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Gamma Ray Spectroscopy of ^{105}Ru from a $(d,\ p\gamma)$ Reaction

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Abstract. This contribution presents nuclear structure data on ^{105}Ru, produced via the ^{104}Ru$(d,\ p\gamma)^{105}$Ru reaction. Excited states with energies up to 1.05 MeV have been studied. The γ-rays were detected by using ROSPHERE – the ROmanian array for SPectroscopy in HEavy ion REactions, in a mixed configuration consisting of 14 HPGe detectors and 11 $LaBr_3$:Ce scintillators. The (d, pγ) reaction populates predominantly low-spin states which can also be populated in the n-capture on ^{104}Ru. For the first time, γ rays emitted after the $(d,\ p)$ ^{105}Ru reaction are observed. ^{105}Ru is interpreted as a triaxial nucleus and its excited states are analyzed by using the Triaxial Rotor plus Particle Model.

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1 Introduction

^{105}Ru [1] is placed in a region of the Segré chart where rigid triaxial deformation occurs. The neighbouring ^{104}Ru is the most neutron rich stable isotope and has a well expressed triaxial properties, established from a Coulomb excitation [2]. Being odd-mass nucleus, ^{105}Ru presents an excellent opportunity to study the persistence of the triaxial deformation when moving one neutron away from ^{104}Ru. It also gives the chance to study how the odd particle affects the even-even core.

In spite that ^{105}Ru is just one neutron away from the last stable Ru isotope, and hence not so exotic, there are only few experimental methods through which its excited states can be populated. To date, excited states in ^{105}Ru have been populated in the β^- decay of ^{105}Tc [3], in thermal neutron capture on ^{104}Ru [4, 5], and in ^{104}Ru(d,p) reaction [6, 7]. However, due to the high selectivity of the β- decay process or due to the low angular momentum transfer in the single nucleon transfer reactions, only low-spin states have been populated. With the advent of the multidetector γ-ray arrays, however, high-spin yrast and near-yrast states were observed in the induced fission reactions ^{173}Yb(^{24}Mg,Xγ) [8] and ^{168}Er(^{30}Si,Xγ) [9].

In the present work we report on the partial results obtained from a series of experiments exploiting neutron stripping reactions with deuterium and carbon beams. In particular, we present the results we have obtained from the $(d, p\gamma)$ reaction.

2 Experimental Details

Excited states in ^{105}Ru were populated in ^{104}Ru(d,p) reaction. A chopped beam was provided by the 9-MV tandem accelerator from IFIN-HH, Romania. The beam on/beam off periods were 250 ms and 750 ms, respectively. The deuterium nuclei were accelerated to 6.7 MeV and impinged on a self-supporting 12 mg/cm^2 thick ^{104}Ru target. This energy was chosen to suppress the fusion/evaporation reaction, while keeping the (d, p) reaction cross section maximal.

Gamma rays, emitted by the excited ^{105}Ru nuclei, were detected by using the ROSPHERE spectrometer [10] shown in Figure 1. In the mixed configuration it consists of 14 HPGe detectors and 11 $LaBr_3$:Ce scintillators. However, the focus of this particular experiment was to measure the energies of the excited states in ^{105}Ru and, in particular, to check to what extent a (d, p) reaction can be used for γ-ray spectroscopy in ^{105}Ru.

In order to collect data two parallel data acquisitions were set. The analogue RoSphere data acquisition collected data in coincidences and in downscaled single modes. In the $(d, p\gamma)$ reactions the γ rays are of low multiplicity and often

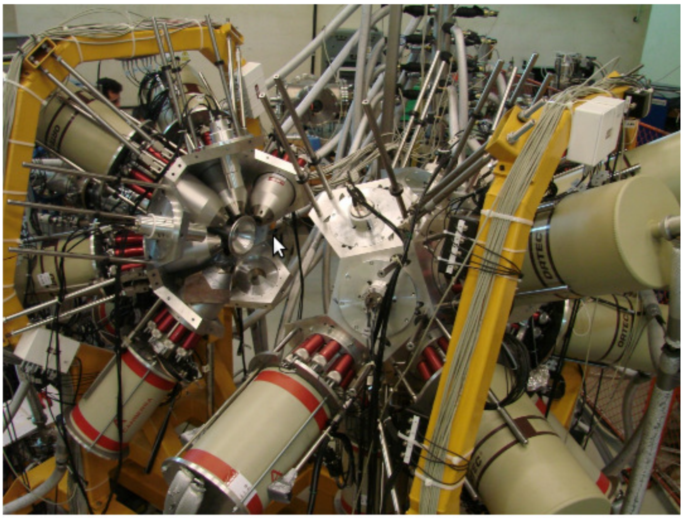

Figure 1. (Color online) The ROSPHERE spectrometer from IFIN-HH.

single γ-rays are emitted. Thus the mode of downscaled singles was used in order to detect the γ rays, that are not emitted in prompt coincidence with other γ rays, while keeping the system dead time low. The coincidence mode was used to establish, where exist, the coincidence between γ rays.

