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Short Note

High-spin structure of the neutron-rich $^{109,111,113}_{45}$Rh isotopes

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Abstract. The ^{109,111,113}Rh 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 the neutron-rich ^{111,113}Rh nuclei have been identified for the first time. Several rotational bands with the odd proton occupying the $\pi g_{9/2}$, $\pi p_{1/2}$ and $\pi(g_{7/2}/d_{5/2})$ sub-shells have been observed. A band of low-energy transitions has been identified at excitation energy around 2 MeV in ^{109,111}Rh, which can be interpreted in terms of three-quasiparticle excitation, $\pi g_{9/2}\ \nu h_{11/2}\ \nu g_{7/2}/d_{5/2}$. In addition another structure built on states located at low excitation energy (608 keV in ^{111}Rh, 570 keV in ^{113}Rh) points out that, as already observed in the lighter isotopes ^{107,109}Rh, triaxial deformation plays a role in the neutron-rich Rh isotopes well beyond the mid-shell.

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

1 Introduction

Low-spin structure of the neutron-rich ^{107,109,111,113}Rh isotopes has been extensively studied from β-decay of Ru isotopes produced by thermal neutron-induced fission of ^{239}Pu [1] and ^{249}Cf [2,3], and by proton-induced fission of ^{238}U [4], respectively. In such experiments, a lot of excited states are populated and unfortunately configurations can be assigned for only a few of them. Even-parity low-energy levels are mainly built on the $\pi g_{9/2}$ sub-shell, whereas some odd-parity levels are built on the $\pi p_{1/2}$ sub-shell. Moreover, the first members of the band corresponding to the intruder $1/2^+[431]$ proton orbital are observed at low energy.

The behaviour of the high-spin states generally provides fruitful information to characterize both the motion of the odd nucleon and the motion of the underlying core. We have recently published [5] experimental results obtained in ^{107,109}Rh produced as fission fragments following the fusion reaction ^{28}Si + ^{176}Yb at 145 MeV bombarding energy.

We report here new results obtained using another fusion reaction, ^{18}O + ^{208}Pb, which populates heavier isotopes as compared to the previous one. New structures have been observed in ^{109}Rh and the high-spin states of the very neutron-rich ^{111,113}Rh nuclei have been identified for the first time.

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 accelera-

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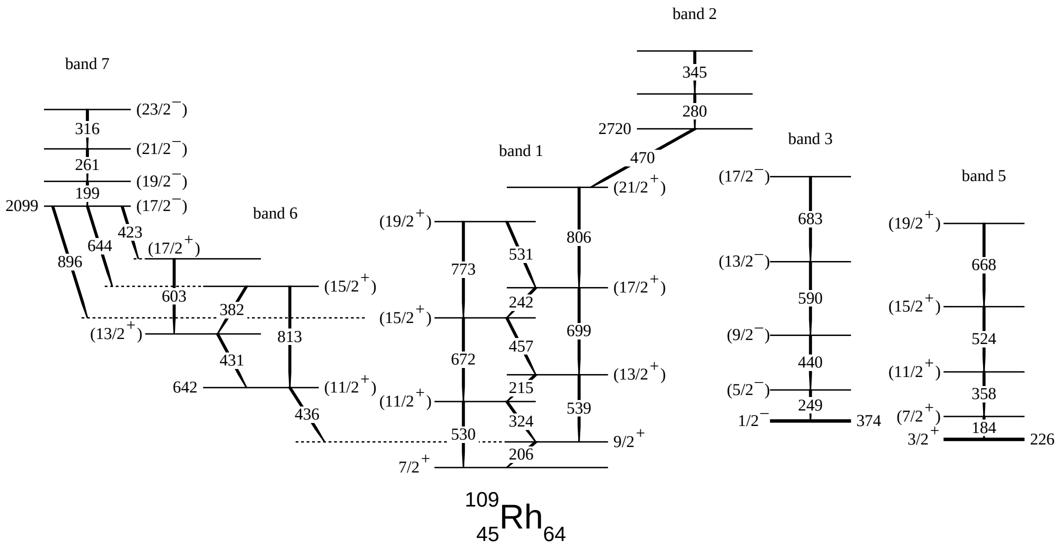

