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Directional correlation of γ rays in 31 yr ^{178}Hf^m decay

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Directional correlations of γ rays observed in the decay of the 16^+ isomeric state in ^{178}Hf were measured with a multidetector system. Multipole mixing ratios for four γ transitions in the rotational band based on the 8^- two-quasiparticle isomeric state in ^{178}Hf are derived, and the structure of this band is discussed.

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The nucleus ^{178}Hf belongs to the small group of nuclei in which long lived K isomers have been observed experimentally. The structure of these levels has been a topic of interest of many groups during recent years [1–5]. The authors [1,3] describe levels of the $K^\pi = 8^-$ band as a mixture of $2n$ and $2p$ states taking into account the results of the analysis of the multipole ratios, $\delta(E2/M1)$, obtained from conversion electron data, from nuclear orientation experiment, and from γ-ray intensity analysis. They conclude that the two-proton contribution in these levels is almost independent of the spin of the band members. However, this model of ^{178}Hf does not explain the results of the Coulomb excitation of the $K^\pi = 8^-$ isomeric state ($T_{1/2} = 4$ s) in ^{178}Hf by heavy ions, which was first reported by Hamilton *et al.* [4] eleven years ago and recently verified again by Xie *et al.* [5]. These results can be explained by inclusion of possible admixtures of other configurations in higher levels of the $K^\pi = 8^-$ band. We therefore tried to obtain more precise experimental data on the $K^\pi = 8^-$ band using the technique of γ-γ correlations. The existence of a strong source of the 16^+ isomer (one order of magnitude stronger than the previous ones) prepared in Joint Institute of Nuclear Research, Dubna as a target for heavy ion reactions [6] made this study possible. Using this source for γ-γ angular correlation measurement represents a unique possibility of determining the multipole mixing ratios of γ transitions in the $K^\pi = 8^-$ band, which is populated in the decay of the 16^+ isomeric state.

The 31 yr ^{178}Hf^m source was produced in (α,2n) reaction by bombarding a ^{176}Yb target (enrichment 85%) with 36 MeV alpha particles from the beam at the Alma Ata cyclotron. Several chemical separations were necessary to remove the unwanted activity of other nuclides. The measurements were carried out 10 months after the irradiation in order to reduce the 70 d ^{175}Hf activity. The strength of the source was 8.5 kBq (i.e., 1.2×10^{13} ^{178}Hf^m atoms).

A multidetector system with seven true-coaxial Ge(Li) detectors was employed for measuring the γ-γ angular correlations. The volume of each Ge(Li) detector was approximately 40 cm^3 and the energy resolution was in the range 2.5–3.5 keV at 1332 keV. All seven detectors were fixed at equal distances around a circle, in the middle of which was the radioactive source. The distance between each detector and the source was 75 mm. In this way, correlation function measurements for angles 51.4°, 102.8°, and 154.3° between detectors could be performed simultaneously. For further details of the equipment, see [7,8].

The dependence $W(\theta)$ of the γ-γ correlation intensity on the angle θ is described by the well known expression

$$W(\theta) \sim 1 + A_{22}Q_{22}P_2(\cos\theta) + A_{44}Q_{44}P_4(\cos\theta). \quad (1)$$

The extracted A_{22} and A_{44} coefficients are presented in Table I. In our analysis we used the solid angle correction factors Q_{22} and Q_{44} determined after Ref. [9]. The values of Q_{22} and Q_{44} depend on the cascade and range in intervals 0.924–0.937 and 0.766–0.801, respectively. The experimental results for the cascades consisting of stretched $E2$ transitions are in a good agreement with the theoretical values $A_{22} = 0.102$ and $A_{44} = 0.009$ (see Table I). In the case of γ transitions with mixed multipolarity, values of the multipole mixing ratios $\delta(E2/M1)$ were determined respecting the sign convention of Steffen and Alder [10]. They are listed in Table II together with the $\delta(E2/M1)$ values calculated from the internal conversion data [1] and those presented in [3]. It is obvious that the δ values for the 237 and 297 keV transitions measured in the nuclear orientation experiment are not in good agreement with the other data. In particular, the sign of our parameter δ for the 13^--12^- transition is negative. The adopted $\delta(E2/M1)$ values (see Table III) were determined from our results and those from Ref. [1]; we used a procedure which minimizes the χ^2 value for both the angular correlation and the conversion coefficient data (see, e.g., [8]).

The transitions listed in Table II are the intraband transitions of the rotational band based on the $K^\pi = 8^-$ isomeric state at 1147 keV. It is known (see, e.g., Refs. [1,3]) that this state is a mixture of two proton ($2p$) state $p9/2^-[514]$+$p7/2^+[404]$ and two neutron ($2n$) state $n9/2^+[624]$+ $n7/2^-[514]$. de Boer *et al.* [1] and Postma *et al.* [3] analyzed the structure (percentage of $2p$ and $2n$

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TABLE I. The directional correlation coefficients of cascades in ^{178}Hf.

