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Osmium isotopes with the (p, t) reaction[*]

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The (p, t) reaction at $E_p = 19.0$ MeV has been used to study five isotopes of Os ($A = 190$, 188, 184, 187, 185) which lie in a transition region between the deformed rare earths and spherical nuclei. Cross sections and angular distributions have been measured to states up to about 2 MeV of excitation in all cases except ^{188}Os and ^{190}Os in which states were seen up to 4 MeV. The energies of the $J^\pi = 0^+$ states which we see and their summed cross sections in percent of the ground state (in parenthesis) are: 913 (4.7), 1551 (1.8), and 1734 keV (6.3) in ^{190}Os, 1087 (5.7), 1480 (3.7), 1705 (1.2), and 1765 keV (<1) in ^{188}Os, and 1042 (8.4) and tentatively 1982 (1.2) and 2268 keV (1.3) in ^{184}Os. The $L = 0$ transitions seen in the odd isotopes are at 9.8, 77, 730, and 1657 keV in ^{187}Os and 1070 and 1213 keV in ^{185}Os. The results show no positive evidence for the existence of strongly populated shape isomeric 0^+ states similar to those seen in the transition region around $N = 88$. In ^{188,190}Os and possibly ^{192}Os the lowest exicted $K = 0$ and $K = 4$ bands have the properties expected for two-phonon γ vibrations. In addition to the rotational excitations in the odd isotopes, two strong transitions have been seen to states at 599 and 802 keV in ^{185}Os which we have postulated to be the $|K_0 \pm 2|$ γ vibrations based on the $1/2^-[5\,1\,0]$state with admixed one quasiparticle components. Similar states have been seen in ^{187}Os. The lowest $L = 0$ transfers to states in ^{185,187}Os were found to have significantly lower intensity than the ground states in the adjacent even-N nuclei. In the case of ^{187}Os the low lying $L = 0$ strength is split between two states. Calculations have been made to understand these phenomena in terms of blocking effects and Coriolis mixing.

NUCLEAR REACTIONS ^{192,190,186,187,189}Os(p,t), $E_p = 19$ MeV; measured $\sigma(\theta)$; deduced ^{190,188,184,185,187}Os levels, J^π; pairing plus DWBA calculations, comparison with expt. for lowest $L = 0$ states.

I. INTRODUCTION

The nuclei of the Os and Pt isotopes are situated in a transition region between the nuclei possessing large equilibrium deformations in the range $152 < A < 180$ and the spherical nuclei near the doubly magic ^{208}Pb.

In recent years, much effort has gone into the study of energy levels, electromagnetic multipole moments, and transition probabilities of the even-even nuclei in the heavy transition region.[1-13] The results of such studies have indicated that the previously well established phenomenological models of nuclear structure do not work well in this region, i.e., a description in terms of rotations about a permanent equilibrium deformation does not give quantitative agreement with the energy levels and transition probabilities.[6,14] The model of harmonic vibrations about a spherical equilibrium shape is also inadequate to explain the energy spectra, electromagnetic transition rates, and the substantial quadrupole moments observed in this region. Thus even for the lower excited states of such nuclei, it is necessary either to consider a model which takes into account strong interactions of the rotational and vibrational modes of excitation or to attempt a microscopic description of the properties of these nuclei.

Figure 1 shows the quadrupole deformation parameter β and the static quadrupole moment Q_{2^+} of the first excited state in the two shape transition regions around Sm and Os. As is clear from the figure, there is a rather sharp increase in the deformation in the Sm region but a fairly slow decline in deformation for the Os isotopes. The rate of change of β with N in the $^{150-152}$Sm region is about 3 times its value in the W, Os, Pt region. However, in the latter region, although β is changing only slowly the quadrupole moment of the first excited 2^+ state changes sign from prolate to oblate in going from Os to Pt. These data suggest a softness in the γ direction around $A = 190$ and a change in shape associated with the asymmetry parameter γ rather than with β.

A consideration of nuclear deformations on the basis of the anisotropic harmonic oscillator including a residual pairing interaction[18,19] has shown that, with respect to γ vibrations, the nuclear potential has a very shallow minimum, i.e., these nuclei are "soft" with respect to γ vibrations. In the calculations of Kumar and Baranger,[17] the potential energy $V(\beta, \gamma)$ and the inertial functions of the Bohr collective Hamiltonian[20] are calculated with pairing plus quadrupole forces. Their potential energy function shows a γ softness, and their predictions for some of the static properties,

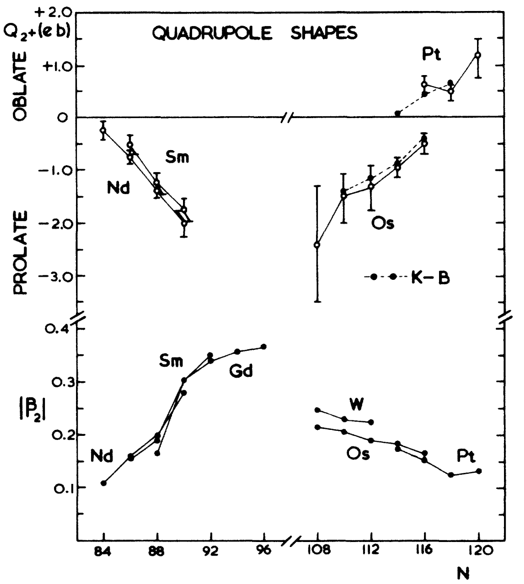

FIG. 1. Static quadrupole moments of 2_1^+ states, Q_2^+, and quadrupole deformations $|\beta_2|$ versus neutron number. The data are taken from Refs. 15–17 (calculated values, K-B).

such as the Q_{2^+}, are in general agreement with experiment as seen in Fig. 1.

Important information has been obtained from (t,p) (Ref. 21) and (p,t) (Ref. 22) reactions for the transition nuclei around $N=88$. The most interesting experimental result is the strong population of excited 0^+ states in the residual nucleus which are believed to have average shapes similar to that of the target ground state. Thus "deformed" excited 0^+ states have been observed in ^{148}Sm and ^{150}Sm in the (p,t) reactions,[22] and a state which is interpreted as a spherical excited 0^+ state is seen in ^{152}Sm in the (t,p) reaction.[21] In this shape transition region, the usual tendency for pair correlations to collect the two-particle transfer strength into the ground state is opposed by the small shape overlap of the A and $A\pm2$ ground states, as has been calculated by Takemasa, Sakagami, and Sano.[23] This results in excited 0^+ strength having a maximum ratio (~1) to the ground-state strength between $N=88$ and 90 where the variation of the quadrupole deformation of the ground state (β) with neutron number is greatest and where excited states of the residual nucleus exist which are similar in shape to the target ground state (shape isomeric states).

Since the transition from deformed to spherical nuclear shapes in the Os region is a gradual one as compared with the Sm region, it is not expected that we will see any strongly populated shape isomers in the Os, except possibly those associated with the γ degree of freedom. However, the (p,t) reaction is an excellent tool for exciting collective vibrational states and for identifying excited 0^+ states. With these considerations a systematic (p,t) study of the Os isotopes has been undertaken. We have done (p,t) studies on three even-even isotopes, namely, ^{192}Os, ^{190}Os, and ^{186}Os and two odd isotopes ^{189}Os and ^{187}Os. Simultaneously and independently a (p,t) study of ^{188,190,192}Os was done at 18 MeV by another group.[24]

In Sec. II we discuss the experimental procedure and the experimental results. Spin and parity assignments and properties of some of the crucial low-lying states are discussed in Sec. III. In this section we attempt to identify states built on 0^+ and 2_γ^+ vibrations of the core in the odd-A nuclei.

In Sec. IV we have made an attempt to understand the low-lying level structure of the even nuclei and some conclusions are drawn regarding the low-lying excited $K=0$ and $K=4$ bands.

Section V is devoted to the discussion of the strength of the $L=0$ transfers. In particular, we have tried to explain the drop in the lowest $L=0$ (p,t) cross sections, in the case of the odd iso-

TABLE I. Composition of enriched targets (targets were fabricated by R. Klein, Rutgers University), target thickness, and Q values for the (p,t) reaction.

Target	$Q_{\text{g.s.}}$[c] (MeV)	Isotopic abundance[a] (%) ^{184}Os	^{186}Os	^{187}Os	^{188}Os	^{189}Os	^{190}Os	^{192}Os	Target thickness (μg/cm^2)
^{186}Os	−6.451	<0.1	61.27	3.31	9.54	7.31	8.77	9.80	300[b]
^{187}Os	−6.074	<0.01	1.43	45.76	25.74	9.27	9.38	8.43	400[b]
^{189}Os	−5.431	<0.05	<0.05	<0.05	1.7	87.3	8.5	2.5	200[b]
^{190}Os	−5.234	<0.05	<0.05	<0.05	0.54	1.41	95.46	2.6	279
^{192}Os	−4.835	<0.05	<0.05	<0.05	0.19	0.37	0.77	98.68	172
^{188}Os	−5.802	(Not run in this experiment)							

[a] Isotopic analysis was performed by the supplier, Oak Ridge National Laboratory.
[b] 20 μg/cm^2 carbon backing was used for these targets.
[c] Reference 26.

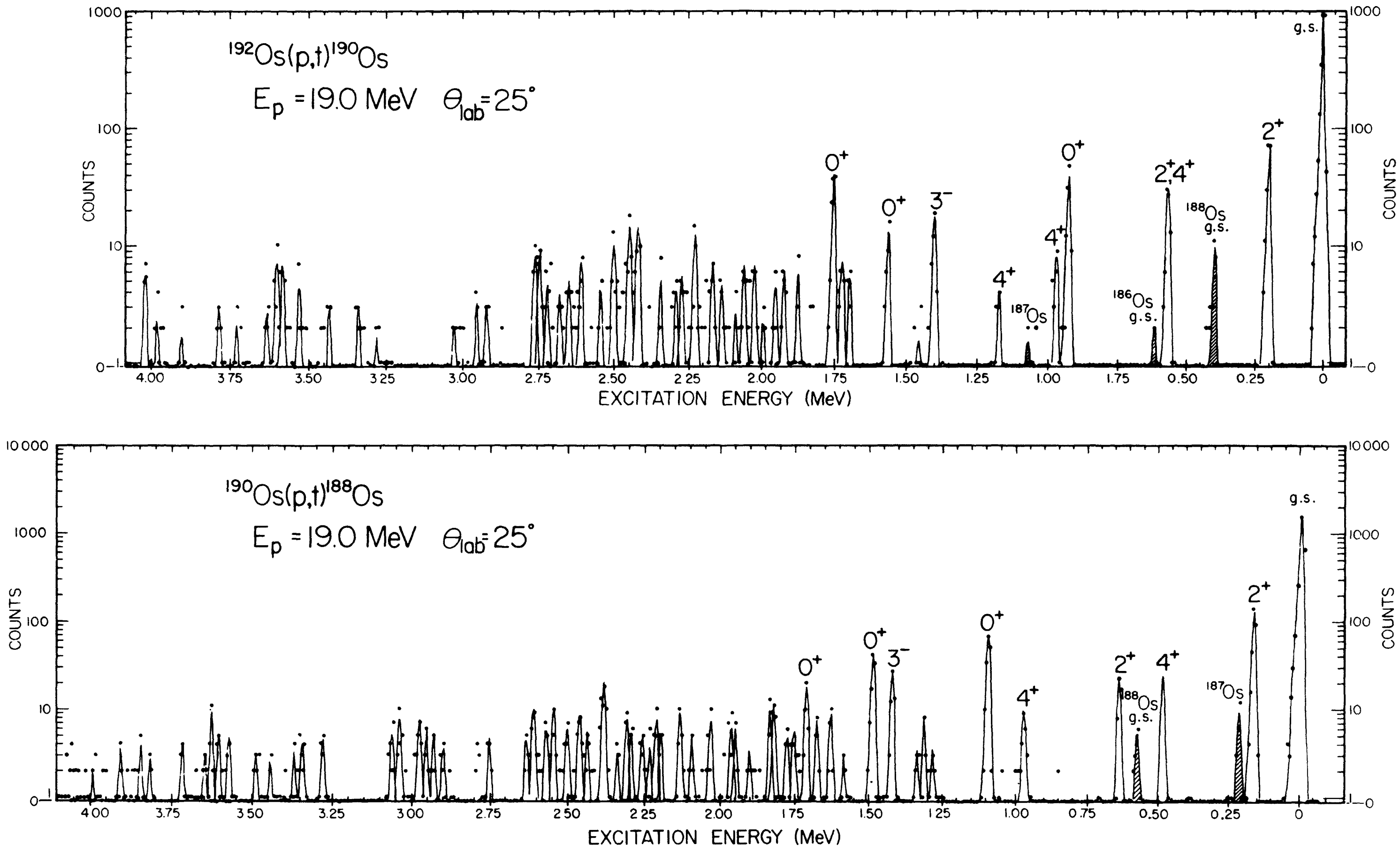

FIG. 2. Triton spectra from $^{190,192}Os(p,t)^{188,190}$ reactions at $\theta_{lab} = 25°$. A few of the low-lying states are marked as to J^{π}.

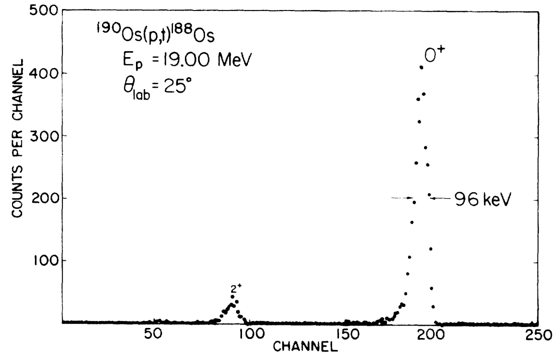

FIG. 3. A typical PSD spectrum at $\theta_{\text{lab}} = 25°$ showing the resolution in the $^{190}\text{Os}(p,t)^{188}\text{Os}$ reaction at $E_p = 19.0$ MeV.

topes, with the blocking effect, i.e., the presence of an odd neutron in an orbit near the Fermi surface. We also discuss Coriolis mixing effects on the excitation of one quasiparticle bands. Section VI is a summary.

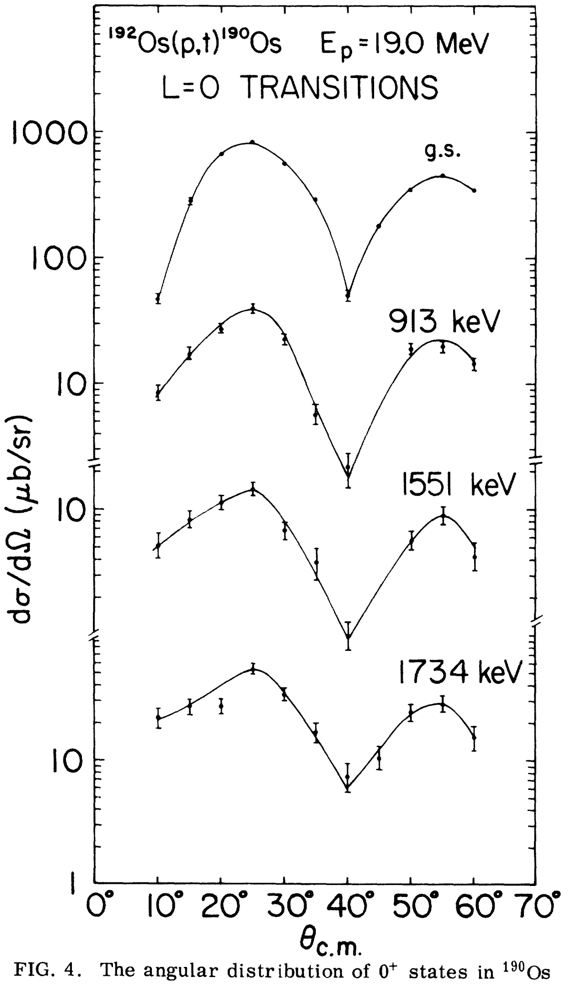

FIG. 4. The angular distribution of 0^+ states in ^{190}Os from the (p,t) reaction. The lines are drawn to guide the eye.

