Recoil decay tagging of γ rays in the extremely neutron-deficient nucleus ^{162}Os

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(Received 18 May 2004; published 21 July 2004)

The neutron-deficient nucleus ^{162}Os, produced in the ^{106}Cd(^{58}Ni$,2n$) reaction, has been studied using the JUROGAM γ-ray spectrometer in conjunction with the RITU gas-filled separator and the GREAT focal plane spectrometer. γ-ray transitions in ^{162}Os have been assigned for the first time through the application of the recoil decay tagging technique. The excitation energy of the 2^+ state and the tentative energy of the 8^+ state are discussed in terms of the systematic energy trends as the $N=82$ shell gap is approached.

DOI: 10.1103/PhysRevC.70.017302 PACS number(s): 27.70.+q, 23.20.Lv, 29.30.Kv

Recent experiments employing selective tagging techniques [1,2] have established excited states in the transitional osmium isotopes from $^{164-169}$Os [3–6] and revealed fundamental changes in the underlying nuclear structure approaching the closed shell at $N=82$. The yrast spectra of this isotopic chain reflects the evolution from the deformed regime near the neutron midshell ($N=104$) through coexisting shapes [7,8] to structures associated with γ-soft rotors [3,4] and weakly deformed vibrational nuclei [5,6]. In the light ($N\leqslant 86$) osmium isotopes, the low-spin yrast states are expected to be based on configurations formed by coupling the spins of aligned valence nucleons. For example, the low-spin structure of the $N=86$ isotones ^{160}W [9] and ^{158}Hf [10] up to 6^+ are formed by $\nu(f_{7/2})^2$ excitations while the 8^+ state may be formed by either the $\nu(f_{7/2},h_{9/2})$ or $\nu(h_{9/2})^2$ configurations. Similar yrast structures are expected in the heavier $N=86$ isotones, such as ^{162}Os. Indeed, changes in the position of the $\nu h_{9/2}$ orbital are manifested in the yrast spectra as variations in the excitation energy of the 8^+ state. For the even-even $_{66}$Dy to $_{76}$Os isotones with $N\geqslant 88$, the 8^+ state is found to exhibit lower excitation energies for lower-Z nuclei. At $N\leqslant 86$, recent experiments [5,9] have established that an inversion in this trend occurs with higher 8^+ excitation energy for the lower-Z isotones. This inversion is interpreted as being caused by a lowering of the $\nu h_{9/2}$ state due to an increasingly attractive proton-neutron interaction between the $\pi h_{11/2}$ and $\nu h_{9/2}$ states with the pairwise addition of $h_{11/2}$ protons [11]. A similar trend for the yrast structures of the $N=84$ isotones up to ^{154}Yb has been successfully reproduced by shell model calculations incorporating experimental two-body matrix elements [11], but few experimental data are available on heavier neutron-deficient nuclei. The residual proton-neutron interaction is expected [11] to be stronger for the very neutron-deficient nucleus ^{162}Os and the extension of experimental studies towards nuclei near the $N=Z=82$ shell gaps and the proton drip line is vital for constraining models which aim to describe the interplay between shell structure and residual interactions at the limits of nuclear existence. This paper reports the first observation of γ-ray transitions in ^{162}Os and discusses the results in terms of level excitation energy systematics.

Investigating the structure of heavy nuclei near the proton drip line with fusion evaporation reactions is exceedingly difficult. The principal obstacle in the investigation of exotic nuclei like ^{162}Os is related to the difficulty of separating γ rays originating from the nucleus of interest populated at extremely low cross sections from the almost overwhelming background of γ rays arising from heavy-ion induced fission. The application of the recoil decay tagging (RDT) technique, where prompt γ rays are correlated with the subsequent α or proton decays of the nucleus of interest, has overcome these limitations and made possible γ-ray spectroscopy on the shore of nuclear stability.

