BRIEF REPORTS

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$K^\pi = 3^+$ band at 1862 keV in ^{178}Hf

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(Received 18 November 1992)

A critical evaluation of results from the ^{177}Hf(d,p) reaction, taken together with gamma-ray data following neutron capture, firmly establishes that the 1862.2 keV 3^+, 1953.1 keV 4^+, and 2068.0 keV 5^+ levels in ^{178}Hf unambiguously constitute a $K^\pi = 3^+$ band, closely interrelated with the well-known $K^\pi = 4^+$ band based at 1513.8 keV. These two bands form a doublet with the $\{7/2^-[514] \mp 1/2^-[510]\}$ two-neutron configuration. This assignment necessitates a revision of an earlier interpretation, adopted by Nuclear Data Sheets, placing these levels as rotational members of a $K^\pi = 2^+$ band based at 1808.3 keV. Detailed arguments for the revised assignment are presented.

PACS number(s): 27.70.+q, 25.45.Hi, 23.20.Lv

The purpose of this Brief Report is to revise an incorrect interpretation, which exists in the published literature, and which has also been adopted in the Nuclear Data Sheets, for a series of levels in ^{178}Hf.

There have been many experiments performed to study electromagnetic transitions in ^{178}Hf following beta decays, neutron capture, in-beam reaction studies, etc., and these have been summarized in the Nuclear Data Sheets [1]. The most extensive and detailed study was reported by Hague *et al.* [2], who performed ^{177}Hf(n,γ) experiments and measured gamma rays with curved-crystal spectrometers as well as conversion electrons and average resonance capture (ARC) spectra. This work provided a large number of multipolarities and precise transition energies, resulting in a much more detailed and complete level scheme than was available earlier.

In contrast, there is very little information available from charged-particle reaction spectroscopy for ^{178}Hf levels. Although ^{177}Hf and ^{179}Hf are both stable, there are no published papers in the literature describing single-nucleon transfer reactions such as ^{177}Hf$(d,p)^{178}$Hf or ^{179}Hf$(d,t)^{178}$Hf. Measurements of both these reactions were performed independently in the 1960s at both the Niels Bohr Institute and Florida State University, but apparently neither group completed a final report for publication in the open literature. There are, however, numerous citations of private communications and preliminary reports (see, e.g., [2–8]), and the results from Florida State University were presented in the doctoral dissertation of Minor [3].

The ^{177}Hf$(d,p)^{178}$Hf spectra of Ref. [3] were measured at angles of 35°, 45°, 55°, 65°, 85°, and 95°, using 12 MeV deuterons. A magnetic spectrograph was used to analyze the reaction products, and the protons were detected with photographic emulsions. A typical spectrum is shown in Fig. 1, which is reproduced from Ref. [3]. By far the most prominent feature below ~2 MeV of excitation energy in the ^{177}Hf$(d,p)^{178}$Hf spectra was a series of large peaks which could be associated with the transfer of a neutron to the $1/2^-[510]$ Nilsson state. This orbital is located just above the Fermi surface in ^{178}Hf and has large $\ell = 1$ and $\ell = 3$ amplitudes which lead to large predicted cross sections. When coupled

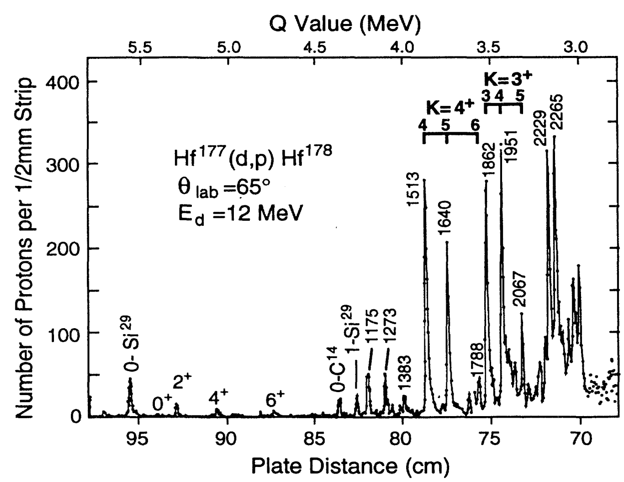

FIG. 1. Spectrum of the levels populated in the reaction ^{177}Hf$(d,p)^{178}$Hf at 65° and 12.0 MeV adapted from Ref. [3]. The positions of the $K = 4^+$ and 3^+ bands in the spectrum are indicated.

