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Isomers and oblate collectivity at high spin in neutron-rich Pt isotopes

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Abstract. Isomers and high-spin structures with rotation-aligned oblate configurations have been studied in several Pt isotopes. The 12^+ states in the even Pt isotopes from $^{192-198}$Pt are found to be metastable, and have $(i_{13/2})^2$ neutron character. The progression of $E2$ transition probabilities from the 12^+ to 10^+ states across the Pt isotopic chain implies reduction in collectivity, followed by an abrupt decrease at N=120 (^{198}Pt). This behavior is quite distinct from the gradual decrease of $B(E2)$ values near the respective ground states. A large contribution from aligned angular momentum, to the rotational sequences built on the 12^+ states, is visible. This is due to the relatively small crossing frequencies for nucleons in low-Ω orbitals at oblate deformation in comparison to higher values for prolate shapes. As a result, oblate rotation is found to be increasingly favored for higher neutron numbers.

1 Introduction

The large majority of nuclei across the periodic chart are deformed, with prolate shapes being the most common. The moment of inertia of a rigid prolate rotor is higher in comparison to that of an oblate one for similar magnitudes of quadrupole deformation [1]. Consequently, the excitation energies for prolate rotational states, particularly at high spin, are expected to be lower than the corresponding oblate ones. While this is generally found to be the case for most nuclei, in a limited region around A=190, collective oblate rotation is the favored excitation mode at high spin. This rather unusual phenomenon is realized since the proton and neutron Fermi levels are located near low-Ω, high-j intruder orbitals for oblate deformation, while for prolate deformation, they are in the vicinity of high-Ω orbitals from the same subshells. Since low-Ω orbitals typically exhibit a higher degree of alignment compared to high-Ω ones over a similar range of rotational frequency, oblate states are found to be lower in energy than the corresponding prolate ones. While this phenomenon was first predicted quite some time ago [2], as yet, there are a relatively small number of nuclei where collective oblate rotation is experimentally observed to the favored excitation mode [3–5]. Oblate shapes are expected to be more favored in neutron-rich nuclei however these are experimentally difficult to explore.

While isotopes of Hf (Z = 72) and W (Z = 74) are established to be well-deformed, rigid rotors [6, 7], with increase in both proton and neutron numbers approaching the doubly magic ^{208}Pb, the ground state deformation is found to decrease gradually. The behavior at high spin is however not as well documented. Proton-rich Pt isotopes have been studied rather extensively *e.g.* [4, 8, 9], and found to exhibit well-developed rotational bands both near the ground states and at high spin. With increase in neutron number from the lightest stable isotope ^{190}Pt (N=112) to the heaviest ^{198}Pt (N = 120), the decrease in ground state deformation and collectivity is evidenced by the increase in 2^+_1 excitation energy in even-A nuclei accompanied by a corresponding reduction in $B(E2; 2^+ \rightarrow 0^+)$ values. Previously, there was little information on the evolution of collectivity at high spin in the Pt isotopic chain.

This work is focused on oblate, rotation-aligned configurations in ^{192,194,196,198}Pt, for which the lowest (12^+) states are metastable in nature. Most of the new information presented here pertains to isomers in the heaviest stable isotopes ^{196,198}Pt, and rotational sequences in ^{192,194,196}Pt. Oblate rotation is found to be particularly favored in energy for higher neutron numbers. In addition, an abrupt reduction in collectivity at high spin is observed for ^{198}Pt (N = 120) compared to lighter isotopes, quite unlike the steady decrease near the respective ground states.

