Nuclear structure implications for controlled energy release of isomers

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Abstract. Heavy-ion induced Coulomb excitation has been used to determine level energies and Eλ matrix elements for rotational bands built on isomeric states in ^{178}Hf. The Eλ matrix elements are consistent with a dramatic increase in K mixing with increasing spin in the ground band, presumably due to Coriolis induced rotation alignment. The spin dependence of the K-distribution for the mixed K ground band states has been deduced. The large K mixing at higher spin provides viable Coulomb excitation paths for stimulated depopulation of high-K isomers in ^{178}Hf.

Introduction

Isomeric states provide a means of storing energy that could have technological benefits if stimulated depopulation of such isomers can be achieved. This paper describes the use of heavy-ion induced Coulomb excitation to electromagnetically excite rotational bands based on isomeric states. This information is crucial for evaluating the possibility of achieving stimulated depopulation of isomeric states as well as for probing nuclear structure. The nucleus ^{178}Hf is an unusually rich source of low-lying K-isomers having a wide range of lifetimes[1]. K-isomers occur in strongly-deformed axially-symmetric nuclei where the projection of the angular momentum onto the nuclear symmetry axis, denoted by the quantum number K, is a good quantum number leading to hindrance of low multipole decays between bands having a large change in K value. Of special interest are the lowest energy K-isomer bands with band head excitation energies, [half lives], and K values of: $1554keV[78nsec]K = 6^+$, $1147keV[4sec]K = 8_1^-$, $2573keV[68\mu sec]K = 14^-$, and $2447keV[31year]K = 16^+$. The $2447keV$ excitation energy and long lifetime of the 31 year $K = 16^+$ isomer makes it an ideal candidate for energy storage and for achieving stimulated depopulation. The present work, which is based on the Ph.D work of A.B. Hayes[2], describes heavy-ion induced Coulomb excitation studies[3][4] of high-K isomeric states in ^{178}Hf and the implications regarding achieving stimulated depopulation of isomers.

The motivation for initiating the present study was to explore the physics underlying the unexpected population of the $K = 8_1^-$ isomer via Coulomb excitation observed in 1982 by Hamilton et al[5] and subsequently confirmed by Xie et al[6]. This result implied large breakdown of the K selection rules for electromagnetic transitions leading to the $K = 8_1^-$ isomeric band in stark contrast to the known 1.9×10^{13} hindrance factor for the B(E1;$8_1^- \rightarrow 8_{gsb}$). Another motivation is the Collins et al.[7][8] report of accelerated decay of the 31-yr $K = 16^+$ isomer induced by <20 keV bremsstrahlung radiation which implies that the $K = 16^+$ isomer is connected to an unknown, almost degenerate state by electromagnetic transition strengths that are at least 5 orders of magnitude larger than can be explained by nuclear structure physics[9]. Ahmad et al.[10][11] used four orders of magnitude more intense synchrotron X-ray radiation plus sensitive detectors in an unsuccessful attempt to replicate the Collins observations. The Collins work has engendered interest among government agencies and the popular press[12].

Experimental Technique

The high-resolution 4π γ-ray detector facility, Gammasphere[13], coupled with the Rochester 4π heavy-ion detector, CHICO[14][15], provides unprecedented sensitivity for the study of the γ-ray feeding and depopulation of isomeric states. This sensitivity is being exploited to study isomeric states in a range of stable and neutron-rich nuclei populated by Coulomb excitation, transfer reactions and fusion-fission.

Gammasphere comprises a closely packed spherical array of 110 large Ge cylindrical crystals, of dimensions $\sim$10cm, each surrounded by a tapered hexagonal bismuth germanate Compton suppressor shield. The high detection efficiency allows observation of high-fold coincidences of γ-rays which enhances the sensitivity and resolving power by several orders of magnitude compared with prior generation γ-ray detector systems.

Detection of the recoiling reaction products in coincidence with their deexcitation γ-rays greatly enhances the selectivity and sensitivity of γ-ray detector arrays. For binary reactions, detection of

both recoiling reaction-products allows complete kinematic reconstruction for each event, enabling simultaneous determination of the Q-value, masses, scattering angles θ,ϕ, and recoil velocities of all reaction products, allowing for the proper Doppler-shift correction, and simultaneous identification of the coincident deexcitation $\gamma-$rays originating from each of the reaction products. The position-sensitive CHICO was developed at Rochester to exploit the advantages of the kinematic coincident technique. CHICO comprises two identical 35.6 cm hemispherical target chambers, one at forward angles and the other at backward angles. Each hemisphere contains ten θ, ϕ position-sensitive parallel-plate avalanche detector panels in a conical array. The cathode is segmented into 1° wide θ stripes for $12°<\theta<85°$ and $95°<\theta<168°$ while ϕ is measured with 4.5° resolution. The detection solid angle is 67% of 4π with a minimum flight path of 13 cm. The anode time resolution is about 500ps. The measured mass resolution is $\Delta m/m = 5\%$ for binary collisions.

