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Deuteron-induced reaction studies of the nuclear structure of ^{178}Hf

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Abstract. The level structure of ^{178}Hf is interpreted on the basis of the population of the states following ^{178}Hf (d,d'), ^{177}Hf (d,p) and ^{179}Hf (d,t) reactions. Evidence for quadrupole and octupole vibrational bands and unmixed and intermixed two-quasiparticle configurations is presented.

Keywords. ^{178}Hf, vibration band; two quasiparticle configurations; deuteron-induced reaction studies.

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1. Introduction

The nucleus ^{178}Hf has been studied extensively especially by thermal neutron capture and by average resonance neutron capture [1]. This has led to a detailed set of levels with assigned spins and parities which have been grouped into rotational bands [2]. Often vibrational or configurational assignments for these bands are lacking or uncertain. This work attempts to remedy this situation by reporting on ^{178}Hf (d,d') studies to look especially for collective vibrations, and ^{177}Hf (d,p) and ^{179}Hf (d,t) reactions to look for the characteristic differential cross-sections ("finger prints") of various configurations.

It is interesting and probably unique to this region of the nuclear periodic table that almost all of the low-lying two quasineutron configurations have corresponding low-lying two quasiproton configurations with the same pairs of Gallagher–Moszkowski K values. As shown in table 1 even the energy ordering of K values is the same. This implies that often the low-lying rotational bands will be admixtures of two quasineutron and two quasiproton configurations. Evidence for this was first observed by Gallagher *et al* [3] who found two excited states in ^{178}Hf at 1148 and 1480 keV following the decay of the high spin 2·1 h ^{178}Ta activity. The spins and parities were determined to be 8^- for both levels and the states were interpreted as highly admixed two-proton and two-neutron configurations.

Table 1. Similar Gallagher–Moszkowski doublets resulting from the low lying two-quasiproton and two-quasineutron configurations in ^{178}Hf. The identical band quantum numbers K_S (for the singlet with antiparallel spins) and K_T (for the triplet with parallel spins) of each Gallagher–Moszkowski doublet with the lower lying K_S underlined is shown in the centre.

Two-quasiproton configurations	K_S, K_T	Two-quasineutron configurations
$\pi\pi[404\downarrow] \pm [514\uparrow]$	$\underline{8}^-, 1^-$	$\nu\nu[514\downarrow] \pm [624\uparrow]$
$\pi\pi[404\downarrow] \pm [402\uparrow]$	$\underline{6}^+, 1^+$	$\nu\nu[514\downarrow] \pm [512\uparrow]$
$\pi\pi[404\downarrow] \mp [541\downarrow]$	$\underline{3}^-, 4^-$	$\nu\nu[514\downarrow] \pm [651\downarrow]$
$\pi\pi[404\downarrow] \mp [411\downarrow]$	$\underline{3}^+, 4^+$	$\nu\nu[514\downarrow] \mp [521\downarrow]$
$\pi\pi[404\downarrow] \pm [523\uparrow]$	$\underline{7}^-, 0^-$	$\nu\nu[514\downarrow] \mp [633\uparrow]$
$\pi\pi[514\uparrow] \mp [402\uparrow]$	$\underline{2}^-, 7^-$	$\nu\nu[624\uparrow] \mp [512\uparrow]$
$\pi\pi[514\uparrow] \pm [411\downarrow]$	$\underline{5}^-, 4^-$	$\nu\nu[624\uparrow] \pm [521\downarrow]$
$\pi\pi[514\uparrow] \mp [523\uparrow]$	$\underline{1}^+, 8^+$	$\nu\nu[624\uparrow] \mp [633\uparrow]$
$\pi\pi[514\uparrow] \pm [541\downarrow]$	$\underline{5}^+, 4^+$	$\nu\nu[624\uparrow] \pm [651\downarrow]$

2. Experimental methods and results

Deuteron-induced reactions were studied by bombarding thin vacuum-evaporated or isotope-separated targets (prepared on the Florida State University Isotope Separator) with well collimated 12 MeV deuterons from the Florida State University Tandem van de Graaff Accelerator. A list of the various reactions and the corresponding targets used in these experiments is given in table 2. Beam currents varied from 0·3 to 1·5 μA. The light outgoing reaction particles were momentum analyzed with the 6/5 scale Florida State University Browne-Beuchner magnetic spectrograph. Charged particles of a given focused momentum were detected by sets of four Kodak NTA 50 micron nuclear plates affixed to the focal curve of the spectrograph by a removable plate holder. The plates were covered with aluminium foil during the (d, p) exposures to stop inelastically scattered deuterons. The developed plates were scanned under a microscope in 1/2 mm × 8 mm strips. The numbers of tracks per 1/2 mm strip were recorded as a function of the distance along the calibrated focal curve of the spectrograph.

