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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(88)91402-5

Publication date:
1988

EVIDENCE FOR SHAPE COEXISTENCE IN ODD-MASS RHODIUM NUCLEI

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Received 25 February 1988

Results from the study of the ^{104}Ru(^{3}He, d)^{105}Rh reaction reveal evidence for shape coexistence in odd-mass rhodium isotopes. The strongly excited states at 786, 806, 969, 1019 and 1355 keV in ^{105}Rh are good candidates for a rotational-like positive-parity band with $J^{\pi}=1/2^{+}, 3/2^{+}, 5/2^{+}, 7/2^{+}$ and $9/2^{+}$, respectively, coexisting with spherical shell-model states like $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ as well as core-coupled configurations.

The occurrence and the features of shape coexistence in medium-heavy and heavy nuclei with closed-shell configurations ± 1 and ± 3 nucleons have recently been reviewed in detail by Heyde et al. [1]. For the odd-mass indium ($Z=49$) and silver ($Z=47$) nuclei, it has been shown that the $2d_{5/2}$ and/or $1g_{7/2}$ shell-model states intrude across the $Z=50$ shell closure giving rise to a rotational-like positive-parity band with $J^{\pi}=1/2^{+}, 3/2^{+}, \ldots$ (intruder band), coexisting with spherical hole states ($1g_{9/2}^{-1}, 2p_{1/2}^{-1}, 2p_{3/2}^{-1}, 1f_{5/2}^{-1}$) as well as $1g_{9/2}^{-1}$ and $2p_{1/2}^{-1}$ core-coupled configurations. In the indium nuclei, where the most extensive spectroscopic information is available, an interpretation of these intruder bands in terms of a single $1/2^{+}$ [431] Nilsson configuration was suggested by Dietrich et al. [2]. However, the presence of the nearby $3/2^{+}$ [422] and other Nilsson orbitals implies Coriolis mixing for a quantitative description. The latter could be shown to be equivalent to an interpretation as decoupled bands built on the $2d_{5/2}$ and $1g_{7/2}$ orbitals with some degree of mixing [1,3].

For the silver isotopes, the data have been less complete and especially nothing has been known on the more neutron-rich nuclei including the mid-shell region at neutron number $N\approx 66$, where a maximum quadrupole deformation, i.e. lowest energy for these intruder bands, is expected on the basis of the residual proton–neutron interaction. Meanwhile, evidence for shape coexistence has been obtained also for these nuclei from our own studies [4] as well as from the Studsvik group [5], showing that the intruder band reaches an energy minimum in ^{113}Ag, i.e. at $N=66$ exactly in the middle of the $N=50$ and 82 shell closures.

In the present paper we report on the successful attempt to extend the concept of shape coexistence to nuclei with five nucleons outside the $Z=50$ shell closure, i.e. the rhodium ($Z=45$) nuclei. Here, the more deformed underlying cores may probably favour an identification and interpretation as rotational bands

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built on a single Nilsson configuration. According to the fingerprints for shape coexistence outlined in ref. [1], pick-up and stripping reactions are a useful tool for the identification of intruder states because of their complementarity in exciting hole or particle states. As known already for the indium and silver nuclei [1], also in the rhodium isotopes the intruder states, being particle excitations, should be strongly populated in stripping reactions like (^{3}He, d) and not or only weakly be observed in pick-up reactions like (d, ^{3}He) or (t, α). Unfortunately, the most neutron-rich rhodium isotope accessible for both transfer reactions is ^{105}Rh with $N=60$, while the heavier rhodium isotopes can only be studied by pick-up reactions and/or by post β-decay γ-ray spectroscopic measurements [4,6,7]. For ^{105}Rh, valuable information on the pick-up strength is available from the ^{106}Pd($\vec{t}$, α) work of Flynn et al. [8], while the (^{3}He, d) study of Dittmer and Daehnick [9] did not reveal unambiguous results, probably due to the low incident beam energy and missing forward angle information. Especially there was no evidence for any $l=0$ transfer pointing towards the $J^\pi=1/2^+$ head of an intruder band.