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to the $7/2^-[514]$ neutron which forms the ground state of the ^{177}Hf target it is expected to form bands with $K^\pi = 3^+$ and $K^\pi = 4^+$, and the latter of these is expected to occur at the lowest energy. On the basis of the strongly populated levels observed, both groups of researchers independently assigned (Fig. 1) the levels at 1513.8 keV, 1640.4 keV, and 1788.6 keV as the spin 4, 5, and 6 members of the $K^\pi = 4^+$ band, and the 1862.2 keV, 1953.1 keV, and 2068.0 keV levels as the spin 3, 4, and 5 members of the $K^\pi = 3^+$ band, respectively. The level energies quoted here are the more precise values from Hague *et al.* [2]. These assignments for the $K^\pi = 3^+$ and $K^\pi = 4^+$, $7/2^-[514] \pm 1/2^-[510]$ bands were adopted for several years [5–7], and the results of Hague *et al.* [2] show that all of these spins and parities are indeed correct.

However, Hague *et al.* [2] proposed a different interpretation for the upper band, based on the "completeness" argument that their ARC measurements should populate all levels with spins from 2 to 5. They observe a level at 1808.3 keV with $I^\pi = 2^+$, and do not find any higher-lying 3^+ or 4^+ levels at reasonable energies to be rotational excitations, except for the $K^\pi = 3^+$ band at 1862.2 keV discussed above. Hence, they assigned the $I^\pi = 3^+$, 4^+, and 5^+ levels as rotational members of a $K^\pi = 2^+$ band based at 1808.3 keV.

However, the interpretation of Hague *et al.* [2] ignores the strong arguments from the (d,p) data which were used to make the original $K^\pi = 3^+$ assignment. For single-nucleon transfer reactions in well-deformed nuclei the cross sections for various members of a rotational band have a characteristic pattern, or "fingerprint," which can be readily predicted from the Nilsson model wave functions [9]. Table I, which is reproduced from Ref. [3], shows the comparison of observed cross sections at 45° for the 1513.8 keV $K^\pi = 4^+$ and 1862.2 keV $K^\pi = 3^+$ bands with predicted values for bands based on the $\{7/2^-[514] \pm 1/2^-[510]\}$ configurations. The predicted values were obtained from standard Nilsson model wave functions and distorted-wave Born approximation calculations for the $^{177}\text{Hf}(d,p)^{178}\text{Hf}$ cross sections. The agreement in Table I is seen to be very good, and constitutes strong support for the $K^\pi = 3^+$, $\{7/2^-[514] - 1/2^-[510]\}$ interpretation for the 1862.2 keV band. It should also be reiterated that the transitions being discussed are among the strongest ones in the (d,p) spectra, and therefore are the ones which can be interpreted most reliably. Also, there is no $K^\pi = 2^+$ band which should occur at such low excitation energy and be so strongly populated in the (d,p) reaction.

Against this strong argument for $K^\pi = 3^+$, the ARC preference for a $K^\pi = 2^+$ assignment is weak, because the "completeness" argument for levels populated in the ARC experiment is being used outside the region for which completeness is claimed. Hague *et al.* [2] claim that their level scheme is complete for $2 \leq I \leq 5$ up to only ~1800 keV of excitation energy, but in this case are applying the argument above ~1850 keV. The validity of the "completeness" argument in this region is also weakened by the fact that an $I^\pi = 2^+$ level exists at 1561.5 keV for which no higher rotational members have been detected in the ARC data. Since any rotational excitations based on the 1561.5 keV level were not observed, and these should be within the expected range of completeness, it is also very possible that ones based on the 1808.3 keV $I^\pi = 2^+$ level could have escaped detection.

Further, an examination of the rotational spacings within the suggested $K^\pi = 2^+$ band reveals that its constituent levels do not have a consistent bandlike structure. Specifically the moment of inertia parameter A ($= \hbar^2/2\Im$) from the 3^+-2^+ energy spacing is 9.0 keV in contrast with its values of 11.4 and 11.5 keV, respectively, from the 4^+-3^+ and 5^+-4^+ spacings. These values for $I \geq 3$ levels, interpreted here to constitute a $K^\pi = 3^+$ band, are much closer to the average value of A ~12.3 keV observed for the 1513.8 keV $K^\pi = 4^+$ band having the same two-quasiparticle $\{7/2^-[514] \pm 1/2^-[510]\}$ configuration.