The present experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. Excited states in ^{162}Os were populated using the ^{106}Cd(^{58}Ni$,2n$) reaction at a bombarding energy of 270 MeV. The ^{106}Cd target was a self-supporting foil of nominal thickness 900 μg/cm^2 and 96% isotopic enrichment. The average beam intensity provided by the K130 cyclotron was 6 pnA. Prompt γ rays were detected at the target position by the JUROGAM γ-ray spectrometer consisting of 43 EUROGAM-type escape-suppressed germa-

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nium spectrometers (ESS) [12]. The ESSs were distributed over six angular positions relative to the beam direction with five ESSs at 158°, ten at 134°, ten at 108°, five at 94°, five at 86°, and eight at 72°. The total photopeak efficiency of the JUROGAM array was measured to be 4.2% at 1.3 MeV.

The recoiling fusion-evaporation residues were separated from fission products and beam by the RITU gas-filled recoil separator [13,14] and deposited in the GREAT spectrometer [15] at the focal plane. The GREAT spectrometer is a composite detection system comprising a multiwire proportional counter and silicon and germanium detectors. At the focal plane, recoiling nuclei were distinguished from the residual scattered beam by energy loss and time of flight methods using the GREAT multiwire proportional counter and implantation detector. The GREAT implantation detector comprises two double-sided silicon strip detectors (DSSSD), each with an active area of 60 mm × 40 mm and a thickness of 300 μm. A strip pitch of 1 mm in both directions gives a total of 4800 pixels, giving a detector of high granularity. Each strip was gain matched and calibrated using known α-decay lines from the embedded fusion products. All detector signals were passed to the GREAT total data readout acquisition system [16] where they were time stamped with a precision of 10 ns to allow accurate temporal correlations between recoil implants and their subsequent radioactive decays.

The RDT technique provides high-confidence correlations between prompt γ rays and subsequent radioactive decays under the optimal conditions of short decay half-lives and high branching ratios. The neutron-deficient nucleus ^{162}Os is a known α emitter and is ideally suited to exploitation by the RDT technique with recent measurements yielding a decay half-life of 1.9(2) ms and an estimated branching ratio of 99% [17]. Temporal and spatial correlations were performed offline using the GRAIN software package [18]. A spectrum showing α decays observed up to 8 ms following a recoil implantation in the DSSSD is shown in Fig. 1(a). The characteristic ^{162}Os α decay, measured in this experiment as 6614(12) keV, is consistent with previous measurements [17,19,20] and well resolved from the other short-lived α decays. The reaction cross section for the 2*n* exit channel leading to ^{162}Os was estimated as 400 nb. The inset of Fig. 1(a) shows the decay curve corresponding to the time difference between an ^{162}Os implant and its subsequent α decay. In order to select ^{162}Os decays uniquely an extra correlation was demanded with the characteristic α decay of the daughter, ^{158}W [E_α=6445(3) keV, half-life 1.5 (2) ms [17]], with a search time of 3 ms. Analysis of the decay curve yields a half-life of 2.1(1) ms, which is consistent with the previous measurements [17,19,20]. A spectrum showing γ rays correlated with the characteristic ^{162}Os α decay within a search time of 8 ms is shown in Fig. 1(b), and the energies and relative intensities are recorded in Table I.

The γ-ray spectrum in Fig. 1(b) is complex and it is difficult to order the low-lying states. Indeed the complexity of the spectrum reflects the close proximity of ^{162}Os to the N =82 shell gap where the angular momentum of low-lying excited states is generated via the spin alignments of individual valence nucleons. However, relative intensity measurements show that the 707 keV γ ray is the most intense and as such is assigned as the $2^+ \rightarrow 0^+$ transition. Figure 2(a) shows the variation of 2^+ state excitation energy in the even-N osmium isotopes from the neutron midshell at N=104 to the lightest known isotope, ^{162}Os. The transition towards near-spherical shapes with greater neutron deficiency is supported by trends in the 2^+ state energies of the even-N iso-