2.1 *Inelastic deuteron scattering experiments*

The reaction ^{178}Hf (d, d') was studied at laboratory angles of 60°, 70°, 80° and 100°. These spectra were accumulated simultaneously with the ^{178}Hf (d, t) spectra. The elastic and inelastic deuteron spectrum taken at 100° is shown in figure 1. The corresponding excitation energies and their respective intensities are given in table 3. The excitation energies quoted in table 3 correspond to the more accurate energies given by Browne [2]. Elastic deuteron groups from light impurities (e.g. ^{37,35}Cl) have been identified by their large kinematic shifts.

2.2 *Stripping and pick-up reactions*

The reaction ^{177}Hf (d, p) was studied at laboratory angles 35°, 45°, 55°, 65°, 85° and 95°. The spectrum at 65° with respect to the incident beam is shown in figure 2. The

Table 2. Nuclear reactions, angles and targets used in studying ^{178}Hf.

Reaction	Angle	Target
^{177}Hf (d,p)	55° 65°	Evaporated Oxide $\sim 75\,\mu g/cm^2$ on C ^{176}Hf 0·76% ^{177}Hf 91·67% ^{178}Hf 4·85% ^{179}Hf 0·92% ^{180}Hf 1·80%
^{177}Hf (d,p)	35° 45° 85° 95°	Direct deposition on F.S.U. Isotope Separator $\sim 30\,\mu g/cm^2$ on C $\sim 99\%$ ^{177}Hf
^{179}Hf (d,t)	75° 85° 95°	Isotope separated $\sim 10\,\mu g/cm^2$ on C $\sim 99\%$ ^{179}Hf
^{178}Hf (d,d)	60° 70° 80° 100°	Evaporated Oxide $\sim 100\,\mu g/cm^2$ on C ^{177}Hf 2·1% ^{178}Hf 95·5% ^{179}Hf 1·2% ^{180}Hf 1·2%

a) Isotopic composition of the targets was furnished by the Isotopes Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

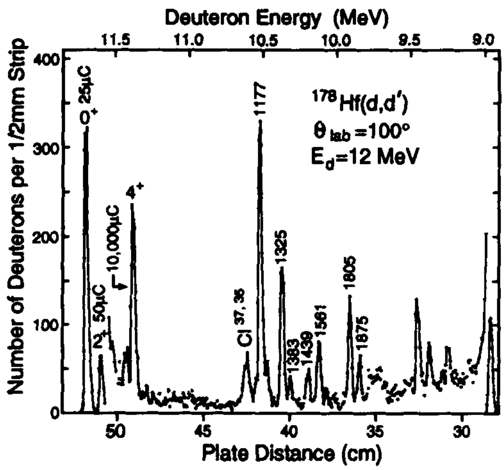

Figure 1. The deuteron spectrum observed at 100° with respect to the beam direction in the reaction ^{178}Hf (d,d') using 12·0 MeV deuterons. The energies of prominent peaks below 2 MeV are labeled by their energies in keV. Different total exposures are shown in microcoulombs (μC).

Table 3. Levels, assignments and differential cross-sections observed in the ^{178}Hf(d,d'), ^{177}Hf(d,p) and ^{179}Hf(d,t) reactions.

