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^{188,190,192}Os(t,p) reaction at 15 MeV

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A study of the heavier osmium isotopes ^{190}Os, ^{192}Os, and ^{194}Os has been made with the (t,p) reaction using a 15 MeV triton beam. The osmium nuclei may be considered as transitional nuclei going from a deformed to a spherical shape with increasing neutron number and the (t,p) reaction is used to probe this change. The study principally investigates the position and strength of the 0^+ states, a number of new such states being observed. The nucleus ^{194}Os is also reported in some detail for the first time with 15 excited levels observed and 7 spin assignments made.

[NUCLEAR REACTIONS ^{188,190,192}Os(t,p), E_t=15 MeV. Measured $\sigma(\theta)$; enriched targets; DWBA calculations deduced J,π.]

I. INTRODUCTION

The osmium nuclei are known to represent a rather slow transition region between deformed and spherical nuclei as they are situated near the top of the deformed nuclides and just below the spherical nuclides surrounding ^{208}Pb. In addition, the quadrupole deformations change from prolate to oblate with increasing mass. All of these features suggest that a study of the neutron rich nuclei with the two neutron stripping reaction is appropriate to help understand the various interplays between these complex nuclear modes. In particular, the nucleus ^{194}Os which lies two neutrons above the heaviest stable isotope has only been studied by double neutron capture with but three excited states reported.[1] The extension of systematic two neutron transfer reactions to this heavier nucleus should help to reveal how fast the transition from deformed to spherical shapes is taking place.

To study this transition region, we have used the (t,p) reaction on targets of ^{188,190,192}Os. This selection permits exploration of the heaviest osmium isotope possible with this reaction and provides data on a series of nuclei to establish a systematic trend of level energies and differential cross sections. It also provides an overlap with several two neutron pickup reaction studies so that such systematics can be studied even further.[2,3] In the analysis of the data, the 0^+ states are emphasized both because of their clear experimental signature as well as the specific information they give regarding the various nuclear modes. The role of two nucleon transfer studies in the study of known transition nuclei[4] and in showing new regions of shape transitions[5] has been pointed out before as being a valuable tool.

There is also the theoretical interest in the change from prolate to oblate shapes and the possible role this may play in disturbing the pairing correlations. Such an effect has previously been noted experimentally in the (p,t) reaction in the actinide nuclei by the observation of a consistent excited 0^+ state near 1 MeV over a range of nuclei and with approximately constant strength.[6] The theoretical explanation of this has been the occurrence of oblate orbitals below the Fermi surface with prolate at and above this surface.[7] The opposite effect is expected in the osmium nuclei with the oblate orbitals being somewhat above the Fermi surface, producing a possible effect on (t,p) reactions to 0^+ states not seen, or weakly excited, by (p,t) reactions. In the actinides, no excited 0^+ states were seen except at the $N=152$ subshell closure.[8]

II. EXPERIMENTAL PROCEDURE

The experiment was performed using a 15 MeV triton beam from the Los Alamos Scientific Laboratory's FN Van de Graaff accelerator. Beam currents of approximately 400 nA were employed with the beam focused onto a $\frac{3}{4}\times 3$ mm spot on the targets. The targets were isotopically separated osmium metal which had been evaporated on a C backing with an Os thickness of 150–200 μg/cm^2. The isotopic purity of the targets was 94.47% for ^{188}Os, 95.46% for ^{190}Os, and 99.06% for ^{192}Os.

The reactions took place in a 50 cm scattering chamber where the targets formed the object for a quadrupole-dipole-dipole-dipole (Q3D) spectrometer.[9] The reaction protons were detected in a

1 m helix detector[10] located in the focal plane of the Q3D. This detector measured the magnetic rigidity, as well as the particle type, with sufficient spatial accuracy to produce an energy resolution of 10–15 keV. The spectrometer was placed at nine different scattering angles ranging from 12° to 60° in 6° steps.

