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New bands and spin-parity assignments in ^{111}Ru

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Abstract. The ^{111}Ru nucleus, populated in the spontaneous fission of ^{248}Cm has been studied by means of prompt gamma spectroscopy using the EUROGAM2 array. Spin and parity assignments, based on angular correlations, linear polarization, and conversion coefficient measurements differ from those available in the literature. New bands are reported, which incorporate γ transitions seen previously but not placed in the scheme of ^{111}Ru or placed incorrectly. The bands are interpreted as neutron excitations into subshells originating predominantly from the $h_{11/2}$, $g_{7/2}$ and $s_{1/2}$ spherical orbitals. The $s_{1/2}$ band, strongly mixed with the $d_{3/2}$, $d_{5/2}$ and $g_{7/2}$ configurations, is observed for the first time in this region.

PACS. 23.20.Lv γ transitions and level energies – 21.60.Cs Shell model – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

1 Introduction

In our previous study of the neutron-rich ($N \sim 70$) Ru nuclei we have demonstrated that even-even Ru isotopes with masses from $A = 108$ up to $A = 114$ exhibit features characteristic of triaxial deformation [1]. Such a behavior is expected in the region between strongly deformed nuclei around $Z = 40$ and spherical nuclei at $Z = 50$. Transitional in character, ruthenium nuclei are moderately deformed and susceptible to various distortions, depending on the details of the underlying single-particle structure. It is therefore of prime importance to identify single-particle levels near the Fermi level in these isotopes, before attempting any detailed theoretical interpretation.

Information about single-particle levels can be obtained from studies of odd-A nuclei. Such studies require a good knowledge of experimental decay schemes as well as unique identification of spins and parities of excited levels. We have developed techniques, which provide such data for the neutron-rich fission-fragment nuclei [2,3]. In this paper we report on the experimental investigation of the single-particle structure of ^{111}Ru, where we have identified bands based on orbitals close to the Fermi level in this nucleus. Among them there is a complex $1/2^+$ band, which is observed for the first time in this region.

The new experimental data on ^{111}Ru provides grounds for further tests of the theoretical model used to describe even-even Ru isotopes, where pairing vibrations were introduced as a new degree of freedom, improving the description of even-even Ru nuclei, as compared to previous pictures [1,4]. It is interesting to check how this model will perform in the odd-A ruthenium isotopes.

2 Data analysis and the results

The level scheme of ^{111}Ru, first deduced from a prompt-gamma measurement [5], has been recently reinvestigated in five reports [6–10], which partially contradict each other. In the prompt-gamma study [6] the authors have extended the level scheme of ^{111}Ru reported in [5] and proposed that the observed scheme is related to the excitation of the $\nu h_{11/2}$ orbital, though they did not specify which subshell is active. Because of the similarity of ^{111}Ru level scheme to that of the better known ^{109}Ru, they guessed that the 392.1 keV level in ^{111}Ru has spin and parity $I^\pi = 11/2^-$. No spin-parity assignments were proposed for the lower-lying levels. The authors reported some angular

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correlation data, concluding that the 150 keV transition is a dipole and the 166 keV transition is a stretched quadrupole. We note here that the angular correlations between γ-rays separated by another one of an unknown multipolarity (the 358-(76)-150 keV and 150-(63)-104 keV cascades reported in [6]) are generally not predictable.

The same group reported again on ^{111}Ru [7], changing the placement of the 150 keV transition, which became the transition to the ground state. In ref. [7] spins and parities of the low-lying states were assigned by analogy to the level scheme of ^{109}Ru. Spins and parities of $I^\pi = 5/2^+$ and $I^\pi = 5/2^-$ were assigned to the ground state and to the 150 keV excited state, respectively, suggesting an $E1$ multipolarity for the 150 keV transition. The 150 keV level was proposed as the head of the band corresponding to the $5/2^-[532]$ neutron excitation, with the 167.0 keV transition (166.3 keV in [6]) being the first in-band, $E2$ transition. Such assignments coincide with multipolarities reported in [6]. On the other hand, with the changed level scheme, the angular correlations of ref. [6] should be reinterpreted.

In the study of β^- decay of ^{111}Ru to levels in ^{111}Rh [8], Lhersonneau *et al.* concluded that the spin and parity of the ground state of ^{111}Ru is $I^\pi = 5/2^+$. This assignment is based on the analysis of the observed $\log(ft)$ values, assuming that the spin and parity of the ground state of ^{111}Rh is $I^\pi = 7/2^+$. The assumption is based on a firm spin systematics, available for Rh isotopes. The $I^\pi = 5/2^+$ ground state in ^{111}Ru was interpreted as the $5/2^+[402]$ neutron configuration, with possible admixtures of the $\nu 5/2^+[413]$ configuration [8].

Shortly afterwards, the first study of β^- decay of ^{111}Tc to excited levels in ^{111}Ru was published [9], complementing and correcting the prompt-gamma works [5,6]. The important new result reported in ref. [9] is the $M1 + E2$ multipolarity of the 150 keV transition. The assignment is based on the conversion coefficient measurement for this transition. The authors deduced also that the 150 keV transition corresponds to a $\Delta I = 1$ spin change and, therefore, the spins and parity of the 150.2 keV level is $I^\pi = 7/2^+$. It has been also confirmed that the 150 keV transition is the ground-state transition, in accord with ref. [7], correcting the placement done in [6]. The order of the 63 keV and 104 keV transitions has been reversed with respect to that reported in [6,7] and, consequently, the authors of ref. [9] have introduced a new level at 213.1 keV, not reported earlier. A tentative spin and parity assignment of $I^\pi = 9/2^+$ was proposed for this level.

One should also mention the unpublished study of β^- decay of ^{111}Tc [10]. Though no level scheme of ^{111}Ru was proposed there, a number of gamma lines were assigned to ^{111}Ru in that work, which were not reported in ref. [9]. We will discuss these transitions later in the text.

