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Anomalous Ratio of Reduced Transition Probabilities in the Yrast Band of ^{166}W

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Lifetimes of excited states in the yrast band of the neutron-deficient nuclide ^{166}W have been measured utilizing the DPUNS plunger device at the target position of the JUROGAM II γ -ray spectrometer in conjunction with the RITU gas-filled separator and the GREAT focal-plane spectrometer. Excited states in ^{166}W were populated in the $^{92}\text{Mo}(^{78}\text{Kr},4p)$ reaction at a bombarding energy of 380 MeV. The measurements reveal an anomalously low value for the ratio of reduced transition probabilities for the lowest-lying transitions ($B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+) = 0.33(5)$). Such behavior is exceedingly rare for collective excitations and inconsistent with model predictions.

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The evolution of deformation in atomic nuclei outside closed-shell configurations and the collective excitations that subsequently arise is an important paradigm in many-body quantum physics [1, 2]. The spectral features associated with vibrational excitations near the closed shells and collective rotational bands near midshells are usually interpreted within the context of nuclear collective models. Experimental techniques have also evolved to allow precise measurements of excited state properties such as reduced transition probabilities, $B(E2)$ values, which are sensitive to nuclear collectivity [3–5].

A universal prediction of collective models is that the ratios of reduced transition probabilities $B_{4/2} \equiv B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+)$ should yield values greater than unity [2]. At the collective limits expected for harmonic vibrators and axially deformed rotors, collective models yield the ratios $B_{4/2} = 2.00$ and 1.43, respectively [2, 6]. A survey of extant data was carried out by Çakirli *et al.* [7] who identified nine nuclei having anomalously low $B_{4/2}$ ratios that are incompatible with these predictions. While the low ratios of reduced transition probabilities are expected due to shape coexistence where the 2^+ and 4^+ states belong to differently deformed configurations [8, 9] or in nuclei near the closed

shells due to seniority structures [10] such behavior is not expected in deformed nuclei with collective excitations.

Although some of the cases reported by Çakirli *et al.* [7] have been remeasured using complementary experimental techniques and the anomaly corrected (e.g. ^{98}Ru , ^{180}Pt [11] and ^{134}Ce [12]), the anomaly persists in several other nuclei, such as ^{114}Xe and ^{114}Te [13, 14]. Further anomalous cases have since been reported, including $^{48,50}\text{Cr}$ [15], $^{72,74}\text{Zn}$ [16] and ^{168}Os [5]. This paper reports lifetime measurements for low-lying states in ^{166}W , which is a lighter even-mass isotone of $^{168}\text{Os}_{92}$, which is found to exhibit the $B_{4/2}$ anomaly.

Excited states in ^{166}W were populated using the $^{92}\text{Mo}(^{78}\text{Kr},4p)$ reaction. A 380 MeV $^{78}\text{Kr}^{15+}$ beam provided by the K130 cyclotron at the University of Jyväskylä Accelerator Laboratory bombarded a 0.6 mg/cm^2 ^{92}Mo target. A nominal beam intensity of 3 pA was delivered to the target. The reaction provided an initial recoil velocity of $v/c = 4.3\%$. The γ rays emitted by the recoiling nuclei were detected by the JUROGAM II Ge detector array consisting of 15 Phase 1-type [17] and 24 Compton suppressed HPGe segmented Clover detectors [18].

