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Evolution of the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration in the neutron-rich $^{110,112}_{45}$Rh and $^{114,116}_{47}$Ag isotopes

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Abstract. The ^{110,112}Rh and ^{114,116}Ag nuclei have been produced as fission fragments in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV. Their level schemes have been built from gamma-rays detected using the Euroball IV array. High-spin states of these neutron-rich nuclei have been identified for the first time. The yrast structures consist of rotational bands in which the odd proton occupies the $\pi g_{9/2}$ sub-shell and the odd neutron the $\nu h_{11/2}$ sub-shell. The evolution of the $\pi g_{9/2} \otimes \nu h_{11/2}$ band structure is analyzed as a function of the neutron number.

PACS. 21.60.Ev Collective models – 23.20.Lv γ transitions and level energies – 25.85.Ge Charged-particle-induced fission – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The behaviour of the high-spin states generally provides fruitful information to characterize both the motion of the unpaired nucleons and the motion of the underlying core. We have recently published experimental results obtained in the neutron-rich ^{106,108}Rh and ^{110,112}Ag isotopes produced as fission fragments following the fusion reaction ^{28}Si + ^{176}Yb at 145 MeV bombarding energy [1]. The yrast high-spin states of these four odd-odd nuclei, consist of rotational bands in which the odd proton occupies the $\pi g_{9/2}$ subshell and the odd neutron the $\nu h_{11/2}$ subshell. The proton Fermi level is located among the high-K orbitals of the $\pi g_{9/2}$ subshell, while the neutron Fermi level lies at the bottom of the $\nu h_{11/2}$ subshell. Therefore, a perpendicular coupling of the angular momenta of the strongly coupled odd proton and of the decoupled odd neutron leads to a spin value $I \sim 6$ for the first level corresponding to this configuration.

When the spin increases, the observed rotational bands do not display regular structure, excited levels with one signature being shifted as compared to the ones with the other signature. Moreover, the signature splitting is anomalous: the odd-spin states are observed to be favored, contrary to the expectation for such a $j_n \otimes j_p$ configuration [2]. It is worth noting that observation of anomalous signature splitting is a common feature in many mass regions (see, for instance, [3–5]) and the signature inversion effect has been studied in various theoretical frameworks (see, for instance, [2,6–8]) leading to different explanations.

We report here new results obtained using the fusion-fission reaction, ^{18}O + ^{208}Pb, which populates heavier isotopes as compared to the one we have previously used, ^{28}Si + ^{176}Yb. The high-spin states of the ^{110,112}Rh and ^{114,116}Ag nuclei have been identified for the first time. They are also built on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. The staggering observed in the yrast bands of the odd-odd

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$^{102-112}$Rh and $^{104-116}$Ag nuclei is discussed as functions of spin and neutron number.

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 20 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 and each Clover detector consists of four smaller Ge crystals.

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. About 0.7×10^9 coincidence events were registered. The offline analysis consisted of both usual γ-γ sorting and multi-gated spectra using the Fantastic software [10] and a three-dimensional "cube" built and analysed with the Radware package [11].

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 the majority of 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 [12,13]. 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 [14]. 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 evaporated neutrons (sum of the pre- and post-fission emitted neutrons) is mainly 5-6. This has been used to identify the γ-ray cascades of ^{110,112}Rh and ^{114,116}Ag nuclei, as explained in the next section.

3 Experimental results

Several odd-A Rh isotopes (^{107,109,111,113}Rh) have been identified from the fusion-fission $^{18}O + ^{208}Pb$ reaction, the maximum of the yields being centered around $A = 110$ [15]. In this reaction the complementary fragments of $_{45}$Rh isotopes are the other Rh isotopes, $Z = 45$ being half the atomic number of the ^{226}Th compound nucleus. The main complementary fragment of ^{110}Rh (^{112}Rh, respectively) is ^{111}Rh (^{109}Rh, respectively). The transitions, depopulating the high-spin states of ^{112}Rh for instance, can be identified from double gates set on two transitions of ^{109}Rh. Obviously, they are not to be observed in the analogue gated spectra built from our previous data set obtained using the $^{28}Si + ^{176}Yb$ fusion-fission reaction [16]. Then these new transitions are used for further investigations of the coincidence data. Examples of double-gated spectra showing new transitions depopulating high-spin states of ^{110,112}Rh are given in fig. 1. One can notice that a transition having the same energy (159 keV) is observed in both isotopes.

