Eur. Phys. J. A **28**, 153–159 (2006)
DOI 10.1140/epja/i2006-10050-8

THE EUROPEAN PHYSICAL JOURNAL A

Beyond the N = 50 shell closure: High-spin excitations of ^{87}Kr and ground-state spin of ^{87}Br

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Received: 1 March 2006 / Revised: 11 May 2006 /

Communicated by D. Schwalm

Abstract. The ^{87}Kr nucleus has been produced as fission fragment in the fusion reaction $^{18}\mathrm{O} + {}^{208}\mathrm{Pb}$ at 85 MeV bombarding energy and studied with the Euroball IV array. High-spin states of this neutron-rich isotope have been identified for the first time. Its level scheme has been obtained up to 6.3 MeV excitation energy and spin $I \sim 23/2\hbar$. Its structure is interpreted by analogy with those of the heavier isotones. The proposed configurations involve both proton and neutron excitations from several sub-shells located close to the Fermi levels, particularly $\nu d_{5/2}$, $\pi p_{3/2} f_{5/2}$ and $\pi g_{9/2}$. Moreover, a revised spin value of $5/2^-$ for the ^{87}Br ground state is proposed.

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

1 Introduction

The study of the evolution of nuclear structure in new mass regions far from stability is opening up thanks to the advent of radioactive beams. While quenchings of shell closure or changes in magic numbers and in single-particle order can be already predicted in the light nuclei, the situation is less favourable in the medium-A nuclei. In many cases 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 interaction of the fp protons ($28 < Z < 38$) and the dg neutrons ($N > 50$) 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.

Using various fusion-fission reactions, we have undertaken the study of high-spin states of many neutron-rich isotopes ($_{37}$Rb, $_{36}$Kr, $_{35}$Br, and $_{34}$Se) located around the $N = 50$ shell closure. The analysis of the $^{84}\mathrm{Se}_{50}$ excitations and the comparison with the behaviour of the heavier isotones has been already published [1], pointing out a weakening of the $N = 50$ spherical shell gap when Z is decreasing from 38 to 34. In this paper we report on new results obtained in the $^{87}\mathrm{Kr}_{51}$ nucleus produced in the fusion-fission reaction $^{18}\mathrm{O} + {}^{208}\mathrm{Pb}$ at 85 MeV bombarding energy and studied with the Euroball IV array. Its high-spin states have been identified up to 6.3 MeV excitation energy and spin $I \sim 23/2\hbar$. From the comparison with the excited states known in the heavier isotones, we propose configurations involving both proton and neutron excitations from several sub-shells located close to the Fermi levels, particularly $\nu d_{5/2}$, $\pi p_{3/2} f_{5/2}$ and $\pi g_{9/2}$. Moreover, the first five excited states of ^{87}Kr observed in our experiment had been also observed in the β-decay of ^{87}Br. They cannot have the low-spin values which had been derived from the spin and parity values of the ^{87}Br ground state ($I^\pi = 3/2^-$, adopted in [2]). Hence the ^{87}Br(g.s.) spin value has to be revised. The new value, $I^\pi = 5/2^-$, is dis-

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cussed in terms of deformation which would arise as soon as the neutron number departs from $N = 50$ provided that several proton sub-shells with $\Delta l = 2$ are active.

2 Experimental procedures and analysis

The ^{18}O + ^{208}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 [3]. 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 [4] and each clover detector consists of four smaller Ge crystals [5].

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 [6].

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 [7,8]. 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 [9]. 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 ^{87}Kr nucleus, as shown in the next section.

3 Experimental results

3.1 Level scheme

The excited states of ^{87}Kr had been already studied from neutron-transfer and neutron-capture reactions, and from ^{87}Br β-decay. All the spin values assigned to these states [2] are lower or equal to 5/2 (which is the spin of the ground state) except the 2258(10) keV level which has been populated with $L = 5$ in the neutron-transfer reaction and assigned as $I^\pi = (9/2^-, 11/2^-)$. In such a case only the 2258(10) keV level is expected to be populated in the present fusion-fission reaction. As its γ-decay has not been measured, we have infered that transitions depopulating yrast states of ^{87}Kr were completely unknown at the begining of this work.

