private communication.
[13]W. J. Thompson and W. R. Hering, Phys. Rev. Letters 24, 272 (1970).
[14]J. A. Nolen, Jr., and J. P. Schiffer, Ann. Rev. Nucl. Sci. 19, 471 (1969), and references therein.
[15]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).
[16]R. L. Kozub and D. H. Youngblood, preceding paper, Phys. Rev. C 7, 404 (1973).
[17]F. Rauch, Z. Physik 243, 105 (1971).
[18]K. Hesse and E. Finckh, Nucl. Phys. A141, 417 (1970).
[19]J. P. Schiffer, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), Chap. 13.
[20]A. Z. Mekjian, Phys. Rev. Letters 25, 888 (1970).
[21]N. Auerbach, Nucl. Phys. A182, 247 (1972).
[22]R. Sherr, B. F. Bayman, E. Rost, M. E. Rickey, and C. G. Hoot, Phys. Rev. 139, B1272 (1965).
[23]E. Rost, Phys. Rev. 154, 994 (1967).

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Study of High-Lying States in ^{179}Hf and ^{183,184}W with the (n,γ) Reaction

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The nuclei ^{179}Hf, ^{183,184}W were studied with the (n,γ) reaction for neutrons of several resonant energies. High- and low-energy γ radiation following resonant capture was observed with Ge(Li) detectors. Level schemes were constructed from these data in conjunction with previous information from charged-particle reactions and decay studies. Some discrepancies among previous studies were clarified and a large number of spin assignments suggested. From these and data from the (d,p) reaction an analysis is made of the fractionation and distribution of the single-particle Nilsson strength in the energy region 1.3–2.3 MeV. It is found that the Nilsson model breaks down rather suddenly above the vibrational energy: A much larger than expected number of rotational bands are observed and the (d,p) strength is severely fragmented. This mixing appears to be larger in ^{183}W than in ^{179}Hf and still larger in ^{184}W. The data for 2^+ and 1^+ states in ^{184}W are compared with recent random-phase-approximation calculations: Again, much more configuration mixing is observed than is calculated and significant (d,p) strength occurs lower than predicted in the spectrum.

INTRODUCTION

In its description of the low-excitation-energy region of heavy deformed nuclei the Nilsson model[1] has been remarkably successful.[2-5] Through it, an immense body of data from charged-particle reactions and electromagnetic decay studies has been interpreted and correlated.

In odd nuclei (for example the $150 \leq A \leq 190$ deformed region) it has been possible to interpret most states up to ~1200 keV in terms of simple one-quasiparticle-proton or -neutron excitations. The Nilsson model provides simple predictions for one-nucleon-transfer-reaction cross sections that are generally in very good agreement with experimental results. It is often necessary to incorporate an analysis of the effects of Coriolis or $\Delta N = 2$ mixing or occasionally of hexadecapole deformations on these cross sections, but numerous examples exist[6-8] for which, once done, the absolute values and systematics of stripping- and picking-reaction cross sections are excellently reproduced. Similarly the model establishes many electromagnetic and β-decay selection rules and estimates of matrix elements that have been found to be in satisfactory agreement with experiment. In turn, as with the charged-particle data, these have allowed the assignment of most low-lying levels to the excitation of various Nilsson orbitals and to the rotational bands built upon them.

At about 1 MeV (in the rare-earth region) vibrational excitations can occur and the lowest lying of these (γ and β vibrations) have been reasonably successfully interpreted both microscopically and macroscopically.[9-12] These excitations are obtained theoretically[9,11] typically as the lowest roots of secular equations in the random-phase approximation. Higher roots should also exist but have seldom been unambiguously identified experimentally.

In fact, at energies above the first vibrational excitations the entire model appears to break down. It rapidly becomes difficult or impossible to assign Nilsson orbitals to rotational bands (or even to locate well-behaved bands) above ~1500 keV.[13,14] Generally, only high-spin levels at these energies can be successfully understood,[15-18] presumably due to the relative lack of other high-spin levels with which to mix.

The model's failure above the vibrational energy (or the energy of the lowest three-quasiparticle excitations) has usually been ascribed to mixing of the simple states with the other excitations energetically permissible. Clearly the possible excitations are many and mutually interacting. There has therefore been little study of low-spin states in the 1.3–2.3-MeV region of excitation and only a few detailed theoretical predictions of the expected distribution of states (and of one-particle-transfer strength).

Corresponding to this theoretical situation, and partly responsible for it, is the general lack of detailed experimental spectroscopic information on the energy levels above ~1.5 MeV. The present study was undertaken with these ideas in mind as an effort to explore representative nuclei at the heavier end of the $A = 150-190$ deformed region.

Relatively complete (d, p), (d, t), and $(^3He, \alpha)$ data exist on the odd and even W nuclei[6, 15, 19, 20] and the Coriolis mixing has been studied extensively.[6, 15, 19-22] The reaction $^{182}W(n, \gamma)^{183}W$ was chosen partly because it has convenient neutron resonances available to our facility.

One of the few prior experimental studies of higher excitation energies in this region was the work of Rickey and Sheline[14] on ^{177}Hf and ^{181}Hf. Briefly, they located, using the (d, p) and (d, t) reactions, a much larger number of $K^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$ bands between 1.2 and 1.8 MeV than could be explained in a simple way. They noted, however, that although the (d, t) and (d, p) spectroscopic strength was severely fractionated that in both nuclei 97% of the low-spin strength below 2 MeV was indeed found.

We have also chosen, therefore, to investigate ^{179}Hf to determine independently if this fragmentation is general in the Hf nuclei and in particular to compare the trends in it between the neighboring Hf and W nuclei.

The above discussion applies with obvious modifications to even-even nuclei as well. Here levels up to typically 1600–1800 keV have been well understood in terms of elementary two-quasiparticle excitations and the lowest vibrational excitations. The experimental situation is not as complete, though, due to the much larger number of possible two-quasiparticle excitations of comparable energy, combined with the severe charged-particle-reaction selection rules and similar limitations on final-state population in β and γ decay due to the widely varying K quantum numbers present.

A fortunate situation occurs in the Hf, W region in which the dominant spectroscopic strength expected for the (d, p) reaction is concentrated in a very few orbitals of low-K value (both in even and odd final nuclei) so that both the (n, γ) and (d, p) reactions may populate the same levels. Specifically, above ~1700 keV in ^{184}W, the (d, p) reaction on ^{183}W, with its $\frac{1}{2}\frac{1}{2}-[510]$ ground state, is expected to populate strongly only the $\frac{1}{2}-[510]+\frac{1}{2}-[501]$, $K=0, 1$; $\frac{1}{2}-[510]+\frac{3}{2}-[501], K=1, 2$; and $\frac{1}{2}-[510]+\frac{5}{2}-[503], K=2, 3$ even-parity orbitals. Similarly the (n, γ) reaction on ^{183}W is expected to populate strongly $J^\pi = 0, 1, 2^+$ levels in ^{184}W. Experimentally both here and in the odd final nuclei it is easy to investigate the (d, p) reaction to these higher-lying states, since the Q dependence of the reaction mechanism is such as to favor lower-Q values.[6, 20]

An additional reason for choosing specifically the $^{183}W(n, \gamma)^{184}W$ reaction is that a large body of new experimental information is presently available on ^{184}W providing an opportunity for a rather-detailed experimental study. In particular, in addition to the (d, p)[20] reaction, the (d, d'),[23] (p, t),[24] and (t, p)[25] reactions as well as several decay studies[26-28] leading to ^{184}W have recently been performed. Use of the natural-parity selection rules for (d, d') and (t, p) in combination with the spin selection rules for (n, γ) and the present decay information has yielded a number of spin assignments up to 2.3 MeV.

Finally, some preliminary theoretical calculations of higher roots for 2^+ and 1^+ states in ^{184}W are now available[29-31] and can be compared with the observed distributions of the energies and stripping strengths.

PREVIOUS STUDIES

There have been a number of previous investigations of the nuclei studied here. We shall make extensive use below of the (d, p) data into all three nuclei.[6, 20, 32] These data provide cross sections for many states up to above 2 MeV and some limitations on possible spins from the angular distributions. They also provide detailed one- and two-quasiparticle assignments for low-lying states and microscopic information on γ-vibrational states. However, extracted transferred l values are accurate only to ±1 unit and, therefore, spin assignments to states not specifically assignable to rotational bands were not made. Part of the general approach in our discussion will be to use the results of the present study to establish or limit the spins of a number of levels. In many cases states at these energies are also seen in (d, p) allowing an investigation of the distribution of spectroscopic strength to states of given spin and parity.

Extensive decay data also are available on all three nuclei.[26-28,33,34] Generally, they deal with the lower-energy regions of excitation and provide spin-parity assignments and extremely accurate level energies. We have made use of this information in interpreting the decay radiation from the higher-lying levels.

Finally, the (n, γ) reaction leading to the three nuclei studied has been investigated previously.[35-39] For ^{183,184}W there is unfortunately considerable discrepancy between these studies,[35,36] both in terms of the level energies deduced [thus inhibiting identification of corresponding levels populated in (d, p) and (n, γ)] and even in the determination of which levels are populated by primary radiation from the capture state. In fact these discrepancies were partially the initial impetus for this work. Furthermore, only high-energy primary transitions were reported in those studies, and therefore few firm spin assignments were made.

In ^{179}Hf a previous study[37] with thermal neutrons established several levels populated in primary capture. Again, no low-energy γ radiation was observed or firm spin assignments made.

As the present article was being written a detailed study[38] of thermal neutron capture leading to ^{179}Hf appeared. Many of the same levels observed here were reported in that study although a number of levels were seen in each work that were not observed in the other due to the statistical nature of the decay following thermal or resonant capture. The thermal-capture study also reported a number of the stronger deexcitation transitions, many of which are also observed here. However, the resolution in that study was such that the consistency demanded for the energy sums for transitions into or out of a given state was about ±2 keV. With ~150–200 transition energies possible between 500 and 1500 keV, the number of incorrect but energetically consistent deexcitation transitions is rather large. In the present study firm transitions were placed only if their energies were consistent with those of other relevant transitions to within ±0.4 keV. This eliminated a couple of deexcitation transitions assigned in Ref. 38, and permitted the assignment of many others. Secondly, the much larger Ge(Li) detectors used here and the much larger resonant-capture cross section permitted the observation of a number of weaker decay transitions (frequently transitions from states populated by primary-capture radiation to known $\frac{7}{2}^-$ levels) that greatly facilitated spin assignments.

A part of this work has been reported previously.[40]

EXPERIMENTAL PROCEDURES AND RESULTS

The neutron beam was obtained from the High Flux Beam Reactor at Brookhaven National Laboratory with the use of a neutron monochromator to select appropriate neutron energies. This technique makes use of Bragg diffraction from a

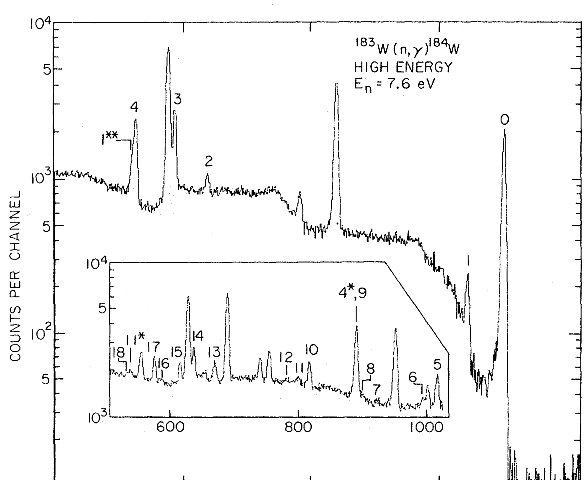

FIG. 1. Spectrum of the primary-capture γ radiation from the reaction ^{183}W$(n,\gamma)^{184}$W at $E_n = 7.6$ eV. Usually only full-energy peaks are labeled. First- (*) and second- (**) escape peaks are noted in a few cases to avoid confusion or to reiterate the evidence for weak peaks.

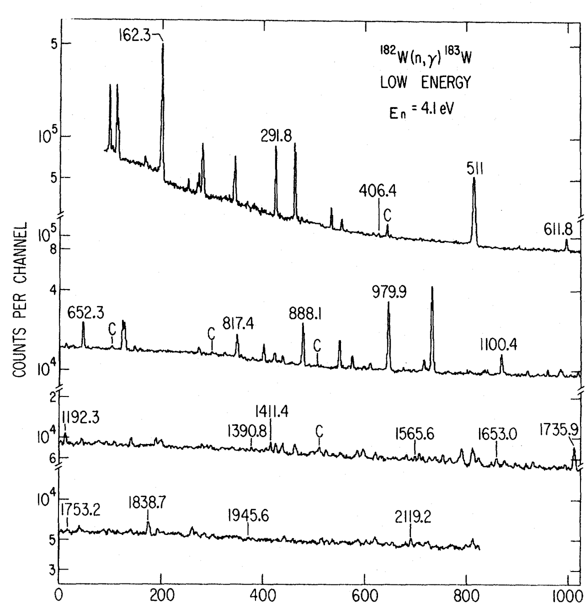

FIG. 2. Spectrum of the low-energy γ radiation from the reaction ^{182}W$(n,\gamma)^{183}$W at $E_n = 4.1$ eV. Some transition energies (keV) are given for orientation. The notation C denotes a contaminant peak.

large Be crystal and has been described in detail.[41] Neutron energies up to ~26 eV are available in first-order diffraction. The neutron beam profile is approximately a square 1 in. on a side. The targets were mounted at 45° with respect to both the beam and the Ge(Li) detector which was itself at 90° to the beam.

