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Бочев Б. и др. **E7 - 10180**

Времена заселения и времена жизни ираст-уровней ядер Hf

Были измерены интенсивности и времена заселения, а также времена жизни ираст-уровней в четно-четных изотопах $^{166,168,170}_{72}$Hf. Использованы реакции ^{122,124}Sn(^{48,50}Ti,4n)$^{166-170}$Hf. Применен допплеровский метод измерения расстояния отдачи. Времена жизни и, следовательно, B(E2)-значения показывают ту же самую тенденцию сравнительно слабого отклонения от модели жесткого ротатора, как и в известных случаях изотопов $_{68}$Er и $_{70}$Yb. Кроме быстрой компоненты независимого заселения уровней, показывающей поведение, подобное поведению такой же компоненты в ядрах $_{70}$Yb, наблюдается другая, медленная компонента заселения уровней ираст-полосы с низким спином.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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Bochev B. et al. **E7 - 10180**

Feeding and Life Times of Yrast Levels in Hf Nuclei

Feeding intensities and times, as well as lifetimes of yrast levels in doubly-even ^{166,168,170}Hf nuclei have been measured. The reactions $^{122,124}_{50}$Sn($^{48,50}_{22}$Ti,4n)$^{166-170}_{72}$Hf have been investigated using the recoil-distance Doppler-shift method. The lifetimes and hence the B(E2) values measured show the same trends of rather small deviations from the rigid rotor as in the known $_{68}$Er and $_{70}$Yb cases. In addition to the fast feeding component showing a rather similar behaviour to that of the Yb nuclei, another type of slow feeding, related to the low spin yrast levels, is observed.

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1. INTRODUCTION

Two aspects related to high spin nuclear levels can be clarified by the intensity and lifetime measurements /1/. The first aspect concerns the mechanism of backbending. By studying deviations in lifetimes and, consequently, the B(E2) values from the rigid rotor ones in the backbending region /1,2/ one can throw light (ref. /1/) on the validity of different theoretical proposals for the interpretation of backbending /3/.

The second one is related to the mechanism of population of the yrast band. It is treated by the study of feeding intensities and side feeding times /1/. Such data are complementary to the study of the multiplicity and the energy distribution of the γ-ray continuum /4,5/. They can also be useful in studying the still higher spin levels and the structure of the yrast band from the point of view of the behaviour of nuclei at very high angular velocities e.g., the possible existence of form isomers and "traps" at such velocities /7,8/. There is evidence for high-spin two-, four- and six-quasiparticle (q.p.) isomeric states which can possibly be interpreted as yrast traps in ^{174,176,178}Hf and ^{180}W (refs. /9-12/).

This work, performed using the Doppler-shift recoil-distance method, is an extension of our previous investigation on several $_{70}$Yb doubly even nuclei [1] to ^{166,168}, $^{170}_{72}$Hf. The choice of $_{72}$Hf was connected with, first, the possibility of studying the high spin regions of the nucleus showing backbending ($^{168}_{72}$Hf) and that of the adjacent nucleus not exhibiting this phenomenon ($^{170}_{72}$Hf) [13] simultaneously, and second, with the existence of 8- 2 q.p. isomeric states in the heavier stable doubly-even Hf isotopes (A= 176,178,180) [9-15], which can change the pattern of side feeding if they exist and are populated in our case.

2. EXPERIMENT AND DATA HANDLING

The yrast levels of Hf nuclei were populated in the reactions $^{122,124}_{50}$Sn($^{48}_{22}$Ti,4n) $^{166,168}_{72}$Hf and $^{124}_{50}$Sn($^{50}_{22}$Ti,4n) $^{170}_{72}$Hf on an external heavy ion beam of the Dubna U-300 cyclotron with an energy of 195 and 198 MeV of the ^{48}Ti and ^{50}Ti ions, respectively, on the target. The details of the experimental arrangement and the data handling procedure are described in our previous publication [1].

