The Collective Structure of $^{106,108}\text{Ru}$

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Levels in $^{106,108}\text{Ru}$ have been studied by measuring $\gamma\gamma$ coincidences and $\gamma\gamma$ directional correlations of the $\gamma$-rays following the $\beta^-$-decay of 36 s $^{106}\text{Tc}$ and 5 s $^{108}\text{Tc}$. Tc activities were separated chemically from the fission products of thermal neutron induced fission of $^{239}\text{Pu}$ by the continuously running system “SISAK 2” and the $\gamma$-radiation was measured on-line. An extended level scheme for $^{108}\text{Ru}$, spin assignments, $E2/M1$ multipole mixing ratios and $B(E2)$ ratios for $^{106}\text{Ru}$ and $^{108}\text{Ru}$ have been obtained. The collective structure of the two nuclei is discussed in the framework of different nuclear models.

1. Introduction

The neutron-rich Ru isotopes are known to form a shape transitional region between spherical and deformed nuclei. The most detailed information is available for the heaviest stable isotope $^{104}\text{Ru}$ from multiple Coulomb excitation experiments [1, 2]; from the $B(E2)$ values and static quadrupole moments as determined in these experiments, a phase transition to soft triaxial rotors could be established rather than to axially symmetric rigid rotors on the basis of some distinctly different $E2$ properties for the two classes of nuclei. The aim of the present investigation is to extend this information on the nuclei $^{106,108}\text{Ru}$, i.e., towards the middle of the $N=50–82$ neutron shell, where in analogy to higher shells maximum deformation is expected.

The level schemes of $^{106,108}\text{Ru}$ have previously been investigated [3] by measuring $\gamma\gamma$ coincidences of the $\gamma$-radiation following the $\beta$-decay of 36 s $^{106}\text{Tc}$ and 5 s $^{108}\text{Tc}$ and from these experiments, numerous excited levels could be established for $^{106,108}\text{Ru}$. The systematical continuous decrease of the $2_1^+$ excitation energies together with the gradual increase of the energy ratio $E(4_2^+)/E(2_2^+)$ points to a smooth continuation of the trend observed in $^{98–104}\text{Ru}$. This is supported by two measurements [4, 5] of the lifetimes of the $2_1^+$-states in $^{108,110,112}\text{Ru}$, which give $B(E2)$ values 12–25% larger as compared to $^{104}\text{Ru}$.

Both $^{106}\text{Ru}$ and $^{108}\text{Ru}$ are unstable against $\beta^-$-decay and consequently multiple Coulomb excitation is no more a suitable tool to extend the information on the two nuclei. We therefore have chosen again the $\beta^-$-decay of the corresponding Tc precursors to populate excited states in $^{106,108}\text{Ru}$; the Tc precursors are produced by fission and to account for their short half-lives (36 s and 5 s) we have designed a new technique to measure $\gamma\gamma$ directional correlations on-line applying a continuous chemical separation of technetium from the fission product mixture. The experiment and the analysis of the data obtained are outlined in Sect. 2. In Sect. 3 the resulting spin assignments and $E2/M1$ multipole mixing ratios for $^{106,108}\text{Ru}$ and an extended level scheme of $^{108}\text{Ru}$ are presented. By comparing the present data to calculations in the framework of different nuclear models the collective shape variables can be extracted.

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(Sect. 4). A systematic discussion of the phase transition in the Ru isotopes in the framework of the interacting boson model including the present information on $B(E2)$ ratios is given in a separate publication [6]. Consequently in Sect. 4 we only will discuss some new aspects of the collective properties, which were not included there, as well as the $E2/M1$ multipole mixing ratios.

2. Experiments

In order to obtain maximum intensity for $\gamma$-activities corresponding to transitions in the nuclei $^{106,108}$Ru, which are the objects of the present investigation, and simultaneously to suppress the background due to other decay activities as far as possible the experiments were designed under the following aspects:

(i) To increase both the cumulative yields of the corresponding isobaric chains and the independent fission yield for the isotopes $^{106,108}$Tc (sitting on the heavy mass end of the light fission fragment branch) we used $^{239}$Pu rather than $^{235}$U as target.