A monitor detector of known geometry was used to accurately measure relative target thicknesses as well as establish an absolute cross section scale using an optical model prediction for the elastic triton scattering.[11]

Energy calibration was accomplished by using known levels in ^{190}Os (Ref. 12) and ^{192}Os (Ref. 13) to provide input to a fitting routine which then provided a calibration polynomial for unknown peaks. In the case of ^{194}Os, where only the first four states are tentatively assigned,[1] exposures of both ^{188}Os and ^{190}Os targets were made at exactly the same magnetic field and detector position and the known levels from ^{190}Os and ^{192}Os used to calibrate the ^{194}Os levels.

TABLE I. Levels populated in the ^{188}Os$(t,p)^{190}$Os reaction.

Present experiment					
Level No.	E_x (keV)	J^π	$d\sigma/d\Omega$ 30° (μb/sr)	Previous results[a,b,c,d] E_x	J^π
0	0	0^+	285	0	0^+
1	187 ±5	2^+	17	186.7	2^+
2 & 3	548 + 558	$2^+(4^+)$	24	547.8, 558.2	2^+, 4^+
				756.1	3^+
4	912	0^+	6	912.4	$0^{(+)}$
5	956		2.2	955.6	4^+
6	1113	(2^+)	2.2	1115.2	2^+
7	1164	(4^+)	5.6	1163.5	4^+
8	1388		7.5	1387.5, 1383.3	3^-, (1, 2)
9	1436		3.6	1436.2	(2^+)
				1546.1, 1570	$(0,3)^+$
				1583.6, 1666.9	4^-, 8^+
10	1676 ± 8		5.8	1678.3, 1681.6	$[(1), 2^+], 5^-$
11	1710		9.5	1705.8, 1708.3	$10^-, [3, 4^+]$
12	1734	0^+	12	1734.4	0^+
13	1776		5.0		
				1823.2, 1836.2	6^+
				1857	$(1,3)^+$
14	1868		6.2	1870.7, 1872	5^-
				1887, 1903.3	(4^-)
				1910, 1912	$(1,3)^+$
15	1926		8.5		
				1946, 1963.9	$(4,5)^+$
16	2006 ± 10		16	1995.6	$(2,3)^+$
17	2054		11	2054	
				2068.8	(5^+)
18	2113		14	2112, 2258	(5, 6)
				2130, 2161	
19	2176		11	2180	
				2212, 2258	
20	2299		(41)	2298	
				2330	
21	2358		16	2352.4, 2366	(2, 3)
22	2400		18	2417	
23	2451	(0^+)	35	2450	
24	2484		6.5	2476	
25	2526		20	2511, 2541	
26	2574		14		

[a]Reference 2.
[b]Reference 3.
[c]Reference 12.
[d]Reference 20.

TABLE II. Levels populated in the ^{190}Os(t,p)^{192}Os reaction.

Present experiment				Previous results [a]	
Level No.	E_x (keV)	J^π	$d\sigma/d\Omega$ 30° (μb/sr)	E_x (keV)	J^π
0	0	0^+	257	0	0^+
1	206 ± 5	2^+	14	205.8	2^+
2	489	2^+	9.1	489.0	2^+
3	580	4^+	7.6	580.3	4^+
				690.4	3^+
				909.0	4^+
4	956	0^+	11	956.3	(0^+)
				1069.3	(4^+)
				1088.6	6^+
				1143.4	(5^+)
5	1206	0^+	23		
6	1343		3.0		
				1361.7	(6^+)
7	1455		4.8	1465.0	(6^+)
8	1670		3.1		
				1708.1	(8^+)
				1712.6	(7^+)
9	1789 ± 8		6.8		
10	1833		5.3		
11	1870		3.0		
12	1897		5.3		
13	1924	0^+	21		
14	1945		15		
				1967.4	(8^+)
				2015.0	(10^-)
15	2097 ± 10		6.8		
16	2126		8.1		

[a] From Ref. 12.

III. EXPERIMENTAL RESULTS

Tables I–III give the energy levels, spin assignments, cross section at 30°, and previously known results for the residual nuclei ^{190,192,194}Os, respectively. Typical spectra for the three targets are shown in Figs. 1 through 3. The angular distributions for these three nuclei, where there were sufficient data points, are shown in Figs. 4 through 6.

