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Evolution of collective structures in the heavy transitional nuclei above the N = 82 closed shell

D. T. Joss[1,a]

[1] *Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom*

Abstract. The emergence of collectivity in atomic nuclei is a fundamental paradigm in nuclear structure physics. Considerable progress has been made towards the identification of excited states in heavy neutron-deficient nuclei above the $N = 82$ closed shell. This paper summarises recent progress in the spectroscopic study of the Ta, W and Re nuclides with $N \sim 90$ obtained from recoil and recoil-decay tagging experiments. The nuclei near $N = 90$ occupy a γ-soft transitional region where the nuclear shape is particularly sensitive to the interplay between collective excitations and the underlying single-particle structure. The consequences of these interactions for low and high-spin states are discussed.

1 Introduction

The identification of excited states in atomic nuclei spanning complete shells is crucial for understanding the evolution of nuclear structure from both experimental and theoretical perspectives. The character of the low-lying excited states changes as the number of valence nucleons increases beyond closed shells from single-particle multiplets to collective excitations arising from the correlated motion of many nucleons. The $82 \leq N \leq 126$ shell presents the largest range of nuclei where the properties of excited states can be measured experimentally with current techniques. In particular, the advent of selective experimental methods has allowed the identification of excited states at the extremes of this shell where the onset or demise of collective behaviour occurs [1, 2].

Much progress has been made towards identifying the excited states in the neutron-deficient nuclei above the $N = 82$ shell gap. However, extending knowledge to those isotopic chains heavier than Hf is challenging due to their relatively low production cross sections in fusion evaporation reactions. For example, excited states have been established in the closed shell nuclide ^{154}Hf ($N = 82$) [3] but the lightest isotopes with low-lying excited states in heavier even-Z chains are ^{160}W [4], ^{162}Os ($N = 86$) [5], and ^{168}Pt ($N = 90$) [6]. Moreover, collective effects and the underlying single-particle structure cannot be completely decoupled and the identification of excited states in odd-A nuclei and their spectroscopic study, particularly in the transitional region, can provide more detailed insights into nuclear shapes and correlations. This paper summarises recent results for the even mass W [7] and odd mass Re [8] and Ta [9, 10] nuclides in the $N \sim 90$ transitional region obtained from recoil and recoil-decay tagging experiments and discusses the implications for nuclear structure in this region.

[a] e-mail: david.joss@liverpool.ac.uk

2 Experimental Methodology

Excited states in several neutron-deficient Ta, W and Re nuclides were populated using fusion-evaporation reactions in experiments performed at the Accelerator Laboratory of the University of Jyväskylä, Finland. Prompt γ rays were detected at the target position by the Jurogam γ-ray spectrometer [11]. The recoiling fusion-evaporation residues were separated from fission products and scattered beam by the RITU gas-filled recoil separator [12] and implanted into the double-sided silicon strip detectors (DSSD) of the GREAT spectrometer [13] at the focal plane. Recoiling nuclei were distinguished from the residual scattered beam and radioactive decays by energy loss and (in conjunction with the DSSDs) time of flight methods using the GREAT multiwire proportional counter.

All detector signals from Jurogam and GREAT were passed to the total data readout acquisition system [14] where they were time stamped with a precision of 10 ns to allow accurate temporal correlations between γ rays detected at the target position, recoil implants at the focal plane and their subsequent radioactive decays. These triggerless data were sorted into γ-γ matrices and γ-γ-γ cubes using GRAIN [15] and analysed with the RADWARE software packages [16].

The recoil-decay tagging (RDT) technique correlates γ rays detected at the target position with the characteristic radioactive decays of the residual nucleus at the focal plane of a recoil separator [1]. The RDT technique provides high-confidence correlations under the optimal conditions of short decay half-lives and high decay branching ratios. Gamma-ray emissions from ^{162}W, ^{163}Re and ^{165}Re

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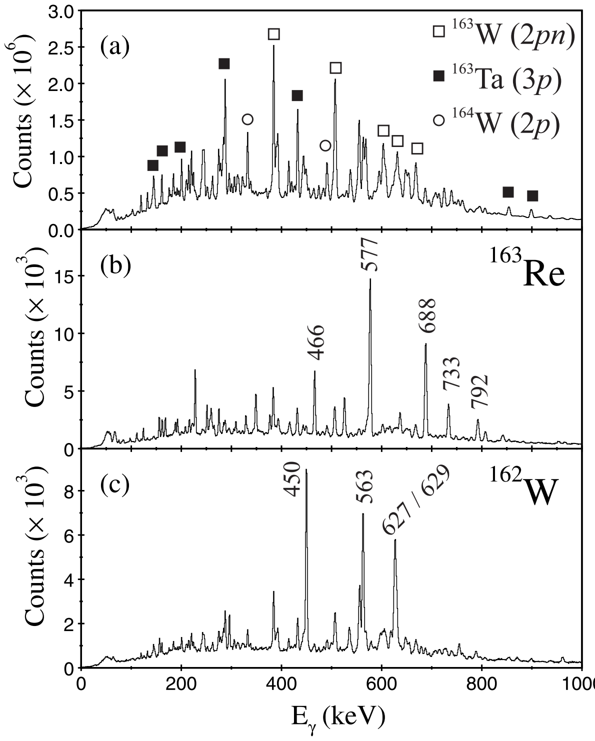

