First observation of excited states in the neutron deficient nuclei ^{164}Os and ^{166}Os

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Excited states have been observed for the first time in the neutron deficient nuclei ^{166}Os and ^{164}Os. The nuclei were produced using the reactions ^{106}Cd(^{63}Cu,$p2n$)^{166}Os, ^{112}Sn(^{58}Ni,$2p2n$)^{166}Os, and ^{106}Cd(^{60}Ni,$2n$)^{164}Os at beam energies of 292, 286, and 257 MeV, respectively. The γ rays emitted by ^{166}Os and ^{164}Os were identified by correlating the associated recoil evaporation residues with their subsequent characteristic α decays. The deduced level schemes indicate that ^{166}Os and ^{164}Os continue the trend of decreasing deformation moving away from the $N=104$ midshell. The level energy systematics of the low-spin states are presented.

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The γ-ray spectroscopy of osmium and platinum isotopes reveals a rich underlying nuclear structure. For the platinum isotopes the structure varies with decreasing neutron number from oblate to triaxial ground states, through shape coexistence near the neutron midshell ($N\approx 104$) and then to triaxial and near-spherical ground states [1,2]. For the osmium isotopes a similar pattern is observed, with coexisting shapes appearing at $N\leqslant 96$ [3]. The lightest even-even osmium isotopes with published level schemes are ^{170,172}Os [4,5]. Their yrast positive parity states can be understood as arising from the coexistence of three different structures: a low-deformation band, which is yrast at low spin, a more strongly deformed prolate structure, and a band based upon a $\nu(i_{13/2})^2$ excitation. The energy of the deformed band head is higher in nuclei further from the neutron midshell so that the influence of the deformed band on the energies of the low-deformation, low-spin states diminishes rapidly. In addition, the systematics for lighter isotones indicate that this low-deformation band becomes less deformed as the $N=82$ shell closure is approached. In our previous studies of the platinum isotopes $^{168,170-172}$Pt [1,2] the trend of increasing excitation energy of the low-lying states with decreasing neutron number has been established. It is therefore of interest to investigate if this trend is also followed by the osmium isotopes. Studying these very neutron deficient nuclei using conventional techniques is extremely difficult because of the small production cross sections. In order to identify prompt γ-ray transitions in ^{164,166}Os the nuclei were tagged by their characteristic α decays [6].

The nuclides ^{164,166}Os were studied in three separate experiments performed at the Accelerator Laboratory of the University of Jyväskylä. Excited states in ^{166}Os were populated by the reactions ^{106}Cd(^{63}Cu,$p2n$)^{166}Os and ^{112}Sn(^{58}Ni,$2p2n$)^{166}Os, while ^{164}Os was produced in the reaction ^{106}Cd(^{60}Ni,$2n$)^{164}Os. The beam energies were 292, 286, and 257 MeV, respectively, and the average beam intensities produced by the JYFL K130 cyclotron were 0.8 pnA for ^{63}Cu, 4.8 pnA for ^{58}Ni, and 2.3 pnA for ^{60}Ni. The self-supporting ^{112}Sn target had a thickness of 400 μg cm^{-2} and 93% isotopic enrichment, while the ^{106}Cd target thickness was 550 μg cm^{-2} and the isotopic enrichment was 80%.

In the experiments to study ^{166}Os, prompt γ rays were detected using the escape-suppressed Ge detectors of the JUROSPHERE spectrometer located at the target position. JUROSPHERE is a composite array of Eurogam I Ge detectors [7] and TESSA Ge detectors [8]. In the ^{58}Ni experiment there were five Eurogam detectors at 157.6° and nine at 133.6°, with five TESSA detectors at 79° and five at 101° with respect to the beam direction. In the ^{63}Cu experiment, there were seven Eurogam detectors and three TESSA detectors were positioned inside three Eurogam suppression shields at 133.6°. The detectors at the other angles were the same as for the ^{58}Ni experiment. The total photopeak efficiency at 1.3 MeV was measured to be $\approx 1.5\%$ for the ^{58}Ni experiment and $\approx 1.4\%$ for the ^{63}Cu experiment.

For the ^{60}Ni reaction the prompt γ rays were detected using the SARI array of four unsuppressed segmented clover Ge detectors placed at 45° to the beam line. These detectors comprise four Ge crystals placed within a single cryostat [9]. The total photopeak efficiency of SARI was measured to be $\approx 3.6\%$ at 1.3 MeV.

