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Triaxial Isomer in ^{103}Ru

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Abstract. ^{103}Ru was produced in (α,nγ) reaction. Gamma rays, emitted by the excited nuclei, were detected by the ROSPHERE multidetector array. The half-life of the 297-keV state in ^{103}Ru was measured by using the in-beam delayed coincidence technique. The reduced transition probability of the isomeric transition was evaluated. Rigid triaxial rotor plus particle model calculations were performed. The model shows a good description of the ^{103}Ru level energies. The theoretical reduced transition probability for the isomeric transition is consistent with the experimental data. The isomeric state is thus interpreted as triaxial.

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1 Introduction

^{103}Ru is placed in a transitional region, located between the spherical ^{96}Ru$_{52}$ and the mid-shell deformed ^{110}Ru$_{66}$ nuclei, where rigid triaxial deformation emerges [1]. In this region, the even-mass Ru isotopes are extensively studied, but the data for the odd-mass Ru nuclei is often scarce and controversial. For example, in ^{103}Ru, which is in the focus of the present study, half-life data is available only for few excited isomeric states and the spin assignments made to several of the low-lying states are still disputed [2]. In particular, the 297-keV level in ^{103}Ru was populated in a number of experiments performed in the last 40 years, but its structure remains obscure. In 1975, this state was populated in (α,nγ) reaction and, based on angular distribution measurement, $J^\pi = 7/2^-$ was assigned [3]. Later, the $7/2^-$ assignment was confirmed in ^{102}Ru(n$_{th}$,γ) experiment [4]. In 1971 and 1982, the level was populated via (d,p) and (p,d) reactions and interpreted as a $\ell = 3$ state, but the authors could not exclude $\ell = 2$ assignment [5, 6]. In 1986, based on excitation function analysis and angular distribution measurement from (α,nγ), $J^\pi = 3/2^+$ assignment was suggested [7]. More recently, in 1994, the level was populated in (d,t) reaction [8]. Transferred angular momentum $\ell = 3$ was deduced from DWBA angular distribution analysis, supporting $J = 5/2, 7/2$ assignment. In 1998, the same team studied ^{103}Ru via (d,p) reaction [9] and, based on the DWBA analysis, $J^\pi = 3/2^-, 5/2^-, 7/2^-$ was ascribed to the level. Even though in the most recent data evaluation [2] $J^\pi = 7/2^-$ was adopted, still there are no strong arguments for it. Recently, the half-life of the state was measured and found to be unexpectedly long, which sheds light on its structure.

2 Experimental Set Up

Excited states in ^{103}Ru were populated in (α,nγ) reaction. Beam of α particles, accelerated to 15-18 MeV by the 9-MV Tandem accelerator at IFIN-HH (Romania), bombarded a 4-mg/cm^2 thick ^{100}Mo target. In order to stop the recoils the target was backed by a 28-mg/cm^2 thick Pb layer.

Gamma-rays, emitted by the excited nuclei, were detected by ROSPHERE – a γ-ray array comprising 11 LaBr$_3$:Ce and 14 HPGe detectors. Data were collected in an event-by-event mode and recorded only when three or more detectors, of which at least two LaBr$_3$:Ce and one HPGe, were fired in coincidence.

The experimental data were analyzed with the GASPware package [10]. Three-dimensional $(E_\gamma, E_\gamma, \Delta t)$ matrices were constructed, where E_γ denotes the γ-ray energies detected by the LaBr$_3$:Ce scintillators and Δt is the detection time difference. The matrices were constructed such as for each matrix element $(E_{i,\gamma}, E_{j,\gamma}, \Delta t_{ij})$ with $\Delta t_{ij} = t_0 + (t_i - t_j)$ there is a symmetric element $(E_{j,\gamma}, E_{i,\gamma}, \Delta t_{ji})$ with $\Delta t_{ji} = t_0 + (t_j - t_i)$. Here t_i and t_j denote the moments at which the two γ-rays were detected by the i^{th} and j^{th} detectors, respectively, and t_0 is an arbitrary offset. A more detailed description of the experimental set-up and the analysis procedures are given in Ref. [10].