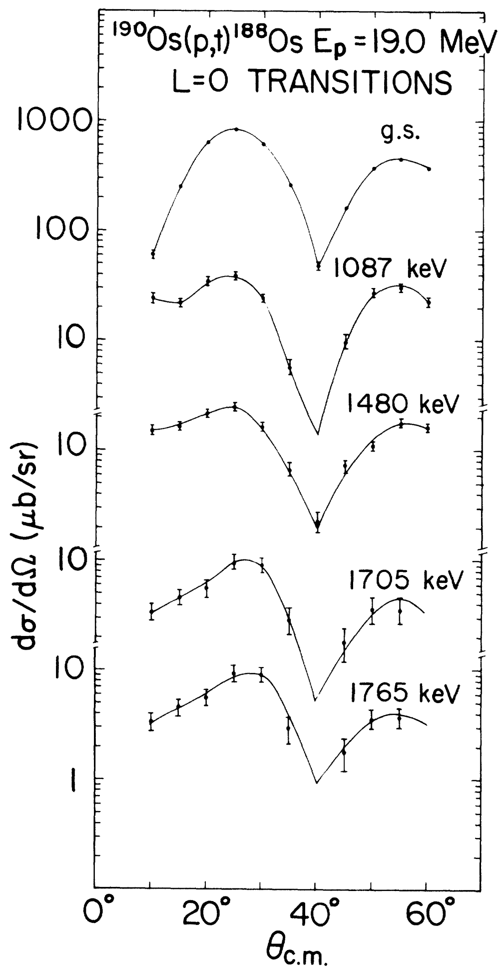

FIG. 5. The angular distribution of 0^+ states in ^{188}Os from the (p,t) reaction. The lines are drawn to guide the eye.

II. EXPERIMENTAL PROCEDURE

The experiments were done using 19.0 MeV protons from the J. H. Williams Laboratory MP-II tandem accelerator. The outgoing tritons were detected using an array of six position sensitive detectors (PSD) in the focal plane of the Enge split-pole spectrograph. Two exposures with nuclear emulsion plates (50 μm Kodak NTB) were also made for ^{190}Os and ^{192}Os targets at $\theta_{\text{lab}} = 25°$ for accurate energy calibrations.

Self-supporting, isotopically enriched targets were used for ^{190}Os and ^{192}Os. Targets with 20 μg/cm^2 thick carbon backing were used for $^{189,187,186}\text{Os}$. The isotopic composition and the target thickness is given in Table I. Targets were made by electrodeposition of Os on Cu with subsequent removal of the backing.[25] The slight amount of residual Cu does not affect the experiment because of the large negative (p, t) Q value for the Cu isotopes. The Q

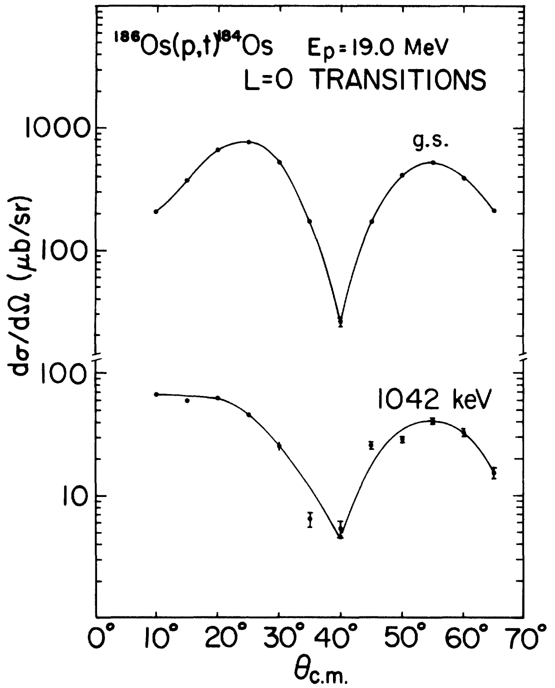

FIG. 6. The angular distribution of 0^+ states in ^{184}Os from the (p, t) reaction. The lines are drawn to guide the eye.

values for the Os isotopes were taken from Ref. 26.

Elastic proton scattering data for all of the targets were taken from $\theta_{\text{lab}} = 20°$ to $60°$ for target thickness and spectrometer solid angle calibration. The experimental cross sections were compared with optical model calculations using the Becchetti-Greenlees parameters,[27] which gave very good fits. The data were then normalized to the optical model predictions to obtain absolute cross sections.

Defining slits at the image of the analyzing magnet were set to give a 3–5 keV spread in the beam energy. The over-all resolution was 10 keV full width at half maximum (FWHM) for ^{190,192,189}Os. Due to target thickness the resolution was ~15 keV FWHM in the case of ^{186}Os and ^{187}Os.

Figure 2 shows the plate spectra from ^{190}Os and ^{192}Os targets at 25° where $L = 0$ transitions have the maximum cross section. Close lying states were unfolded using the computer code "AUTOFIT."[28] Figure 3 shows a spectrum from a single PSD in the case of $^{190}\text{Os}(p, t)^{188}\text{Os}$ at $\theta_{\text{lab}} = 25°$. The angular distributions were taken from $\theta_{\text{lab}} = 10°$ to $60°$ for the ^{192,190,189}Os targets and up to $\theta_{\text{lab}} = 65°$ for the ^{186,187}Os targets, in 5° steps. At several angles spectra were taken with natural Os targets to aid in contaminant subtraction. The error in the absolute (p, t) cross section, determined from the optical model fits is estimated to be 10–15%. Relative errors are somewhat smaller and are shown in the figures. Errors in energy calibration were generally ±5–7 keV. Angular distributions for the $L = 0$ transitions are shown in Figs. 4–8. Figures 9 and 10 show the angular distribution of some 2^+ and 4^+ states excited in ^{190}Os and ^{188}Os, respectively. Figure 11 shows some $L = 3$ transitions. In Tables II–VI we have summarized our results.[28a] A detailed discussion of some of the states excited in this experiment is given below.

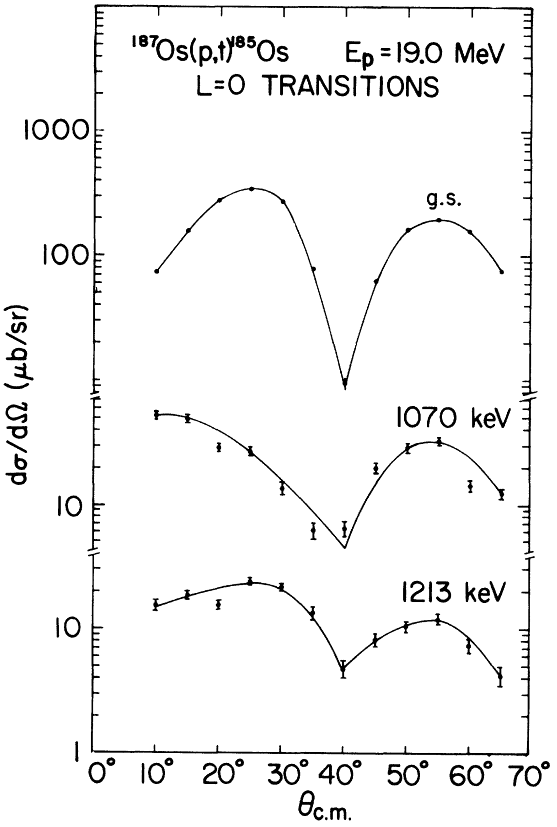

FIG. 7. The angular distribution of $L = 0$ transitions in the $^{187}\text{Os}(p, t)^{185}\text{Os}$ reaction at $E_p = 19.0$ MeV. The lines are drawn to guide the eye.

III. DISCUSSION OF INDIVIDUAL LEVELS

A. ^{190}Os

In Table II, we have listed the ^{190}Os levels seen in the (p, t) experiment along with those known from other experiments.[29-31] The (p, t) data have extended the known states up to 4 MeV. The ^{190}Os ground-state and γ bands are firmly established from earlier studies.[29] The members of the ground bands in the even Os isotopes are excited with intensity pattern similar to those seen for rotational nuclei in the rare earth region.[26] The

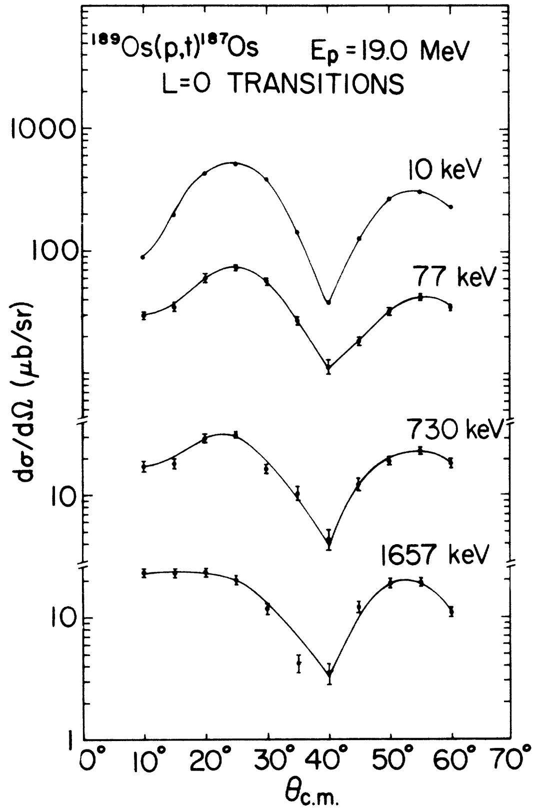

FIG. 8. The angular distribution of $L=0$ transitions in the ^{189}Os$(p,t)^{187}$Os reaction at $E_p = 19.0$ Mev. The lines are drawn to guide the eye.

2_γ^+ and 4_g^+ in ^{190}Os are, however, too close to be resolved in this experiment.

In addition to the known 0^+ state at 912 keV we have seen two new 0^+ states at 1551 and 1734 keV. Mariscotti, Kane, and Emery[5] reported levels at 1546.1 and 1734.4 keV in their ^{189}Os$(n,\gamma)^{190}$Os experiment, but no spin-parity assignments were made by them.

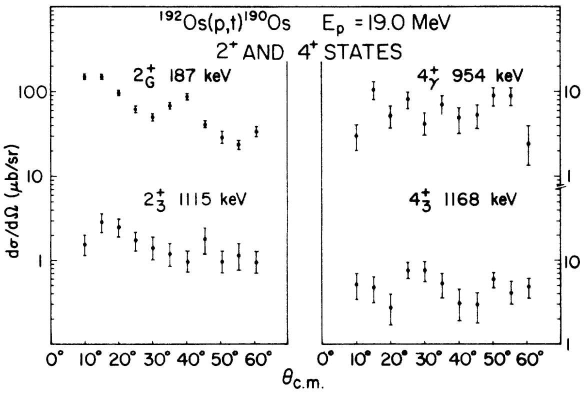

FIG. 9. The angular distributions of 2_g^+(187 keV), 4_γ^+ (954 keV), 2_3^+(1115 keV), and 4_3^+(1168 keV) states in ^{190}Os.

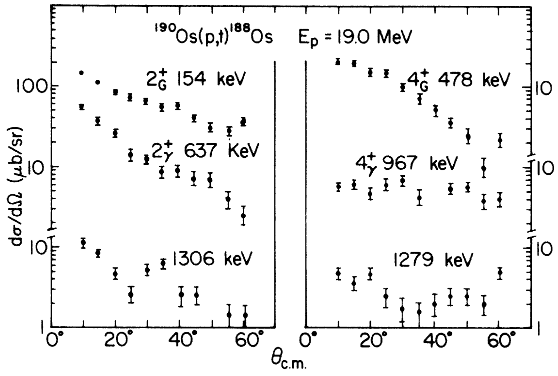

FIG. 10. The angular distributions of 2_g^+, 4_g^+, 2_γ^+, and 4_γ^+ states along with those of states at 1279 and 1306 keV in ^{188}Os in the (p,t) reactions.

1115 keV state. This level has been seen in (n,γ) by Mariscotti *et al.*[5] who assign $(1^+, 2^+)$ and by Yates, Cunnane, and Daly[30] in a (d,p) experiment with no spin assignment. Since 1^+ states have not been seen in the (p,t) reactions on deformed nuclei, a 2^+ assignment is favored. This tentative assignment[31a] makes it a good candidate for the 2^+ member of the $K=0$ two-phonon γ vibration with the bandhead at 913 keV.[32] This level will be further discussed in Sec. IV in connection

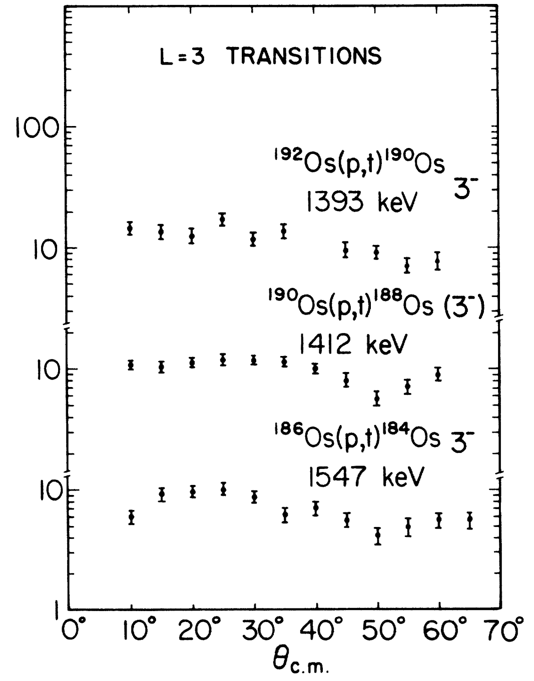

FIG. 11. The angular distribution of $L=3$ transitions to 3^- states at 1393 keV in ^{190}Os and 1547 keV in ^{184}Os. The angular distribution of the 1412 keV state in ^{188}Os, a probable 3^-, is shown for comparison.

TABLE II. States in ^{190}Os. The asterisk indicates a doublet and the dagger indicates that the uncertainty in energy is 5 keV for states up to 2 meV and 10 keV above that.

Present experiment			Other experiments [c]		
Energy †	$\sum \frac{d\sigma}{d\Omega} \sin\theta$ [a]	J^{π} [b]	Energy	J^{π}	Reference
0	2221.2	0^+	0	0^+	
187	345.9	2^+	186.8	2^+	d, e, f
556 *	122.2	$2^+ + 4^+$	548.1	4^+	d, e, f
			557.9	2^+	d, e, f
			756.0	3^+	d, e, f
913	104.9	0^+	912.0	(0^+)	d, f
954	40.9	4^+	955.4	4^+	d, e, f
			1050.4	6^+	d, e, f
1115	9.3	2^+	1115.2	$1^+, 2^+$	d, f
1168	30.4	4^+	1163.2	4^+	d, e, f
			1203.5	5^+	d, e, f
			1383	$(1, 2), (0, 1)^+$	d, f
1393	62.8	3^-	1387.2	3^-	d, e
			1436.2	(2^+)	d
1450	16.8		1446.0	(5^+)	d
1551	39.3	0^+	1546.1	$(0, 3)^+$	f
			1570(3)		e
			1583.6	4^-	d
			1666.9	8^+	d, e
			1678.3	$(1), 2^+$	f
1686	34.1	5^-	1681.6	5^-	d, e
			1705.8	10^-	d
1712	61.2		1708.29	$3, 4^{(+)}$	e
1734	139.1	0^+	1734.4	$(0, 3)^+$	d, f
			1823.2		d, f
			1836.23	6^+	e
			1857	$(1, 3)^+$	f
			1870.7		d
1869			1872	5^-	e, f
			1887		d, f
			1903.29	(4^-)	e
			1910	$(1, 3)^+$	f
1916			1912(5)		e
1946					
			1963.9	$(4, 5)^+$	d, e, f
1990			1995.6	$(2, 3)^+$	e
2018					
2054					
			(2061.1)	$(7^-, 6^+)$	e
			2068.82	(5^+)	e
2083					
			2112(3)		e
			2121.28	(5, 6)	e
2130					
2161			2150(5)		e
			2180(3)		e
2211			2212(3)		e
2266			2258(5)		e
2286			2298(5)		e
2339			2330(5)		e
			2352.4	(2, 3)	e
			2366(6)		e
2412			2417(6)		e
2440			2450(5)		e
			2476(6)		e
2493					
			2511(6)		e

TABLE II (Continued)

Present experiment Energy †	$\sum \frac{d\sigma}{d\Omega} \sin\theta$ [a]	J^{π} [b]	Other experiments [c] Energy	J^{π}	Reference
2538			2541(6)		e
2603			2618(7)		e
2645			2655(7)		e
2674			2686(7)		e
2715			2717(6)		e
2739					
2755			2770(7)		e
			2812(8)		e
2915					
2947			2945(10)		e
			2992(10)		e
3023					
			3045(10)		e
3278					
3336					
3430					
3525					
3577					
3595					
3628					
3724					
3781					
3900					
3978					
4015					

[a] The cross sections are in (μb/sr) summed from 10° to 60° with an interval of 5°.