The DPUNS differential plunger device [19] was in-

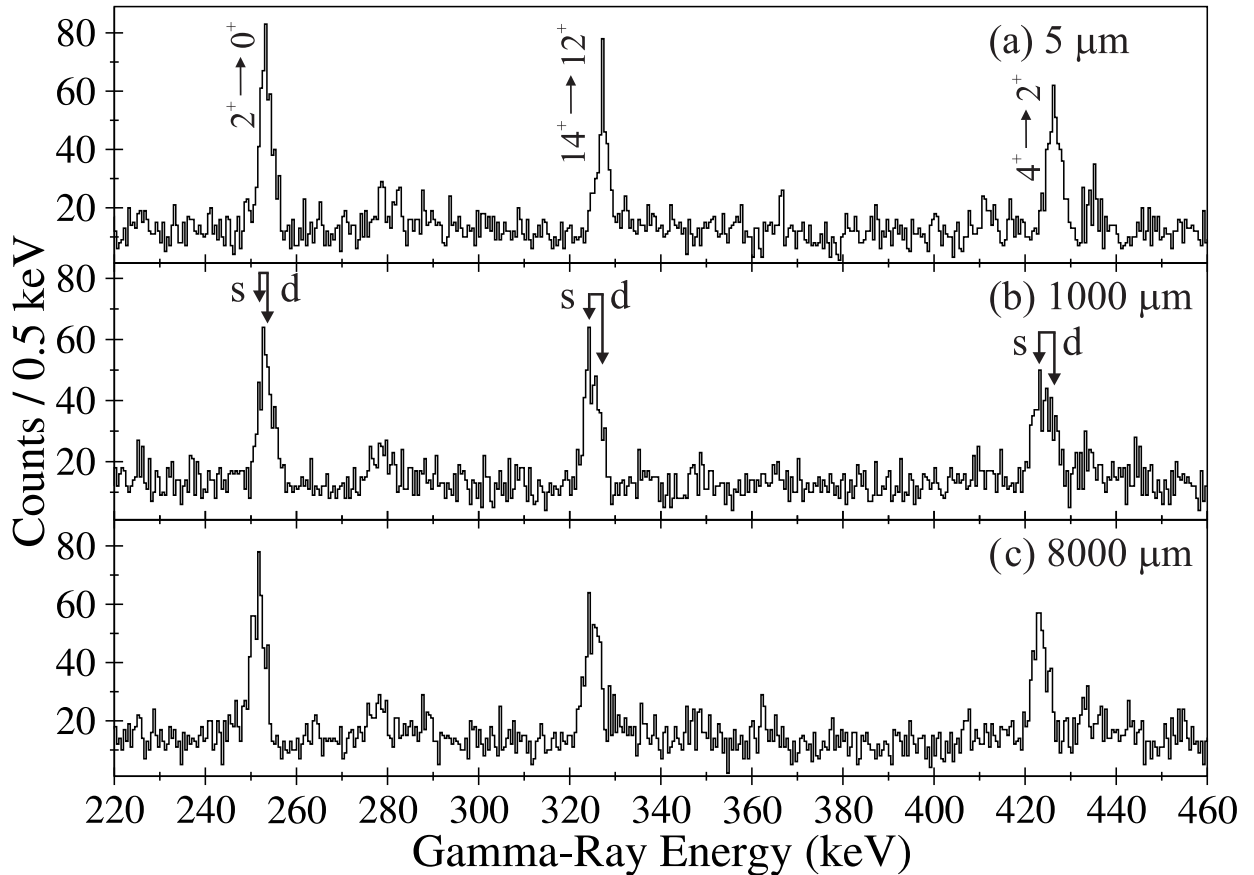


FIG. 1: Gamma-ray coincidences correlated with implanted nuclear recoils detected in the DSSDs of the GREAT spectrometer. Spectra for three different target-to-degrader distances of (a) $5 \mu\text{m}$ (b) $1000 \mu\text{m}$ (c) $8000 \mu\text{m}$ with the ten JUROGAM II Ge detectors at 133° . Each spectrum is in coincidence with the 480 keV ($12^+ \rightarrow 10^+$) transition, which was chosen to eliminate the contributions from energy doublets in the side bands. The fully Doppler-shifted (s) and degraded (d) components of the 252 keV , 326 keV and 424 keV γ -ray transitions are labeled.

stalled at the JUROGAM II target position in order to measure excited state lifetimes using the Recoil Distance Doppler-Shift (RDDS) technique [20]. A 1 mg/cm^2 thick Mg degrader was employed to slow down evaporation residues to $v/c = 3.3\%$ and therefore allowing reaction products to recoil into the RITU gas-filled separator [21–23] and transported to the focal plane. The recoiling fusion-evaporation residues were implanted into the double-sided silicon strip detectors (DSSDs) of the GREAT spectrometer [24] located at the RITU focal plane. The energy loss of the recoils, measured in the MWPC, and time-of-flight (in conjunction with the DSSDs) were used to discriminate fusion-evaporation residues from scattered beam. The GREAT triggerless data acquisition system [25] was utilised to collect data time stamped to a precision of 10 ns . Gamma-ray spectra in delayed coincidence with the implanted recoils were sorted

with the GRAIN data analysis package [26]. The NAPATAU software [27] for the Differential Decay Curve Method (DDCM) analysis [20] was used to analyze γ -ray intensities.

Recoil-correlated γ -ray coincidences were recorded at nine target-to-degrader distances of the DPUNS device ranging from $5 \mu\text{m}$ to $8000 \mu\text{m}$ for ~ 25 hours at each distance. This range was chosen to span the region of sensitivity where the relative intensities of the fully shifted and degraded components of the depopulating transitions for the low-lying yrast states in ^{166}W varied, see Fig. 1. Recoil-correlated γ -ray coincidences with the 480 keV ($12^+ \rightarrow 10^+$) and 686 keV ($10^+ \rightarrow 8^+$) transitions were analysed in order to eliminate the influence of energy doublets and unobserved feeding transitions on the lifetimes under investigation.