To improve the experimental knowledge of ^{111}Ru at medium spins and to search for other possible neutron configurations, we reinvestigated this nucleus. The present work reports new experimental results obtained for ^{111}Ru in the prompt-gamma measurements following spontaneous fission of ^{248}Cm. High-fold coincidences between prompt-gamma rays were measured using the EUROGAM2 array [11]. More details on the experiment and the data analysis can be found in ref. [12]. In our work we used triple-γ coincidences, which in most cases allows unique assignments of gamma lines to nuclei as well as their unique placement in the scheme. Special attention has been paid to the assignment of spins and parities and relative positions of low-energy levels in ^{111}Ru.

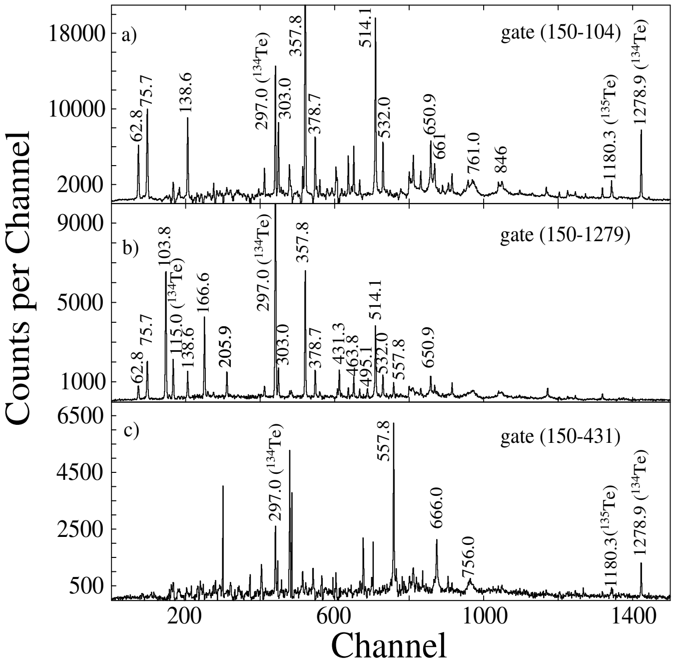

Fig. 1. γ-γ coincidence spectra double gated on lines in ^{111}Ru and ^{134}Te. Transition energies are given in keV.

The double-gate set in our data on the 150 keV and 104 keV lines of ^{111}Ru, shown in fig. 1a, confirms the 138.6 keV transition proposed in ref. [7] and allows to reject the 213 keV level proposed in ref. [9], because the 62.8 keV transition is indeed placed above the 103.8 keV one, as proposed in ref. [7]. We confirm all the levels and transitions reported in ref. [7] and add new levels at 489.5, 669.0, 705.6, 1432.0, 2134 and 3345 keV and several new transitions to the band structure based on the 254.0 keV level. We also confirm the 279.8 keV level reported in ref. [9]. The new levels are displayed in fig. 2, in a level scheme of ^{111}Ru, obtained in the present work.

The double-gate set on the 150 keV line and the 1278.9 keV line belonging to the complementary fission fragment ^{134}Te, shown in fig. 1b, reveals a number of new gamma lines in coincidence with the gating transitions. The spectrum in fig. 1c, double gated on the 150 keV line and the new 431.3 keV line from fig. 1b shows, that this new line belongs to ^{111}Ru, the 1278.9 keV line of ^{134}Te as well as the 1180.0 keV line of ^{135}Te are seen here. New lines seen in this and further gates form a new band in ^{111}Ru based on the ground state. This band comprises the previously reported 150.2 keV level and the newly established 356.0, 581.5, 851.1, 1139.3, 1455.5, 1805.3, 2151.0, 2560.0 and 2921.0 keV levels plus a tentative 3380 keV level. We

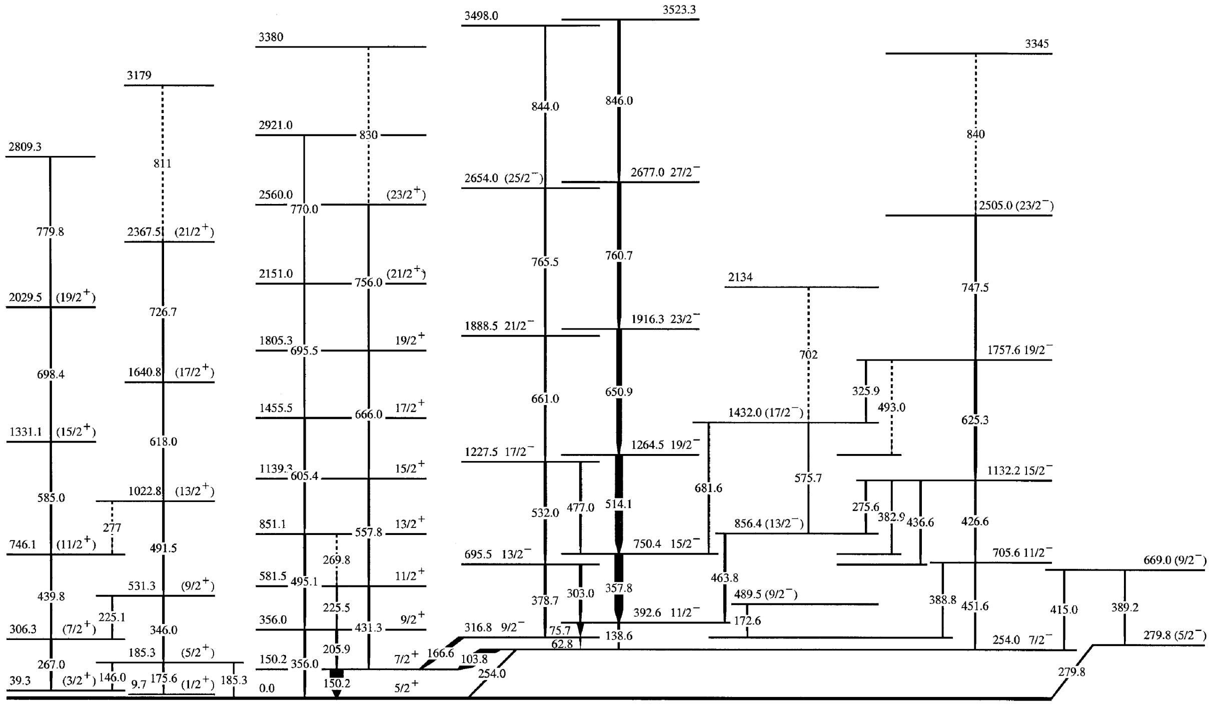

Fig. 2. Partial decay scheme of ^{111}Ru as obtained in this work.

note that the 205.9 keV transition from the 356.0 keV level has been observed also in ref. [9] and assigned to ^{111}Ru, though not placed in the scheme.