Two Ge(Li) detectors were used, 40 and 15 cm^3 in volume. The former was used primarily for the high-energy primary transitions but gave coarse dispersion results for lower-energy decay transitions as well. The ratios of full energy to first- and second-escape-peak intensities in the 4–7-MeV region are such that all three peaks are expected. This provides a useful means for distinguishing weak primary transitions from fluctuations in the background, as well as alternate checks on the primary γ-ray energies and a relative energy calibration within this region. The peaks recorded with this detector typically have 6–8 keV resolution full width at half maximum at 6 MeV. The data were analyzed and stored in a 16 384-word memory TMC analyzer in groups of 4096 channels with a dispersion of ~1.5 keV/channel. The spectra were searched for peaks using the nonlinear least-squares computer code PALMUD[42] which calculates peak channel numbers, peak areas and widths, and the errors on these quantities. Absolute energies were obtained to within ±3 keV. Relative (excitation) energies obtained from the primary radiation are accurate to ±1 keV, except for the weakest transitions (but see below also).

The 15-cm^3 detector was used for high-resolution analysis of the low-energy radiation. The resolution was ~1.0 keV at 122 keV and the dispersion was ~0.5 keV/channel. The γ-ray energies were determined by performing pulser calibrations along with the use of standard sources and normalization to one or two well-known transitions. It is felt that the energies determined are accurate to ±0.2 keV, except where indicated otherwise (e.g., for doublets). It was possible to compare our energies of transitions between levels below 1500 keV in ^{184}W and ^{179}Hf with a number of accurately known energies from previous decay studies. In all cases for $E_\gamma > 300$ keV the agreement was within ±0.2 keV and usually within ±0.1 keV.

Data were recorded at the following resonant energies: 4.1 and 21.2 eV on an isotopically enriched ^{182}W target (94.3%), the 7.6-eV resonance in ^{183}W on a natural W target, and the 7.78-eV resonance in ^{178}Hf on a natural Hf target. The quality of the 21.2-eV data is only sufficient to permit observation of the three strongest primary transitions. Off-resonance runs were recorded at energies of 7.0 and 8.0 eV to identify a number of contaminant lines from support materials surrounding the targets and from impurities in the targets themselves. Most runs were repeated to check the reproducibility of the data. The neutron flux varies with neutron energy so that the duration of the runs ranged from ~2 days (4.1 eV) to ~9 days (21.2 eV).

Typical high- and low-energy spectra from resonance capture are shown in Figs. 1 and 2. Generally only the full-energy peaks are labeled. When a peak contains both a full-energy peak and an escape peak from some other transition, an indication of the latter is made (see captions).

TABLE I. Primary-capture γ rays from the reaction $^{183}W(n,\gamma)^{184}W$, $E_n = 7.6$ eV.

No.[a]	E_γ[b] (keV)	$S(n)-E_\gamma$[c] (keV)	$E_{adopted}$[d] (keV)	I(rel)[e]	Comments
0	7413.2	0	0	1000	
1	7302.2	111.0	111.2	~67.4	
2	6510.5	902.7	903.2	98.8	
3	6411.7	1001.5	1002.3	689	f
4	6292.1	1121.1	1121.3	362	
5	6026.7	1386.5	1386.2	208	
6	5982.0	1431.2	1430.9	20.5	
7	5840.6	1572.6±3	1570.6	19.6	
8	5796.9	1616.3±3	1615.2±1	19.2	
9	5785.1	1628.1	1627.6	~100	f
10	5638.0	1775.2	1775.5	157	
11	5603.7	1809.5±1.5	1809.5±1.5	38.4	
12	5566.6	1846.6±1.5	1846.6±1.5	13.3	g
13	5350.7	2062.5	2062.5±0.5	139	
14	5286.6	2126.6	2126.2	207	
15	5245.7	2167.5	2167.9	82.8	
16	5190.5	2222.7	2222.7	~36	f
17	5166.2	2247.0	2246±1.0	~145	
18	5084.9	2328.3±1.2	2328.7±1.2	~22.6	g

[a] These numbers correspond to the peak numbering in Fig. 1.

[b] Primary full-energy transition energies, corrected for recoil. Absolute errors are ±3 keV, relative errors are ±1 keV except for some of the weakest peaks. See Ref. c.

[c] Excitation energies obtained from the primary transition energies. Errors are ±1.0 keV unless otherwise indicated. A larger error implies a corresponding error on the primary transition energy.

[d] Adopted excitation energies. These are generally based on the deexcitation transition energies. The errors are ±0.2 keV unless otherwise indicated. Where no decay transitions were firmly established the error and energy are the same as for the previous column.

[e] Relative intensities, normalized to 1000 for the highest-energy transition. Errors on entries with $I > 20$ are ±15%, with $I \leq 20$ or preceded by a ~ are ±30%.

[f] Primary energies and intensities based on first- or second-escape peak.

[g] Level not definitely established.

The results of these studies are presented in Tables I–VI. The energies are corrected for recoil and the intensities for absorption and relative detector efficiency. Tables I–III summarize the data on primary transitions, while Tables IV-VI give those for low-energy deexcitation transitions. The latter tables also list the initial-and final-state energies for those transitions placed in the level schemes of Figs. 3–5.

In comparing the apparent energies for various levels deduced from the low-energy transitions with those obtained from the high-energy primary-capture radiation it was found that in most cases the agreement was within ±0.5 keV. For some of the weaker primary transitions or for cases where partially resolved doublets were involved it was sometimes necessary to adjust the apparent level energy from the high-energy primary radiation by amounts up to 2.0 keV. For all levels for which firm deexcitation transitions were observed the final level energies were obtained from the latter. Possible errors are typically ±0.2 keV; they are given in the tables specifically. For those states for which no secondary transitions were observed larger errors are demanded, typically ±1.5 keV. In any case the excitation energies given in the tables and in Figs. 3–5 are the best values.

CONSTRUCTION OF THE LEVEL SCHEMES

From the data level schemes for the three nuclei were constructed. The results are summarized in Figs. 3–5. Also included (see discussion below) in these figures are some results of (d, p), (d, d'), (t, p), and $(\vec{d}, p)$[43] studies where they are of specific interest for the discussion to follow. In the low-energy region a number of levels not populated by primary transitions are included as they are the termini of observed secondary transitions or are known levels for which new information has been obtained. Above 1400 keV certain levels not observed in the present study are included (and so identified) to facilitate the later discussion. Otherwise, only those levels populated by primary transitions are incorporated in the level schemes. Possible new levels at energies consistent with the low-energy data but whose existence is not directly supported by primary radiation are not included.

The secondary transitions were incorporated in the level scheme on the basis of accurate energy sums. As indicated, firm deexcitation transitions of accurately known energy are consistent in energy with the levels involved to ±0.4 keV at most (typically ±0.1–0.2 keV). The dashed lines in Figs. 3–5 represent transitions where either the energy fit differs by slightly more or where the same transition energy is used twice and the corresponding peak in the spectrum does not appear broad.

The assignment of spins has been based on the following considerations. It is assumed that the levels populated most strongly (I_γ/E_γ^3) in primary capture radiation are fed by $E1$ radiation from the capture state. More specifically, if it is assumed that, on the average $M1$ transitions are a factor of 4 less intense than $E1$ transitions in this mass region and that the average observed primary tran-

TABLE II. Primary-capture γ rays from the reaction $^{182}W(n,\gamma)^{183}W$, $E_n = 4.1$ eV.

No. [a]	E_γ [b] (keV)	$S(n) - E_\gamma$ [c] (keV)	$E_{adopted}$ [d] (keV)	I (rel) [e]	Comments
0	6192.8	0	0	1000	
1	6146.4	46.4	46.5	361	
2	5984.4	208.4	208.8	42.6	f
3	5258.8	934.0	934.6	63.7	
4	5166.0	1026.8	1026.2	1888	f
5	4755.1	1437.7 ± 1.3	1437.2	96.0	
6	4647.5	1545.3 ± 4	1545.3 ± 4	···	g
7	4582.0	1610.8 ± 1.2	1612.0	28.4	
8	4562.9	1629.9	1629.9	87.0	
9	4519.6	1673.2	1673.4	115	
10	4381.6	1811.2	1811.2	37.3	
11	4369.1	1823.7	1823.8	89.8	
12	4325.4	1867.4 ± 1.5	1866.4 ± 0.7	28.6	
13	4307.4	1885.4	1885.4	252	
14	4247.5	1945.3	1944.8	314	
15	4209.9	1982.9 ± 1.2	1983.6	18.7	
16	4094.3	2098.5	2099.0	106	
17	4066.1	2126.7	2126.6	68.2	
18	4027.6	2165.2	2165.5	60.6	

[a] State number.

[b] Primary full-energy transition energies, corrected for recoil. Absolute errors are ±3 keV, relative errors are ±1 keV except for some of the weakest peaks. See Ref. c.

[c] Excitation energies obtained from the primary transition energies. Errors are ±1.0 keV unless otherwise indicated. A larger error implies a corresponding error on the primary transition energy.

[d] Adopted excitation energies. These are generally based on the deexcitation transition energies. The errors are ±0.2 keV unless otherwise indicated. Where no decay transitions were firmly established the error and energy are the same as for the previous column.

[e] Relative intensities, normalized to 1000 for the highest-energy transition. Errors on entries with $I > 20$ are ±15%, with $I \leq 20$ or preceded by a ~ are ±30%.

[f] Primary energies and intensities based on first- or second-escape peak.

[g] Data for this state obtained from the 21.2-eV resonance. The primary transition energy has a relative uncertainty of ±4 keV. The relative intensity is not indicated since it pertains to a different resonance. At 21.2 eV this state is populated with 71% the ground-state intensity.

sition strength is roughly the average $E1$ transition strength, then a primary transition of intensity greater than three-fourths the average has only a few percent probability of being $M1$. For transitions of this or greater intensity, $E1$ character is therefore assumed. In practice this corresponds to roughly the most intense 30% of the primary transitions. Transitions of slightly lower

TABLE III. Primary-capture γ rays from the reaction $^{178}Hf(n,\gamma)^{179}Hf$ at $E_n = 7.8$ eV.

No. [a]	E_γ [b] (keV)	$S(n) - E_\gamma$ [c] (keV)	$E_{adopted}$ [d] (keV)	I (rel) [e]	Comments
0	5726.1	374.8	374.8	1000	
1	5680.6	420.3	420.7	234	
2	5421.8	679.1	679.3	208	
3	4804.5	1296.4	1296.3	30	g
4	4667.8 ± 1.5	1433.1	1432.7	131	
5	4529.0	1571.9	1572.2	123	
6	4434.1 ± 3	1667 ± 3.0	1667 ± 3	~99	h
7	4394.8	1706.1	1706.0	304	f
8	4373.9	1727.0	1725.7	736	
9	4346.1	1754.8	1755.5	785	i
10	4337.3	1763.6	1762.7	181	i
11	4317.6	1783.3	1783.0	84	
12	4279.7	1821.2	1821.4	33	
13	4254.2 ± 1.5	1846.7	1846.6	115	
14	4187.3	1913.6	1913.3	60	j
15	4170.9	1930.0	1930.0 ± 1.0	61	
16	4058.1	2042.8	2042.8 ± 1.0	~68	i
17	4050.6	2050.3	2050.3 ± 1.0	~68	i
18	4018.0	2082.9 ± 2.0	2081.5	258	
19	4008.6	2092.3	2093.3	140	
20	3958.6	2142.3	2142.3 ± 1.0	113	
21	3932.4	2168.5	2168.5 ± 1.0	98	
22	3918.1	2182.8	2182.8 ± 1.0	112	

[a] State number.

[b] Primary full-energy transition energies, corrected for recoil. Absolute errors are ±3 keV, relative errors are ±1-keV except for some of the weakest peaks. See Ref. c.

[c] Excitation energies obtained from the primary transition energies. Errors are ±1.0 keV unless otherwise indicated. A larger error implies a corresponding error on the primary transition energy.

[d] Adopted excitation energies. These are generally based on the deexcitation transition energies. The errors are ±0.2 keV unless otherwise indicated. Where no decay transitions were firmly establsihed the error and energy are the same as for the previous column.

[e] Relative intensities, normalized to 1000 for the highest-energy transition. Errors on entries with $I > 20$ are ±15%, with $I \leq 20$ or preceded by a ~ are ±30%.

[f] Primary energies and intensities based on first- or second-escape peak.

[g] Level not definitely established.

[h] Level exists, population by primary radiation in (n_{res}, γ) not definitely established.

[i] Partially resolved doublet.

[j] Broad peak, may be doublet.

intensity (but above half the average) are likely $E1$ transitions but $M1$ is not excluded. Levels populated more weakly may well be fed by $M1$ transitions and the weakest primary transitions may be of $E2$ multipolarity. In interpreting the deexcitation transitions it is again assumed that the strongest are of $M1$ or $E1$ nature in the odd final nuclei and of $E2$ or lower multipolarity in ^{184}W.