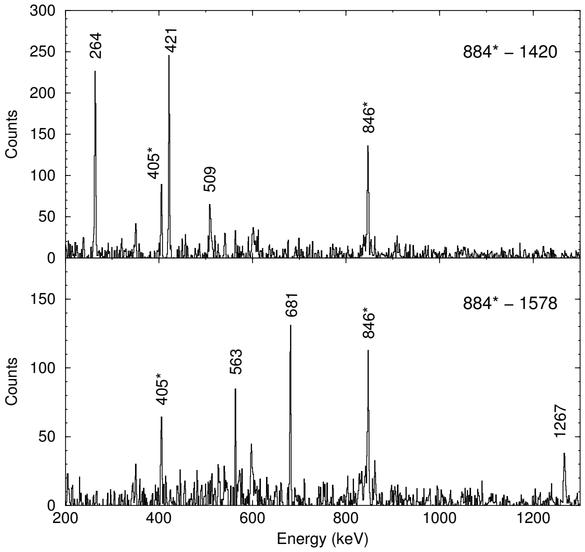

Fig. 1. Spectra of γ-rays in double coincidence with the 884 keV transition of ^{134}Xe and the 1420 keV transition (top spectrum) or the 1578 keV transition (bottom spectrum) newly identified in ^{87}Kr. The transitions marked with a star belong to ^{134}Xe.

We have first looked for the ^{87}Kr transitions using spectra gated only by the first transitions of its main complementary fragment ^{134}Xe (5n channel). Besides the γ-rays already known in ^{86}Kr [1] and ^{88}Kr [10], several new transitions are observed and can be assigned to ^{87}Kr. We have, in a second time, analyzed spectra in double coincidence with one transition of ^{134}Xe and one new transition. Examples of such double-gated spectra are given in fig. 1.

The coincidence relationships have been carefully analyzed in order to build the level scheme shown in fig. 2. All the transitions assigned to ^{87}Kr are given in table 1.

It is worth pointing out that the five excited states identified below 2.3 MeV in this work had been already observed in the ^{87}Br β-decay. Their γ-decay properties are mainly the same (some minor differences will be discussed below). Nevertheless, the low-spin values chosen in the last compilation [2] would have hindered their observation in our experiment. The most striking point is the 2259 keV level. Two different states with the same energy are quoted in the adopted level list [2]. The characteristics of the first one, $I^\pi = (9/2^-, 11/2^-)$, have been mentioned above. Such a state cannot be directly linked to the 1578 keV level assigned as $(1/2^+, 3/2, 5/2^+)$ in ref. [2] from the ^{87}Br β-decay measurement. Therefore another state, which is located at 2258.67(7) keV, had been proposed. Our results indicate that there is only one excited state at this energy and moreover, most of the spin values assigned to the previously known excited states of ^{87}Kr [2] have to be changed. This will be discussed in the two next sections.