Excitation energy[a] (keV)	Assignment KJ^{π}	(d,d') differential Cross-section (μb/sr) 80°	100°	(d,p) differential Cross-section (μb/sr) 35°	45°	55°	65°	85°	95°	(d,t) relative Cross-section 95°	Configuration
0	$0\,0^+$	$1\cdot35\times10^5$	$4\cdot5\times10^4$				~1				G.S. Band
93·2	$0\,2^+$	9700	4400	3			8	5	11	~3	G.S. Band
306·6	$0\,4^+$	94	72	4	9		5	4	6	7	G.S. Band
632·2	$0\,6^+$	~8	~6				3			5	G.S. Band
1058·6	$0\,8^+$						~1	~1			G.S. Band
1147·4	$8\,8^-$					~4	~3	3		5	$\nu\nu[514\downarrow]+[624\uparrow]_{8}+\pi\pi[404\downarrow]+[514\uparrow]_{8^-}$
1174·6	$2\,2^+$	220	120	b	15	26	29	13	12		γ-band
1199·4	$0\,0^+$			~5		~2	~3?	3			$K=0^+$ two-quasiparticle?
1260·3	$2\,2^-$									25	$K=2^-$; Oct.; $\nu\nu[624\uparrow]-[512\uparrow]_{2^-}$
1268·5	$2\,3^+$			24	31	31	21	14	14		γ-band
1276·7	$0\,2^+$	9									2^+ on 1199·4 keV $K=0^+$
1310·1	$1\,1^-$					7	3	~2	~2		$K=1^-$; Oct.; $\nu\nu[514\downarrow]-[624\uparrow]_{1^-}$
1322·5	$2\,3^-$	130	62							30	3^- on 1260·3 keV $K=2^-$
1362·6	$1\,2^-$					~2	5	4	6		{2^- on 1310·1 keV $K=1^-$ and
1364·1	$8\,9^-$									20	{9^- on 1147·1 keV $K=8^-$
1384·5	$2\,4^+$	18	15	10	11	15	14	7	11		γ-band
1409·4	$2\,4^-$									30	4^- on 1260·3 keV $K=2^-$
1433·6	$1\,3^-$	15	20	25?		3	4	4	3	23	3^- on 1310·1 keV $K=1^-$
1450·4	$0\,4^+$			~8			~2				4^+ on 1199·4 keV $K=0^+$
1479·0	$8\,8^-$						5	17	3	5	$\pi\pi[404\downarrow]+[514\uparrow]_{8^-}+\nu\nu[514\downarrow]+[624\uparrow]_{8^-}$
1496·5	$0\,2^+$	13									$K=0^+$, $\beta+$pairing vib.?
1512·6	$2\,5^-$									(13)	5^- on 1260·3 keV $K=2^-$
1513·6	$0\,2^+$	17									$K=0^+$, $\beta+$pairing vib.?
1513·8	$4\,4^+$			160	200	170	150	91	98		$\nu\nu[514\downarrow]+[510\uparrow]_{4^+}$
1533·2	$2\,5^+$			~15	~40	27	23	11	10		γ-band
1538·8	$1\,4^-$									10	4^- on 1310·1 keV $K=1^-$

1554·0	6 6^+		6		7	12	4			$\nu\nu[514\downarrow]+[512\uparrow]_{6^+}$
1561·5	(2) 2^+	28								2^+ unassigned
1601·5	8 10^+			10	7	9	5	3		10^- on 1147·1 keV $K=8^-$
1636·7	5 5^-								180	$\nu\nu[624\uparrow]+[521\downarrow]_{5^-}$
1640·5	4 5^+		110	110	120	100	69	70		5^+ on 1513·8 keV $K=4^+$
1648·8	2 6^-								~10	6^- on 1260·3 keV $K=2^-$
1697·5	8 9^-				7	6	3	8		9^- on 1479·0 keV $K=8^-$
1758·1	3 3^+		12	8	14	12	8	8		$\nu\nu[514\downarrow]-[521\downarrow]_{3^+}$
1781·3	5 6^-								25?	6^- on 1636·7 keV $K=5^-$
1788·6	4 6^+		14	38	17	c	21	18		6^+ on 1513·8 keV $K=4^+$
1803·4	3 3^-	42								$K=3^-$ Oct. Band
1808·3	(2) 2^+		24	24	26	29	18	22	20	2^+ unassigned
1862·2	3 3^+		150	170	240	150	150	120	40	$\nu\nu[514\downarrow]-[510\uparrow]_3$
1875[d]	(0 3)	24								tentative $K=0^-$ $J=3^-$ Oct.
1891·3	? 2^+		9	21	23	33	17	8		2^+ unassigned
1913·6	3 4^-		9	4	15	15				4^- on 1803·4 $K=3^-$
1953·1	3 4^+		130	160	230	150	120	110		{ 4^+ on $K=3^+$ and 7^+ on $K=4^+$
1953·7	4 7^+									at 1862·2 and 1513·6 keV }
2068·0	3 5^+		49	47	65	58	40	43		5^+ on 1862·2 keV $K=3^-$
2139[d]	(4 8^+)		15		23	18	3	6		tentative 8^+ on 1513·6 keV $K=4^+$