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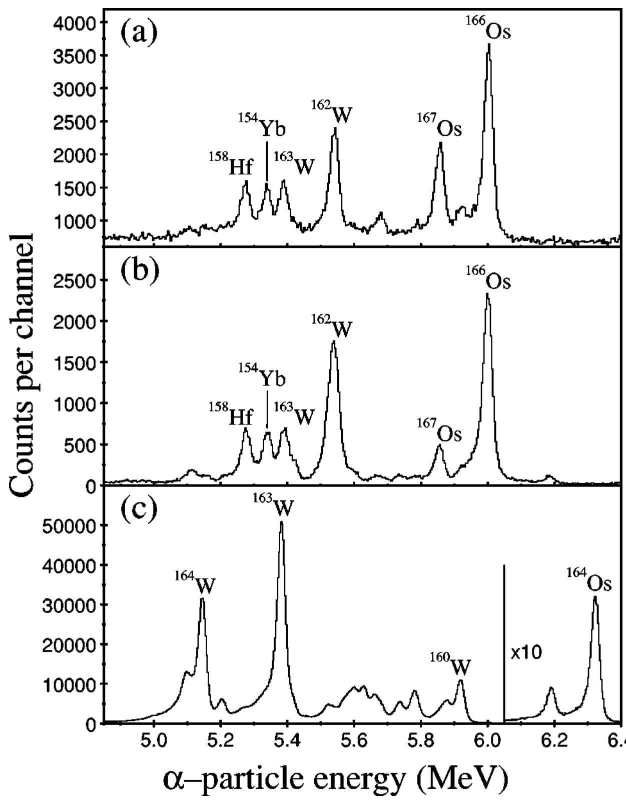

FIG. 1. Energy spectra of α particles observed in the (a) ^{112}Sn(^{58}Ni,$2p2n$)^{166}Os, (b) ^{106}Cd(^{63}Cu,$p2n$)^{166}Os, and (c) ^{106}Cd(^{60}Ni,$2n$)^{164}Os reactions. For (a) there was no beam pulsing, for (b), the beam pulsing was 3 ms on and 7 ms off, and (c) 2 ms on and 4 ms off. The beam pulsing was used to obtain clean α-particle energy spectra, such as those shown in (b) and (c), which are for the beam off periods only.

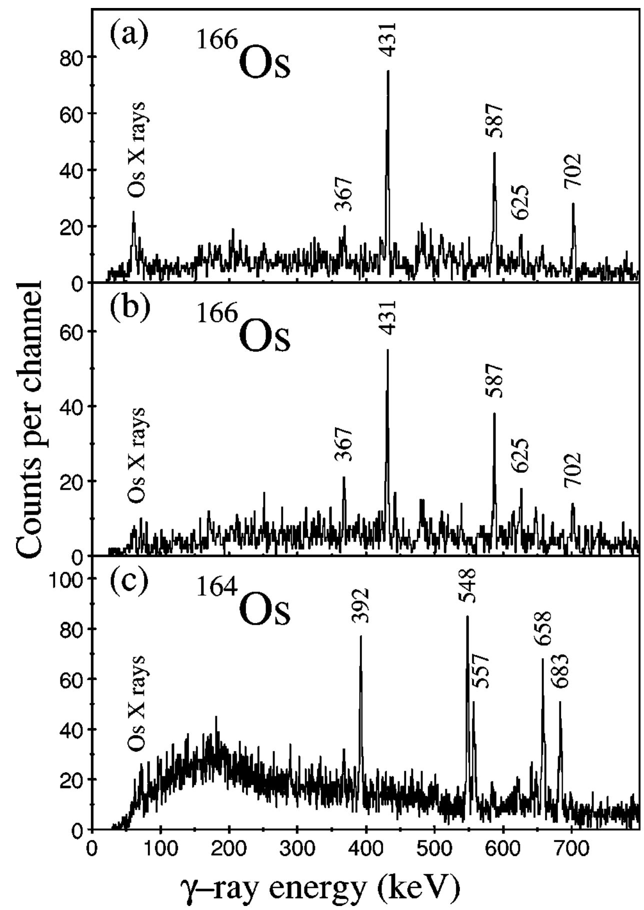

FIG. 2. Energy spectra of γ rays emitted from recoils correlated with characteristic ^{164}Os or ^{166}Os α decays for (a) the ^{112}Sn(^{58}Ni,$2p2n$)^{166}Os, (b) the ^{106}Cd(^{63}Cu,$p2n$)^{166}Os, and (c) the ^{106}Cd(^{60}Ni,$2n$)^{164}Os reactions. Peaks assigned to ^{164,166}Os are labeled according to their energies in keV.