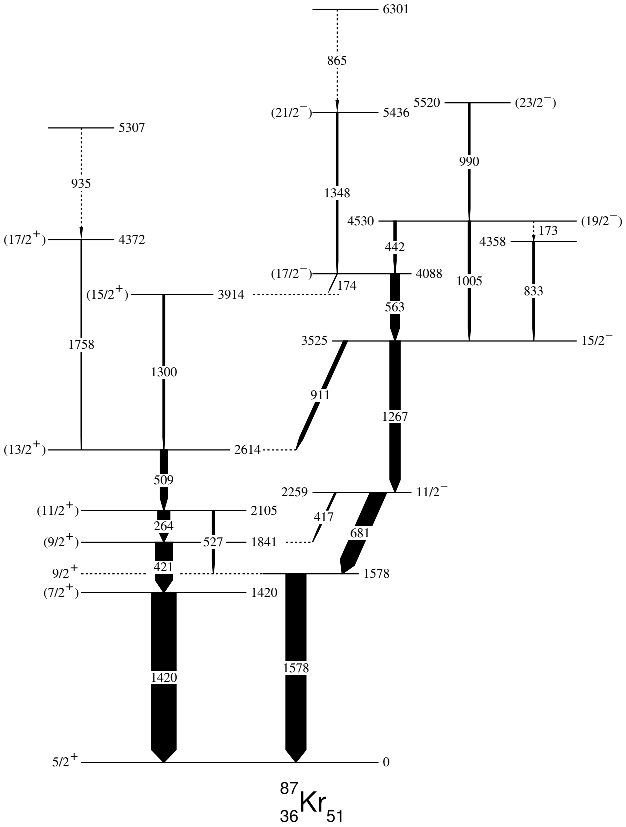

Fig. 2. Level scheme of ^{87}Kr obtained as fission fragment in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV beam energy. While several values of spin and parity can be assigned to the excited states lying above 2.3 MeV, only one value (given in parenthesis) has been selected (see the discussion).

Two additional transitions linking the first excited states have been observed in this work: 417 keV and 527 keV (see table 1). They had not been previously identified, because of the very weak population of the 2105 and 2259 keV states in the ^{87}Br β-decay experiment. On the other hand, we do not confirm the direct decay of the 2259 keV level to the ground state, which is proposed in ref. [11] with a branching ratio $I_\gamma(2259\,\text{keV})/I_\gamma(681\,\text{keV}) = 39(3)\%$. From our gated spectra, the branching ratio of a 2259 keV transition would be less than 1%. According to ref. [11], the position of the 2258.4 keV γ-ray in the level scheme had been only supported by its energy, no coincidence relationship being observed for this transition, which casts doubt on its location.

Two γ-rays of 681.0 and 1578.5 keV have been recently proposed to belong to the yrast structure of ^{82}Ge [12], as they have been found to be in coincidence with the 1347.6 keV transition de-exciting its 2_1^+ state. One can remark that three transitions having such energies (680.9, 1348.1, and 1577.6 keV) belong to the ^{87}Kr level scheme (see fig. 2 and table 1). Since medium-spin states of ^{87}Kr can be populated in the deep inelastic reaction used in ref. [12], the 681.0 and 1578.5 keV transitions could correspond to ^{87}Kr contaminants and their assignment to ^{82}Ge would have to be examined again.

Table 1. Properties of the transitions assigned to ^{87}Kr observed in this experiment.

$E_\gamma^{(a)}$(keV)	$I_\gamma^{(a)}$	$J_i^\pi \to J_f^\pi$	E_i	E_f
172.7(3)	0.4(2)	$(19/2^-) \to (17/2^-)$	4530	4358
173.9(2)	3.2(9)	$(17/2^-) \to (15/2^+)$	4088	3914
263.6(2)	27(3)	$(11/2^+) \to (9/2^+)$	2105	1841
417.1(3)	2.6(8)	$11/2^- \to (9/2^+)$	2259	1841
421.5(2)	38(4)	$(9/2^+) \to (7/2^+)$	1841	1420
441.8(3)	5.0(15)	$(19/2^-) \to (17/2^-)$	4530	4088
509.1(3)	16(3)	$(13/2^+) \to (11/2^+)$	2614	2105
527.5(3)	4.8(14)	$(11/2^+) \to (9/2^+)$	2105	1578
562.9(2)	19(3)	$(17/2^-) \to 15/2^-$	4088	3525
680.9(2)	34(3)	$11/2^- \to 9/2^+$	2259	1578
832.6(4)	4(1)	$(17/2^-) \to 15/2^-$	4358	3525
864.6(5)	1.5(7)		6301	5436
910.8(3)	8.0(15)	$15/2^- \to (13/2^+)$	3525	2614
935(1)	0.4(2)		5307	4372
989.7(5)	3(1)	$(23/2^-) \to (19/2^-)$	5520	4530
1005.2(4)	5.0(15)	$(19/2^-) \to 15/2^-$	4530	3525
1266.6(3)	23(5)	$15/2^- \to 11/2^-$	3525	2259
1299.7(4)	3.8(9)	$(15/2^+) \to (13/2^+)$	3914	2614
1348.1(5)	3.1(9)	$(21/2^-) \to (17/2^-)$	5436	4088
1419.7(3)	55(4)	$(7/2^+) \to 5/2^+$	1420	0
1577.6(3)	45(3)	$9/2^+ \to 5/2^+$	1578	0
1757.9(7)	1.3(5)	$(17/2^+) \to (13/2^+)$	4372	2614