Twenty-seven levels were observed in ^{190}Os, seventeen in ^{192}Os, and sixteen in ^{194}Os. Most of these levels have previously been observed in the ^{190,192}Os nuclei but the levels of ^{194}Os were previously unknown except for the first four states.[1] Several new 0^+ assignments are made for the lighter Os isotopes.

Only the $L=0$ states give distinctive unambiguous angular distributions. The $L=2$ transitions have two different shapes which are characterized by the first and second excited 2^+ states of each isotope. Although each 2^+ state has a rather distinctive shape, it is difficult to use this shape to assign unknown 2^+ states because of the possibility of shapes intermediate to this both for $L=2$ and other L transfers. This represents a common problem in deformed nuclei and has been discussed before for Os (p,t) reactions.[2] Thus we shall not use here the angular distributions to assign spins other than $L=0$ where there exists no previous information except for the lower states of ^{194}Os where the systematic shapes of the lighter Os nuclei may be used.

TABLE III. Levels populated in the ^{192}Os(t,p)^{194}Os reaction.

Present experiment				Previous results [a]	
Level No.	E_x (keV)	J^π	$d\sigma/d\Omega$ 30° (μb/sr)	E_x (keV)	J^π
0	0	0^+	264	0	(0^+) [b]
1	218 ± 5	2^+	15	218.5	(2^+)
2	601	4^+	20	590.1	(4^+)
3	655	2^+	9.5	656.5	(2^+)
4	696	0^+	15		
5	1063		1.7		
6	1311 [c]		11		
7	1466				
8	1540 ± 8	0^+	16		
9	1668		15		
10	1737		18		
11	1835	0^+	28		
12	1878		15		
13	1956		23		
14	2118 ± 10		15		
15	2168		6.9		

[a] From Ref. 1.
[b] Brackets are ours to indicate difficulty of assignments in this technique.
[c] Probable unresolved doublet.

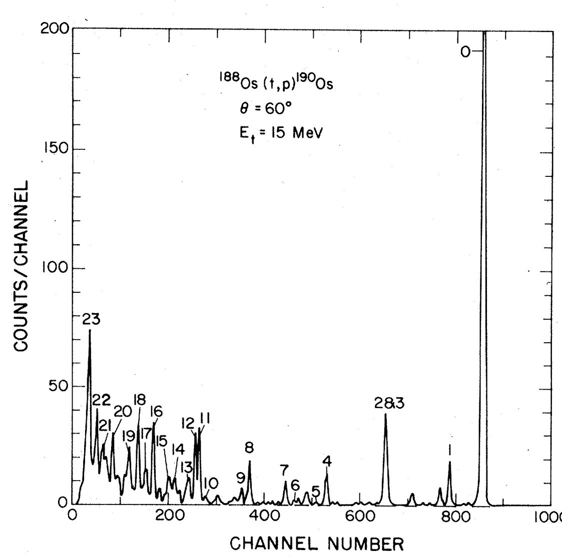

FIG. 1. The ^{188}Os(t,p)^{190}Os spectrum.

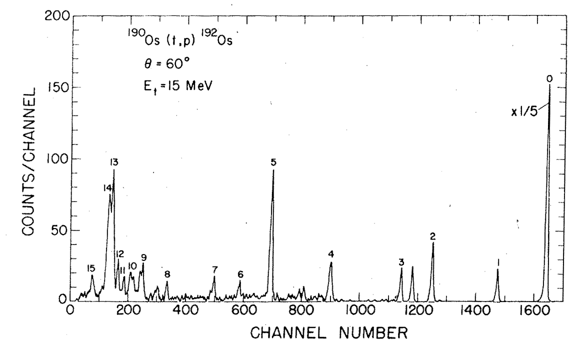

FIG. 2. The $^{190}Os(t,p)^{192}Os$ spectrum.