In all three experiments the recoiling evaporation residues entered the gas-filled separator RITU [10] and were implanted into a 16 strip, 80 mm×35 mm Si detector covering approximately 70% of the recoil distribution at the focal plane. The energies, positions, and times of recoil nuclei and α decays were recorded, as were the energies of γ rays detected in delayed coincidence with the implantation of a recoil ion in the Si strip detector. The position sensitivity of the strip detector and the time stamp information enabled the subsequent characteristic α decays to be correlated with the implanted recoils. The γ rays associated with these correlated recoils can then be identified as being emitted by specific nuclides.

The half-lives of ^{164}Os and ^{166}Os have been measured previously to be 21 ± 1 and 220 ± 7 ms, respectively [11]. In the ^{166}Os analysis, γ rays were selected when the associated recoil and 5.98 MeV ^{166}Os α particle were position correlated within a time window of 500 ms and 440 ms for the ^{63}Cu and ^{58}Ni reactions, respectively. In the ^{164}Os analysis, the corresponding maximum time interval between the recoils and 6.32 MeV ^{164}Os α particles was 60 ms. The α-particle energy spectra for each of the reactions are shown in Fig. 1. The α-decay tagged γ-ray spectra for ^{166}Os and ^{164}Os are shown in Fig. 2. Osmium x rays are visible in all three spectra. The appearance of the same γ-ray lines in the spectra from the different reactions producing ^{166}Os supports their assignment to this nucleus. In addition, the transitions in ^{166}Os have been reported independently [12]. The production cross section for ^{166}Os was estimated to be 500 and 300 μb for the ^{63}Cu and ^{58}Ni induced reactions, respectively, and for ^{164}Os was estimated to be 20 μb.

The energies and absolute intensities of the γ rays assigned to ^{164}Os are presented in Table I and those for ^{166}Os

TABLE I. Energies and relative intensities of γ rays identified in ^{164}Os, normalized to the 548 keV transition.

E_γ (keV)	Intensity (%)	Assignment
392.2(2)	64(4)	$(8^+)\rightarrow(6^+)$
548.0(2)	100(5)	$(2^+)\rightarrow(0^+)$
557.4(2)	56(2)	$(10^+)\rightarrow(8^+)$
658.3(2)	81(5)	$(4^+)\rightarrow(2^+)$
683.4(2)	67(4)	$(6^+)\rightarrow(4^+)$

TABLE II. Energies and relative intensities of γ rays identified in ^{166}Os obtained from the combined data for both reactions used in the present work. The intensities are given relative to the 431 keV transition.

E_γ (keV)	Intensity (%)	Assignment
367.3(3)	20(3)	
430.8(2)	100(6)	$(2^+)\rightarrow 0^+$
587.0(2)	70(5)	$(4^+)\rightarrow(2^+)$
625.1(3)	17(5)	$(8^+)\rightarrow(6^+)$
702.1(2)	47(4)	$(6^+)\rightarrow(4^+)$

in Table II. The statistics obtained in both cases were insufficient to allow a γ-γ coincidence or unambiguous angular distribution analysis. Based on the measured intensities and assuming all the γ rays correspond to stretched $E2$ transitions, we propose the tentative level schemes shown in Fig. 3. The absolute γ-ray intensities and the level scheme for ^{166}Os are based on the combined, and consistent, data from the two reactions.

The energy level systematics of even-even osmium isotopes shown in Fig. 4 indicate that ^{164}Os and ^{166}Os continue the trend of increasing excitation energy of the 2^+ state with decreasing neutron number, implying a corresponding fall in deformation as the $N=82$ shell closure is approached. The energies of the 4^+ and 6^+ states also display the same trend.

Although the level schemes shown in Fig. 3 are tentative it is interesting to speculate on the nature of the assumed 8^+ states in ^{164}Os and ^{166}Os where a change in the energy level systematics occurs (see Fig. 4). In order to facilitate a wider comparison of the 8^+ states deduced for ^{164,166}Os with those of neighboring even-even nuclei, the energy level systematics are considered as a function of both neutron number and the factor $P=N_pN_n/(N_p+N_n)$, where N_p and N_n are the number of valence protons and neutrons counted from closed shells. The P parameter embodies the assumption that deformation arises from the proton-neutron interaction between valence nucleons and is very successful in the description of energy level systematics [15]. The energy systematics of 8^+ states for a range of nuclei in this region are displayed in Fig. 5. It is particularly striking how the P scheme has coalesced the different trend lines for the separate isotopes and isotones into a narrow envelope in Fig. 5.