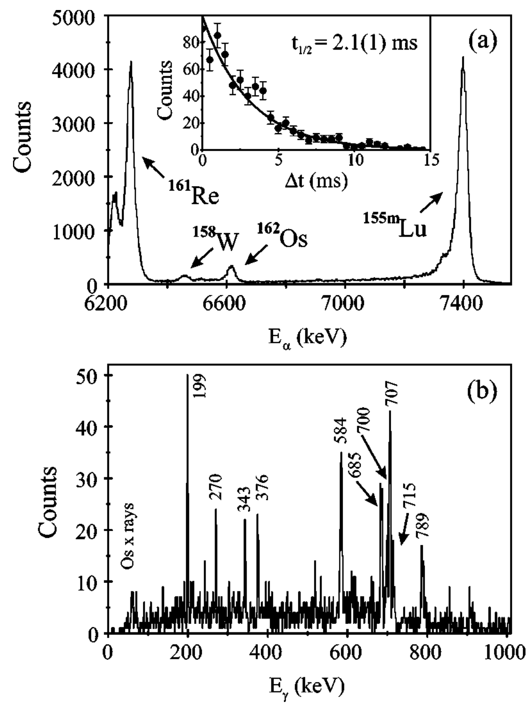

FIG. 1. (a) Spectrum showing α decays, in the region 6200 keV to 7600 keV, measured within 8 ms of a recoil implantation in the same pixel of the DSSSD. The inset shows the decay curve generated by noting the time difference between a recoil implant and a subsequent ^{162}Os α decay. This decay curve is also correlated with the characteristic α decay of the daughter nucleus ^{158}W. The solid line represents a fit to the data of an exponential function. (b) A γ-ray energy spectrum correlated with the characteristic 6614 keV α decay of ^{162}Os. The search time for correlations was limited to 8 ms. The Os x rays are indicated and the strongest γ-ray transitions are labeled to the nearest keV.

TABLE I. Transition energies and relative intensities of γ rays assigned to ^{162}Os obtained from the α tagged singles γ-ray spectrum. The asterisk indicates a doublet in the α-γ-γ analysis.

Transition energy (keV)	Relative intensity
198.9(1)	34(6)
270.3(2)	14(4)
342.9(2)	19(5)
375.5(2)	23(6)
584.1(2)*	73(14)
685.2(2)	76(15)
699.8(7)	64(16)
706.7(3)	100(19)
715.0(4)	28(8)
788.7(5)	61(13)

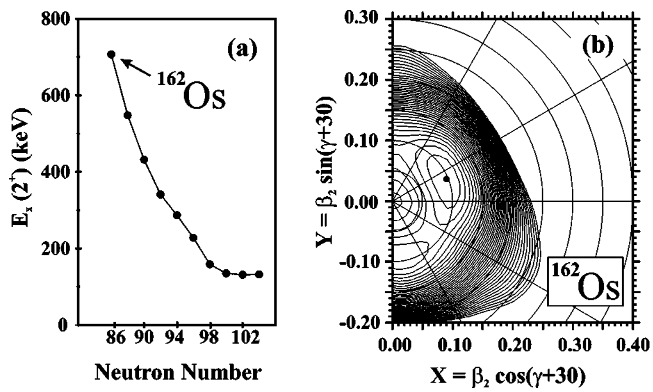

FIG. 2. (a) Variation in 2^+ excitation energy as a function of neutron number for Os isotopes. (b) A total Routhian surface calculated for the (parity π, signature α) =(+,0) configuration in ^{162}Os at zero rotational frequency. The energy difference between contour lines is 100 keV.

topes which increase with decreasing neutron number. Total Routhian surface (TRS) calculations [21] at zero rotational frequency predict a minimum with average deformation parameters of $\beta_2=0.097$, $\beta_4=0.003$, $\gamma=-7.7°$; see Fig. 2(b), which is consistent with this interpretation.

