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NEW BAND-MIXING ANOMALIES IN ^{178}Hf

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γ-$\gamma(\theta)$ measurements with a NaI-Ge(Li) detector arrangement were carried out to measure the $M1$ admixture in the 1183-keV, $2^+ \to 2^+$ transition in ^{178}Hf. These results yield $M1 = (85.6^{+1.1}_{-2.1})\%$ for the 1183-keV transition. Accurate branching ratios were also obtained from singles spectra taken with a large-volume Ge(Li) detector. It is possible to obtain from these intensities the same Z_β value from the different branching ratios if a $(73.0 \pm 1.3)\%$ $M1$ admixture is assumed in the $2^+ \to 2^+$ transition. Thus the measured $M1$ admixture yields branching ratios that are not explained by the present band-mixing picture in contrast to earlier reports.

Since the first reports[1,2] of what seemed to be anomalous gamma-ray branching ratios from the 2^+ members of β-vibrational bands in ^{152}Sm and ^{154}Gd, there has been much interest in establishing the cause of this effect. An early suggestion was that there existed a very large $M1$ component in the $2_\beta{}^+ \to 2_g{}^+$ transitions of these two nuclei despite the long-standing prediction of essentially no $M1$ admixtures in the quadrupole beta vibrations.[3] At the International Conference on Nuclear Structure in Tokyo, however, Mottelson[4] pointed out how the theory could be modified to include sizable $M1$ admixtures and stressed the crucial importance of observing these $M1$ admixtures in order to preserve the application of rotational relationships to these nuclei. Our directional correlation measurements in ^{154}Gd have shown,[5] however, that the 692-keV, $2_\beta{}^+ \to 2_g{}^+$ transition has less than or equal to 2% $M1$ admixture. The 50% $M1$ component required[1,2] to obtain a consistent band-mixing parameter, Z_β, from the reduced transition probabilities in ^{154}Gd is clearly ruled out.

On the other hand, Nielsen, Nielsen, and Rud[6] carried out γ-$\gamma(\theta)$ measurements on ^{178}Hf, the 1183-93 keV cascade which originates at a 1276-keV, 2^+ level, assigned as a beta vibrational state. An $M1$ admixture of $(85 \pm 10)\%$ (as calculated from their δ) was found in the 1183-keV transition. When this large $M1$ admixture was considered, they obtained[6] a consistent band-mixing parameter for the 1276-keV level as a beta vibrational state.

In support of our finding of a very low $M1$ admixture in the $2_\beta{}^+ \to 2_g{}^+$ transition in ^{154}Gd, recent Coulomb-excitation work[7,8] has shown similar results in ^{152}Sm. However, it now appears[7,9] that instead of the $2_\beta{}^+ \to 2_g{}^+$ transitions being responsible for the inconsistent branching ratios, the problem is in the $2_\beta{}^+ \to 4_g{}^+$ transition. Thus, it is surprising to find reported[6] in ^{178}Hf that it is the $2^+ \to 2_g{}^+$ transition that is involved in the alteration of the $B(E2)$ branching ratios.

Nielsen, Nielsen, and Rud[6] carried out their γ-$\gamma(\theta)$ studies with two NaI detectors. In the NaI spectrum the 0.11%, 1183-keV transition is seen as a weak shoulder on the 0.44%, 1106-keV photopeak. The problem is also complicated by a 0.02%, 1189-keV transition (in a skip correlation) that is very difficult to resolve even by computer. More important, we also have discovered an unreported[10] 1174-keV transition with 0.015% intensity that was not considered in the work of Nielsen, Nielsen, and Rud.[6] It is important to establish that it is indeed an $M1$ admixture in the $2^+ \to 2_g{}^+$ transition in ^{178}Hf that gives rise to inconsistent Z_β values in contrast to ^{154}Gd where it appears that the $2_\beta{}^+ \to 4_g{}^+$ transition[7,9] is responsible. Thus, we have repeated the ^{178}Hf γ-$\gamma(\theta)$ measurement with our directional correlation arrangement which has one Ge(Li) detector so that the 1183-keV transition is well resolved in the spectrum. We also have measured the intensities of the transitions in ^{178}Hf with a much larger Ge(Li) detector in order to have accurate values for computation of relative $B(E2)$ values. From these data, one can ascertain what value of an $M1$ admixture is needed to obtain a consistent Z_β.