[b] Only 0^+ states are assigned unambiguously in this experiment. Other assignments are based on energy systematics, selection rules, and angular distributions as discussed in the text.

[c] The states above 1.87 MeV seen in the present experiment and in other experiments are associated only because of energy proximity.

[d] Reference 29.

[e] Reference 30.

[f] Reference 31.

with two-phonon γ vibrations in the Os nuclei.

1168 keV state. This level was first seen by Harmatz and Handley[8] who assigned it 3^+, but later Yamazaki[9] assigned it $J^{\pi} = 4^+$ from an angular correlation experiment. This latter assignment is consistent with the (p, t) experiment, since all of the known unnatural parity states in the rare earth region have intensity $\leq 1\%$ of the ground state in (p, t) reactions.[26] Its angular distribution (Fig. 9) is consistent with $L = 4$, but a unique assignment cannot be made on this basis at $E_p = 19$ MeV.

B. ^{188}Os states

States up to 4 MeV were seen in the ^{190}Os(p, t)-^{188}Os experiment. The over-all features of the spectrum are similar to ^{190}Os (Fig. 2) in that a few well resolved states are seen up to ~1.75 MeV after which a large number of weak closely spaced states occur up to 4 MeV.

In Table III we have summarized the levels of ^{188}Os seen in this experiment along with levels from other experiments.[2,3,33-36]

0^+ states. Figure 5 shows the angular distribution for the five $L = 0$ transitions seen in ^{188}Os. Of the four excited 0^+ states at 1087, 1480, 1705, and 1765 keV, only the 1087 and 1765 keV 0^+ states were known at the time of this experiment. In the (p, t) experiment of Thompson *et al.*,[24] the 1765 keV level is not assigned $L = 0$, but a state at 1823 keV is claimed to be $L = 0$.

1279 and 1306 keV states. We see weak states at 1279 and 1306 keV (~1% of the ground state) with angular distributions consistent with either 2^+ or 4^+ for each state (Fig. 10). A tentative J^{π} assignment of 4^+ was made for a state at 1279.6 keV by Yamazaki and Sato.[7] The only basis for

TABLE III. States in ^{188}Os. An asterisk indicates a doublet.

	Present experiment		Other experiments		
Energy	$\sum \frac{d\sigma}{d\Omega}\sin\theta$ [a]	J^{π} [b]	Energy	J^{π}	Reference
0	2254.6	0^+	0	0^+	
154	325.4	2^+	155.03	2^+	c, d, e
478	39.7	4^+	477.96	4^+	c, d, e
637	66.9	2^+	633.12	2^+	c, d, e
			790.02	3^+	c, d, e
			939.8	6^+	d, e
967	30.9	4^+	965.4	4^+	c, d, e
1087	128.1	0^+	1085.4	0^+	c, f, g, h
			1181.6	5^+	d, e
1279	16.6	$(2^+, 4^+)$	1279.6	(4^+)	d, e
1306	19.6	$(2^+, 4^+)$	1304.7	(2^+)	g
1412	56.9	3^-	1413.5	(3^-)	e, h
			1424.7	(6^+)	e
			1457.9	2^+	g, h
			1462.1	2^-	c, g, h
			1471.8		f
1480	82.3	0^+	1478.4	0^+	g, h
			1514.6	8^+	d, e
			1515.9	(5^+)	e
1574	14.2	(5^-)			
			1620.4	3^+	c, g
1622	33.1				
			1668.3	(5^-)	e
			1685.2		g
1705	26.1	0^+	1704.3	0^+	h
			1705.0	(2^+)	c
			1729.8	$(2, 3)^+$	c, g
1765	20.5	0^+	1764.5	0^+	h
			1770.5	(7^-)	e
			1807.7	2^+	f, g, h
1824			1825	2, 3	h
			1842.9	1^+	f, g, h
1855					
			1941.07	(1, 2)	h
			1957.4	1, 2	f, g, h
			1964.8	2^+	g
1972			1975(3)		g
			1993.3		e
			2015(2)		g
2023			2021.2		c, f, h
			2054.0		e
			2068.7	$(1, 2)^+$	g
2088			2085.5	$(2, 3^+)$	g
			2099.5	$(1, 2^+)$	c, g
2124					
			2167	(+)	c
			2169.5	10^+	d, e
2206			2205.1	+	c, g
			2214.6	1^+	c
2228					
2251 *			2252.8	$2, 3^+$	c, g, h
			2264(3)		g
2288			2287		c, f, g
2302			2301		c, g
2333			2326.2		g
			2349.5	2^-	c, f, g
			2374.2		g
2377			2377.1	(2^+)	c, g

TABLE III *(Continued)*

Present experiment			Other experiments		
Energy	$\sum \frac{d\sigma}{d\Omega} \sin\theta$ [a]	J^{π} [b]	Energy	J^{π}	Reference
			2416.0		f, g
2432			2446.0		c, f, g
2457			2462.4		c, g
			2491.1		g
2497			2498.8		c
			2505.2		f, g
			2520.6		f, g
2540			2549.3		g
2556			2567(3)		g
			2581.9		g
2605					
2628			2622.5		f, g
			2660.2		f, g
			2701.6		f, g
2743			2746.6		f
			2760.7		f
			2815.8		f, g
			2861.1		f
2891			2888.0		f, g
2923					
2945			2938(6)		g
2968					
			3007.9		f
3031 *			3021.9		f
			3066.5		f
			3140.6		f
			3176.8		f
			3259.3		f
3272			3274.1		f
			3311.4		f
3337					
3362					
3434					
3479					
3567					
3600					
3622					
3644					
3810					
3837					
3900					
3984					

[a] Cross sections are in (μb/sr) summed from 10° to 60° with an interval of 5°.

[b] Only 0^+ states are assigned unambiguously in this experiment. Other assignments are based on energy systematics, selection rules, and angular distributions as discussed in the text.

[c] Reference 33.

[d] Reference 2.

[e] Reference 3.

[f] Reference 35.

[g] Reference 34.

[h] Reference 36.

their assignment is that this state is populated by the decay of the isomeric state which is supposed to have a large K quantum number. A (4^+) state at 1277.7 keV was also seen by Yates, Cunnane, and Hochel[3] in an $(\alpha, 2n\gamma)$ experiment. A 1304.7 keV level has been recently reported by Thompson *et al.*[34] to which they assign (2^+). From the (p, t) angular distribution we cannot positively determine a spin assignment, although the rise at small angles favors $J^\pi = 2^+$ for the 1306 keV state.[31a] The importance of a knowledge of J^π for these states will be discussed in Sec. IV.

1412 keV. This state has an intensity and angular distribution very similar to the known 3^- states in ^{184}Os(1547 keV), ^{186}Os(1480 keV), and ^{190}Os(1393 keV) as shown in Fig. 11. It also fits smoothly into the energy systematics for 3^- states in this region (Fig. 15). The presence of a level at 1413.5 keV has been reported by Yates *et al.*[3] Its γ decay is consistent with our 3^- assignment.

1574 keV state. There is no previously known state at this energy. The spin of the state cannot be inferred from the angular distribution. It is probably too close to the 1480 keV 0^+ state to be 2^+ member of the band. From the energy difference between 3^- and 5^- states in ^{184}Os and ^{186}Os it is a good candidate for a 5^- state. Thompson *et al.*[24] have done ^{188}Os$(p,t)^{186}$Os and have seen the known 3^- and 5^- states at 1481 and 1628 keV, respectively. The intensity ratio of their 1481 to 1682 keV states is very similar to the ratio of our 1412 and 1574 keV states.

1622 keV state. Harmatz and Handley[8], and subsequently Yamazaki and Sato,[7] have identified a 3^+ state at 1620.7 keV. Their evidence is based on the fact that it deexcites to a 2^+ by $M1$ and by $M1+E2$ to a 4^+ state. It is unlikely that their 1620.7 keV state could be the same as our 1622 keV state because of its intensity in (p,t), about 1.5% of the ground state.

The energy difference with the 1480 keV 0^+ state suggests that it is the 2^+ member of the same band. The summed intensity of this state is about 40% that of the 1480 keV which is rather high but is not unknown in the rare earth region for the 2^+ member of an excited $K=0$ band.[26]

C. ^{184}Os states

Because of the low isotopic purity of the ^{186}Os target (61.27%) it was impossible to identify states in ^{184}Os above 2 MeV. Moreover, the thickness of the target limited the resolution to ~15 keV FWHM.

In Table IV we have shown the energy levels, relative strengths, and J^π assignments from the present (p,t) experiment along with the results from other experiments.[2,3,37]

The ground-state band is seen in the (p,t) reaction up to the 8^+ member.

An excited 0^+ state was found in ^{184}Os at 1042 keV with 8.4% of the ground-state strength. Definite $L=0$ transitions were also seen at 1982 and 2268 keV with summed cross sections of 1.2 and 1.3%, respectively, of the ground state if they belong to ^{184}Os. We can tentatively assign these to ^{184}Os, since from the target composition (Table I) these would be 9–10% of the ground-state strength if they belonged to ^{186,188}Os or ^{190}Os. The 1042 keV 0^+ state in ^{184}Os is the strongest $L=0$ (8.4%) seen in the even Os isotopes. Its angular distribution together with that of the ground state is shown in Fig. 6.

1208 keV state. No state in this vicinity was previously known. The (p,t) angular distribution does not allow a J^π assignment to be made. However, the energy difference with the 0^+ state at 1042 keV and its intensity is such that it is tempting to identify it as 2^+ state associated with the 1042 keV bandhead. As in the excited $K=0$ bands of the other even isotopes the moment of inertia would then be somewhat lower than that of the ground band.

A further discussion of some of these states will be made when we compare the low-lying spectra of the even-even isotopes with nuclear models.

D. ^{185}Os states

The results from the present (p,t) experiment (summed cross sections) along with the results of a recent ^{183}W$(\alpha, 2n\gamma)^{185}$Os study by Sodan *et al.*[38] on the energy levels of ^{185}Os are summarized in Table V and Fig. 12. The only other information on ^{185}Os is from the decay of ^{185}Ir.[6,39,40] Five low-lying rotational bands have been identified in the ^{183}W$(\alpha, 2n\gamma)^{185}$Os experiment.[38]

Since the ground state of the ^{187}Os nucleus is $\frac{1}{2}^-[510]$, we expect the (p,t) reaction to populate strongly the members of the "favored" band built on the $\frac{1}{2}^-[510]$ orbit, which in this case happens to be also the ground band of ^{185}Os. Transitions with predominantly $L=0$ shapes were seen to the ground state and to states at 1070 and 1213 keV, which can therefore be assigned $J^\pi = \frac{1}{2}^-$. The higher bands can in general only be populated by pickup of particles from different orbits, leading to one or three quasiparticle states of the residual nucleus. For brevity, we will call these two quasiparticle transitions. These will usually be relatively weakly excited, typically a few percent or less of the favored band,[26] however, in one case,[41] a strong two quasiparticle transitions has been observed in ^{182}W$(t,p)^{184}$W with ~50% of the ground-state cross section. We also expect to populate somewhat more strongly states in which the $\frac{1}{2}^-[510]$ particle is coupled to the collective quadrupole and octupole vibrations of the core. The (p,t) reaction is almost the only way to excite such states in the unstable ^{185}Os.

$\frac{1}{2}^-[510]$ band. In the (p,t) reaction, we have seen the $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}$ members of the band at 0, 38, 98, and 198 keV, respectively. The 98 keV level is not resolved from the $\frac{7}{2}^-$, $\frac{7}{2}^-[503]$ level

TABLE IV. States in ^{184}Os. The asterisk indicates a doublet and the dagger indicates that the uncertainty in energy is 5 keV.

Present experiment			Other experiments		
Energy	$\sum \frac{d\sigma}{d\Omega} \sin\theta$ [a]	J^{π} [b]	Energy	J^{π}	Reference
0	2277.8	0^+	0	0^+	c, d, e
121	373.0	2^+	119.79	2^+	c, d, e
386	81.8	4^+	383.77	4^+	c, d, e
776	20.6	6^+	774.13	6^+	c, d, e
946	88.2	2^+	942.76	2^+	c, d, e
1042	190.7	0^+			
			1081.03	3^+	c, d, e
1208	56.9	(2^+)			
1230	37.2	4^+	1225.08	4^+	c, d, e
1275		8^+	1274.86	8^+	c, d, e
			1428.27	5^+	c, d, e
1444			1445.67	$(3, 4)^+$	c
(1507)			1500.70	$(3, 4)^+$	c
1547	40.1	3^-	1543.95	3^-	c, e
			1613.21	(6^+)	c
			1620.72	4^-	c, e
			1631.61	(5^+)	
			(1697.89)		c
			1707.64	(4^-)	c
1721		5^-	1718.19	5^-	c, e
			1832.79	(6^-)	c, e
1836*			1836.30		
			1840.28		
			1871.4	10^+	d, e
1877			1877.79		c
(1982)	27.8	0^+			
(2268)	28.9	0^+	(2324.54)		c
			2399.04		c
			2446.63	$5^{(+)}$	c
			(2719.87)		c

[a] The cross sections are in (μb/sr) summed from 10° to 60° with an interval of 5°.

[b] Only 0^+ assignments are from this experiment. Other assignments are either previously known or tentatively assigned on the basis of various evidence as discussed in the text.

[c] Reference 37.

[d] Reference 2.

[e] Reference 3.

identified previously[38] at 102.3 keV. The ground-state $L = 0$ cross section is smaller by a factor of 2.4 from that of the neighboring even-even isotopes. A calculation which will be discussed in Sec. V has been made to account for this loss of the ground-state intensity in terms of the blocking effect.

$\frac{3}{2}^-[512]$ *band.* We have seen known[38] states of this band at 127 ($\frac{3}{2}^-$) 224 ($\frac{5}{2}^-$), 354 ($\frac{7}{2}^-$) keV and a level at 519 keV which we identify as the $\frac{9}{2}^-$ state. The $\frac{11}{2}^-$ member of this band is tentatively identified at 707.5 keV but is not seen in (p, t).

The state at 519 keV lies within ~7 keV of the energy obtained for the upper $\frac{9}{2}^-$ level from Coriolis coupling of the $\frac{1}{2}^-[510]$ and $\frac{3}{2}^-[512]$ bands (Table IX). The Coriolis mixing calculations are discussed in Sec. V.

$\frac{7}{2}^-[503]$, $\frac{11}{2}^+[615]$, *and* $\frac{9}{2}^+[624]$ *bands.* Several members of these previously known bands are seen as weakly populated states in the (p, t) reaction. These are shown in Table V where the identification is based mostly on the observed energy, but to some extent on the intensity expected for two quasiparticle transitions.

These bands, plus the $\frac{1}{2}^-[510]$ and $\frac{3}{2}^-[512]$ bands discussed above account for all of the states seen in the (p, t) spectra up to 519 keV.

599 and 802 keV states. As seen in Fig. 12 these two states, not previously known, are rather strongly populated in the (p, t) spectrum of ^{185}Os with almost equal intensity and similar (non $L = 0$) angular distributions.

From the single-particle and quasiparticle energies calculated by Ogle *et al.*[42] the $\frac{5}{2}^-[512]$,

TABLE V. States in ^{185}Os. An asterisk indicates a doublet.