Therefore, we have reinvestigated the ^{104}Ru(^{3}He, d)^{105}Rh reaction using a 50 MeV ^{3}He beam from the KVI cyclotron at Groningen. The target consisted of a ^{104}Ru layer (enriched to 99%) of ≈70 μg/cm^2 produced by sputtering the material on a thin carbon backing of ≈20 μg/cm^2. The outgoing deuterons have been momentum analyzed with the QMG/2-spectrograph and detected in the focal plane of the spectrograph with a new multi-wire drift chamber [10], where an energy resolution of ≈11 keV could be obtained. Measurements have been performed at eight laboratory angles ranging from 1.5 to 30.5° with an opening angle $\Delta\theta=6°$. With the computer program PAXMWDC [11] the whole opening angle could be divided into two parts, so that we ended up with spectra at 16 angles ranging from $\theta_{lab}=0.75$ to 32.0° with an opening angle $\Delta\theta=3°$. As an example the deuteron spectrum taken at 13° is shown in fig. 1. More details concerning the data handling and the optical model parameters used are given elsewhere [6,12]. For precise energy calibration the level energies from the β$^-$-decay study [13] have been used, so that energies of levels only observed in the (^{3}He, d) reaction are accurate within

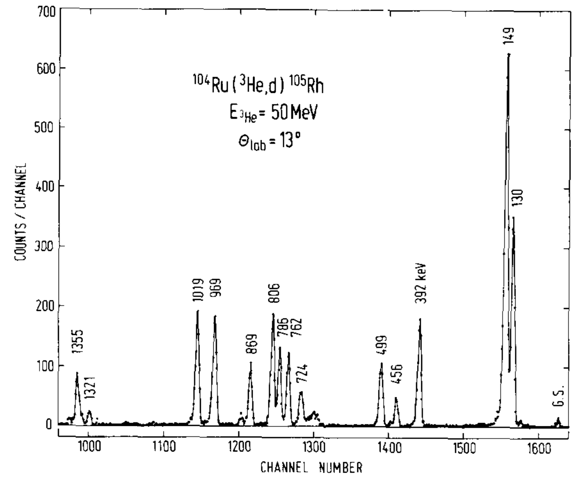

Fig. 1. Deuteron spectrum taken at $\theta_{lab}=13°$ in the ^{104}Ru(^{3}He, d)^{105}Rh reaction at $E_{^3He}=50$ MeV. Excitation energies of levels in ^{105}Rh are given in keV.

±1 keV. Compared to the former study of the ^{104}Ru(^{3}He, d) reaction [9] we were able to make unambiguous l-transfer assignments favoured by both the more pronounced structure in the angular distributions at higher incident ^{3}He beam energy and by the measurement at extreme forward angles. Among the levels observed in our (^{3}He, d) stripping reaction work the five states at 786, 806, 969, 1019 and 1355 keV were strongly excited while they were not or only weakly excited in the ($\vec{t}$, α) pick-up reaction [8]. This proves the particle character of these states making them candidates for being members of an intruder band. In fig. 2, we present angular distributions of the deuterons together with the one-step DWBA predictions of these five candidates and for four "normal" states, which have their origin below the $Z=50$ shell closure.

From fig. 2 it is clear that the level at 786 keV is excited by an $l=0$ transfer which leads unambiguously to $J^\pi=1/2^+$ for this state. Considering this level as the $1/2^+$ [431] Nilsson state it becomes interesting to search for possible rotational band members and to compare with theoretical predictions concerning level energies and spectroscopic factors. Proper candidates for the $3/2^+$ and $5/2^+$ members are the states at 806 and 969 keV which are both excited by an $l=2$ transfer (see fig. 2). Taking into account the γ-decay pattern of these levels obtained by Aras and