A total of 3370 α(^{162}Os)-correlated γ-γ coincidences were collected during the present experiment. These were analyzed using the ESCL8R software package [22] in order to deduce the yrast structure of ^{162}Os. A γ projection of the α(^{162}Os)-correlated γ-γ coincidence matrix is shown in Fig. 3(a). Figure 3(b) shows a spectrum of γ rays in coincidence with either the 707 or 199 keV transition. Despite the low level of statistics in these data the 707, 700, 584 and 199 keV transitions are found to be in coincidence and the 707 keV γ ray is the most intense, which is consistent with it

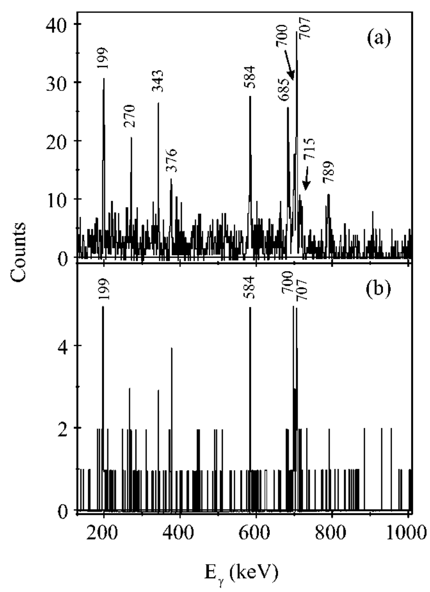

FIG. 3. (a) Total projection of the ^{162}Os α-correlated γ-γ coincidence matrix. The search time for correlations was limited to 8 ms. (b) Transitions in coincidence with the 707 or 199 keV transitions.

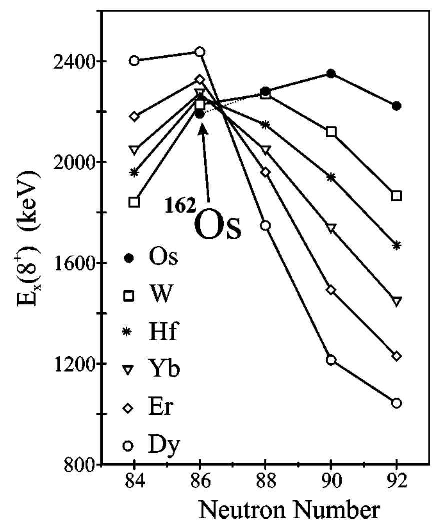

FIG. 4. The variation of excitation energy of 8^+ states as a function of neutron number for the even-Z isotones from Dy to Os. The data are taken from the present work and Refs. [4–6,9,10,17,23–25].

being the $2^+ \rightarrow 0^+$ transition. A meaningful angular correlation analysis of the data was not possible due to the low level of statistics.

Assuming that these four transitions have stretched $E2$ character and form the yrast sequence and in the order 707, 700, 584, and 199, then the excitation energy of the 4^+ and 6^+ states is consistent with the smoothly varying change in the systematics of the region as the $N=82$ shell gap is approached. Clearly more coincidence data are required to confirm this assumption and assign all the transitions that are listed in Table I firmly in the level scheme of ^{162}Os. The 8^+ state is tentatively assigned to have an excitation energy of 2190 keV, regardless of the order of the yrast transitions. It is then interesting to speculate on the excitation energy trends for the 8^+ states for the even-even isotones from Dy to Os with $N \leqslant 92$; see Fig. 4. The tentative 8^+ excitation energy for ^{162}Os continues the trend of decreasing energy as a function of increasing Z and reinforces the interpretation of an increasingly attractive proton-neutron interaction between the $\pi h_{11/2}$ and $\nu h_{9/2}$ states as the $N=82$ shell gap is approached.