	Present experiment		Other experiments [c]	
Energy	$\sum\frac{d\sigma}{d\Omega}\sin\theta$ [a]	L transfer,[b] and/ or level assignment	Energy	Level assignment
0	939.8	0	0	$\frac{1}{2}, \frac{1}{2}[510]$
38	85.3	2	37.4	$\frac{3}{2}, \frac{1}{2}[510]$
98 *	110.5	2	97.4	$\frac{5}{2}, \frac{1}{2}[510]$
			102.3	$\frac{7}{2}, \frac{7}{2}[503]$
127	19.0		127.9	$\frac{3}{2}, \frac{3}{2}[512]$
198	17.0		198.1	$\frac{7}{2}, \frac{1}{2}[510]$
224	42.1		222.4	$\frac{5}{2}, \frac{3}{2}[512]$
257			260.5	$\frac{9}{2}, \frac{7}{2}[503]$
270			275.7	$\frac{11}{2}, \frac{11}{2}[615]$
			317.8	$\frac{9}{2}, \frac{1}{2}[510]$
354			351.7	$\frac{7}{2}, \frac{3}{2}[512]$
410 *			402.6	$\frac{9}{2}, \frac{9}{2}[624]$
			414.4	$\frac{13}{2}, \frac{11}{2}[615]$
			448.7	$\frac{11}{2}, \frac{7}{2}[503]$
			476.5	$\frac{11}{2}, \frac{1}{2}[510]$
519	14.5	$(\frac{9}{2}, \frac{3}{2}[512])$		
			590.6	$\frac{15}{2}, \frac{11}{2}[615]$
			591.5	$\frac{11}{2}, \frac{9}{2}[624]$
599	153.3	$(\frac{3}{2}^-\{\frac{1}{2}[510]-2_\gamma^+\}$ $+1$ q.p.)		
			660.4	$\frac{13}{2}, \frac{1}{2}[510]$
			666.3	$\frac{13}{2}, \frac{7}{2}[503]$
679	13.8		(707.5)	$(\frac{11}{2}, \frac{3}{2}[512])$
			776.6	$\frac{17}{2}, \frac{11}{2}[615]$
			782.4	$\frac{13}{2}, \frac{9}{2}[624]$
802	151.8	$(\frac{5}{2}^-\{\frac{1}{2}^-[510]+2_\gamma^+\}$ $+1$ q.p.)		
			865.2	$\frac{15}{2}, \frac{1}{2}[510]$
			907.6	$\frac{15}{2}, \frac{7}{2}[503]$
			1024.8	$\frac{19}{2}, \frac{11}{2}[615]$
			1025.8	$\frac{15}{2}, \frac{9}{2}[624]$
1070	155.7	$L=0\{\frac{1}{2}[510]$ coupled to 0^+ (core)$\}$		
			1117.3	$\frac{17}{2}, \frac{1}{2}[510]$
1123	33.8	$\frac{3}{2}^-$ of 1070 keV band		
			1173.3	$\frac{17}{2}, \frac{7}{2}[503]$
1213	74.9	$L=0, J=\frac{1}{2}^-$		
			1222.6	$\frac{21}{2}, \frac{11}{2}[615]$
1275	55.6	$\frac{3}{2}^-$ of 1213 keV band		
			1354.2	$\frac{19}{2}, \frac{1}{2}[510]$
			1461.7	$\frac{19}{2}, \frac{7}{2}[503]$
			1565.8	$\frac{23}{2}, \frac{11}{2}[615]$
			1671.4	$\frac{21}{2}, \frac{1}{2}[510]$
			(1745.2)	$\frac{25}{2}, \frac{11}{2}[615]$
			(1930)	$(\frac{23}{2}, \frac{1}{2}[510])$
			(2310.7)	$(\frac{25}{2}, \frac{1}{2}[510])$

TABLE V *(Continued)*

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[a] The cross sections are in (μb/sr) summed from 10° to 60° with an interval of 5°.

[b] Only $L = 0$ assignments are from this experiment. Other assignments are based on the selection rules, energy and cross-section systematics, and previous assignments as discussed in the text.

[c] Reference 38.

$\frac{7}{2}^+[633]$, $\frac{1}{2}^-[521]$, and $\frac{7}{2}^-[514]$ bands, so far unidentified, are expected in this region. An estimate of the (p, t) cross section expected for these bands, assuming a pure one quasiparticle configuration and using the equations of Yoshida[43] indicates that the $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ members of the $\frac{1}{2}[521]$ bands and the $\frac{5}{2}^-$ member of the $\frac{5}{2}[512]$ band would each be populated ($L = 0$ for the $\frac{1}{2}^-$, $L = 2$ for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states) with a cross section of ~20–50 μb/sr at 25°, comparable to the observed value of ~33 μb/sr for the 599 and 802 keV states. The higher members of the above bands and the $\frac{7}{2}^+[633]$ and $\frac{7}{2}^-[514]$ bands (all $L \geq 4$) are predicted to be much weaker. However, an $L = 0$ is not seen in this region to indicate the presence of the $\frac{1}{2}, \frac{1}{2}[521]$ state, and the spacing of the 599 and 802 keV states is too large for them to be adjacent spin states of the same kind. Furthermore, the calculated two quasiparticle cross sections are likely to be overestimates as discussed in Sec. V.

Strong $L = 2$ transitions are also expected in this region to states formed by coupling the target odd particle, $K_0 = \frac{1}{2}[510]$ to the $K^\pi = 2^+$, γ vibration, of the even core to form the $|K_0 \pm 2| = \frac{3}{2}$ and $\frac{5}{2}$ γ bands. These states have been found in a number of odd-A nuclei[44] with the $K_0 + 2$ band generally near the energy of the γ vibration in the even core (~850 keV in this case) and the $|K_0 - 2|$ band several hundred keV lower. Such states have been seen in (p, t) reactions to ^{169,171}Yb (Ref. 26) and to ^{187}Os as discussed in Sec. III E. The $L = 2$ strength seen to the γ vibration of the even core should divide equally between the two

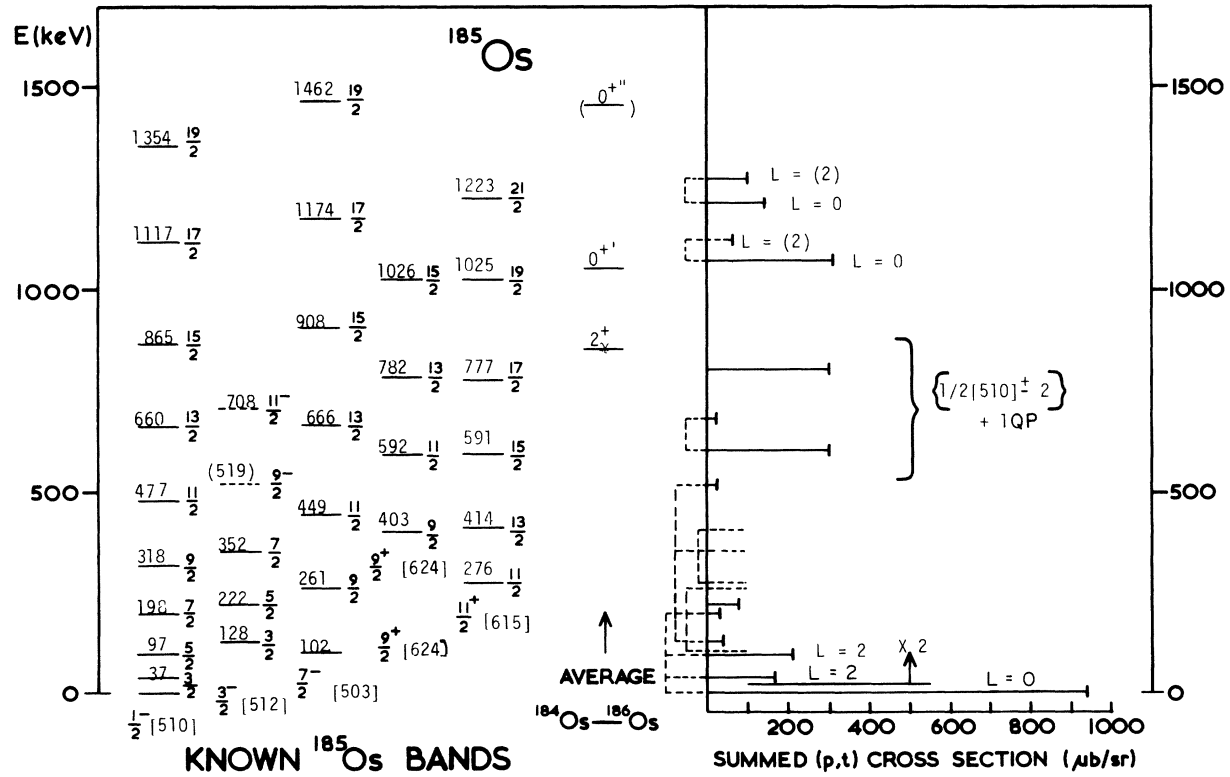

FIG. 12. The energy levels of ^{185}Os from Ref. 38 along with the relative (p, t) summed cross sections. The dashed lines are drawn to connect members of a rotational band. The states drawn with dotted lines in the (p, t) experiment indicate the presence of weak states with cross sections ≲0.5% of the ground state. The average energies of 2^+_γ and 0^+ excited states in neighboring nuclei are shown at the right.

bands in the odd nucleus and be distributed within the $|K_0 \pm 2|$ bands in proportion to

$$\langle I_i, 2, K_0, \pm 2 | I_f, K_0 \pm 2\rangle^2$$

("Alaga rule"). It should be noted that a pure $|K_0 \pm 2|$ band could only be populated by $L \geq 2$ in the (p, t) reaction from a target ground-state component K_0 even when $J_f = J_i$ which would allow $L = 0$ by the J-selection rule alone, since a γ vibration must be excited in the core ($\Delta K = 2$). The same conclusion would follow from the K-selection rule which requires $L \geq \Delta K$. Band mixing in the target ground-state and one quasiparticle admixtures to the $|K_0 \pm 2|$ bands can, of course, relax the K-selection rule.

For the case of ^{187}Os$(p, t)^{185}$Os, the Alaga rule would predict ~45 μb/sr ($L = 2$ summed cross section) for the $\frac{5}{2}^-$ bandhead of the $K_0 + 2 = \frac{5}{2}$ band and ~36 and ~9 μb/sr for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of the $|K_0 - 2| = \frac{3}{2}$ band, respectively. A weak state is observed at 679 keV which could fit as the $\frac{5}{2}^-$ member of the $|K_0 - 2|$ band, if the bandhead is assumed to be the 599 keV state. The experimental summed cross sections to the states at 599 and 802 keV are, however, about 150 μb/sr each, and the angular distributions are consistent with either $L = 2$ or $L = 4$, and so this simple description of the states fails badly. However, the γ vibrations in odd-A nuclei frequently contain large one quasiparticle admixtures which will drastically alter the simple intensity ratios. For the $K_0 + 2$, γ vibration, based on the $\frac{1}{2}$[510] state in ^{185}Os, Soloviev and Fainer[45] calculate a 48% admixture of the $\frac{5}{2}$[512] one quasiparticle state. The $|K_0 - 2| = \frac{3}{2}$ band based on the same state is expected to mix with the $\frac{3}{2}^-$[512] one quasiparticle state as is observed in ^{187}Os (see Ref. 46 and Sec. III E). Calculations are now being done to obtain a more quantitative description of these states; however, data on γ-decay rates and single nucleon transfer spectroscopic factors is also needed. In the meantime the assignments above must be considered rather speculative.

Higher excited bands. We have seen two excited $K^\pi = \frac{1}{2}^-$ bandheads at 1070 and 1213 keV. The angular distribution of these two states is shown in Fig. 7. The 1070 keV state is excited with ~15% of the intensity of the ground state and is comparable in absolute cross section with the 0^+ states in ^{184}Os at 1042 keV and ^{186}Os at 1061 keV. Thus this state is probably the $\frac{1}{2}^-$[510] particle (hole) coupled to the 0^+ state in ^{184}Os (^{186}Os).

The state at 1123 keV has an angular distribution which is very similar to that of the 38 keV $\frac{3}{2}^-$, $\frac{1}{2}^-$[510] state which must go by $L = 2$ (see Fig. 13). Given the energy separation of this state from the 1070 keV $\frac{1}{2}^-$ bandhead, its intensity and angular distribution, it is tempting to interpret it as the $\frac{3}{2}^-$ member of the $\frac{1}{2}^-$ bandhead at 1070 keV. The moment of inertia of this band is a bit lower than the ground band which is quite consistent with the behavior of excited $K^\pi = 0^+$ bands in the neighboring even-even isotopes.

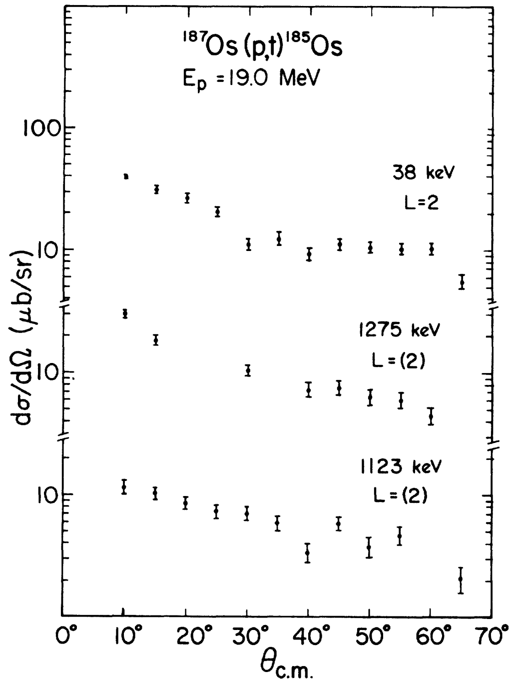

FIG. 13. Angular distributions of known $L = 2$ or assigned $L = 2$ transitions in ^{187}Os$(p, t)^{185}$Os.

The states seen at 1213 keV, with an angular distribution characteristic of $L = 0$ transition (Fig. 7), and at 1275 keV with an angular distribution similar to $\frac{3}{2}^-$ states (Fig. 13) indicate the population of two members of another excited $K = \frac{1}{2}^-$ band. The moment of inertia of this band is even smaller than the moment of inertia of the 1070 keV band. We saw no 0^+ states in this excitation range in ^{184}Os but a second excited 0^+ state has been reported[24] at 1456 keV in ^{186}Os. The $\frac{1}{2}^-$ state at 1213 keV also has about the right cross section to be the head of the missing $\frac{1}{2}$[521] band mentioned above.

E. ^{187}Os states

There have been several previous investigations[38,39,46–50] of the level structure of ^{187}Os. The first detailed study, by means of high resolution conversion electron spectroscopy, was performed by Harmatz, Handley, and Mihelich[39] who proposed a ^{187}Os level scheme based on the Nilsson model. The scheme has been extended and many new excited members of the rotational bands have been added in the recent $(d, 2n)$ and (p, n) work of Sodan *et al.*[38] Several collective vibrational excitations

TABLE VI. States in ^{187}Os. The asterisk indicates a doublet; the cross section is the summation for both peaks. The dagger indicates unresolved ground and 9.8 keV states.

Present experiment			Ref. 46		Ref. 38		Ref. 50	
Energy	$\sum\sigma(\theta)\sin\theta$ [a]	L transfer, [b] and/or level assignment	Energy	Level assignment	Energy	Level assignment	Energy	Level assignment
					0	$\frac{1}{2}, \frac{1}{2}[510]$	0	$\frac{1}{2}, \frac{1}{2}[510]$
9.8†	1494.8	0			9.8	$\frac{3}{2}, \frac{3}{2}[512]$	9.8	$\frac{3}{2}, \frac{3}{2}[512]$
77	224.4	0	74.5	$\frac{3}{2}, \frac{1}{2}[510]$	74.5	$\frac{3}{2}, \frac{1}{2}[510]$	74.4	$\frac{3}{2}, \frac{1}{2}[510]$
					75.1	$\frac{5}{2}, \frac{3}{2}[512]$	75.1	$\frac{5}{2}, \frac{3}{2}[512]$
100			100	$\frac{7}{2}, \frac{7}{2}[503]$	100.7	$\frac{7}{2}, \frac{7}{2}[503]$	100.5	$\frac{7}{2}, \frac{7}{2}[503]$
					187.5	$\frac{5}{2}, \frac{1}{2}[510]$	187.5	$\frac{5}{2}, \frac{1}{2}[510]$
190	206.5				190.1	$\frac{7}{2}, \frac{3}{2}[512]$	190.7	$\frac{7}{2}, \frac{3}{2}[512]$
					257.4	$\frac{11}{2}, \frac{11}{2}[615]$	257.1	$\frac{11}{2}, \frac{11}{2}[615]$
261					263.1	$\frac{9}{2}, \frac{7}{2}[503]$		
			332	$\frac{7}{2}, \frac{1}{2}[510]$	332.7	$\frac{7}{2}, \frac{1}{2}[510]$	333.2	$\frac{7}{2}, \frac{1}{2}[510]$
336	14.9				(341.1)	$(\frac{9}{2}, \frac{3}{2}[512])$		
			418	$\frac{13}{2}, \frac{11}{2}[615]$	419.1	$\frac{13}{2}, \frac{11}{2}[615]$		
					(445.1)	$(\frac{9}{2}, \frac{9}{2}[505])$	(445.1)	$(\frac{9}{2}, \frac{9}{2}[505])$
					459.6	$\frac{11}{2}, \frac{7}{2}[503]$		
504	36.5	$(\frac{3}{2}, \frac{1}{2}\{\frac{3}{2}[512]-2_\gamma^+\}$ $+\frac{1}{2}[510])$	501	$\frac{3}{2}\{\frac{1}{2}[510]-2_\gamma^+\}$ $+\frac{3}{2}[512]$			501.4	$\frac{3}{2}\{\frac{7}{2}[503]-2\}$ $+\frac{3}{2}[501]$
					(508.5)	$\frac{9}{2}, \frac{1}{2}[510]$		
					(511.1)	$\frac{11}{2}, \frac{3}{2}[512]$		
					556.7	$\frac{9}{2}, \frac{9}{2}[624]$	556.7	$\frac{9}{2}, \frac{9}{2}[624]$
			593	$\frac{5}{2}^-$ of 501 keV band			586.3	$\frac{5}{2}^-$ of 501.4 keV band
							596.3	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
					618.0	$\frac{15}{2}, \frac{11}{2}[615]$		
667	21.9	$(\frac{5}{2}, \frac{5}{2}\{\frac{1}{2}[510]+2_\gamma^+\}$ $+\frac{5}{2}[512])$					664.1	$(\lvert K_0-2_\gamma^+\rvert$ on $\frac{1}{2}[510])$
					684.0	$\frac{13}{2}, \frac{7}{2}[503]$		
					(684.3)	$(\frac{11}{2}, \frac{9}{2}[505])$		
							711.2	$\frac{5}{2}, \frac{5}{2}[503]$