2 Experiment and results

Excited states in Pt isotopes were populated through multinucleon transfer using a 1450-MeV ^{209}Bi beam incident on a thick (≈50 mg/cm^2) ^{197}Au target. The beam was delivered by the ATLAS accelerator at Argonne National Laboratory and γ rays emitted in the deexcitation of the reaction products were detected by the Gammasphere array consisting of 100 high-purity, Compton-suppressed Ge detectors [10]. The data were sorted into both symmetric and asymmetric histograms ranging from two- to four-fold, depending on the energy and time parameters involved; details may be found in [11]. Lifetimes of isomeric states were determined, and both prompt and delayed (from isomeric decays) transitions were established from the data

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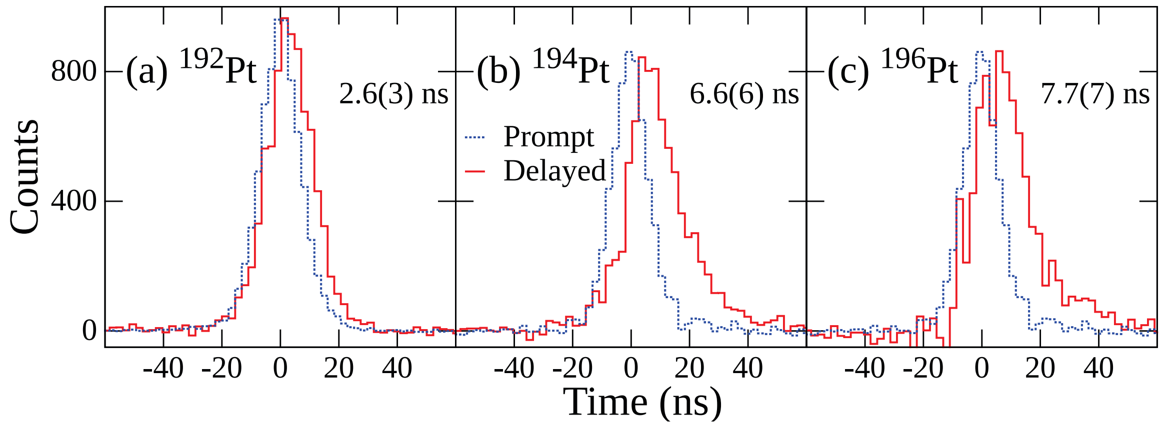

Figure 1. (Color online) Centroid-shift analysis for determination of half-lives of 12^+ states in: (a) ^{192}Pt (b) ^{194}Pt (c) ^{196}Pt. The dotted (blue) and solid (red) lines indicate the time distributions for prompt and delayed transitions, respectively.

Table 1. Isomer half-lives, reduced $E2$ transition probabilities for 2^+_1, and 12^+ (isomeric) decays in even Pt isotopes and their comparison with Weisskopf estimates. The values marked with asterisks are upper limits.

Isotope	$T_{1/2}$ (12^+) ns	$B(E2; 2^+ \rightarrow 0^+)$ e^2b^2	$B(E2; 12^+ \rightarrow 10^+)$ e^2b^2	$\frac{B(E2; 2^+ \rightarrow 0^+)}{B_W(E2; 2^+ \rightarrow 0^+)}$	$\frac{B(E2; 12^+ \rightarrow 10^+)}{B_W(E2; 12^+ \rightarrow 10^+)}$
^{192}Pt	2.6(3)	0.377(8)	0.339(23)	57(1)	52(4)
^{194}Pt	6.6(6)	0.329(5)	0.387(35)	49(1)	58(5)
^{196}Pt	7.7(7)	0.275(1)	0.158(32)	41(1)	23(2)
^{198}Pt	36(4)	0.215(1)	0.016*	31(1)	2.4*

analysis. The yrast positive parity states in ^{196}Pt were extended from 8 $\hbar$ to (26) $\hbar$. In ^{192,194}Pt as well, states up to I^π=(26$^+$) were identified.

The 12^+ states in even-Pt isotopes from $^{188-198}$Pt are isomeric in nature; in ^{196}Pt, this state is newly identified. The half-lives for these states (except for the one in ^{198}Pt) have been determined using the centroid shift method. This is illustrated in Fig. 1, wherein the centroid of the time distribution of a delayed transition is shifted with respect to that of a prompt one by an amount equal to the mean life of the state. For ^{198}Pt, the half-life has been determined by observing the time variation in cumulative intensity of delayed transitions [11]. Isomer half-lives and $B(E2)$ values are listed in Table 1.