To find possible new transitions in ^{111}Ru, which are not in coincidence with the known transitions of ^{111}Ru, we set double gates on lines belonging to ^{134}Te, the most abundant fission fragment complementary to ^{111}Ru. The spectrum shown in fig. 3a shows new, unassigned lines at 146.0, 175.6, 185.3, 267.0 and 346.0 keV, which were not seen in the 1279-150 keV gate (fig. 1b). In the double-gate set on the 175.6 keV and the 346.0 keV lines, which is shown in fig. 3b, the 1278.9 keV line of ^{134}Te and the 1180.0 keV line of ^{135}Te are seen. This proves that both gated lines belong to a Ru isotope. Further gating on the newly observed lines has revealed that they form a band comprising 13 levels. The new band is shown to the left-hand side of fig. 2. The assignment of this band to ^{111}Ru is based on the analysis of the ratio of intensities of the 1180.0 keV line in ^{135}Te and the 1278.9 keV line in ^{134}Te, $I_\gamma(1180.0 \text{ keV})/I_\gamma(1278.9 \text{ keV})$, found in spectra double gated on bands in various Ru isotopes. Such a ratio is correlated with the mass of the gated Ru isotope (see, *e.g.*, [13]). The results are shown in fig. 4. The points corresponding to the bands already identified in ^{111}Ru are clearly located between points corresponding to ^{110}Ru and ^{112}Ru. The point corresponding to the new band in a ruthenium isotope, shown as an open circle, is consistent with the assignment to the ^{111}Ru nucleus. An important additional argument is the assignment of the 146.0 keV,

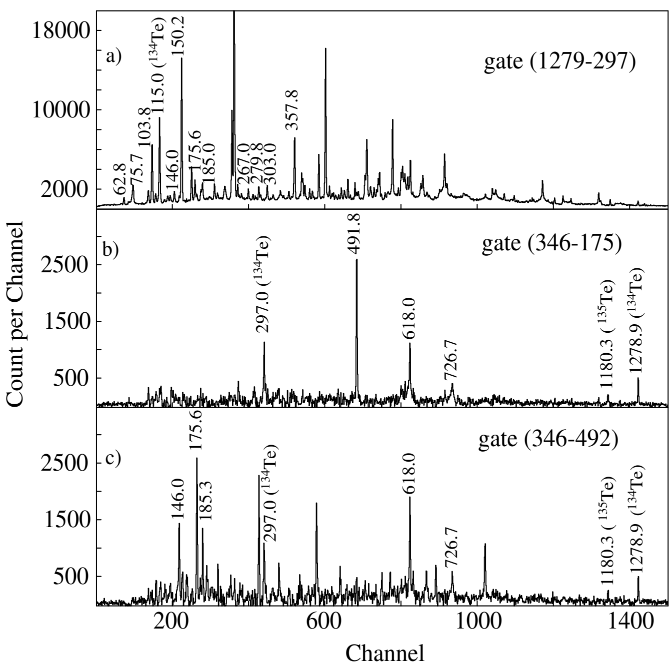

Fig. 3. γ-γ coincidence spectra double gated on lines in ^{111}Ru and ^{134}Te. Transition energies are given in keV.

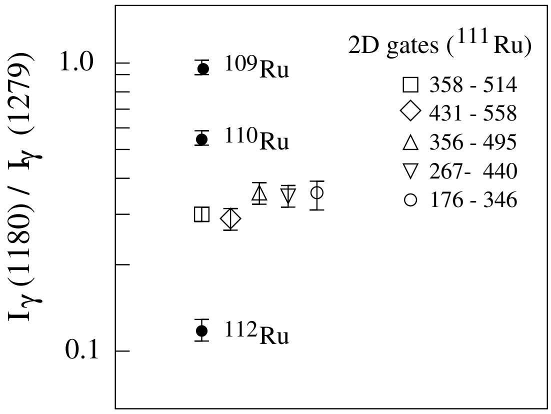

Fig. 4. The ratio $I_\gamma(1180.0 \text{ keV})/I_\gamma(1278.9 \text{ keV})$ as seen in spectra double gated on bands in various Ru isotopes.

175.6 keV and 267.0 keV lines to ^{111}Ru done in ref. [10], as mentioned above. We note that the 185.3 keV line is probably also present in the data from the β^- decay of ^{111}Tc, as can be seen in fig. 4.3 of ref. [10]. Summarizing, we conclude that there is sufficient evidence to assign unambiguously the new band to the ^{111}Ru nucleus.

The properties of transitions in ^{111}Ru, as found in this work are summarized in table 1, where their energies, intensities and angular and directional-polarizaton correlations, obtained using methods described in refs. [2,3] are shown. In the last column the energies of the reference, quadruple transitions, E_γ^{ref}, used in correlations with lines listed in the first column, are shown. Angular correlations in table 1 correspond to the Legendre polynomial expansion $W(\theta) = A_0 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$. Theoretical values for γ-γ correlations for stretched transitions, are $A_2 = 0.10$ and $A_4 = 0.01$ for a quadruple-quadruple cascade; $A_2 = -0.07$ and $A_4 = 0$ for a quadruple-dipole cascade; and $A_2 = 0.05$ and $A_4 = 0$ for a dipole-dipole cascade ($A_0 = 1$).

