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Structural Changes in the Yrast States of ^{178}Hf*

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Abstract

High spin levels in ^{178}Hf, including the ground state band, several 2-quasiparticle (qp) bands, and two 4-qp isomers have been identified from $(\alpha,2n)$ studies. Changes in the structure of the yrast line are observed. The 4-qp isomers with $K^{\pi} = 16^{+}$ and 14^{-} are yrast traps.

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**Present address.

The present interest in nuclei at high spin is partly motivated by a desire to understand how nuclei behave under the stress of large angular momentum. In this connection, it is pertinent to ask how angular momentum is generated in nuclei with the least expenditure of energy. In deformed nuclei, collective rotation has been commonly observed to be energetically the most favourable mode for generating spin. However, one might enquire whether few-particle degrees of freedom can be a competitive mode in this respect. That they indeed can has been demonstrated in a recent study of ^{176}Hf [1], where it has been found that some 4- and 6-quasiparticle (qp) states can occur lower in energy than members of the ground state band (gsb) with corresponding spin. It is important to determine if there are other systems where similar few-qp states become yrast.

A good candidate is ^{178}Hf, where a 31y $K^{\pi} = 16^{+}$ isomer is known [2,3] to exist at ≈ 2.45 MeV, an unusually low energy for a state of such high spin. In fact, if one extrapolated the gsb, previously known only to its 8^{+} member, one would expect its 16^{+} member to lie above the $K^{\pi} = 16^{+}$ isomer. Therefore, we set out to find the higher-lying members of the gsb and also other high-K qp states.

We employed the $^{176}Yb(\alpha,2n)^{178}Hf$ reaction, using 24-35 MeV α-beams, and performed conventional in-beam γ-ray spectroscopic measurements with Ge(Li) detectors. Gamma ray spectra were recorded in singles and coincidence modes with the McMaster FN tandem accelerator; γ-ray angular distribution, excitation function, and delayed-γ-ray measurements were performed with the Michigan State University

Cyclotron. In searching for isomers, γ-rays were observed a) in a 580 ns beam-off interval corresponding to the period between every ninth pulse from the cyclotron, and b) in a 500 μs period between beam bursts of 100 μs duration. The experimental techniques are described in more detail in refs. [4 and 5].

A partial level scheme for ^{178}Hf which includes only states with $K \geq 4$ is shown in Fig. 1. The gsb to spin 8, the lower $K^\pi = 8^-$ band to spin 13, and the $K^\pi = 8^-, 4^+, 16^+$ states at 1479, 1514 and ≈ 2450 keV, respectively, were known from previous studies [2,3,6,7]. The remaining levels of Fig. 1 are reported here for the first time. These include the members of the gsb to spin 14, the $K^\pi = 14^-$ isomer, and the rotational bands built on the $K^\pi = 8_2^-$, 5^-, and 6^+ states. The newly discovered isomers at 1554 and 2574 keV have half-lives of 78 ± 1 ns and 68 ± 2 μs, respectively. The probable configurations of the band-heads are given in Table I. The spins and parities have been assigned on the basis of angular distribution and excitation function data. Band assignments are based on very regular energy- and decay-systematics. While the 78 ns half-life of the 1554 keV isomer renders the angular distribution of the deexciting transitions isotropic, strong arguments can be made for the $I^\pi = 6^+$ assignment from its decay to the $I^\pi K = 4^+0$, 6^+0, 4^+4, 4^+2 (not shown in Fig. 1) and 8^-8 states. The $I^\pi = 14^-$ assignment for the 2574 keV isomer is based on the M1 character of the 140 keV transition and the observed decay branches to 12^-, 13^-, and 16^+ states. The M1 multipolarity of the 140 keV line was determined from its total conversion coefficient, $\alpha_{tot} = 1.52 \pm 0.5$, found from intensity balance considerations, in the delayed γ-spectra.

While the 126.1 ± 0.3 keV line deexciting the 14^- isomer is weak and somewhat masked by stronger lines from long-lived contaminants, it was clearly visible in early time spectra after subtracting contributions from long-lived activities (Fig. 2). From such subtracted spectra, the decay half-life of the 126 keV line was determined to be 61 ± 12 μs, in agreement with those of the stronger lines deexciting the isomer. The 126 keV transition probably connects the $K^\pi = 14^-$ isomer to the $K^\pi = 16^+$ isomer and hence defines the energy of the latter. A recent study [3] restricted the energy of the 16^+ isomer to between 2445 and 2450 keV. The isomerism of the 14^- state arises from the K-forbidden decays to the $K^\pi = 8_1^-$ band. The branch to the $K^\pi = 16^+$ isomer is K-allowed but is a slow, low-energy, presumably M2 transition; the partial half-life of this branch agrees with the value calculated using the empirical half-life [8] (in ^{181}Ta) for the $5/2(402)_p \rightarrow 9/2(514)_p$ transition involved.

