States in ^{191}Os observed with the ^{192}Os$(p,pn\gamma)$ reaction

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States in ^{191}Os have been observed with the ^{192}Os$(p,pn\gamma)$ reaction. The most intense γ ray observed is the decay from the head of a previously assigned oblate decoupled band. Gamma rays in coincidence with this transition reveal a band structure up to spin $19/2^+$. These results, together with those from a previous single-nucleon transfer study, are better reproduced in calculations assuming $\epsilon=0.17$ and $\gamma=24°$, rather than $\epsilon=0.37$ and $\gamma=43°$ as previously suggested. Candidates for members of the ground state band are also suggested. [S0556-2813(98)02712-5]

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Rotational bands in ^{191}Os have been difficult to observe because of the lack of a suitable reaction that could populate them with moderate amounts of angular momentum. As a result, only the relatively low-spin levels populated in (n,γ) or nucleon-transfer reactions are known [1,2]. During the course of investigations into the level structure of ^{190}Ir with the $(p,3n)$ reaction, it was discovered that there was sufficient intensity for selected ^{191}Os lines that spectroscopy of that nucleus could be performed, although only to a limited extent. It is the purpose of this report to communicate the results that lead to new levels in ^{191}Os.

The experiments, with the intended aim of studying ^{190}Ir, were performed at the Paul Scherrer Institute (PSI) at Villigen, Switzerland. Beams of protons, obtained from the Philips variable energy cyclotron, bombarded targets which were approximately 7–8 mg/cm^2 thick and enriched to 99.0% in ^{192}Os. The targets were produced by the centrifuging of Os metal powder samples, obtained from the Isotope Sales Division of the Oak Ridge National Laboratory, onto Kapton foils approximately 1 μm thick. The experiments included excitation functions, angular distributions, and $\gamma\gamma$ coincidence measurements.

For the excitation function measurements, γ-ray spectra were recorded at five different beam energies, 18.6, 20.8, 24.2, 27.2, and 31.1 MeV, with the Fribourg anti-Compton spectrometer [3] utilizing a PGT 13-cm^3 Ge detector. The resolution achieved was 0.9 keV full width at half maximum (FWHM) at 100 keV. The spectrometer was at 55° with respect to the beam line, and the target-detector distance was $\simeq 70$ cm. Five targets, one for each beam energy, were used. In order to obtain a precise energy calibration, spectra were recorded at beam energies of 20.8 and 27.2 MeV where the reaction γ rays and lines from radioactive sources of ^{182}Ta and ^{192}Ir were superimposed. The efficiency calibration was performed using a source of ^{110}Ag in addition to the above sources placed at the target position.

Shown in Fig. 1 is a γ-ray spectrum obtained during the angular distribution experiment using a 25 MeV proton beam. Spectra were recorded at 8 angles between 25° and 90°. The γ rays were detected with a 19-cm^3 detector with a FWHM of 680 eV at 122 keV. For normalization purposes, a 6.5 cm^3 monitor detector was placed 60 cm from the target at an angle of approximately 125° with respect to the beam line. The efficiency and anisotropy (found to be less than 2%) of the system were determined using radioactive sources at the target position. Dead-time corrections were applied to all data.

For the $\gamma\gamma$ coincidence experiment, four Ge detectors were utilized, three of which had BGO/NaI anti-Compton shields. The three anti-Compton spectrometers were placed at an angle of 90° with respect to the beam line, and the detector-target distance was $\simeq 10$ cm, as outlined in Ref. [4]. The fourth Ge detector, which was not Compton suppressed, was placed at an angle of approximately 150°. Fur-