Fig. 1. Level scheme of ^{109}Rh obtained as a fission fragment in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV beam energy. The spin and parity values given without parenthesis have been established from β-decay measurements [6]. The γ-decays of the isomeric states located at 226 keV ($T_{1/2} = 1.66\ \mu$s) and 374 keV ($T_{1/2} = 33$ ns) are not drawn for sake of clarity, they can be found in ref. [6].

tor 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 [7]. 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 [8] and a three-dimensional "cube" built and analysed with the Radware package [9].

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 [10,11]. 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 [12]. 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 6. This number has been used to identify the γ-ray cascades of ^{111,113}Rh nuclei, as explained in the next section.

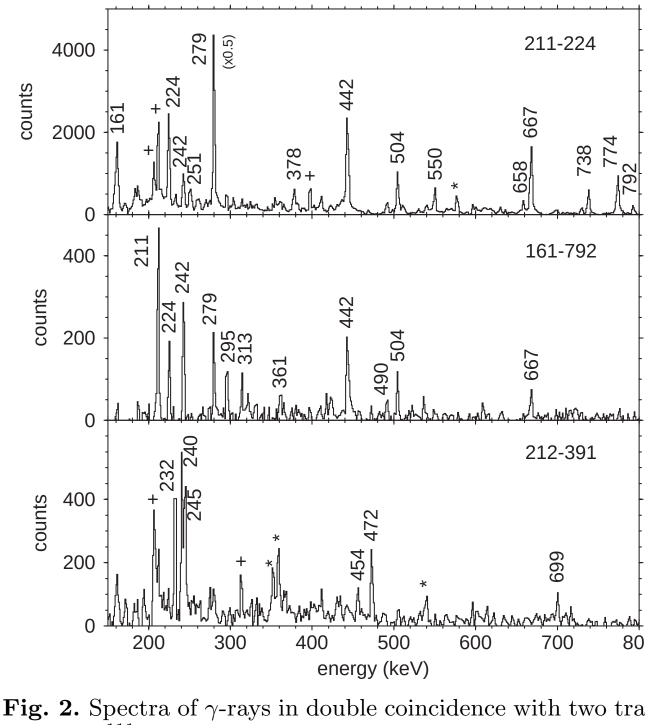

Fig. 2. Spectra of γ-rays in double coincidence with two transitions of ^{111}Rh (top spectrum: 211 and 224 keV, middle spectrum: 161 and 792 keV), of ^{113}Rh (bottom spectrum: 212 and 391 keV). The lines marked with a cross belong to their complementary fragments. Those marked with a star belong to other fission fragments. The 279 keV peak (top spectrum) has been reduced by a factor of 2.