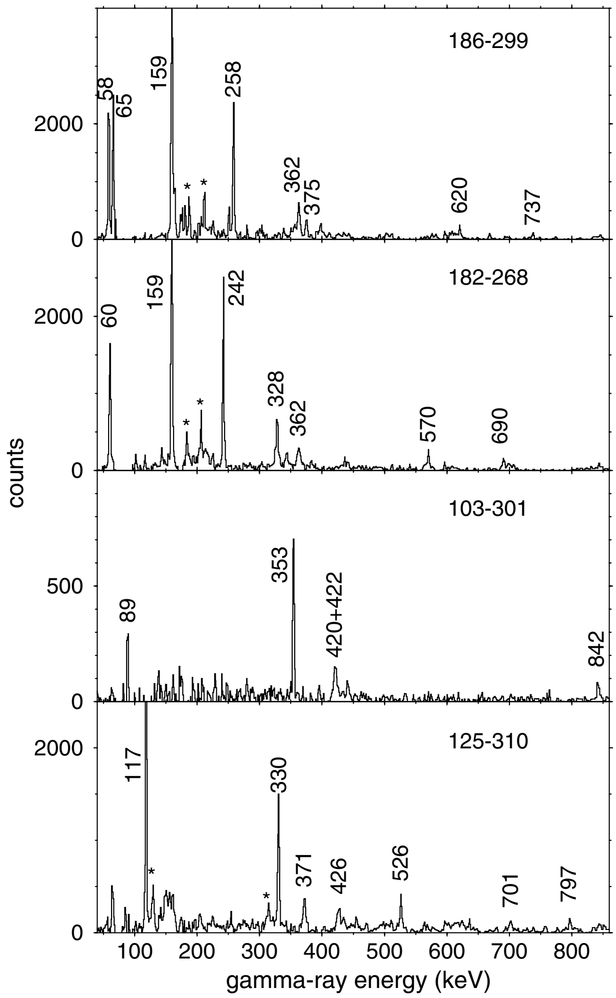

Fig. 1. Spectra of γ-rays in double coincidence with two transitions of ^{110}Rh (186 and 299 keV), of ^{112}Rh (182 and 268 keV), of ^{114}Ag (103 and 301 keV), and of ^{116}Ag (125 and 310 keV). The lines marked with a star belong to their complementary fragments.

The high-spin level schemes of ^{110,112}Rh deduced in the present work are presented in fig. 2. All the new transitions assigned to these two isotopes are given in table 1. The new structures comprise firstly, several low-energy transitions (58, 65, and 159 keV in ^{110}Rh and 60, and 159 keV in ^{112}Rh) and secondly, a set of six coincident gamma rays with the corresponding cross-over transitions, which leads to three parallel cascades. They display the same features as the ^{106,108}Rh ones [1]. Therefore, the three parallel

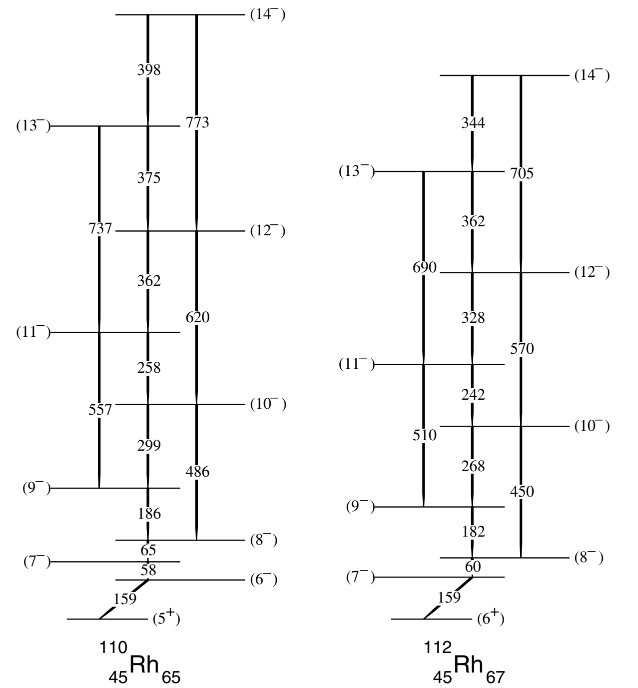

Fig. 2. High-spin level schemes of ^{110,112}Rh, obtained as fission fragments in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV beam energy. The energies of the (5^+) and (6^+) long-lived isomeric states ($T_{1/2} = 28.5$ s and $T_{1/2} = 6.8$ s, respectively [17]) are not known.