Three excited 0^+ states are observed in each residual nucleus. All are weakly populated compared to the ground state transition. In ^{190}Os, the three 0^+ states and their cross sections relative to the ground state are at 912 keV (2.1%), 1734 keV (4.0%), and 2451 keV (12.3%). In ^{192}Os these levels are at 956 keV (3.9%), 1206 keV (7.0%), and 1924 keV (8.1%). In ^{194}Os they are at 696 keV (5.6%),

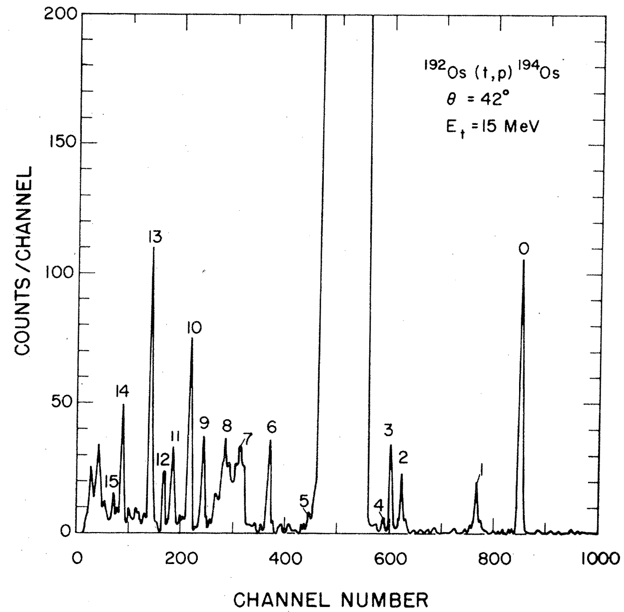

FIG. 3. The $^{192}Os(t,p)^{194}Os$ spectrum.