The main factors which allowed going into the backbending region [1] can be summarized as follows:

(i) the background suppression and the elimination of background peaks;

(ii) the construction of a high-precision Doppler chamber with a distance measurement accuracy of 2 μm (including the zero-distance determination), which corresponds to a recoiling nucleus time-of-flight accuracy of 0.3 ps;

(iii) the development of a computational method for the simultaneous extraction of lifetime τ_I and side feeding time ϕ_I of each level with spin I with the help of a fitting procedure. The experimental ratios $R_I = N_u/(N_u+N_s)_{I\to I-2}$ (N_u is the intensity of the peak (u) with an unshifted energy E_u, N_s is the intensity of the peak (s) with a Doppler shifted energy E_s) for each transition as a function of time-of-flight, are fitted to formula (3) from ref. [1], which is dependent on τ_k, ϕ_k and P_k ($k \geq I$). This formula was derived using a model of parallel cascades of transitions. The side feeding intensities $P_I / \sum_I P_I$, where $P_I = N_I - N_{I+2}$, and $N_I = (N_u + N_s)_{I\to I-2}$, have not been fitted, but determined in additional experiments. In the case of two clearly observable side feeding components with very different times, their relative intensities have been determined from the intensity of the long-lived tail of the decay curve $R_I(t)$.

Some special points here have been the following:

(i) the application of metallic Sn targets prepared by rolling;

(ii) the extension of the previously described correction procedure [16,1] to the case of the complicated decay law $R_I(t)$ with two or more exponentials $r_k e^{-t/\tau_k}$ with rather different mean times, τ_k, in order to take into account the long-lived tails appearing in this experiment. The corrections have been made by the formula

$$R_{corr}(t_{corr}) = R_{uncorr}(t_{uncorr}) \sum_k \frac{W_k}{1+\delta_k}, \qquad (1)$$

where t_{corr} is determined according to ref.[1] $1+\delta_k$ is the correction factor for one exponential with the time parameters τ_k[16] and W_k is a weight factor:

$$W_k = r_k \exp(-t/\tau_k) / \sum_i r_i \exp(-t/\tau_i) . \qquad (2)$$

3. RESULTS

Figures 1, 2 and 3 show experimental points* of decay curves $R_I(t)$ (with corrections included) for the isotopes $^{166,168,170}_{72}Hf$ studied, as compared with the calculated curves obtained by fitting the τ_I and ϕ_I values.

The side feeding intensities $P_I / \sum_I P_I$, mean side feeding times ϕ_I, and mean lifetimes τ_I are given in table 1. The values of τ_I, deduced from the experimental value of τ_2 and from the rigid rotor reduced transition probabilities $B_{rot}(E2)$ are also given for comparison.

Here, for the highest levels I_m the P_{I_m} value is the total feeding intensity N_{I_m} since side feeding cannot be separated in this case. The quantity ϕ_I is an average side feeding time approximating the side feeding of level I by one exponential (except for the cases of long-lived tails, see below). Moreover, the ϕ_{I_m} value of the highest level represents an average total feeding time including side feeding and feeding via the yrast band.

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x/ Due to the lack of space not all of the experimental points in the short-time regions have been included in Figs. 1,2,3.