cascades of transitions have been placed above the (8^-) state of the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration. The decays of this state involving 3 (2) gamma rays in ^{110}Rh (^{112}Rh) are consistent with the spin values proposed for the long-lived isomeric states of ^{110,112}Rh, (5^+) and (6^+) respectively, which are known to de-excite by β-decays to the medium-spin states of Pd [18]. Multipolarity are usually assigned to low-energy transitions located in the bottom of level schemes, using the values of their total internal conversion coefficients which can be deduced, in some selected gated spectra, from the values of their gamma-ray intensities and intensity imbalances. Whereas such an analysis has been done for ^{106,108}Rh obtained in our previous experiment [1], it could not be performed in the present one for ^{110,112}Rh because any gated spectrum is misleading to make use of intensities of gamma rays located below the gates, i) the complementary fragment of ^{110}Rh is often ^{110}Rh (the total number of evaporated neutrons can be 6), ii) the first transition in the two isotopes has the same energy (159 keV) and the complementary fragment of ^{112}Rh is sometimes ^{110}Rh.

The main complementary fragment of ${}^{114}_{47}$Ag (${}^{116}_{47}$Ag, respectively) isotope is ${}^{107}_{43}$Tc (${}^{105}_{43}$Tc, respectively), in the fusion-fission reaction, ^{18}O + ^{208}Pb, at 85 MeV bombarding energy. The gamma rays de-exciting the high-spin states of ^{105,107}Tc have been already measured from spontaneous fission of ^{252}Cf [19]. Therefore, several transitions depopulating high-spin states of ^{114,116}Ag (103, 301, and 353 keV, and 117, 125, and 310 keV, respectively) have been identified from double gates set on two transitions of ^{107,105}Tc. Then these transitions have been used to build double-gated spectra in order to identify the other transitions. Examples of these double-gated spectra are given in fig. 1 and all the new transitions assigned to ^{114,116}Ag are given in table 2. The level schemes of ^{114,116}Ag deduced in the present work are presented in fig. 3. The yield of ^{114}Ag being low, its level scheme is slightly less developed. The structures of ^{114,116}Ag are very similar to the ones of the lighter isotopes, ^{110,112}Ag [1] and of the Rh nuclei. Only one low-energy transition has been found below the (8^-) state of the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration (103 keV in ^{114}Ag and 117 keV in ^{116}Ag), so we can assume that the two transitions involved in the expected cascade $8^- \to 7^- \to 6^-$ (cf. the lower-mass isotopes [1,20,21]) have probably escaped from our experimental detection (they are noted by X and Y in fig. 3).

It is worth pointing out that the first transition of the ^{115}Ag isotope ($9/2^+ \to 7/2^+_{gs}$ [17]) has the same energy

Table 1. Properties of the new transitions assigned to ^{110,112}Rh produced as fission fragment in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV. The γ-rays were detected with the Euroball IV array, with the requirement that a minimum of three unsuppressed Ge detectors fired in prompt coincidence.

	$E_\gamma^{(a)}$ (keV)	$I_\gamma^{(a,b)}$	$J_i \to J_f$
^{110}Rh	57.7 (4)	–	$(7^-) \to (6^-)$
	64.7 (4)	–	$(8^-) \to (7^-)$
	158.8 (2)	–	$(6^-) \to (5^+)$
	186.2 (2)	100 (10)	$(9^-) \to (8^-)$
	257.6 (2)	36 (5)	$(11^-) \to (10^-)$
	299.3 (2)	60 (6)	$(10^-) \to (9^-)$
	362.1 (3)	24 (4)	$(12^-) \to (11^-)$
	374.8 (4)	10 (3)	$(13^-) \to (12^-)$
	397.6 (5)	4 (2)	$(14^-) \to (13^-)$
	486.3 (7)	7 (2)	$(10^-) \to (8^-)$
	557.4 (7)	18 (4)	$(11^-) \to (9^-)$
	619.8 (5)	13 (3)	$(12^-) \to (10^-)$
	737.3 (7)	8 (2)	$(13^-) \to (11^-)$
	772.8 (7)	4 (2)	$(14^-) \to (12^-)$
^{112}Rh	59.7 (4)	–	$(8^-) \to (7^-)$
	158.6 (2)	–	$(7^-) \to (6^+)$
	182.4 (2)	100 (10)	$(9^-) \to (8^-)$
	241.5 (2)	45 (5)	$(11^-) \to (10^-)$
	268.2 (2)	52 (5)	$(10^-) \to (9^-)$
	327.8 (4)	20 (5)	$(12^-) \to (11^-)$
	343.5 (5)	5 (2)	$(14^-) \to (13^-)$
	362.2 (4)	9 (3)	$(13^-) \to (12^-)$
	449.9 (7)	10 (3)	$(10^-) \to (8^-)$
	510.0 (5)	13 (3)	$(11^-) \to (9^-)$
	569.7 (5)	8 (2)	$(12^-) \to (10^-)$
	690.5 (5)	11 (3)	$(13^-) \to (11^-)$
	705.3 (5)	4 (2)	$(14^-) \to (12^-)$