3 Discussion

The lightest stable Pt isotopes have considerable deformation which is manifested in enhancement of $B(E2; 2^+ \rightarrow 0^+)$ values. For ^{192}Pt, the enhancement is 57 times greater than the single-particle (Weisskopf) estimate (Table 1). With increase in neutron number, the shell closure at $N = 126$ is approached, leading to reduction in deformation and collectivity. This is reflected in the trend of gradually decreasing $B(E2; 2^+ \rightarrow 0^+)$ values from ^{192}Pt to ^{198}Pt (Table 1). However, a considerable amount of collectivity is evident even in ^{198}Pt, where the $2^+ \rightarrow 0^+$ transition is enhanced by a factor of 31 over the Weisskopf value. The trend in the variation of $B(E2; 12^+ \rightarrow 10^+)$ values is rather different: these are similar in ^{192}Pt and ^{194}Pt (Table 1). A significant drop is evident in ^{196}Pt, though the transition is enhanced 23 times over the Weisskopf estimate. A much more abrupt decrease in visible in ^{198}Pt, with $B(E2; 12^+ \rightarrow 10^+)$ being at most 2.4 times the single-particle estimate (Table 1), providing strong evidence for quenching of collectivity at high spin around N=120. This aspect is in marked contrast to the smooth decrease in collectivity near the respective ground states.

In addition to other observables, the collective character of the 12^+ isomers is suggestive of a rotation-aligned interpretation for these states. In the $A \approx 190$ region, spin of 12 $\hbar$ for a two-quasiparticle state can only be a realized from the full alignment of a pair of $i_{13/2}$ neutrons. Measured values of g factors for the 12^+ states *viz.* -0.18(9), -0.17(7) in ^{192,194}Pt [12] substantiate this assignment.

Results of cranking calculations performed using standard Nilsson parameters in the Ultimate Cranker (UC) code [13] and the universal parameterization of the Woods-Saxon potential [14] aid in a detailed understanding of the observed phenomena. Pairing energies were adapted from five-point odd-even mass differences [7, 15, 16]. Total Energy Surface plots for ^{192,194}Pt indicate oblate energy minima near and beyond the 12^+ states as illustrated in Fig. 2. The rotation-aligned configurations therefore have oblate character. The energies for oblate configurations deduced from UC calculations are in good