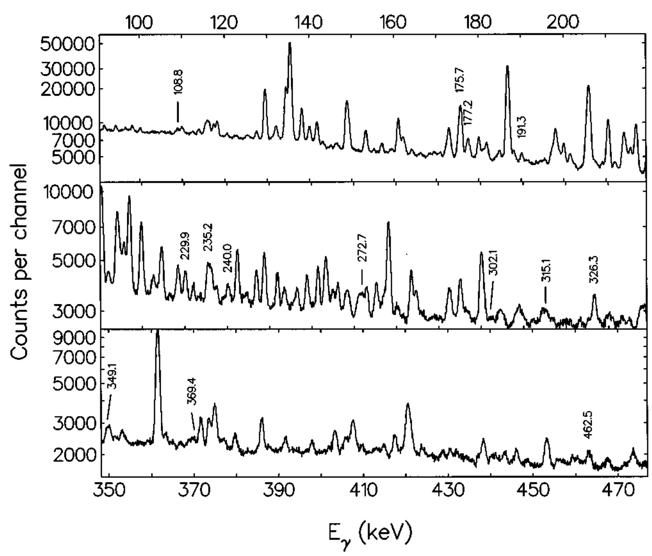

FIG. 1. Gamma-ray spectrum observed in the bombardment of ^{192}Os with 25 MeV protons. Some of the γ rays assigned to ^{191}Os are labelled with their energies. Other ^{191}Os γ rays are part of unresolved multiplets and were observed only in the $\gamma\gamma$ coincidence matrix.

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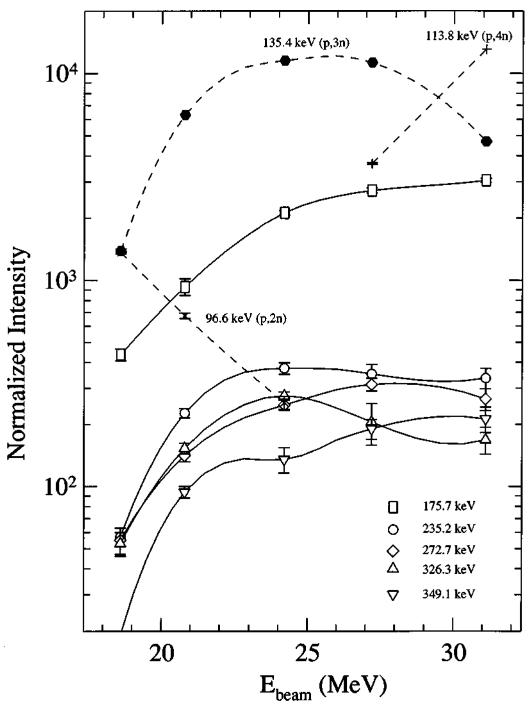

FIG. 2. Excitation functions of selected γ rays observed in the experiment. Curves for γ rays from the (p,pn) reaction (solid curves with open symbols) are labeled with their energies in the legend. The shapes of the excitation functions for transition belonging to the $(p,3n)$ and (p,pn) channels are similar. The interpolation curves are drawn to guide the eye.

ther details will be given elsewhere [5].

By examining the intensity of a γ ray as a function of the bombarding energy, the isotopic channel to which the γ ray belongs can be ascertained in many cases. The γ-ray spectra were normalized to the Os K_α x-ray intensities using the procedure described in Ref. [6]. Differences in the x-ray intensity due to varying target thickness were accounted for by calculating the attenuation within the target. Shown in Fig. 2 are some typical excitation function curves for various transitions belonging to ^{192}Os(p,xn) reactions, and those which will be assigned to the ^{192}Os(p,pn) channel. It can be seen that the shape of the $(p,3n)$ and (p,pn) channels are similar. In fact, a curve with contributions from both $(p,3n)$ and $(p,4n)$ γ rays, as would happen if γ rays from ^{190}Ir and ^{189}Ir were unresolved, could easily mimic the shape of the (p,pn) curve. Thus the excitation functions alone cannot be used to identify (p,pn) channel lines, and the coincidence results must be relied upon to a great deal. However, this implies that one must have *a priori* knowledge of γ rays on which to set gates. One possibility is the 175.7-keV transition; this γ ray depopulates a bandhead at 175.7 keV. The coincidence spectrum shown in Fig. 3 displays several lines previously assigned to ^{191}Os which should be in coincidence with the 175.7-keV line; namely the 108.8-, 235.2-, and 343.7-keV γ rays. In addition, the $13/2^+$ member of the band had been tentatively assigned at 352.8 keV, although no transition from it had been observed. In the 175.7-keV coincidence gate, the strongest line is one at 177.2 keV, in agreement with the energy difference between the known 352.8- and 175.7-keV levels. It should also be noted that there are no γ rays which are attributed to ^{190}Ir in this gate [5]. Therefore, it is concluded that the 175.7-keV line is due solely to a ^{191}Os transition, and all lines in coincidence with it are from ^{191}Os.