Cascade E_γ (keV)		Spin sequence	A_{22}	A_{44}
89+93[a]	- 213[b]		0.05(8)	0.06(16)
89+93[a]	- 326[b]		0.12(5)	0.00(9)
89+93[a]	- 426[b]		0.14(6)	0.00(12)
326	- 213[b]	6^+- 4^+- 2^+	0.145(32)	0.02(6)
426	- 213[b]		0.088(32)	−0.02(6)
237	- 217	10^-- 9^-- 8^-	0.28(14)	0.10(24)
495	- 217	11^-- 9^-- 8^-	0.192(33)	0.11(6)
574	- 217[b]		0.147(36)	0.01(7)
258	- 237	11^--10^-- 9^-	0.05(11)	0.08(23)
574	- 237[b]		0.12(17)	−0.37(28)
258	- 454	11^--10^-- 8^-	−0.07(8)	−0.08(17)
574	- 258	13^--11^--10^-	0.00(8)	0.13(15)
297	- 454[b]		−0.35(11)	−0.21(22)
297	- 535	13^--12^--10^-	−0.24(10)	−0.15(19)
426	- 326	8^+- 6^+- 4^+	0.111(30)	−0.02(5)
574	- 495	13^--11^-- 9^-	0.110(33)	−0.04(6)

[a] Not resolved doublet.

[b] Correlation with one or more γ rays unobserved.

states) of some levels in this band. We are able to extend this analysis due to our more complete set of $\delta(E2/M1)$ parameters.

We follow a similar procedure as in Ref. [1]. The experimental $(g_K-g_R)^{\rm exp}$ values (see Table III) were extracted from the adopted $\delta(E2/M1)$ values using the quadrupole moment $Q_0 = 6.95$ b (Refs. [1,3]). Drawing on the expression for $M1$ matrix element (see, e.g., [11]), we assume that the following equation applies to $M1$ transition between states with spins I and $I-1$:

$$(g_K - g_R)^{\rm exp} = A(I)A(I-1)(g_K^{2n} - g_R^{2n}) + B(I)B(I-1)(g_K^{2p} - g_R^{2p}), \qquad (2)$$

where $A(I)$ and $B(I)$ are the amplitudes of $2n$ and $2p$ wave functions, respectively $[A(I)^2 + B(I)^2 = 1]$. The gyromagnetic ratios for the $2n$ state (g_K^{2n}, g_R^{2n}) and for the $2p$ state (g_K^{2p}, g_R^{2p}) are calculated in the same way as in [1]. We suppose a smooth dependence of amplitudes $A(I)$ on the spin. In the present calculation we use the simple formula $A(I) = a+bI(I+1)$, where a and b are the parameters to be fitted. The resulting values of weighting factors (percentages) $C(I) = A(I)^2$ for the $2n$ wave function are shown in Table III. We obtained a good fit to the experimental data ($\chi^2 \sim 1$). Our estimate of $C(8)$ is in agreement with the value of 62.6(1.9)% calculated from logft values (Ref. [1]).

Let us also mention that our results for band-mixing probabilities are consistent with the pattern of decay from the levels of the second $K^\pi = 8^-$ rotational band at 1479 keV [12].

Concluding, we summarize that we obtained new experimental information concerning transitions in the $K^\pi = 8^-$ band based on the isomeric state at 1147 keV.

TABLE II. The values of the multipole mixing ratios $\delta(E2/M1)$ of the γ rays in ^{178}Hf.

E_γ	I_i^π - I_f^π	δ	$\mid\delta\mid$ [1]	$\mid\delta\mid_{\rm br}$ [a] [3]	$\delta_{\rm NO}$ [b] [3]
217	9^-- 8^-	$0.55^{+0.21}_{-0.13}$ or $2.3^{+0.9}_{-0.7}$	1.6(2)		$0.64 \le \delta \le 1.88$
237	10^-- 9^-	0.44(24) or $2.2^{+1.6}_{-0.7}$	1.5(3)	1.8(2)	$5.9 \le \delta \le 14$
258	11^--10^-	0.07(10) or < -10 or > 4.2	$3.6^{+2.0}_{-0.8}$	$3.2^{+1.7}_{-0.7}$	
277	12^--11^-		> 1.13	$2.5^{+1.0}_{-0.5}$	
297	13^--12^-	$-2.3^{+1.2}_{-1.6}$ or $-0.45^{+0.18}_{-0.45}$	> 3.3	$3.1^{+1.3}_{-0.6}$	$\delta \ge 11$

[a] Calculated from the branching ratios of γ-ray intensities.

[b] Obtained from the nuclear orientation experiment.

TABLE III. The weighting factors $C(I)$ for the $2n$ wave function in the $K = 8^-$ band.

I	$\delta(E2/M1)$ $I \to I-1$	$(g_K - g_R)^{\mathrm{exp}}$	$C(I)^{\mathrm{a}}$ (%)
8			64
9	$1.63^{+0.22}_{-0.18}$	0.097(12)	67
10	$1.57^{+0.31}_{-0.24}$	0.099(18)	70
11	$4.3^{+2.6}_{-1.2}$	0.036(13)	74
12	$\mid \delta \mid > 1.13$	0.00(12)	78
13	$-3.8^{+1.2}_{-2.8}$	$-0.039(18)$	82

[a] The errors of $C(I)$ values are 1–2 (in units of this table) taking into account only the errors of the $(g_K - g_R)^{\mathrm{exp}}$.

Our data are in an overall agreement with the data of de Boer *et al.* [1], but at variance with more recent results of Postma *et al.* [3]. At present we cannot explain this discrepancy between our data based on γ-γ correlations and those of Postma *et al.* [3], which are derived using the nuclear spin orientation method. The model analysis of our data and [1] leads to the following: the percentage of $2n$ state in the levels of this band is growing with the spin. The use of only one parameter $g_R = 0.262$ (Ref. [1]) instead of two (different for the $2p$ and $2n$ states) does not change the result significantly. To explain our data, we do not need any assumption about admixtures of other configurations than those mentioned above. Therefore, we still cannot solve the puzzle — strong feeding of the 8^- isomeric state in Coulomb excitation.

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