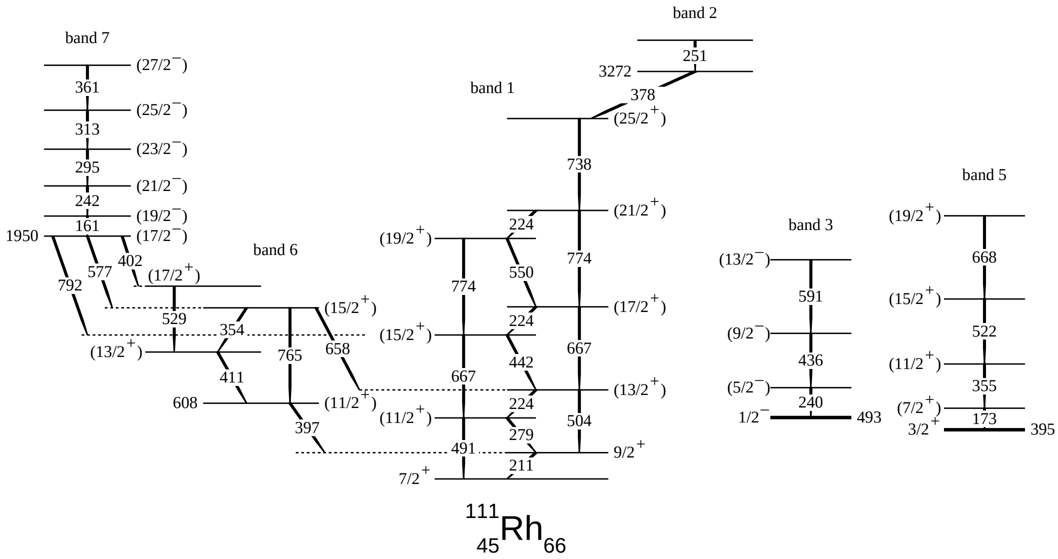

Fig. 3. Level scheme of ^{111}Rh obtained as a fission fragment in the fusion reaction ^{18}O + ^{208}Pb at 85 MeV beam energy. The spin and parity values given without parenthesis have been established from β-decay measurements [3]. The γ-decays of the isomeric states located at 395 keV ($T_{1/2}$ = 87 ns) and 493 keV ($T_{1/2}$ = 6.8 ns) are not drawn for sake of clarity, they can be found in ref. [3].

3 Experimental results

Several odd-A Rh isotopes (^{107,109,111,113}Rh) are populated in the fusion-fission reaction used in this work, the maximum of the yields being centered around $A = 110$. The high-spin states of ^{107}Rh observed in this work extend up to spin (29/2) and are in complete agreement with those already known from our previous work [5]. A more complete level scheme of ^{109}Rh has been deduced from the present experiment. As in lighter isotopes [5,13, 14], the levels have been grouped into structures according to their rotational behaviours (see fig. 1). Two structures, band 2 and band 5, have been observed for the first time.

In the ^{18}O + ^{208}Pb reaction the complementary fragments of $_{45}$Rh isotopes are other Rh isotopes, $Z = 45$ being half the atomic number of the ^{226}Th compound nucleus. The main complementary fragment of ^{111}Rh (^{113}Rh, respectively) is ^{109}Rh (^{107}Rh, respectively). Therefore new transitions, depopulating high-spin states of ^{111}Rh for instance, can be identified from double gates set on one transition of ^{109}Rh and one transition belonging to the low-energy part of the ^{111}Rh level scheme, which is known from β-decay measurement [3]. Then these new transitions are used for further investigations of the coincidence data. Examples of double-gated spectra built from our data set showing new transitions depopulating high-spin states of ^{111,113}Rh are given in fig. 2.

The level scheme of ^{111}Rh deduced in the present work is presented in fig. 3. It displays the same features as the ^{109}Rh one. The building of band 1 has been very difficult because of the occurence of two unresolved doublets (667 and 774 keV) and one triplet (224 keV) of transitions. These doublets and triplet have been proved by a careful analysis of many multi-gated spectra. First of all, the double gating on 211 and 504 keV transitions gives the 224, 442, 550, 667, 738, 774 keV transitions. Taking into account the coincidence relationships observed in spectra obtained by gating on all double combinations among these eight transitions, a first sequence, comprising the 504, 667, 774, and 738 keV transitions (right part of band 1), and a second one, comprising the 279, 224, 442, 224, 550 keV transitions (middle part of band 1), can be placed on the 211 keV level. The second member of the 667 keV doublet (feeding the 491 keV level) is given thanks to one of the decay paths of the 1950 keV level of band 7 (792 keV transition). A double gate on the 161 and 792 keV γ-rays (see the middle spectrum of fig. 2) shows a 667 keV which does de-excite the $(15/2^+)$ level. Moreover, three 224 keV transitions are observed in self-coincidence: a 224 keV transition is observed in a spectrum obtained by double gating on 224 and 224 keV transitions. The observation of a 224 keV transition in the spectrum obtained in coincidence with 738 and 550 keV γ-rays implies the location of the third 224 keV transition, which de-excites the $(21/2^+)$ level. In such a level scheme, the second member of the 774 keV doublet cannot be proved from any spectrum, but it has to be placed here, $(19/2^+) \to (15/2^+)$, in order to provide this expected link. All the new transitions assigned to ^{111}Rh are given in table 1.

