $[\pi p_{3/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$, are almost degenerated in energy (556 and 557 keV, respectively), the 6^- state being a long-lived isomeric state. Finally, the first state of the $[\pi g_{9/2}]^{+1} \otimes [\nu g_{9/2}]^{-1}$ configuration is the 7^+ state at 1558 keV [22].

Assuming a successive filling of the proton orbits betwen $Z = 35$ and $Z = 37$, we could expect that the nature of the $\pi f_{5/2}$ and $\pi g_{9/2}$ excitations in ^{84}Br remains the same as in ^{86}Rb (hole and particle, respectively), whereas the $\pi p_{3/2}$ excitation changes to be of particle type. In that case (given in the second part of table 5), all the low-lying states of ^{84}Br would be the same as those observed in ^{86}Rb, but the 6^- state, which is no longer expected to be isomeric as the 5^- state coming from the same configuration, would be much favoured in energy. This is obviously at variance with the experimental results [17], the spin value of the long-lived isomeric state of ^{84}Br being $I^\pi = 6^-$.

One can remark that depending on the proton-pair distribution among the two sub-shells, $\pi f_{5/2}$ and $\pi p_{3/2}$ (close in energy, as said in sect. 4.1), the nature of the odd proton occupying the latter can easily flip from particle, $[\pi f_{5/2}]^6 \otimes [\pi p_{3/2}]^1$, to hole, $[\pi f_{5/2}]^4 \otimes [\pi p_{3/2}]^{-1}$. The occupation probabilities of the two proton sub-shells can be assessed from the results obtained in ^{85}Br using the (d, ^{3}He) pick-up reaction [23]. The measured spectroscopic factors imply that the $\pi f_{5/2}$ sub-shell is not completely filled ($C^2S = 4.46$) and the $\pi p_{3/2}$ sub-shell contains more than one proton ($C^2S = 1.7$). Hence a mixing of the $[\pi p_{3/2}]^{+1}$ and $[\pi p_{3/2}]^{-1}$ proton states can be foreseen in ^{84}Br.

The residual-interaction energies in the $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration have been calculated as a function of the $\pi p_{3/2}$ occupation, using the same method as in ref. [24], following the prescriptions of ref. [25]. The starting point of this calculation is the experimental energies of the four states of the $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration, either in the particle-particle/hole-hole case or in the particle-hole one. As only two members of the multiplet have been unambiguously identified in ^{86}Rb, we have used results obtained in $^{70}_{29}$Cu$_{41}$, in which the $\pi p_{3/2}$ and $\nu g_{9/2}$ sub-shells start to be filled. The 6^- and the 3^- members, which are expected at a lower energy than the other states in this case of particle-particle configuration, are, respectively, the ground state and the first excited state at 101 keV [26, 27]. The 4^- state at 228 keV has been observed in the β-decay of ^{70}Ni [26], as well as in the (t,^{3}He) reaction [27]. The last member ($I^\pi = 5^-$) has been observed in the latter reaction which strongly favours the whole multiplet. The energies of residual interactions for the four states of the $\pi p_{3/2} \otimes \nu g_{9/2}$ multiplet, calculated as a function of the number of protons filling the $\pi p_{3/2}$ sub-shell ($1 \leq n \leq 3$), are drawn in fig. 9. It can be noticed that the lowest state of the multiplet is the 6^- level as soon as the $\pi p_{3/2}$ sub-shell is half-full. Hence the long-lived isomeric state with $I^\pi = 6^-$ measured in ^{84}Br can be interpreted as an experimental evidence of the proton-pair scattering among the fp sub-shells.

The left part of fig. 10 displays the excitation energies of some selected high-spin states of ^{84}Br (see fig. 4) with respect to the 2^- ground state not observed in our experiment. The uncertainty ($\pm$100 keV) on the excitation energy of the 6^- long-lived isomeric state [17] affects the energy of all the states located above it. In the neighbouring isotone ^{86}Rb, the distance in energy between the two states of the $[\pi f_{5/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$ configuration having the extreme spin values, 2^- and 7^-, is 780 keV (see the right part of fig. 10). Therefore one can assume that the level of ^{84}Br located 530 keV above the 6^- isomeric state, *i.e.* 850(100) keV above the 2^- ground state, is the 7^- state coming from the $[\pi f_{5/2}]^{-1} \otimes [\nu g_{9/2}]^{-1}$ configuration. For the higher excitations, we can rely on the ones observed in ^{85}Br. As discussed in sect. 4.1, the $\pi g_{9/2}$ excitation and the breaking of one fp proton pair are in the same energy range. Therefore, the $[\pi g_{9/2}]^{+1} \otimes [\nu g_{9/2}]^{-1}$ configuration can explain the states located at 1502, 1696 and 2422 keV above the 6^- isomeric state (see fig. 4), thus assigned to be (7^+), (8^+), and (9^+). One can notice that their excitation energies above the ground state is slightly higher than those of the corresponding states of ^{86}Rb (see fig. 10), in agreement with the increase of the energy of the $\pi g_{9/2}$ subshell between ^{87}Rb and ^{85}Br.

