# Quadrupole vs. single-particle excitations in $^{99,101,103}$Ru isotopes, produced in ($\alpha$,n$\gamma$) reactions

S. Kisyov[1], S. Lalkovski[1], D. Ivanova[1], N. Mărginean[2], D. Bucurescu[2], L. Atanasova[3], D. L. Balabanski[3], Gh. Căta-Danil[2], I. Căta-Danil[2], D. Deleanu[2], P. Detistov[3], D. Filipescu[2], I. Gheorghe[2], D. Ghiţă[2], T. Glodariu[2], R. Lica[2], R. Mărginean[2], C. Mihai[2], A. Negret[2], T. Sava[2], E. Stefanova[3], L. Stroe[2], R. Suvaila[2], S. Toma[2], N.V. Zamfir[2]

[1]*Faculty of Physics, University of Sofia "St. Kliment Ohridski", Sofia, Bulgaria;*
[2]*National Institute for Physics and Nuclear Engineering "Horia Hulubei", Magurele, Romania;*
[3]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, Sofia, Bulgaria.*

**Abstract**

We propose to measure half-lives of excited states in $^{99,101,103}$Ru isotopes, produced in fusion-evaporation reactions. The states of interest will be populated via ($\alpha$,n$\gamma$) reactions with a beam of $\alpha$-particles at 14-15 MeV. The sub-nanosecond half-lives will be measured by the delayed coincidence technique, applied with a mixed detector array of $LaBr_3$:Ce and HPGe detectors.

## 1 Motivation

A large variety of nuclear structure phenomena are presented in the $A \sim 100$ region, where different shapes, as prolate, oblate and spherical, exist. In several nuclei triaxiality arises. Also, given the proximity of the $\Delta l$=$\Delta j$=3 orbitals, enhanced octupole collectivity is expected at around $N$=56. Among the most neutron-rich stable Zr and Mo isotopes shape co-existence occurs. In fact, the collective behaviour of the nuclei in this mass region arises with the number of the valence particles, soon after filling the $N$=50 shell closure. The shape change in the Zr and Mo isotopic chains is abrupt, while the shape change in Ru isotopic chain is more modest (Fig. 1) [1]. Ruthenium isotopic chain is placed between the rotational neutron-rich Zr and Mo nuclei and the vibrational Cd and transitional Pd nuclei. In particular, $^{96,98}$Ru have vibrational behaviour, while the mid-shell Ru isotopes are triaxialy deformed. Thus, $^{99,101,103}Ru_{55,57,59}$ isotopes are placed in the region where the onset of deformation is expected to occur [1, 2]. The low-lying parts of their spectra have similar structure (Fig. 2) [3]. The $5/2^+$, $7/2^+$, $3/2^+$, $1/2^+$, $11/2^-$ states, appearing at low energies, suggest that the $2d_{5/2}$, $1g_{7/2}$, $2d_{3/2}$, $3s_{1/2}$ and $1h_{11/2}$ single-particle orbitals dominate. On the other side, states can arise from collective excitations from the coupling of a triaxial rotor to an unpaired particle. Thus, in order to track the evolution of collectivity in the medium-mass Ru isotopes, we propose to measure the half-lives of the lowest-lying states in these nuclei. The half-lives are related to the matrix elements and hence will allow a systematical study of the evolution of collectivity in the mass region.

Besides the low-lying states, also half-lives of higher-spin states in $^{99,101,103}$Ru can be studied by using the fast-timing technique. In the odd-$A$ nuclei, from the $A \sim 110$ mass region, intense $\Delta I$=2 transitions built on top of the $11/2^-$ states arise. These quasi-rotational bands often have $15/2^-$ states with half-lives within the RoSphere time range. Thus, for example, the half-life of the $15/2^-$ state in $^{107}$Cd is $T_{1/2}$=21(8) ps [3] and the half-life of the $15/2^-$ state in $^{105}$Pd was recently measured $T_{1/2}$=28(4) ps [4]. Now, by measuring the $T_{1/2}$ of the $15/2^-$ state in $^{103}$Ru, we will track the evolution of the quasi-rotational bands, built on top of $11/2^-$ in the $N$=59 isotonic chain. Similarly, we would like to measure the half-lives of the $15/2^-$ states in $^{99,101}$Ru, in order to complete the systematics .

