Structure of the $7/2_1^+$ state in ^{97,99}Rh populated in (^{6}Li,3$n\gamma$) reactions

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Abstract

With the present proposal we would like to continue our systematical study of the matrix elements connecting low-lying states in odd-A nuclei via fast-timing measurements. In the focus of the present proposal is the structure of the $7/2_1^+$ state in $^{97,99}_{45}$Rh$_{52,54}$ which has only few neutrons away from the $N = 50$ shell gap. The Rh nuclei have also five valence proton holes below the $Z = 50$ shell gap, which suggest they are more transitional nuclei rather then being "classical" Shell model examples.

1 Motivation

1.1 physics case

In the focus of the present study is the structure of the $7/2_1^+$ state in ^{97,99}Rh. A systematics of the $7/2_1^+$ level energy in $_{49}$In, $_{47}$Ag and $_{45}$Rh nuclei [1] normalized with respect to the $9/2_1^+$ level energy is plotted in Fig.1 as a function of the neutron number. This state appears as an excited state in all In isotopes, where $9/2_1^+$ is the ground state. The $7/2_1^+$ state is placed 1 MeV above the ground state in the In$_{64,66}$ and decreases with energy to 721 keV at ^{119}In$_{70}$. In the extreme neutron deficient and neutron-rich indium nuclei with $60 \geq N \geq 72$, which are closer to the respective neutron shell-gaps, the $7/2_1^+$ level was not observed.

In the odd-mass silver isotopes $9/2_1^+$ is the ground state at $N = 50, 52$, while in the heavier silver isotopes it appears as an excited state. In general, the $7/2_1^+$ state in Ag nuclei is placed lower in energy then in In isotopes and evolves more abruptly with the neutron number. The $7/2_1^+$ level is placed above $9/2_1^+$ in the silver isotopes with $N = 52, 54$ and falls in energy below $9/2_1^+$ for $56 \leq N \leq 76$. In $N = 78$, $9/2_1^+$ is again the ground state [6]. The $7/2_1^+$ state was not observed in ^{125}Ag [6], suggesting it is much higher in energy then in the neighboring silver nuclei. Thus, in contrast to the indium nuclei, the medium mass silver isotopes exhibit a $I = j - 1$ anomaly, which has been extensively discussed in the past. Several theoretical approaches were used with different success in interpreting the anomalous ordering of the $7/2_1^+$ and $9/2_1^+$ states in the silver isotopes. In contrast to the In isotopes where the nature of these states is well understood from the shell model point of view, the same state in Ag nuclei seems to have a more complex structure [6] involving three valence-particle $\pi 1g_{9/2}^{-3}$ clusters [2], thee- valence hole

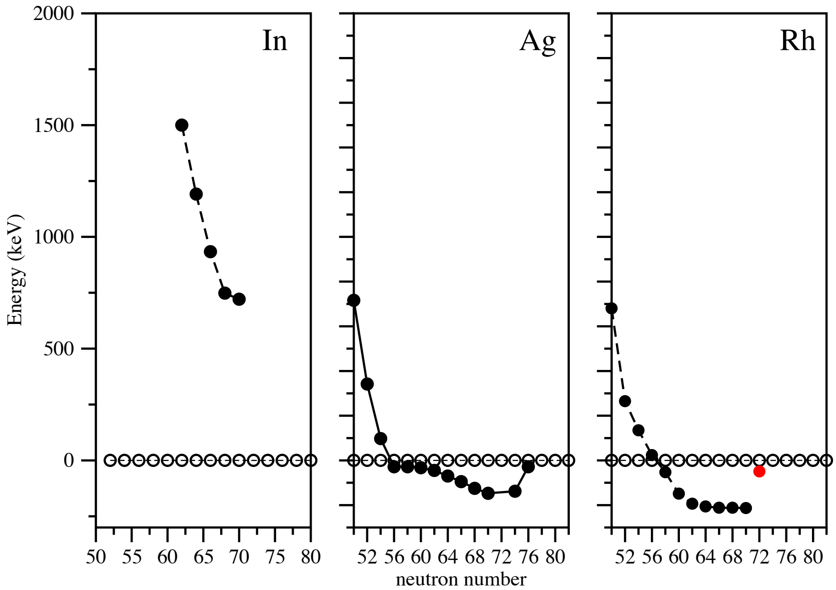

Figure 1: Systematics of the $7/2_1^+$ level energy (full circles) in $_{49}$In, $_{47}$Ag and $_{45}$Rh nuclei, normalized to $E(9/2_+)$ (open circles). The data is taken from [1], unless otherwise noted. The data for $^{117}_{45}\mathrm{Rh}_{72}$ is from [5]

cluster $\pi 1g_{9/2}^{-3}$ coupled to a quadrupole vibrational core [3]. Octupole collectivity and triaxiallity were also considered [4]. The models give not only different ordering of the $7/2_1^+$ and $9/2_1^+$ doublet but they are also sensitive to the $B(E2; 7/2^+ \rightarrow 9/2^+)$ transition strength, which can help to disentangle different excitation modes at low energies.