(a) The number in parentheses is the error in the last digit.
(b) The intensity has been normalized using the spectrum gated by the first γ-rays of the cascades (159 and 65 keV transitions for ^{110}Rh, 159 and 60 keV transitions for ^{112}Rh).

Table 2. Properties of the new transitions assigned to ^{114,116}Ag (see caption of table 1).

	$E_\gamma^{(a)}$ (keV)	$I_\gamma^{(a,b)}$	$J_i \rightarrow J_f$
^{114}Ag	88.9 (3)	–	$(9^-) \rightarrow (8^-)$
	102.8 (2)	–	$(6^-) \rightarrow (5^+, 6^+)$
	301.2 (2)	38 (5)	$(11^-) \rightarrow (10^-)$
	353.3 (2)	100 (10)	$(10^-) \rightarrow (9^-)$
	420.5 (3)	20 (5)	$(13^-) \rightarrow (12^-)$
	422.0 (4)	37 (5)	$(12^-) \rightarrow (11^-)$
	653.5 (3)	43 (5)	$(11^-) \rightarrow (9^-)$
	722.5 (4)	11 (3)	$(12^-) \rightarrow (10^-)$
	841.8 (4)	34 (5)	$(13^-) \rightarrow (11^-)$
^{116}Ag	117.4 (2)	–	$(6^-) \rightarrow (5^+)$
	125.4 (2)	–	$(9^-) \rightarrow (8^-)$
	310.4 (2)	100 (10)	$(10^-) \rightarrow (9^-)$
	329.7 (2)	53 (5)	$(11^-) \rightarrow (10^-)$
	371.4 (2)	34 (5)	$(12^-) \rightarrow (11^-)$
	425.3 (3)	17 (3)	$(13^-) \rightarrow (12^-)$
	426.5 (3)	12 (4)	$(14^-) \rightarrow (13^-)$
	454.5 (4)	6 (2)	
	525.8 (3)	17 (4)	
	640.5 (3)	54 (5)	$(11^-) \rightarrow (9^-)$
	701.4 (4)	18 (3)	$(12^-) \rightarrow (10^-)$
	796.6 (4)	29 (4)	$(13^-) \rightarrow (11^-)$
	851.3 (5)	9 (3)	$(14^-) \rightarrow (12^-)$
	910.4 (4)	13 (3)	$(15^-) \rightarrow (13^-)$

(^{a}) The number in parentheses is the error in the last digit.
(^{b}) The intensity has been normalized using the spectrum gated by the two first γ-rays of the cascades (89 and 103 keV transitions for ^{114}Ag, 117 and 125 keV transitions for ^{116}Ag).