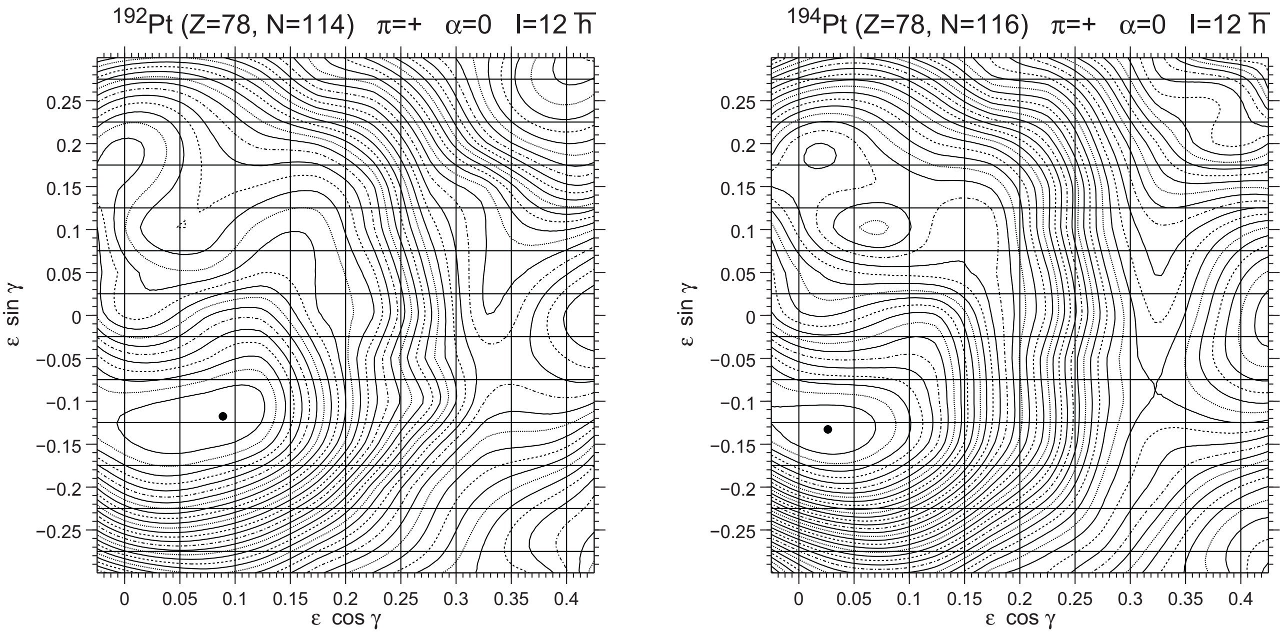

Figure 2. Total energy surface plots obtained using the Ultimate Cranker code [13] for the 12^+ states in ^{192}Pt and ^{194}Pt. The energy minima lie at (ε_2, γ) = (0.148, -53^o) for ^{192}Pt, and at (ε_2, γ) = (0.136, -78^o) for ^{194}Pt. The spacing between adjacent contours is 200 keV.

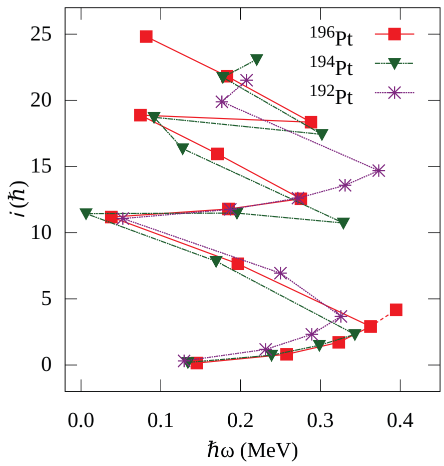

Figure 3. (Color online) Aligned angular momentum as a function of rotational frequency in ^{192,194,196}Pt. The reference rotor has $J_0 = 8\hbar^2$ MeV^{-1} and $J_1 = 35\hbar^4$ MeV^{-3}. Two nucleon alignments are clearly visible in all three isotopes. The first alignment occurs at $\hbar\omega\approx0.2$ MeV in all isotopes. The second alignment in ^{192}Pt ($\hbar\omega\approx0.3$ MeV) is delayed in comparison to the corresponding ones in ^{194,196}Pt ($\hbar\omega\approx0.2$ MeV).

agreement with the ones inferred from experiment; prolate minima are predicted to become progressively more non-yrast with increasing neutron number [11]. The magnitude of quadrupole deformation is predicted to decrease for higher neutron numbers consistent with the reduction in $B(E2; 2^+ \to 0^+)$ values described earlier. Shape evolution for lighter isotopes (up to ^{192}Pt) follows a similar pattern with triaxial shapes being favored at intermediate spin ($I \leq 10\hbar$), and oblate ones lowest in energy at high spin. In ^{194,196}Pt though, an oblate shape is realized at lower spin and persists to high spin [11]. The excitation energy of the 12^+ states gradually decreases with increase in neutron number up to ^{194}Pt, and is associated with the lowering of the oblate energy minimum evident from calculations [11]. Beyond ^{194}Pt, the 12^+ energy increases since the complete filling of the $i_{13/2}$ subshell at N=120 (^{198}Pt) approaches, as a result of which more energy is required to excite a pair of neutrons from this state. The excitation energy for the 12^+ state is highest in ^{198}Pt.