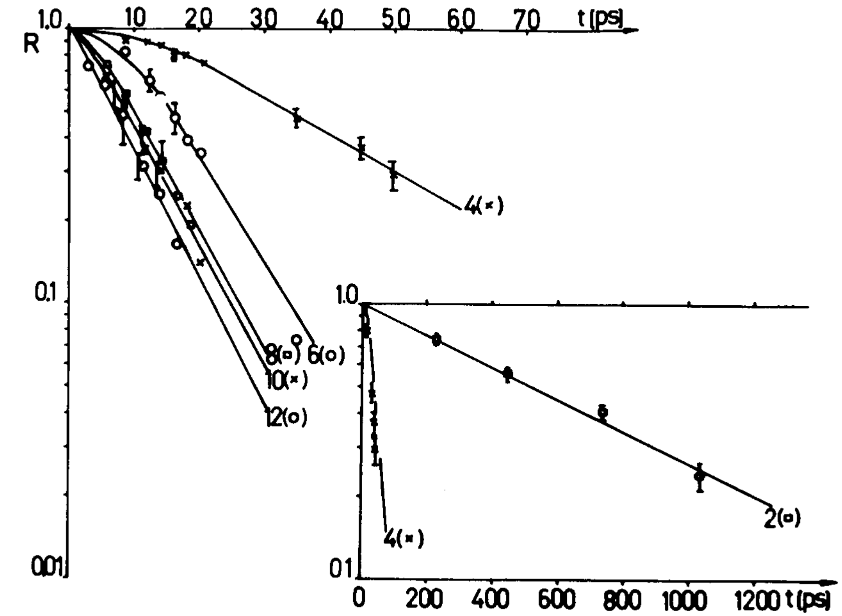

Fig. 1. Decay curves of yrast levels for $^{166}_{72}Hf$: relative intensities R_I versus time of flight. Points are experimental results for spin I. Solid lines are the calculated best-fit curves. Spin I and type of experimental point are indicated on each curve.

4. PROPERTIES OF YRAST STATES

The systematics of the energy properties J and E_4/E_2, together with the properties

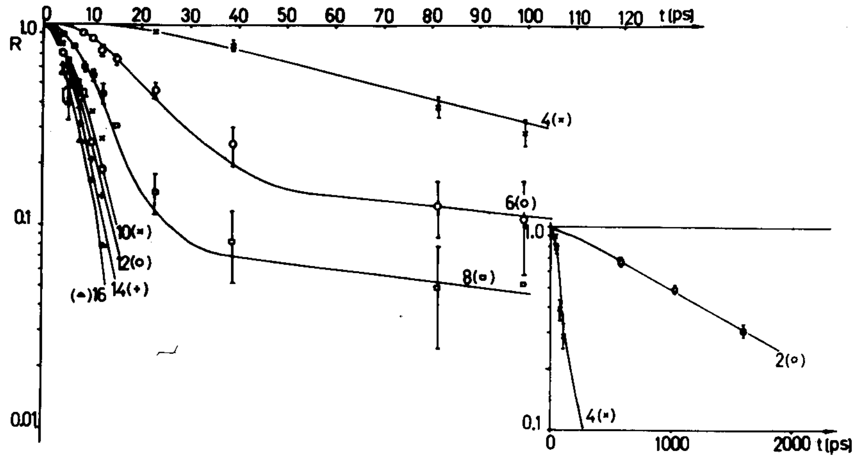

Fig. 2. The same as in Fig. 1, for the ^{168}Hf isotope.

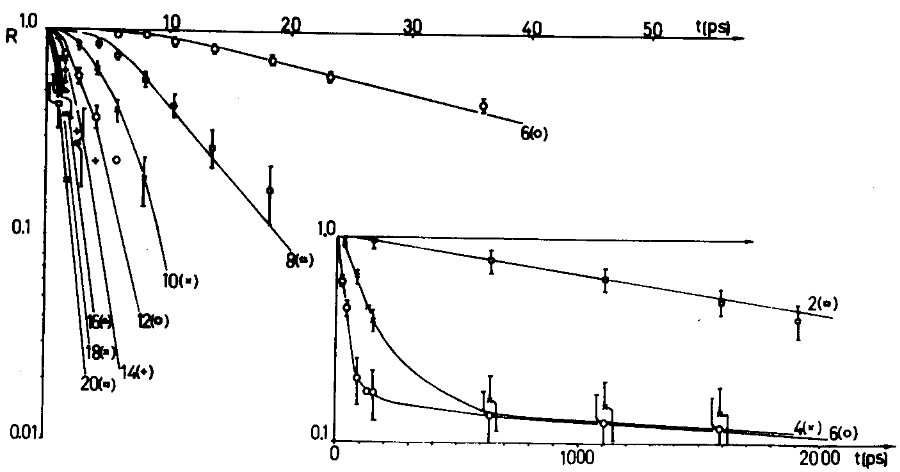

Fig. 3. The same as in Fig. 1, for the ^{170}Hf isotope.

Table 1

Transition energies $E_{I\to I-2}$, side feeding intensities $P_I/\sum_I P_I$, mean side feeding times ϕ_I and mean lifetimes τ_I (at spin I) of the yrast bands of $^{166,168,170}_{72}$Hf.