The data from table 1 were used to assign spins and parities, shown in fig. 2. We will now discuss in more detail the most important spin and parity assignments. We start with the assumption, taken after ref. [8], that the spin and parity of the ground state in ^{111}Ru is $I^\pi = 5/2^+$. The 150.2 keV transition was reported to be of a $\Delta I = 0$, $E1$ character in ref. [7], while in ref. [9] it was reported as having $\Delta I = 1$, $M1 + E2$ character. We support the $\Delta I = 1$, $M1+E2$ character of the 150.2 keV, as observed in [9]. Therefore spin and parity of the 150.2 keV level is $I^\pi = 7/2^+$. The spin difference $\Delta I = 1$ is indicated by the angular correlations between the 150.2 keV and 431.3 keV transitions. In our experiment we have measured triple coincidences, where one gamma was registered by a Low Energy Photon Spectrometer (LEPS) and the other two by the EUROGAM Ge detectors. This allowed observation of low-energy transitions in the LEPS spectara, double gated on Ge detectors. The $E1$ character of the 150.2 keV transition is inconsistent with the $\alpha_K = 1.2(3)$ conversion coefficient, obtained for this transition from the LEPS spectra

Table 1. Properties of γ-transitions in the ^{111}Ru nucleus, as observed in the present work.

E_γ (keV)	I_γ (rel.)	A_2/A_0	A_4/A_0	Pol.	E_γ^{ref}
62.8	22(1)	−0.08(4)	−0.04(4)		378.7
75.7	56(2)	−0.09(2)	−0.08(4)		357.8
103.8	85(4)	0.10(2)	0.05(3)		357.8
		−0.14(3)	−0.05(4)		150.2
138.6	9.9(6)	0.08(2)	−0.06(4)		357.8
146.0	3.1(3)	−0.12(3	−0.09(5)		346.0
150.2	100(5)	−0.10(2)	0.03(2)		378.7
		−0.07(2)	−0.06(4)		431.3
		0.00(1)	0.00(2)		1278.9
166.6	25(1)	−0.09(2)	0.00(3)		378.7
		0.09(2)	−0.03(3)		150.2
172.6	3.0(6)				
175.6	5.0(3)	0.09(2)	−0.08(4)		346.0
185.3	2.4(3)	−0.06(2)	0.04(3)		346.0
205.9	10.2(6)	−0.12(3)	0.01(5)		495.1
225.1	0.6(2)	0.01(2)	−0.08(5)		491.5
225.5	1.9(4))				
254.0	3.7(4)				
267.0	7.6(4)	0.09(2)	−0.02(3)		439.8
269.8	0.9(3)				
275.6	4.6(3)				
277	0.3(1)				
279.8	2.7(4)				
303.3	12.8(5)	−0.12(4)	0.08(6)		532.0
325.9	2.3(4)				
346.0	7.2(5)	0.05(1)	0.01(3)		491.5
356.0	19(2)	0.07(2)	−0.04(2)		495.1
357.8	62(3)	0.09(2)	0.08(4)	+0.14(6)	514.1
378.7	13.5(6)	0.08(2)	0.01(3)		532.0
382.9	1.2(4)				
388.8	3.0(7)	−0.13(4)	−0.04(6)		426.6
389.2	1.5(5)				
415.0	1.6(4)				
426.6	4.6(5)	0.11(3)	−0.07(4)		451.6
431.3	10.0(5)	0.12(3)	−0.05(3)		557.8
436.6	5.3(6)				
439.8	5.4(5)	0.09(2)	−0.02(3)		267.0
451.6	4.3(5)	−0.08(3)	0.05(3)		103.8
463.8	10.5(6)	−0.02(1)	−0.06(3)		138.6
477.0	6.5(6)				
491.5	7.0(4)	0.05(1)	0.01(3)		346.0
493.0	0.8(4)				
495.1	8.7(6)	0.07(2)	−0.04(2)		356.0
514.1	52(4)	0.09(2)	0.08(4)	+0.09(3)	357.8
532.0	12.6(8)	0.08(2)	0.01(3)		378.7
557.8	7.2(5)	0.12(3)	−0.05(3)		431.3
575.7	1.8.3)				
585.0	3.8(3)	0.08(2)	−0.03(2)		sum
605.4	5.9(7)	0.14(5)	−0.08(7)		sum
618.0	5.7(6)	0.4(1)	−0.04(3)		491.5
625.3	14(2)	0.09(3)	0.07(4)		sum
650.9	33(3)	0.11(3)	−0.05(3)	+0.07(3)	sum
661.0	8.0(7)				
666.0	4.2(5)	0.12(3)	−0.04(5)		sum
681.6	3.5(6)	−0.10(3)	−0.12(7)		357.8
695.5	3.0(6)				
698.4	1.8(3)	0.08(2)	−0.03(3)		sum
702	1.2(5)				

Table 1. Continued.

E_γ (keV)	I_γ (rel.)	A_2/A_0	A_4/A_0	Pol.	$E_\gamma^{\rm ref}$
726.7	2.9(7)				
747.5	7.0(6)				
756.0	2.6(5)				
760.7	23(2)	0.11(3)	0.03(2)		sum
765.5	6.4(9)				
770.0	2.4(5)				
779.8	1.5(3)				
811	0.9(4)				
830	1.8(6)				
840	5.0(7)				
844.0	3.4(7)				
846.0	16(2)				

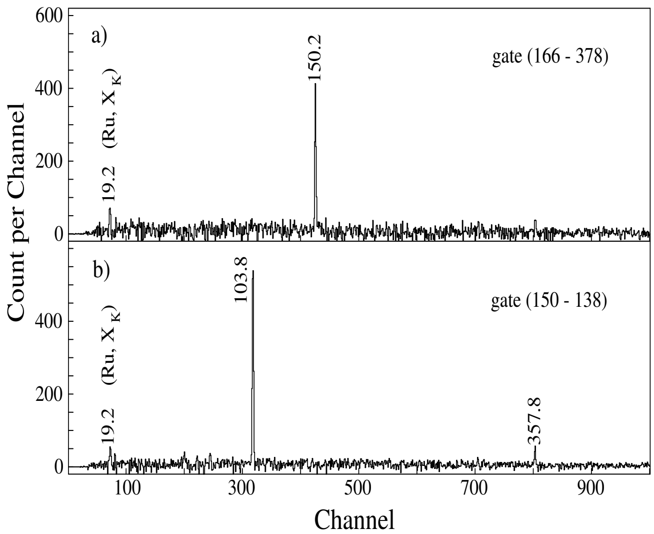

Fig. 5. LEPS spectra double gated on lines in ^{111}Ru. Peak and gated energies given in keV. See text for more explanations.

double gated on the 166.6 keV-378.7 keV pair of transitions. The resulting spectrum is displayed in fig. 5a, where one can see a line at 150.2 keV and the X_K line of ruthenium. Other transitions in the band have energies higher than 530 keV and their conversion coefficients are much lower. Therefore, we neglected their contributions to the intensity of the X_K line, assuming that it is due to the conversion of the 150.2 keV transition only.