a. Ref. 1;
b. Obscured by impurity;
c. Partially obscured by edge of plate;
d. Energy uncertainty 5 keV

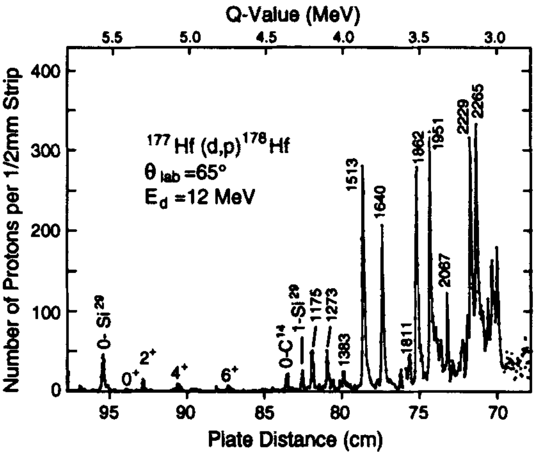

Figure 2. The proton spectrum observed in the reaction ^{177}Hf (d,p) ^{178}Hf using 12·0 MeV deuterons. The angle of observation was 65° with respect to the beam direction. Prominent peaks are labeled by their energies in keV. The ground state band is also labeled with the appropriate spins, and impurities are indicated.

excitation energies (corresponding to ref. 2) and differential cross-sections at each of the angles are given in table 3. The (d,p) Q-value to the ground state of ^{178}Hf is determined to be 5397 ± 10 keV which is in good agreement with the neutron separation energy of $7626{\cdot}34 \pm 0{\cdot}30$ keV [1] measured using the thermal neutron capture reaction.

The (d,t) reaction leading to ^{178}Hf has been studied at angles 75°, 85° and 95°. The ^{179}Hf target was prepared on the Florida State University Isotope Separator using natural $HfCl_4$. The ion source production efficiency was very poor resulting in an exceedingly thin target. No attempt was made to extract absolute cross-sections. The states observed at all three angles and the relative intensities at 95° are given in table 3. The ^{179}Hf (d,t) ^{178}Hf ground state Q-value is determined to be 153 ± 10 keV.

3. The ^{178}Hf level scheme and discussion

A level scheme for ^{178}Hf is presented in figure 3. It utilizes the extensive level structure observed in a large number of previous studies and summarized in Nuclear Data Sheets [2], but interprets the levels in terms of vibrational bands and two-quasiparticle configurations largely deduced from this research. No attempt is made to plot all levels previously observed unless they are part of rotational bands observed in this study, and no levels above ~2200 keV are considered. The levels populated in this research are shown bold with a triangle above the line to the right representing (d,p) population, below the line (d,t) population, and above the line to the left, (d, d') population. The level structure will be described in what follows in terms of the ground state rotational band, collective vibrational states and two-quasiparticle configurations, in that order.

The ground state rotational band is observed through spin 6^+ in the (d,d') reaction and tentatively through 8^+ in the (d,p) reaction.