$^{(a)}$ The number in parenthesis is the error in the last digit.

3.2 Spin values of the excited states of ^{87}Kr

In order to determine the spin values of the low-lying states of ^{87}Kr, we have analyzed several γ-γ angular correlations. In angular-correlation measurement, the coincidence rate of two successive γ-transitions is analyzed as a function of the average relative angle between the two fired detectors. The Euroball IV spectrometer has C_{239}^2 combinations of 2 detectors, 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 in interest have been calculated for several combinations of spin values, corresponding to typical multipole orders (see table 2). Angular correlations of transitions belonging to the yrast cascades of the fission fragments having well-known multipole orders have been analyzed and such values have been found in all cases.

Table 2. Values of the angular-correlation functions expected for several combinations of spin values, normalized to the ones calculated at 75°.

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

Table 3. 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°)$^{(a)}$
681-1578	0.94(6)	0.98(4)	1.00(4)
1267-681	0.95(6)	0.97(4)	1.00(4)
1267-1578	1.08(6)	1.04(4)	1.00(4)
421-1420	0.95(6)	0.98(4)	1.00(4)
264-1420	0.92(6)	0.96(4)	1.00(4)
264-421	1.07(5)	1.04(4)	1.00(4)
509-264	1.04(5)	1.02(4)	1.00(4)
509-421	1.11(5)	1.05(4)	1.00(4)

$^{(a)}$ The number in parenthesis is the error in the last digit.

The experimental results obtained for the transitions emitted by ^{87}Kr are given in table 3. They indicate that the 1578 keV and 1267 keV transitions have the same character (dipole or quadrupole), whereas the 681 keV transition has a different character. Moreover, as in the heavier isotones, only one negative-parity state is expected below 2.5 MeV excitation energy: this is the 2259 keV state $(9/2^-, 11/2^-)$ which has been populated with $L = 5$ in neutron transfer reaction [2]. Therefore the parity change has to be induced by the 681 keV transition, which is assigned to be $E1$, and the 1578 keV and 1267 keV transitions are $E2$. Taking also into account that i) the spin value of the ground state is $5/2^+$ [2], ii) only the yrast states are populated in the fusion-fission reaction, meaning that the spin values have to increase with the excitation energy, the following spin values can be assigned: $I^\pi = 9/2^+$ for the 1578 keV state, $I^\pi = 11/2^-$ for the 2259 keV state and $I^\pi = 15/2^-$ for the 3525 keV state.

The second set of values given in table 3 implies that the 1420 keV transition and the three low-energy ones have a different character. As quadrupole transitions with low energy are less likely in such a nucleus close to shell closure, the 421 keV, 264 keV and 509 keV transitions are assigned to be dipole and the 1420 keV transition to be quadrupole. However, the $I^\pi = 9/2^+$ value for the 1420 keV state has to be ruled out because this would lead to two inconsistencies, i) the γ-decay of the 2105 keV state involving an $E2$ transition of only 527 keV, ii) the spin values then deduced for the 2105 keV and the 2614 keV levels ($I^\pi = 13/2^+$ and $15/2(^+)$), meaning that they are the yrast states, while the right part of the level scheme is the most populated (see fig. 2 and table 1). On the other hand, the $I^\pi = (7/2^+)$ value could be assigned for the 1420 keV state (in accordance with its configuration, discussed in sect. 4.1), leading to $I^\pi = (9/2^+)$ for the 1841 keV state, $I^\pi = (11/2^+)$ for the 2105 keV state, and $I^\pi = (13/2^+)$ for the 2614 keV state.