Angular correlations between the 378.7 keV, 532.0 keV and 661.0 keV transitions and between the 138.6 keV, 357.8 keV, 514.1 keV and 650.9 keV transitions, shown in table 1, indicate the stretched quadruple character for all these transitions. The angular correlation between the 166.6 keV and 378.7 keV transitions indicate that the 166.6 keV transition is of a $\Delta I = 1$ character. Consequently, the spin of the 316.8 keV level is 9/2.

Angular correlation of the 138.6 keV and 103.8 keV pair indicates a $\Delta I = 0$ character for the 103.8 keV transition and, consequently, spin 7/2 for the 254.0 keV level. This spin value is also consistent with angular correlations of the 138.6 keV-254.0 keV pair, which indicates a $\Delta I = 1$ character of the 254.0 keV transition.

In fig. 5b a LEPS spectrum, double gated on the 138.6 keV and 150.5 keV lines, is shown. The spectrum shows gamma lines of 103.8 keV and 357.8 keV. The ruthenium X-rays, seen also in this spectrum, are due to the conversion of these two transitions (the 303.0 keV transition is much weaker). Therefore one can deduce from this spectrum the α_K conversion coefficient for the 103.8 keV transition, after correcting for the conversion of the 357.8 keV, $E2$ transition. The obtained value $\alpha_K = 0.2(1)$ is consistent with the theoretical α_K value for an $E1$ multipolarity, though an $M1$ multipolarity cannot be entirely rejected. If it was an $M1$ transition, however, then the admixture of an $E2$ component should be rather small, considering the obtained α_K value. Usually, the pure $M1$ transition with an energy of 103.8 keV should be faster than the observed rate of the transition depopulating the 254.0 keV level with the half-life of 14 ns [14]. On the other hand, such a half-life is consistent with an $E1$ character of the 103.8 keV transition. The $B(E1)$ rate deduced from the half-life for the 103.8 keV transition is $B(E1; 104) = 1.6\times10^{-5}$ W.u., a value typical for $E1$ rates. A similar argument can be drawn for the 166.6 keV transition, depopulating the 316.8 keV level, for which a half-life $T_{1/2} = 6$ ns has been reported [14,9]. For this transition we cannot obtain any α_K value, due to the lack of a suitable gated spectrum. The $B(E1; 167\ \text{keV}) = 2.4 \times 10^{-6}$ W.u. rate, however, is again typical of a $E1$ rates, while an $M1$ transition of this energy should be faster than suggested by the observed half-life. We note that the parities of the 254.0 keV and the 316.8 keV levels should be the same, since the 62.8 keV transition has an $M1 + E2$ multipolarity. This is deduced from the $\alpha_K = 2.7(9)$ value for the 62.8 keV transition, obtained from the LEPS spectrum, double gated on the 378.7 keV and 103.8 keV transitions, after correcting for the conversion of the 150.2 keV transition. In ref. [9] the 62.8 keV transition was also found to be of an $M1 + E2$ character.

In conclusion, the arguments given above indicate that parity of both the 254.0 keV and 316.8 keV levels is negative. Because the 138.6 keV transition is a quadruple, it must have an $E2$ multipolarity, since an $M2$ transition of this energy would cause a long half-life for the 392.6 keV level, which is not observed. Consequently, spin and parity of the 392.6 keV level is $I^\pi = 11/2^-$. This is the first experimental confirmation of this spin and parity. In previous works [6,7] the $I^\pi = 11/2^-$ spin for the 392.6 keV level has been proposed based on the observation that the 392.6 keV level shows a behavior characteristic of an intruder high-j orbital, which in odd-A Ru isotopes with masses $A \sim$110 corresponds to the neutron $h_{11/2}$ excitation.

Finally, we comment on the multipolarity of the 166.6 keV transition depopulating the 316.8 keV level. A stretched $E1$ character of this transition has been deduced in this work. In ref. [7] this transition was reported to be a stretched $E2$ in character, based on the angular correlation of the 150-166 keV cascade found in ref. [6]. The angular correlation for this cascade, shown in our table 1 and that reported in ref. [6] are indeed both similar to the angular correlation for a quadruple-quadruple cascade. However, theoretical A_k values for two stretched dipole transitions in a cascade, $A_2 = 0.05$ and $A_4 = 0$ [3], are similar to those for a Q-Q cascade.

Spins of the higher-lying levels in the band built on the 392.6 keV level were assigned on the basis of the stretched quadruple character of the cascade transitions (see above) and assuming that spins are growing with the excitation energy, as commonly observed in nuclei populated in fission. No half-lives longer than 10 ns were observed in this work for any of the quadruple transitions in ^{111}Ru. Therefore we conclude that all stretched quadruple transitions with energies lower than 750 keV, seen in ^{111}Ru in our data, are of an $E2$ character rather than $M2$. Consequently, parities of levels linked by these transitions are the same.

We observe in our data the 279.8 keV line, reported in ref. [9]. On top of the 278.9 keV level we found the 389.2 keV transition, which together with the 415.0 keV line seen in the 150.2 keV-103.8 keV double gate, defines a new level at 669.0 keV. We tentatively propose spins $I^\pi = 5/2^-$ and $I^\pi = 9/2^-$ for the two levels, respectively, based on their population and decay properties.

