Violations of *K*-Conservation in ^{178}Hf

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Abstract. Coulomb excitation of $K^{\pi}=6^{+}(t_{1/2}=77$ ns), $8^{-}(t_{1/2}=4.0$ s) and $16^{+}(t_{1/2}=31$ y) ^{178}Hf isomers has led to the measurement of a set of Eλ matrix elements, coupling the isomer bands to the γ- and ground state bands. The resulting matrix elements, derived using a coupled-channel semiclassical Coulomb excitation search code, have been used to probe the *K*-components in the wave functions and revealed the onset and saturation of *K*-mixing in low-*K* bands, whereas *K*-mixing is negligible in the high-*K* bands. The implications can be applied to other quadrupole-deformed nuclei. An upper limit on the Coulomb depopulation yield of the 16^{+} isomer was calculated based on the present set of matrix elements.

Keywords: isomer, *K*-isomer, *K*-mixing, Coulomb excitation
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INTRODUCTION

Studies of electromagnetic (EM) excitation and de-excitation of high-*K* isomeric states[1—5] have demonstrated significant violations of the *K*-selection rule in axially symmetric, quadrupole-deformed nuclei. The *K*-selection rule[6] does not allow EM transitions between two states $|I_i M_i K_i\rangle$ and $|I_f M_f K_f\rangle$ of an axially symmetric nucleus for which the forbiddenness $\nu \equiv |\Delta K| - \lambda$ is greater than zero, where λ is the multipole order and $\Delta K \equiv K_f - K_i$. The degree of hindrance of a *K*-forbidden transition can be expressed in terms of the "reduced hindrance" $f_\nu \equiv (B(\mathcal{M}\lambda)_{W.u.}/B(\mathcal{M}\lambda))^{1/\nu}$, where $B(\mathcal{M}\lambda)_{W.u.}$ is the Weisskopf single-particle estimate. The EM population of high-*K* states from the ground state band (GSB) is unlikely, either through highly hindered *K*-forbidden transitions or through multiple-step transitions of low or zero forbiddenness. For *K*-forbidden transitions, $f_\nu >> 1$ is expected. The present work has used the hindrance of the K-forbidden transitions to probe *K*-admixtures in the ^{178}Hf rotational bands and has revealed the breakdown of *K*-selection as a function of spin.

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EXPERIMENT

The $K^{\pi}=6^{+}$, 8^{-} and 16^{+} isomer bands in ^{178}Hf were populated using a 650 MeV ^{136}Xe beam from ATLAS to bombard a thin 0.5 mb/cm^2 89% enriched ^{178}Hf target. Prompt γ decays were detected in coincidence with scattered ions by Gammasphere plus the CHICO PPAC array. Prompt γ-decay yields as a function of scattering angle θ_{scat} in the $K^{\pi}=6^{+}$ and 8^{-} isomer bands were measured as high as 10^{-3} of the $8^{+}\rightarrow 6^{+}$ GSB strength. A remarkably high $19^{+}\rightarrow 18^{+}$ yield, about 10^{-4} of the GSB strength, was unexpectedly observed in the known $K^{\pi}=16^{+}$ isomer band (Figure 1)[3,7]. In most cases, the coupled-channel semi-classical Coulomb excitation code GOSIA was used to adjust matrix elements for the relevant transitions and reproduce the experimental data. Typically, a single model-dependent parameter was obtained as the measure of the coupling strength between bands, including errors correlated with all other adjustable parameters. While the Alaga rule accurately reproduced yields due to K-allowed transitions, a spin-dependent mixing (SDM) reproduced yields due to K-forbidden paths[6] for low K.

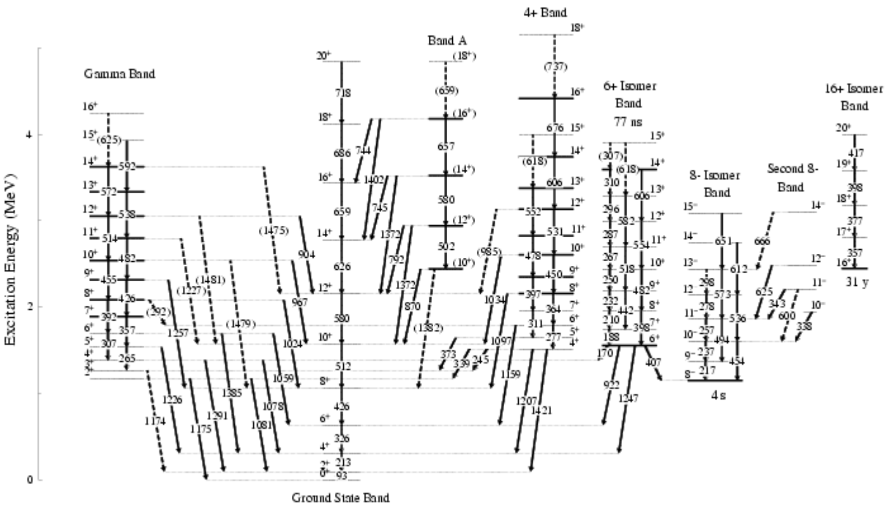

FIGURE 1. A partial level diagram for ^{178}Hf. Band A has been tentatively identified as previously unobserved states in the β-vibrational band.