Another fully digital acquisition system, build especially for this experiment, was used to correlate the γ rays, detected by the HPGe detectors with the beam pulses. It was running in singles and the aim of the system was to search for isomeric decays in the microsecond range. These two acquisition systems combined allowed the coverage of a time range spanning 12 orders of magnitude from few picoseconds where the $LaBr_3$:Ce are sensitive, up to 1s, which is the length of the chopper time cycle. In the present experiment microsecond nor millisecond isomers were found. Here, we present the data obtained with the standard analogue acquisition system.

In a follow up experiment, the excited states in ^{105}Ru were obtained from a ^{13}C induced n-transfer reaction. The aim of this particular experiment was to compare the excitation function to that obtained from the $(d, p\gamma)$ study, but also to test if the ^{13}C induced n-transfer can enhance the population of some low-lying yrast states. Results from this experiment will be present elsewhere.

3 Data Analysis

The off line data analysis was performed by using the GASPware software [11]. Two dimensional spectra (2D), or matrices, were constructed to study γ-ray en-

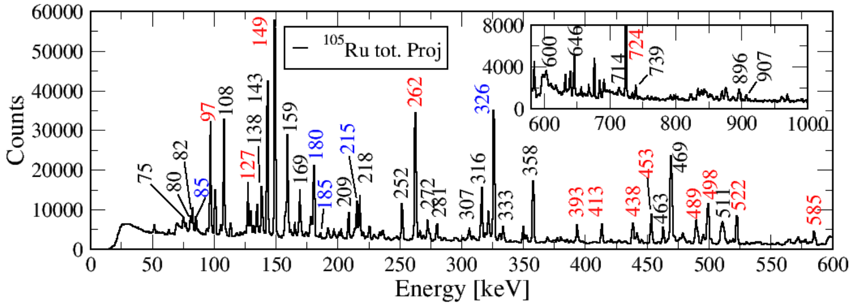

Figure 2. (Color online) Total projection of the ^{105}Ru γ ray spectrum obtained in the present study. The inset shows the part of the spectrum in the energy range 600-keV to 1000 keV. The lines, marked with red numbers, represents contaminants from ^{105}Rh produced in the competing fusion/evaporation channel.

ergy coincidences. Then one dimensional (1D) spectra were built from the 2D matrices, by imposing coincidences on particular γ-ray energies. The 1D spectra were analysed by using RADware software package [12]. Example spectrum, showing the total projection obtained with the HPGe detectors, is pre-

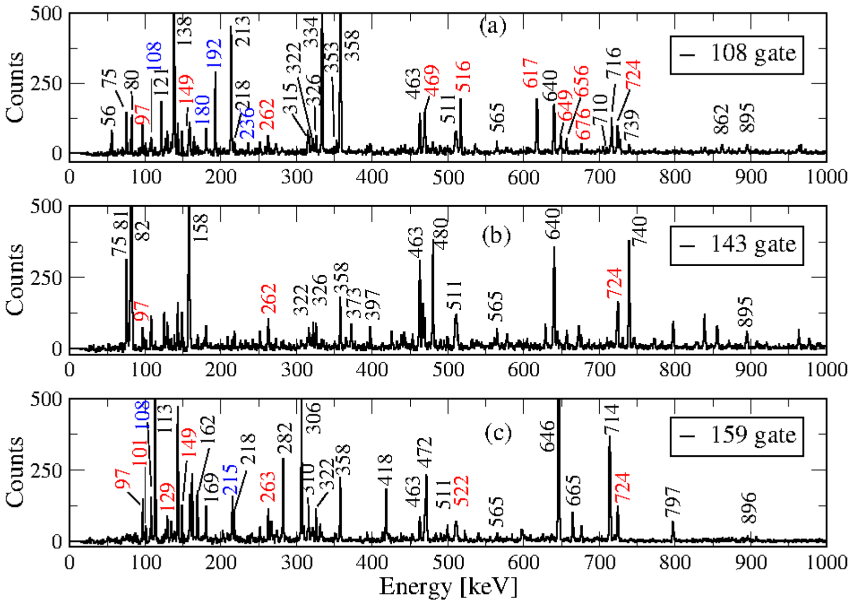

Figure 3. (Color online) Coincidence spectra gated on: (a) 108-keV; (b) 143-keV; and (c) 159-keV transitions. The energies, corresponding to γ lines in the ^{105}Rh contaminant, are written in red.