The high-spin states of ^{113}Rh have been also studied from our data set. We have used the same method as described in the previous paragraph in order to identify the main transitions populating the first excited state known at 211.7 keV [6]. The main complementary fragment of ^{113}Rh is ^{107}Rh. The spectrum of γ-rays in coincidence with the first transitions of the two isotopes (194 keV and 212 keV) exhibits the main transitions of ^{107}Rh [5] and new transitions which can be assigned to ^{113}Rh, such as 232,

Table 1. Properties of the new transitions assigned to ^{111,113}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)	$I_\gamma^{(a)}$	$J_i \to J_f$
^{111}Rh	160.6(5)	20(5)	$(19/2^-) \to (17/2^-)$
	172.5(4)	2(1)	$(7/2^+) \to 3/2^+$
	211.2(3)	100(10)	$9/2^+ \to 7/2^+$
	224.4(5)	29(6)	$(13/2^+) \to (11/2^+)$
		13(3)$^{(b)}$	$(17/2^+) \to (15/2^+)$
			$(21/2^+) \to (19/2^+)$
	239.8(3)	20(4)	$(5/2^-) \to 1/2^-$
	242.0(4)	12(3)	$(21/2^-) \to (19/2^-)$
	250.6(5)	3(2)	
	279.2(3)	32(7)	$(11/2^+) \to 9/2^+$
	294.8(4)	7(2)	$(23/2^-) \to (21/2^-)$
	312.7(5)	5(2)	$(25/2^-) \to (23/2^-)$
	354.2(3)	13(3)	$(15/2^+) \to (13/2^+)$
	355(1)	7(3)	$(11/2^+) \to (7/2^+)$
	361.3(7)	3(1)	$(27/2^-) \to (25/2^-)$
	377.6(5)	5(2)	$\to (25/2^+)$
	396.7(3)	29(5)	$(11/2^+) \to (9/2^+)$
	401.8(3)	9(2)	$(17/2^-) \to (17/2^+)$
	410.6(3)	32(7)	$(13/2^+) \to (11/2^+)$
	435.6(4)	16(3)	$(9/2^-) \to (5/2^-)$
	442.2(3)	24(5)	$(15/2^+) \to (13/2^+)$
	490.7(4)	16(3)	$(11/2^+) \to 7/2^+$
	503.9(4)	24(5)	$(13/2^+) \to 9/2^+$
	521.9(4)	5(2)	$(15/2^+) \to (11/2^+)$
	529.0(4)	12(3)	$(17/2^+) \to (13/2^+)$
	549.7(5)	7(3)	$(19/2^+) \to (17/2^+)$
	576.8(4)	13(3)	$(17/2^-) \to (15/2^+)$
	591(1)	8(2)	$(13/2^-) \to (9/2^-)$
	658.0(4)	7(2)	$(15/2^+) \to (13/2^+)$
	667.1(4)	12(3)	$(15/2^+) \to (11/2^+)$
		22(3)	$(17/2^+) \to (13/2^+)$
	668(1)	3(1)	$(19/2^+) \to (15/2^+)$
	737.7(6)	7(2)	$(25/2^+) \to (21/2^+)$
	765.2(4)	8(2)	$(15/2^+) \to (11/2^+)$
	774(1)	13(3)$^{(b)}$	$(19/2^+) \to (15/2^+)$
			$(21/2^+) \to (17/2^+)$
	792.1(4)	5(2)	$(17/2^-) \to (15/2^+)$
^{113}Rh	211.6(3)	100(15)	$(7/2^+) \to (9/2^+)$
	231.6(3)	31(5)	$(11/2^+) \to (9/2^+)$
	240.3(3)	40(5)	$(13/2^+) \to (11/2^+)$
	244.5(4)	15(4)	$(17/2^+) \to (15/2^+)$
	347.5(5)	10(3)	$(15/2^+) \to (13/2^+)$
	358.4(4)	26(5)	$(11/2^+) \to (9/2^+)$
	365.0(4)	20(4)	$(13/2^+) \to (11/2^+)$
	390.9(4)	20(4)	$(15/2^+) \to (13/2^+)$
	443.5(4)	25(5)	$(11/2^+) \to (7/2^+)$
	454.4(6)	15(4)	$(19/2^+) \to (17/2^+)$
	472.1(4)	29(5)	$(13/2^+) \to (9/27^+)$
	475.7(7)	6(2)	$(17/2^+) \to (13/2^+)$
	631.4(5)	8(2)	$(15/2^+) \to (11/2^+)$
	635.7(5)	16(4)	$(17/2^+) \to (13/2^+)$
	698.9(8)	6(2)	$(19/2^+) \to (15/2^+)$
	717.6(8)	6(2)	$(21/2^+) \to (17/2^+)$