Sufficient γ -ray coincidences were collected with JU-

ROGAM II between the detection angles at 158° (five detectors) and 133° (ten detectors) with all other detectors to allow the measurements of the low-lying yrast states using the differential decay curve method (DDCM) [20]. In the DDCM, the mean lifetimes are obtained from the relative intensity variation with target-to-degrader distance of the fully Doppler-shifted and degraded components of the γ -ray transitions feeding and depopulating the level of interest through the equation

$$\tau = \frac{Q_{\text{depop}}^d(x) - Q_{\text{feed}}^d(x)}{v \frac{d}{dx} [Q_{\text{depop}}^s(x)]}, \quad (1)$$

where $Q_j^i(x) = I_j^i / (I_j^s + I_j^d)$ and $I_j^i(x)$ are the γ -ray intensities for the shifted ($i = s$) and degraded ($i = d$) components measured at the target-to-degrader distance x for the depopulating ($j = \text{depop}$) and feeding ($j = \text{feed}$) transitions, respectively. Therefore, the γ -ray intensities I recorded with different distances x are normalized by the sum of their fully shifted and degraded components. The final lifetime is an error-weighted average of individual lifetimes (Eq. 1) obtained at the different target-to-degrader distances within the region of sensitivity where the derivative of the decay curve is greater than zero. Lifetime determination for the 2^+ and 4^+ states are as shown in Fig. 2.

In order to obtain statistically viable γ -ray spectra, coincidences were demanded between the full lineshape of the 480 keV ($12^+ \rightarrow 10^+$) and 686 ($10^+ \rightarrow 8^+$) keV indirect feeding transitions recorded with the whole JUROGAM II spectrometer, and the lower-lying depopulating transitions recorded in the JUROGAM II detectors at 133° or 158° , in order to extract the lifetimes of the 2^+ , 4^+ and 6^+ states, respectively. The indirect γ -ray feeding intensities were measured by demanding coincidences below the states of interest. The validity of this method has been demonstrated in Ref [28].

In order to extract the lifetimes of the 12^+ and 14^+ states, the spectra for the feeding and depopulating transitions were obtained by demanding coincidences with the full γ -ray lineshape of transitions directly depopulating and feeding the levels of interest, respectively [28, 29]. Table I lists the measured mean lifetimes τ and the deduced $B(E2)$ reduced transition probabilities.

The evolution of collective behavior can be reflected in the excitation energies of the low-lying excited states. Figure 3(a) shows the variation in the ratio of the ex-

TABLE I: Lifetimes and reduced transition probabilities of the yrast states in ^{166}W .

E_γ [keV]	$I_i^\pi \rightarrow I_f^\pi$	τ (ps)	$B(E2)[e^2b^2]_\downarrow$	$B(E2)$ [W.u.]
252	$2^+ \rightarrow 0^+$	86(6)	0.81(5)	150(9)
424	$4^+ \rightarrow 2^+$	21(3)	0.27(3)	50(7)
550	$6^+ \rightarrow 4^+$	16(4)	0.09(2)	18(4)
480	$12^+ \rightarrow 10^+$	27(4)	0.11(1)	21(3)
326	$14^+ \rightarrow 12^+$	21(2)	0.98(8)	182(16)