The two 8^- bands are of mixed proton-neutron character (see Table I) as is already well-known [2,3,9]. The interband decay of the upper 8^- band directly to the lower 8^- band, rather than by the usual intraband transitions, provides another signature of the mixing [10]. The $K^\pi = 6^+$ band is also determined to be of mixed neutron-proton character, using cascade-crossover ratios as described in ref. [10]. Further discussion of the mixing between neutron and proton 2-qp configurations will be deferred to a subsequent publication.

We concentrate our discussion here on the structural changes that are observed in the yrast states. In Fig. 1 it is seen that the gsb is yrast only up to spin 10; members of the $K^{\pi} = 8_1^-$ band become yrast for $I \geq 12$. Further changes of the yrast structure occur at higher spin when the 68μs 14^- and 31y 16^+ isomers take over. In fact, the 16^+ state has lower energy than the 14^- isomer. This anomalous spin inversion of the yrast line is largely responsible for the remarkably long half-life of the 31y 16^+ isomer, making it a particularly striking example of a yrast trap.

The occurrence of the 4-qp states along the yrast line may be understood from the fact that the energy for collective rotation increases quadratically with spin. When the spin becomes sufficiently large, it may then become preferable to generate spin by breaking a few nucleon pairs with high-Ω, particularly when the Fermi level lies among high-Ω orbits. This is the case for ^{178}Hf, and also for ^{176}Hf [1]. The angular momenta of the yrast multi-qp band-heads in these isotopes are formed by aligning the spins of only a few nucleons along the symmetry axis, such that $I = K = \sum_i \Omega_i$.

One may associate a moment of inertia, $\mathcal{J}$, with such aligned few-nucleon structures [11]. In other words, the energies of such states will, on the average, have a rotation-like dependence on spin, i.e. $E = (\hbar^2/2\mathcal{J})\, I\,(I + 1)$. For a non-interacting Fermi gas, $\mathcal{J}$ is the rigid body value for rotation about the symmetry axis along which the nucleon spins align [11]. Residual nucleon interactions and shell effects may cause significant departures from this value. For the Hf isotopes, the tendency of pairing to increase $\mathcal{J}$ is counteracted by the shell effect (i.e. large density of high-Ω orbits around the Fermi surface) and residual nucleon

interactions [12], so that $\mathcal{J}$ remains close to the rigid body value [1]. On the other hand, the moment of inertia for collective rotation (about an axis perpendicular to the symmetry axis) is only about half the rigid body value because of pairing effects. As a consequence, the moment of inertia associated with collective rotation is smaller than that associated with nucleon-alignment. Thus, a crossing of the collective and few-particle structures may be expected, with the latter then becoming yrast.

Rotation-alignment [13] is another mode of excitation which can also compete favourably with collective rotation. In this case, the Coriolis force tends to align a pair of high-j particles (or holes) along the usual rotation vector, i.e. perpendicular to the symmetry axis. Spins larger than $2j - 1$ are obtained with increasing amounts of collective rotation. Often the rotation-aligned structure intersects the gsb, becomes yrast, and gives rise to backbending [13]. This usually occurs at the extremities of the $150 < A < 190$ region where, with the small deformation and concomitant small moment of inertia, the Coriolis force is strong and the rotational energies large.

In the middle of the same mass region, the deformation and, hence, moment of inertia are larger; collective rotation thus requires less energy than rotation-alignment, and many examples are obtained of the yrast line showing "good rotor" behaviour. However, at sufficiently high spin (with corresponding high rotational energies) few-nucleon structures may again emerge into the yrast line, as in ^{176}Hf and ^{178}Hf.

In a much higher spin domain ($I > 30\hbar$) it is anticipated [11] that the large centrifugal stress may induce oblate shapes in some nuclei. Then the spins of the yrast states will probably be generated by aligning the spins of a few nucleons about the oblate symmetry axis, instead of by collective rotation. Under these circumstances, yrast traps may be expected [11]. The role of few-particle motion and the occurrence of traps bear a striking resemblance to that observed in ^{178}Hf, and also in ^{176}Hf [1], although a prolate nuclear shape is preserved in these latter cases.