In ^{184}W additional criteria were adopted. The target has $J^\pi = \frac{1}{2}^-$ and the resonance is 1^- so that strong primary transitions populate 0^+, 1^+, or 2^+ levels. An observed ground-state transition rules out a 0^+ assignment. Furthermore, if a state is observed in (t,p) or (d,d') it is highly suggestive of natural parity: Combined, for example with strong primary population and a ground-state transition, this would yield a 2^+ assignment.

In each nucleus ~60% of the observed deexcitation transitions comprising about 90% of the total γ-ray intensity, is placed in the level schemes. Specific comments on some of the levels are in order.

^{184}W

Levels at 1002.3 and 1005.9 keV. It has been known for some time[23, 26, 44] that two levels existed near 1 MeV with spins of 0^+ and 3^+. The present low-energy data confirm the evidence of Refs. 26 and 44 for the decay routes and provide an accurate energy for the 1002.3-keV level.

1430.9 keV. This level deexcites to the first two members of the ground-state band. It is weakly populated by a primary transition. A level is also observed in (d,d') at 1432 keV[23] with moderate intensity thereby arguing against a 1^+ assignment. The ground-state γ-ray transition eliminates 0^+ spin-parity. The Alaga rules,[45] which might be expected to hold this low in the spectrum, are also consistent with $K=2$. A recent study[28] of the ^{184}Re decay indicates that the level may be very weakly populated. Combined with its lack of population in (d,p)[20] or (t,p)[25] this is suggestive of a two-proton state. The population by ^{184}Re decay also suggests that one of the proton orbitals involved might be the $\frac{5}{2}+[402]$. If so then, on model-dependent grounds, a 2^+ assignment is favored over a 1^- two-quasiparticle assignment as there are no low-lying $K=\frac{3}{2}$ or $\frac{7}{2}$ odd-parity orbitals available to form a $K=1$, $\pi = -$ state. It is unlikely that this state is a 1^- octupole vibration since the main octupole strength is expected[46] to be concentrated in the $K=3$ state, and the $K=1$ excitation should occur about 500 keV higher. On the other hand, a $K=2$, $\pi=+$ band may easily be formed from the $\frac{1}{2}+[411]$ and $\frac{5}{2}+[402]$

TABLE IV. Low-energy γ rays in ^{184}W following neutron capture on ^{183}W at $E_n = 7.6$ eV.

E_γ (keV)	I (rel)[a]	Assignment[b] Initial (keV)	Final (keV)	E_γ (keV)	I (rel)[a]	Assignment[b] Initial (keV)	Final (keV)
2328.7	3.0	(2328.7	0)	~1045.9	1.7	2167.9	1121.3
~2245[c]	1.2	(2246.0	0)	~1033.9	~0.9	2167.9	1133.7
2168.0	0.5	2167.9	0	1022.3	4.6	1133.7	111.2
2135.4	3.2	2246.0	111.2	1018.5	3.9	1129.9	111.2
2097.6	3.7			1010.1	34.6	1121.3	111.2
2090.6	1.1			~1004.5	2.5	2126.2	1121.3
2056.5	5.0	2167.9	111.2	996.0	4.0	2126.2	1129.9
2015.0[d]	6.1	2126.2	111.2	920.8	2.5	(1285.2	364.0)
2004.9	1.7			903.1	100	903.2	0
2000.5	2.4			894.6	62.2	1005.9	111.2
1996.0	6.6			891.1	60.1	1002.3	111.2
1951.7	13.5	2062.5	111.2	882.6	1.9		
1945.2	3.8			~871.7	6.4	1775.5	903.2
1877.4	1.9			810.3	2.1		
1858.7	0.6	2222.7	364.0	803.3	0.8		
1849.2[c]	2.4			792.0	95.3	903.2	111.2
~1698.1	2.6	2062.5	364.0	769.3	13.2[e]	1133.7	364.0
1668.9	3.2					1775.5	1005.9
1624.5	1.3			763.1	5.8		
~1570.6	~1.8	1570.6	0	757.4	23.1	1121.3	364.0
1557.6	~1.5			743.2	3.3	2167.9	1424.6
1545.9	1.6			724.3	15.4	1627.6	903.2
1503.7	1.7	1615.2	111.2	~710.5[c]	7.4	1615.2	903.2
1501.3	1.7			678.1	3.1		
1431.0	8.1	1430.9	0	646.6	3.1		
1421.4	1.4			641.8	7.7	1005.9	364.0
1411.9	7.1	1775.5	364.0	635.8	1.2		
1386.2	14.7	1386.2	0	551.3	1.2		
1376.4	1.1			483.0	2.5	1386.2	903.2
1368.0	2.0			479.4	5.7		
1319.5	9.3	1430.9	111.2	418.8	5.8	1424.6	1005.9
		(2222.7	903.2)	~384.5[c]	~1.4	748.2	364.0
1313.5	5.1	1424.6	111.2	383.3[c]	~5.5		
~1305.5	≤3.1			339.6	3.6[f]		
~1302.9	1.4			318.3	17.4	1221.1	903.2
				295.3	8.7	(1424.6	1129.9)
1274.8	17.7	1386.2	111.2	273.3	1.3		
~1264.7 }[c]	1.0	2167.9	903.2	252.8	85.4	364.0	111.2
~1263.2 }		1627.6	364.0	226.8	71.5	1129.9	903.2
1121.1	14.2	1121.3	0	215.6	9.5	1221.1	1005.9
1109.8	2.6	1221.1	111.2	204.5	1.4		
				201.8	1.9		
1063.1	1.2			145.6	4.7	1570.6	1424.6
1060.7	1.2	1424.6	364.0	111.2	167	111.2	0

[a] Relative intensities, normalized to 100 for the 903.1-keV transition. These numbers are accurate to ±20% unless preceded by an ~ in which case the accuracy is ±40%.

[b] Routes enclosed in parentheses are dotted in the level schemes and are considered tentative, either because the energy fit is not good or the transition energy is used twice.

[c] Peak is either broad or a partially resolved doublet with approximate energies given.

[d] The data for this and higher energy peaks were obtained in the same runs as the primary transition data. Consequently, the energies are accurate only to ±0.5 keV and the intensities were obtained with a separate normalization to the 1996-keV transition. They are subject to an additional 20% uncertainty.

[e] About half of this intensity belongs to the 1775.5→1005.9-keV transition after the 1133.7→364.0-keV intensity is subtracted using the known branching ratio for the latter state's deexcitation.

[f] For this and lower energies intensity uncertainties are ±(35–50)%, depending on the transition strength, and energies are subject to an additional uncertainty of ±0.5 keV.

TABLE V. Low-energy γ rays in ^{183}W following neutron capture on ^{182}W at $E_n = 4.1$ eV.

E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)
~2170 ± 8 [c]	~0.9	(2165.5	0)
2138.1	~4.5		
2135.3	~2.7		
2126.5 [c]	~2.7	2126.6	0
2119.2	4.1	2165.5	46.5
2099.1	3.0	2099.0	0
2092.9	1.9		
2080.8	5.8	(2126.6	46.5)
2071.2	2.2		
2062.6	~3.3		
2035.4	1.9		
2029.2	1.7		
2023.5	3.4		
1984.0	4.3	1983.6	0
1945.6	2.9	(1944.8	0)
1907.2	3.3		
1898.3 [c]	5.1	1944.8	46.5
1889.9	3.4	2099.0	208.8
1885.5	7.6	1885.4	0
1853.4 [c]	2.6		
1848.6	5.2		
1838.7	12.4	1885.4	46.5
1819.6	~1.9	1866.4	46.5
1796.6	1.9		
1790.8	1.9		
1764.7	3.5	1811.2	46.5
1753.2 [c]	~1.8	2165.5	412.1
1735.9	21.0	1944.8	208.8
1725.9	2.2		
1713.5	2.0		
1691.6	4.5	1983.6	291.7
1684.3	2.0		
1676.4	1.8	1885.4	208.8
1673.1	2.5	(2126.6	453.1)
		(1673.4	0)
1661.1	3.6		
1653.0	~6.4	1944.8	291.7
1633.5	8.7		
1627.2 [c]	22.0	1673.4	46.5
1615.3	14.5	1823.8	208.8
1612.0	~5.3	1612.0	0
1602.5	4.0	1811.2	208.8
1595.1	4.5		
1586.7	3.8		
1580.0	3.1		
1569.9	3.5		
1565.9	~2.6	1612.0	46.5
1556.5	~2.9		
1528.7	~2.9		
1523.2	4.8		
1510.2	7.5		
1503.8	5.8		
1485.8	4.0		
1470.6	3.4		
1454.8 [c]	~3.0	1866.4	412.1
1437.5	9.7	1437.2	0
1423.8	7.2		
1416.6	~7.0		
1411.4	~7.0	1823.8	412.1
1406.4	1.3		
1390.8	~1.3	1437.2	46.5
~1371.9 } [c]	~1.1		
~1370.0 }	~1.4	1823.8	453.1
1347.3	1.4		
1343.4	~1.3		
1337.9 [c]	1.4	(1437.2	99.1)
		(1629.9	291.7)
1294.2	~3.0		
1288.9	4.5		
1262.6	2.2		
1245.0	~1.9		
1236.0	1.9		
1228.2	1.8	1437.2	208.8
1209.9	3.1		
1192.3	~6.9	2126.6	934.6
1182.6	2.5		
1164.9 } [c]	~4.5	2099.0	934.6
1163.4 }	~3.7	2165.5	1002
1149.8	2.4		
1128.3	2.8		
1100.4	11.6	2126.6	1026.2
1026.4	100	1026.2	0
1017.8	5.2		
979.9	60.1	1026.2	46.5
960.0	3.0		
953.6	1.2	1052.9	99.1
941.2	~6.4		
927.2	15.2	1026.2	99.1
888.1	27.1	934.6	46.5
866.4	33		
857.6	4.9	904.5	46.5
846.1	9.9	1052.9	207.0
834.5	1.2		
825.9	~0.6		
821.8	~1.1	1823.8	1002
817.4	12.3	1026.2	208.8
804.4	1.3		
776.3	4.0		
734.4	0.6	1026.2	291.7
713.3	0.9		
707.6	1.9		
695.4 [c]	28.8	904.5	208.8
		1629.9	934.6

TABLE V *(Continued)*

E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)	E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)
652.3	11.9			313.3	35.4	412.1	99.1
~640.2 [c]	0.9	1052.9	412.1	291.8	30.6	291.7	0
633.9	2.3			245.6	21.3	453.1	208.8
611.8	4.7					453.1	207.0
559.7	0.9					291.7	46.5
464.6	0.4			209.4 [e]	24.6	208.8	0
451.9	0.5	904.5	453.1	205.1	~7.6	412.1	207.0
419.8	0.8					(412.1	208.8)
406.4	0.8	453.1	46.5	192.9	~3.3	291.7	99.1
400.7	0.9			162.3	202	208.8	46.5
371.4	0.4			143.0	6.4	(453.1	308.9)
365.5	2.9	412.1	46.5	107.8	99.4	207.0	99.1
353.9	5.1	453.1	99.1			(208.8	99.1)
326.4	0.7			98.8	99.6	99.1	0
320.9	1.2 [d]						

[a] Relative intensities, normalized to 100 for the 1026.4-keV transition. These numbers are accurate to ±20% unless preceded by an ~ in which case the accuracy is ±40%.

[b] Routes enclosed in parentheses are dotted in the level schemes and are considered tentative, either because the energy fit is not good or the transition energy is used twice.

[c] Peak is either broad or a partially resolved doublet with approximate energies given.

[d] For this and lower energies intensity uncertainties are ±(35–50)%, depending on the transition strength, and energies are subject to an additional uncertainty of ±0.5 keV.

[e] For peaks of this and lower energies some weak known transitions are not listed (see Ref. 34).

orbitals (with the complementary $K=3$ state lying somewhat higher). These speculative parity arguments are supported by the work of Ref. 39 in which this level is reported to be strongly populated in the 1^- 66-eV resonance. Thus a spin-parity of 2^+ is favored over 1^-.

1570.6 keV. Decay branches to both the ground state and a 3^+ level eliminate a 3^- assignment and determine the even-parity choice for the lower-spin alternatives as well.

1615.2 keV. This state is also seen by Samour *et al.*[36] in the 101-eV 0^- resonance indicating a 1^+ assignment. This is consistent with the present results. However it should be cautioned that the states at 2167.9 and 2222.7 keV are also assigned 1^+ spins and parities in Ref. 36 on the basis of similar arguments. Their decay branches, as observed here, and other data, are inconsistent with these assignments and indicate 2^+ assignments instead.

1627.6, 1775.5, and 2062.5 keV. As these levels are moderately or strongly populated by primary-capture radiation and are observed to decay to a 4^+ state we suggest J^π values of 2^+. The first is also observed in (t,p) with an angular distribution not consistent with a 0^+ assignment,[25] thereby confirming the 2^+ choice. The 1775.5-keV level was observed by Spencer and Faler[35] but not by Samour *et al.*[36] in the primary-capture radiation. It corresponds to peak number 10 in Fig. 1. The decay intensities of the 1775.5-keV level are somewhat puzzling. The Alaga rules would imply that the strong branch to the 4^+ level at 364.0 keV indicates $K\neq 2$, while the decay, if $E2$, to the 3^+ member of the γ band suggests that $K\neq 1$. It is, of course, possible that one of these deexcitation routes is not correct, but it is also not surprising that the Alaga ratios do not work since there is independent evidence from the (d,p) reaction (see below and Ref. 20) that the state is highly mixed and probably represents only a fragment of a higher-lying two-quasiparticle excitation.