All these new spin values are reported in table 1. For the higher-energy states, we have firstly chosen spin values increasing ($\Delta I = 1$ or 2) with excitation energy and satisfying all the parallel decay paths. Then we have selected some spin values (given in fig. 2 and table 1) using the systematic behaviour of the heavier isotones and some analogies with the level structure of the neighbouring ^{86}Kr [1], as discussed below (see sect. 4.1).

3.3 Revised spin assignments of the ^{87}Kr states populated from the β-decay and of the ^{87}Br ground state

In order to reconcile the results of the present experiment with those of the ^{87}Br β-decay measurement, most of spin values previously assigned to the excited states of ^{87}Kr [2] have to be increased. In the following we will only discuss some specific cases, because of their issue on the ^{87}Br ground-state spin value.

The 4710 keV and 4961 keV levels are linked [2,11] to the 1578 and 1841 keV levels (see fig. 3) assigned as $9/2^+$ in this work. That implies that their spin values are at least 5/2 (with positive parity) or 7/2 (with negative parity). Then, their strong populations ($\log ft = 5.7$ and 5.5, respectively) in the ^{87}Br β-decay, implying allowed transitions ($\Delta J = 0{,}1$; no parity change), are no longer compatible with the $3/2^-$ spin value of the ^{87}Br ground state adopted in ref. [2], but they lead to I^π (^{87}Br g.s.) $= 3/2^+$, $5/2^+$, $7/2^+$ or $5/2^-$, $7/2^-$, $9/2^-$. A positive parity and a spin value greater than 5/2 are not likely for the 35th proton, as the proton Fermi level is expected to be located within the orbits coming from the $\pi f_{5/2}$ and $\pi p_{3/2}$ subshells. Hence, the spin and parity of the ^{87}Br ground state

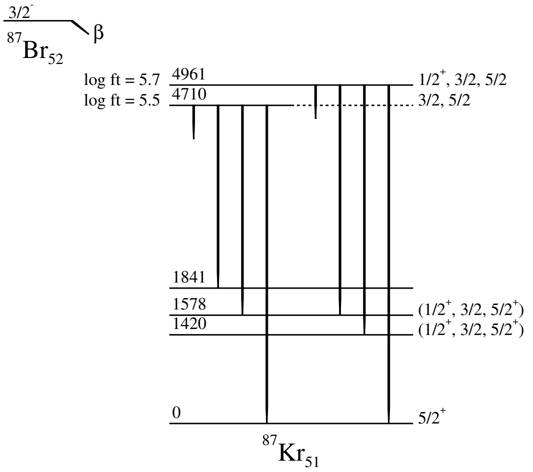

Fig. 3. Partial β-decay scheme of ^{87}Br, showing the spin values adopted in ref. [2].

are most probably $5/2^-$ (the 4961 and 4710 keV levels of ^{87}Kr being $7/2^-$).

Another argument can be put forward to substantiate the change of the ^{87}Br(g.s.) spin value, from 3/2 (which is the value measured [13] for its neighbouring isotone, ^{89}Rb) to 5/2. The levels observed in the β-decays of the two isotones (^{87}Br and ^{89}Rb) are not the same. In particular, the low-lying $9/2^+$ and $11/2^-$ levels of ^{89}Sr$_{51}$ [13] are not observed in the β-decay of ^{89}Rb, contrary to the $A = 87$ case as pointed out in this work.