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Table I. Probable Configurations of Observed High-K States

Band-head energy (keV)	K	Configuration[a]
1147	8^-	$64\%[7/2_n\ 9/2_n] + 36\%[7/2_p\ 9/2_p]$[b]
1479	8^-	$36\%[7/2_n\ 9/2_n] + 64\%[7/2_p\ 9/2_p]$[b]
1514	4^+	$[1/2_n\ 7/2_n]$[c]
1554	6^+	$69\%[7/2_p\ 5/2_p] + 31\%[7/2_n\ 5/2_n]$
1637	5^-	$[1/2_n\ 9/2_n]$
2447	16^+	$[7/2_n\ 9/2_n\ 7/2_p\ 9/2_p]$[b]
2574	14^-	$[7/2_n\ 9/2_n\ 7/2_p\ 5/2_p]$

[a]Single particle orbits are $7/2_n$, 7/2(514); $9/2_n$, 9/2(624); $5/2_n$, 5/2(512); $1/2_n$, 1/2(510); $5/2_p$, 5/2(402); $7/2_p$, 7/2(404); $9/2_p$, 9/2(514).

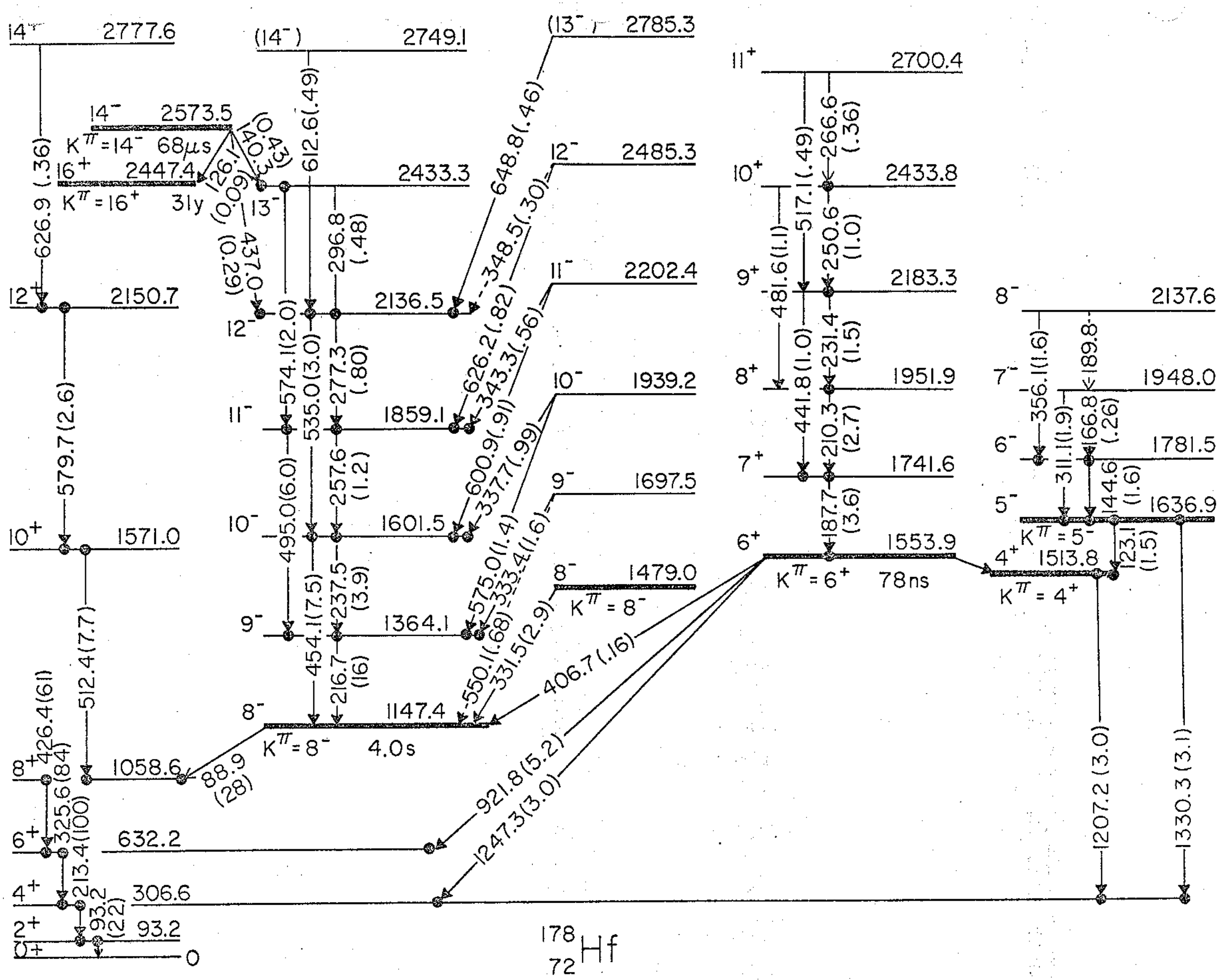
[b]Refs. [2 and 3].