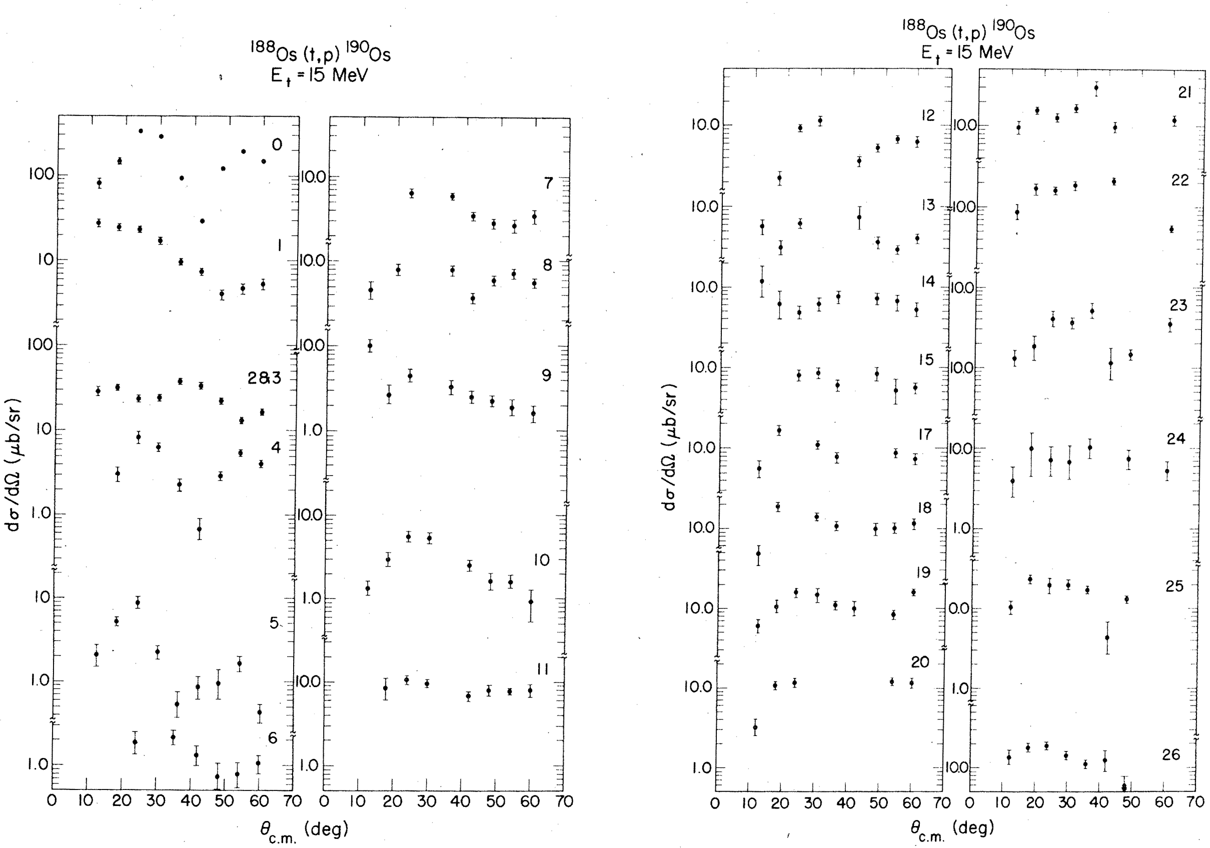

FIG. 4. Angular distributions for the $^{188}Os(t,p)^{190}Os$ reaction.

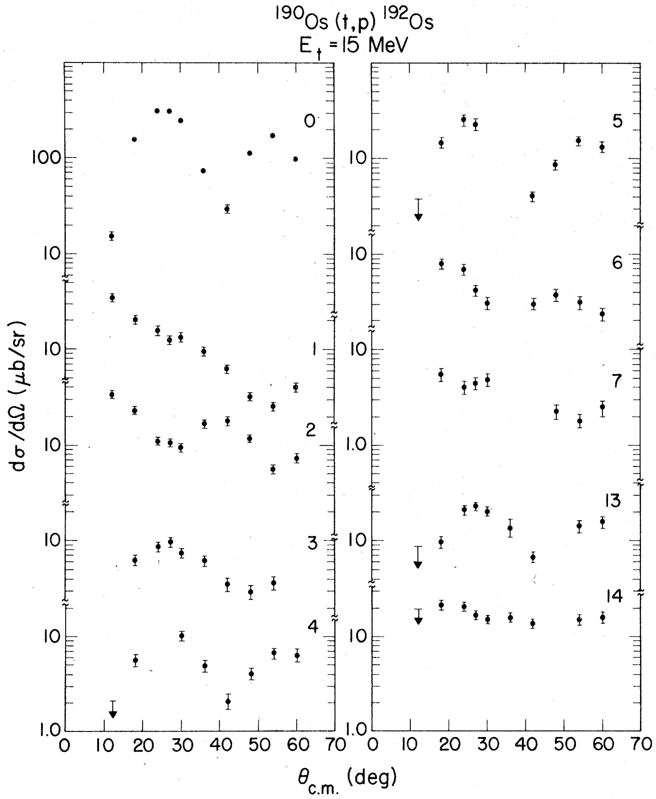

FIG. 5. Angular distributions for the ^{190}Os$(t,p)^{192}$Os reaction.

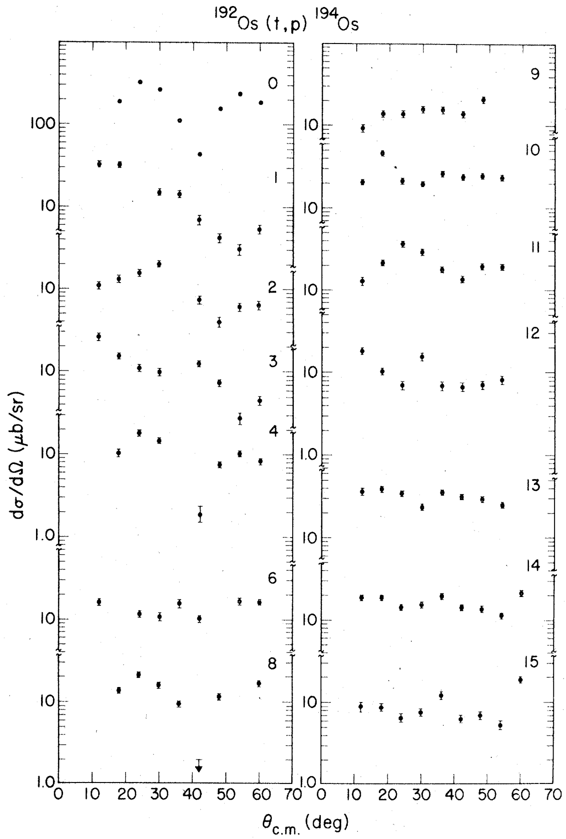

FIG. 6. Angular distributions for the ^{192}Os$(t,p)^{194}$Os reaction.