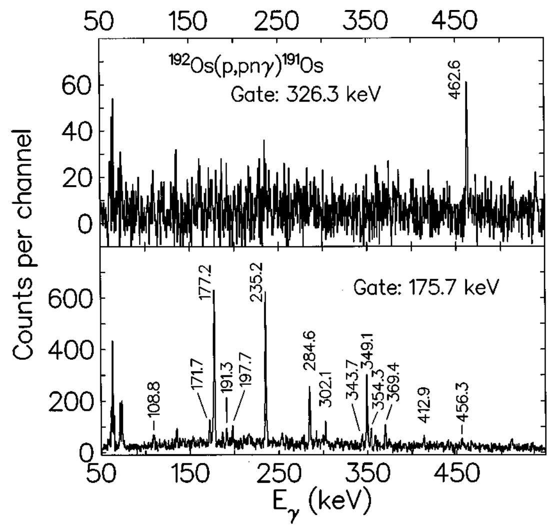

FIG. 3. Spectrum of γ rays in coincidence with the 326.3-keV and 175.7-keV γ rays of ^{191}Os. Several other γ rays previously assigned to ^{191}Os are observed in the 175.7-keV spectrum, and no transitions which can be attributed to ^{190}Ir are present.

Table I lists the γ rays from ^{191}Os based on coincidence relations, behavior of the excitation functions, and knowledge of γ rays assigned to ^{191}Os from previous experiments [1]. For those observed in the angular distribution measurement and resolved from other γ rays, a_2 and a_4 coefficients are listed resulting from the fit

$$W(\theta)=I_\gamma(1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)). \qquad (1)$$

The intensities listed in Table I are normalized to the 135.4-keV γ ray, one of the dominant transitions in ^{190}Ir, defined to have 1000 units. Figure 4 displays the new part of the level scheme established in the present work. The most notable feature is the extension of the band based on the $11/2^+$ state to spin $19/2^+$. This band is well developed with the observation of (assumed) $M1$ transitions and cross-over $E2$ transitions. Only the 349.1-keV γ ray is resolved and of sufficient intensity to yield a reliable angular distribution, and is consistent with an $E2$ multipolarity.

The assignment of γ rays to the ground state band is not as straightforward, since no rotational band members have been observed previously. While this band should be populated with approximately the same intensity as the aforementioned positive-parity band, the lack of a *single* γ ray which carries all of this intensity (like the 175.7-keV $E1$ transition) means that the recognition of the band will not be as apparent. If it is assumed that the moment of inertia is similar to that of the positive-parity band, the $13/2^- \rightarrow 9/2^-$ transition is expected to be in the range of 300–350 keV. One possible candidate is a γ ray observed at 326 keV; it displays coincidences only with a 463-keV transition (see Fig. 3), has an excitation function (see Fig. 2) showing similar trends to other assigned ^{191}Os lines, and has an angular distribution consistent with an $E2$ multipolarity. The intensity of the 326-keV line is greater than that of the 349-keV γ ray, as would be expected for a $13/2^- \rightarrow 9/2^-$ transition versus a $15/2^+$

TABLE I. γ rays assigned to ^{191}Os from the $^{192}Os(p,pn\gamma)$ reaction.