3 Data Analysis

The partial level scheme of ^{103}Ru, as observed in the present study, is shown in Figure 1. The energy spectrum generated with signals from all of the LaBr$_3$:Ce detectors is compared to the total HPGe energy spectrum in Figure 2(a). The total HPGe spectrum represents events when at least two HPGe detectors were fired in coincidence. At low energies the spectrum is rather complex. In addi-

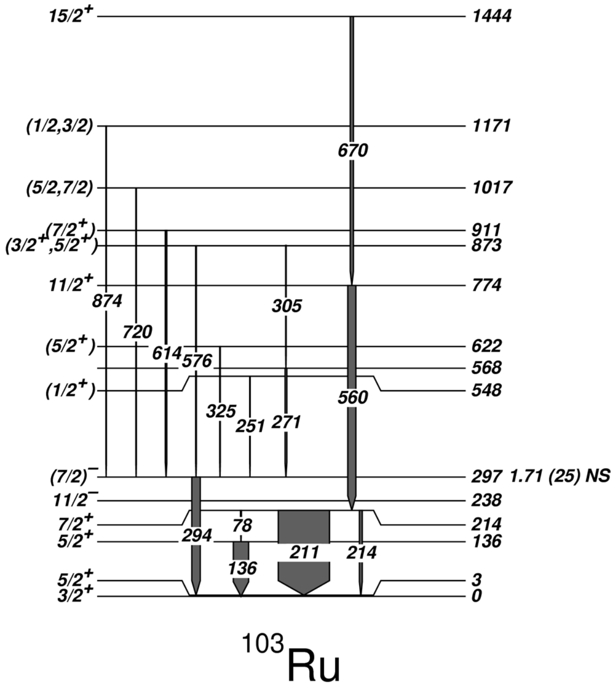

Figure 1. Partial level scheme of ^{103}Ru.

tion to ^{103}Ru lines, lines from ^{102}Ru, populated in the (α,2nγ) reaction channel, were also observed. It has to be noted that lines, well resolved by the HPGe detectors, often overlap in the $LaBr_3$:Ce spectrum because of the poorer resolution of the scintillator detector. To clean up the spectra, triple coincidences were used. The $LaBr_3$:Ce spectra, gated on the high-resolution HPGe detectors, are characterized by a lower peak density and a higher peak-to-background ratio. This is illustrated in Figure 2(b), where a cascade of γ-rays populating and de-exciting the 297-keV level was selected by imposing a 305-keV HPGe energy condition. Indeed, Figure 2(b) shows an increased peak-to-background ratio for the 271-keV and 294-keV lines, which are otherwise buried in the background in Figure 2(a).

The time structure of the positive parity states was analysed previously [11]. The half-life of the 297-keV state, measured for the first time in the present study, was deduced from the time spectrum shown in Figure 3. It shows the distribution $\Delta t_{271,294}$ of the time intervals between the feeding 271-keV and de-exciting 294-keV transitions detected by the $LaBr_3$:Ce detectors. The distribution has a slope on the right hand side of the peak which is typical for time spectra where

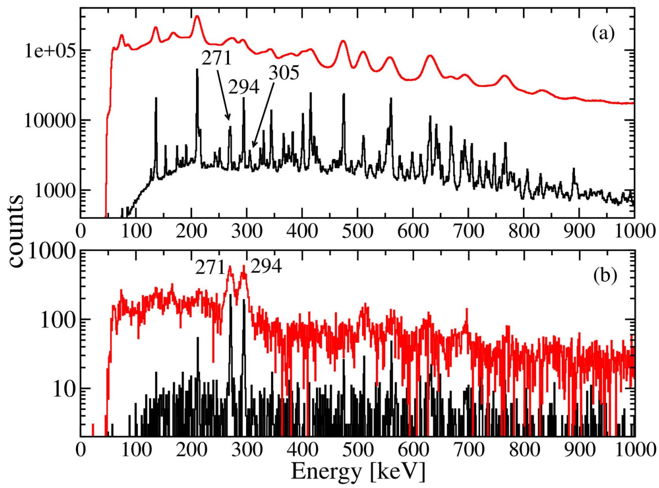

Figure 2. (Color online) Total projection (a) and gated (b) energy spectra, obtained with HPGe (in black) and $LaBr_3$:Ce (in red) detectors. The gated spectra are incremented with a condition on 305-keV transition imposed on the HPGe detectors.

level's half-life is longer than the detectors time resolution. For half-lives comparative or longer than the detector's time resolution the deconvolution or slope methods are usually applied. The deconvolution method, applied to the time spectrum in Figure 3, leads to $T_{1/2}$ = 1.71 (25) ns which is consistent with the half-life $T_{1/2}$ = 1.8 (3) ns obtained from the slope method.