There are also several aspects of the gamma-ray decay modes for these levels which favor the $K^\pi = 3^+$ interpretation presented here. The strongest decay mode for each of the 3^+, 4^+, and 5^+ levels at 1862.2 keV, 1953.1 keV, and 2068.0 keV is by $M1$ transitions to members of the $K^\pi = 4^+$ band at 1513.8 keV. Any valid interpretation would have to explain why these $M1$ transitions dominate over possible competing $E1$ and $M1$ transitions of much greater energy to lower-lying bands with $K^\pi = 2^+$, 2^-, 1^-, etc. When the 1862.2 keV level and its rotational members are interpreted as the $K^\pi = 3^+$, $\{7/2^-[514] - 1/2^-[510]\}$ configuration it would be natural to expect favored $M1$ transitions to the band formed by coupling the same two neutrons to $K^\pi = 4^+$, because of the similarity in wave functions. There could also be some Coriolis mixing between these two bands, which would further increase the overlap of the wave functions. In contrast, if the $I^\pi = 3^+$, 4^+, and 5^+ levels had $K = 2$, the $M1$

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

	$K^\pi=3^+$ $7/2^-[514] - 1/2^-[510]$		$K^\pi=4^+$ $7/2^-[514] + 1/2^-[510]$	
I^π	$d\sigma/d\Omega$ (μb/sr) 45°		$d\sigma/d\Omega$ (μb/sr) 45°	
	Predicted	Expt.	Predicted	Expt.
3^+	173	170		
4^+	134	160	212	200
5^+	51	47	128	110
6^+	12		27	38
Sum	370	377	367	348

transitions to the $K = 4$ band would be K forbidden. Thus, the observed decay modes appear to argue against the $K^\pi = 2^+$ assignment of Hague *et al.* [2].

Finally, the observed branching ratios for these strong $M1$ decays to the $K = 4$ band are in reasonable agreement with the Alaga rule predictions assuming $K = 3$ for the parent states. From the intensity data reported by Hague *et al.* [2] it is possible to obtain ratios for two cases. For M1 decay of the 4^+, 1953.1 keV level to the $I, K^\pi = 4,4^+$ and $5,4^+$ levels the ratio $I_\gamma(4^+ \rightarrow 4^+)$:$I_\gamma$ $(4^+ \rightarrow 5^+)$ is 27:73, in good agreement with the Alaga rule prediction of 20:80 for the initial K value being K_i=3. For decay of the 5^+ level at 2068.0 keV to the I, K^π=4,4$^+$, 5,4$^+$, and 6,4$^+$ levels the $M1$ intensity ratios observed are $\leq$ 7:51:42, while the ratios expected for K_i=3 are 2:30:68.

In summary, a careful evaluation of the available experimental data from the particle-transfer reaction and neutron-capture studies clearly establishes that the 1862.2 keV 3^+, 1953.1 keV 4^+, and 2068.0 keV 5^+ levels constitute a K^π=3^+ band having the $\{7/2^-[514] - 1/2^-[510]\}$ configuration and that the 1808.3 keV 2^+ level is not related to this band sequence. The K^π=3^+ assignment is based on the observed strong peaks, associated with the $1/2^-[510]$ neutron-transfer coupling to the $7/2^-[514]$ ^{177}Hf target state, in the (d,p) spectra and agreement between the observed cross sections for various rotational members with predicted values. Additional confirmation for the K^π=3^+ assignment comes from the connection (evidenced by strong interband $M1$ transitions) with the 1513.8 keV K^π=4^+ band having a confirmed $\{7/2^-[514] + 1/2^-[510]\}$ configuration, branching ratios for these interband transitions in agreement with Alaga rule predictions, and similar rotational parameters for the $K = 3$ and $K = 4$ bands. In view of this overwhelming evidence, the "adopted" K^π=2^+ assignment for these levels in the Nuclear Data Sheets [1] should be revised.

This investigation was supported by the National Science Foundation under Contract No. PHY92-07336 with Florida State University, by the Natural Sciences and Engineering Research Council of Canada, and by the Department of Atomic Energy, Government of India.

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