1540 keV (6.0%), and 1835 keV (10.8%). As in the case of the second 2^+ level, there seems to be an abrupt change in the position of the lowest 0^+ state of ^{194}Os from the lighter isotopes. In ^{194}Os this state lies at 696 keV, whereas a value above 900 keV is noted in all of the other Os nuclei (see, e.g., Fig. 16 of Ref. 3). In the only nucleus of this study which overlaps with (p,t) reaction [2,3] studies, ^{190}Os, the 0^+ states at 912 and 1734 keV agree with their assignments. We do not see a 0^+ state near 1550 keV as reported in the two neutron pickup reactions. The ratio of the 912 keV strength to that of the ground state in (t,p) is only one-half of that noted in (p,t), whereas the 1734 keV level is excited in a comparable manner by both reactions. A tentative 0^+ state has been reported [13] by other studies in ^{192}Os at 956 keV. This is confirmed by the present experiment.

IV. DISTORTED WAVE ANALYSIS

The code DWUCK[14] was used to calculate theoretical angular distributions to compare with the present data. The triton and proton optical potentials were chosen from appropriate surveys of elastic scattering of these particles.[11,15] The two neutron stripping form factor was that of Bayman and Kallio.[16] A comparison of these predictions to the ground state, the 2_2^+ and the 4_1^+ states is shown in Fig. 7. As in the case of the (p,t) reaction[2] the 2_1^+ state is not well described by distorted wave (DW) calculations, whereas the 2_2^+ is. This is presumably due to strong coupled channel effects caused by the inelastic channel to the 2_1^+ and its large β_2. The 4_1^+ state is reasonably well described by the calculation.

The ground state angular distributions fit the DW calculation quite well, as might be expected for these strong transitions since multistep effects would be small in comparison. If one uses the expression[17] $d\sigma/d\Omega = 218\epsilon\sigma_{DW}$ then $\epsilon = 4.0$ (compared to a pure $2f_{7/2}{}^2$ transfer). This would indicate a situation intermediate between a highly superconducting nucleus such as tin and a shell model nucleus such as lead. Actually, the tendency towards superconductivity is also suggested by the near equality of all ground state transitions; they are all within 6% of 269 μb/sr at 30°. Thus they illustrate the familiar quality of pairing rotational states found in superconducting nuclei.

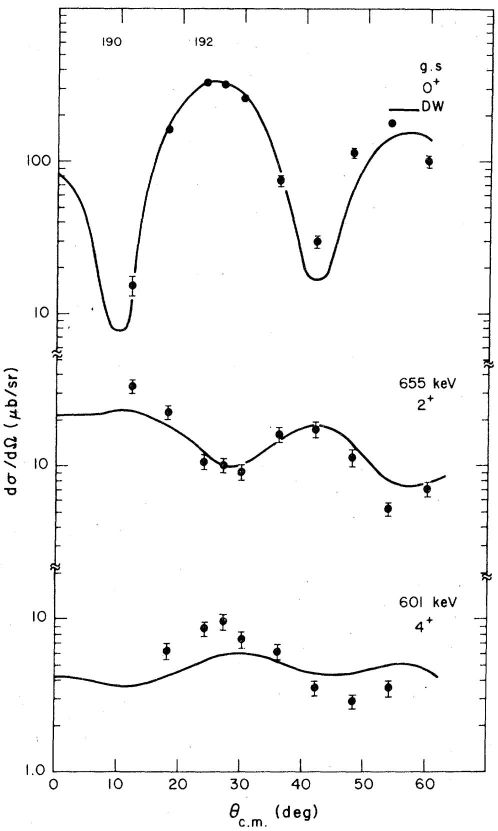

FIG. 7. Comparison of the distorted wave Born approximation calculations to the ground state, second 2^+ and first 4^+ transitions of the $^{192}Os(t,p)^{194}Os$ reaction.