Successive rotation alignments are evident in the yrast positive parity bands of ^{192,194,196}Pt (Fig. 3). The alignment gain at the first band crossing ($\approx 11\hbar$), and the crossing frequency ($\hbar\omega \approx 0.2$ MeV), are quite similar for all three isotopes. The second alignments in ^{194,196}Pt are evident at the same frequency (0.2 MeV), with aligned angular momentum $\approx 7\hbar$. In ^{192}Pt, the second alignment is visible at a somewhat higher frequency ($\approx$ 0.3 MeV) (Fig. 3). The first crossing is associated with the $(\nu i_{13/2})^2$ alignment based on the quasineutron levels for oblate deformation obtained from Woods-Saxon cranking calculations (Fig. 4). The $(\nu i_{13/2})^2$ alignment is expected at $\hbar\omega \approx 0.2$ MeV for oblate deformation consistent with the experimental value, while that for prolate deformation is expected at a significantly higher frequency ($\hbar\omega$ = 0.38 MeV). The second alignment may be attributed to $h_{11/2}$ protons or a second pair of $i_{13/2}$ neutrons (Fig. 4). The latter interpretation is considered more likely due to the observation of different alignment frequency in ^{192}Pt compared with ^{194,196}Pt. With $h_{11/2}$ proton character for the second crossing, the frequencies

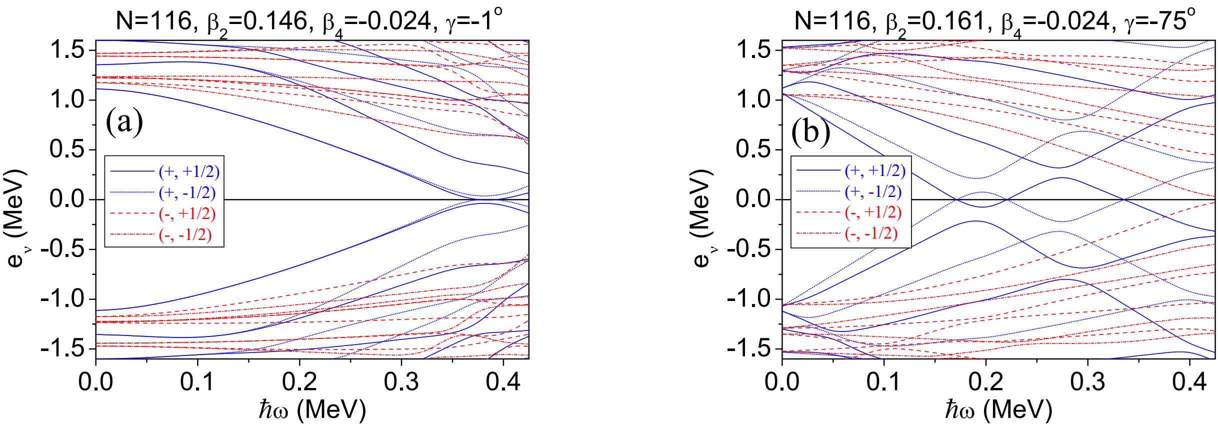

Figure 4. (Color online) Neutron quasiparticle levels for ^{194}Pt calculated using the universal parameterization of the Woods-Saxon potential [14] for prolate deformation (a) and oblate deformation (b).

would have been similar in all three cases. The higher frequency for the second crossing in ^{192}Pt may be understood in terms of the aligning $i_{13/2}$ neutrons occupying relatively higher-Ω orbitals for oblate deformation, as the neutron Fermi level is at lower energy in ^{192}Pt compared to ^{194,196}Pt.

4 Summary

Rotation-aligned states in an oblate deformed potential well have been studied across the Pt isotopic chain. The 12^+ states in the aligned configurations are isomeric with half-lives in the nanosecond range. Reduced $E2$ transition probabilities for deexcitation of the isomeric states point to a sudden drop in collectivity at high spins near $N = 120$ unlike the more gradual decrease near the ground state. Considerable contribution from aligned angular momentum to the rotational sequences at high spin is indicated both from experiment and results of cranking calculations.

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