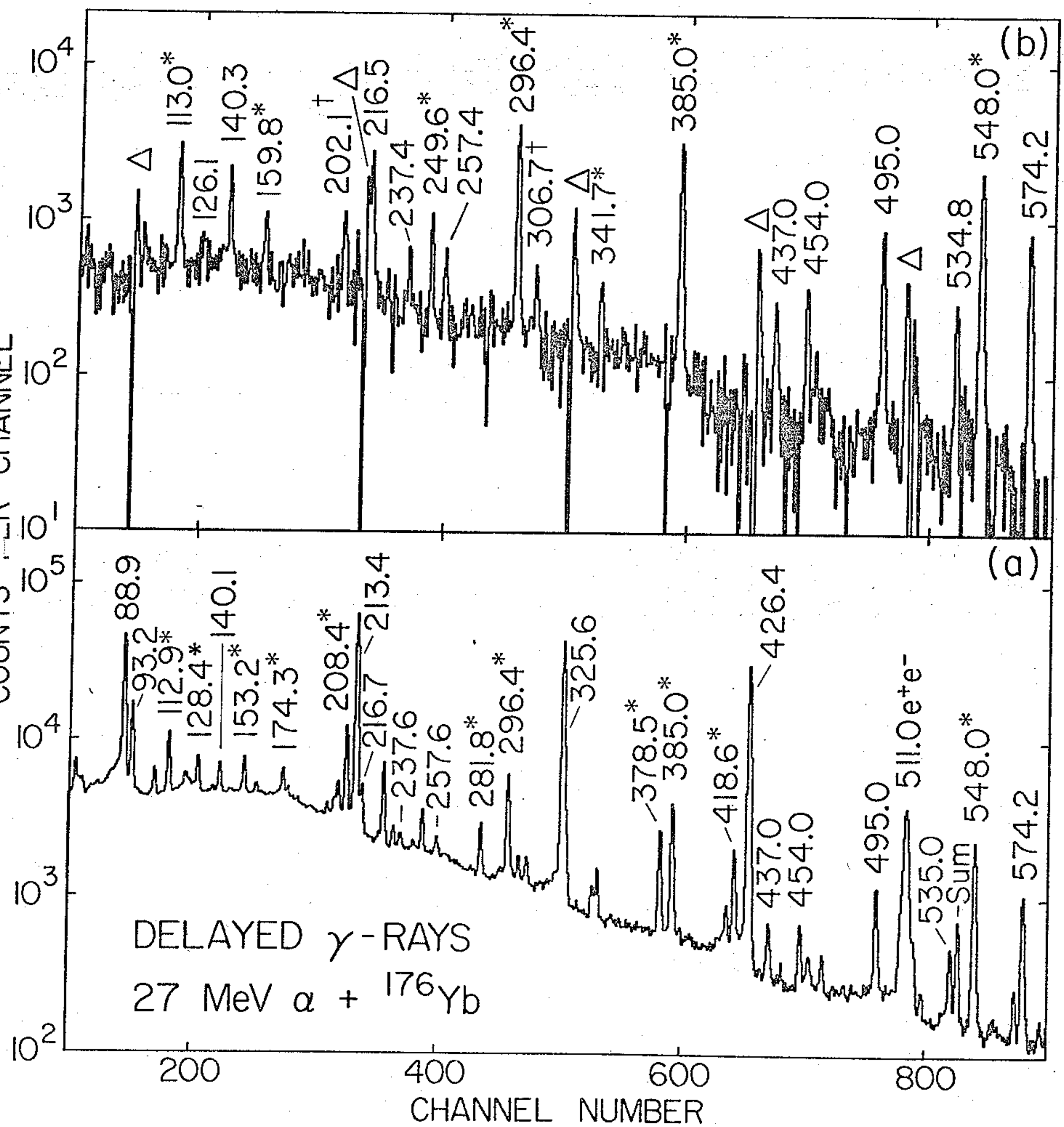
[c]Refs. [6 and 7].