The apparatus for the γ-$\gamma(\theta)$ measurements was the same as used previously[5] except that new detectors were used. The experiment was performed at first with a Ge(Li) detector which had a resolution of 2.8 keV full width at half-maximum at 1.33 MeV, and at the same energy an efficiency of 3.8% relative to that of a 3×3 in. NaI detector. The whole experiment was repeated with a much larger Ge(Li) detector which had a 10% efficiency and 2.5 keV resolution at 1.33 MeV. With our two-gate system, we simultaneously measured the correlations of all gamma rays coincident with the 93-keV, $2_g^+\rightarrow 0_g^+$ transition and with the Compton background just above the 93-keV peak (the latter was found to be negligible). A lead-cadmium-copper absorber was placed over the Ge(Li) detector to attenuate the low-energy portion of the spectrum, and a 0.5 mm cadmium absorber over the NaI detector to reduce the ^{178}Hf K x rays in that detector. A biased amplifier was used to cut out the Ge(Li) spectrum below 500 keV. The gamma-ray singles spectrum was also measured with the Ge(Li) detector with the larger efficiency. The source was ^{178}W ($T_{1/2}=22$ days) in the form of H_2WO_4 dissolved in dilute NaOH.

The correlations with gates set on the 93-keV peak and on the Compton background just above it were measured simultaneously. The first of the two separate experiments was carried out for fourteen cycles and the second for seven cycles. Each three-day cycle consisted of a 23 h running time at 90, 135, and 180° for a total of 42 days in the first measurement and for a total of 21 days with the larger detector. Alternation of the sequence of angles through 90, 135, 180; 180, 135, and 90° compensated for the source decay to better than 1%. The NaI gate counts recorded for each 23 h period were constant to better than 1%. These counts were used to normalize the coincidence results, and coupled with the measured 2τ and the Ge(Li) singles spectra taken between each run, were also used to calculate chance corrections for both the 93 keV and background correlations. The true-to-chance ratio varied from 9 to 25. Since the 93-keV state has a relatively long half-life ($T_{1/2}=1.50$ nsec), correlations involving it are attenuated. The attenuation corrections Q_2G_2 and Q_4G_4 for the Ge(Li) and NaI detectors were obtained from known correlations in the decay. The solid-angle corrections for the Ge(Li) detector also were calculated by computer.

There are three 0^+ states[10,11] with prominent transitions to the 2^+ level of the ground-state rotational band. Cascades with $0\rightarrow 2\rightarrow 0$ spins have unique correlation coefficients $A_2=0.357$ and $A_4=1.14$. Therefore, from the experimental $Q_2G_2A_2$ and $Q_4G_4A_4$ coefficients of these cascades we obtain Q_2G_2 and Q_4G_4 for each run. The results of the second measurement with the large detector are given in Table I. Note the excellent consistency in Table I of the $Q_2G_2A_2$ and $Q_4G_4A_4$ values for these correlations. These corrections were applied to the 1183-93 and 1403-93 keV, $2^+\rightarrow 2^+\rightarrow 0^+$ cascades and the resulting A_2 and A_4 values are given in columns 4 and 5 of Table I. Within the limits of error the same results were obtained in the measurements with the smaller Ge(Li) detector but with larger errors because of the poorer statistics. The corresponding values obtained by Nielsen, Nielsen, and Rud[6], also given in Table I, include statistical errors only. When systematic uncertainties that include effects from weak unresolved lines with unknown correlations were taken into account, they found[6] $\delta=-(0.41\pm0.17)$ and an $M1$ admixture of (85 ± 10)%. From a weighted average of our data ($A_2=-0.054\pm0.023$ and $A_4=0.041\pm0.033$), we find $\delta=-(0.410\pm0.036)$ which corresponds to an $(85.6^{+1.1}_{-2.1})$% $M1$ admixture. Because of our good resolution, there are no known systematic effects from unresolved gamma rays and Compton backgrounds to distort these data. Thus, a large $M1$ admixture in the 1183-keV transition is firmly established.

The relative intensities of the transitions from the 1276 keV, 2^+ state as obtained with our more efficient detector, are given in Table II along with the previous results.[6,12] From our branching-ratio data, an $M1$ admixture of (73.0 ± 1.3)% in the $2^+\rightarrow 2^+$, 1183-keV transition would yield a consistent Z_β for the various branching ratios from the 1276-keV, 2^+ state. Siddiqi, Carlson, and Emery[12] recently obtained from these branching ratio data an $M1$ admixture of (70.5 ± 1.5)% in agreement with our results. When one subtracts the 85.6% $M1$ admixture in this $2^+\rightarrow 2^+$ transition found from our γ-$\gamma(\theta)$ work, it is im-

Table I. Directional correlation coefficients of cascades in ^{178}Hf as obtained with a 10% efficient Ge(Li) detector.

Energies (keV); spins	$Q_2G_2A_2$	$Q_4G_4A_4$	A_2	A_4
1106-93 (0-2-0)	0.245 ± 0.011	0.577 ± 0.010		
1341-93 (0-2-0)	0.253 ± 0.006	0.572 ± 0.007		
1351-93 (0-2-0)	0.252 ± 0.006	0.580 ± 0.006		
Average of above three	0.250 ± 0.004	0.577 ± 0.005		
1183-93 (2-2-0)	−0.045 ± 0.020	0.032 ± 0.022	−0.064 ± 0.028	0.063 ± 0.043
			−0.056 ± 0.051[a]	−0.025 ± 0.057[a]
1403-93 (2-2-0)	0.346 ± 0.009	0.072 ± 0.010	0.494 ± 0.015	0.143 ± 0.020
			0.415 ± 0.035[b]	0.122 ± 0.040[b]

[a]Data from Ref. 6. The errors include statistical ones only. When systematic effects were taken into account (Ref. 6), the errors on delta were increased a factor of 2 over that obtained from the statistical errors (see text).