A second experiment measured the Coulomb excitation function of the 16^{+} isomer in order to extract model-independent $\langle I_{K=16}||E2||I_{GSB}\rangle$ reduce matrix elements. A stack of five 1 mg/cm^2 natural Ta targets was irradiated by a $\approx$10 pnA, 858 MeV ^{178}Hf beam from ATLAS for E_{beam}=72% (target 5) to 88% (target 1) of the Coulomb barrier E_{Coul}. The targets were arranged normal to the beam, separated by 42 mg/cm^2 tantalum cylinders to collect scattered Hf ions over $40^{\circ} < \theta^{lab,scat} < 90^{\circ}$, so that <<1% of the nuclei Coulomb-excited to the 16^{+}_{isom} state were lost or embedded in downstream targets. A 1.0(1) mg/cm^2 Ta scattering foil was used to scatter beam and target particles into a silicon detector mounted at $\theta_{scat}=45^{\circ}$ to measure the absolute dose, 1.7(2) pmC, and the absolute activation cross sections (Figure 2). The GSB cascade following an isomer decay of the activated projectiles was used to count the activities five months later at Yale University's Wright Nuclear Structure Laboratory using two Ge “clover” detectors. The absolute efficiencies (≈3% for the 326 and 426 keV transitions in the GSB cascade) and the detection probabilities of relevant combinations of γ rays were calculated, including angular correlation and summing effects. Count rates were obtained from the >1-fold matrix by gating on the 326 keV $6^+ \rightarrow 4^+$ GSB transition and counting the coincident 426 keV $8^+ \rightarrow 6^+$ γ rays.

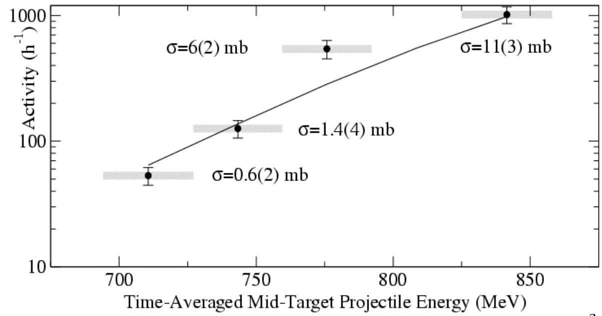

FIGURE 2. Measured and calculated activity after a direct fit of matrix elements (χ^2=3.5). The cross sections include errors in the total beam dose and measured target ablation. Target 2 (84% E_{Coul}) was not measured.

In the Xe beam experiment, it can be argued that the isomer bands could be populated through transfer reactions involving the ^{177,179}Hf contaminants in the target. An upper limit on ^{178}Hf(^{136}Xe,^{135}Xe)^{179}Hf transfer reactions was set using the only observed transition which could possibly be assigned to a ^{135}Xe transition (288 keV) in coincidence with a double gate on the ^{178}Hf GSB transitions. In the safe Coulomb excitation region, $25^{\circ} < \theta_{scat} < 52^{\circ}$, an upper limit on ^{177}Hf(^{136}Xe,^{135}Xe)^{178}Hf transfer was set at 10^{-5} of the ^{178}Hf GSB excitation. Assuming that the cross sections for ^{177}Hf(^{136}Xe,^{135}Xe)^{178}Hf (Q=-0.4 MeV) and ^{178}Hf(^{136}Xe,^{135}Xe)^{179}Hf (Q=-1.9 MeV) are similar, the upper limit on ^{177}Hf(^{136}Xe,^{135}Xe)^{178}Hf reactions in the 4.36% ^{177}Hf impurity is $\sim 10^{-4}$ compared to Coulomb excitation of the ^{178}Hf GSB in the unsafe region, $52^{\circ} < \theta_{scat} < 78^{\circ}$, divided among several bands. Moreover, transfer to a 4 quasiparticle state (*e.g.* the 16^+_{isom} band) is very unlikely, since breaking a second pair of nucleons is a higher-order effect. Since no transfer is seen in the safe region, there should not be significant transfer near 52°, even in the unsafe region, where strong K≤8 isomer populations are already seen far above background in the double-gated data. In the ^{178}Hf beam activation experiment 16^+ isomer activation was observable at 72% E_{Coul}, consistent with the Coulomb excitation function (Figure 2). Nuclear interference is small at 88% E_{Coul} and $\leq 10^{-3}$ of the E2 contribution[8—10] for $E_{beam} \leq 80\% E_{Coul}$.