E_γ	I_γ	a_2	a_4	E_i-E_f
108.760(22) [a]	20.3(8)	−0.17(8)	0.05(12)	519.7−410.9
138.1(2) [b]				410.9−272.7
171.7(1) [b]				524.6−352.9
175.668(20) [a]	263.4(51)	−0.185(15)	−0.008(22)	175.7−0.0
177.161(46)	48.2(74)			352.9−175.7
189.5(1) [b]				462.5−272.7
191.261(35)	8.4(5)	−0.61(18)	0.02(22)	602.3−410.9
197.7(1) [b]				722.3−524.6
229.932(21) [c]				314.4−84.5
235.231(21) [a]	73.1(14)	−0.061(29)	−0.059(41)	410.9−175.7
239.972(26) [a]	29.8(9)	−0.28(6)	−0.02(10)	314.2−74.4
272.708(22) [a]	65.7(14)	−0.080(35)	−0.011(50)	272.7−0.0
284.6(1) [b]				637.6−352.9
302.148(39)	12.6(9)	−0.54(16)	−0.12(23)	939.8−637.6
315.052(25) [c]	36.7(17)			(446.9−131.9)
326.299(22)	87.6(16)	0.194(31)	−0.014(42)	(326.3−0.0)
343.7(1) [b]				519.7−175.7
349.127(41)	38.1(19)	0.41(13)	0.00(18)	524.6−175.7
354.3(1) [b]				765.1−410.9
364.9(1) [b]				637.6−272.7
369.408(39)	31.2(15)			722.3−352.9
412.9(1) [b]				588.6−175.7
456.3(3) [b]				980.9−524.6
462.552(26) [c]				(462.5−0.0)
463.0(1) [b]				(789.3−326.3)

[a]Transition assigned previously [1] to ^{191}Os.
[b]Line observed only in the coincidence matrix. This γ ray not observed in singles or is obscured by a stronger close-lying γ ray.
[c]Transition assigned previously [1] to ^{191}Os. The line is part of an unresolved doublet with a ^{190}Ir γ ray.

$\rightarrow 11/2^+$ transition. The 326-keV γ ray is therefore suggested to be the $13/2^- \rightarrow 9/2^-$ transition, with the 463-keV line as the $17/2^- \rightarrow 13/2^-$ transition. The absence of $M1$ $11/2^- \rightarrow 9/2^-$ or $13/2^- \rightarrow 11/2^-$ transitions may be due to the weakness of the 463-keV gating γ ray. Several other new γ rays have also been observed, but no information concerning the issuing levels can be ascertained since angular distributions for these transitions could not be obtained.

Börner *et al.* [1] have argued, based on γ-ray intensities observed following the (n,γ) reaction, that the band built on the $11/2^+$ 175.7-keV level is a highly-decoupled band built on a coexisting oblate shape. Particle-rotor calculations performed [1] assuming an oblate triaxial shape found that the nonyrast levels could be qualitatively (and for most levels quantitatively) described by assuming a deformation of $\epsilon=0.37$ and $\gamma=43°$. It was also shown that the K-value for the band was not a good quantum number, but rather most levels had significant K admixtures with low K-values domi-

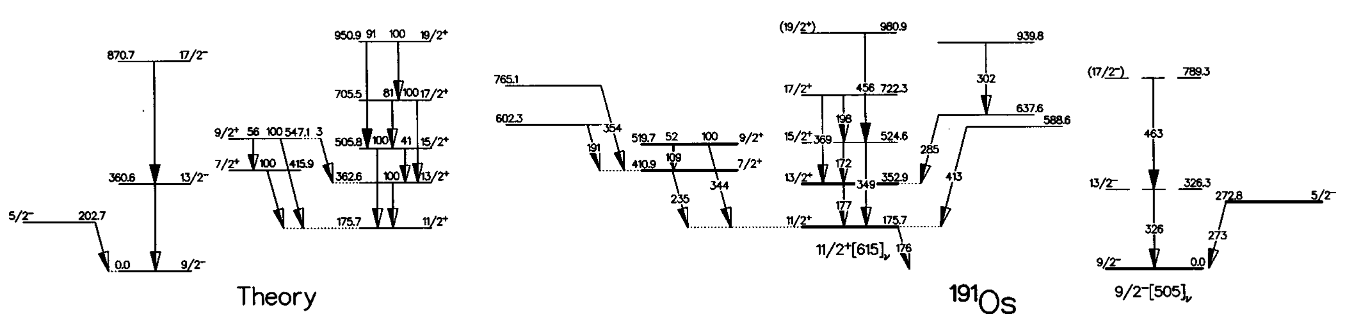

FIG. 4. Partial level scheme for ^{191}Os (right) established in the present work. Only those results leading to new levels (previously known levels are indicated by bold lines) or used in confirming the reaction channel are shown, expect for the previously known $5/2^+$ level at 273 keV. The $13/2^-$ and $17/2^-$ levels assigned to the ground-state band must be regarded as tentative. The left part of the figure shows results of calculations using $\epsilon=0.175$ and $\gamma=24°$ for the bands labelled as the $11/2^+[615]_\nu$ and $9/2^-[505]_\nu$ configurations. Numbers above the γ rays are branching ratio's predicted. Due to the complexity of the spectra, the only branching ratio known experimentally is for the $9/2^+$ level, determined in Ref. [1].