TABLE VI *(Continued)*

Present experiment			Ref. 46		Ref. 38		Ref. 50	
Energy	$\sum\sigma(\theta)\sin\theta$ [a]	L transfer, [b] and/or level assignment	Energy	Level assignment	Energy	Level assignment	Energy	Level assignment
730	113.3	$L=0,\ \frac{3}{2}^{-},\ \frac{3}{2}$	726	$\frac{3}{2}^{-}$ of $\lvert K-2_{\gamma}^{+}\rvert$			725.6	$(K+2_{\gamma}^{+}$? on $\frac{1}{2}^{-}$ [510])
		$\{\frac{1}{2}[510]-2\}$		(on $\frac{3}{2}[512]$)?				
		$+\frac{3}{2}[512]\}$		$+\frac{1}{2}[510]$				
					727.5	$\frac{11}{2},\ \frac{9}{2}[624]$		
745		$\frac{7}{2}\{\frac{3}{2}[512]+2_{\gamma}^{+}\}$	752	$\frac{7}{2}^{-}$ of 501				
	126.6 *	+ 1 q.p.		keV band				
759		unassigned			817.4	$\frac{17}{2},\ \frac{11}{2}[615]$		
			836	$(\frac{7}{2}^{-})\ K+2_{\gamma}^{+}$				
				(on $\frac{1}{2}[510]$?				
				$+\frac{5}{2}[512]$)	(886.0)	$\frac{13}{2},\ \frac{9}{2}[624]$		
			888	$\frac{7}{2}(\{\frac{3}{2}[512]+2_{\gamma}^{+}\}$				
				$+\frac{7}{2}[514])$				
			933	Unassigned	934.9	$\frac{15}{2},\ \frac{7}{2}[503]$	935	$\frac{3}{2}^{-},\ \frac{5}{2}^{-}$
			958	Unassigned			941.2	$\frac{5}{2}^{+}$ ($N=6$)
							987.3	$\frac{3}{2}^{-}$ [501]
			1006	Unassigned				
			1048	$\frac{9}{2}^{-}$ of 888 keV band				
1069								
			1080	$\frac{7}{2},\ \frac{7}{2}[514]$				
					1083.6	$\frac{19}{2},\ \frac{11}{2}[615]$		
							1090.3	$\frac{5}{2}^{-}$ of 987.3 keV band
			1110	Unassigned			1111.9	$\frac{1}{2}^{-},\ \frac{3}{2}^{-}$
1193								
					1210.6	$\frac{17}{2},\ \frac{7}{2}[503]$		
1227	37.8	$\frac{3}{2}[512]$ coupled						
		to 3^{-} (core)						
			1246	$\frac{9}{2},\ \frac{7}{2}[514]$				
			1354	Unassigned				
1369								
			1563	Unassigned				
			1619	Unassigned				
		$J^{\pi}=\frac{3}{2}^{-}$	1647	Unassigned				
1657	85.5	$L=0,\ \frac{3}{2}^{-}[512]$						
		(coupled to 0^{+} core)						

[a] The cross sections are in (μb/sr) summed from 10° to 60° with an interval of 5°.

[b] These assignments are discussed in the text.

have been tentatively assigned by Malmskog *et al.*[49] and Ahlgren and Daly[50] in the decay of ^{187}Ir. Similar assignments have also been made in the two recent studies of ^{187}Os by single nucleon transfer[46,48] reactions. Morgen *et al.*[48] have also done (*d*, *d'*) on ^{187}Os.

There is fair agreement in the literature about the rotational bands built on the lowest single quasiparticle states; the status of the collective vibrational excitations is much more uncertain and there are many conflicts in the literature. The situation is complicated because the collective vibrations of the core are strongly mixed with one quasiparticle states. By virtue of this mixing these states are seen in single nucleon transfer[46] and ^{187}Ir decay studies.[50] The two lowest bands, the $\frac{1}{2}^-$[510] and $\frac{3}{2}^-$[512] are very close and are strongly mixed in both ^{187}Os (Ref. 46) and ^{189}Os (Ref. 51), the $\frac{1}{2}^-$ band being lowest in ^{187}Os and the $\frac{3}{2}^-$ in ^{189}Os. We might also expect these bands to mix in the vibrations built upon them. The (*p*, *t*) data might help in sorting out the various components, since they will most strongly populate states containing target ground state one quasiparticle amplitudes and vibrations upon it.

The levels seen in this experiment along with the results of other experiments[38,46,50] are summarized in Table VI. Figure 8 shows the angular distributions of the $L=0$ transitions at 9.8, 77, 730, and 1657 keV. In Figs. 14 and 15 we have plotted the energies and intensities of ^{187}Os states populated in the (*d*, *t*), (*d*, *d'*), and (*p*, *t*) experiments along with our tentative band assignments (Fig. 14).

$\frac{1}{2}^-$*[510] and* $\frac{3}{2}^-$*[512] bands*. The bandheads of these two bands are separated by 9.8 keV and some of the higher members lie within a few keV of each other. These nearly degenerate members of the two bands are not resolved in the (*p*, *t*) experiment, but the angular distribution of the two lowest members of each band do give information on the relative cross section for the $L=0$ transitions to the $\frac{3}{2}^-$ states of each band.

The angular distribution of the peak at 10 keV as seen in Fig. 8 is very similar to the angular distribution of the pure $L=0$ ground-state transitions in the even-even Os nuclei; thus implying very little contribution of $L=2$. Therefore, we conclude that the ground-state bandhead $\frac{1}{2}^-$[510] is very weakly excited, with most of the strength being due to the transition to the $\frac{3}{2}^-$[512] bandhead. The total $L=0$ cross section to the $\frac{3}{2}^-$[512] bandhead is lower by a factor of ~1.5 relative to the ground state of the even-even nuclei. A calculation has been made, which will be discussed in Sec. V, to understand this decrease in intensity in terms of blocking and Coriolis mixing.

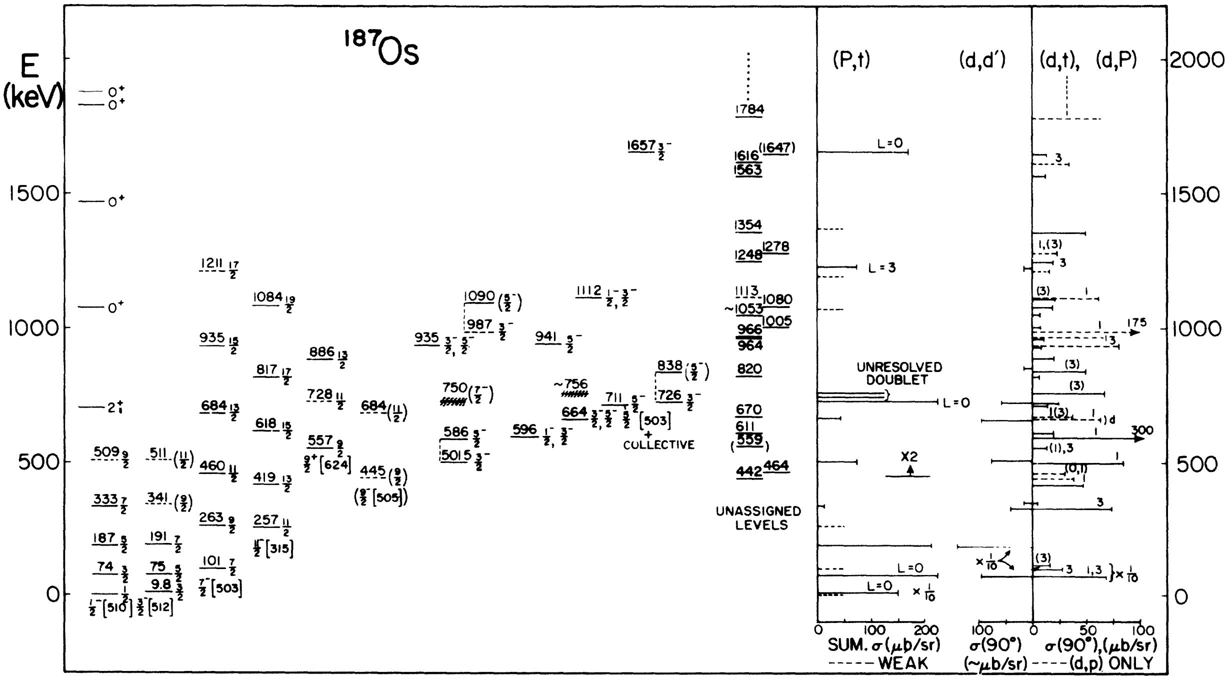

FIG. 14. The energy levels of ^{187}Os from Refs. 38, 46, 48–50, and this work. Also shown are cross sections in the reactions (*p*, *t*), (*d*, *d'*), (*d*, *t*), and (*d*, *p*) from this work and Refs. 46, 48, and 52. The average energies of 2_γ^+ and 0^+ excited states for neighboring nuclei are shown at the left. *l* values are shown for the (*d*, *t*) and (*d*, *p*) data.

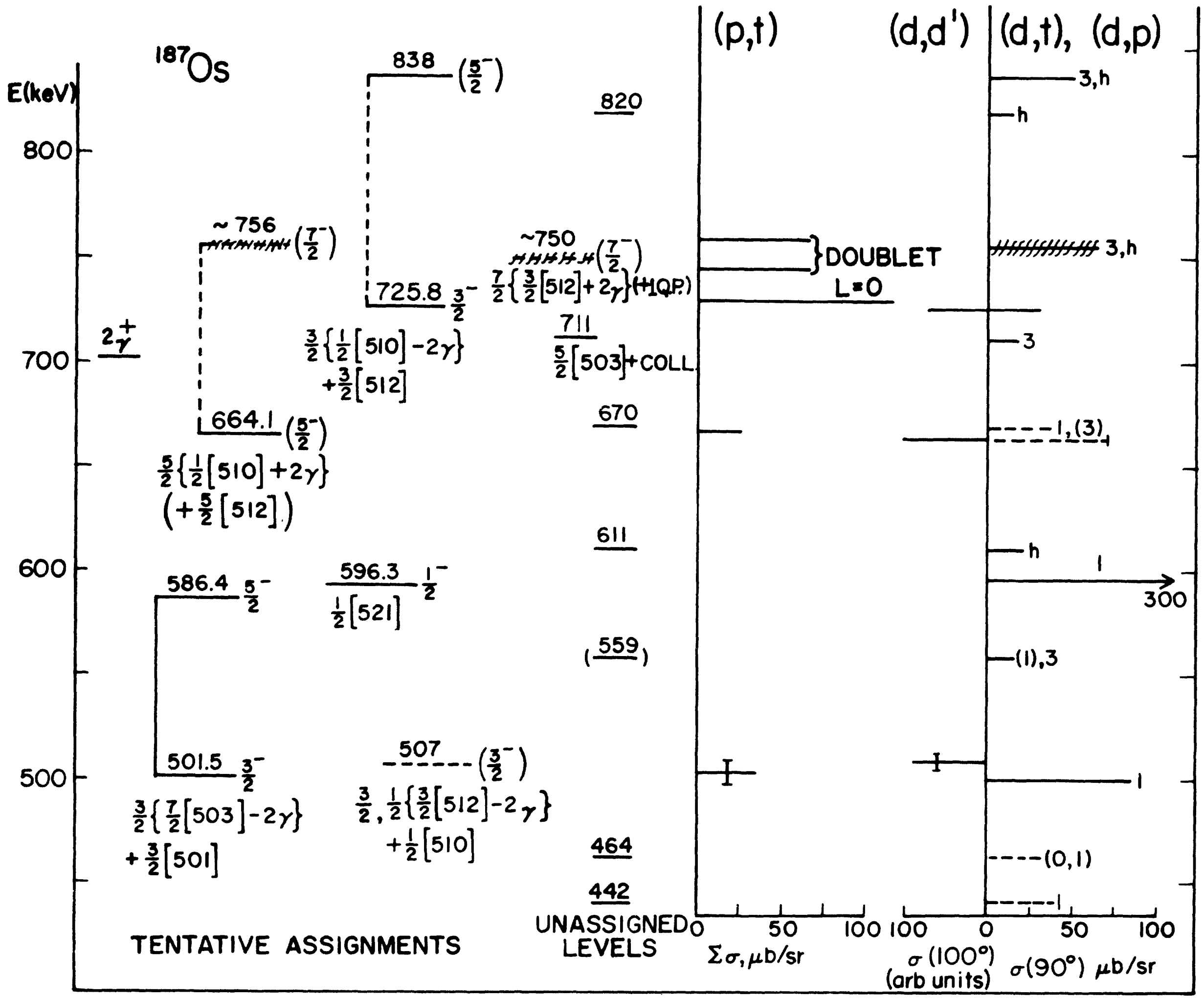

FIG. 15. Tentative assignments and cross sections for ^{187}Os levels in the region 450–850 keV. The (p,t) cross sections are sums as defined in the Table II caption. Single nucleon transfer cross sections (l values indicated; h: $l > 3$) are for (d,t) (Refs. 46 and 48, solid lines) unless the state is seen only in (d,p) (dashed lines, Ref. 48). Levels and cross sections known to correspond to members of lower bands (Fig. 14) are not plotted. The average energy of the γ vibrations for the neighboring nuclei is shown at the left (the lowest 0^+ excitations are at ~1070 keV for these nuclei).

As seen in Fig. 8 the angular distribution of the peak at 77 keV is characteristic of a dominantly $L=0$ transfer but the minimum at 40° is slightly filled in; which allows a rough estimate of the $L=2$ strength of around 15%. The $L=0$ transition can populate only the $\frac{3}{2}^-$, $\frac{1}{2}^-[510]$ state, whereas $L=2$ can populate both the $\frac{5}{2}^-,\frac{3}{2}^-[512]$ and $\frac{3}{2}^-,\frac{1}{2}[510]$ states. The relatively large amount of $L=0$ strength to the $\frac{3}{2}^-$, $\frac{1}{2}^-[510]$ state confirms the strong mixing expected for the two bands in either the target or residual nucleus or both. If both the initial and final bands were pure, an $L=0$ transition would be forbidden between $\frac{3}{2}^-,\frac{3}{2}^-[512]$ and $\frac{3}{2}^-$, $\frac{1}{2}^-[510]$ states by the K-selection rule. However, band mixing will give $L=0$ amplitudes between the target and both final $\frac{3}{2}^-$ states. Coriolis mixing calculations have been done for these bands in ^{185,187,189}Os and are discussed in Sec. V.

Higher members of these two bands appear as unresolved doublets at 190 and 336 keV but are not seen above this. We do see a state at 504 keV which is close to the tentatively assigned $\frac{9}{2}^-,\frac{1}{2}^-[510]$ and $\frac{11}{2}^-$, $\frac{3}{2}^-[512]$ states,[38] but in view of the strength of the lower members of these bands the intensity of this state is too high to be either or both of the above alone. The placement of the state at 504 keV is discussed further in this section.

$\frac{7}{2}^-[503]$ and higher bands. Two members of this band are populated rather weakly at 100 and 261 keV, respectively. Higher members have not

been seen. The state at 261 keV may be a mixture of the $\frac{11}{2}^+, \frac{11}{2}^+[615]$ and $\frac{9}{2}^-, \frac{7}{2}^-[503]$ states. Since these bands are populated only by two quasiparticle transfer, the cross sections to these states are, in general, expected to be small.

The higher members of these four low-lying bands are not excited with observable intensity, since they require an L transfer of 5 or more. The states at higher excitation are assigned to be collective excitations of the core coupled to various single quasiparticles and are discussed below.