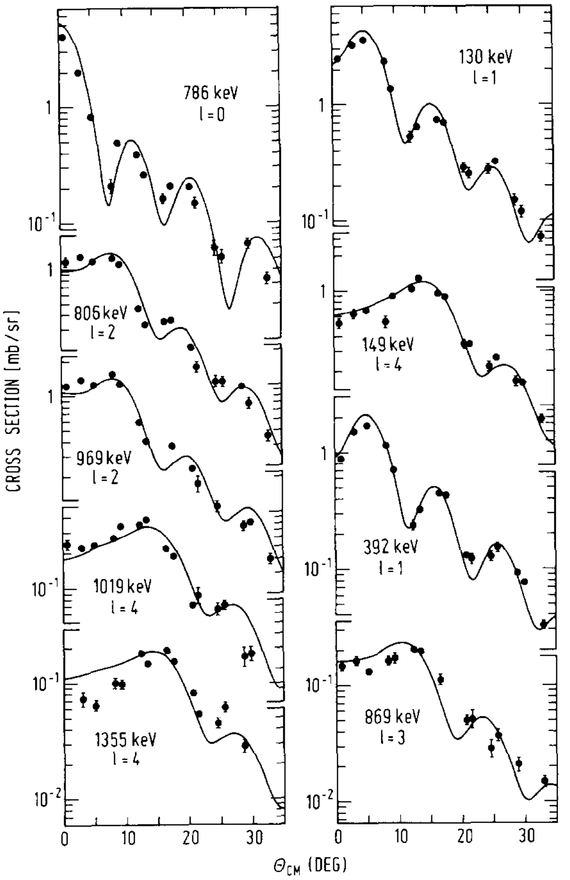

Fig. 2. Examples of angular distributions of deuterons from the ^{104}Ru(^{3}He, d)^{105}Rh reaction at $E_{^3He}=50$ MeV (for details see text). The curves are one-step DWBA predictions for the indicated l-transfers.

Walters [13], $J^\pi=3/2^+$ can be assigned to the 806 keV level and $J^\pi=5/2^+$ seems to be the most reasonable choice for the 969 keV state. Fitting these three level energies to the $K=1/2$ rotational band formula, one obtains $A=19.70$ keV, $a=-0.66$ and $E_0=758.1$ keV. The predicted energies for the $7/2^+$ and $9/2^+$ levels are then 1016 and 1311 keV, which have to be compared with experimental values of 1019 and 1355 keV, respectively. As shown in fig. 2, both levels are excited by an $l=4$ transfer. Assuming that the 1019 keV state is identical to the weakly excited level at 1024 ± 8 keV observed in the $(\vec{t}, \alpha)$ experiment of Flynn et al. [8], $J^\pi=7/2^+$ can clearly be assigned from our angular distribution result for this level and the analyzing power data of ref. [8].

Normalized spectroscopic factors $(\sum C^2S'_j=1)$ for the different members of the lowest $K^\pi=1/2^+$ band (mainly the $1/2^+$ [431] Nilsson orbital) are calculated for deformations ϵ_2 between 0.25 and 0.35. The results are obtained from a band-mixing calculation taking into account all Nilsson orbitals from the $N=4$ harmonic oscillator shell [14]. In table 1 the values are given for $\epsilon_2=0.25$, 0.30 and 0.35 together with the experimental results. The agreement is quite satisfactory especially for the higher ϵ_2 values and is improved in an important way over the pure $1/2^+$ [431] band description, especially for the $5/2^+$ and $7/2^+$ levels.

At the same time, we also calculated the decoupling parameter a for the $1/2^+$ [431] Nilsson orbital, corresponding with the main component of the lowest $K^\pi=1/2^+$ band. The values $a=+0.28$, -0.13 and -0.36 were obtained for $\epsilon_2=0.25$, 0.30 and 0.35, respectively. The wave functions, resulting from the band-mixing calculations, contain admixtures of the other $1/2^+$ Nilsson orbitals too. As an example we give the $1/2^+$ wave function corresponding to the result for $\epsilon_2=0.35$:

$$|1/2^+\rangle=-0.045|1/2^+[440]\rangle$$
$$+0.995|1/2^+[431]\rangle+0.078|1/2^+[420]\rangle$$
$$+0.028|1/2^+[411]\rangle.$$

The small admixtures will contribute to the "effective" decoupling parameter characterizing the lowest $K^\pi=1/2^+$ band head.