4 Discussion

4.1 Excited states of ^{87}Kr

The energy levels of the $N = 51$ isotones can be divided into two groups: levels containing a large part of single-particle strength and those produced by the coupling of a single neutron to the core-excited states. In order to select the neutron sub-shells which are involved in the ^{87}Kr *yrast states* measured in the present work, we can rely on the single-neutron energies commonly used in the shell model calculations when ^{88}Sr$_{50}$ is chosen as the closed-shell core: $\epsilon(\nu d_{5/2}) = 0$ MeV, $\epsilon(\nu s_{1/2}) = 1.26$ MeV, $\epsilon(\nu d_{3/2}) = 2.23$ MeV, $\epsilon(\nu g_{7/2}) = 2.63$ MeV, and $\epsilon(\nu h_{11/2}) = 3.50$ MeV (*e.g.*, see ref. [14]). These sub-shell relative energies indicate that the *yrast states* of ^{87}Kr observed in this work can be directly compared to the coupling of the yrast excitations of its core, ^{86}Kr$_{50}$ [1,15], to a $d_{5/2}$ neutron, since the sub-shells with a higher-j value ($\nu g_{7/2}$ and $\nu h_{11/2}$) are located too high in energy.

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 $Z = 50$, namely $\pi f_{5/2}$, $\pi p_{3/2}$, $\pi p_{1/2}$, and $\pi g_{9/2}$. The 2_1^+ and 4_1^+ states of ^{86}Kr, at 1565 keV and 2250 keV, respectively, involve the re-orientation of the angular momenta in the fp sub-shells which are not completely filled. As for the 3^-, 5^-, 6^-, and 7^- states identified above 2.5 MeV excitation energy, their main configuration is $\pi[f_{5/2}/p_{3/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$.

The coupling of the $\nu d_{5/2}$ single neutron to the first positive-parity excitations of ^{86}Kr generates a lot of states. In the approximation of a weak-coupling scheme, the ^{87}Kr level scheme would exhibit, around 1565 keV excitation energy, a multiplet of 5 states ($1/2^+ \leq I \leq 9/2^+$) and around 2250 keV excitation energy, another multiplet of 6 states ($3/2^+ \leq I \leq 13/2^+$). It is worth pointing out that the energies of the 5 states, $\nu d_{5/2} \otimes 2_1^+$, are known in the ^{89}Sr neighbouring isotone [16,13]. The center of gravity of the quintet is found to be close to the 2_1^+ energy (this is discussed for any particle-core interaction in ref. [17]), nevertheless the splitting in energy between the quintet members is very large (almost 600 keV). Since there is no other multiplet with positive parity in this energy range in ^{89}Sr, the residual interactions only lift the degeneracy of these 5 states. On the other hand, in ^{87}Kr, the two multiplets, $\nu d_{5/2} \otimes 2_1^+$ and $\nu d_{5/2} \otimes 4_1^+$, are close in energy and the states with same spin values do strongly interact. Therefore complete shell model calculations are needed to assign *precise* configurations to the first positive-parity states identified in this work, as well as those observed from the ^{87}Br β-decay [2]. Nevertheless, the $\nu d_{5/2} \otimes \pi[f_{5/2}]^{-1} \otimes \pi[p_{3/2}]^{+1}$ configuration can be assigned to the 2614 keV state, since this is here the only one giving the maximum spin value, $13/2^+$.

The coupling of the $\nu d_{5/2}$ single neutron to the negative-parity excitations of ^{86}Kr, $\pi[f_{5/2}/p_{3/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$, leads to a lot of states with spin values up to $19/2^-$. The group of 4 states lying between 3525 and 4530 keV excitation energy in ^{87}Kr which exhibit the same characteristics (excitation energy as well as decay properties) as the 5^-, 6^-, and 7^- states of ^{86}Kr can be interpreted in terms of $\nu d_{5/2} \otimes \pi[f_{5/2}/p_{3/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$. As mentioned above, the 2259 keV state had been already observed in neutron transfer reaction, ^{86}Kr (d, p) ^{87}Kr. The very low value of its spectroscopic factor [2] indicates that it cannot have the pure single-particle configuration $\nu h_{11/2}$, but is in favor of a main configuration coming from the coupling $\nu d_{5/2} \otimes \pi[p_{3/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$. Similar $11/2^-$ states have been observed in the neighbouring isotones, ^{89}Sr and ^{91}Zr, their spectroscopic factors are low [13,18] and their excitation energies also exhibit strong correlation with the one of the 3^- state in the corresponding $N = 50$ core. This means that the energy of the first $11/2^-$ states of these $N = 51$ isotones is not a measure of the excitation energy of the $\nu h_{11/2}$ sub-shell, a similar conclusion on the $\pi h_{11/2}$ sub-shell has been already drawn from the study of the $_{51}$Sb isotopes [19].