Deeper in the fourth proton shell, in the nuclei far away from the neutron magic numbers, the $7/2_1^+$ state should have a more collective nature. Indeed, the overall trend of the state in the neutron mid-shell Rh nuclei presented on Fig. 1 resembles the trend of the silver states with the $7/2_1^+$ descending even deeper below $9/2_1^+$ then in the silver case. In $^{117}_{45}$Rh [5], the $7/2_1^+$ was assumed to be the lowest lying positive-parity state, placed just 49 keV below the $9/2_1^+$ according to Triaxial-Rotor plus particle calculations. Indeed, the Triaxial-Rotor plus particle model calculations seems to reasonably explain the observed isomerism in one of the most neutron-rich rhodium isotopes $^{117}_{45}\mathrm{Rh}_{72}$ [5].

Thus, by studying the transition probabilities in the $^{97,99}\mathrm{Rh}_{52,54}$ we would like to obtain a more detailed information about the transition between single-particle and collective modes in this region which eventually can contribute also to the better understanding of the structure of the neutron-deficient silver nuclei.

1.2 exotic nuclei and data evaluation

In addition, a more detailed knowledge on the decay properties of the lowest-lying states in the odd-A nuclei will help in the understanding of the experimental data from the most exotic nuclei. Usually, the first spectroscopic information obtained from the facilities working with exotic beams is scarce and incomplete. Most often, γ-ray energies, intensities and lifetimes of some of the states are measured. However, in order to extract the matrix elements connecting different states, γ-ray multipolarities, mixing ratios, conversion coefficients and branching ratios are also needed. Some of these ingredients are coming from calculations, other from systematics and in very few cases from experimental measurements. In several cases, the only available experimental information for a given nucleus is one isomeric state, decaying via a single γ-ray. In this case the angular distributions and angular correlation studies with exotic beams are

Table 1: Decay properties of $7/2^+$ and $9/2^+$ states in neutron deficient Rh isotopes.

nucleus	$J_i^{\pi,a}$	$J_f^{\pi,a}$	$E^a_{level,i}$	$E^a_{level,f}$	$T^a_{1/2}$ (ns)	Mult.	δ
$^{95}Rh_{50}$	$7/2^+$	$9/2^+$	680	0	^{b}	^{b}	^{b}
$^{97}Rh_{52}$	$7/2^+$	$9/2^+$	265	0	^{b}	(M1+E2)	^{b}
$^{99}Rh_{54}$	$7/2^+$	$9/2^+$	200	65	^{b}	M1	assumed pure M1
$^{101}Rh_{56}$	$7/2^+$	$9/2^+$	181	157	1.91	M1+E2	0.020(6)
$^{103}Rh_{58}$	$9/2^+$	$7/2^+$	93	40	1.11	M1	assumed pure M1
$^{105}Rh_{60}$	$9/2^+$	$7/2^+$	149	0	$\leq$0.3	M1+E2	0.34(1)

^{a}From the adopted levels and gammas in ENSDF, unless otherwise noted

^{b}not given

inapplicable. In addition, in the In-Flight-separation based facilities thick secondary targets are used to stop relativistic beams which makes it impossible to measure conversion electrons and hence to determine experimentally the γ-ray multipolarity. In such cases, the spin/parity of the exotic nuclei can be tentatively based on the evolution of the level energies and their decay rates as a function of the number of valence particles. Then, the systematics can be extrapolated towards the nucleus of interest, which helps to restrict the number of possible J^π assignments to the initial and final states.

Therefore, it is crucial to have a detailed experimental data for low-lying transitions in the nuclei placed close to the line of β-stability. However, even there the experimental data is incomplete. Table. 1 lists the experimental information available for several Rh isotopes in the beginning of the fifth neutron shell. According to ENSDF [1], the $7/2_1^+$ half-life was measured in only two of the nuclei. An upper limit is given for the $T_{1/2}$ in ^{103}Rh. The mixing ratio is also known only for two of the cases. In other two of the cases, i.e. $^{99.103}$Rh, the respective transition is assumed to be of pure $M1$ nature. However, this assignment seems to disagree with the neighbouring ^{101,105}Rh as well as with the multipolarity assignments in ^{99,101}Ag, where $M1 + E2$ nature is assigned to the respective $7/2_1^+ \rightarrow 9/2_1^+$ transition.

Because of the structural evolution, some of the states which appear as long-lived isomers close to the shell gaps [5, 6] often have shorter half-lives in the mid-shell regions, which makes them suitable for measurements with RoSphere. Therefore, starting with the Rh nuclei, we would like to undertake series of fast-timing experiments on the odd-Z even-N nuclei, placed below $Z = 50$.

2 Experimental details and estimations

Prior to this study, excited states in ^{97,99}Rh were populated in ^{94,96}Mo(^{6}Li,3$n\gamma$) reactions [11, 12]. The partial level scheme of ^{99}Rh, shown on Fig. 2, is based on the coincidence measurements in [12]. In [12, 11], only two Ge(Li) detectors were used to construct the level scheme. The $7/2^+$ state in ^{99}Rh is fed by a 264-keV transition and decays via a 136-keV transition. The two γ-rays are observed in weak coincidence with 386-keV and 410-keV transitions, which will allow us to use the $\gamma - \gamma - \gamma(t)$ coincidences to clean the spectra and to obtain the half-life of the $7/2^+$ state in ^{99}Rh.