(^{a}) The number in parenthesis is the error in the last digit.
(^{b}) Total intensity of the doublet.

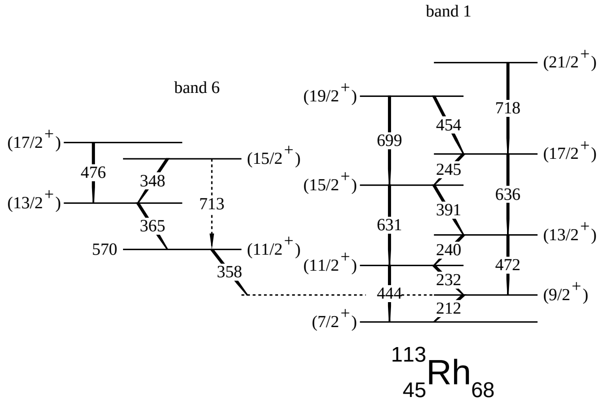

Fig. 4. Level scheme of ^{113}Rh obtained as a fission fragment in the fusion reaction $^{18}O + ^{208}Pb$ at 85 MeV beam energy. The first two excited states have been already observed in β-decay measurements [6,4].

240, 358 and 391 keV. All the new transitions assigned to ^{113}Rh are given in table 1 and one example of double-gated spectrum is given in fig. 2. It is worth pointing out that the 232 keV transition had been already observed in the β-decay of ^{113m}Ru [6]. The level scheme deduced from all the coincidence relationships is given in fig. 4. It is less developed than the lighter Rh isotopes, because of its lower yield. Only band 1 and band 6 have been identified. Their behaviours are very similar to the ones of the lighter isotopes.

One can notice that the direct decay of the second excited state to the ground state $(11/2^+ \to 7/2^+)$ strongly increases with the number of neutrons: The branching ratio $I_\gamma(11/2^+ \to 7/2^+)$ / $I_\gamma(11/2^+ \to 9/2^+)$ is 0.2 in ^{109}Rh, 0.5 in ^{111}Rh, and 0.8 in ^{113}Rh.