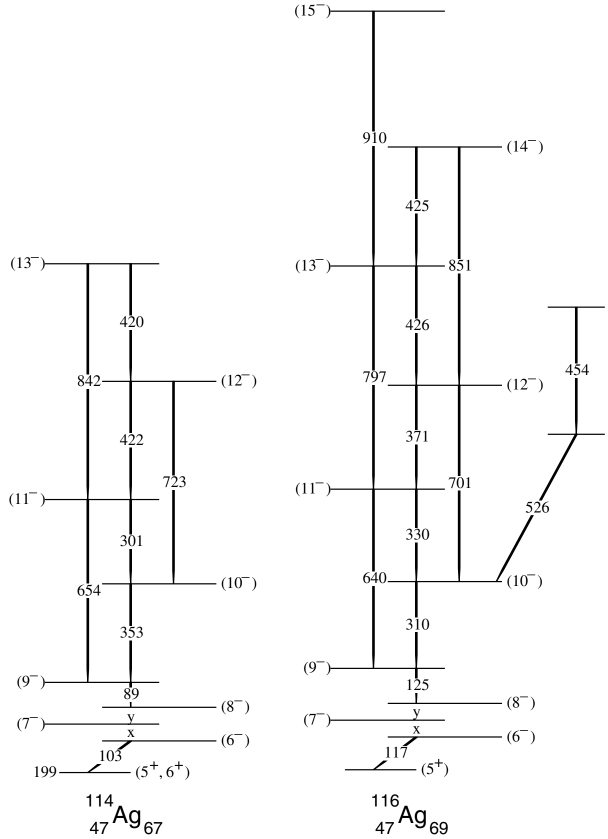

Fig. 3. High-spin level schemes of ^{114,116}Ag, obtained as fission fragments in the fusion reaction $^{18}O + ^{208}Pb$ at 85 MeV beam energy. The (5^+, 6^+) state at 199 keV of ^{114}Ag is known to be isomeric, $T_{1/2} = 1.5$ ms [25]. The energy of the (5^+) long-lived state in ^{116}Ag ($T_{1/2} = 10.4$ s [17]) is not known.

as one of the yrast cascade found in ^{116}Ag (125 keV). The existence of such a doublet has been proved by a careful analysis of many multi-gated spectra involving the corresponding Tc complementary fragments. A complete high-spin level scheme of ^{115}Ag has been built from our data set [22]. Finally, the band labelled D in the ^{115}Ag level scheme recently published by other authors [23] comprises the transitions actually belonging to the yrast cascade of ^{116}Ag (see fig. 3).

4 Discussion

The new structures observed in ^{110,112}Rh and ^{114,116}Ag are similar to the ones measured in the lighter isotopes, ^{106,108}Rh and ^{110,112}Ag, which have been already discussed in our previous paper [1]. The $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration has been assigned to the 6^- band-head state, because of the value of its g-factor measured in ^{104}Rh [24]. The present results allow us to discuss the evolution of these yrast structures built on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration, when the neutron number increases well beyond the 50-82 mid-shell.

The most striking feature of these yrast structures is the signature splitting which evolves as a function of angular momentum. The signature splitting can be evaluated from the value of the staggering defined as $S(I) = [E(I) - E(I-1)] - \frac{1}{2}\{[E(I+1) - E(I)] + [E(I-1) - E(I-2)]\}$, where $E(I)$ is the excitation energy of the state of spin I. Whereas the values obtained in the odd-A Rh and Ag isotopes remain almost constant as a function of spin values, the staggering strongly decreases when the spin is increasing in the odd-odd Rh and Ag isotopes (see, for instance, fig. 6 of [1]). Moreover, the energies of the odd-spin states are lowered, whereas the favored signature α_f [2] of the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration is expected to be equal to 0, meaning that the signature splitting observed here is anomalous.

Anomalous signature splitting has been observed in many mass regions, $A \sim 80$ for the $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration [3], $A \sim 120$ for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration [4], $A \sim 150$ for the $\pi h_{11/2} \otimes \nu i_{13/2}$ configuration [5]. This effect has been studied in various theoretical frameworks, giving different explanations, for instance the influence of triaxial shapes [6] or the particular locations of the two Fermi levels among the orbitals originating from high-j subshells for axial shapes [2,7]. Moreover, a significant residual proton-neutron interaction can also induce an anomalous signature splitting followed by signature inversion [8].

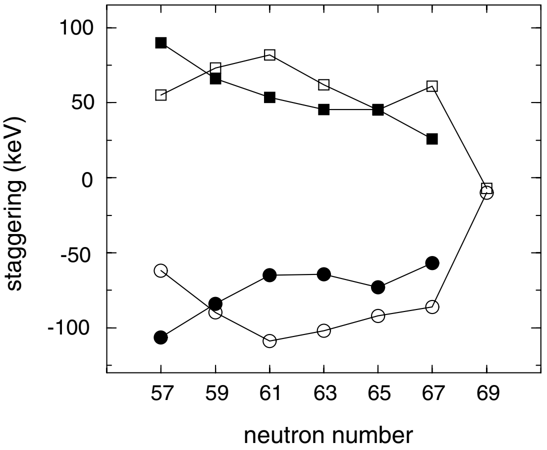

Fig. 4. Staggerings observed in the $\pi g_{9/2} \otimes \nu h_{11/2}$ bands of Rh and Ag isotopes as functions of neutron number: values for $I = 11^-$, Rh (filled circles), Ag (empty circles); values for $I = 12^-$, Rh (filled squares), Ag (empty squares).