In summary, γ-ray transitions in the lightest known osmium isotope ^{162}Os have been observed in a recoil-decay tagging experiment. The excitation energy of the 2^+ state has been established as 707 keV, which is interpreted as a continuation of the trend towards near-spherical shapes as the $N=82$ shell gap is approached. This is consistent with the predictions of TRS calculations of a low deformation shape. A modest coincidence analysis has been used to speculate about the structure of the yrast sequence up to 8^+. Further experiments with greater statistics are required to confirm the yrast sequence above the 2^+ state.

The authors wish to extend their thanks to the crew at the Accelerator Laboratory at the University of Jyväskylä for their excellent technical support. This work has been supported by the U.K. Engineering and Physical Sciences Research Council (EPSRC); the Swedish Research Council; the Academy of Finland under the Finnish Centre of Excellence Programme (Project No. 44875 Nuclear and Condensed Matter Physics Programme at JYFL); the European Union Fifth Framework programmes "Improving Human Potential—Access to Research Infrastructure" (HPRI-CT-1999-00044) and EXOTAG (Contract No. HPRI-1999-CT-50017). K.L. would like to acknowledge the support of the Royal Society. We also thank the UK/France (EPSRC/IN2P3) Loan Pool and EUROBALL owners committee for the EUROGAM detectors of JUROGAM.

[1] R. S. Simon, K.-H. Schmidt, F. P. Hessberger, S. Hlavac, M. Honusek, H. G. Clerc, U. Gollerthan, and W. Schwab, Z. Phys. A **325**, 197 (1986).
[2] E. S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
[3] D. T. Joss *et al.*, Phys. Rev. C **66**, 054311 (2002).
[4] D. T. Joss *et al.*, Nucl. Phys. **A689**, 631 (2001).
[5] S. L. King *et al.*, Phys. Rev. C **62**, 067301 (2000).
[6] D. E. Appelbe *et al.*, Phys. Rev. C **66**, 014309 (2002).
[7] J. L. Durell, G. D. Dracoulis, C. Fahlander, and A. P. Byrne, Phys. Lett. **115B**, 367 (1982).
[8] P. M. Davidson, G. D. Dracoulis, T. Kibedi, A. P. Byrne, S. S. Anderssen, A. M. Baxter, B. Fabricius, G. J. Lane, and A. E. Stuchbery, Nucl. Phys. **A568**, 90 (1994).
[9] A. Keenan *et al.*, Phys. Rev. C **63**, 064309 (2001).
[10] K. Y. Ding *et al.*, Phys. Rev. C **62**, 034316 (2000).
[11] C. T. Zhang *et al.*, Phys. Rev. C **54**, R1 (1996).
[12] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992).
[13] J. Uusitalo *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 638 (2003).
[14] M. Leino, Nucl. Instrum. Methods Phys. Res. B **126**, 320 (1997).
[15] R. D. Page *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 634 (2003).
[16] I. H. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
[17] H. Mahmud, C. N. Davids, P. J. Woods, T. Davinson, D. J. Henderson, R. J. Irvine, D. Seweryniak, and W. B. Walters, Phys. Rev. C **62**, 057303 (2000).
[18] P. Rahkila (unpublished).
[19] S. Hofmann *et al.*, Z. Phys. A **333**, 107 (1989).
[20] C. R. Bingham *et al.*, Phys. Rev. C **54**, R20 (1996).
[21] W. Satula and R. Wyss, Phys. Scr. **T56**, 159 (1995).
[22] D. C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[23] M. P. Carpenter, Z. Phys. A **358**, 261 (1997).
[24] G. D. Dracoulis, B. Fabricius, P. M. Davidson, A. O. Macchiavelli, J. Oliviera, J. Burde, F. Stephens, and M. A. Deleplanque, AECL Report No. 10613 (unpublished), Vol. 2, p. 94.
[25] *Table of Isotopes*, edited by V. S. Shirley (Wiley, New York, 1996).