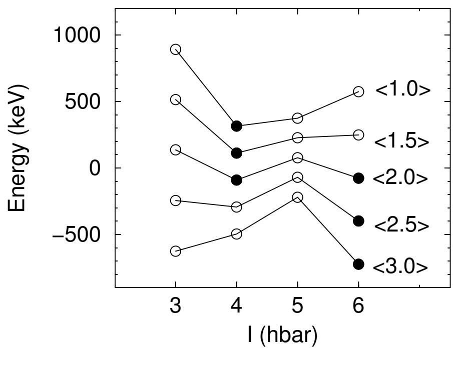

Fig. 9. Energies of residual interaction in the $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration as a function of the angular momentum I, calculated for five values of the $\pi p_{3/2}$ occupation (see text). The full symbol indicates the lowest state of the multiplet for each case.

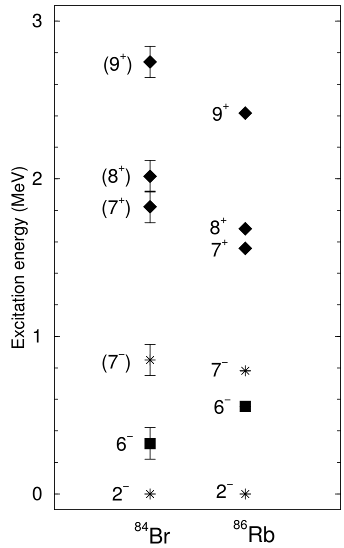

Fig. 10. Experimental excitation energies of selected states observed in $^{84}_{35}$Br$_{49}$ compared to those known in $^{86}_{37}$Rb$_{49}$. The states issued from the $\pi f_{5/2} \otimes \nu g_{9/2}$ configuration are drawn with stars, those from the $\pi p_{3/2} \otimes \nu g_{9/2}$ configuration with squares, and those from the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration with diamonds.

When considering the break of one proton pair among the fp sub-shells and the re-orientation of the proton angular momenta, one can notice that the maximum spin corresponding to the coupling of three proton holes within the $\pi f_{5/2}$-$\pi p_{3/2}$ sub-shells and one neutron hole in the $\nu g_{9/2}$ sub-shell is 10^-. The three states at 1696, 1971, 2390 keV above the 6^- isomeric state can be interpreted from such fp excitations.

5 Summary

The ^{84,85}Br isotopes have been produced as fission fragments in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV. The emitted γ-rays have been detected using the Euroball IV array. The high-spin states of ^{84}Br have been identified for the first time, using the fact that prompt γ-rays emitted by complementary fragments are detected in coincidence. The already-known high-spin level scheme of ^{85}Br has been improved thanks to timing measurements and analysis of angular correlations. Spin and parity values have been assigned to most of the observed states. Most of the excited states observed in ^{85}Br have been interpreted in terms of proton excitations within the $\pi f_{5/2}$-$\pi p_{3/2}$ sub-shells, possibly added to the $\pi g_{9/2}$ sub-shell. Similarly, the excited states of the odd-odd ^{84}Br nucleus have been discussed in terms of both neutron and proton excitations, involving the sub-shells located close to the Fermi levels, $\nu g_{9/2}$ and $\pi f_{5/2}$, $\pi p_{3/2}$, $\pi g_{9/2}$. The differences in excitation energy between corresponding states in ^{84}Br and ^{85}Br, as well as those within the states of the multiplet issued from each configuration, can be related to various residual two-body interactions, which are also involved in several other neighbouring nuclei. This will be analyzed in a forthcoming paper [28].

The Euroball project was a collaboration between France, the United Kingdom, Germany, Italy, Denmark and Sweden. The Euroball IV experiment has been supported in part by the EU under contract HPRI-CT-1999-00078 (EUROVIV). This work was partly supported by the collaboration agreement Bulgarian Academy of Sciences - CNRS under contract No. 16946. We thank the crews of the Vivitron. We are very indebted to M.-A. Saettle for preparing the Pb target, P. Bednarczyk, J. Devin, J.-M. Gallone, P. Médina, and D. Vintache for their help during the experiment.

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