(ii) To relatively enhance the short-lived isotopes $^{106,108}$Tc with respect to longer-lived Tc activities, which also are produced by fission directly or via $\beta^-$-decay of the corresponding Mo precursors, the time between fission and the start of the measurements was minimized. Thereby also the activities of the Ru and Rh daughter products are suppressed.

(iii) The distance between the $\gamma$-ray source and the gamma detectors was chosen as close as possible together with maximum source dimensions thereby only requiring, that a reliable correction of the entailed finite dimension and solid angle effects was still possible.

2.1. Gamma-Gamma Directional Correlation Measurements

The Tc activity was produced by thermal-neutron induced fission of $^{239}$Pu ($\approx 700 \mu$g) in the Mainz TRIGA reactor at a flux of $6 \times 10^{11}$ thermal neutrons/cm$^2$·s. A $N_2/\text{KCl}$ gas jet system [7] was used to transport the fission products into a chemical separation set-up, the continuously working on-line system “SISAK 2” [8]. The “SISAK 2” system is based on several consecutive liquid-liquid extraction steps and provides a continuous flux of the selected elements. For a detailed description of the chemical separation procedure used for the Tc isotopes see [9]. Two series of experiments were performed, one (i) especially designed to measure $\gamma\gamma$ directional correlations in $^{106}$Ru, the other (ii) yielded comparable intensities for $\gamma$-transitions in $^{108}$Ru and $^{108}$Rh.

(i) The chemical separation of Tc was performed in three liquid-liquid extractions steps [9]. The aqueous solution containing the Tc activity reached the measuring position about 7 s after fission and run through a polyethylene chamber (diameter 1 cm, length 4 cm) with a continuous flux of $\approx 10$ ml/s. By filling the polyethylene chamber with an anion exchange resin (DOWEX 1 $\times$ 4), the Tc activity could be retained in the measuring position on an average of 30 s, corresponding to about one half-life of the investigated isotope $^{106}$Tc. Activities of $^{104}$Tc and $^{107,108}$Tc were observed to have about 15% of the $^{106}$Tc intensity, whereas other Tc isotopes and Ru/Rh daughter products were less than 5%. The overall source strength was 0.8 MBq ($\approx 22$ gCi). The $\gamma$-radiation was measured continuously with two Ge(Li) detectors (active volume 73 cm$^3$, true coaxial, FWHM = 2.1 keV at 1,332 keV) each positioned at a distance of 5 cm from the center of the source and at relative angles $\theta_1 = 90^\circ$, $135^\circ$, $180^\circ$, $225^\circ$, $270^\circ$ between the two. The $\gamma\gamma$ coincidences and their time relation were recorded in a usual fast-slow coincidence set-up and written on magnetic tape on an event-by-event basis; in 56 h of active measuring time $2.25 \times 10^7$ coincidences could be collected.

(ii) The timing of the second series of experiments was designed to yield analogous information for $^{108}$Ru, which has a 5 s half-life Tc precursor. The “SISAK 2” system was reduced to two extraction steps and the measurements started $\approx 5$ s after fission. To suppress longer-lived activities the hold-up time in the measuring position was reduced to about 1 s by providing a continuous flux (of 12 ml/s) of the aqueous Tc solution through an unfilled polyethylene chamber (diameter 2 cm, length 4 cm). Comparable intensities of $^{106}$Tc and $^{108}$Tc were observed with this set-up. Also comparable was the intensity of $\gamma$-rays of $21$ s $^{107}$Tc, whereas $\gamma$-rays of $^{101-105}$Tc and of the decay products $^{107-110}$Ru and $^{107-110}$Rh were clearly suppressed (the strongest $\gamma$-rays of these isotopes being 1–8% of the corresponding strongest lines of $^{106-108}$Tc). The average source strength was 0.7 MBq ($\approx 19$ gCi). The $\gamma\gamma$ coincidences were recorded with 3 Ge(Li) detectors (active volume 138 cm$^3$, true coaxial, FWHM = 2.1 keV at 1,332 keV); two of them were fixed at a relative angle of $\theta_2 = 90^\circ$, the position of the third one was altered between $\theta_2 = 180^\circ$ and $225^\circ$. Each of the three $\gamma$-detectors could start a time-to-amplitude converter, which then was stopped by the next signal coming from either of the two other detectors. In an active measuring time of 55 h $7.9 \times 10^7$ $\gamma\gamma$ coincidences were re-