The 297-keV level decays to the first excited $5/2^+$ state via 294 keV transition. In Ref. [7], based on angular distribution measurements, a pure dipole nature was deduced for this transition. Also there, Ref. [7], excitation function measurements were performed and $J^\pi = 3/2^+$ was assigned to the 297-keV level and hence the 294-keV transition links two states of positive parities. As a result, the authors deduce that the 294-keV transition is of $M1$ nature. It has to be noted, however, that the reaction data supports $7/2^-$ assignment to the isomeric state, which puts into question the magnetic nature of the isomeric transition. Due to these ambiguities, a dipole nature of the 294-keV transition was adopted in the most recent data evaluation [2].

Based on the half-life data from the present work and the internal electron conversion coefficients, calculated with BrICC [12], reduced transition probabilities $B(M1) = 4.9 \times 10^{-4}$ (8) W.u. and $B(E1) = 7.0 \times 10^{-6}$ (11) W.u. were calculated for a magnetic or electric dipole transition with an energy of 294 keV, respectively. Both values are consistent with the Löbner's systematics [13], where the $E1$ transitions are typically retarded by two to eight orders of magnitude with respect to the Weisskopf estimates and $M1$ hindrance may be up to four orders of magnitude. Hence, the new half-life data alone can not solve the ambiguity and

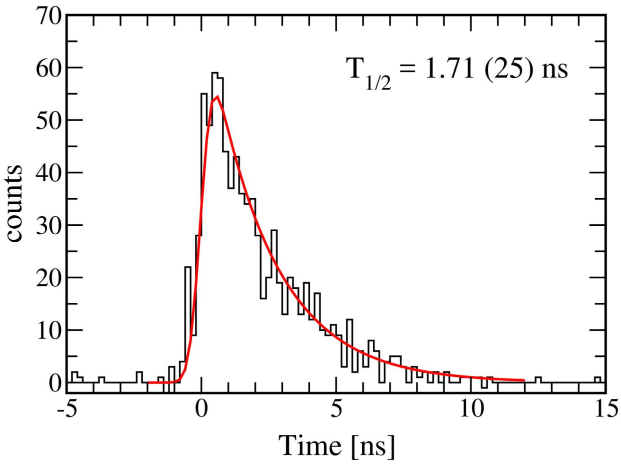

Figure 3. (Color online) Time spectrum for the 297-keV state in ^{103}Ru. The deconvolution method was applied to the distribution.

other arguments have to be used for the spin assignment to the isomer. These are: All direct measurements show that the 294-keV transition has a dipole nature; The 297-keV state is relatively well populated in the (α, nγ) reaction. Hence, it is more likely to be an yrast or near-yrast state; No primary transition to the 297-keV level from the $1/2^+$ n-capture states was observed [4]. Given that the primary transitions are typically of dipole nature, the missing primary transition to the 297-keV level suggests that $J^\pi \geq 5/2\hbar$; $\log ft = 7.6$ (3) [2] for the 297-keV level is more consistent with a first forbidden transition from the $5/2^+$ ground state in ^{103}Tc rather than with allowed transition.

Based on these arguments and the new data from the present experiment, we tentatively assign $(7/2^-)$ to the 297-keV state. We should note also that these are only "weak" arguments, according to the ENSDF standards, and $3/2^+$ can not be ruled out completely. However, if the state was indeed a $3/2^+$ state, then the isomeric transition would have been ℓ-forbidden, similar to the one observed in ^{105}Ru [14]. However, the (d,p) reaction data shows a small spectroscopic factor for the 297-keV level and indeed supports its collective structure.