The 2^+ gamma vibrational band head at 1174·6 keV is the most strongly populated state in the inelastic deuteron spectrum (figure 1), except for some members of the

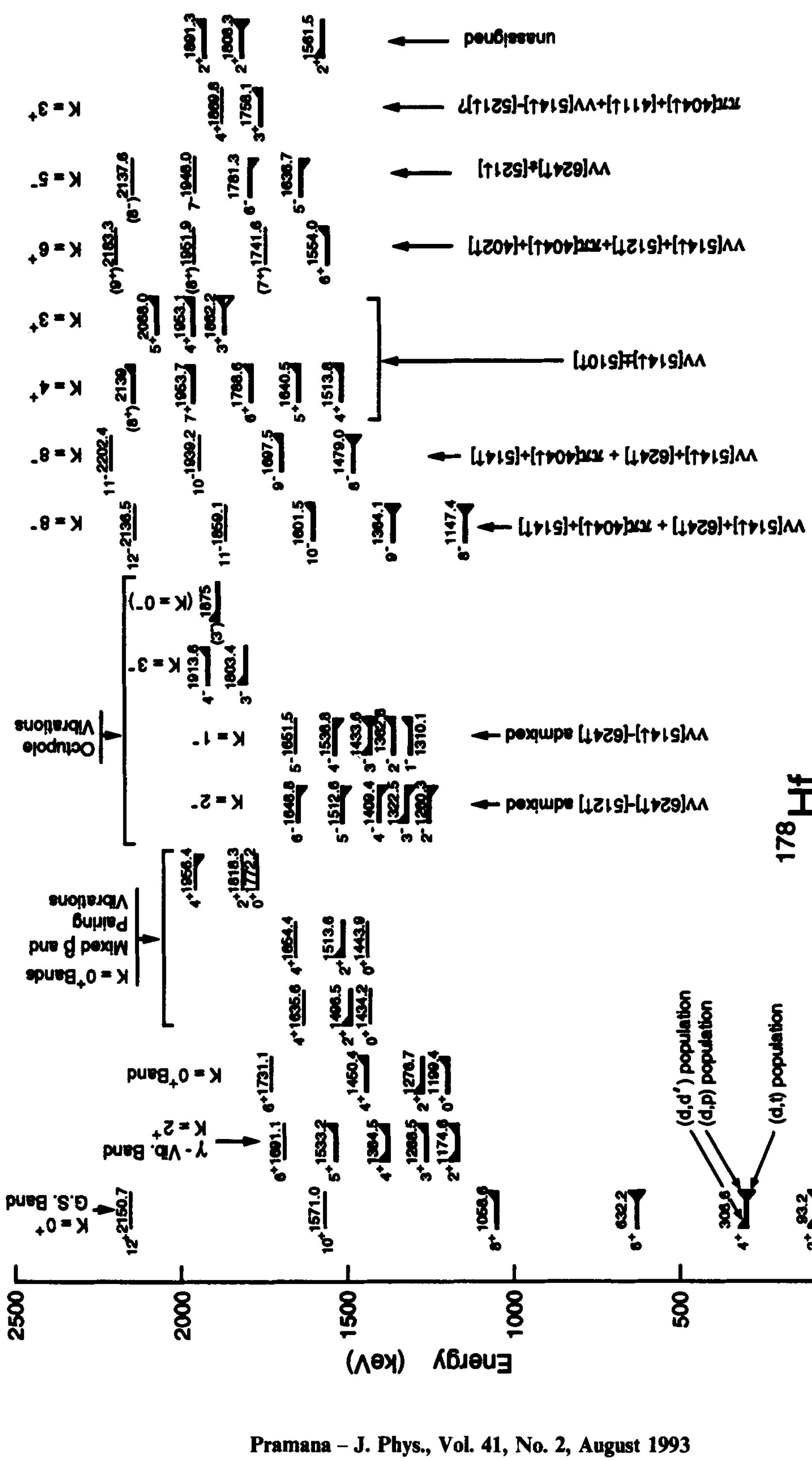

Figure 3. Level structure of ^{178}Hf as populated in (d,d'), (d,p) and (d,t) reactions. Only levels with flags on them were populated in this study. All other levels and the energies, rounded to 1 decimal, were taken from ref. [2].

Table 4. Differential cross-sections in the population of the gamma vibrational band in the (d,p) reaction in ^{178}Hf.