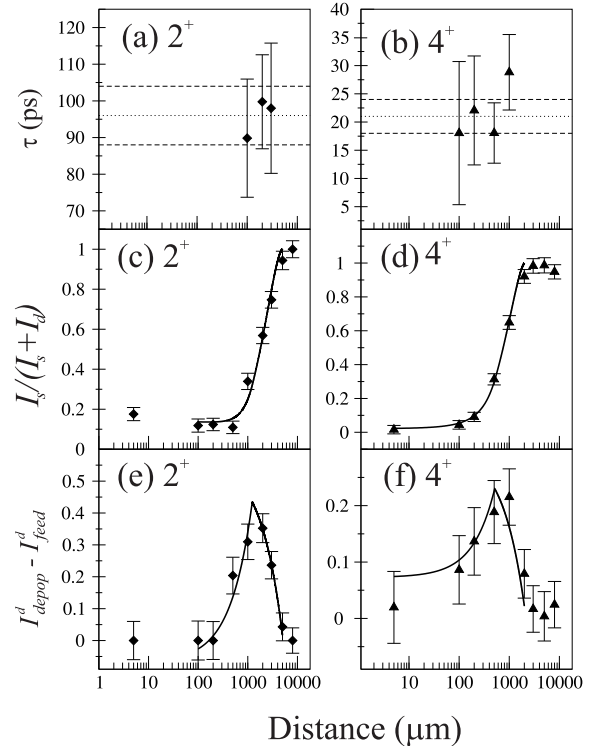


FIG. 2: Lifetime determination using the differential decay curve method (DDCM). The individual mean lifetimes and error bars are represented as the solid and dashed horizontal lines, respectively for (a) the 2^+ state in ^{166}W and (b) the 4^+ state in ^{166}W . The decay curves extracted from coincidence spectra gated indirectly above the (c) 2^+ state and (d) 4^+ state. The line drawn through the experimental points is the fit to the decay curve. All spectra are collected from the ten detectors at 134° . (e) The numerator of Eq. (1) and the derivative of the decay curve for the 2^+ state and (f) the 4^+ state.

citation energies of the yrast 4^+ to 2^+ states in the W isotopes as a function of the neutron number. The systematic trends show ratios consistent with the transition from collective vibrations at $^{160}\text{W}_{86}$ [30], through γ -soft rotors ($^{166}\text{W}_{92}$) [31] to well-deformed rotors near the neutron midshell ($^{178}\text{W}_{104}$) [32]. As the neutron number increases further, and the valence space reduces towards $N = 126$, the excitation energy ratio decreases towards values consistent with γ -soft nuclei near $^{190}\text{W}_{116}$ [33].

The measurement of reduced transition probabilities, $B(E2)$ values, can provide more detailed insights into the development of collectivity. Figure 3(b) shows the variation of the $B(E2)$ values as a function of the neutron number. While the $E_{4/2}$ ratio increases steadily in the transitional region as valence neutrons are added to the $N = 82$ closed shell, the $B(E2; 2^+ \rightarrow 0^+)$ value for $^{166}\text{W}_{92}$ shows a local peak at ~ 150 W.u. before falling to lower values (~ 130 W.u.) for $N = 94$ and $N = 96$ and peaking again at $N = 98$ (~ 200 W.u.).

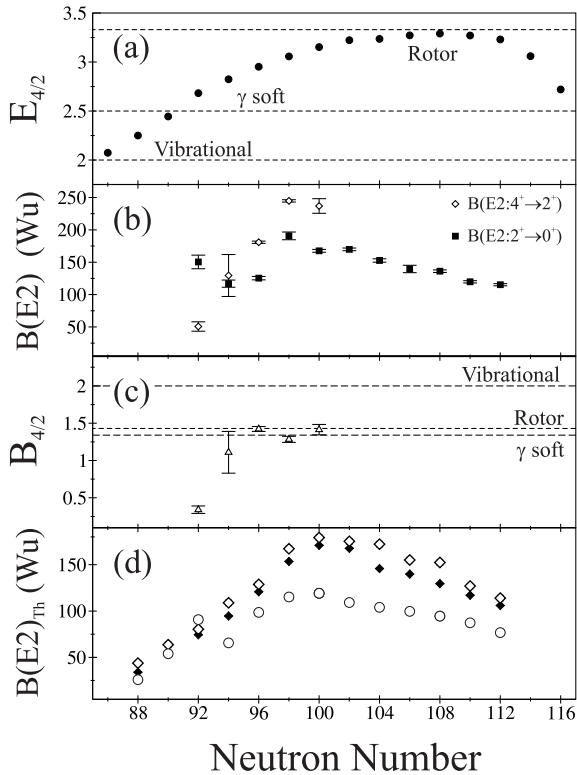


FIG. 3: (a) Ratios of the 4^+ and 2^+ state excitation energies ($E_{4/2}$) for the even mass W isotopes. (b) Measure reduced transition probabilities $B(E2)$ for the $4^+ \rightarrow 2^+$ (open diamonds) and $2^+ \rightarrow 0^+$ (filled squares) transitions. (c) Ratios of reduced transition probabilities ($B_{4/2}$) measured for the even-mass W isotopes. (d) Theoretical reduced transition probabilities $B(E2)$ for the $2^+ \rightarrow 0^+$ transitions in the even-mass W isotopes. Model predictions using the finite range droplet model (open diamonds), Woods-Saxon model (filled diamonds) and dynamical microscopic model (open circles) are displayed. The values for ^{166}W correspond to neutron number $N = 92$. Data for the heavier isotopes were obtained from reference [34–37]