1809.5 and 1846.6 keV. These are both populated very weakly in the present study. The former is observed weakly by Samour *et al.*[36] in the 4.1-eV resonance but apparently not in any other. They do not observe the 1846.6-keV state in any resonance. This generally weak population for both levels may suggest negative parity or perhaps 3^- spin and parity, especially for the 1846.6-keV state. The 1809.5-keV level is probably the same as one observed at ~1810 keV in (t,p) and therefore natural parity is favored.

2126.2 keV. This state is very strongly fed by primary radiation, and a state at about this energy is observed in (d,d').[23] The deexcitation includes branches to two 2^+ levels and most strongly to a 2^- state at 1129.9 keV. Consistent J^π val-

TABLE VI. Low-energy γ rays in ^{179}Hf following neutron capture in ^{178}Hf at $E_n = 7.8$ eV.

E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)	E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)
1973.3	~5.9			1082.4 [c]	8.8	1783.0	700.7
1933.6	6.8					(1296.3	214.1)
~1892.0 [c]	5.8			1078.1	15	(2081.5	1004.0)
~1890.6 [c]	5.8			1061.9	20	1762.7	700.7
1862.8	4.8			1054.6	61	1755.5	700.7
~1839.4 ± 4 [c]	~1.7			1046.3	9.0	1725.7	679.3
				1035.4	22	1755.5	720.2
~1709.4 [c]	2.8			1025.2 [c]	~3.0	1725.7	700.7
~1707.0 [c]	3.8	(2182.8	476.1)	1017.2	11		
1672.5	14	2093.3	420.7	1012.7	12	(1432.7	420.7)
1660.5	4.1	2081.5	420.7	1004.0	97	1004.0	0
1635.0	5.5			997.8	~7.4		
1605.0	~5.4	2081.5	476.1	985.7	9.4	1706.0	720.2
1602.8	~5.4			975.7 [c]	7.3	(1846.6	871.6)
1548.4	3.3	1762.7	214.1	956.4 [c]	19	(1572.2	615.2).
1502.4	5.1					1432.7	476.1
1463.7	~11			922.5	~3.5		
1446.6	12	1821.4	374.8	918.1	~11	1706.0	788
1388.0	15	1762.7	374.8	~914.9	~5.4	1432.7	518.2
1381.1 } [c]	~11	2081.5	700.7	894.2 [c]	4.6		
1379.7 }	~8.3	(1755.5	374.8)	873.7	5.8		
1351.4	12	(1725.7	374.8)	870.3	~15		
1342.1	13	1762.7	420.7	868.0	~14		
~1334.7 } [c]	~14	1755.5	420.7	859.0	14		
~1331.8 }	~14	(1913.3	581.9)	852.3	8.7	1572.2	720.2
		(1706.0	374.8)	848.3	6.5		
1305.3	3.8	(1725.7	420.7)	~818.5 [c]	~5.5	1432.7	614.0
		(2093.3	788)	~817.4 [c]	~4.7	1432.7	615.2
1293.8	18 [d]	2081.5	788	811.1	19		
1291.3	~10			~805.8	~4.6		
1285.9 [c]	~10	(1706.0	420.7)	779.1	5.7	1783.0	1004.0
1279.5	11	1755.5	476.1	765.1	19		
1266.5	10			761.5	11		
1245.1	5.9	(1762.7	518.2)	729.8	43		
1237.6	8.4	1755.5	518.2	712.9	5.4	1432.7	720.2
~1231.6 [c]	~2.2	1846.6	615.2	655.7	23		
~1229.4 [c]	~2.7			653.4	21		
1207.0	16	1821.4	614.0	635.1	14		
1197.6	~13	1572.2	374.8	616.6	2.0	1296.3	679.3
1192.9	7.5	1913.3	720.2	612.8	1.2		
1187.8	13	1706.0	518.2	596.0	3.0	1296.3	700.7
1183.6	13			589.3	13		
1175.2	16			582.5	2.5		
1167.2	14	1846.6	679.3	~573.5 [c]	~3.1	788	214.1
1151.6	8.9	1572.2	420.7	~571.7 [c]	~19		
1141.3	25	1755.5	614.0	548.6	8.0		
		(1821.4	679.3)	528.6	13		
1121.0	20	1821.4	700.7	518.5	12		
1117.5	5.4			~508.3	97	(720.2	214.1)
1111.7	20	1725.7	614.0	485.9 [c]	~15		
1103.6	~3.3	1783.0	679.3	483.2 [c]	~10		
1099.6	~3.3			478.0	2.6		
1095.9	~3.3	1572.2	476.1	470.8 [c]	10		

TABLE VI *(Continued)*

E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)	E_γ (keV)	I (rel) [a]	Assignment [b] Initial (keV)	Final (keV)
465.4 [c]	8.7			311.9	5.7		
456.1	4.3			304.0 [e,f]	549	518.2	214.1
429.6	6.2			299.7	44	720.2	420.7
413.1	5.6			279.1	21	615.2	336.5
409.8	2.5			269.9	20	788	518.2
402.5	7.2			258.8	96	679.3	420.7
395.1	5.0			244.4	13	720.2	476.1
386.0	4.0			239.2	43	614.0	374.8
372.6	4.8			234.6	5.4		
352.9	2.8			232.3	8.8		
345.4	10	720.2	374.8	224.7	4.6	700.7	476.1
338.0 [c]	11			214.1	1000	214.1	0
332.0	50			202.3	140	720.2	518.2
325.6	42			193.3	239	614.0	420.7
318.9	3.6			182.7	12	(518.2	336.5)
314.8	4.1			171.3	22	(788	614.0)
				161.1	268	581.9	420.7

[a] Relative intensities, normalized to 1000 for 214.1-keV transition. These numbers are accurate to ±20% unless preceded by an ~ in which case the accuracy is ±40%.

[b] Routes enclosed in parentheses are dotted in the level schemes and are considered tentative, either because the energy fit is not good or the transition energy is used twice.

[c] Peak is either broad or a partially resolved doublet with approximate energies given.

[d] Up to 30% of this intensity may be due to a γ transition from the β decay of ^{116}In.

[e] For this and lower energies intensity uncertainties are ±(35–50)%, depending on the transition strength, and energies are subject to an additional uncertainty of ±0.5 keV.

[f] For peaks of this and lower energies some weak known transitions are not listed (see Ref. 33).

ues are 0^+ and 2^+ with the latter preferred by the strength of the branch to the 1129.9-keV state: $J^\pi = 0^+$ would demand a low-energy $M2$ transition to compete with possible higher-energy $E2$ transitions.

2167.9 keV. The state is populated fairly strongly by primary radiation and decays to a 0^+ level (weakly), three 2^+ states, a 3^+ and a 4^+ level.

2222.7 keV. Though only weakly populated by primary radiation its decay to a 4^+ and probably a 2^+ level indicates a spin-parity of 2^+. Its observation and angular distribution in (t,p)[25] confirms this assignment.

2246.0 keV. The $1^+, 2^+$ assignment is based on evidence of population in the 101-eV, 0^- resonance by Samour *et al.*[36] which indicates a J^π of 1^+ and the suggestion of spin 1 or 2 (latter preferred) from circular polarization data, in work of Stecher-Rasmussen *et al.*[47] The tentative present observation of γ decay to the ground state also suggests nonzero spin.

A final note may be added on the 1754-keV level which is not seen in the present studies but which is included in Fig. 3 for later convenience. The state is seen in (d,p)[20] with an angular dependence suggestive of high spin for the state (≥ 3). It is seen in both (d,d')[23] and (t,p)[25] again with an angular dependence appropriate for a 4^+ level. The 1795-keV level is likewise included in Fig. 3 as it also has a large (d,p) cross section.[20] It probably[20] has high spin.

^{183}W

Levels Near 1 MeV. Included in Fig. 4 are several levels near 1 MeV not observed in the primary radiation but which have recently been detected in the (d,t) reaction.[6] Those at 904.5 and ~1002 keV were identified[6] as the first two levels of the band built on the $\frac{5}{2}-[512]$ orbital. The 934.6-, 1026.2-, and 1052.9-keV levels were proposed as the $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ states of the $\frac{1}{2}-[521]$ band. The present study has assigned 12 transitions to the decay of 4 of the levels, and provided more accurate excitation energies than afforded by the (d,t) reaction. The proposed[6] spin of the 934.6-keV level is consistent with the observed transition to the 46.5-keV level. The three to five transitions placed for the decay of each of the other levels strongly support the spin assignments suggested in Ref. 6 and, therefore, the Nilsson orbital identifications.

The once-K-forbidden transition from the 904.5 state to the 46.5-keV level is about 3 times weaker than the dominant decay to the 208.8-keV $\frac{3}{2}\frac{3}{2}-[512]$ level, and probably proceeds partly through the Coriolis admixture of the latter state into the former (mixing amplitude ~−0.15[6]). The absence of any observable decay to the 291.7-keV $\frac{5}{2}\frac{3}{2}-[512]$ level is consistent with the expected branching calculated from the Alaga rules for a pure $K=\frac{5}{2}$ band, again supporting the assignment of Ref. 6.

1437.2 keV. This level is populated moderately by primary radiation corresponding to about 4 times larger probability of the primary transition being $E1$ than $M1$ and so odd parity is preferred but not established.

~1550 keV. A level at ~1545 keV is populated very strongly in the 21.2-eV resonance and perhaps very weakly in the 4.1-eV resonance. The former indicates a J^π of $\frac{1}{2}^-$, $\frac{3}{2}^-$. The present data at 21.2 eV are consistent with Samour *et al.*[36] who obtain, however, a higher energy for this level and who observe rather different relative intensities for transitions to the ground and first excited states. A state at about this energy is populated strongly with $l\sim 1$ in the (d, p) reaction. The $(\vec{d}, p)$ reaction with polarized deuterons has also recently been performed.[43] Between the two choices allowed by the (n, γ) and (d, p) data, the $\frac{3}{2}^-$ assignment is clearly preferred.[43]

A state at 1476 keV was also assigned in Ref. 43 as a $\frac{1}{2}^-$ level by combining $(\vec{d}, p)$ data with the fact of its observation in higher-energy resonances[39] in the (n, γ) reaction. Though not observed at either resonance in the present work it is included in Fig. 4 for completeness as it will be discussed below.

1629.9 keV. This level is labeled $(\frac{1}{2}, \frac{3}{2})^{-(+)}$. The intensity of population by primary radiation is sufficient to suggest the preference for odd parity.

1673.4 keV. Its population here by primary radiation suggests odd parity. It is also observed strongly[39] in several higher-energy resonances, confirming the odd parity. The assigned deexcitation transitions do not allow a definite spin assignment.

1823.8 keV. This level is populated relatively strongly in both (n, γ) and (d, p). It is indicated to decay to three $\frac{7}{2}^-$ states and (most strongly) a $\frac{3}{2}^-$ level. This is certainly rather strange, but while fortuitous energy sums are possible (2 or 3 may be expected to be indicated in each decay scheme presented here) it is hardly likely that all three transitions to $\frac{7}{2}^-$ states are fortuitous. The $\frac{3}{2}^-$ assignment is therefore rather firm.

1866.4 keV. Though populated weakly here its preferential decay to the $\frac{7}{2}^-$ 412.1-keV level (as well as the $\frac{3}{2}^-$ state at 46.5 keV) strongly suggests a $\frac{3}{2}^-$ assignment. Odd parity is supported by the data of Refs. 36 and 39 in which this level is seen rather strongly in the 21.2-eV resonance.

1944.8 keV. This level is fed very strongly by primary radiation and decays to two $\frac{3}{2}^-$ states, a $\frac{5}{2}^-$ level, and possibly to the ground state as well. The $\frac{5}{2}^-$ decay branch is not weak. A $\frac{3}{2}^-$ assignment is strongly indicated. The spin of $\frac{3}{2}$ is consistent with the tentative suggestion of Stecher-Rasmussen *et al.*[47] who analyzed the circular polarization of the primary radiation populating this level.

1983.6 keV. This state decays to a $\frac{1}{2}^-$ and, more intensely, to a $\frac{5}{2}^-$ level. It is weakly populated in the present study at the 4.1-eV resonance and J^π values of $\frac{3}{2}^\pm$ are suggested. A state at roughly this energy is populated in the 21.2-eV resonance.[36] If this is the 1983.6-keV level, odd parity is indicated: The tentative nature of the identification does not allow the other assignment to be precluded.

2099.0 keV. The $\frac{1}{2}^-$ preference over $\frac{3}{2}^-$ is weak but is suggested by the absence of any observed decay to $\frac{5}{2}^-$ or $\frac{7}{2}^-$ states. A similar argument is applied to the 1885.4-keV level.

2126.6 keV. This level decays by three firm branches to $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels and by tentative routes to another $\frac{3}{2}^-$ and a $\frac{7}{2}^-$ level. The latter, if correct, would indicate a $\frac{3}{2}^-$ assignment. The odd parity is independently suggested by the moderately strong population in the primary radiation for the 4.1-eV resonance and is confirmed by strong population in a higher-energy resonance.[39]

2165.5 keV. This level decays to two $\frac{7}{2}^-$ states as well as $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels. Unfortunately both peaks containing the transitions to $\frac{7}{2}^-$ states are partially resolved doublets, but, nevertheless, the extracted transition energies agree with those required for the indicated transitions to within 0.2 keV. It is populated moderately by primary radiation and a $\frac{3}{2}^-$ assignment appears indicated. Samour *et al.*[36] also report strong population of this level in the 21.2-eV resonance and therefore the odd parity is supported.