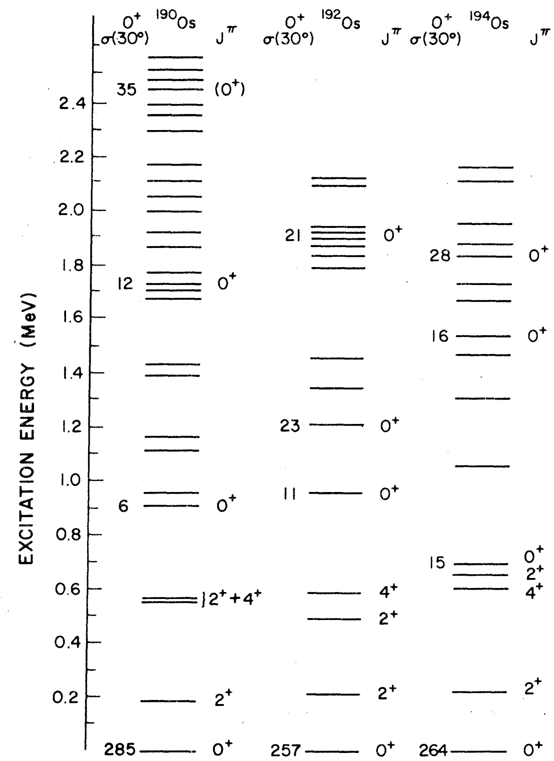

FIG. 8. Comparison of the level diagrams for $^{190,192,194}Os$. The spins assigned in the present work are shown. Also illustrated are the $L=0$ transition strengths at 30° scattering angle.

V. DISCUSSION

The principal objective of the present experiment was to investigate the effects of the transition from deformed to spherical shapes which should occur as the neutron number approaches the magic number 126. In addition, qualitative aspects of changes from prolate to oblate shape were also sought. Either of these effects should influence the position and relative strengths of the $L=0$ transitions as a function of neutron number of the residual nucleus. This is dramatically illustrated in the transition region at the light end of the deformed nuclei by abrupt changes in ground and excited 0^+ strength as one goes from spherical to deformed nuclei.[4] The second effect, which is caused by the relative position of oblate and prolate orbitals, is also amply illustrated in the actinide nuclei by the presence of a strongly populated low-lying excited 0^+ state.[6] The heavier osmium nuclei are indeed predicted to be oblate soft vibrators[18] with a shape transition between oblate and prolate occurring as one goes to light nuclei.

A summary of the levels observed in the present experiments is given in Fig. 8. The similarity of the ground state intensities indicates that no abrupt change occurs in this region in ground state configurations. Thus at least the ground states of $^{190,192,194}Os$ show no evidence for either deformed to spherical or prolate-oblate (γ) isomerism. However, the (t,p) strength to excited 0^+ states increases by ~2%, relative to the constant value for the ground state transitions, for each pair of neutrons added. The strengths of the 0_3^+ states increase slightly with N but their energy does not behave in a systematic fashion. The 0_4^+ states, which are the most strongly populated excited 0^+ states, seem to average near 10% of the ground state. The lowest two 0^+ states are presumably associated with the two phonon γ and β bands. This higher 0^+ state may be evidence for the spherical coexistence state although this is highly speculative. It is also noted that the total (t,p) strength to excited 0^+ states is about 20% of the ground state value (ranging from ~18% in ^{190}Os to ~22% in ^{194}Os). In contrast, the (p,t) experiments[2,3] showed summed $L=0$ strengths to excited states that were typically only ~10% of the ground state strengths. This difference may result from the presence of oblate orbitals above the Fermi surface as suggested in the introductory section.

The ^{194}Os case is especially interesting. The energy of the 0_2^+ state suddenly drops 200 keV compared with the lighter isotopes and the 2_2^+ level rises by 150 keV. Indeed the clustering of 0^+, 2^+, 4^+ states near 650 keV is highly suggestive of a vibrational two-phonon triplet although the ratio of this energy to the 2_1^+ energy is 3.0 instead of 2.0 suggesting a large vibrational-rotational interaction if this assumption were correct. If one compares this behavior of the 0_2^+ and 2_2^+ levels of ^{194}Os with those in the platinum isotone, ^{196}Pt, one notes a very similar behavior for these levels. The platinum nuclei have also been studied by the (p,t) reaction for shape changes with similar conclusions to the present results.[19]

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