ANALYSIS

In both experiments, a possible excitation path was determined to be insignificant if it could not reproduce the measured data using reasonable reduced transition probabilities for the particular multipolarity and change in collective or single-particle structure, *e.g.*, ≈1 W.u. for transitions between different quasiparticle configurations. Intrinsic matrix elements were fit to the ^{178}Hf(^{136}Xe,^{136}Xe)^{178}Hf data, connecting the

K=0$^+$ GS, γ-, 4$^+$, 6$^+$ and 8$^-$ bands using Alaga and SDM systematics (Figure 3). The yield data for the 8$^-$ bands were reproduced most accurately, and with the lowest B(E3) values (<4 W.u., reasonable in comparison to the 4 W.u. strength of the $3^-_{K=2}\rightarrow 0^+_{GSB}$ transition[11]) by two-step excitations to both 8$^-$ bands through the γ-band in conjunction with single-step excitations from the GSB, both using Alaga rule coupling systematics for K=5 admixtures in the low-K bands. It was necessary to attenuate the <8$^-$||E3||GSB> and <8$^-$||E3||K^π=2$^+$> Alaga matrix elements smoothly by approximately an order of magnitude per unit spin as I_{GSB} decreases from 6 to 10 in order to keep the isomer cross section from growing unreasonably large compared to the other quasiparticle isomers in ^{178}Hf and to preserve the 4.0(2) s half life.

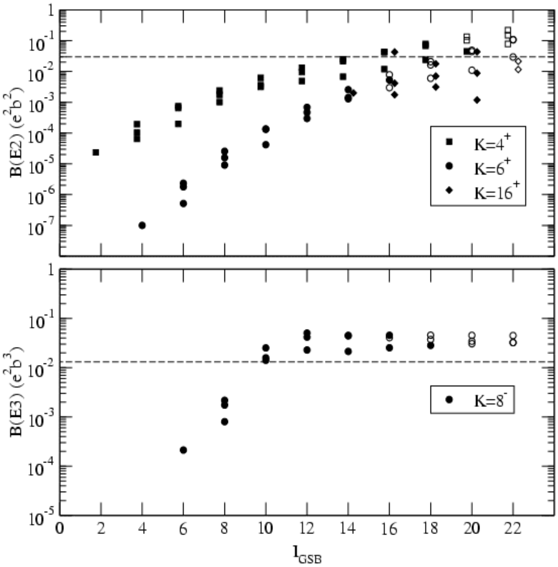

FIGURE 3. The three strongest reduced transition probabilities from each GSB level for GSB→K^π transitions. GSB→4$^+$,6$^+$ matrix elements follow SDM systematics. GSB→8$^-$ matrix elements follow the Alaga rule, attenuated at low spin. Transitions to unobserved high-spin levels (hollow) are extrapolated to clarify the spin-dependence of the intrinsic matrix elements in the models used. Weisskopf estimates (dashed lines): $B(E2\uparrow)_{W.u.}$=0.0297 e^{2}b^2. $B(E3\uparrow)_{W.u.}$=0.0132 e^{2}b^3.

A simultaneous fit to the 16$^+$ isomer activity data and the prompt $19^+_{K=16}$ yields of the first experiment led to a coherent set of $<I_{K=16}||E2||I_{GSB}>$ matrix elements with B(E2;K=0→K=16)≤1.4 W.u. with upper limits, several lower limits and several diagonal (uncorrelated) errors. The fit was constrained by measured upper limits on both the GSB→16$^+$ feeding intensity (≈10^{-4} normalized to the $8^+_{GSB}\rightarrow 6^+_{GSB}$ yield in the Hf(Xe,Xe)Hf experiment), reasonable B(E2;GSB→K^π=16$^+$) values, etc. GSB→K^π=16$^+$ feeding is not insignificant, but the matrix elements which reproduce the yields are consistent with non-observation of feeding. In particular, the strength of the 1% $20^+_{GSB}\rightarrow 20^+_{K=16}$ γ-decay branch is 3 times smaller than the observable lower limit, while the observational lower limits for the energetically favored transitions are much higher, due to the unavailability of double-γ gates and clean single-γ gates. It was found that ≈75%—80% of the isomer activation comes directly from connections between the GSB and the $17^+_{K=16}$ and $16^+_{K=16}$ states for any set of matrix elements, as long as K-mixing between the GSB and the isomer band does not decrease with increasing spin and a liberal 10 W.u. upper limit is imposed on the B(E2;GSB→*K*=16) strengths.