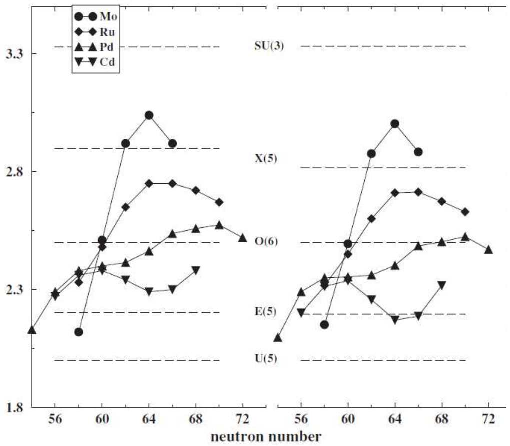


Figure 1: The excitation energy ratios $R_4$ and $R_6$ in neutron-rich Mo, Ru, Pd and Cd isotopes, plotted as a function of the neutron number [1]

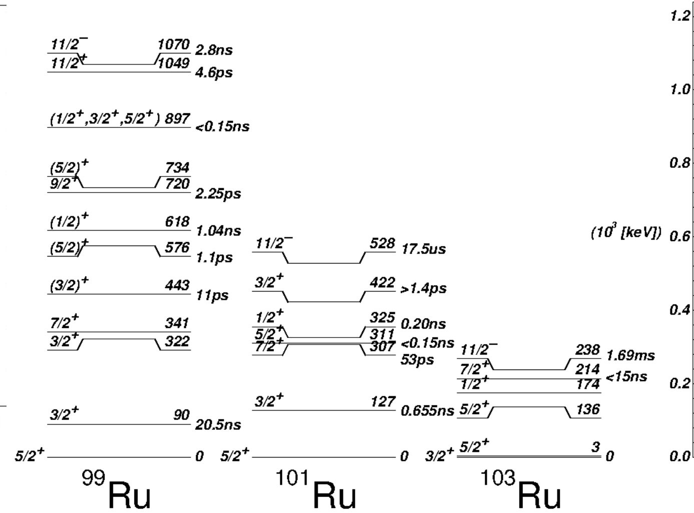


Figure 2: Low-lying excited states in $^{99,101,103}$Ru isotopes [3]

## 2 Half-lives estimation

The half-lives estimations were made on the basis of the known half-lives of the $7/2_1^+$ state in $^{101}$Ru and the $15/2^-$ states in $^{101,103,105}$Pd. Assuming that the structure of the $7/2_1^+$ states does not change abruptly in the neighbouring $^{99}$Ru, $^{101}$Ru and $^{103}$Ru nuclei, estimations of the unknown half-lives of the $7/2_1^+$ states in $^{99}$Ru and $^{103}$Ru were performed. The same mixing ratio as in $^{101}$Ru ($\delta$=-0.10) was accepted for the M1+E2 transitions, de-exciting $7/2_1^+$ in $^{99}$Ru and $^{103}$Ru. Under such assumption $T_{1/2}$=32 ps and $T_{1/2}$=325 ps for the half-lives of the $7/2_1^+$ states in $^{99}$Ru and $^{103}$Ru respectively, were obtained. The two values are within the RoSphere timing range.

Assuming a similar structure of the quasi-rotational bands in the region we estimate the half-lives of the $15/2^-$ states in $^{99,101,103}$Ru. The calculations are based on the transition probabilities, previously measured for the analogous states in $^{101,103,105}$Pd. Evaluated values for the $15/2^-$ states in $^{99}$Ru, $^{101}$Ru, $^{103}$Ru are $T_{1/2}$=14 ps, 70 ps and 60 ps respectively.

## 3 Experimental set up and preceding experience

The half-lives in the sub-nanosecond region will be measured with a specially designed system for fast-timing measurements at NIPNE. It comprises 14 HPGe detectors, working in coincidence with 11 $LaBr_3$:Ce detectors. The system is triggered by at least two $LaBr_3$:Ce detectors, fired in coincidence with a HPGe detector. The half-lives of the levels of interest will be measured by using the time interval between the feeding and de-exciting $\gamma$ rays detected by any two of the $LaBr_3$:Ce detectors, under the condition that the cascade is fed by a third transition with a $\gamma$ ray detected in a HPGe detector. In the last three years we have already used the experimental

Table 1: Estimated half-lives for the $7/2^+$ and $15/2^-$ excited states in $^{99,101,103}$Ru.

| Isotope | $J^{\pi\dagger}$ | $E^{\dagger}_{level}$ [keV] | $E^{\dagger}_{\gamma}$ [keV] | $T_{1/2}$ [ps] |
|---|---|---|---|---|
| $^{99}$Ru | $7/2^+$ | 341 | 341 | 32 |
| $^{101}$Ru | $7/2^+$ | 307 | 307 | $53^{\dagger}$ |
| $^{103}$Ru | $7/2^+$ | 214 | 211 | 325 |
| $^{99}$Ru | $15/2^-$ | 1572 | 502 | 14 |
| $^{101}$Ru | $15/2^-$ | 958 | 431 | 70 |
| $^{103}$Ru | $15/2^-$ | 654 | 416 | 60 |

$^{\dagger}$data from NNDC [3]

set up for several fast-timing experiments [4, 5, 6, 7]. The $^{7}$Li+$^{107}$Ag reaction was used to populate $^{111}$Sn. The structure of low-lying excited states in $^{103,105,107}$Cd was studied. In-beam experiments were carried out in order to measure half-lives of high-spin states in $^{95,96}$Mo. In January 2012 a fast-timing experiment was performed on $^{102-106}$Pd. Sample timing spectra from this experiment are presented on Fig. 3. The present experiment is focused on the odd-mass Ru isotopes, which will allow to make a systematical study in the region and to track the evolution of collectivity for specific states. This will shed light on the influence of particular single-particle orbits onto the collective motion.