Nucleus	Level	$E_{I\to I-2}$ [kev] b)	$P_I/\sum_I P_I$	φ_I [ps]	τ_I [ps] Experi-ment	τ_I [ps] Rigid rotor
$^{166}_{72}$Hf$_{94}$	2→0	158.7	0	—	717.4 ±33	717.4 a)
	4→2	312.0	0.21±0.05	10.5±4.2	24.3±1.5	25.65
	6→4	426.9	0.18±0.05	14.1±5.3	5.11±0.68	5.053
	8→6	509.5	0.10±0.03	5.0±3.7	1.80±0.66	2.014
	10→8	564.0	0.07±0.03	16.4±13.3	0.95±0.70	1.185
	12→10	593.8	0.44±0.05	8.9±2.0	1.29±1.02	0.901
$^{168}_{72}$Hf$_{96}$	2→0	123.7	0	—	1278 ±54	1278 a)
	4→2	261.5	0	—	51.5±5.2	49.57
	6→4	371.2	{0 / 0.11±0.04}	{— / ~200}	8.51±0.83	8.397
	8→6	456.6	{0.06±0.03 / 0.07±0.04}	{3.0±2.4 / ~200}	2.86±0.27	2.898
	10→8	522.0	0.14±0.03	3.9±1.2	1.45±0.22	1.455
	12→10	569.8	0.12±0.03	9.2±3.2	0.75±0.26	0.925
	14→12	551.6	0.10±0.04	3.0±1.1	1.21±0.26	1.074
	16→14	452.9	0.40±0.08	3.2±0.5	2.62±0.29	2.845
$^{170}_{72}$Hf$_{98}$	2→0	100.3	0	—	1771 ±396	1771 a)
	4→2	220.9	0	—	89.8±9.5	88.35
	6→4	320.4	{0.15±0.04 / 0.15±0.04}	~50 / ~6000	15.6±1.3	13.88
	8→6	400.2	0.13±0.02	8.9±4.8	4.57±0.44	4.578
	10→8	462.0	0.06±0.03	2.7±2.2	2.19 ±0.27	2.196
	12→10	510.7	0.13±0.03	1.0±0.5	1.46 ±0.19	1.314
	14→12	550.6	0.08±0.03	0.8±0.7	0.95 ±0.21	0.894
	16→14	584.4	0.09±0.03	~0.2	~0.64	0.659
	18→16	614.1	0.05±0.02	~0.2	~0.50	0.511
	20→18	653.6	0.16±0.04	~0.8	~0.34	0.373

deduced from the 2^+ level lifetimes, such as Q and β, is given in table 2, compared with the previous $_{70}$Yb results [1]. The same tendency of a simultaneous decrease in all parameters with N approaching the magic

Table 2

Moments of inertia $J=3/E_{2\to0}$, energy ratios $E_4/E_2=(E_{4\to2}+E_{2\to0})/E_{2\to0}$, intrinsic E2 moments $Q=Q(2\to0)$ and quadrupole deformation parameters $\beta=\beta(2\to0)$ of the $_{70}$Yb and $_{72}$Hf isotopes

Nucleus	$\mathcal{J}$ [MeV^{-1}] b)	E_4/E_2 b)	Q (barn)	β
$^{160}_{70}Yb_{90}$ a)	12.34	2.626	4.81±0.08	0.207±0.003
$^{162}_{70}Yb_{92}$ a)	18.02	2.924	6.07±0.45	0.257±0.019
$^{164}_{70}Yb_{94}$ a)	24.29	3.128	6.79±0.13	0.284±0.006
$^{166}_{70}Yb_{96}$ a)	29.33	3.228	7.26±0.18	0.301±0.008
$^{166}_{72}Hf_{94}$	18.90	2.966	5.94±0.14	0.241±0.005
$^{168}_{72}Hf_{96}$	24.25	3.114	6.49±0.14	0.261±0.006
$^{170}_{72}Hf_{98}$	29.91	3.202	7.14±0.30	0.284±0.012

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a) Ref. [1].

b) Ref. [13].

number 82 is observed. One can see that $^{166}_{72}$Hf (the neutron number is 94) can be considered as the beginning of the transitional region between the deformed and spherical nuclei, whereas this was $^{162}_{70}$Yb(N=92) in the Yb case, and $^{158}_{68}$Er(N=90) in the Er case (see ref. [17] for the Q and β values calculated using data from ref. [18]). Thus a systematic deviation of the transitional region frontier from above the neutron magic number 82 is observed (from 8 neutrons in the $_{68}$Er case to 12 neutrons in the $_{72}$Hf case) when the proton magic number is approached from below (14 protons in the $_{68}$Er case to 10 protons in the $_{72}$Hf case).