INTERPRETATION

The systematic decrease with increasing spin of the hindrance of *K*-forbidden transitions is apparent from Figure 3. For each of the high-*K* isomer bands observed, reproduction of the measured yields requires that the interband B(Eλ) values increase with increasing spin and saturate at ≈1 W.u. for I≥12 in the GSB and the γ-band. This saturation point represents the maximum mixing of *K*. For I≥12, reduced hindrance values of *K*-forbidden transitions from low-*K* to high-*K* bands are as low as $f_\nu \sim 1$, showing that the *K*-selection rule has little predictive power at high spin—highly *K*-forbidden transitions have similar strength to allowed interband transitions.

Band interactions are reflected in the measured moments of inertia by an increase in slope of the moment of inertia I(ω), seen at I≈6 and I≈10 in the γ- and GS bands, respectively, while the B(Eλ) values (Figure 3) saturate at ~1 W.u. as low as I≈8 and I≈10 for transitions from the γ-band and the GSB respectively, in order to reproduce the measured γ-ray yields in the $K^\pi=4^+$, 6^+, 8^- and 16^+ bands. Moreover, Coriolis alignment is expected to happen at much lower spin in low-*K* bands than in high-*K* bands[12] which are strongly deformation-coupled. The moments of inertia of the high-*K* bands are relatively constant in slope, with the exception of the 6^+ band at I≈12, suggesting that the high-*K* bands are not *K*-mixed to the same degree as the low-*K* bands. The 16^+ band has a remarkably constant moment of inertia[7] up to I=22. In contrast with the *K*=0,2 transitions to the high-*K* isomer bands, the $16^+_{isom}\rightarrow K^\pi=8^-$ and $14^-_{isom}\rightarrow K^\pi=8^-$ γ decays are strongly hindered with $33\leq f_\nu \leq 165(5)$ in all of the five known branches[13,14], showing that the onset of significant high-*K* admixtures in the 8^- band must occur at I>18, if at all, whereas less hindered $f_\nu \sim 1$ transitions from the γ- and GS bands are required to reproduce the present measured yields. That is, the strongly hindered decays of the $K^\pi=16^+$ and $K^\pi=14^-$ isomers to the $11^- < I_{K=8} < 13^-$ states are consistent with *K* being a good quantum number for the high-*K* bands, suggesting that mixing in the low-*K* bands is primarily responsible for the *K*-selection violations and that the EM matrix elements coupling to the high-*K* bands are sensitive probes of the *K*-distributions in the low-*K* bands. Coulomb excitation of a band with projection *K*, assuming that it is reasonably pure, would require admixtures *K*' in the low-*K* (nominally K_i) bands of $K-\lambda \leq K' \leq K+\lambda$. Hence, the mixing fractions of the $2\leq K' \leq 6$ components are depicted in Figure 3 as a function of spin by the B(E2;K_i → *K*=4) values, the $4\leq K' \leq 8$ components by the B(E2;K_i → *K*=6) values, etc.

The present results have revealed paths by which Coulomb depopulation of the ^{178}Hf 16^+ isomer could be achieved. The 16^+→GSB *K*-forbidden E2 paths would allow Coulomb depopulation of the isomer using heavy ions below the Coulomb barrier with a probability of ≤1% compared to the in-band excitations[15]. This path is not expected to be effective for photo depopulation, since photon absorption is dominated by E1 transitions, but this does not rule out photo depopulation via a 463 keV E1 transition to the known $15^-_{K=14}$ state, for example, calculated to be a ≤0.1% effect using heavy ion bombardment and assuming B(E1;$K^\pi=14^-\rightarrow K^\pi=16^+$)≈1 W.u. for all transitions. The $K^\pi=16^+$ to $K^\pi=8^-$ transitions are highly forbidden, making this path ineffectual. While potential low-yield Coulomb depopulation paths have been discovered, intermediate states which might mediate x-ray photo depopulation were not found.

CONCLUSION

The present work has revealed the Coulomb excitation paths of the $K^{\pi}=4^{+}$, 6^{+}_{isom}, 8^{-}_{isom} and 16^{+}_{isom} rotational bands in ^{178}Hf by rapidly increasing *K*-mixing with increasing spin (I) in low-*K* bands, while the high-*K* bands remain very pure, even at the same spin levels where the low-*K* bands are completely mixed. The rapid increase in the K-forbidden interband B(Eλ) values coincides with the rotational alignment of low-*K* bands which has a noticeable effect on the moment of inertia above the $I\approx10$ levels of the γ-band and the GSB. Previous measurements of isomer decay branching ratios are inconsistent with significant mixing occurring in the high-*K* rotational bands, while high-*K* band heads are pure in *K*. It appears that higher-*K* components are admixed in the nominally low-*K* bands with increasing spin, until the reduced transition probabilities saturate near ~1 W.u. for I≥12, signifying the total breakdown of the *K* quantum number.

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