Figure 1. Gamma rays detected in the Jurogam spectrometer following the ^{106}Cd(^{60}Ni, xp,yn,zα) reaction at 270 MeV. (a) γ rays in delayed coincidence with any recoil implantation detected in the GREAT DSSDs located at the RITU focal plane. Gamma rays are associated with the main reaction products in the legend. (b) Gamma rays correlated with recoil implantations followed by the characteristic α decay from the 11/2$^-$ isomer in ^{163}Re within the same DSSD pixel of the GREAT spectrometer. The recoil-α correlation time was limited to 600 ms. (c) Gamma rays correlated with recoil implantations followed by the distinct ground-state α decay of ^{162}W within the same DSSD pixel of the GREAT spectrometer. The recoil-α correlation time was limited to 2.4 s.

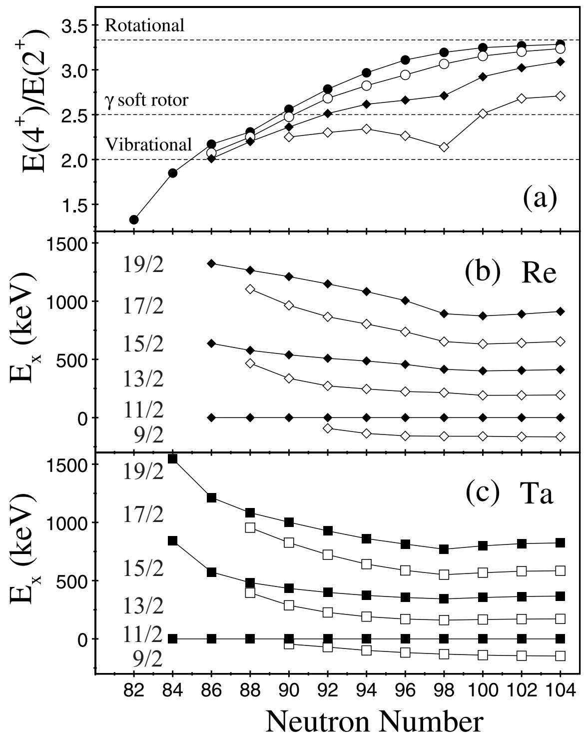

Figure 2. (a) Ratios of the 4$^+$ and 2$^+$ state excitation energies as a function of neutron number for the Hf (filled circles), W (open circles), Os (filled diamonds) and Pt (open diamonds) nuclides. The limiting cases for vibrational, γ-soft and rotational nuclei are indicated by dashed lines. Excitation energies of the low-lying excited states in the $\pi h_{11/2}$ bands of the neutron-deficient (b) Re isotopes and (c) Ta isotopes. The level energies are plotted relative to the 11/2$^-$ state. Open (filled) symbols correspond to states in the $\alpha = +1/2$ ($\alpha = -1/2$) signature partner.

could be identified by correlations with their characteristic α decays. Other nuclides with less favourable α-decay properties, such as ^{161}Ta, ^{163}Ta and ^{164}W were studied using γ rays detected in Jurogam that were in delayed coincidence with recoils implanted in the focal plane detector. Figure 1 shows examples of spectra obtained with the RDT technique.

3 The Heavy N > 82 Transitional Nuclei

3.1 Low-Lying Excited States

The development of collective behaviour outside the N = 82 shell gap is reflected in the variation of low-lying excited states as a function of neutron number. The ratio of the 4$^+$ and 2$^+$ state excitation energies in even-Z, even-mass nuclei, $E(4^+)/E(2^+)$, is often used as an indicator of collectivity. Figure 2(a) shows the variation of the $E(4^+)/E(2^+)$ ratio across the Hf, W, Os and Pt isotopes against the reference limits for vibrational, γ-soft and rotational nuclei. Isotones with higher atomic numbers have lower $E(4^+)/E(2^+)$ ratios as a consequence of their smaller number of valence protons. The Hf, W and Os isotopes show a smooth increase in $E(4^+)/E(2^+)$ as a function of neutron number indicating the emergence of collectivity from single-particle type excitations ($N \sim 82$), through γ-soft triaxial shapes ($N \sim 90$) to axially symmetric deformed rotors near the neutron midshell at ($N = 104$). The $N \sim 98$ platinum isotopes (and their osmium isotones to a lesser extent) show a marked deviation from the gradual increase in $E(4^+)/E(2^+)$ ratio with increasing neutron number. This arises from perturbations to the yrast sequences arising from mixing between coexisting bands [17–19].