Collective Bands. From the discussion of ^{185}Os it is recalled that the (p, t) reaction can be expected to populate $|K_0 \pm 2|$ γ vibrational states built on the target ground-state band (K_0). In the case of the ^{189}Os target, the $\frac{3}{2}^-[512]$ and $\frac{1}{2}^-[510]$ orbitals are both present with amplitudes of ~0.95 and 0.32, respectively (see Sec. V). We thus might expect to see four bands with $K = \frac{1}{2}, \frac{7}{2}, \frac{3}{2}$, and $\frac{5}{2}$ populated in (p, t) with $L = 2$ angular distributions. Conflicting assignments have been made for these bands by previous authors.[46,48–50] In what follows we will use the (p, t) and recent (d, d') data[48,52] in an attempt to reconcile the various experimental results. It should be said at once that no completely quantitatively satisfactory set of assignments is possible at present, partially because of the existence of close doublets which have not been resolved and excitation energy uncertainties in the charged particle experiments.

From the energies of the γ vibrations in ^{186}Os and ^{188}Os (767 and 633 keV, respectively) and the systematics of known $|K_0 \pm 2|$ bands, we expect these bands in ^{187}Os to be in the vicinity of ~400–800 keV. In this energy range we see five moderately strong transitions at 504 (36.5), 667 (21.9), 730 (113.3), and 745/759 (unresolved, 126.6) keV (the summed cross sections are given in parentheses).

The one quasiparticle bands which are expected in this region, and so far unassigned, are the $\frac{5}{2}^-[512]$, $\frac{7}{2}^+[633]$, and $\frac{1}{2}^-[521]$. The $\frac{7}{2}^-[514]$ and $\frac{3}{2}^-[501]$ bands are expected to lie somewhat higher (>1 MeV). Estimates of the summed (p, t) cross sections to these bands indicate that none are expected to be larger than 5–10 μb/sr except for the $\frac{1}{2}^-[521]$ which could be somewhat larger.

The 730 keV state is populated mostly by $L = 0$ and therefore has $J^\pi = \frac{3}{2}^-$; further, a small $L = 0$ component is possible in the 504 keV transition. In the (d, d') experiment of Morgen *et al.*,[48] strong $L = 2$ transitions were seen in this energy range at 659 and 724 keV. On this basis, they assigned the states (without preference as to order) to be the $|K_0 \pm 2|$ bandheads built on the $\frac{1}{2}[510]$ ^{187}Os ground state. Their (d, d') intensity pattern favors assigning $J = K = \frac{5}{2}$ ($K_0 + 2$ band) to the lower and $J = K = \frac{3}{2}$ ($|K_0 - 2|$band) to the upper state. This order is inverted relative to the usual systematics of the $|K_0 \pm 2|$ bands. However, the $|K_0 - 2| = \frac{3}{2}$ band is expected to mix strongly with the $\frac{3}{2}[512]$ one quasiparticle state which lies below the collective excitation, whereas the $K_0 + 2 = \frac{5}{2}$ band is expected to mix with the $\frac{5}{2}[512]$ one quasiparticle state, which has not yet been found but which is expected to lie higher.[42] This inverted order is also the same as calculated by Soloviev and Fainer[45] for these bands in ^{185}Os. Ahlgren and Daly[50] observe states at 664.1 keV ($\frac{3}{2}^-, \frac{5}{2}^-$) and 725.6 keV ($\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$) in the decay of ^{187}Ir whose decay properties are consistent with their being the $|K_0 \pm 2|$ vibrations in the ground state. If the states seen in the various experiments are the same (the energy accuracy in the charged particle experiments is generally ±3 – 5 keV) the evidence then suggests the 664.1 keV state is the $\frac{5}{2}^-$ bandhead of the $\{\frac{1}{2}[510] + 2\}$ and the 725.6 keV state the $\frac{3}{2}^-$ bandhead of the $\{\frac{1}{2}[510] - 2\}$ vibrations. The strong $L = 0$ transition which we see at 730 keV then implies a $\frac{3}{2}^-[512]$ one quasiparticle admixture of about 8% to the upper band. The lower band seen in (p, t) at 667 keV would be populated through the $\frac{1}{2}[510]$ component of the ^{189}Os ground state, and by two quasiparticle amplitudes to the $\frac{5}{2}[512]$ admixture expected. The single nucleon transfer experiments seem to be mostly consistent with this interpretation. The (d, t) strength should go almost entirely to the $J^\pi = \frac{7}{2}^-$ member of the $K = \frac{5}{2}$ band for a $\frac{5}{2}[512]$ admixture, which is possibly the state seen at 752 keV by Thompson and Sheline[46] and at 760 keV ($l = 3$) by Morgen *et al.*[48] and one member of the doublet seen in (p, t) at 745/759 keV. For the $|K_0 - 2| = \frac{3}{2}$ band the fingerprint associated with a $\frac{3}{2}[512]$ admixture implies a population of only the $\frac{3}{2}$ and $\frac{5}{2}$ members, in the ratio $\frac{1}{2}$, with observable intensity. Thompson and Sheline[46] see such cross sections at 726 and 836 keV. The data of Morgen *et al.*[48] is less clear on these states. It should be emphasized that the association of the upper states (~756 and 836 keV) with the $|K_0 \pm 2|$ bands is speculative and is suggested only by the single nucleon transfer data. Our assignments are also a modification of those of Thompson and Sheline,[46] but their data seem consistent with our interpretation which is strongly supported by the more recent (p, t) and (d, d') data.

The state seen in (p, t) at "504 keV" presents a more difficult problem. There is strong evidence from the γ-decay data[49,50] for a $\frac{3}{2}^-$ state at 501.5 keV and a $\frac{5}{2}^-$ member of the same band at 586.4 keV. Both states decay by strong $E2$ transitions to the $\frac{7}{2}[503]$ bandhead at 101 keV, and on this basis, Ahlgren and Daly[50] make this the $\{\frac{7}{2}[503]-2\}$, $K=\frac{3}{2}$ collective vibration, populated in the ^{187}Ir decay through a small $\frac{3}{2}[501]$ admixture. The state we see at 504 keV seems too strong to fit this assignment as the (p,t) transitions to the $\frac{7}{2}[503]$ band are themselves very weak and the occupation probability of the $\frac{3}{2}[501]$ orbit in the ^{189}Os ground state is unlikely to be more than a few percent. The state was not seen in the (d,d') experiment of Morgen et al.,[48] however, this region was obscured by a contaminant peak due to ^{189}Os. We have recently repeated the (d,d') experiment,[52] on ^{187}Os at 17 MeV, and tentatively see a state at 509.8 ± 2 keV with intensity comparable to the states at 664 and 726 keV, which we also see and which were discussed above. In the (d,p) and (d,t) experiments[46,48] very strong transitions were seen to states at 501 ($l=1$) and 596 (Ref. 48) or 593 (Ref. 46) keV ($l=1$ favored) with the upper state having several times the cross section of the lower. This fingerprint and strength is inconsistent with the character of the band as assigned by Ahlgren and Daly[50] for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states at 501.5 and 586.4 keV. The (d,t) fingerprint is, however, roughly that expected for the $\frac{3}{2}[512]$ orbit. On that basis, and the expectation of low-lying vibrational excitations in ^{187}Os, Thompson and Sheline[46] have assigned the states at 501, 593, and 752 keV to be the $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ members of the collective band, $\{\frac{1}{2}[510]-2\}$, which is expected to mix strongly with the $\frac{3}{2}[512]$ one quasiparticle state. However, if this interpretation is correct, the absolute cross sections seen in the (d,p) and (d,t) experiments are of such magnitude that they would imply a ~50% admixture of the $\frac{3}{2}[512]$ state, which would lead to a summed $L=0$ transition in the (p,t) reaction of ~700 μb/sr, far in excess of what is observed. Furthermore, such a band would not show the strong $E2$ transitions to the $\frac{7}{2}[503]$ band as observed for the states at 501.5 and 586.4 keV by Ahlgren and Daly.[50]

An alternative explanation of the reaction data would be to postulate a second state, in the vicinity of 507 keV. A possible choice for the character of the state, if the assignments above for the $|K_0\pm2|$ bands based on the $\frac{1}{2}[510]$ orbit are accepted, would be to make it the $\frac{3}{2}^-$ member of the $K=\frac{1}{2}$, $\{\frac{3}{2}[512]-2\}$ collective band, with the expected[45] $\frac{1}{2}[510]$ one quasiparticle admixture. The state would then be observed in (d,d') through the $\frac{1}{2}[510]$ component, and by strong $L=2$ and weak $L=0$, transitions in (p,t) of about the right magnitude from the dominantly $\frac{3}{2}[512]$ ^{189}Os ground state. In single neutron transfer, mainly the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states would be observed in the ratio of ~4/1, with the $\frac{1}{2}^-$ member having very low intensity. The large $l=1$ cross section seen in (d,t) at 593 keV and in (d,p) at 596 keV would then belong to the bandhead of the $\frac{1}{2}[521]$ one quasiparticle state at 596.5 keV as originally suggested by Morgen *et al.*[48] and which is consistent with the spin assignment of $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$ by Ahlgren and Daly.[50] The problems which then remain are as follows.

(1) The $\frac{1}{2}^-$ bandhead of the $\{\frac{3}{2}[512]-2\}$ band, which should be very weak in single neutron transfer, but somewhat stronger in (p,t), has not been identified. Weak $l=1$ (or possibly $l=0$) transitions were seen at 442 and 464 keV in the (d,p) experiment of Morgen *et al.*,[48] but these have not been confirmed by other experiments. The simple Alaga rule would predict equal strength in (p,t) to both the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of such a band. A weak (~$\frac{1}{3}$ of the 507 keV state) group was seen near 460 keV at a few angles in (p,t).

(2) The $\frac{1}{2}^-$ state should be populated in the decay of ^{187}Ir and should decay to the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of the $\frac{3}{2}[512]$ band. Such decays have not been seen.

(3) The $\frac{5}{2}^-$ member, unless it is close to the 596.5 keV state, should have been seen in (d,t) and (d,p), and weakly in (p,t). A candidate for the $\frac{5}{2}^-$ state has been seen at 559 keV in (d,t) by Morgen *et al.*[48] with about the right cross section and $l=3$ preferred, but this assignment makes the rotational parameter for the band rather small ($A\sim11$ keV), although the band has been tentatively identified in ^{185}W with $A\simeq7.5$ keV.[40]

(4) The state at 596.5 keV, if it is the $\frac{1}{2}[521]$ bandhead, should have been seen in (p,t) with an estimated cross section of ~ 10–20 μb/sr at 25°. No such state was seen. However, the absolute cross section calculations for two quasiparticle transitions are uncertain and are likely to be overestimates as discussed in Sec. V.

The remaining strength seen in (p,t) as an unresolved doublet at ~745/759 keV is close to a state seen in (d,t) at 752 keV by Thompson and Sheline,[46] who assign it $\frac{7}{2}$, $\frac{3}{2}$, $\{\frac{1}{2}[510]-2\}$, and at 760 keV ($l=3$) by Morgen *et al.*,[48] who make no assignment for the state. However, the evidence discussed above, especially the (d,d') and (p,t) experiments, favors placing the $\frac{3}{2}$, $\frac{3}{2}$ $\{\frac{1}{2}[510]-2\}$ bandhead at 725.6 keV, which would make the 752 (or 760) keV state too low to be a member of this band. Furthermore, its (d,t) cross section is too large by about a factor of 2 for it to fit the $\frac{3}{2}[512]$ fingerprint expected for the $\{\frac{1}{2}[510]-2\}$ band.

An alternative possibility for one member of the (p,t) doublet would be to make it the bandhead of the remaining $|K_0\pm2|$ group to be identified and expected to be strong in (p,t), namely, the $\frac{7}{2}$, $\frac{7}{2}\{\frac{3}{2}[512]+2\}$ state with a $\frac{7}{2}[503]$ or $\frac{7}{2}[514]$ one quasiparticle admixture to account for at least part of the (d,t) strength. However, the state is not seen in (d, p) and no other information exists to confirm this speculation.

We have no explanation at present for the other member of the doublet seen in (p, t) except possibly as the $\frac{7}{2}^-$ member of the $K=\frac{5}{2}, \{\frac{1}{2}[510]+2\}$ band as discussed above which would then account for the remaining (d, t) strength seen in the 752–760 keV region.

A summary of our revised (tentative) assignments for the states in this region is shown in Fig. 15.

1227 keV state. The only collective states seen in the even nuclei near this energy are the 3^- states at 1547 keV in ^{186}Os and 1412 keV ^{188}Os. The angular distribution of the 1227 keV state is very similar to the $L=3$ shapes shown in Fig. 11. This suggests the state is an octupole vibration coupled to the $\frac{3}{2}^-[512]$ target ground state.

1657 keV state. This state is populated by an $L=0$ transition (see Fig. 8) and therefore has $J^\pi=\frac{3}{2}^-$. The neighboring even isotopes of Os do have 0^+ states in this excitation range of comparable strength, so one would expect it to be the $\frac{3}{2}^-[512]$ particle coupled to a 0^+ excitation of the core.

The above assignments for ^{187}Os, especially for the γ vibrations, must be considered quite tentative because of experimental conflicts and the possibility of close doublets with different states being populated in the several reactions. A recheck of the (d, t), (d, d'), and (p, t) experiments with ≤5 keV resolution and ±1 keV energy calibration accuracy may be necessary to resolve these discrepancies.

IV. EXCITED $K=0$ AND $K=4$ BANDS IN EVEN Os NUCLEI

All of the $L=0$ transitions seen in the $^{186-192}$Os-(p, t) reactions are given in Table VII, along with absolute and relative cross sections. Our results for ^{188,190}Os are in agreement with those of Ref. 24 except as noted above for ^{188}Os. The most strongly populated 0^+ state is in ^{184}Os at 1042 keV and it is only 8.4% of the ground state which is considerably less than the intensity of the shape isomeric states seen in the samarium region.

It appears that the situation in the Os transition region is quite different from that around $N=88$ with respect to the existence of a shape isomeric state populated strongly in two-neutron pickup. In the Sm region the excited 0^+ states are believed to be a consequence of the sharp change in the β value between ^{150}Sm and ^{152}Sm and the onset of a secondary minima in the nuclear potential energy $V(\beta, \gamma)$ around $\beta=-0.2$ at $N=90$.[53]

TABLE VII. $L=0$ transitions in osmium nuclei.

Nucleus	Energy	$\sum_{\theta=10}^{60}\sigma(\theta)\sin\theta$	Relative strength
^{190}Os	0	2221.2	100
	913	104.9	4.7
	1551	39.3	1.8
	1734	139.1	6.3
^{188}Os	0	2254.6	100
	1087	128.1	5.7
	1480	82.3	3.7
	1705	26.1	1.2
	1765	20.5	0.9
	1820 [a]	(20) [a]	(0.9) [a]
^{187}Os	10	1494.8	b
	77	191.0	8.5
	730	113.3	5.0
	1657	85.5	3.8
^{186}Os [b]	0	(2068 ± 250) [a]	100
	1061		3.39
	1456		1.80
	1953		0.82
	1990		0.95
^{185}Os	0	939.8	b
	1070	155.7	6.9
	1213	74.9	3.3
^{184}Os	0	2277.8	100
	1042	190.7	8.4
	1982	~28	~1.2
	2268	~29	~1.2

[a] The data for ^{188}Os$(pt)^{186}$Os are taken from Ref. 24. The experiment was done at $E_p=18.0$ MeV. The value shown for the summed cross section has been estimated for $E_p=19.0$ MeV. The 1820 keV state in ^{188}Os is also taken from Ref. 24.

[b] The relative strengths for the odd-A nuclei are normalized to the average of the neighboring even-even ground-state cross sections.

In the Os region, one could possibly have shape isomers as a result of a secondary minimum in the γ direction. These would be strongly populated in (p, t) and (t, p) if the average value of γ were changing rapidly with N. The absence of strong $L=0$ transitions in the even Os isotopes indicates that deep secondary minima in the γ direction probably do not exist. In any case, since $\langle\gamma\rangle_{\text{av}}$ is changing only slowly[54] with N, the shape isomers would be weak in two-neutron transfer. The γ softness of the nuclear potential and the absence of deep minima in the γ direction have been found theoretically by several authors.[17-19]

Also in contrast to the Yb isotopes where a rapid decrease in the pairing gap Δ, with A, gives rise to strongly populated excited 0^+ states in ^{176}Yb$(p, t)^{174}$Yb,[26,55] the gap parameter is large and increasing slowly with A for the Os isotopes,[56] and thus no strong pairing vibrations are expected in (p, t).