Table 3 presents the values of B(E2; $I\to I-2$), $Q(I\to I-2)$ and $\beta(I\to I-2)$ deduced from the experimental values of τ_I (table 1) up the bands, and also the enhancement factors $B(E2)/B_{rot}(E2)$. The possible deviations of enhancement factors from unity, as well as of Q and β from constants with I, are a measure of deviations of the nuclear properties from rigid-rotor one. These deviations are better visible in fig. 4, where the β versus I dependence is presented in comparison with Ward's results on $_{68}$Er [2] and our previous results obtained for $_{70}$Yb [1].

One can see the complete similarity of all these cases. A general trend of a small (within the experimental accuracy) retardation in transitions near the backbending point or a little before it is observed in all cases. The only exception is the $^{164}_{70}$Yb case [1], where it is somewhat beyond the experimental errors. There is no such trend in $^{170}_{72}$Hf, and this is in accordance with the absence of backbending in this nucleus.

In ref. [1] we concluded that such behaviour indicates that only the effects

Table 3

Reduced transition probabilities $B(E2; I \to I-2)$, enhancement $B(E2; I \to I-2)/B_{rot}(E2; I \to I-2)$ factors, intrinsic E2 moments $Q(I \to I-2)$ and deformations $\beta(I \to I-2)$ up the yrast bands in the $_{72}$Hf isotopes

Nucleus	Transition $I \to I-2$	$B(E2; I \to I-2)$ $[e^2b^2]$ Experiment	$B(E2; I \to I-2)$ $[e^2b^2]$ Rigid rotor	$B(E2; I \to I-2)/B_{rot}(E2; I \to I-2)$	$Q(I \to I-2)$ [barn]	$\beta(I \to I-2)$
$^{166}_{72}Hf_{94}$	2 → 0	0.701 ± 0.032	0.701[a]	1.000 ± 0.046	5.94 ± 0.14	0.241 ± 0.005
	4 → 2	1.056 ± 0.065	1.001	1.055 ± 0.065	6.10 ± 0.19	0.247 ± 0.008
	6 → 4	1.090 ± 0.145	1.102	0.989 ± 0.132	5.90 ± 0.39	0.240 ± 0.016
	8 → 6	1.29 ± 0.47	1.154	1.12 ± 0.41	6.28 ± 1.15	0.254 ± 0.047
	10 → 8	1.48 ± 1.09	1.185	1.25 ± 0.92	6.63 ± 2.44	0.268 ± 0.099
	12 → 10	0.84 ± 0.67	1.206	0.70 ± 0.55	4.96 ± 1.96	0.203 ± 0.080
$^{168}_{72}Hf_{96}$	2 → 0	0.838 ± 0.035	0.838[a]	1.000 ± 0.042	6.49 ± 0.14	0.261 ± 0.006
	4 → 2	1.152 ± 0.116	1.197	0.962 ± 0.097	6.37 ± 0.32	0.256 ± 0.013
	6 → 4	1.300 ± 0.127	1.319	0.986 ± 0.096	6.44 ± 0.31	0.259 ± 0.013
	8 → 6	1.398 ± 0.132	1.379	1.013 ± 0.096	6.53 ± 0.31	0.262 ± 0.012
	10 → 8	1.422 ± 0.216	1.417	1.003 ± 0.152	6.50 ± 0.49	0.261 ± 0.020
	12 → 10	1.78 ± 0.62	1.442	1.23 ± 0.43	7.21 ± 1.25	0.288 ± 0.050
	14 → 12	1.296 ± 0.278	1.460	0.888 ± 0.191	6.11 ± 0.66	0.246 ± 0.026
	16 → 14	1.600 ± 0.177	1.474	1.086 ± 0.120	6.76 ± 0.37	0.271 ± 0.015
$^{170}_{72}Hf_{98}$	2 → 0	1.015 ± 0.227	1.015[a]	1.000 ± 0.224	7.14 ± 0.80	0.284 ± 0.032
	4 → 2	1.428 ± 0.151	1.451	0.984 ± 0.104	7.09 ± 0.38	0.282 ± 0.015
	6 → 4	1.425 ± 0.120	1.598	0.892 ± 0.075	6.75 ± 0.28	0.268 ± 0.011
	8 → 6	1.675 ± 0.161	1.672	1.002 ± 0.098	7.15 ± 0.34	0.284 ± 0.014
	10 → 8	1.723 ± 0.212	1.718	1.003 ± 0.124	7.15 ± 0.44	0.284 ± 0.018
	12 → 10	1.573 ± 0.205	1.748	0.900 ± 0.117	6.78 ± 0.44	0.270 ± 0.018
	14 → 12	1.67 ± 0.37	1.770	0.94 ± 0.21	6.93 ± 0.77	0.276 ± 0.031
	16 → 14	~ 1.84	1.787	~ 1.03	~ 7.25	~ 0.288
	18 → 16	~ 1.84	1.799	~ 1.02	~ 7.22	~ 0.287
	20 → 18	~ 1.98	1.810	~ 1.10	~ 7.48	~ 0.296