The transitional nuclei near $N = 90$ are soft to triaxial deformation due to spatial density distributions of the proton and neutron orbitals at the top or bottom of their respective shells [20]. For example, in ^{164}W$_{90}$, the proton Fermi surface lies in a region of low level density near the high-Ω $h_{11/2}$ states while the neutron Fermi surface lies close to the lowest-Ω $\nu i_{13/2}$ orbital and negative-parity orbitals originating from both the $\nu f_{7/2}$ and $\nu h_{9/2}$ subshells. Further evidence for soft triaxial shapes at $N \sim 90$ can be

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found by probing the structure of the neighbouring odd-mass Re and Ta nuclides. Figure 2(b) and 2(c) show the variation of the excitation energies of the low-lying yrast states in the Re and Ta isotopes, respectively.

The lightest even-N Re and Ta isotopes have ground states that are near-spherical and based on the low-Ω $s_{1/2}$ or $d_{3/2}$ proton states with a low-lying isomer formed by exciting the odd proton into the high-Ω $h_{11/2}$ state [21–26]. Gamma rays associated with the characteristic radioactive decays of the $h_{11/2}$ isomer in ^{157}Ta [27] (N = 84), ^{159}Ta [4] and ^{161}Re [28] (N = 86) have revealed non-collective excited states formed by coupling the odd proton to the few valence neutrons in $f_{7/2}$, $h_{9/2}$ and $i_{13/2}$ states. In these nuclei the odd-proton is decoupled from the underlying W cores. With the addition of a few neutrons, coupled bands with a large degree of signature splitting are observed in the 88 $\leq N \leq$ 94 nuclides [8–10, 29–31]. This splitting is attributed to triaxiality, which relieves the degeneracy of the high-Ω $h_{11/2}$ orbital. As the maximum number of valence neutrons is reached at N = 104, the $\alpha = +1/2$ ($13/2^-$ and $15/2^-$) states lie near the midpoints of the levels in the $\alpha = -1/2$ signature partner [32, 33]. This is interpreted as a restoration of signature degeneracy in the $\pi h_{11/2}$ orbital due to the onset of axial prolate symmetry arising from maximal correlations between nucleons at the neutron midshell.

3.2 High-Spin Structures

The yrast cascades for the transitional (N = 88, 90) Ta and W nuclides are observed to spins beyond the first rotational alignment. At present, excited states in their Re isotones have not been observed to sufficiently high spin to characterise rotationally aligned structures. The high-spin structure of the $N \sim 90$ nuclides can be discussed in terms of the γ-ray energy, E_γ, as a function of the angular momentum of the initial emitting state I_i, see Fig. 3. This formulation is chosen over the familiar alignment plots as a function of rotational frequency since it relies entirely on experimental data and removes the need to specify K, which is ill-defined in triaxial nuclei.

A comparison of Fig. 3(a) and 3(b) shows that band 1 in ^{162}W has a lower alignment gain than band 1 in its heavier even-mass neighbour, ^{164}W. Gamma-ray spectroscopy studies of $N < 90$ nuclei suggest that the low average deformation of these nuclei favours excitations involving the negative-parity ($\nu f_{7/2}$, $\nu h_{9/2}$) states [10, 34–38]. The quadrupole deformation of ^{164}W is predicted be larger ($\beta_2 = 0.161$) than ^{162}W ($\beta_2 = 0.116$) [39], which is sufficient to bring the lowest Ω $\nu i_{13/2}$ orbital close to the Fermi surface. Indeed, the $i_{13/2}$ neutron orbital dominates the yrast spectra of the $N \geq 90$ W isotopes where excitations of one or two $\nu i_{13/2}$ quasineutrons are favoured at low spin and excitation energy [7, 36, 40, 41].

The excited band (band 2) in ^{162}W has a similar degree of alignment to the excited bands (bands 2 and 3) in ^{164}W. The excited bands in the W isotopes are interpreted as two quasiparticle configurations formed by coupling a single $\nu i_{13/2}$ orbital to the available $\nu f_{7/2}, \nu h_{9/2}$ negative-parity states. The excited bands have angular momentum values that are greater than the $(\nu f_{7/2}, \nu h_{9/2})^2$ aligned configuration of ^{162}W yet lower than the $(i_{13/2})^2$ aligned configuration in ^{164}W.