Angle	I^π Energy (keV)	Differential cross-sections (μb/sr) 2^+ 1176	3^+ 1269	4^+ 1384	5^+ 1532
45° Theory[a]		17·6	16·1	9·3	3·3
Expt.		15	31	11	~40[b]
65° Theory[a]		17·4	17·0	10·2	3·8
Expt.		29	21	14	23[b]

[a] Reference [4]; [b] see text

ground state rotational band. The 4^+ member of this band is also populated in the inelastic deuteron experiment, but, as expected for states of unnatural parity, there is no evidence for the 3^+ and 5^+ members of this band. All members of the gamma vibrational band from spins 2^+ to 5^+ are observed in the (d,p) reaction, as expected because of the importance of the $\nu\nu[514\downarrow]$–$[512\downarrow]$ configuration in the gamma vibration. Furthermore, their differential cross-sections agree moderately well with the calculations of Kern *et al* [4], although in general the experimental cross-sections are 35–40% higher than the calculations. This is shown in table 4. The level at 1532 keV, assigned as the 5^+ member of the gamma band, appears as a shoulder on the strong 1513 keV (d,p) peak, and therefore may be weaker than that indicated in table 4. It might also be pointed out that the experimental cross-sections to the gamma band are approximately twice as strong as the most recent calculations of Soloviev [5]. Perhaps the experimental data reflect that their calculated admixture of the $\nu\nu[514\downarrow]$–$[512\downarrow]$ configuration is too small.

The first $K^\pi = 0^+$ band beginning at 1199·4 keV, which has been assigned as a beta vibrational band [6], is only populated sporadically and very weakly in these experiments. Thus, the inelastic deuteron experiment populates only the 2^+ member of this band, while the (d,p) experiment populates very weakly the 0^+ and 4^+ members of this band. It is also significant that the ^{180}Hf (p,t) experiment [7] which is known to pick out $K^\pi = 0^+$ states does not populate this band. This may imply that the $K^\pi = 0^+$ band at 1199·4 keV is neither the beta vibration, which should have been populated more strongly in the inelastic deuteron experiment, nor the pairing vibration which should have been populated strongly in the (p,t) reaction.

Two more $K^\pi = 0^+$ bands are observed at 1434·2 and 1443·9 keV, respectively. The 2^+ members of each of these bands are populated in the deuteron inelastic scattering reaction, but are not populated in the (d,p) reaction. Furthermore, the 1443·9 and possibly the 1434·2 keV states are strongly populated in the (p,t) reaction [7]. In view of the 10 keV resolution in the (p,t) experiment, it is difficult to differentiate between these states which are only 9·7 keV apart. The combination of the nuclear reaction spectroscopic data suggests that the beta and pairing vibrations are highly mixed and occur at about 1·4 MeV as predicted by the calculations of Mikoshiba *et al* [8]. A fourth $K^\pi = 0^+$ band is observed at 1772·2 keV and is strongly populated in the (p,t) reaction [7]. Presumably a part of the pairing strength is also present in this rotational band. It is quite clear from the above discussion that the four excited $K^\pi = 0^+$ bands in ^{178}Hf below 2 MeV need to be better understood and require additional experimental and theoretical characterization.

The octupole vibrations are particularly prominent in the nuclear reaction spectroscopy of ^{178}Hf. The band head of the 2^- octupole is observed at 1260·3 keV and, as expected, the 3^- member at 1322·5 keV is strongly populated in the deuteron inelastic scattering reaction. Population of this rotational band is not observed in the (d,p) reaction. However, all members of the band from spin 2^- through 6^- are observed in the (d,t) reaction. This suggests that the $K^\pi = 2^-$ octupole band may have an appreciable two quasineutron component from the configuration $\nu\nu[624\uparrow]$–$[512\uparrow]$. The character of this configuration implies that it would be populated by the (d,t) reaction, but not by the (d,p) reaction. Indeed the most recent calculation of Soloviev [5] suggests a 79% admixture of the $\nu\nu[624\uparrow]$–$[512\uparrow]$ configuration in the 2^- octupole vibration. The $K^\pi = 1^-$ octupole vibrational band begins at 1310·1 keV. The 1433·6 keV 3^- member of this band is populated in the inelastic deuteron scattering experiment, but much more weakly than the 3^- member of the $K^\pi = 2^-$ octupole band. The $J^\pi = 1^-, 2^-$ and 3^- members of this band are populated in the (d,p) reaction but only the 3^- and 4^- states are populated in the (d,t) reaction. This suggests that the $K^\pi = 1^-$ octupole band may have an important contribution from the two-neutron quasiparticle state $\nu\nu[514\downarrow]$–$[624\uparrow]$ which should be populated by both (d,p) and (d,t) reactions. Although Soloviev [5] suggested that the 1^- octupole band is dominated by the two-proton configuration $\pi\pi[404\downarrow]$–$[514\uparrow]$, in a more recent publication [9] he has suggested the two-neutron configuration suggested above. The $K^\pi = 3^-$ octupole band head is observed at 1803·4 keV. It is strongly populated in the inelastic deuteron scattering experiment, but not in the (d,p) reaction. However, the 4^- state is indicated in the (d,p) reaction. A state at 1875 keV is populated in the (d,d') reaction and also in the (p,t) reaction [6] which may be the 3^- member of the $K^\pi = 0^-$ octupole vibration.