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 [15]. They are located in the same energy range as the proton particle-hole states with negative parity (around 4 MeV). As the break of the neutron core is also expected in ^{87}Kr, it could be assumed that the 4372 keV level is the state having the maximum spin value of the configuration, $\nu[g_{9/2}]^{-1} \otimes \nu[d_{5/2}]^{+2}$, *i.e.* $17/2^+$, and the 3914 keV level would be the $15/2^+$ state.

Figure 4 sums up the energies of the ^{86,87}Kr states associated with the different proton particle-hole configurations, as well as those coming from the breaking of the neutron core. It is worth pointing out that, in each structure, a simple configuration can be assigned to the state having the maximum spin value:

- $\pi[f_{5/2}]^{-1} \otimes \pi[p_{3/2}]^{+1}$ for the 4^+
  and $\nu d_{5/2} \otimes \pi[f_{5/2}]^{-1} \otimes \pi[p_{3/2}]^{+1}$ for the $13/2^+$,
- $\pi[f_{5/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$ for the 7^-
  and $\nu d_{5/2} \otimes \pi[f_{5/2}]^{-1} \otimes \pi[g_{9/2}]^{+1}$ for the $19/2^-$,
- $\nu[g_{9/2}]^{-1} \otimes \nu[d_{5/2}]^{+1}$ for the 7^+
  and $\nu[g_{9/2}]^{-1} \otimes \nu[d_{5/2}]^{+2}$ for the $17/2^+$.

The differences in excitation energy between the corresponding states in ^{87,86}Kr can be related to the residual two-body interactions, $V_{res}(\nu d_{5/2}\pi f_{5/2})$, $V_{res}(\nu d_{5/2}\pi p_{3/2})$ and $V_{res}(\nu d_{5/2}\nu g_{9/2})$. The values extracted from the levels of ^{87,86}Kr and those extracted from the levels of some

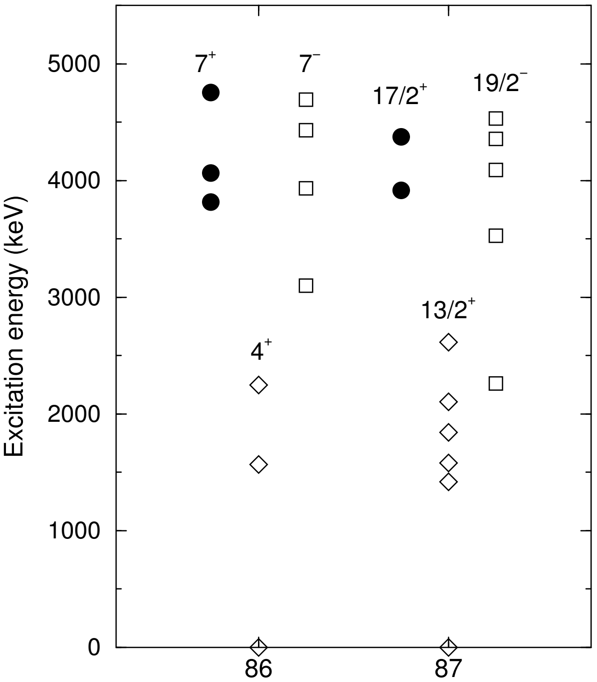

Fig. 4. Energies of the yrast states of ^{86}Kr [1] and ^{87}Kr (this work). States with proton configurations within the $\pi p_{3/2}f_{5/2}$ shells are drawn with empty diamonds, those containing the $\pi g_{9/2}$ shell are drawn with empty squares. States due to neutron-core excitation are drawn with filled circles. The maximum spin value within each structure is written above the corresponding state.

neighbouring odd-odd nuclei will be discussed in a forthcoming paper.