^{179}Hf

1004.0 keV. This level is seen weakly[38] in thermal capture and is observed to decay to the $\frac{9}{2}^+$ ground state, suggesting a $\frac{5}{2}^+$ assignment. This is indicated in Fig. 5 as the strong 1004.0 decay transition is observed here as well.

1296.3 keV. This level decays to a $\frac{3}{2}^-$ and a $\frac{5}{2}^-$ level and quite likely to the 214.1-keV $\frac{7}{2}^-$ state. Though the primary transition populating this level is very weak, its full-energy, first- and second-escape peaks were all observed, firmly establishing the level. The spin (assuming the decay to 214.1 keV) is more likely $\frac{3}{2}^-$ or $\frac{5}{2}^+$ than $\frac{3}{2}^+$ as the latter requires an $M2$ transition to compete

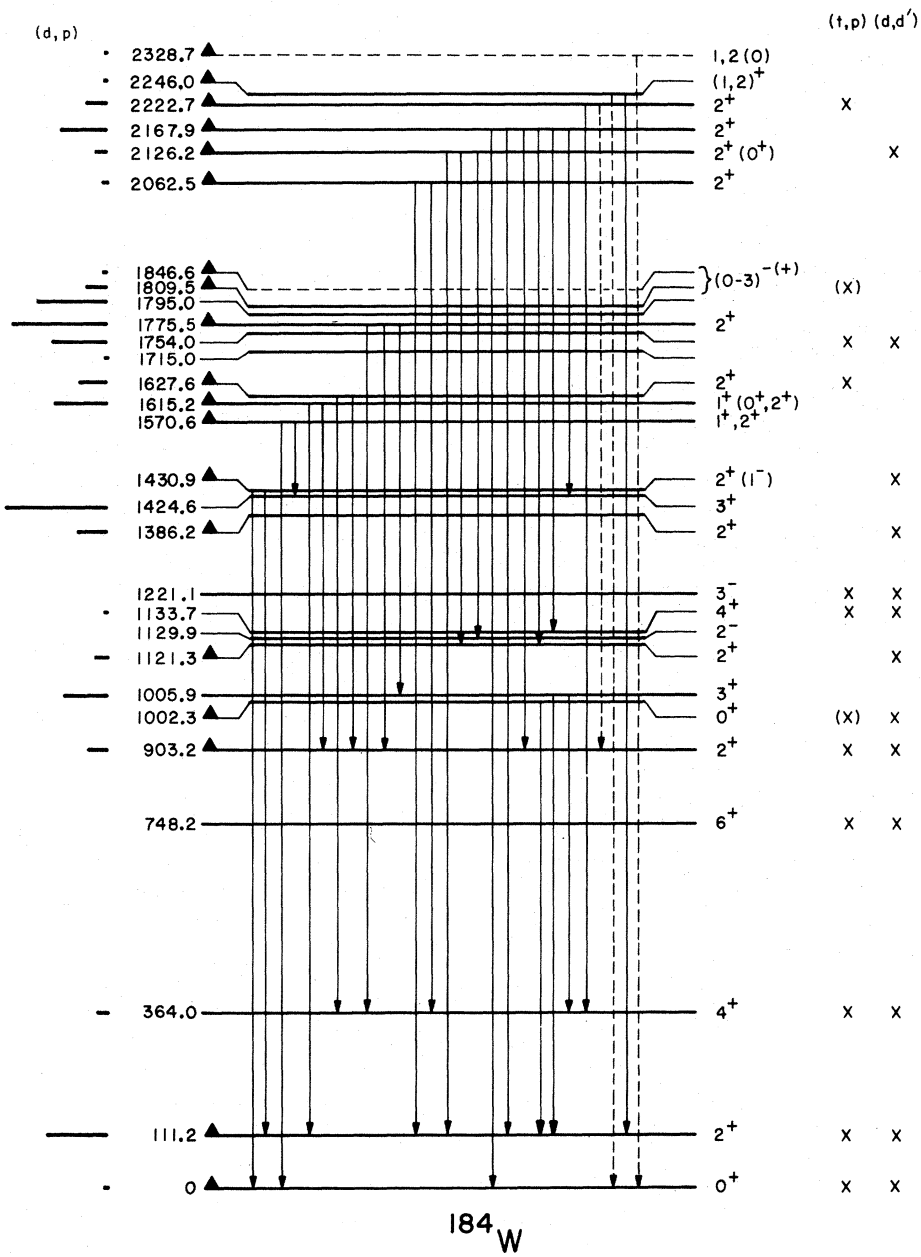

FIG. 3. Level scheme for ^{184}W. Dashed levels are likely but not definitely established. A solid triangle at the left indicates the level is observed in the primary-capture radiation. Dashed deexcitation transitions are tentative: For these, either the energy fit is poor, or the transition energy is used twice. The suggested spin-parity assignments are those indicated by all available data. Parentheses on J^{π} assignments either indicate a scale of preference [e.g. $2^{+}(1^{-})$] or that a parity preference applies identically to more than one equally likely spin choice [e.g. $(0\text{-}3)^{-(+)}$]. Braces are used for simplicity when the same J^{π} assignment applies to two or more adjacent levels. At the left the bars have lengths proportional to the (d,p) cross sections (see Ref. 20) at $\theta_{\text{c.m.}}=90°$ modified (see Ref. 20) by a distorted-wave Born-approximation correction factor to $Q=3.0$ MeV. If a state is observed in (t,p) (see Ref. 25) or (d,d') (see Ref. 23) an × is placed opposite it on the right. Some levels and some transitions between low-lying levels are known and were observed which for simplicity were not included in the figure. All the deexcitation transitions indicated in the figure were previously unknown.

with the $E1$ decays.

1432.7 keV. This level is populated moderately, suggesting odd parity but not eliminating even parity. It decays to $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ levels, most strongly to the $\frac{5}{2}^-$. A J^π value of $\frac{3}{2}^-$ is indicated.

1572.2 keV. Four firm and one tentative branchings are identified. The weak decay to a $\frac{5}{2}^-$ level and the possible decay to the $\frac{7}{2}^-$ level at 615.2 keV indicate a $\frac{3}{2}^-$ assignment. Alenius *et al.*[38] assign transitions from this level to states at 374.8, 518.2, and 1004.0 keV only one of which is firmly indicated in Fig. 5. The latter two γ rays were observed here at essentially identical energies which, however, are not those proper for the indicated decay routes, differing by 0.6 and 3.5 keV, respectively, from the required energies. The de-

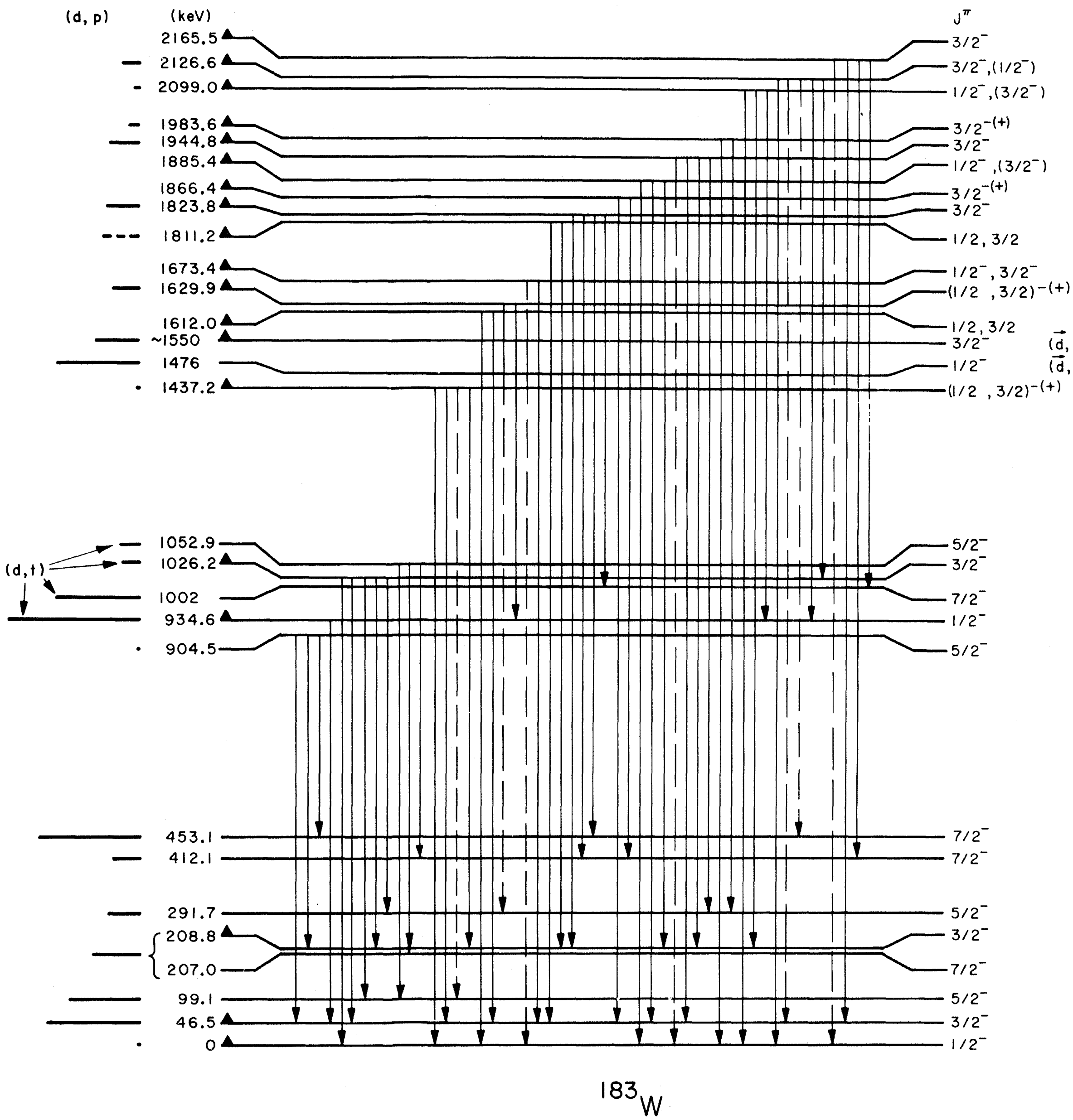

FIG. 4. Level scheme for ^{183}W. See caption to Fig. 3. For a group of levels near 1 MeV the (d,t) rather than (d,p) cross sections (see Ref. 6) are shown. A dashed bar indicates some uncertainty in the identity of the levels populated in (n,γ) and (d,p). As indicated, the spin assignments for the 1476 and 1550 keV are taken essentially from a recent $(\vec{d},p)$ study (see Ref. 43) although the latter state is also observed here. The deexcitation transitions shown are those that were previously unknown.

cay to the 518.2-keV level may therefore be correct although the transition fits more naturally on both energy and intensity grounds as the 1755.5 → 700.7-keV transition. The decay to 1004 keV is highly doubtful. In any case, the $\frac{3}{2}^-$ assignment is indicated. (A $K=\frac{3}{2}$ description is consistent with the branching ratios observed using the Alaga rules.)

A general comment on the comparison of our results with Alenius *et al.*[38] is appropriate here. For the states above 1700 keV seen in common in both studies all but 1 of the 11 deexcitation transitions (7 firm assignments) placed in Ref. 38 are also identically located here. However an additional 32 transitions are also placed in the present study. 7 of these were observed by Alenius *et al*[38] and either not placed or placed differently. The other transitions are either unresolved or too weak to be specifically identifiable in that work, but are consistent with the spectra shown, particularly if it is recalled that certain states (e.g., 2081.5 keV) are much more strongly populated on resonance than in thermal capture.