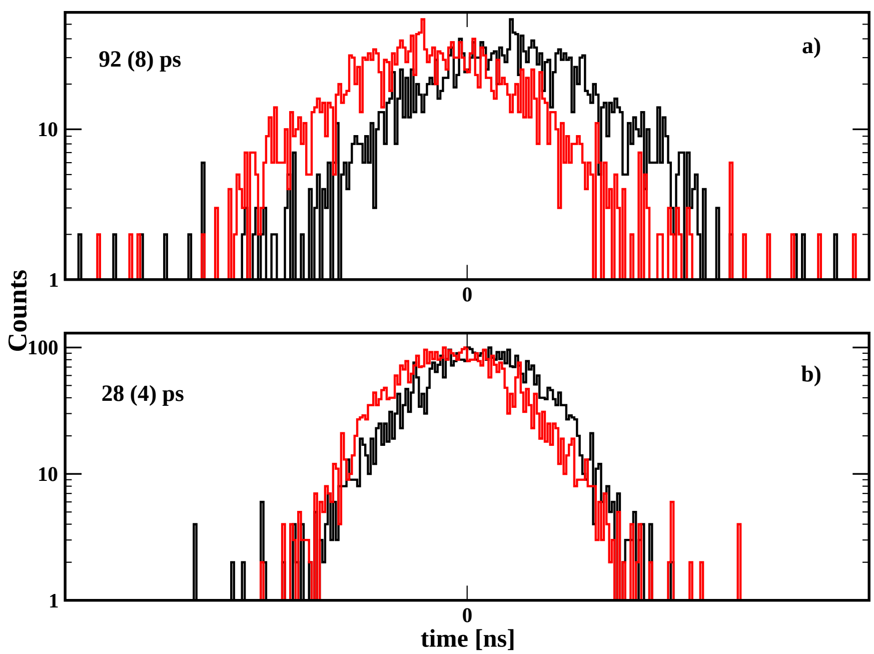


Figure 3: Time spectra, obtained for the decay of the $7/2^+_1$ state in $^{105}$Pd (a) and for the $15/2^-$ state in $^{105}$Pd [4]

# 4 Beam time estimation

Excited states in $^{99,101,103}$Ru will be populated in ($\alpha$,n$\gamma$) reactions. Targets of $^{96}$Mo, $^{98}$Mo and $^{100}$Mo will be used. The cross section for a beam energy of 15 MeV is estimated by using the

CASCADE code to ≈500 mb and ≈400 mb for $^{96}$Mo($\alpha$,n$\gamma$)$^{99}$Ru and $^{98}$Mo($\alpha$,n$\gamma$)$^{101}$Ru reactions respectively. $^{103}$Ru will be populated in $^{100}$Mo($\alpha$,n$\gamma$)$^{103}$Ru reaction with beam energy of 14 MeV and $\sigma$≈100 mb. $^{100}$Ru and $^{102}$Ru will be populated as side channels in the reactions. The energy loss *(dE/dx)* of the $\alpha$-particles in the three reactions is ≈0.19 MeV/(mg/cm$^2$). Hence, $^{96,98,100}$Mo targets with thickness of 10 mg/cm$^2$ will be used. The typical currents for $\alpha$-particles at NIPNE are of order of 20 nA. Thus, the expected yield for $^{103}$Ru in triple coincidences in an 8-hour shift is 402 counts. Therefore, **6 days of beam-time are requested** to measure the half-lives of the lower-lying positive-parity states and half-lives in the negative-parity quasi-rotational bands in $^{99,101,103}$Ru.

## 5 Conclusion

We propose to measure half-lives of excited states in $^{99,101,103}$Ru by using the in-beam delayed coincidence method. The measurements will give important information about the degree of collectivity in the odd-nuclei from the $A \sim 100$ mass region. The values, estimated for the half-life of the $15/2^-$ states in $^{101}$Ru and $^{103}$Ru, are in the range of RoSphere. A number of low-lying positive-parity states also have half-lives well within the range of RoSphere. The experimental data will be used for S. Kisyov PhD thesis, which is expected to start in the beginning of year 2013.

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