In [?] the 265-keV transition is observed in ^{94}Mo(^{6}Li,3$n\gamma$) reaction, however, no feeding transitions were reported. [1] presents gammas which feed the $7/2^+$ and $(5/2^+, 7/2^+)$ levels in ^{97}Rh. These were observed in ^{96}Ru(^{3}He,$pn\gamma$) reaction. Given the similarity with the ^{99}Rh, we expect to populate the same structure in ^{97}Rh.

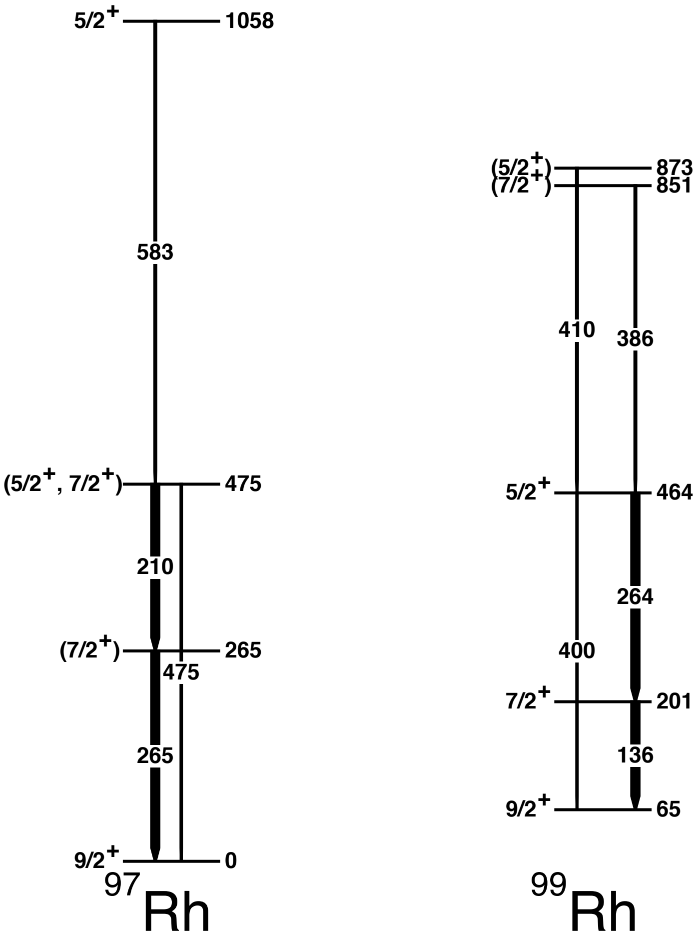

Figure 2: ^{97,99}Rh level schemes

2.1 half-life estimation

The $7/2_1^+$ half-life was previously measured in ^{101,103}Rh. By using $\delta = 0.020(6)$ mixing ratio for the 24-keV transition in ^{101}Rh, depopulating the $7/2^+$ state [1] $B(M1) = 0.0373(13)$ and $B(E2) = 23(12)$ W.u. were obtained. Then, the half-life of the $7/2_1^+$ state in ^{97}Rh and ^{99}Rh, decaying via 265-keV and 135-keV transitions, respectively, would be in the range from 6 ps to 200 ps. This estimation is consistent with the half-lives of the $7/2_1^+$ states in a number of odd-N, even-Z nuclei measured at NIPNE [7, 8, 9, 10] and is well within RoSphere time range.

2.2 beam time estimation

According to CASCADE calculations ^{97,99}Rh can be produced with a cross-section of about 500 mB at a beam energy E = 32 MeV. In order to stop the recoils and to obtain higher yield, 10 mg/cm^2 thick ^{94}Mo and ^{96}Mo targets will be used. Given that the RoSphere efficiency is about 1% for the HPGe part and about 2% for the LaBr$_3$:Ce part and based on our previous experience [7, 8, 9, 10], we expect to collect about 700 counts in the time spectra per shift, gated on three γ-ray energies detected in one HPGe and two LaBr$_3$:Ce. We expect to collect about 6.3 thousand counts in three days of measurements in each case, which will allow a half-life estimation with a statistical uncertainty of about 10%.

3 Summary

We request 6 days of beam-time. 3 days of the beam-time will be used for fast-timing measurements in ^{99}Rh and 3 days for spectroscopy in ^{97}Rh. Of particular interest is the observation of transitions feeding the $7/2^+$ state in ^{97}Rh.

Experimental details:

- **Beam:** ^{6}Li, E=32 MeV
- **Targets:** 10 mg/cm^2 enriched to ≈90% in ^{94}Mo
- **Cross section:** ≈ 500 mB from CASCADE
- **Detectors:** RoSphere
- **Efficiency:** ≈1% for HPGe, ≈2% for $LaBr_3$:Ce
- **Population of the level of interest:** ≈ 5%

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