1667 keV. No decay radiation was observed from

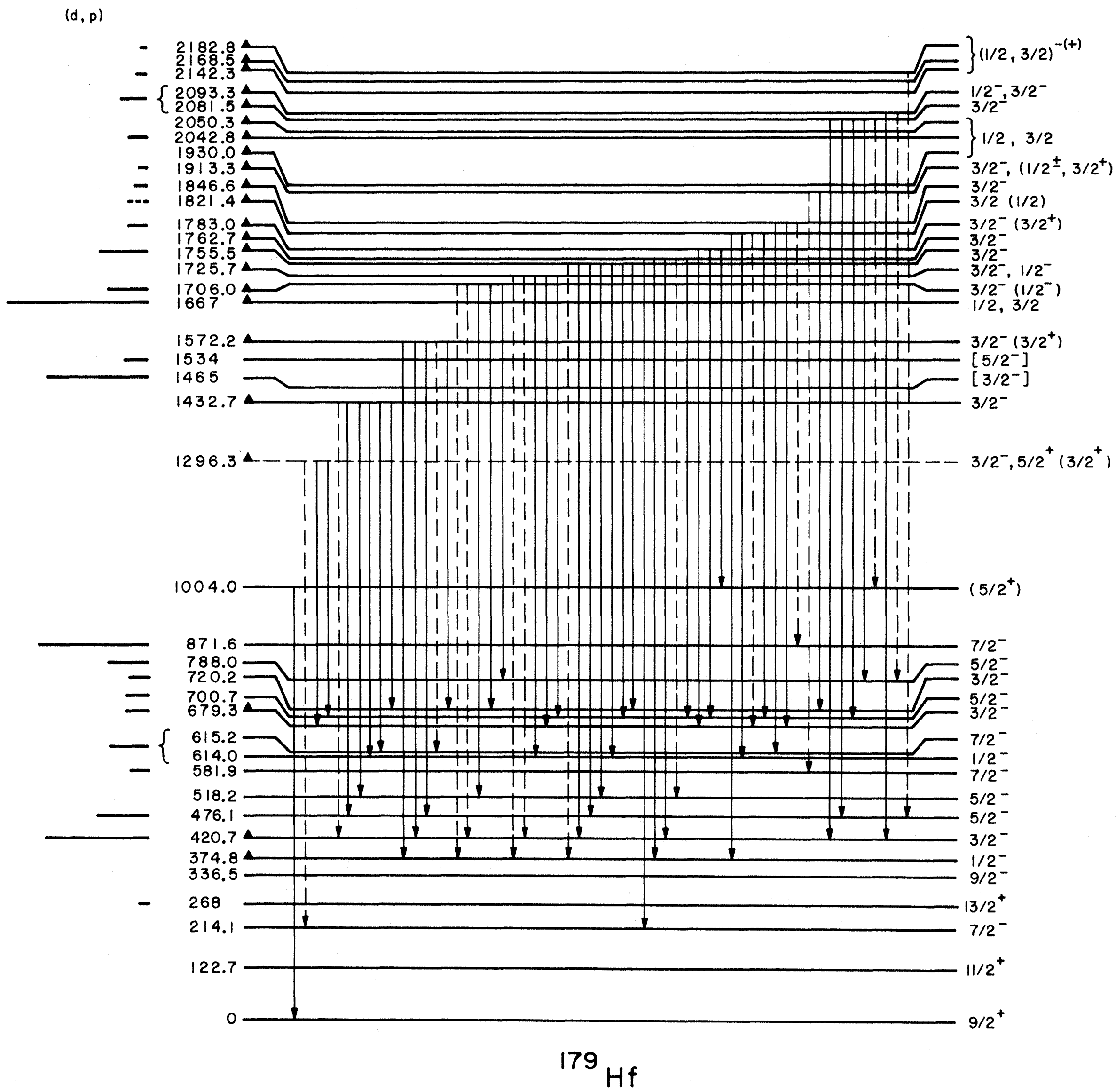

FIG. 5. Level scheme for ^{179}Hf. See caption to Fig. 3. The (d,p) cross sections are taken from Ref. 32. All the deexcitation transitions shown were previously unknown except for those reported in the concurrent study by Alenius *et al.* (Ref. 38). A strong 1004-keV γ ray was observed in this study: Its placement as deexcitating the 1004.0-keV level is taken from Ref. 38.

this level. In primary capture its presence is partially obscured by contaminants and an unambiguous proof of its population is not possible. The intensity quoted in Table III (state No. 6), if correct, would suggest but not demand negative parity and would virtually eliminate a $\frac{5}{2}^+$ assignment. The latter is also extremely unlikely in view of the large (d, p) cross section.[32]

1706.0, 1725.7, 1755.5, 1762.7 keV. These states are all observed strongly in both thermal and resonant capture suggesting $\frac{1}{2}^-$ or $\frac{3}{2}^-$ assignments. At least five deexcitation transitions (some tentative) are observed from each of these states and each decays to one or more $\frac{5}{2}^-$ states. The latter also decays to a $\frac{7}{2}^-$ state. The decay of the 1755.5-keV level is dominated by three branches to $\frac{5}{2}^-$ levels, that of the 1725.7-keV level has only one (weak) $\frac{5}{2}^-$ branch, and the 1706.0 keV decays strongly to two $\frac{5}{2}^-$ levels. The 1725.7-keV level is $\frac{1}{2}^-$, $\frac{3}{2}^-$. The others are likely $\frac{3}{2}^-$ levels although $\frac{1}{2}^-$ cannot be excluded for the 1706.0-keV state.

1783.0 keV. Noting the moderate feeding by primary radiation and the weaker decay of the state to $\frac{3}{2}^-$ and $\frac{5}{2}^-$ levels than to the $\frac{5}{2}^+$ level, a $\frac{3}{2}^{-(+)}$ assignment is suggested.

1821.4 keV. Weak population by primary radiation coupled with strong decays to both $\frac{5}{2}^-$ and $\frac{1}{2}^-$ levels suggests either $\frac{3}{2}^{\pm}$ assignments and eliminates $\frac{5}{2}^+$. $\frac{1}{2}^-$ is not definitely excluded by the decay routes.

1846.6 keV. This state is populated fairly strongly by the primary radiation, decays strongly to a $\frac{3}{2}^-$ level and more weakly to one and possibly two $\frac{7}{2}^-$ states. The weak branches to the latter states and the primary population intensity indicate $\frac{3}{2}^-$ rather than $\frac{3}{2}^+$.

1913.3 keV. Fed fairly weakly by primary radiation and decaying to a $\frac{3}{2}^-$ (and possibly a $\frac{7}{2}^-$ level), this level has likely spin-parity of $\frac{1}{2}^{\pm}$, $\frac{3}{2}^{\pm}$. Assuming the correctness of the $\frac{7}{2}^-$ decay branch eliminates $\frac{1}{2}^{\pm}$ and $\frac{3}{2}^+$.

2081.5 keV. This state is populated strongly in the primary radiation spectrum, decays most strongly to two $\frac{5}{2}^-$ states, considerably more weakly to another $\frac{5}{2}^-$ and $\frac{3}{2}^-$ level and tentatively rather strongly to the $\frac{5}{2}^+$ level at 1004.0 keV. A J^{π} assignment of $\frac{3}{2}^-$ is rather definite.

DISCUSSION

Nilsson Model

The ^{179}Hf ground state has one quasiparticle predominantly in the $\frac{9}{2}+[624]$ orbital[32] while ^{183}W has a neutron in the $\frac{1}{2}-[510]$ orbital.[6] In ^{184}W the latter is essentially filled and the $\frac{3}{2}-[512]$ orbital is the lowest with a large value of U^2.[20]

The next orbitals with $U^2 \sim 1$ and with large $C_J = \frac{1}{2}, \frac{3}{2}$ coefficients[1] are the $\frac{1}{2}-[501]$ and $\frac{3}{2}-[501]$ excitations. Both may be expected in the 1.3–2.5-MeV region. Their $J=\frac{1}{2}, \frac{3}{2}$ band members should dominate the (d, p) spectra. The $\frac{1}{2}-[770]$ orbital may mix with the $\frac{1}{2}-[501]$ via a $\Delta N = 2$ interaction, but otherwise the low-spin band members would not be expected in the (d, p) reaction. The $\frac{3}{2}-[761]$ also gives rise to little (d, p) strength to low-spin states. Part of the strength in (d, p) to the $\frac{1}{2}+[651]$ orbital ($\frac{5}{2}^+$ level) has been tentatively located[43] in ^{183}W at 1158 keV but the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ band members should not be strongly excited. It should also be remarked that the Nilsson model for this region provides no way for a strong $KJ^{\pi} = \frac{1}{2}\frac{3}{2}^-$ state not to be accompanied by a stronger $\frac{1}{2}\frac{1}{2}^-$ level nearby.

In ^{184}W, the states expected to be observed in the (d, p) reaction in first order are those of the configurations $\frac{1}{2}-[510]+K'\pi(Nn_z\Lambda), K=K'\pm\frac{1}{2}$. At higher excitation energies (above ~1500 keV) the dominant candidates for the second quasiparticle are again the $\frac{1}{2}-[501]$ and $\frac{3}{2}-[501]$ orbitals leading to positive-parity two-quasiparticle states with $K=0, 1, 2, \pi=+$. Again any strong 2^+ state is expected to be either an intrinsic excitation or to be accompanied by a stronger 1^+ state nearby.

In both odd and even final nuclei studied here precisely the same states are expected to be populated by $E1$ primary radiation in (n, γ) and with the largest spectroscopic strength in (d, p).

The above describes the simplest interpretation of the Nilsson model. In practice one may expect vibrational and higher-order quasiparticle excitations as well. Some of these may be excited in (d, p) via mixing with the appropriate elementary states[20] and in (n, γ), since they can form states with allowed spins and parities. It is in fact partly to provide empirical results for comparison with possible calculations of such mixing that this study was undertaken.

COMPARISON WITH EXPERIMENT

Orbital Assignments

The present results (spin-parity assignments or limitations) combined with the cross-section and partial-angular-distribution information of Refs. 6, 20, and 32 allow a discussion of possible Nilsson assignments to some of these higher-lying excited states.

In ^{179}Hf the (d, p) strength above $E_x = 1400$ keV is concentrated in the levels at 1465 and 1667 keV.[32] Moderately populated states just above these, at 1534 and either 1706.0 and 1755.5 keV, respectively, may be rotational excitations based on these levels. A consistent interpretation of the (d, p) data (see Table VII) could label the

1465- and 1534-keV states as the $\frac{3}{2}\frac{3}{2}-[501]$ and $\frac{5}{2}\frac{3}{2}-[501]$ states, while those data and the present results could support the suggestion that the 1667- and 1755.5-keV levels are the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the $\frac{1}{2}-[501]$ orbital. The rotational and decoupling parameters inferred from these spacings are reasonable ($\frac{3}{2}-[501]$: $\hbar^2/2\mathscr{I}=13.8$ keV; $\frac{1}{2}-[501]$: if $\hbar^2/2\mathscr{I}\equiv 13.8$ keV, then $a=1.13$). The $\frac{3}{2}-[501]$ assignment is consistent with similar assignments[32] at 1434 and 1503 keV in ^{177,181}Hf, respectively, and strong $\frac{1}{2}^-$, $\frac{3}{2}^-$ states with similar relative cross sections are observed[32] at 1634 and 1701 keV in ^{177}Hf. The (d,p) angular distribution[32] for the 1534-keV level and the absence of its observation, in thermal or resonant neutron capture give weak additional support to the $\frac{5}{2}^-$ assignment. Finally, the relative cross sections are in fair agreement with the Nilsson-model predictions (see Table VII). (The bracketed J^π labels for the 1465- and 1534-keV levels in Fig. 5 are based on these considerations. The large cross section to the former in itself at least suggests that $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$.)

A similar interpretation of ^{183}W is more difficult. The 1476- and ~1550-keV levels are perhaps the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels of the $\frac{1}{2}-[501]$ band, assuming the $(\vec{d},p)$ assignments.[43] It is puzzling that the $\frac{3}{2}-[501]$ orbital is not observed at a lower energy although the low energy of the $\frac{1}{2}-[501]$ orbital may be systematic in the W isotopes.[43]

A serious difficulty with these assignments is the absolute (d,p) strength. The strongest bandhead cross sections observed are only 30–50% of those expected.[48] Also, many more states receive significant (d,p) strength than would be anticipated (see below). One can conclude that the assignments suggested above are at most small fragments of the severely fractionated single-particle strength. This fractionation is not typical of existing theoretical calculations. For the Hf nuclei Soloviev *et al.*[11] have calculated the low-lying spectra with a model incorporating the multipole interaction of phonons with quasiparticles. For $N\geq 107$ (^{179,181}Hf) these calculations predict nearly pure quasiparticle spectra above 1400 keV, particularly in terms of the distribution of (d,p) strength and of $K^\pi=\frac{1}{2}^-$, $\frac{3}{2}^-$ intrinsic excitations. The calculations do predict the (d,p) spectra below 2 MeV to be dominated by the $\frac{3}{2}-[501]$ orbital but with a purity of ≥90% in contrast to the ~30% typically observed and to the rather strong population in (d,p) of a number of other states between 1400 and 2300 keV. Our main interest will therefore center on an analysis of this fractionation.

Before turning to this we note a similar situation in ^{184}W. The most plausible two quasiparticle assignments above 1600 keV are also summarized in Table VIII. The $K=4$ assignment is based on the cross sections and angular distributions reported in Ref. 20. Neither candidate state is observed here. The 1775.5-keV level is most likely 2^+, and since there is no lower-lying candidate for a strong 1^+ state at a reasonable energy spacing the contributing amplitude must be predominantly $\frac{1}{2}-[510]+\frac{3}{2}-[501]$, $K=2$ rather than $\frac{1}{2}-[510]+\frac{1}{2}-[501]$, $K=0,1$. Granted this, one expects[49] the

TABLE VII. Possible Nilsson neutron orbital assignments for ^{179}Hf and ^{183}W.

	$\frac{3}{2}^-[501]$		$\frac{1}{2}^-[501]$	
	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
^{179}Hf				
E_x (keV)	1465	1534	1667	1755.5(?)
σ_{exp} [a]	294	59	446	140
σ_{Th} [a]	923	76	794	169
^{183}W				
E_x (keV)	···	···	1476	~1550
σ_{exp} [a]	···	···	232	124
σ_{Th} [a]	···	···	778	166

[a] The cross sections are in μb/sr at $\theta_{c.m.}=90°$. The theoretical cross sections are calculated at $Q=+3.0$ MeV and the experimental entries are modified to this Q value by a small distorted-wave Born-approximation (DWBA) correction factor. The experimental cross sections are taken from Refs. 32 and 6 for ^{179}Hf, ^{183}W, respectively. Those for ^{179}Hf are based on a cross section of 340 μb/sr ($\theta=90°$) for the 871-keV state based on the quoted C_j^2 value and DWBA calculations similar to those described in Ref. 6 and in the text.