a) Normalized to experiment.

giving a drastic increase in moments of inertia J, but small changes in intrinsic E2 moments Q, can be responsible for backbending

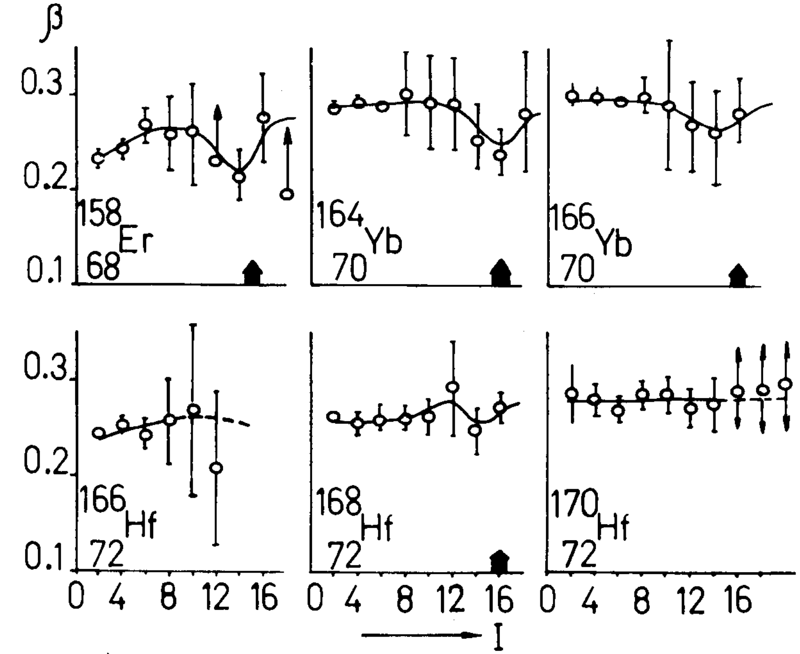

Fig. 4. Quadrupole deformation parameters $\beta = \beta(I \to I-2)$ versus level spin I up the yrast band in $_{68}$Er (ref. [12]), $_{70}$Yb (ref. [1]) and $_{72}$Hf nuclei (the present paper).

in this region of nuclei. These may be either the Coriolis antipairing, or the rotational alignment. Any strong changes in deformation or in the collectivity of yrast states can thus be eliminated.

Recently a drastic decrease (by a factor of nearly 25) in B(E2) has been reported to take place in the $^{134}_{58}$Ce case [19], which has not been observed before even in the $^{130}_{58}$Ce case [2]. The authors of ref. [19] relate it to a drastic structure change in the yrast sequence. As can be seen from the discussion presented above, this effect is absent in