4 Discussion

To interpret the structure of the isomeric state, Rigid triaxial rotor plus particle model calculations were performed with the GAMPN, ASYRMO and PROBAMO codes [15]. The single-particle energies in a triaxially deformed modified harmonic oscillator potential were calculated with the GAMPN program [15]. The standard Nilsson parameters $\kappa_4 = 0.070$ and $\mu_4 = 0.39$,

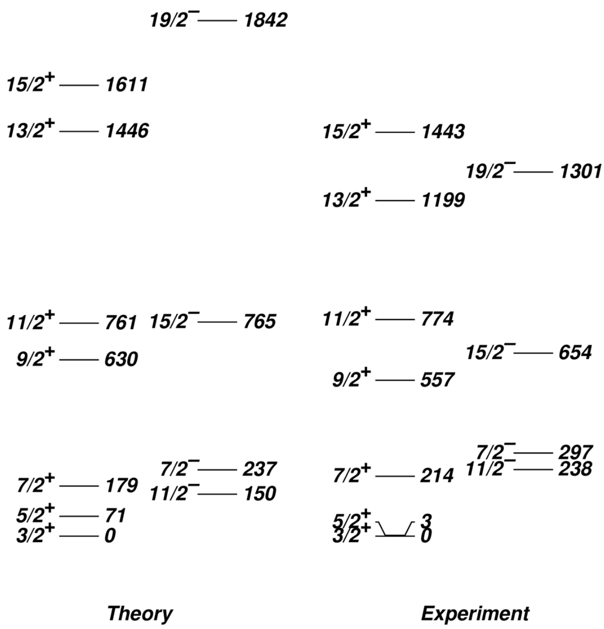

Figure 4. Theoretical and experimental ^{103}Ru level energies.

and $\kappa_5 = 0.062$ and $\mu_5 = 0.43$ [16, 17] were used for the fourth and fifth oscillator shell, respectively. The initial values of the deformation parameters ϵ_2 and ϵ_4 were adopted from Ref. [18]. The parameter of triaxial deformation $\gamma = (1/3)\arcsin\sqrt{(9/8)(1-(X-1)^2/(X+1)^2)}$ is deduced from the level energy ratio $X = E_{2_2^+}/E_{2_1^+}$, calculated from data for the neighbouring even-even core. The core moment-of-inertia was calculated from the $E_{2_1^+}$ level energy, obtained from the neighbouring even-even nuclei [19]. The particle-rotor level energies were calculated with the ASYRMO code [15]. A Coriolis attenuation parameter $\chi = 0.8$ was used. The parameters were then varied about the initial values in order to obtain a better fit to the experimental positive-parity level energies. The best description of the experimental data was obtained with the parameters listed in Table 1. The same set of parameters was then used to generate the negative-parity level energies. The theoretical results are compared to the experimental data in Figure 4.

Table 1. Rigid Triaxial Rotor plus Particle model (RTRPM) parameters for ^{103}Ru.

Nucleus	ϵ_2	ϵ_4	γ	$E_{2_1^+}$
^{103}Ru	+0.230	-0.04	26.0	0.39

The band head of the negative-parity band is well reproduced. $7/2^-$ state appears 87 keV above the $11/2^-$ band head. The theoretical $B(E1) = 0.22\times10^{-6}$ W.u., calculated for the transition leading to the $5/2_1^+$ level is consistent with the experimental value $B(E1) = 7.0 \times 10^{-6}$ (11) W.u. for the 294-keV transition in ^{103}Ru. Therefore, we interpret the 297-keV state as a triaxial state, having the same deformation as the other negative-parity states.

5 Conclusion

The half-life of the 297-keV state in ^{103}Ru was measured for the first time in the present study. The reduced transition probabilities, calculated for $M1$ and $E1$ transitions with energy of 294-keV, are consistent with the systematics. However, the analysis of historical data support the $7/2^-$ assignment to the state and hence the $E1$ nature of the isomeric transition.

Rigid triaxial rotor plus particle model calculations were performed for the positive and negative-parity states in ^{103}Ru. The overall description of the level energies is good. The model predicts a $7/2^-$ level to lie close above the $11/2^-$ band-head. The calculated reduced transition probability is consistent with the experimental value. As a result, we interpret the 297-keV isomeric state in ^{103}Ru as triaxial, having the same deformation parameters as the rest of the states discussed in the present work.

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