TABLE VIII. Possible Nilsson neutron orbital assignments for ^{184}W.

	$\frac{1}{2}^-[510]+\frac{3}{2}^-[501]$			$\frac{1}{2}^-[510] + \frac{7}{2}^-[503]$
	$K=1$		$K=2$	$K=4$
^{184}W	1^+	2^+	2^+	4^+
E_x (keV)	1615.2	1627.6	1775.5	1754 (1795) [b]
σ_{exp} [a]	67	34	123	74 (93)
σ_{Th} [a]	339	137	458	209

[a] The cross sections are in μb/sr at $\theta_{c.m.}=90°$. The theoretical cross sections are calculated at $Q=+3.0$ MeV and the experimental entries are modified to this Q value by a small distorted-wave Born-approximation (DWBA) correction factor. The experimental cross sections are taken from Ref. 20.

[b] These possibilities are discussed in more detail in Ref. 20 and are taken from that reference since neither state was observed in the present study.

$K=1$ combination to lie lower. The only possible members of this band are the probable 1^+ level at 1615.2 keV and the 2^+ one at 1627.6 keV. Their relative (d,p) cross sections[20] are large and in reasonable ratio (though small absolutely) but their energy spacing gives a very small rotational parameter, $\hbar^2/2\mathfrak{g}$, of 3.1 keV. A further obstacle to establishing these assignments is that the $\frac{1}{2}-[510]+\frac{3}{2}-[512]$, $K=1$ combination has not yet been located.

From Table VIII it is noted that only 20–30% of the expected strength for any of these states is concentrated in a single level. As in the odd nuclei, the mixing must be such that it is nearly meaningless to speak of the assignments in Tables VII and VIII as more than plausible suggestions for minor components of these levels.

FRACTIONATION AND DISTRIBUTION OF NILSSON STRENGTH

Using the spin-parity results presented above, an informative way to see the fractionation is to tabulate the minimum number of intrinsic excitations, of odd-parity excitations and of odd-parity excitations also populated[6,32] in (d,p), that are consistent with the data. The conservative values obtained, giving wide latitude to reasonable rotational and decoupling parameters are listed in Table IX, for $E_x \geq 1400$ keV for ^{179}Hf and ^{183}W. The entries are obtained assuming the favored spin-parity assignments and the 1465-keV level is assumed to be $\frac{3}{2}^-$. (If all J^π values allowed in Figs. 4 and 5 are considered the entries in Table IX are typically reduced by about 3 units. If the 1465-keV level assignment is eliminated the entries N_- and $N_-(d,p)$ are reduced by one unit for ^{179}Hf.) On the other hand, the entries are conservative lower limits to the number of bands present as they deal (1) essentially only with levels observed in primary capture in (n,γ) and (2) any two reasonably spaced levels that could possibly be $\frac{1}{2}$ and $\frac{3}{2}$ levels are counted as one band while in fact they could represent two separate band heads with $K=\frac{1}{2}, \frac{3}{2}$, respectively.

It is evident that there are many more rotational bands than can be accounted for easily with the Nilsson model. At most the latter specifies five or six. The model also predicts only two odd-parity orbitals with large $J=\frac{1}{2}^-$, $\frac{3}{2}^-$ (d,p) strength and at most two others, while at least seven odd-parity intrinsic excitations are populated[6,32] in (d,p) in both ^{179}Hf and ^{183}W. Mixing with vibrational excitations built on the $\frac{1}{2}-[510]$ and $\frac{3}{2}-[512]$ orbitals are likely mechanisms for production of some of the other states. However, it is interesting to note that the energy distribution of the observed bands is comparable in ^{179}Hf and ^{183}W although one might expect the unperturbed energies of admixed vibrational excitations to lie ~400 keV higher in the former.

Similar though these statistics are for the two nuclei there is, however, a difference between them. This is shown in Table IX where the summed and maximum (d,p) cross sections for low-spin states are compared to theory. The detailed meaning of these entries is explained in the footnotes to the table. The experimental uncertainties on these entries are ~20%. It is unlikely, however, that they should obliterate the main points, also visible in Figs. 4 and 5, that: (1) The maximum measured cross section for any given state (max σ) in ^{179}Hf is twice that in ^{183}W; (2) the (d,p) strength is likewise much more concentrated in ^{179}Hf (cf. column 8 and Figs. 4, 5); and (3) that while the

TABLE IX. Distribution of Nilsson strength for $E_x \geq 1400$ keV.

	N_T [a]	N_- [a]	$N_-(d,p)$ [a]	$\sum\sigma_{exp}$ [b] (n,γ)	$\sum\sigma_{exp}$ [c] (n,γ) $(l\leq 1)$	Max σ	$\sum\sigma$ ($\sigma>100$ μb/sr $l\leq 1$)	$\sum\sigma_{Th}$ [d] $\frac{1}{2}^-$, $\frac{3}{2}^-$
^{179}Hf	14	12	8	~1275	~1500	~446	~997	1886
^{183}W	10	9	7	714	1036	232	486	1848
^{184}W					384 [e]	123	123	2087

[a] N_T, N_-, and $N_-(d,p)$ are, respectively, lower limits on the total number of rotational bands between 1400 and 2300 keV, the number of odd-parity bands, and the number of odd-parity bands populated in (d,p).

[b] Cross section (μb/sr, $\theta_{c.m.}=90°$, $Q=3.0$ MeV) summed over all states observed in the primary radiation plus the states at 1465 and 1476 keV in ^{179}Hf and ^{183}W, respectively. The cross section data are taken from Refs. 6, 32, and 20.

[c] Same as b plus additional states probably populated via $l\leq 1$ based on the angular distributions of Refs. 6, 32, and 20. For ^{184}W the sum is over all states observed in (n,γ) plus a few with probable $J\leq 2$.

[d] Summed theoretical cross section (μb/sr, $\theta_{c.m.}=90°$, $Q=3.0$ MeV) for the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states of the $\frac{1}{2}-[501]$ and $\frac{3}{2}-[501]$ bands. The sum for ^{184}W also includes a contribution of the $\frac{5}{2}-[503]$ orbital as it can combine with the $\frac{1}{2}-[510]$ to yield a $K=2$ rotational band.

[e] If *all* states observed in (d,p) (see Ref. 20) from 2300 to 2700 keV in ^{184}W are also included, this entry becomes 653 μb/sr, still only ~30% the calculated intensity.

summed strength in ^{179}Hf is close to the Nilsson-model predictions this is not the case for ^{183}W (or for ^{184}W – see below). In ^{177,181}Hf the (d,p) cross section below 2 MeV was also found[32] to approximately equal the expected strength.

Lower limits on the number of different rotational bands are similar in ^{179}Hf and ^{183}W but apparently there is either a greater number in ^{183}W, such that many individual states are too weak to be observed in (d,p), or, much of the strength lies higher in energy contrary to the expectations of the Nilsson model, the energy systematics of the low-lying states or the empirical Fermi level locations. If this implies a greater breakdown in the Nilsson-model simplifications due to proximity in tungsten to the edge of the deformed region, it should be more evident in Os. An experiment is in progress to investigate this point.

Turning now to ^{184}W, Table IX gives a comparison of the summed experimental[20] and theoretical (d,p) cross sections to the expected even-parity orbitals in this energy region. This reiterates the point discussed earlier that the former is only about one-fifth the latter, in agreement with, but more extreme than, the trend noted in the odd-mass nuclei.

A comparison can be made between the odd and even nuclei that perhaps suggests the extent of the fragmentation. The energies of two-quasiparticle states of the form $\frac{1}{2}-[510]+K\pi[Nn_z\Lambda]$ $(\neq\frac{1}{2}-[510])$ should occur in ^{184}W in the same order (considering for example all particle states) and energy spacing as in ^{183}W but commencing at some energy above the pairing gap. Similarly the sequence $\frac{3}{2}-[512]+K\pi[Nn_z\Lambda]$ should be at an energy above the former series by an amount $\{E(\frac{3}{2}-[512]) - E(\frac{1}{2}-[510])\} = 209$ keV.

One can thus examine the resulting ^{184}W sequence in comparison to ^{183}W by subtracting from the ^{184}W two-quasiparticle energies the energy (1206.0 keV) of the $\frac{1}{2}-[510]+\frac{3}{2}-[512]$ configuration. In ^{184}W this is split into two components at 903.2 and probably 1386.2 keV and the (d,p) cross sections give a centroid energy of 1206 keV. [The splitting of the γ vibration and its microscopic structure are deduced in Ref. 20 from the (d,p) data where a detailed discussion may be found.] An additional 209 keV can be subtracted from the energies of the $\frac{3}{2}-[512]+K\pi[Nn_z\Lambda]$ configurations and extra data points obtained. The energies for the two sequences in ^{184}W should then be equal to each other and to those of the relevant single-quasiparticle states in ^{183}W. This is shown in Fig. 6 where for definiteness we have considered the lower-lying band head associated with the pair of different K-value excitations allowed for each two-quasiparticle combination. The assignments for this comparison are taken from Refs. 6, 20, 26, and 27. The results are quite consistent and indicate the adequacy of the Nilsson-model interpretation for the low-lying states.

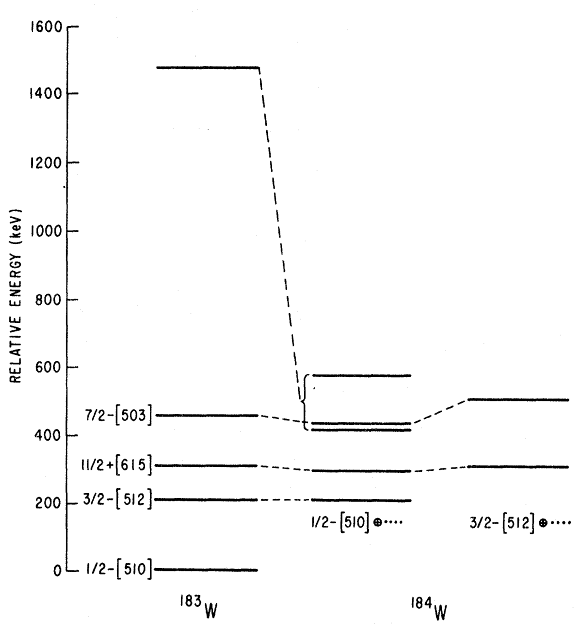

FIG. 6. Comparison of the relative Nilsson orbital energies for ^{183,184}W. See text for discussion. The energies for ^{184}W are obtained by subtracting 1206 (left column) or 1206 + 209 keV (right column) from the observed band-head excitation energies.

However, also plotted in the figure are the energies of the next lowest significant $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$ strength in ^{183}W and the next significant low-spin (d,p) strength in ^{184}W. The brackets indicate that the latter can be taken as either the likely $K=1$ 1615.2-keV level or the state at 1775.5 keV. In either case this state must contain an amplitude involving the $\frac{1}{2}-[510]$ quasiparticle and so can be placed in the scheme. Although comparable agreement is not expected since these are only fragments of the respective intrinsic excitations, the discrepancy is striking. It can be interpreted to imply a greater amount of fragmentation in ^{184}W than ^{183}W or ^{179}Hf. This is perhaps reasonable as there are many more intrinsic excitations available for mixing in ^{184}W. It is also consistent with the observation that even a smaller fraction ($\sim\frac{1}{5}$) of the expected (d,p) strength (in the 1.5–2.3-MeV region) is found in ^{184}W than in ^{183}W ($\sim\frac{1}{2}-\frac{2}{3}$): That is, if we assume that the (d,p) strength is spread throughout the energy region of mixing that region may be ~1–2 MeV larger in ^{184}W than in ^{183}W and significant portions of the (d,p) strength may occur above 2.5 MeV in ^{184}W. More conservatively the effect illustrated in Fig. 6 can indicate the sort of energy range, common to both $^{183,184}W$, for the fragmentation of these orbitals: That is ≥1 MeV. Rather large mixing matrix elements are therefore implied (several hundred keV) and it is likely that most wave functions of low-spin states (with $E_x \gtrsim 1400$ keV) in either nucleus are rather complex linear combinations involving significant amplitudes of many components.

At least for 2^+ states such is not the result of some recent theoretical calculations[29] that can be compared in detail to the experimental results. Figure 7 shows this comparison in which the calculated spectrum is obtained from the energies and wave functions of the lowest 21 roots of the secular random-phase-approximation equations. The experimental cross sections are taken from Ref. 20 using the present spin-parity assignments. It must be noted that the calculated wave functions and (d, p) cross sections and therefore the calculated fragmentation are essential results of the model but the detailed energies are only semiquantitative.[29]

As discussed in Ref. 20, the states at 903.2 and 1386.2 keV likely contain the configuration $\frac{1}{2}-[510]+\frac{3}{2}-[512]$, $K=2$. The former is considered the γ vibration and the latter largely a noncollective state containing the remainder of this configuration.