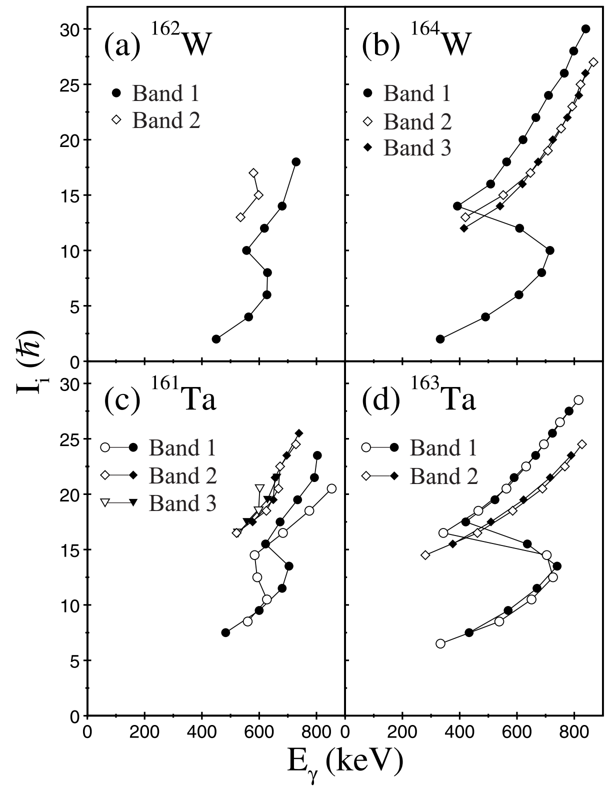

Figure 3. Angular momentum of the initial emitting state I_i versus γ-ray energy E_γ for collective bands in (a) ^{162}W, (b) ^{164}W, (c) ^{161}Ta, (d) ^{163}Ta. Open (filled) symbols correspond to states in the $\alpha = +1$ ($\alpha = -1$) signature partner in the even-Z, even-A W isotopes or the $\alpha = +1/2$ ($\alpha = -1/2$) signature partners in the odd-Z, odd-A Ta isotopes

Figures 3(c) and 3(d) show that similar features are observed in the Ta isotones resulting from coupling an single $h_{11/2}$ quasiproton to the underlying W core configurations. The excited bands in ^{161}Ta (bands 2 and 3) show increases in angular momenta that are consistent with the initial stages of a transition from three to five quasiparticle configurations. It is apparent from Fig. 3(c) that there is considerable signature splitting both below and above the first rotational alignment in ^{161}Ta. Signature splitting at low spin is also observed in ^{163}Ta, which vanishes at high spin following the $(i_{13/2})^2$ alignment. This indicates that the rotational alignment of $\nu i_{13/2}$ neutrons has a greater polarising effect on the soft-triaxial core than the ($\nu f_{7/2}$, $\nu h_{9/2}$) negative-parity alignments.

4 Summary

This paper has reviewed the recent progress made in understanding the development of collectivity in the transitional Ta, W and Re isotopes located above the N = 82 closed neutron shell. Level schemes in these nuclei have been established and extended in a campaign of recoil (-decay) tagging experiments at the University of Jyväskylä

Accelerator Laboratory using the Jurogam and GREAT spectrometers in conjunction with the RITU gas-filled separator.

The evolution of low-spin states as a function of neutron number reveals the onset of collectivity from single-particle excitations to well-deformed collective rotors. The nuclei in the transitional ($N \sim 90$) region between these two regimes display features that are consistent with γ-soft triaxial rotors.

The high-spin structure of the transitional Ta and W isotopes highlights the interplay between collective excitations and specific nucleon orbitals at the Fermi surface. A comparison of the rotational properties of $^{162}W_{88}$ and $^{164}W_{90}$ indicates that the $\nu f_{7/2}, h_{9/2}$ rotational alignment is favoured over the $\nu i_{13/2}$ pair alignment at $N = 88$. An increase in deformation at $N = 90$ alters the relative positions of the $\nu f_{7/2}, h_{9/2}$ and $\nu i_{13/2}$ orbitals and configurations involving the latter become favoured for the $N \geq 90$ W isotopes. Spectroscopic investigations of the odd-Z nuclides $^{161}Ta_{88}$ and $^{163}Ta_{90}$ highlight the sensitivity of the γ-soft core to the occupation of core-polarizing orbitals at the Fermi surface. The low-spin states in both nuclei are single $h_{11/2}$ quasiproton configurations that exhibit a significant degree of signature splitting. It is shown that while the rotational alignment of a pair of $f_{7/2}, h_{9/2}$ neutrons in ^{161}Ta does little to alter the γ-soft triaxial shape, the $\nu i_{13/2}$ pair alignment in ^{163}Ta is sufficient to polarise the triaxial core towards an axially symmetric prolate shape.

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