As a consequence, the decoupling parameter a, obtained from fits to the experimental data will show quite important deviations from the parameter a deduced under the assumption of a pure $1/2^+$ [431] band. This is the case not only in ^{105}Rh but also in ^{107,109}Rh. Analogous results were obtained in the odd-mass indium nuclei where a phenomenological analysis for pure $1/2^+$ bands gives decoupling parameters varying from -2.0 to -4.0 (for ^{115}In to ^{119}In). Here the calculated decoupling parameters for a pure $1/2^+$ [431] band are almost an order of magnitude smaller [2,3].

In fig. 3 the present results for the intruder band in ^{105}Rh are compared with our former studies [6,7] on the more neutron-rich isotopes ^{107,109}Rh. As expected, the excitation energy strongly decreases with increasing neutron number and probably reaches a

Table 1
Normalized spectroscopic factors for the $K^{\pi}=1/2^+$ band members (mainly the $1/2^+$ [431] band) excited in the $^{104}Ru(^3He, d)^{105}Rh$ stripping reaction.

Level energy (keV)	J^{π}	$C^2S'_j/\Sigma C^2S'_j$			
		experiment	theory		
			$\epsilon_2=0.25$	$\epsilon_2=0.30$	$\epsilon_2=0.35$
786	$1/2^+$	0.07	0.11	0.14	0.09
806	$3/2^+$	0.18	0.18	0.26	0.19
969	$5/2^+$	0.14	0.24	0.20	0.11
1019	$7/2^+$	0.49	0.32	0.40	0.38
1355	$9/2^+$	0.12	0.15	0.0009	0.23

minimum close to $N=66$, i.e. in the middle of the $N=50$ and 82 shell closures.

We can conclude that good evidence has been found for the five discussed levels in ^{105}Rh to form an intruder band coexisting with spherical shell-model states. Those five levels show two of the fingerprints for intruder states, namely they are strongly excited in stripping and not or only weakly in pick-up reactions and they exhibit a rotational band structure.

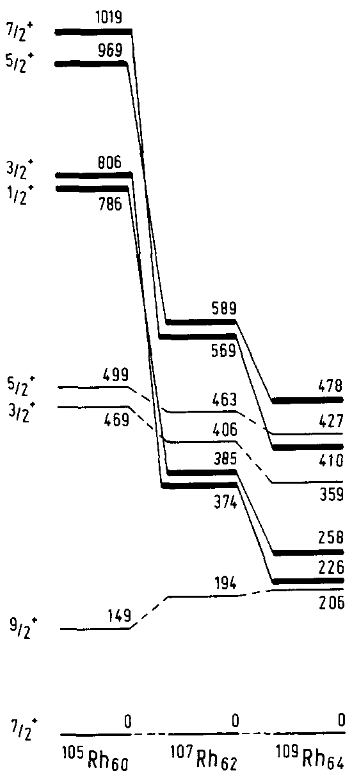

Fig. 3. Low-lying positive-parity states in ^{105}Rh (present results and ref. [13]), ^{107}Rh (ref. [6]) and ^{109}Rh (ref. [7]). Level energies are given in keV. Candidates for members of the intruder band are drawn as thick lines.

The authors are grateful to H. Folger, GSI Darmstadt, for preparation of the targets. This research was supported by the Bundesministerium für Forschung und Technologie (Fed. Rep. Germany) under contract number 06 MZ 552, the Interuniversity Institute for Nuclear Sciences (Belgium) under contract number 4.0014.88N and 4.0016.88N, and the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (ZWO). Part of this work has been carried out under the research contract NATO 0452/86.

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