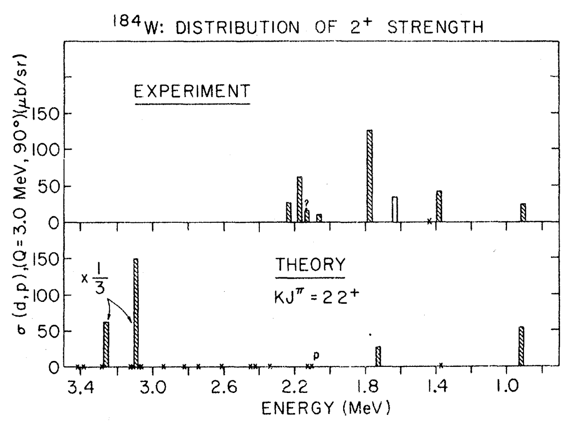

FIG. 7. Comparison of the observed and calculated spectrum of intrinsic 2^+ states in ^{184}W. An × indicates a 2^+ state with no (observed or calculated) (d,p) cross section. The open bar for the state observed at 1627.6 keV indicates that this is most likely not an intrinsic 2^+ state but rather has $KJ^\pi = 12^+$ (see text). All the other observed 2^+ states are thought to be band heads. The ? above the 2126.2-keV level indicates it has only a tentative 2^+ assignment. The P next to the 2.1-MeV level indicates it is the lowest calculated state with a dominant two-proton configuration. For the known 2^+ band heads at 903.2 and 1386.2 keV and for the other 2^+ states above 1400 keV the (d,p) cross sections are taken from Ref. 20.

tion. The calculation correctly predicts roughly comparable cross sections to the two excitations (at 903 and 1720 keV) although the second occurs 350 keV lower than is calculated. The model predicts no further (d, p) strength until 3 MeV while the data indicate several times this (d, p) intensity below 2300 keV.

An important feature to note is the strong state observed at 1775.5 keV. It is probably a 2^+ level populated via a $\frac{1}{2}-[510]+\frac{3}{2}-[501]$, $K=2$ component and represents an amplitude of ~0.6 for this configuration. On the other hand, the calculations predict this configuration to be 99% pure two quasiparticle and to lie at ~3.1 MeV. The other feature of interest is the group of 2^+ levels that are likely band heads (intrinsic excitations) populated near 2 MeV. The calculated spectrum provides configuration mixing among some of the two-quasiparticle basis states but, except in the 903- and 1720-keV 2^+ states, not among those containing the $\frac{1}{2}-[510]$ orbital, and therefore not in the (d, p) spectrum. The data indicate that considerably greater configuration mixing involving this orbital occurs than the calculations provide resulting in a number of moderately populated 2^+ states. The mixing is sufficient to force considerable fragments of the total 2^+ cross section down at least 1 MeV in energy.

Finally, the possible two-proton character of the 1430.9-keV level has been discussed above. If true, the lowest two-proton 2^+ strength also occurs ~700 keV lower in the spectrum than is calculated.

Similar calculations have been performed[31] for 1^+ states and are of considerable theoretical interest: They relate[31] to the distribution of the $\nu=\pm1$ vibrational mode and possibly to the empirically determined need for reduction in Coriolis mixing matrix elements.[6,16,19-21] The calculations indicate a similar distribution of (d, p) strength to 1^+ states as for 2^+ levels but somewhat greater configuration mixing. The present experiment provides little new information on these states. If the 1615.2-keV level represents a fraction of the $\frac{1}{2}-[510]+\frac{3}{2}-[501]$, $K=1$ band head, it occurs about 1500 keV lower in energy than the calculated position (3.07 MeV) and with ~25% the intensity predicted for the dominant state with this configuration.

CONCLUSIONS

The higher-excitation-energy region (~1.3–2.3 MeV) of ^{179}Hf, $^{183,184}W$ has been investigated using the (n, γ) reaction at resonant neutron energies. Primary and secondary radiation was detected and level schemes constructed with a number of new firm or tentative spin assignments. In establishing these, available data from other studies have been considered.

Combining the information with recent (d, p) studies evidence was presented for considerable fragmentation and distribution of the single- or two-quasiparticle strengths: This occurs in all three nuclei but apparently with somewhat more severity in W than in Hf and more so in ^{184}W than in ^{183}W.

While it is possible to suggest a few Nilsson assignments it is clear that the corresponding states represent only the lowest and minor fragments of the respective intrinsic excitations. Therefore the emphasis has not been on detailed explanation of the quasiparticle character of each state but rather on the distribution of strength for selected spins.

The explanation of the fractionation is not clear but must involve considerable and complex mixing of the pure quasiparticle excitations with those involving larger numbers of quasiparticle components and with vibrational excitations. For ^{179}Hf, earlier calculations by Soloviev, Vogel, and Jungclaussen[11] predict the $\frac{3}{2}-[501]$ orbital below 2 MeV but otherwise do not adequately reproduce the low-lying states or the distribution of (d, p) strength.

A comparison with a specific calculation for 2^+ states in ^{184}W was presented. The data indicated considerable (d, p) strength between 1.5 and 2.5 MeV, and, correspondingly, many low-lying states with large two-neutron quasiparticle amplitudes including $\frac{1}{2}-[510]$. In particular, evidence for low-lying wave-function components of the form $\frac{1}{2}-[510]+\frac{3}{2}-[501]$, $K=2$ was presented. The calculated mixing of the two-quasiparticle states, on the other hand, was not such as to provide fragmentation of the (d, p) strength in the higher-lying levels.

It would be useful to push the experimental results to higher energies although the greatly increased level density makes this difficult, both for reasons of resolution and for relatively unambiguous association of levels seen in (d, p) and (n, γ). Also of interest would be similar investigations of the Os isotopes and of nuclei (e.g. Er or Dy) more centrally located in the deformed region.

Theoretically, additional detailed calculations of these higher-lying levels are needed and it is hoped that data of this sort may encourage them. These might be carried out within the general framework of the Nilsson model. Alternatively the apparent sudden and considerable collapse of that model above vibrational energies perhaps suggests that an approach from a different basis might also be fruitful by allowing the higher-lying levels to be recognized still as elementary excitations.

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[1]S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 16 (1955).

[2]M. E. Bunker and C. W. Reich, Rev. Mod. Phys. 43, 348 (1971).

[3]W. Ogle, S. Wahlborn, R. Piepenbring, and S. Fredriksson, Rev. Mod. Phys. 43, 424 (1971).

[4]B. Elbek and P. O. Tjøm, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1969), Vol. 3.

[5]B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. Skrifter 1, No. 8 (1959); C. J. Gallagher and V. G. Soloviev, *ibid.* 2, No. 2 (1962).

[6]R. F. Casten, P. Kleinheinz, P. J. Daly, and B. Elbek, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 38, No. 13 (1972).

[7]I. Kanestrøm and P. O. Tjøm, Nucl. Phys. A138, 177 (1969).

[8]J. Borgreen, G. Løvhøiden, and J. C. Waddington, Nucl. Phys. A131, 241 (1969).

[9]D.R.Bès and Cho Yi-Chumg, Nucl. Phys. 86, 581 (1966).

[10]D. R. Bès, P. Federman, E. Maqueda, and A. Zuker, Nucl. Phys. 65, 1 (1965).

[11]V. G. Soloviev, P. Vogel, and G. Jungclaussen, Izv. Akad. Nauk SSSR, Ser. Fiz. 31, 518 (1967) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 515 (1967)]; V. G. Soloviev and P. Vogel, Nucl. Phys. A92, 449 (1967).

[12]A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 27, No. 16 (1953); O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 1, p. 601.

[13]D. G. Burke, B. Zeidman, B. Elbek, B. Herskind, and M. C. Olesen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 35, No. 2 (1966).

[14]F. A. Rickey, Jr., and R. K. Sheline, Phys. Rev. Letters 17, 1057 (1966).

[15]P. Kleinheinz, R. F. Casten, and B. Nilsson, to be published.

[16]S. A. Hjorth, H. Ryde, K. A. Hagemann, G. Løvhøiden, and J. C. Waddington, Nucl. Phys. A144, 513 (1970).
[17]S. Wahlborn and R. K. Gupta, Phys. Letters 40B, 27 (1972).
[18]F. S. Stephens and R. S. Simon, Nucl. Phys. A183, 257 (1972).
[19]J. R. Erskine, Phys. Rev. 138, B66 (1964).
[20]P. J. Daly, P. Kleinheinz, and R. F. Casten, to be published.
[21]R. T. Brockmeier, S. Wahlborn, E. J. Seppi, and F. Boehm, Nucl. Phys. 63, 102 (1964).
[22]R. F. Casten, P. Kleinheinz, P. J. Daly, and B. Elbek, Phys. Rev. C 3, 1271 (1971).
[23]C. Gunther, P. Kleinheinz, R. F. Casten, and B. Elbek, Nucl. Phys. A172, 273 (1971).
[24]J. V. Maher, J. R. Erskine, A. M. Friedman, R. H. Siemssen, and J. P. Schiffer, Phys. Rev. C 5, 1380 (1972).
[25]R. F. Casten and O. Hansen, to be published.
[26]A. H. Kukoč, B. Singh, J. D. King, and H. W. Taylor, Nucl. Phys. A143, 545 (1972).
[27]P. J. Daly and S. W. Yates, Bull. Am. Phys. Soc. 17, 29 (1972); and private communication.
[28]P. J. Daly, private communication.
[29]I. Hamamoto, private communication.
[30]J. D. Immele and G. L. Struble, Nucl. Phys. A187, 459 (1972); J. D. Immele, private communication.
[31]I. Hamamoto, Nucl. Phys. A177, 484 (1971); and private communication.
[32]F. A. Rickey, Jr., and R. K. Sheline, Phys. Rev. 170, 1157 (1968); M. N. Vergnes and R. K. Sheline, *ibid.* 132, 1736 (1963).
[33]P. Manfrass, A. Andreeff, R. Kästner, W. Bondarenko, N. Kramer, and P. Prokofjew, Nucl. Phys. A102, 563 (1967).
[34]P. Alexander and R. S. Hager, Phys. Rev. 139, B288 (1965); V. Hönig, K. E. G. Löbner, and M. Vetter, Nucl. Phys. 86, 657 (1966).
[35]R. R. Spencer and K. T. Faler, Phys. Rev. 155, 1301 (1967).
[36]C. Samour, J. Julien, R. N. Alves, S. de Barros, and J. Morgenstern, Nucl. Phys. A123, 581 (1969).
[37]A. Namenson and H. H. Bolotin, Phys. Rev. 158, 1206 (1967).
[38]G. Alenius, S. E. Arnell, C. Schale, and E. Wallander, Nucl. Phys. A186, 209 (1972).
[39]M. Beer, O. A. Wasson, and R. Chrien, private communication.
[40]R. F. Casten and W. R. Kane, Bull. Am. Phys. Soc. 17, 17 (1972).
[41]W. R. Kane, D. Gardner, T. Brown, A. Kevey, E. der Mateosian, G. T. Emery, W. Gelletly, M. A. J. Mariscotti, and I. Schröder, in *Proceedings of the International Symposium on Neutron Capture Gamma Ray Spectroscopy, Studsvik, 11–15 August, 1969* (International Atomic Energy Agency, Vienna, 1969), p. 105.
[42]M. A. J. Mariscotti, Nucl. Instr. Methods 50, 309 (1967).
[43]R. F. Casten, P. W. Keaton, Jr., and G. P. Lawrence, Phys. Rev., to be published.
[44]R. R. Spencer, K. T. Faler, and R. A. Harlan, Phys. Rev. 175, 1495 (1967).
[45]G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 29, No. 9 (1955).
[46]K. Neergaard and P. Vogel, Nucl. Phys. A145, 33 (1970).
[47]F. Stecher-Rasmussen, J. Kopecky, K. Abrahams, and W. Ratynski, Nucl. Phys. A181, 250 (1972).
[48]It is important to note that, in both ^{179}Hf and ^{183}W, the observed and calculated (d, p) cross sections to all states below 1400 keV *agree* (see Ref. 6 and 32) to within experimental errors: This applies individually to the $l=1$ transitions as well. Thus the adequacy of the distorted-wave Born-approximation calculations is demonstrated, or, at least, any questions of optical-model-parameter dependence are unimportant. The present results could be discussed equally in terms of double ratios of experimental to calculated cross sections at high and low excitation energies. The Q dependence of different distorted-wave Born-approximation calculations is very similar even if the absolute cross sections are not.
[49]C. J. Gallagher and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).

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Study of ^{95}Nb by Means of the ^{94}Zr(^{3}He, d) Reaction*

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The ^{94}Zr(^{3}He, d)^{95}Nb reaction was studied with 35.6-MeV ^{3}He particles from the Argonne cyclotron. Experimental angular distributions are compared with distorted-wave Born-approximation calculations to determine l values and spectroscopic factors. The results are compared with the previous data on (^{3}He, d) and (d, ^{3}He) reactions and β decay. The proton configurations of ^{95}Nb are discussed in terms of this data and recent theoretical results.

I. INTRODUCTION

The proton structure of $N \approx 50$ nuclei has been studied extensively. In the case of ^{95}Nb, only four states have been observed[1] from ^{95}Zr decay. The reported results[2–4] of pickup and stripping reactions reveal the existence of several unresolved doublets, and the spin assignments are consequent-