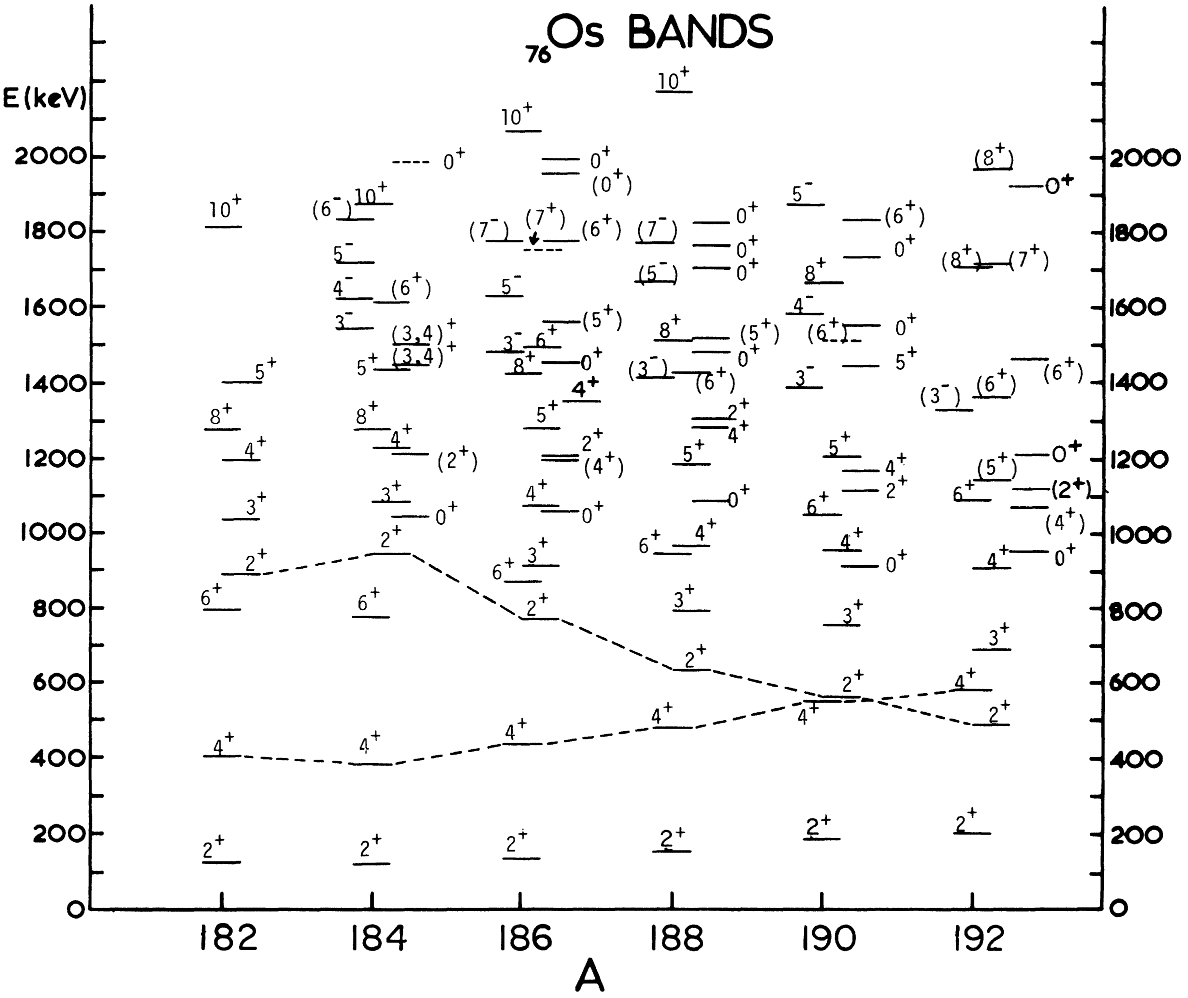

FIG. 16. Energy levels of the Os isotopes $A=182-192$. All of the known low-lying collective bands are included. A few levels above ~1500 keV have been omitted. The data are taken from references given in the text and from this experiment.

In Fig. 16, we have collected all of the known states below the pairing gap for $^{182-192}$Os from this experiment and earlier work. The γ softness of the Os nuclei is reflected in the fact that the energy of the second 2^+ state, if interpreted as a γ vibration, is low and is decreasing rapidly with increase in neutron number. In fact, Wilets and Jean[57] showed some time ago that for a γ-unstable potential (no restoring for in the γ direction) the 2_γ^+ state will be degenerate with the 4_g^+ rotational state as is observed at ^{190}Os. From Fig. 16, it is also clear that the heavy Os isotopes have systematically occurring low-lying $K=0$ and $K=4$ bands at roughly twice the energy of the lowest $K=2$ band.

It has been suggested previously[9,14,32,58] that the $K=0$ and $K=4$ bands can be described, at least approximately, as two-phonon $(K=2\pm2)$ γ vibrations of a symmetric rotor. In this model the lowest $K=2$ band is the one-phonon γ vibration. For a deformed harmonic vibrator, the two-phonon states will not occur at precisely twice the one-phonon energy because of the rotation-vibration interaction.[59,60] The vibration in the γ direction results in a nonvanishing moment of inertia about the 3 axis, even for an axially symmetric rotor, and thus leads to an additional contribution to the rotational energy. We have shown previously[32] that in the case of ^{188}Os and ^{190}Os the energies of the two-phonon states are fitted remarkably well by a simple formula first given by Davydov,[60] and later by Belyak and Zaikin,[59] from an approximate treatment of the Bohr-Hamiltonian[20] for an axially symmetric rotor. In the limit of zero coupling between the γ vibration and the other degrees of freedom, i.e., $\mu \rightarrow O(\hbar\omega_\beta \rightarrow \infty)$,

TABLE VIII. Possible two-phonon bands in $^{184-192}$Os and comparison with the Davydov model. The asterisk indicates that the best known experimental energies for 2_1^+ and 2_2^+ were used in the calculation and those for 0_2^+, 2_3^+, and 4_3^+ are listed.

Nucleus	J^π	Energy* (keV) Expt.	Davydov [a]
^{184}Os	0_2^+	1042	1766
	0_3^+	1982	
	(2_3^+)	1208	1886
^{186}Os [b]	0_2^+	1061	1398
	0_3^+	1456 [b]	
	(2_3^+)	1208	1535
	4_3^+	1352.0	1581
^{188}Os	0_2^+	1085.4	1111.2
	(2_3^+)	1305.0	1266.2
	(4_3^+)	1279	1317.9
^{190}Os	0_2^+	912.0	929.0
	2_3^+	1115.2	1115.8
	4_3^+	1163.2	1178.0
^{192}Os	(0_2^+)	956.3 [c]	772.3
	2_3^+	1125 [c]	978.1
	(4_3^+)	1069.3	1046.7

[a] Reference 60.

[b] Reference 24.

[c] References 61 and 61(a).

both authors obtain

$$E_\lambda(I) = h\omega_\gamma(2\lambda + \tfrac{1}{2}K) + A[I(I+1) - \tfrac{3}{4}K^2] + O(\mu^2), \tag{1}$$

where

$$\mu^2 = \frac{6A}{h\omega_\beta} = \frac{E(2_1^+)}{E(0_\beta^+)}, \quad \lambda = 0, 1, 2, \ldots .$$

This equation has been derived by treating the γ dependence of the collective potential energy in an approximate way and by assuming the β and γ dependence of the moments of inertia to be given by the hydrodynamic model.

In Table VIII, we show the experimental and calculated energies for the two-phonon 0^+, 2^+, and 4^+ states in $^{184-192}$Os using Eq. (1) with $\mu = 0$ and taking the rotational and vibrational parameters from experiment. The value of A is taken from $E(2_1^+)$ and that of $h\omega_\gamma$ from $E(2_2^+) = h\omega_\gamma + 3A$. The fit is almost perfect for ^{190}Os and good for ^{188}Os, but the experimental (tentative) 4_3^+ and 2_3^+ are in the wrong order for ^{188}Os. Definitive spin assignments for these states would be desirable. In the case of ^{192}Os (Ref. 61), 4_3^+ is within 23 keV of the predicted value. However, the 0_2^+ is predicted at 772 keV where no state has been seen. A state at 956 keV has been tentatively assigned 0^+, mainly on the basis of the absence of an observable decay to the ground state. However, its decay pattern is similar to that which would be expected for the 2^+ member of the $K = 0$ two-phonon band, in that the crossover transition ($n_\gamma = 2 \rightarrow n_\gamma = 0$) is strongly inhibited. Furthermore, its energy is close to the predicted value for the 2_3^+ state. It is planned to study the ^{190}Os$(t, p)^{192}$Os reaction to search for 0^+ states in this energy region.[61a]

The simple Davydov model starts to depart from experiment at ^{186}Os. The first excited 0^+ state is observed at 1061 keV, but there is an additional 0^+ state at 1456 keV which is close to the calculated value of 1399 keV. However, the observed 4_3^+ which has been designated $4_{\gamma\gamma}^+$ by Yamazaki, Nishiyama, and Hendrie[2] is quite low as compared with the prediction. The agreement with theory is even worse for ^{184}Os. The lowest excited 0^+ states are at 1042 keV, which is much too low, and at 1982 keV, too high, to qualify as two-phonon γ vibrations for which the simple model predicts 1766 keV. This behavior for the lighter isotopes is not surprising, since the 2_γ^+ is now quite high and thus the energy range where one expects two-phonon γ vibrations is very near the pairing gap 2Δ. The lowest states in ^{184}Os and ^{186}Os are evidently either β vibrations or are similar to the pairing states seen in Yb, Hf,[26] and W.[64] Nothing else is known about these 0^+ states as they have not been seen in previous experiments.

The two-phonon picture for the excited $K = 0$ and $K = 4$ bands in ^{188}Os and ^{190}Os is further supported by the (p, t) intensity pattern as compared with that observed in the Pd-Cd region and by the inhibition of the crossover ($n_\gamma = 2 \rightarrow n_\gamma = 0$) relative to the stopover ($n_\gamma = 2 \rightarrow n_\gamma = 1$) $B(E2)$'s.[31a] This evidence has been discussed in our earlier paper.[32] γ transition rates have not been determined for the remaining Os excited $K = 0$ and $K = 4$ bands. It is observed that the 4_3^+ states do not decay to the ground band but only to the $K = 2$ one-phonon band, which would be required in any case for $E2$ transitions, by the K-selection rule.

The main difficulty with the two-phonon picture is the strong population of the ^{190}Os 1115 keV, 2_3^+ state in the (d, p) reaction as pointed out by Thompson *et al.*,[34] although the corresponding state at 1305 keV in ^{188}Os is not seen in (d, t). The other objection, which has been raised by Yamazaki,[9] seems to be based on an error in applying the equations of Davydov, Rostovky, and Chaban[62] to calculate the stopover to crossover ratio in ^{188}Os. As mentioned in an earlier paper,[32] the lowest order estimates of Belyak and Zaikin[59] are in fair agreement with experiment for this ratio in ^{188}Os and ^{190}Os. There are also serious objections to the theoretical treatment of the anharmonicities in the γ-vibrational modes, along the lines of Davydov[60] and Belyak and Zaikin,[59] since the hydrodynamic model has been used for the γ dependence of the moments of inertia and anharmonic terms in the kinetic and potential energies have been left out.[63]

It should be noted that Kumar and Baranger[17] in their pairing plus quadrupole dynamic collective model, obtain 0_2^+ and 2_3^+ states in ^{188}Os and ^{190}Os near or a bit lower than the observed energies and with γ-decay properties similar to those found experimentally. However, their predicted energies for the 0_2^+ states in ^{186}Os and ^{188}Os are about 260 keV too low and they do not extend their calculations to include the $K=4$ bands.

V. PAIRING FORCE AND CORIOLIS MIXING CALCULATIONS FOR $L=0$ TRANSFERS

A. Pairing force calculations

The summed cross sections and energies for all of the observed $L=0$ transitions are given in Table VII. The summed cross sections for the lowest (the ground state except for ^{187}Os) $L=0$ transitions are plotted in Fig. 16 along with the results of predictions from pairing force Coriolis mixing and distorted-wave Born-approximation (DWBA) calculations which are discussed below.

The pairing force calculations make use of three programs written by Bayman,[65] SPRING, NORTON, and TWOPAR. The program SPRING[66] does an exact diagonalization of a constant matrix element monopole-pairing Hamiltonian for the lowest n, $J=0$ states (n is usually taken to be 30) of an arbitrary number of particles in a given set of single-particle levels. The program calculates energies, wave functions, and two-particle transfer spectroscopic factors. One quasiparticle states in odd-A nuclei can be calculated by running the program with the appropriate orbital omitted. Two effects of the missing orbit will then be accounted for, namely, the blocking, which causes a rearrangement of the remaining particles, and the loss of the blocked orbit in the two-particle transfer.[67] If Nilsson single-particle states are used in SPRING, program NORTON can be used to convert the transfer spectroscopic amplitudes from a Nilsson to a spherical shell model basis. Program TWOPAR has been described elsewhere[26] and is a general zero-range DWBA program for calculating two-particle transfer cross sections, given optical model parameters and spherical spectroscopic factors.

Using these programs we have calculated cross sections for the lowest $L=0$ transitions for all of the Os nuclei and have obtained estimates for cross sections to higher $L=0$ monopole pairing states. In program SPRING, the values of the pairing force strength G were taken to be 0.12, 0.24, and 0.30 and the single particle energies used were those of Ogle *et al.*,[42] version I. For $A \geqslant 187$ it was necessary to use the levels given for ^{187}Os. Fifteen single-particle levels around the Fermi surface were used.

In using the program SPRING it was found that the conventional value of $G \simeq 24/A$ used in large space BCS calculations was too small to reproduce the experimental odd-even mass difference (P_n) and one quasiparticle energies. For example with $G=0.12$ a value of $P_n=0.135$ MeV was obtained for ^{186}Os, whereas $G=0.3$ gave $P_n=0.570$ MeV which is close to but still slightly smaller than the experimental value of 0.740 MeV. The lowest few one quasiparticle energies were quite well reproduced for $G=0.3$ but were much too high for $G=0.120$. Presumably the large value of G needed in SPRING, as compared with the BCS solution, is because the usual BCS wave functions have larger amplitudes for distant configurations than the truncated exact diagonalization of SPRING.

In program TWOPAR the optical model parameters were the same as quoted in Ref. 26 but modified using the Becchetti-Greenlees[27] prescription to extrapolate to the Os region. The $L=0$ fits to the data were very good and the cross sections were summed in the same way as the data for comparison.

The results of the calculation for $G=0.12$ and 0.3 MeV are shown in Fig. 17 along with the data. For both values of G, the calculations were normalized to experiment at ^{188}Os. Except for ^{184}Os (final nucleus) the fit is quite satisfactory for $G=0.3$. The large reduction in the calculated (p,t) cross section to ^{184}Os, relative to the heavier isotopes, is entirely a Coulomb barrier effect, due to the large negative Q value (Table I) and thus is more sensitive to the optical model parameters used than is the case for the heavier isotopes. In the case of ^{189}Os$(p,t)^{187}$Os the calculation, in which only the $\frac{3}{2}^-[512]$ orbit was blocked, gave a value of 1829 μb/sr for the summed cross section which was not in good agreement with the experimental value of 1495 μb/sr. However, the $\frac{3}{2}^-$ states in both nuclei contain appreciable amplitudes of $\frac{3}{2}^-$, $\frac{1}{2}^-[510]$ due to band mixing as discussed below. In Fig. 18 we have plotted the amplitudes for $L=0$ pair pickup from individual Nilsson orbits for average parameters

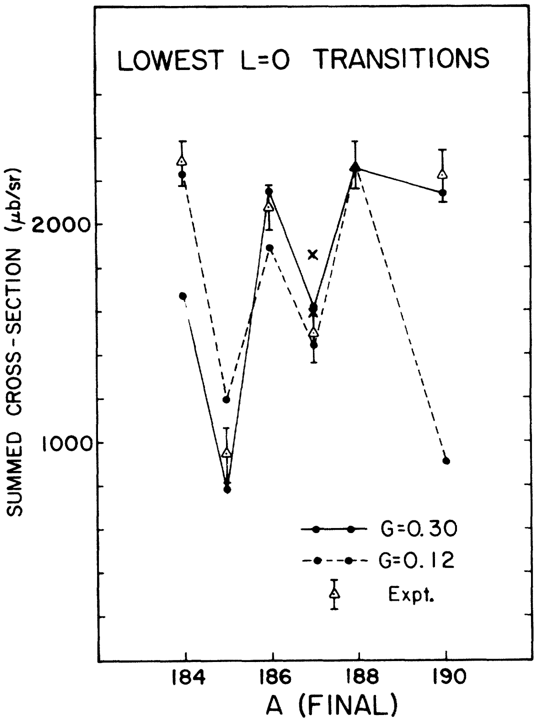

FIG. 17. Summed cross sections for ground (or lowest, favored) $L=0$ (p,t) transitions in the Os isotopes. Data points are shown as open triangles. The pairing force calculations for $G=0.120$ and $G=0.300$, as discussed in Sec. V, are shown by solid dots connected by lines. The crosses at ^{187}Os show the calculated values neglecting band mixing in ^{187}Os and ^{189}Os.