The calculations of Neergård and Vogel [10] for the energies and $B(E3)$ values for the octupole vibrations in ^{178}Hf are shown in table 5. It is clear that their calculations have reproduced, in a reasonable way, the systematics of the experimentally observed octupole bands in ^{178}Hf. Specifically the calculated energies agree reasonably well and the predicted larger $B(E3)$ values for the $K = 2^-$ and 3^- bands are reflected in the much larger inelastic deuteron cross-sections to the 3^- members of these bands.

The lowest two-quasiparticle states in ^{178}Hf occur as a result of the mixing of the

Table 5. The experimental and theoretical energies and the theoretical $B(E3)$ values for the octupole vibrational bands in ^{178}Hf.

	E(MeV)		B(E3)^b
K^π	Expt^a	Theor^b	$(10^{-74}\,\text{cm}^6\cdot\text{e}^2)$
2^-	1·26	1·32	6·2
1^-	1·31	1·40	0·6
3^-	1·80	1·74	7·0
0^-	(1·77)^c	1·89	0·8

a. These results; b. Reference [10]; c. Energy of the $K^\pi = 0^-$, $J^\pi = 1^-$ state calculated assuming $\hbar^2/2\mathscr{I} = 10{\cdot}4$ keV and the observed 1875 keV state assumed to be the $K^\pi = 0^-$, $J^\pi = 3^-$ state.

two-quasiparticle neutron configuration $\nu\nu[514\downarrow]+[624\uparrow]$ and the two-proton configuration $\pi\pi[404\downarrow]+[514\uparrow]$, both of which yield $K=8^-$. The lowest 8^- state is observed at 1147·4 keV. The 8^-, 9^- and 10^- members of this rotational band are seen weakly in the (d,p) reaction, and the 8^- and 9^- members are observed in the (d,t) reaction. The second 8^- band head is observed at 1479·0 keV and is populated in both (d,p) and (d,t) reactions. The 9^- member of this $K=8^-$ band is also observed in the (d,p) reaction. Since the stripping and pick-up reactions can only populate the two-neutron quasiparticle states, the intensities of these two bands populated in such reactions can, in principle, provide a measure of their configuration mixings. Unfortunately the statistics on the population of these two states are inadequate to deduce a quantitative measure of this high degree of mixing.

The next two quasiparticle states observed in these studies result from the two-neutron configuration $\nu\nu[514\downarrow]\pm[510\uparrow]$. This configuration gives rise to a $K=4^+$ band expected to lie low and a $K=3^+$ band expected to lie somewhat higher in energy. Both of these bands are prominently observed in the data with the (d,p) populations going from a 4^+ state at 1513·8 keV all the way through a tentative 8^+ state at 2139 keV, not previously observed. Using the simple $I(I+1)$ dependent rotational energy formula, the observed 7^+-6^+ energy separation yields a moment of inertia parameter value of 11·8 keV; this, in turn, predicts the 8^+ level to occur around 2142 keV. Accordingly the observed peak at (2139 ± 5) keV in the (d,p) spectrum is tentatively identified as the 8^+ level of this band. The $K=3^+$ band beginning at 2862·2 keV is populated through the 5^+ state at 2068 keV. The apparent population of the 3^+ state at 1862·2 keV in the (d,t) reaction must be questioned. Presumably another state or an impurity must be involved since there is no reasonable $K=3^+$ configurational component which can be strongly (d,t) populated. Table 6 shows the comparison between the experimental and theoretical (d,p) cross-sections observed for these two bands taken from the thesis of Minor [11]. In view of the agreement we are quite confident in the assignment of this configuration. However, it should be noted that in the Nuclear Data Sheets [2] and in [1], all the levels of this $K=3^+$ band are shown as members of a $K=2^+$ band beginning at 1808·3 keV with no configurational assignment. We have summarized a number of arguments including the agreement between the experimental and theoretical differential cross-sections [12] which show conclusively that the 1808 keV 2^+ state is not a part of this band. The additional confirmation for the $K=3^+$ assignment comes from the connection (evidenced by strong inter-band M1 transitions) with the 1513·8 keV