In contrast to the 2^+, 4^+, and 6^+ states, it is clear that the 8^+ states in ^{164,166}Os do not continue the trend of increasing energy approaching $N=82$ shown by their lighter isotones (see Fig. 5). Although the $8^+\rightarrow 6^+$ transition in ^{166}Os cannot be uniquely determined from the intensity measurements alone (see Table II) the alternative choice of the 367 keV γ ray as the $8^+\rightarrow 6^+$ transition would place the 8^+ state at 2087 keV. This is below the 8^+ states in both ^{164}Os and ^{168}Os, and represents an even more marked deviation from the systematics of the heavier even-even isotopes. The 8^+

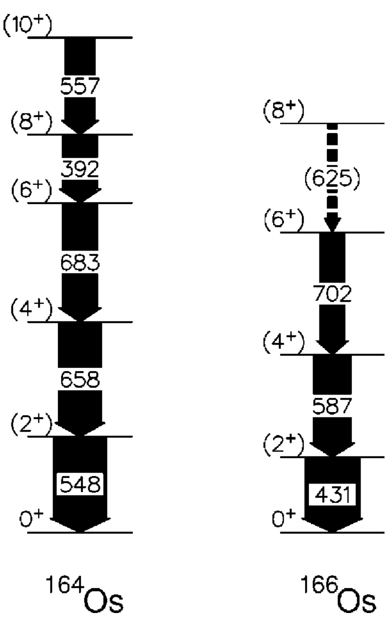

FIG. 3. Tentative level schemes for ^{164}Os and ^{166}Os. The arrow widths are proportional to the measured intensities. Parentheses and dotted lines indicate tentative assignments.

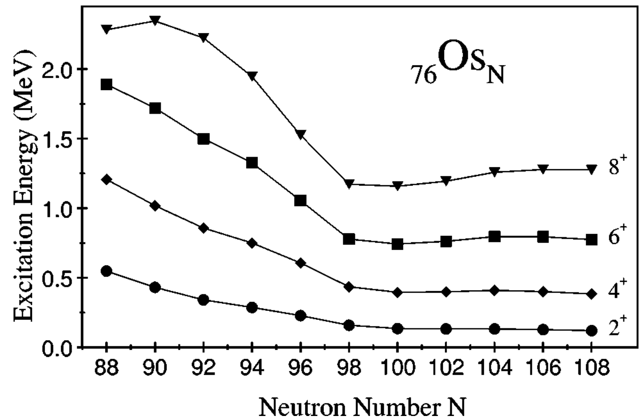

FIG. 4. Energies of yrast positive parity states in osmium isotopes as a function of neutron number N. Data are taken from Refs. [13,14] and the present work.

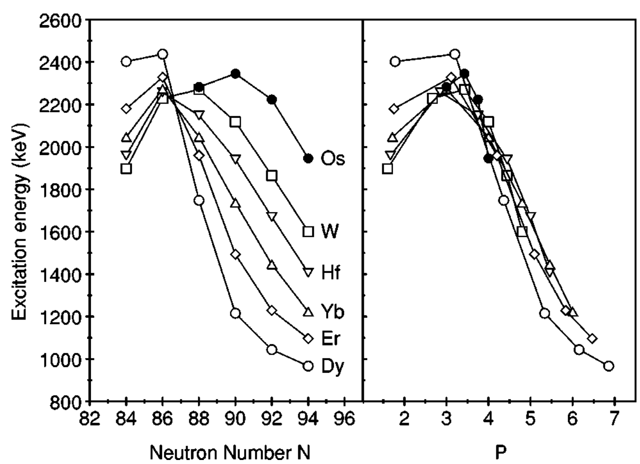

FIG. 5. Energies of 8^+ states as function of neutron number N and the parameter $P=N_pN_n/(N_p+N_n)$ [15]. The data are taken from Refs. [13,14,16] and the present work.

states proposed here are compatible with the P systematics shown in Fig. 5.

The lowering of the 8^+ states in ^{164,166}Os can be attributed to a $\nu(f_{7/2}h_{9/2})$ or $\nu(h_{9/2})^2$ 8^+ excitation, which becomes increasingly energetically favorable as the $N=82$ shell closure is approached [17]. The excitation energy of the 8^+ state in ^{164}Os also deviates from the trend established by its lighter isotones, reflecting an increasing energy gain by interaction of the $h_{9/2}$ neutrons with the $h_{11/2}$ protons as the $\pi h_{11/2}$ subshell is filled. The excitation energy of the proposed 10^+ state at 2839 keV in ^{164}Os is very close to the values deduced for its lighter isotones ^{162}W [16] and ^{160}Hf [18].

In summary, we have identified transitions in the extremely neutron deficient nuclei ^{164,166}Os for the first time. Tentative level schemes have been deduced that continue the trend of decreasing deformation as a function of decreasing neutron number as the $N=82$ shell closure is approached.

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