In our fission data we did not see the 368.8 keV transition, reported as the strongest transition in β^- decay of ^{111}Tc [9]. This suggests rather low spin (of 5/2 or even 3/2) for the 368.8 keV level, a fact which is not consistent with the strong population in β^- decay, if the ground-state spin of ^{111}Tc is ($7/2^+$, $9/2^+$) as suggested in ref. [9]. Therefore it is likely that spin and parity of the ground state in ^{111}Tc is $5/2^-$, as proposed in the lighter technetium isotopes. Such an assignment would also explain rather strong population of negative-parity states in ^{111}Ru in the β^- decay of ^{111}Tc.

The 185.3 keV level in the new, 9.7 keV band in ^{111}Ru, decays by three transitions, the 146.0 keV, 175.6 keV and 185.3 keV, as illustrated in fig. 3c. These decays define levels at 9.7 keV and 39.3 keV, for which we could not observe depopulating transitions, probably due to experimental limitations. Therefore, the position of the 185.3 keV level, relative to the ground state is still not uniquely determined. The level scheme shown in fig. 2 is, however, consistent with the observed multipolarities, the population of the levels, observed in fission and the $5/2^+$ spin and parity for the ground state in ^{111}Ru [8]. The arguments are the following. The spin of the level depopulated by the 146.0 keV, 175.6 keV and 185.3 keV transitions should explain the observed low population of the new band. Considering the fact that fission populates predominantly yrast levels, the low population indicates that the new band is non-yrast. The assumption of spin $5/2^+$ is consistent with the observed population. Similar arguments suggest that the level depopulated by the 267.0 keV transition has spin $7/2^+$. Angular correlations indicate that the 175.6 keV and 267.0 keV transitions both have a stretched quadruple character while the 146.0 keV and 185.3 keV transitions have $M1+E2$ multipolarities. Therefore, spins and parities of the levels populated by the 146.0 keV, 175.6 keV and 185.3 keV transitions are $3/2^+$, $1/2^+$ and $5/2^+$, respectively.

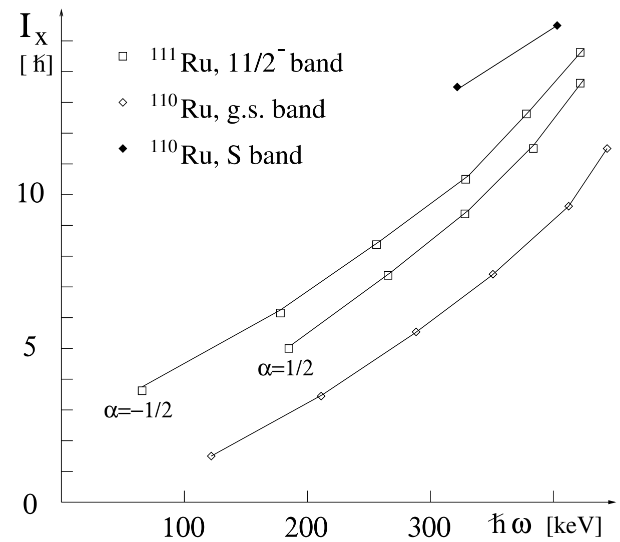

Fig. 6. Total angular-momentum alignment, I_x, for the negative-parity band in ^{111}Ru and the g.s. band in ^{110}Ru. Lines are drawn to guide the eye. See text for more explanation.

Because of some doubts remaining, it is of a great interest to perform further studies of the decay properties of the new, low-lying levels in ^{111}Ru to obtain the decisive information on their positions in the level scheme and their spins and parities.

3 Discussion and conclusions

Inspecting the Nilsson diagram for this region (see, *e.g.*, [15,16]) one finds that for neutron-rich, odd-A ruthenium isotopes, neutron orbitals, expected in these nuclei, originate from the $2d_{5/2}, 1g_{7/2}, 3s_{1/2}$ and $2d_{3/2}$ positive-parity orbitals and from the $1h_{11/2}$ negative-parity, intruder orbital. In the ^{111}Ru nucleus, having $N = 67$ neutrons, the Fermi level is expected near the middle of the $h_{11/2}$ and $g_{7/2}$ orbitals, assuming the deformation $\beta \approx 0.25$ [16].

The level pattern of the negative-parity band in ^{111}Ru is characteristic for a decoupled, rotation-aligned configuration. Useful information about the underlying single-particle structure can be obtained from the analysis of spin alignment, I_x, in the band. In fig. 6 we show the I_x values for the negative-parity bands in ^{111}Ru, calculated as a function of the rotational frequency, ω, from a simple formula $I_x = \sqrt{(I_a + 1/2)^2 - K^2}$, where $I_a = (I_i - I_f)/2$ and $\hbar\omega = (E_i - E_f)/2$. Calculating I_x for this band we assumed $K = 7/2$. One clearly sees a difference of one unit in the alignment between the two signature branches, a characteristic feature of a decoupled band.

In this band the odd neutron occupies probably the $7/2^-[523]$ subshell, of the $h_{11/2}$ parentage, though the

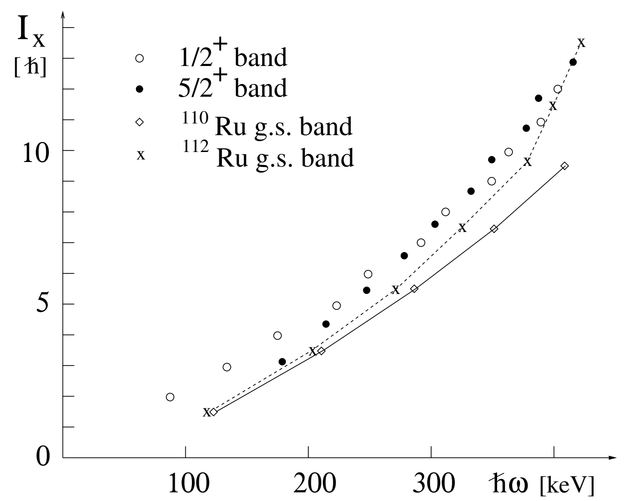

Fig. 7. Total angular-momentum alignment, I_x, for positive-parity bands in ^{111}Ru and g.s. bands in ^{110,112}Ru. Lines are drawn to guide the eye. See text for more explanation.