Table 6. Differential cross-sections in the transfer of $1/2^-[510]$ neutron in ^{178}Hf.

	$K^\pi=3^+\ \nu\nu[514\downarrow]-[510\uparrow]$		$K^\pi=4^+\ \nu\nu[514\downarrow]+[510\uparrow]$	
	dσ/dΩ(μb/sr) 45°		dσ/dΩ(μb/sr) 45°	
I^π	Predicted	exp	Predicted	exp
3^+	173	170		
4^+	134	160	212	200
5^+	51	47	128	110
6^+	12	—	27	38
Sum	370	377	367	348

$K = 4^+$ band having confirmed $\nu\nu[514\downarrow] + [510\uparrow]$ configuration, branching ratios for these inter-band transitions in agreement with Alaga rule predictions, and similar rotational parameters for the $K = 3$ and $K = 4$ bands In consequence the 2^+ state at 1808·3 keV, as also the 2^+ states at 1561·5 and 1891·3 keV, are shown as unassigned in Figure 3.

The next rotational band observed in ^{178}Hf is the $K = 6^+$ band with the tentative two quasineutron configuration $\nu\nu[514\downarrow] + [512\uparrow]$. The band head is observed at 1554·0 keV with tentative rotational members observed through the 11^+ at 2700·4 keV [2]. The 6^+ band head is weakly populated in the (d, p) reaction, but none of the higher rotational levels is populated. There is no evidence for this band in the (d, t) reaction. Unpublished data from the ^{181}Ta (p, α) reaction [13] suggest that an important part of the $K = 6^+$ band of ^{178}Hf is the two quasiproton $\pi\pi[404\downarrow] + [402\uparrow]$ configuration. Khoo and Løvhøiden [14] have given the configuration of this $K = 6^+$ band as 69% $\pi\pi[404\downarrow] + [402\uparrow]$ and 31% $\nu\nu[514\downarrow] + [512\uparrow]$. It seems as if both the (d, p) and (p, α) data are consistent with this description.

A $K = 5^-$ rotational band beginning at 1636·7 keV with rotational members through the tentative 8^- state at 2137·6 keV has been observed. The two lowest members of this band are strongly populated in the (d, t) reaction although possible interference from nearby bands makes this experimental finding less certain. If these strong populations are correct, the most reasonable assignment is $\nu\nu[624\uparrow] + [521\downarrow]$.

Finally, a $K = 3^+$ rotational band has been suggested [2] consisting of only 3^+ and 4^+ rotational members. A possible two quasineutron configuration for this band is $\nu\nu[514\downarrow]$–$[521\downarrow]$. Only the band head at 1758·1 keV is populated in the (d, p) reaction. This band has also been strongly populated in the ^{181}Ta (p, α) reaction [13], and the dominant configuration has been shown to be $K = 3^+$, $\pi\pi[404\downarrow]$–$[411\downarrow]$. It might also be mentioned that the (d, p) population of this $K = 3^+$ band head may also have a contribution from a possible admixture of the $K = 3^+$ band at 1862·2 keV.

4. Conclusions

Considerable portions of the fairly extensive level structure of ^{178}Hf have been studied using the (d, d'), (d, p) and (d, t) reactions. The specificity of the reactions and the "finger print" pattern of the differential cross-sections have allowed us to identify a number of the vibrational and two-quasiparticle configurations in the level structure. A part of the spectra at the highest energies remains unassigned. Clearly high resolution nuclear reaction studies can lead to considerable additional information.

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