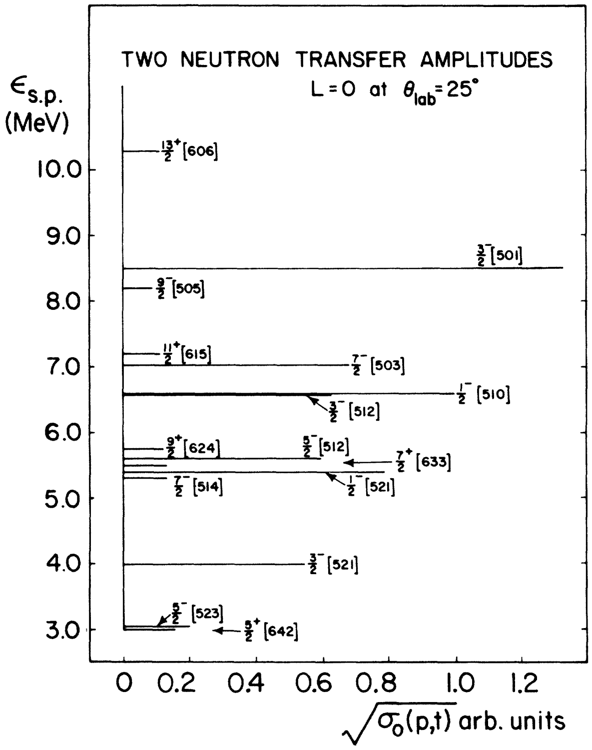

FIG. 18. Two neutron $L=0$ pickup amplitudes calculated with NOTRON and TWOPAR for $A=190$ and $Q=-6$ MeV for pure Nilsson pair states $(\eta=4)$. The single-particle energies are for ^{187}Os from Ref. 42.

in the Os region. It is seen that the $\frac{1}{2}^-[510]$ orbit has almost twice the amplitude, for $L=0$ pair transfer, as the $\frac{3}{2}^-[512]$ orbit. Because of the admixed $\frac{1}{2}^-[510]$ component in ^{187}Os and ^{189}Os, the reduction due to the partial blocking of this orbit will be greater than the calculated value neglecting bandmixing. This effect can be seen in both the experimental and calculated $^{187}\text{Os}(p,t)^{185}\text{Os}$ $L=0$ cross sections where the $\frac{1}{2}^-[510]$ orbit is blocked. A calculation using the Coriolis mixed wave functions given in Table IX brings the calculated value down to 1623 μb/sr, in better agreement with experiment.

The estimates of cross sections, expected for two quasiparticle transitions in odd-A nuclei, quoted in Sec. III, were also obtained with these programs. However, the absolute cross sections given were determined by normalizing the TWOPAR output to the experimental cross sections for ground state, $L=0$, transitions and thus may be somewhat overestimated since the truncated pairing calculations of SPRING are likely to underestimate pair correlations in the ground states.

The pairing force calculations of SPRING also give energies and spectroscopic factors for higher 0^+ pairing states. For the Os isotopes the lowest of these lie in the range of 1.6–1.8 MeV and have predicted strength of $<1\%$ of the ground state for ^{184}Os and ^{186}Os and ≈4 and 8% for ^{188}Os and ^{190}Os. However, the excited 0^+ intensities depend critically on the location of the single-particle levels and these are not known for $A \geqslant 187$. In any case, the excited 0^+ states we have observed lie much lower in energy and so cannot be understood as pure monopole pairing excitations, although quadrupole residual forces will lower the energy of these states and increase their strength in (p,t) reactions.[68,69]

B. Coriolis mixing calculations

The division of $L=0$ strength, in the $^{189}\text{Os}(p,t)^{187}\text{Os}$ reaction, between the two lowest $J^\pi=\frac{3}{2}^-$ states (9.8 and 74.3 keV) provides a sensitive, and fairly direct, measure of the K mixing in the two nuclei.[70] For a simple two-band case, in the approximation of equal $L=0$ transfer amplitudes from the even core for the two components ($K=\frac{1}{2}$ and $\frac{3}{2}$ in this case), the ratio of the "unfa-

TABLE IX. Results of Coriolis mixing calculations for Os isotopes. The amplitudes for the $\frac{3}{2}$[512] components are designated, $a_{3/2}$. The amplitude of the $\frac{1}{2}$[510] component is $a_{1/2} = \pm (1-a_{3/2}),^{1/2}$ (except for nine-band case), the sign being chosen to satisfy orthogonality. The rms deviation from experiment for the calculated energies, δE_{rms}, is given below, along with the parameters used (see text).

	^{185}Os			^{187}Os			^{189}Os						
	Two-band			Two-band			Two-band			Nine-band[d]			
State $I,K[Nn_Z\Lambda]$[a]	E_{exp}[b] (keV)	E_{calc} (keV)	$a_{3/2}$	E_{exp}[b] (keV)	E_{calc} (keV)	$a_{3/2}$	E_{exp}[c,d] (keV)	E_{calc} (keV)	$a_{3/2}$	E_{calc} (keV)	$a_{3/2}$	$a_{1/2}$	$a'_{1/2}$
$\frac{1}{2}$, $\frac{1}{2}$[510]	0	0	0	0	0	0	36.2	36.2	0	32.0	0	0.998	0.065
$\frac{3}{2}$, $\frac{1}{2}$[510]	37.4	35.7	0.358	74.3	74.3	−0.560	95.2	95.2	−0.319	99.4	−0.354	0.923	−0.141
$\frac{5}{2}$, $\frac{1}{2}$[510]	97.4	100.2	0.467	187.4	182.4	−0.617	233.6	190.3	−0.431	236.7	−0.521	0.843	0.090
$\frac{7}{2}$, $\frac{1}{2}$[510]	198.1	195.1	0.526	333.5	326.1	−0.642	365	319.8	−0.496	362.4	−0.503	0.810	−0.275
$\frac{9}{2}$, $\frac{1}{2}$[510]	317.8	321.2	0.563	(508.4)	505.6	−0.656	620	483.1	−0.537	620.3	−0.619	0.761	0.095
$\frac{11}{2}$, $\frac{1}{2}$[510]	476.5	478.8	0.587	···	721.1	−0.665	793	679.7	−0.566	787.7	−0.550	0.731	−0.367
$\frac{3}{2}$, $\frac{3}{2}$[512]	127.9	129.5	−0.934	9.75	9.72	0.828	0	0	.948	0	0.932	0.361	0.036
$\frac{5}{2}$, $\frac{3}{2}$[512]	222.4	224.1	−0.884	75.0	81.6	0.786	69.5	69.5	.902	72.2	0.845	0.497	0.189
$\frac{7}{2}$, $\frac{3}{2}$[512]	351.7	351.7	−0.850	190.7	189.9	0.767	219.4	170.4	.868	221.4	0.595	0.382	0.024
$\frac{9}{2}$, $\frac{3}{2}$[512]	(519± 5)[e]	511.8	−0.826	(341.6)	333.4	0.755	346	303.5	.843	342.6	0.757	0.564	0.290
$\frac{11}{2}$, $\frac{3}{2}$[512]	(707.5)	704.0	−0.809	(511.7)	515.0	0.747	594	469.0	.825	600.0	0.739	0.563	0.027
δE_{rms} (keV)		3.3			4.6			74.4			3.7		
A (keV)		15.9			18.0			16.46					
a		0			0			0			See Ref. 73		
ϵ (keV)		117.5			30.0			−26.49					
A_K (keV)		18.1			17.3			16.61					

[a] Dominant component.

[b] Reference 38.

[c] Reference 75.

[d] Reference 73. Only the $\frac{3}{2}$[512] ($a_{3/2}$), $\frac{1}{2}$[510] ($a_{1/2}$), and $\frac{1}{2}$[521] ($a'_{1/2}$) components are listed here.

[e] This experiment.

vored” (dominant $K=\frac{1}{2}$) to the “favored” (dominant $K=\frac{3}{2}$) (p,t) cross sections is just $\tan^2\alpha$, where α is the angle between the target and residual (favored) state vectors. Thus the (p,t) ratio measures the difference between the bandmixing in the initial and final states. A correction to this simple relation can be made if the core $L=0$ amplitudes are not equal, as discussed above, for the $\frac{1}{2}$[510] and $\frac{3}{2}$[512] one quasiparticle states.

Two-band Coriolis mixing calculations have been made as follows: Sodan *et al.*[38] for ^{185}Os; Malmskog *et al.*,[49] Morgen *et al.*,[48] and Thompson and Sheline[46] for ^{187}Os; McGowan, Stelson and Robinson,[71] Craseman et al.,[72] and Malmskog, Berg, and Backlin[51] for ^{189}Os. In the case of ^{187}Os, the two-band calculations[46,48] give a satisfactory fit to the energies, $B(E2)$ values, and single-neutron transfer spectroscopic factors for the lowest four or five states of each band. For ^{185}Os only the energies are available, but the fit is slightly better than for ^{187}Os. For ^{189}Os, it was noted some time ago[71,72] that the excitation energies and electromagnetic transition rates could not be fitted with a two-band calculation. However, Morgen et al.[73] have recently shown that a satisfactory explanation for most of the energies, $B(E2)$ values, and single-neutron transfer data for the odd-parity bands in ^{189}Os can be given in terms of the (axially symmetric) Nilsson model with pairing, rotation, and Coriolis coupling. Nine single-particle states are included in their calculations, the $\frac{1}{2}$[521] and $\frac{3}{2}$[501] being the most important additions in accounting for the behavior of the lowest (mainly) $K=\frac{1}{2}$ and $\frac{3}{2}$ bands.

We have repeated the two-band Coriolis coupling calculations for ^{185,187,189}Os, using the equations of Kerman,[74] choosing the parameters to fit the energies of the lowest four states of each band.

For the mixing of the $\frac{1}{2}$[510] and $\frac{3}{2}$[512] bands the parameters are the rotational and decoupling constants A_1, A_3, and a, the energy difference between the unperturbed bandheads $\epsilon = E_0(\frac{3}{2}) - E_0(\frac{1}{2})$, and the off-diagonal matrix element A_k. In agreement with previous authors, we have found the best fits to the energies close to the conditions $A_1 = A_3 = A$ and $a = 0$. Our results for the energies and mixing amplitudes are given in Table IX, together with the nine-band values of Morgen *et al.*[73] The parameters found for ^{185}Os are close to those of Sodan et al.,[38] and for ^{187}Os the same as found by Thompson and Sheline,[46] although our amplitudes and $B(E2)$ values differ slightly from theirs. Our calculated $B(E2)$ values for ^{187}Os are in somewhat better agreement with experiment[49] than those of Thompson and Sheline[46] and Malmskog et al.[49] In the case of ^{189}Os it was impossible to fit the third and higher members of the two bands with any reasonable choice of the five parameters, as had been previously noted. The two-band parameters shown in Table IX for ^{189}Os were obtained by fitting exactly the two lowest levels of each band, with $A_1 = A_3$ and $a = 0$.

The ^{189}Os(p, t)^{187}Os cross-section ratio to the $J^\pi = \frac{3}{2}^-$ states of each band, calculated with the amplitudes of Table IX, and using $\sigma_0^{(1/2)} = 0.799\sigma_0^{(3/2)}$ for the ratio of the blocked ($K = \frac{1}{2}$ and $\frac{3}{2}$) $L = 0$ cross sections, is 0.097 (unfavored to favored band) for the two-band wave functions and 0.072 using the nine-band wave functions for ^{189}Os. This is to be compared with the experimental value of 0.128. Agreement with experiment can be obtained by a small change in the mixing amplitude $a_{3/2}$ of either the ^{189}Os ground state or the ^{187}Os $J = \frac{3}{2}^-$ states. For example, if the nine-band solution[73] is used for ^{189}Os, a value of $a_{3/2} = 0.78$ (rather than 0.828) brings exact agreement, illustrating the sensitivity of the (p, t) ratio to the mixing. The two-band solutions of Malmskog et al.[49] for ^{187}Os ($A_1 = A_2 \simeq 30$, $A_k \simeq 90$ keV) obtained by fitting only their $B(E2)$ values cannot give the correct energies. Furthermore, their unrealistically large value of A_k would predict too much mixing to be consistent with the (p, t) data. The two-band parameters of Morgen *et al.*[48] for ^{187}Os (derived from their Table V) are close to ours and give (p, t) ratios of 0.077 and 0.055 when used with the two-band or nine-band ^{189}Os solutions, respectively.

The mixing amplitude for the $\frac{1}{2}$[510] component of the ^{189}Os ground state, found here to agree with the (p, t) ratio, is in agreement with the value deduced recently ($a_{1/2} \sim 0.3$) by Thompson *et al.*[76] from an analysis of the ^{189}Os(d, t)^{188}Os reaction.

In principle, the (p, t) cross sections ($L \geq 2$) can be used to test the mixing amplitudes for other spin members of the two bands in ^{185}Os and ^{187}Os. This is, however, quantitatively much more complicated than for the $L = 0$ transitions, since two quasiparticle as well as multistep inelastic amplitudes must be calculated.

VI. SUMMARY

The (p, t) reaction has been used to study five isotopes of Os with $A = 190$, 188, 184, 187, and 185. In the even isotopes several new $K^\pi = 0^+$ bands have been seen with varying intensities, the strongest one being the 1042 keV state in ^{184}Os with a strength of 8.4 % of the ground state. Thus the conclusion has been drawn that shape isomeric excited states such as those that are strongly populated in the (t, p) and (p, t) reactions in the transition region around $N = 88$ are not excited in the Os isotopes.

It has been shown that the low-lying $K = 0$ and $K = 4$ bands in ^{188}Os, ^{190}Os, and possibly ^{192}Os, fit quite well a two-phonon γ-vibrational description. However, the two-phonon γ states, if they exist, have not been identified for ^{186}Os and ^{184}Os. The lowest 0^+ states observed for these nuclei seem to be related to the pairing or β-vibrational excitations seen in the W and Hf nuclei. These results are in agreement with earlier theoretical predictions that the Os isotopes are increasing in γ softness with increase in mass number and that there are no deep secondary minima in the potential energy surfaces which can give rise to strongly populated shape isomers.

In the odd-N nuclei, ^{185}Os and ^{187}Os, in addition to the low-lying rotational bands, several collective vibrational states have been seen. We have tentatively identified the $|K_0 - 2|$ and $K_0 + 2$ γ vibrational bandheads in ^{185}Os at 599 and 802 keV. Two new higher $K = \frac{1}{2}$ bands, at least one of which is probably formed by coupling the $\frac{1}{2}$[510] one quasiparticle state to a 0^+ excitation of the core have been seen in ^{185}Os. Four states populated in ^{187}Os have been interpreted as $|K_0 - 2|$ and $K_0 + 2$ collective vibrational excitations based on the $\frac{1}{2}^-$[510] and $\frac{3}{2}^-$[512] single quasiparticle states, both of which occur in the target ground state as a result of bandmixing.

Bandmixing calculations have been done to fit the energies of the low-lying rotational members of the $\frac{1}{2}^-$[510] and $\frac{3}{2}^-$[512] bands in ^{185}Os, ^{187}Os, and ^{189}Os. The results of these calculations were used to fit the (p, t) intensities for the $\frac{3}{2}^-, \frac{1}{2}^-$[510] and $\frac{3}{2}^-, \frac{3}{2}^-$[512] states in ^{187}Os. These calculations demonstrate the sensitivity of (p, t) cross-section ratios to admixed amplitudes in the wave functions of the initial and final states.

The cross sections to the favored bands in the odd isotopes (equivalent to ground-state cross sections in the even isotopes) are significantly lower than the ground-state cross sections in the even isotopes. This decrease in intensity has been accounted for by a blocked pairing force calculation, but it was necessary to use bandmixed wave functions in the case of $^{189}\mathrm{Os}(p,t)^{187}\mathrm{Os}$.

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