[b]Data from Ref. 6.

possible to find a consistent Z_β value. It takes 6 standard deviations in the γ-$\gamma(\theta)$ work or 10 standard deviations in our branching-ratio data for the $M1$ admixtures obtained in these two ways to agree. Thus we are forced to conclude that while the $M1$ admixture is large from this state in ^{178}Hf, the branching ratio data are in no better agreement with theory than in ^{154}Gd. Thus this work does not confirm the expectation of Mottelson[4] as earlier reported[6] and removes the one case that appeared to fit the suggested[4] new theoretical description with large $M1$ admixtures.

We have carried out a similar analysis for the next 2^+ level at 1496 keV and the results are shown also in Table II. In this case an $M1$ admixture of $(61.0^{+0.7}_{-1.2})$% was found in the 1403-keV, $2^+ \to 2^+$ transition. This admixture is somewhat smaller than in the 1183-keV transition. If one assumes that this is the 2^+ beta vibrational state, then a 61% $M1$ admixture leads to consistent branching ratios. Since the branching ratios agree with a $K=0$ assignment after subtracting a 61% $M1$ admixture in the $2^+ \to 2^+$ transition, one is tempted to identify this as a beta vibrational state. However, to assign one of the known 0^+ states as the ground-state member of such a beta vibrational band would yield a mo-

Table II. Relative intensities and branching ratios from the 1276.6 and 1496.1 keV 2^+ levels in ^{178}Hf populated in the decay of ^{178}Ta.

Energy, keV	Transitions	Gamma Intensity			Present Work Experimental Relative B(E2) Values[a]			Theoretical Relative B(E2) Values for Z_β Values[b] of:			
		Ref. 12	Ref. 6	This Work	M1 = 0	M1 = 73%	M1 = $85.6^{+1.1\%}_{-2.1\%}$	0	0.020	0.026	0.040
970.0	$2^+ \to 4^+$	3.66 ± 0.21	3.57 ± 1.09	3.54 ± 0.18	86.9 ± 4.4	322 ± 16	603^{+35}_{-32}	180	295	323	437
1183.4	$2^+ \to 2^+$	11.00	11.00	11.00	100	100	100	100	100	100	100
1276.6	$2^+ \to 0^+$	2.52 ± 0.20	2.07 ± 0.64	2.22 ± 0.10	13.8 ± 0.6	51.1 ± 2.2	$95.8^{+4.7}_{-4.3}$	70	54	51.2	40
		Ref. 7		This Work	M1 = 0	M1 = 62.5%	M1 = $61^{+0.7\%}_{-1.2\%}$	0	-0.020	-0.040	-0.060
1189.5	$2^+ \to 4^+$	4.65		5.66 ± 0.28	12.9 ± 0.6	34.4 ± 1.6	33.1 ± 1.6	180	93.3	34.8	4.6
1402.9	$2^+ \to 2^+$	100		100.0	100	100	100	100	100	100	100
1496.1	$2^+ \to 0^+$	65.9		56.3 ± 1.9	40.8 ± 1.4	109 ± 3.7	$104.6^{+3.8}_{-3.6}$	70	87.4	108	129

[a]These values are for various $M1$ components in the 1183.4 and 1402.9-keV, $2^+ \to 2^+$ transitions as indicated.

[b]The notation here is the same as Ref. 1. The lower half of the table is for the 1496.1-keV level and the Z_β values are negative.

ment of inertia quite different from that of the ground-state band. Nielsen, Nielsen, and Rud[6] already have pointed out that the electron capture feeding to the 1493-keV level is a factor of 2 higher than predicted by Alaga's rules for a rotational band built on either the 1434- or 1444-keV, 0^+ states. A more serious problem is the $E0$ strength of the 1403-keV, $2^+ \rightarrow 2^+$ transition. Our electron data and that of earlier work[6,10] indicate that the $E0$ strength of the 1403-keV transition is about 10 times weaker than that of the 1183-keV transition.

The implications of these results are that the levels in ^{178}Hf previously reported[6,10] as beta vibrational in character are not. It certainly is true that the ^{178}Hf $K=0$ bands are quite different in structure than in ^{154}Gd. A succeeding paper[13] will present evidence that these levels in ^{178}Hf at 1199 and 1276 keV are in fact not collective states as previously thought.[6,10] One is clearly left with the problem of the anomalous branching ratios from the beta bands as there is at present no case where there is an adequate theoretical description to explain the branching ratios from these states of the beta vibrational type.

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