The variation of the $B(E2; 4^+ \rightarrow 2^+)$ values as a function of the neutron number are low at $N = 92$ and increase steadily as the number of valence neutrons increases towards the neutron midshell ($N = 104$). The $B(E2; 2^+ \rightarrow 0^+)$ measurements yield higher values than the $B(E2; 4^+ \rightarrow 2^+)$ measurements at $N = 92$, which results in an anomalously low ratio of reduced transition probabilities $B_{4/2} = 0.33(5)$ for ^{166}W compared with the heavier isotopes, see Fig. 3(c). It is interesting to note that the Os isotopes display a very similar trend in the reduced transition probabilities. The $B(E2; 4^+ \rightarrow 2^+)$ measurements in the Os isotopes also peak at $N = 98$ and fall below the $B(E2; 2^+ \rightarrow 0^+)$ measurements at $N = 92$. Consequently, the $B_{4/2}$ ratio extracted recently for the heavier $N = 92$ isotone ^{168}Os is also anomalously low ($B_{4/2} = 0.34(18)$) [5].

The origin of the anomaly in both cases remains an

enigma. The lack of proximity to a closed shell precludes an inversion due to generalized seniority scheme. Moreover, although perturbations in the low-lying yrast states due to shape coexistence are observed in the heavy $N = 96$ Os and Pt isotones, energy level systematics suggest that strong perturbations are not anticipated at $N = 92$ [38]. Furthermore, no evidence could be found for a non-yrast positive-parity structure as seen in ^{168}Os . The absence of a quasi- β band in ^{166}W is not surprising. Kibedi *et al.* performed measurements of the non-yrast states in the even- N W isotopes from ^{178}W to ^{170}W and found that the quasi- β band has a parabolic energy dependence on neutron number [38]. Kibedi *et al.* also noted that comparisons of quasi- β bands in the Os, Pt and Hg isotopes revealed a trend towards higher excitation energies for the excited 0^+ states as the proton number recedes from the $Z = 82$ shell closure.

Theoretical model predictions for $B(E2; 2^+ \rightarrow 0^+)$ values have been compiled by Raman *et al.* for the $2 \leq Z \leq 100$ nuclei [39]. Figure 3(d) shows a comparison between the predictions by the finite range droplet model, Woods-Saxon model and dynamical microscopic model for the $B(E2; 2^+ \rightarrow 0^+)$ values in the tungsten isotopes. Note that in order to allow comparisons with our measured values, the $B(E2; 2^+ \rightarrow 0^+)_{\uparrow}$ measured and theoretical values of Ref [39] have been converted into $B(E2; 2^+ \rightarrow 0^+)_{\downarrow}$ values using the expression

$$B(T\lambda : I_2 \rightarrow I_1) = \frac{2I_1 + 1}{2I_2 + 1} B(T\lambda : I_1 \rightarrow I_2). \quad (2)$$

In general, all three models predict qualitatively the behaviour of experimental measurements for the $N \geq 98$ isotopes. While the finite range droplet model and Woods-Saxon model calculations fail to reproduce the measured experimental $B(E2; 2^+ \rightarrow 0^+)$ values for the $N < 98$ isotopes the dynamical microscopic model appears to show a modest increase in the $B(E2; 2^+ \rightarrow 0^+)$ value for ^{166}W .

The dynamical microscopic model employs generator coordinate method techniques, which may be better suited for describing transitional nuclei through the microscopic determination of the collective dynamics [40, 41]. It has been suggested that anomalous $B_{4/2}$ ratios in the γ -soft nuclei such as ^{168}Os , and therefore by extension ^{166}W , may arise from mixing due to dynamical shape fluctuations [5]. While beyond the scope of this work, a detailed theoretical study of such effects might reveal the underlying physical basis for the unusual nature of the anomalous ratios of reduced transition probabilities in these γ -soft transitional nuclei.

In summary, the lifetimes of 2^+ , 4^+ , 6^+ , 12^+ and 14^+ states in ^{166}W have been measured for the first time using the recoil-distance Doppler shift method. Reduced transition probabilities extracted from these lifetimes of the low-lying states in the ground state band have revealed an abnormal $B_{4/2}$ ratio with the value of 0.33(5), which is lower than the values expected from collective models ($B_{4/2} = 1.43$). The experimental 2^+ systematics in the W isotopes have been compared with theoretical predic-

tions of models compiled by Raman *et al.* The dynamical microscopic model based on the generator coordinate method is able to reproduce qualitatively the experimental behaviour for $92 \leq N \leq 108$ tungsten isotopes [39]. The structural origin of the anomaly remains enigmatic and further work is required to investigate whether the expected triaxiality of ^{166}W might contribute to this puzzling observation.

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