FIGURE CAPTIONS

Fig. 1. Partial level scheme for ^{178}Hf showing levels with $K \geq 4$. Decay branches of $I^{\pi}K = 6^+6$ and 4^+4 band-heads proceeding through the γ-band are not shown. Filled circles indicate transitions entering and leaving a level are in prompt coincidence. Relative γ-intensities in the $^{176}Yb(\alpha,2n)^{178}Hf$ reaction at 26 MeV bombarding energy are given in brackets.

Fig. 2. Delayed γ-spectra from bombarding ^{176}Yb with 27 MeV α-particles. (a) Spectrum observed in a 6-230 μs interval after target irradiation. (b) Difference between spectrum in (a) and one accumulated in a successive interval of equal width. γ-rays with half-lives ≳ 250 μs are removed in the subtraction. Contaminant peaks are indicated: *-^{177}Hf; †-^{176}Hf; Δ-residue from improper subtraction of "tails" of strong peaks.


14⁻ 2777.6
(14⁻) 2749.1
(13⁻) 2785.3
11⁺ 2700.4
14⁻ 2573.5
Kπ=14⁻ 68μs
16⁺ 2447.4
Kπ=16⁺ 31y
2433.3
13⁻
12⁻ 2485.3
10⁺ 2433.8
12⁺ 2150.7
12⁻
2136.5
11⁻ 2202.4
9⁺ 2183.3
8⁻ 2137.6
11⁻
1859.1
10⁻ 1939.2
8⁺ 1951.9
7⁻ 1948.0
6⁻ 1781.5
10⁻
1601.5
9⁻ 1697.5
7⁺ 1741.6
5⁻ 1636.9
Kπ=5⁻
10⁺ 1571.0
6⁺ 1553.9
Kπ=6⁺ 78ns
4⁺ 1513.8
Kπ=4⁺
9⁻
1364.1
8⁻ 1479.0
Kπ=8⁻
8⁻ 1147.4
Kπ=8⁻ 4.0s
8⁺ 1058.6
6⁺ 632.2
4⁺ 306.6
2⁺ 93.2
0⁺ 0
626.9 (.36)
612.6(.49)
648.8(.46)
517.1(.49)
266.6 (.36)
140.3 (0.43)
(26.1)
(0.09)
437.0 (0.29)
296.8 (.48)
348.5(.30)
481.6(1.1)
250.6 (1.0)
579.7(2.6)
574.1(2.0)
535.0(3.0)
277.3 (.80)
626.2(.82)
343.3(.56)
441.8(1.0)
231.4 (1.5)
356.1(1.6)
189.8
495.0(6.0)
257.6 (1.2)
600.9(.91)
337.7(.99)
210.3 (2.7)
311.1(1.9)
166.8 (.26)
144.6 (1.6)
454.1(7.5)
237.5 (3.9)
575.0(1.4)
333.4(1.6)
187.7 (3.6)
123.1 (1.5)
512.4(7.7)
216.7 (16)
550.1(.68)
331.5(2.9)
406.7(.16)
426.4(61)
325.6(84)
88.9 (28)
921.8(5.2)
1247.3(3.0)
1207.2 (3.0)
1330.3 (3.1)
213.4(100)
93.2 (22)
$^{178}_{72}$Hf


(b)
(a)
COUNTS PER CHANNEL
CHANNEL NUMBER
DELAYED γ-RAYS
27 MeV α + 176Yb
88.9
93.2
112.9*
128.4*
140.1
153.2*
174.3*
208.4*
213.4
216.7
237.6
257.6
281.8*
296.4*
325.6
378.5*
385.0*
418.6*
426.4
437.0
454.0
495.0
511.0e+e-
535.0
Sum
548.0*
574.2
113.0*
126.1
140.3
159.8*
202.1†
216.5
237.4
249.6*
257.4
296.4*
306.7†
341.7*
385.0*
534.8