sented in Figure 2. Example coincidence spectra are shown in Figure 3. This figure presents three spectra, showing the γ rays emitted in coincidence with 108-, 143- and 159-keV transitions respectively. The γ rays associated with the ^{105}Ru have been previously observed from ^{104}Ru(n,γ) [4,5] showing a remarkable similarity of the two processes. Besides the ^{105}Ru transitions, however, few other transitions were observed, but not present in the ^{104}Ru(n,γ) data [1]. Those transitions have been found to belong to ^{105}Rh, which is the strongest competitive channel in d-induced fusion/evaporation reaction. Those transitions are denoted in red in Figures 2 and 3. The γ rays associated with ^{105}Ru are listed in Tables 1 and 2 and compared to the γ rays observed in the neutron capture data prior to our study.

Table 1. Experimental ^{105}Ru data. E_i is the initial level energy, J^π – spin and parity of the initial state from NNDC [1], E_f – level energy of the final states, and E_γ is the γ ray energy in keV. Only statistical uncertainties from the fit are given.

E_i	J^π	E_f	E_γ	E_i	J^π	E_f	E_γ
			174.4 (6)	302	$7/2^+$	21	280.9 (6)
			192.8 (6)			0	301.1 (6)
			196.8 (6)	322	$3/2^-$	246	75.5 (6)
			791.8 (6)			164	158.9 (6)
			797.6 (6)			159	162.4 (6)
			833.7 (6)			108	213.7 (6)
108	$5/2^+$		108.1 (6)			21	300.7 (6)
159	$1/2^+$	0	159.3 (6)			0	322.0 (6)
164	$3/2^+, 5/2^+$	108	55.9 (6)	442	$3/2^+, 5/2^+$	273	169.3 (6)
		21	143.3 (6)			159	282.5 (6)
186		0	185.8 (6)			108	333.6 (6)
229	$7/2^+$	108	121.6 (6)			21	420.9 (6)
		21	208.9 (6)	466	$(3/2)^+$	229	236.2 (6)
		0	229.5 (6)			159	306.7 (6)
244		164	81.0 (6)			108	358.0 (6)
		21	223.8 (6)	491	$(3/2)^-$	322	169.6 (6)
246	$(5/2^-, 3/2)$	164	82.7 (6)			273	218.0 (6)
		108	138.4 (6)			164	326.1 (6)
273	$(3/2, 5/2^+)$	186	85.4 (6)			159	331.4 (6)
		164	108.1 (6)	578	$(5/2^+, 3/2)$	159	418.6 (6)
		159	113.4 (6)			108	469.7 (6)
		108	165.2 (6)	582	$3/2^+, 5/2^+$	229	352.9 (6)
		21	252.0 (6)	620		442	178.6 (6)
		0	272.7 (6)	626	$7/2^+, 9/2^+$	229	397.7 (6)
						108	516.7 (6)
				631	$1/2^+$	273	358.1 (6)

Table 2. Same as in table 1), but for level energies $E_i > 630$ keV

E_i	J^π	E_f	E_γ	E_i	J^π	E_f	E_γ
631	$1/2^+$	164	467.0 (6)	836		620	215.4 (6)
		159	471.6 (6)	841	$7/2^+, 9/2^+$	302	538.2 (6)
644	$(5/2, 3/2)$	442	203.2 (6)	873	$1/2+$	273	600.5 (6)
		322	322.0 (6)			159	714.3 (6)
		246	397.8 (6)	887	$3/2^+$	644	242.4 (6)
		164	480.1 (6)			322	565.1 (6)
726	$(5/2^-, 7/2, 9/2^+)$	108	617.9 (6)			246	640.3 (6)
757	$3/2^+, 5/2^+$	442	315.8 (6)	903		164	739.6 (6)
		0	757.1 (6)	957	$(3/2, 5/2+)$	273	683.4 (6)
785	$1/2^-$	322	463.0 (6)			246	709.9 (6)
		246	537.9 (6)	967	$(1/2, 3/2, 5/2^+)$	644	323.4 (6)
801		620	180.9 (6)	1180	$(3/2+, 5/2+)$	302	878.3 (6)
806	$1/2^+$	159	646.3 (6)	1325	$(1/2, 3/2)$	785	541.0 (6)
824	$3/2^+, 5/2^+$	631	192.8 (6)	1330		491	839.1 (6)
		491	333.9 (6)		$(1/2, 3/2, 5/2+)$	466	862.3 (6)
		246	578.0 (6)	1845	$(1/2+, 3/2, 5/2+)$	967	878.3 (6)
		159	665.0 (6)				
		108	716.4 (6)				
		824	823.0 (6)				