4.2 Spin of the ^{87}Br ground state

Some years ago, it has been established that the relative energies of the $\pi f_{5/2}$ and $\pi p_{3/2}$ proton sub-shells in neutron-rich $_{29}$Cu isotopes evolve as a function of the mass number, *i.e.* during the gradual filling of the $\nu g_{9/2}$ orbit [20]. The spin of the ground state of the odd-A Cu nuclei is $3/2^-$ up to $A = 73$, meaning that the first orbit located just above the $Z = 28$ shell closure is $p_{3/2}$. For $A > 69$, the excited $5/2^-_1$ state starts to strongly decrease in energy, so the spin of the ground state of the heavy odd-A Cu is expected to be $5/2^-$ for $A \geq 75$ [21]. This implies that a novel order of the two orbits takes place for that mass number, the $\pi f_{5/2}$ orbit being located just above $Z = 28$ and the $\pi p_{3/2}$ orbit just below $Z = 38$. This order is corroborated by the measured $3/2^-$ spin of the ground state of the *spherical* ^{87}Rb$_{50}$ and ^{85}Br$_{50}$ nuclei.

The $5/2^-$ value we have newly assigned to the ground state of ^{87}Br$_{52}$ has to be discussed within another approach. The behaviour of the excited states could be used with benefit to account for the ^{87}Br ground state. Unfortunately, no conclusion can be drawn from the very scarce results obtained in the β-decay of ^{87}Se [22].

On the other hand, the precise study of the β-decay of ^{89}Kr leads to a very complete level scheme of the neighbouring isotone ^{89}Rb$_{52}$, which could not be understood in terms of single-particle or particle-core coupling configurations associated with a quasi-spherical core [23]. Moreover, the high-spin structures of ^{89}Rb have been newly observed in our experiment, exhibiting a rotational behaviour [24]. When considering prolate deformation, all the low-energy levels can be explained as collective states built on the *deformed* orbitals lying close to the $Z = 37$ proton Fermi level for $\epsilon \sim +0.15$, namely the $3/2^-[301]$ issued from $p_{3/2}$ sub-shell, $5/2^-[303]$ from $f_{5/2}$ sub-shell (below the Fermi level) and $1/2^-[301]$ from $p_{1/2}$ sub-shell (above the Fermi level).

In such a case, the spin value of the ground state of ^{87}Br would turn out to be $5/2^-$, as the $Z = 35$ proton Fermi level is then close to the $5/2^-[303]$ orbital. The study of the high-spin structures in ^{87}Br would allow us to strengthen the appearance of a deformation as soon as the neutron number departs from $N = 50$ provided that several proton sub-shells with $\Delta l = 2$ are active.

5 Summary

The high-spin level scheme of the neutron-rich ^{87}Kr$_{51}$ isotope has been built for the first time. This isotope has been produced as fission fragments in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV, the γ-rays being detected using the Euroball IV array. The excited states of ^{87}Kr have been discussed in terms of both proton and neutron excitations, involving several sub-shells located close to the Fermi levels, particularly $\nu d_{5/2}$, $\pi p_{3/2}f_{5/2}$ and $\pi g_{9/2}$. The spin value of the ground state of ^{87}Br$_{52}$ has been re-evaluated to be $5/2^-$ in order to explain the feeding of some medium-spin states of ^{87}Kr from its β-decay.

The Euroball project was a collaboration between France, 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. M.-G.P. wishes to thank Dr D. Verney for fruitful discussions.

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