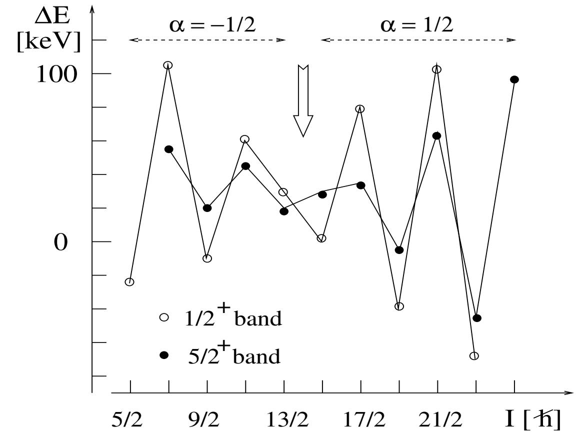

Fig. 8. Staggering in the positive-parity bands in ^{111}Ru. See text for more explanations.

admixture of the $5/2^-$[532] configuration, observed clearly in the ^{109}Ru, is likely. The intruder orbital does not interact strongly with the surrounding subshells. Indeed, there is no strong octupole interactions in ^{111}Ru, as indicated by rather low rates of the observed $E1$ transitions. Because of the high angular momentum of the intruder orbital, the strong Coriolis force quickly aligns spin of the odd neutron from the initial value of $K = \Omega = 7/2$ to the fully aligned state with $I_x = 11/2$, observed already at 392.6 keV. A sizeable single-particle alignment, i, is observed in the band, which can be estimated from the difference between I_x values for this band and the the $K = 0$, g.s band in ^{110}Ru core, also shown in fig. 6. In the range of $\hbar\omega$ between 200 keV and 350 keV the s.p. alignment is nerly constant and yields $i \approx 2.5\hbar$ for the $\alpha = 1/2$ and $i \approx 3.5\hbar$ for the $\alpha = -1/2$ signature branches. The sum of the two alignments, $i \approx 6\hbar$, is equal to the alignment of the S-band in the ^{110}Ru core, obtained from our ^{248}Cm fission data and shown in fig. 6. This supports further the assignments made above.

The $I_x(\omega)$ dependence for the $5/2^+$, g.s. band in ^{111}Ru, calculated assuming $K = 5/2$, is shown in fig. 7. We note that the $I_x(\omega)$ dependence for the $5/2^+$ band resembles more the $I_x(\omega)$ dependence of the ^{112}Ru g.s band than that of the g.s. band of ^{110}Ru. Taking the $I_x(\omega)$ dependence for ^{112}Ru as a reference, one obtains, at the rotational frequency $\hbar\omega > 0.2$ MeV, a small single-particle alignment $i \leq 1\hbar$ for the $5/2^+$, g.s. band in ^{111}Ru. There are two subshells in the vicinity of the Fermi level, which can produce spin $I^\pi = 5/2^+$ and low alignment, the $5/2^+$[413] subshell of the $d_{5/2}$ parentage and the $5/2^+$[402] subshell originating from the $g_{7/2}$ spherical orbital. Most likely both contribute to the $5/2^+$, ground-state configuration.

To learn more, we have analyzed the so-called staggering, which measures the departure of in-band excitation energies from the rigid-rotor formula. The effect of staggering can be illustrated in many ways. In fig. 8 we plot a value of $\Delta E = E_\gamma(I+1 \rightarrow I) - E_\gamma(I \rightarrow I-1)$ as a function of spin, I, for positive-parity bands in ^{111}Ru. With such definition, ΔE for a rigid rotor is constant as a function of spin. In the presence of staggering points with higher values of ΔE correspond to favoured states. For the the $5/2^+$[413] and $5/2^+$[402] configurations, the favourite band corresponds to the $\alpha = 1/2$ and $\alpha = -1/2$ signatures, respectively. From fig. 8 one concludes that the staggering observed in the $5/2^+$ g.s. band at low spins corresponds to the signature $\alpha = -1/2$, *i.e.* the domination of the $5/2^+$[402] orbital in the g.s. band configuration. At spin $I \approx 15/2$ (marked by a thick vertical arrow in fig. 8), the staggering changes sign, however. Above this spin value the staggering in the $5/2^+$ g.s. band corresponds to the signature $\alpha = +1/2$, suggesting the domination of the $5/2^+$[413] configuration.

Somewhat surprising, with the increasing spin, the structure of the $5/2^+$, g.s. band changes from the $g_{7/2}$ at low spins to the $d_{5/2}$ orbital, having lower angular momentum, at medium spins. In the Nilsson diagram the $5/2^+$[413] orbital of the $d_{5/2}$ parentage is located below the $5/2^+$[402] orbital of the $g_{7/2}$ origin. To explain the experiment, one may propose that the $5/2^+$ ground state in ^{111}Ru has an odd neutron in the $5/2^+$[402] orbital [8] and a pair of neutrons in the $5/2^+$[413] orbital. With increasing spin one neutron of the $5/2^+$[413] pair is promoted to the $5/2^+$[402] orbital. This picture is consistent with the alignment in the $5/2^+$, g.s. band, which is similar to that in the ^{112}Ru core, where most likely, both the $5/2^+$[402] and $5/2^+$[413] subshells are filled. The upbend, observed in the g.s. band of ^{111}Ru and the yrast band of ^{112}Ru is probably caused by the aligning pair of $g_{7/2}$ neutrons. In contrast, the promotion from the $d_{5/2}$ to the $g_{7/2}$ orbital does not take place in the negative-parity band of ^{111}Ru, where the odd neutron occupies the $h_{11/2}$ orbital. Due to

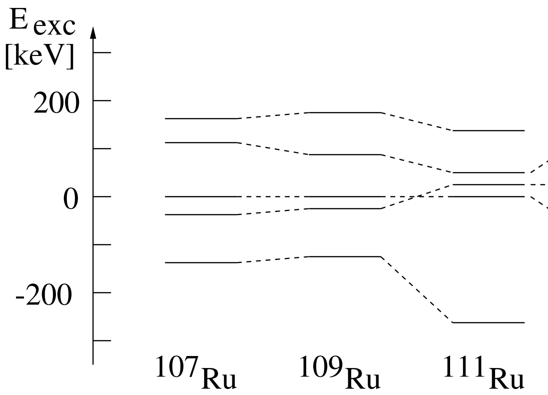

Fig. 9. Energies of near-yrast excitations in ^{107}Ru, ^{109}Ru and ^{111}Ru.