4 Discussion

The ^{105}Ru nucleus is placed in a region where triaxial deformation emerges and Rigid Triaxial Rotor plus Particle Model (RTRPM) was used to describe its excited states. Earlier in [9], the low lying excited states in ^{105}Ru were used to fit the RTRPM parameters. In the present work, we will use the same parameters to check to what extent the states, populated in the $(d,\ p\gamma)$ reaction, have the same deformation parameters as the one obtained in the induced fission reaction [9].

The calculations were performed with the RTRPM with a strong coupling basis [13]. The single-particle wave functions were calculated with GAMPN code, which is part of the ASYRMO package [14]. A standard set of the Nilsson parameters [15] $\kappa_4 = 0.070$, $\mu_4 = 0.39$, $\kappa_5 = 0.062$, and $\mu_5 = 0.43$ was used. The level energies were calculated with ASYRMO [14], which diagonalizes the particle+triaxial-rotor Hamiltonian. The quadrupole deformation ϵ_2 and the moment-of-inertia $\hbar^2/2\Im = E_{2+}/6$ parameters were deduced from the neighbouring even-even nuclei. A Coriolis attenuation factor $\xi = 0.7$ was also used to obtain a better description of the band structure. The pairing was parametrized via GN0 = 22.0, GN1 = 8.0 and IPAIR = 5.0. In order to obtain a better fit to the experimental data in Ref. [9], ϵ_2, ϵ_4, γ, and E_{2+} parameters were varied. A good fit to the experimental level energies was obtained with $\epsilon_2 = 0.24$, $\epsilon_4 = -0.013$, $\gamma = 20°$, and $E_{2+} = 0.2$ MeV [9].