4 Discussion

High-spin states of ^{107,109}Rh isotopes have been already discussed in our previous paper [5]. Several structures are foreseen when the odd proton occupies the $\pi g_{9/2}$, $\pi p_{1/2}$ and $\pi(g_{7/2}/d_{5/2})$ sub-shells, that are band 1, band 3 and band 5, respectively. The evidence of the deviation from the axial symmetry is given by the occurence of low-energy side bands (band 6) de-exciting to the main $\pi g_{9/2}$ excitations. Moreover, two other bands have been identified at excitation energy larger than 2 MeV. In ^{103,105,107}Rh, they can be interpreted in terms of three-quasiparticle excitations, $\pi g_{9/2}$ $(\nu h_{11/2})^2$ for band 2 (positive parity), and $\pi g_{9/2}$ $\nu h_{11/2}$ $\nu g_{7/2}/d_{5/2}$ for band 4 (negative parity).

The new results obtained in this work allow us to put forth the same conclusions for the neutron-rich Rh isotopes well beyond the mid-shell. First of all, a low-energy side band (band 6) de-exciting to the main $\pi g_{9/2}$ excitations has been observed in ^{111,113}Rh, implying a deviation from the axial symmetry. The evolution of the energy of the first excited states of band 1 and band 6 in ^{107,109,111,113}Rh, as a function of neutron number, is very

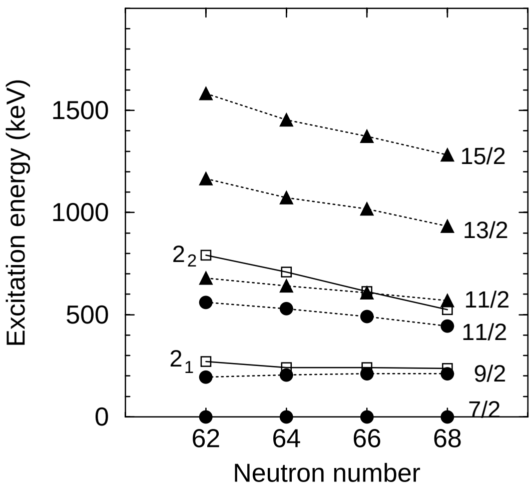

Fig. 5. Evolution of the first positive-parity states in odd-mass ^{A}Rh isotopes (circles for states of band 1, and triangles for states of band 6, linked by dashed lines, [5] and this work), and of the 2_1^+, 2_2^+ states of the corresponding $^{A-1}$Ru cores (empty squares linked by solid lines, [6, 15]).

similar to the one of the energy of the 2_1^+ and 2_2^+ states of their $_{44}$Ru core, as shown fig. 5.

Band 3 is built on the $1/2^-[301]$ orbital from $\pi p_{1/2}$ sub-shell. The γ-ray energies of band 3 in ^{107,109}Rh are very close to the ones of the ground-state band in the corresponding core (^{106,108}Ru), as shown in fig. 12 of ref. [5]. The same effect is again observed in ^{111}Rh and its ^{110}Ru core.

This work sheds light on the interpretation of band 7, which could not be discussed in our previous paper because of too fragmentary results. In ^{103,105,107}Rh, the structure labeled band 4 had been interpreted as a three-quasiparticle excitation, $\pi g_{9/2}\ \nu h_{11/2}\ \nu g_{7/2}/d_{5/2}$. Such a band could not be assigned in ^{109}Rh. Whereas the alignments computed for states of band 7 are very close to those obtained for band 4 of the lighter isotopes (see fig. 8 of ref. [5]), the decay of its band head had been found very different. As a new de-excitation path of this state has been identified in ^{109}Rh and a similar structure has been observed in ^{111}Rh, one can now assume that band 7 of ^{109,111}Rh is the same as band 4 of the lighter isotopes. Therefore, its configuration involves the break of a neutron pair, $\pi g_{9/2}\ \nu h_{11/2}\ \nu g_{7/2}/d_{5/2}$.

5 Summary

In this work several new high-spin states of ^{109}Rh isotope have been identified and the high-spin level schemes of ^{111,113}Rh 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 behaviours of the rotational structures observed in these neutron-rich isotopes strengthen the conclusion of our previous paper concerning the role of triaxial deformation beyond the mid-shell in this isotopic series.

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