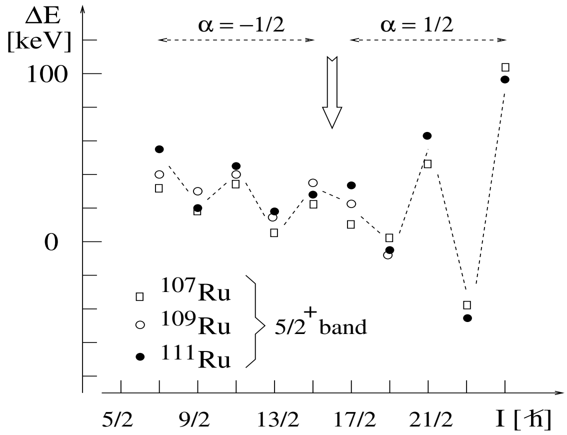

Fig. 10. Staggering in the $5/2^+$, positive-parity bands in ^{107}Ru, ^{109}Ru and^{111}Ru. The data are taken from refs. [7,17] and the present work. See text for more explanations.

the absence of the $g_{7/2}$ pair, one does not observe any upbend, neither in the negative-parity bands of ^{111}Ru nor in the yrast band of ^{110}Ru. Instead in the ^{110}Ru core there is a sharp backbending, due to the aligning pair of $h_{11/2}$ neutrons, which is blocked in ^{111}Ru.

In fig. 9 we show experimental excitation energies in odd-A Ru isotopes for selected levels. The energies were calculated relative to the energy of the $7/2^-$ level, which is well defined in the three Ru isotopes, shown in fig. 9. The energies of the $9/2^-$ and $11/2^-$ levels, which are above the $7/2^-$ level, generally decrease with increasing neutron number. This is consistent with the Fermi level moving towards the $9/2^-[514]$ subshell. On the other hand, the energy of the $5/2^-$ level increases, reflecting the fact that the position of the $5/2^-[532]$ subshell decreases relative to the Fermi level. The most pronounced change is observed for the $5/2^+$ ground-state energy, suggesting a change in the structure of this level. One might expect that this is due to the change in the occupancy by the odd neutron from the $d_{5/2}$ orbital in ^{109}Ru to the $g_{7/2}$ orbital in ^{111}Ru, in accord with the order of these subshells in the Nilsson diagram. The picture is more complex, however. In ref. [17] the authors have noticed a signature inversion in the $5/2^+$ ground-state band of ^{107}Ru, similar to that observed now in ^{111}Ru. In fig. 10 we show ΔE values for the $5/2^+$ ground-state bands in ^{107}Ru, ^{109}Ru and ^{111}Ru. The staggering is very similar in all three bands, with the characteristic signature inversion at around spin $I = 15/2$ in all three Ru isotopes. This indicates that already in ^{107}Ru the odd neutron populates the $5/2^+[402]$ orbital, “bypassing” the $5/2^+[413]$ subshell. In this context, it is very interesting to study the near-yrast excitations in the ^{113}Ru nucleus, where one expects that both the $5/2^+[413]$ and $5/2^+[402]$ orbitals are filled and the odd neutron probably occupies the $d_{3/2}$ shell. Further detailed studies of even-even $^{108-114}$Ru isotopes, both experimental and theoretical, are also of high importance.

To the new band, based on the $(1/2^+)$, 9.7 keV level, one is tempted to assign the $1/2^+[411]$ configuration of the $3s_{1/2}$ parentage. In the Nilsson scheme [16], the $1/2^+[411]$ subshell is close to the Fermi level in ^{111}Ru. This solution can account for the $1/2^+$ level at low excitation energy. There are also problems, however. The $I_x(\omega)$ dependence for the $1/2^+$ band, obtained assuming $K = 1/2$ and shown in fig. 7, gives single-particle alignment of $i \approx 1.5\hbar$. This is too high for the $1/2^+[411]$ configuration. A possible solution is to allow a substantial admixture of the $1/2[400]$ configuration of the $2d_{3/2}$ parentage, which is also near the Fermi level in this region, though higher in energy than the $1/2^+[411]$ subshell [16].

In fig. 8 one sees a significant staggering in the $1/2^+$ band. In the low-spin range the favourite band corresponds to the signature $\alpha = -1/2$. This is consistent with the dominating role of the $1/2^+[411]$ orbital in the structure of this band. At spin $I \approx 15/2$ the staggering changes sign and the favourite band corresponds to the signature $\alpha = +1/2$. Similar effect is observed in the $5/2^+$, g.s. band, as mentioned above. As can be seen in fig. 7 at high rotational frequency the alignment of the $1/2^+$ band shows a similar behavior to that of the $5/2^+$, g.s. band and the yrast band in the ^{112}Ru core, as seen in fig. 7. The experiment indicate thus the dominating role of the $5/2^+[413]$ orbital in the positive-parity bands of ^{111}Ru at medium spins. The structure of the $1/2^+$ band evolves through orbitals with increasing angular momentum $(s_{1/2}, d_{3/2}, d_{5/2})$, when the rotational frequency increases. The evolution of the internal structure in the $1/2^+$ band through the available positive-parity orbitals, makes this band an interesting case for testing nuclear structure models.

At the end we should mention the possible influence of triaxiality, reported in the discussed Ru nuclei [1,17]. First, the K quantum number in these nuclei, which we have used to estimate the aligned angular momentum in ^{111}Ru, should be taken with caution, as the possible triaxiality or gamma softness, reported in Ru nuclei complicates the use of this quantum number. Secondly, the authors of ref. [17] suggested that the signature inversion observed in ^{107}Ru may be caused by the triaxiality. To learn more about these problems, detailed theoretical investigation of Ru nuclei were undertaken, where the gamma softness and other effect are taken into account [18].

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