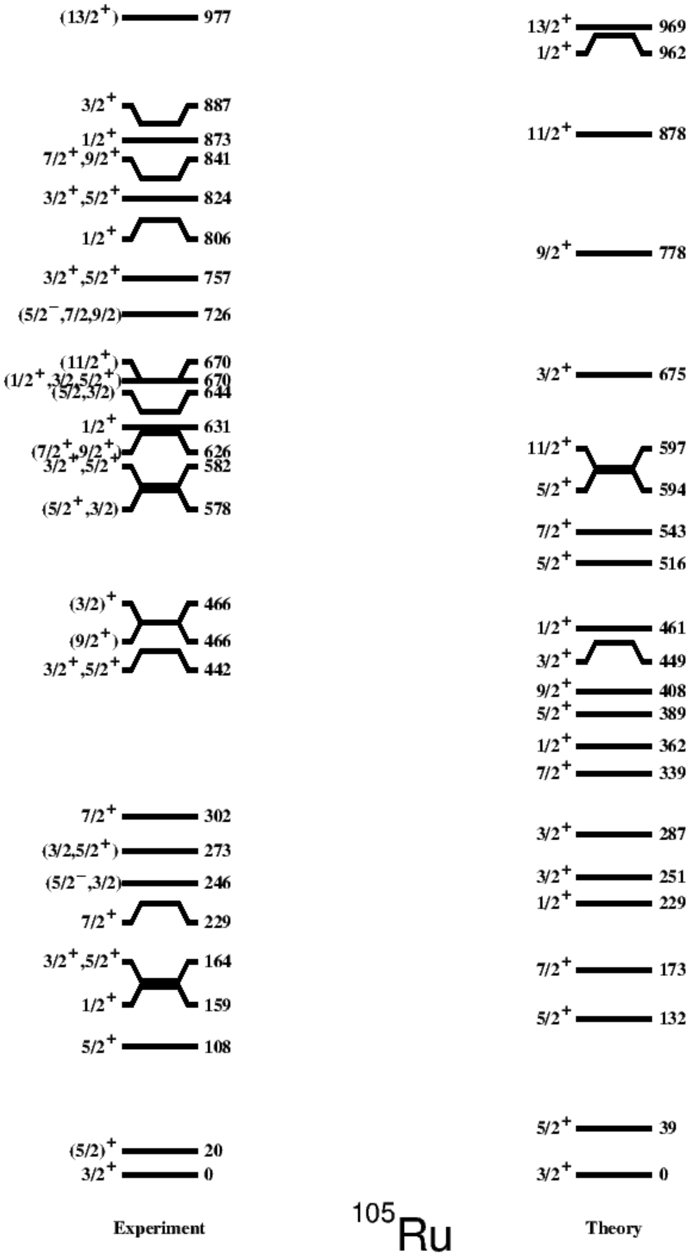

Figure 4. ^{105}Ru level energies. Experimental data from the present experiment, NNDC and Ref. [9] is compared to the RTRPM calculations.

All levels with energies up to 1 MeV, known from various experimental studies [1], including the $(d,\ p\gamma)$ data from the present manuscript, are compared with the low energy part of the RTRPM spectrum. The yrast states are, in general, better described than the non-yrast states. This is somewhat not surprising given that the model parameters were fitted in order to obtain a good fit for the yrast and near-yrast states observed in the induced fission data [9]. A better description of the level scheme can be achieved by taking into account all levels when fitting the Hamiltonian parameters. Such an approach would globally smooth the description of the level scheme, but would also mask the states which now emerge as poorly described.

In the present calculations, the low-spin states like the $1/2^+$ and $3/2^+$ are not well reproduced, even though they exist in the low-energy theoretical spectrum. It should be noted also, that many of these states do not have firm spin/parity assignments, which is a prerequisite for further theoretical studies. Thus, in order to obtain a deeper understanding on the low-energy part of the ^{105}Ru more data is needed.

5 Conclusions

^{105}Ru was populated in (d,p) reaction and its γ rays were observed for the first time by using this reaction. The levels populated in this reaction are identical to the levels obtained in the thermal neutron capture on ^{104}Ru. Given that the nucleus is placed in a region of prominent triaxiality, the Rigid Triaxial Rotor Model was used to describe its excited state. The model parameters were obtained from the fit to the yrast and near-yrast states, observed previously in induced fission reactions. This approach was used to reveal states with structure, different from the structure of the yrast state. Even though the model description can be improved by using all states, when fitting the model Hamiltonian, it is obvious that the low spin states, in general, behave differently then the yrast state. This effect will be masked, if all states were used in the fit. However, to better understand the structure of these states, more experimental data leading to firm spin/parity assignments is needed.

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References

[1] D.De Frenne and E. Jacobs (2005) *Nucl. Data Sheets* **105** 775.

[2] J. Srebrny *et al.* (2006) *Nucl. Phys*. **A766** 25.

[3] K. Summerer, N. Kaffrell, and N. Trautnamm (1975) *Z. Phys.* **A273** 77.

[4] B. Hrasnik, H. Seyfarth, A.M. Hassan, W. Delong, P. Göttel (1974) *Nucl. Phys*. **A219** 381.

[5] H.H. Guven, B. Kardon, H. Seyfarth (1978) *Z. Phys*.**A287** 271.

[6] P. Maier-Komor, P. Glässel, E. Huenges, H. Rösler, H.J. Scheerer, H.K. Vonach, and H. Baier (1976) *Z. Phys*. **A278** 327.

[7] H.T. Fortune, G.C. Morrison, J.A. Nolen, and P. Kienle (1971) *Phys. Rev*. **C3** 337.

[8] N. Fotiades *et al.* (1988) *Phys. Rev. C* **58** 1997.

[9] S. Lalkovski *et al.* (2014) *Phys. Rev. C* **89** 064312.

[10] N. Marginean *et al.* (2010) *Eur. Phys. J. A* **46** 329.

[11] N. Marginean *et al*. `httpps://github.com/rlica/gaspware/blob/master/GASPware`

[12] D. Radford. ***radware.phy.onrl.gov***.

[13] S.E. Larsson, G. Leander, and I. Ragnarsson (1978) *Nucl. Phys.* **A307** 189.

[14] P. Semmes and I. Ragnarsson (1992) The Particle + Triaxial Rotor Model: A User's Guide, presented at the RisoHands-On Nuclear Structure Theory Workshop, June 1992 (unpublished).

[15] T. Bengtsson and I. Ragnarsson (1985) *Nucl. Phys*.**A436** 14.