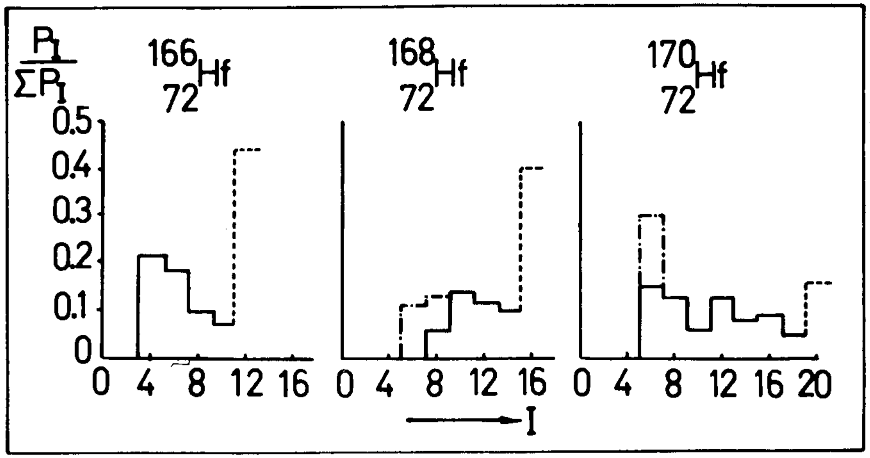

Fig. 5. Intensities of side feeding $P_I / \sum_I P_I$ versus level spin I in the reactions leading to $_{72}$Hf isotopes. Dashed lines indicate total feeding of the highest level observed (i.e., the side feeding of all levels higher than or identical with it). Dashed-dotted lines indicate the slow side feeding of low-spin levels.

the Er , Yb and Hf nuclei, some data on which are summarized in fig. 4.

5. FEEDING OF YRAST STATES

The side feeding intensities and times are presented in table 1, and the intensities can also be seen in fig. 5. One observes here the following two specific features. In addition to the usual fast side feeding component, a slow one is also found. This slow component can be seen directly in figs. 2 and 3, where the long-

lived tails of the decay curves for low-spin transitions (I=8–4) are visible.

The fast component, as in ref. [1], starts again at spins around I=8, and ends at I=20–24. This confirms the idea about enhanced transitions from higher-lying high-spin levels to the yrast band near the backbending point [1], and also the common regularity that $\sqrt{\langle I^2 \rangle} / \sqrt{\langle \ell^2 \rangle}$ decreases with increasing projectile mass [20]. Here $\sqrt{\langle I^2 \rangle}$ is the mean square angular momentum of the levels populated, and $\sqrt{\langle \ell^2 \rangle}$ is the mean square angular momentum of the compound nucleus. Moreover, one observes a saturation of $\sqrt{\langle I^2 \rangle}$ with increasing projectile mass if one compares the data of refs. [20,1] for projectiles up to $^{40}_{18}Ar$, with the results presented here for still heavier projectiles, such as $^{48,50}Ti$. This takes place even if one considers only the fast component. This contradicts the commonly accepted point of view that $\sqrt{\langle I^2 \rangle}$ increases with projectile mass.

The side feeding times ϕ_I (table 1) show the same tendency of increasing with decreasing spin I. The total feeding times θ_I, presented in table 4, are the commonly used composite quantities [18,21], which give the time passed from the reaction end to the decay of level I (i.e., the time at the e^{-1} height on the $R_I(t)$ decay curve). They show the same increase with decreasing N, i.e., for softer nuclei, as observed previously (refs. [17,18,21,1,2]). Some hypotheses proposed to explain this have been discussed in ref. [1].

The slow component has a non-zero intensity for levels with low spins I=8, 6 and

Table 4

Feeding times θ_I of the yrast bands of $_{68}$Er, $_{70}$Yb and $_{72}$Hf isotopes

Reaction \ Level I	Θ_I [ps] 20	18	16	14	12	10	8	6
$^{130}_{52}Te(^{32}_{16}S,4n)\,^{158}_{68}Er$ a)		2.2	4.8	6	7.5	8.6	10	14
$^{128}_{52}Te(^{40}_{18}Ar,4n)\,^{164}_{70}Yb$ b)		6.5±1.5	8.0±1.5	8.3±1.5	8.7±1.5	9.4±2.0	11.8±2.0	19.7±2.0
$^{130}_{52}Te(^{40}_{18}Ar,4n)\,^{166}_{70}Yb$ b)	3.7±2.0	4.9±2.5	6.2±1.5	6.6±1.5	7.2±1.5	8.3±2.5	11.2±2.0	20.9±2.0
$^{122}_{50}Sn(^{48}_{22}Ti,4n)\,^{166}_{72}Hf$					10.2±3.0	11.5±3.0	12.5±2.0	18.3±2.2
$^{124}_{50}Sn(^{48}_{22}Ti,4n)\,^{168}_{72}Hf$			6.2±0.8	7.0±1.0	8.0±1.0	9.0±1.0	12.6±1.1	22.0±2.0
$^{124}_{50}Sn(^{50}_{22}Ti,4n)\,^{170}_{72}Hf$	1.1±0.3	1.4±0.6	1.8±0.5	2.6±0.5	3.8±0.5	6.0±0.5	12.1±1.0	27.0±2.0