nating. The single-nucleon transfer study by Benson *et al.* [2] observed a level at 352 keV, and based on its observed cross section in the (^{3}He,α), (d,t), and (d,p) reactions, was assigned as the $13/2^+$ member of the $11/2^+[615]_\nu$ band. This level was also observed to be strongly populated in the (d,t) measurement performed by Börner *et al.* [1]. This implies that the wave function for the $13/2^+$ state must be dominated by $i_{13/2}$ neutron components that give rise to a large spectroscopic strength. However, calculations (details of which can be found in Ref. [1]) performed using the above values of ϵ and γ indicate that the $13/2^+$ state would have a very small spectroscopic strength, and thus negligible cross section. Therefore, even though the energies and branching ratio's within the band were well reproduced in the previous calculations [1], the failure in the prediction of a large cross section for the $13/2^+$ state is a serious discrepancy. With this in mind, new calculations were undertaken with the aim of reproducing the band structure as well as possible while maintaining a large (d,t) spectroscopic strength for the $13/2^+$ member.

Calculations were performed using the programs GAMPN, ASYRMO, and PROBMO [7]. The Hamiltonian used is described in Ref. [8], and values of κ and μ were taken from Ref. [9]. Following diagonalization of the single-particle Hamiltonian, five orbitals surrounding the Fermi surface were coupled together; the Coriolis attenuation factor was set to 0.7, and the pairing factors were determined from a BCS calculation. The core moment of inertia was adjusted by specifying the 2_1^+ energy. Using shape parameters $\epsilon_2 = 0.175$, $\epsilon_4 = 0.03$, and $\gamma = 24°$, a band with properties consistent with those of the band based on the $11/2^+$ state could be obtained. The results are shown in Fig. 4. This band is labelled as the $11/2^+[615]_\nu$ configuration, even though for such large values of γ the wave functions are significantly K admixed, since it ''evolves'' from this orbital as the value of γ is changed from 0°. The predicted (d,t) spectroscopic strength for the $13/2^+$ level is large ($S \simeq 1$), and thus more in line with the single-nucleon transfer results [2]. A drawback in the present calculations, however, is the position of the low-spin band members; the $3/2^+$ state, for example, is predicted at 1246 keV rather than at the observed [1] location of 764 keV. Other levels are predicted to lie lower in energy, but belong to different configurations and thus do not have a dominant decay to the $7/2^+$ level at 411 keV. Of course, these other configurations may be built on slightly different nuclear shapes, thus affecting their excitation energies and decay probabilities. Until absolute $B(E2)$ values can be measured for transitions from the experimentally observed levels, the question of their configuration may remain unanswered. Also shown in Fig. 4 are the experimentally suggested and calculated ground state band members. The $5/2^-$ state at 273 keV was suggested by Benson *et al.* [2] to be the $J-2$ ground state band member. Using the same parameters for the Hamiltonian as above, the negative-parity ground state band is also well described. It is thus concluded that the present values of ϵ and γ can successfully describe both the positive- and negative-parity yrast bands, including the single-nucleon transfer results.

In summary, levels in ^{191}Os have been observed following the ^{192}Os$(p,pn\gamma)$ reaction with 25 MeV protons. The previously assigned $11/2^+$ band has been extended to spin $19/2^+$, and candidates are suggested for the ground-state band built on the $9/2^-[505]_\nu$ orbital. The results from the present work and from previous single-nucleon transfer studies for the positive-parity states are reproduced better assuming $\epsilon = 0.175$ and $\gamma = 24°$, rather than $\epsilon = 0.37$ and $\gamma = 43°$ as previously suggested [1]. Problems in the interpretation remain, however; notably with the low-spin members of the $11/2^+[615]_\nu$ band being predicted at much higher energies than observed. Further experiments which provide information on the nature of the levels, such as high-resolution single-nucleon transfer studies and measurements of absolute $B(E2)$ values, are clearly needed.

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