The staggerings calculated for the 11^- and 12^- yrast states of the odd-odd Rh and Ag isotopes are drawn as functions of neutron number in fig. 4. A negative value is obtained for $I = 11^-$ and a positive one for $I = 12^-$, meaning that the even spin-states are unfavored, as mentioned above. Whereas the staggering values are almost constant from $N = 57$ to $N = 67$, for both isotopic series, a large change is observed in ^{116}Ag$_{69}$ which exhibits very small signature splitting. It is worth pointing out that only the study of a particular $\pi \otimes \nu$ configuration along wide isotopic chains can lead to such a piece of information. The sudden variation of the staggering values allows us to put forward one explanation for the anomalous signature splitting of the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration observed when $N \leq 67$.

A large change in deformation cannot be invoked since the energies of the $E2$ transitions of the odd-odd isotopes evolve very slowly and regularly, from $N = 57$ to $N = 69$. Likewise the level schemes of the neighbouring nuclei (even-even, odd-Z, and odd-N) do not show any large modification. Therefore, the filling of the orbitals for $N = 69$ is probably responsible for the disappearance of the staggering in ^{116}Ag. Indeed for the moderate prolate deformation of Ag isotopes, the Fermi level corresponding to such a neutron number is located near or above the $\Omega = 3/2$ orbit of the $\nu h_{11/2}$ subshell (see fig. 10 of ref. [26]). Conversely, the location of the Fermi level well below or near the $\Omega = 1/2$ orbit of the $\nu h_{11/2}$ subshell would induce the large signature inversion observed in the odd-odd isotopes with $N \leq 67$.

In the framework of a rotor plus two-particle model, the signature splitting is due to the decoupling parameters of the two $\Omega = 1/2$ orbits, which have very large values for the unique-parity orbits, such as $\nu h_{11/2}$ and $\pi g_{9/2}$. The signature inversion is then the result of the propagation of the decoupling via Coriolis mixings, depending on the location of the neutron and proton Fermi levels among the two subshells. For instance, Hamamoto has shown [2] that the anomalous signature splitting observed in the $\nu i_{13/2} \otimes \pi h_{11/2}$ band of ^{160}Ho for spins lower than 12 can be well reproduced when a $\Omega = 1/2$ neutron and a $\Omega = 5/2$ proton are coupled to an axially deformed core. A similar feature could explain the case of the odd-odd Rh and Ag with $N \leq 67$, whereas the strong decrease of the influence of the $\Omega = 1/2$ neutron orbit, expected when the neutron Fermi level moves up, would lead to a very low signature splitting for $N = 69$.

One can notice that in the odd-N $_{46}$Pd, the high-spin structures built on the $\nu h_{11/2}$ subshell remain almost the same up to $N = 71$ (decoupled bands built on $11/2^-$ states) [27–29]. On the contrary, large difference is observed when the neutron-subshell filling increases if one $h_{11/2}$ neutron is coupled to one $g_{9/2}$ proton, as seen here in the odd-odd Ag isotopes up to ^{116}Ag. The effect of the filling of the $\nu h_{11/2}$ subshell can be also tracked in the $\pi g_{9/2} \otimes \nu h^2_{11/2}$ configuration observed in the odd-A $_{49}$In isotopes, this will be discussed in a forthcoming paper [30].

5 Summary

In this work the high-spin level schemes of ^{110,112}Rh and ^{114,116}Ag isotopes have been built for the first time. These isotopes have been produced as secondary fission fragments in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV, the γ-rays being detected using the Euroball IV array. The rotational structures built on the $\pi g_{9/2} \otimes \nu h_{11/2}$ configuration have been observed. The evolution of the staggering measured in these bands has been analyzed as a function of the neutron number in the two isotopic series. Whereas the staggering remains large and almost constant for $N \leq 67$, it almost disappears in ^{116}Ag$_{69}$ in which the energies of the $M1$ transitions increase regularly as a function of angular momentum. This would mean that the anomalous signature splitting measured in $^{102-112}$Rh and $^{104-114}$Ag originates from the location of the neutron Fermi level among the $\nu h_{11/2}$ orbitals, given the proton Fermi level among the high-K $\pi g_{9/2}$ orbitals.

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