a) Ref. [2].
b) Ref. [1].

even 4. The intensity P_I of the slow component is shown in table 1 and fig. 5. The lifetimes ϕ_I of the long-lived component are presented in table 1. This component manifests itself in the form of long-lived tails of the decay curves for I=8,6,4 (see figs. 2 and 3). Such components have not been observed in the same nuclei before [21]. However, in the latter reference there was some indication of the existence of such component for $^{168}_{72}$Hf with unknown time ϕ_I,

which could not be distinguished from the background, but whose intensity was in rather good agreement with our data. This difference is possibly due to the lighter projectiles. $^{20}_{10}$Ne used in ref. /21/ as compared with $^{48,50}_{22}$Ti used in this work. One can notice the systematic decrease of the times $\phi=\phi_I$ of this component with decreasing A: 6000 ps for $^{170}_{72}$Hf, 200 ps for $^{168}_{72}$Hf, and 12 ps, almost undistinguishable from the fast component, in $^{166}_{72}$Hf. This systematics can be extended in a smooth way to the heavier $_{72}$Hf isotopes (see fig. 6), in which the isomeric

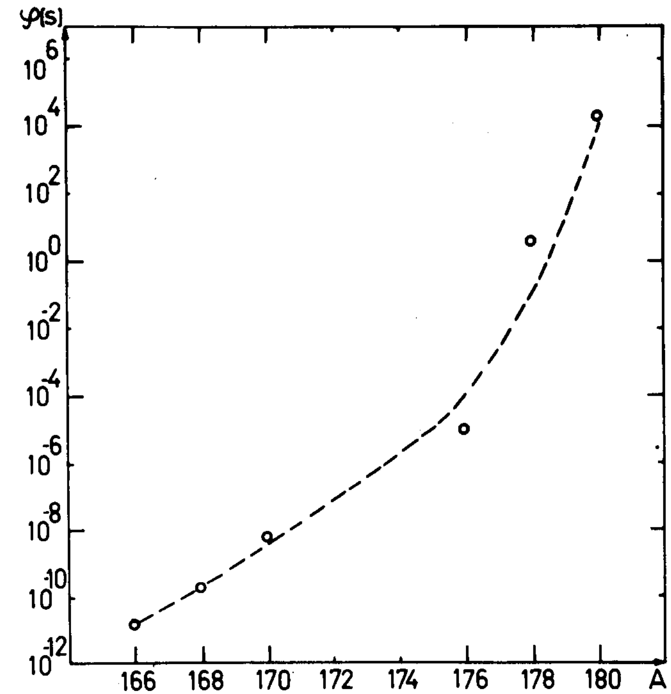

Fig. 6. Lifetimes ϕ of 8- isomeric states in Hf nuclei versus mass number A: known in $^{176, 178, 180}$Hf (refs. /14,15,22/) and hypothetical in $^{166,168, 170}$Hf (the present paper).

8− [7/2(404)p, 9/2(514)p] states have been observed in $^{180}_{72}$Hf (5.5 h), $^{178}_{72}$Hf (45 s) and $^{176}_{72}$Hf (9.8 μs), populating with different intensities the 8^+, 6^+ and 4^+ levels of the ground state band [12,14,15,22]. Such transitions between the yrast band and the 8− isomeric states have also been observed in Coulomb excitation experiments using the stable Hf nuclei [23]. Thus one can put forward the hypothesis that the slow side feeding goes via the so far unobserved isomeric states (possibly 8− [7/2(404)p, 9/2(514)p]) in the $^{166, 168, 170}$Hf isotopes, which could be viewed upon as "traps" near the yrast line, as discussed in ref. [6].

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