Heavy-ion Coulomb excitation is a direct and sensitive measure of the electric multipole moments making it the pre-eminent probe of collective shape degrees of freedom in nuclear structure. During the past two decades we have shown that Coulomb excitation data recorded for a wide range of projectile Z values and scattering angles is sufficient to determine uniquely the complete set of Eλ matrix elements involving the low-lying states excited[16]. These data are analyzed using the Rochester least-squares Coulomb-excitation search code GOSIA [17], making it feasible to measure an essentially complete set of phases and magnitudes of Eλ matrix elements for the lowest 75 or more Coulomb excited states in nuclei. The precision, extent and completeness of the measured set of matrix elements add a new dimension to the study of collective motion in a nucleus.

Coulomb Excitation of ^{178}Hf by 650 MeV ^{136}Xe

A 650 MeV ^{136}Xe beam, from the Argonne ATLAS facility, was used to Coulomb excite a 0.51 mg/cm^2 ^{178}Hf target having 89% enrichment[3]. Gammasphere plus CHICO were used to detect γ-rays in coincidence with the kinematic-coincident detection of both recoiling heavy ions. Prompt as well as delayed γ-rays were used to observe the transitions and the γ-ray yields of several rotational bands in ^{178}Hf were measured relative to the $I^\pi_K = 8^+_0 \rightarrow 6^+_0$ transition for six 9°-wide intervals in the scattering angle range $25° < \theta^{scat}_{lab} < 80°$. The software GOSIA[17] was used to calculate γ-ray yields from pure Coulomb excitation and to fit $E1, E2, E3$, and $M1$ matrix elements to the experimental yields by a χ^2 minimization. Yields for "safe angles" of $\theta^{scat}_{lab} < 53°$ (separation between the nuclear surfaces ≥ 5 fm [18]) were given a higher weight in the fits. Since the collective model works well for the low-lying levels in ^{178}Hf , the number of unknowns was minimized by assuming that the reduced matrix elements $< K_f I_f \| M\lambda \| K_i I_i >$ are correlated by the Alaga rule[19] for K-allowed transitions while the spin-dependant mixing model was used where appropriate for K violating transitions. Figure 1 illustrates schematically the primary Coulomb excitation paths leading to population of the bands shown.

The GS, γ- and K=4$^+$ bands– Intrinsic matrix elements for the GS, γ-band and $K^\pi = 4^+$ bands were determined. In-band matrix elements in the ground band deviated by $\leq$1.5% from the rigid-rotor model. Linking the in-band matrix elements with a single intrinsic matrix element yielded $< K\,|E2|\,K >= \sqrt{5/16\pi}eQ_o$ = 2.164(10), 2.21(8) and 2.07(10) eb, for the GS, γ- and 4^+ bands, respectively, consistent with a single intrinsic moment and in agreement with previous work[20].

The $K^\pi = 6^+$ band– The contribution to the 6^+ isomer band population by Coulomb excitation through the 4^+ band was determined. As illustrated schematically in figure 1, the two-step GSB $\rightarrow K^\pi = 2^+ \rightarrow K^\pi = 6^+$, and GS $\rightarrow K^\pi = 4^+ \rightarrow K^\pi = 6^+$ paths as well as the three-step GS $\rightarrow K^\pi = 2^+ \rightarrow K^\pi = 4^+ \rightarrow K^\pi = 6^+$ path contribute about equally to the total 6^+ band population, whereas direct excitation from the GS band is significant for $\theta^{scat}_{lab} > 60°$.

The $K^\pi = 8^-$ bands– There are two strongly mixed $K = 8^-$ bands; of these the lower $K = 8^-_1$ bandhead is a 4 second isomer. The $E2$ and $M1$ in-band and interband matrix elements for the two 8^- bands were deduced assuming the in-band intrinsic E2 moment.[1][21] The 8^-_1 isomer decays by a single $E1$ transition, that is hindered by a factor 1.9×10^{13}, whereas the Coulomb excitation is dominated by $E3$ transitions. (Calculations show that reasonable $E1$ and $E5$ strengths cannot excite the 8^-_1 band to the measured strength.) The 8^-_1 band cannot be populated to the measured strength via the $K = 6^+$,

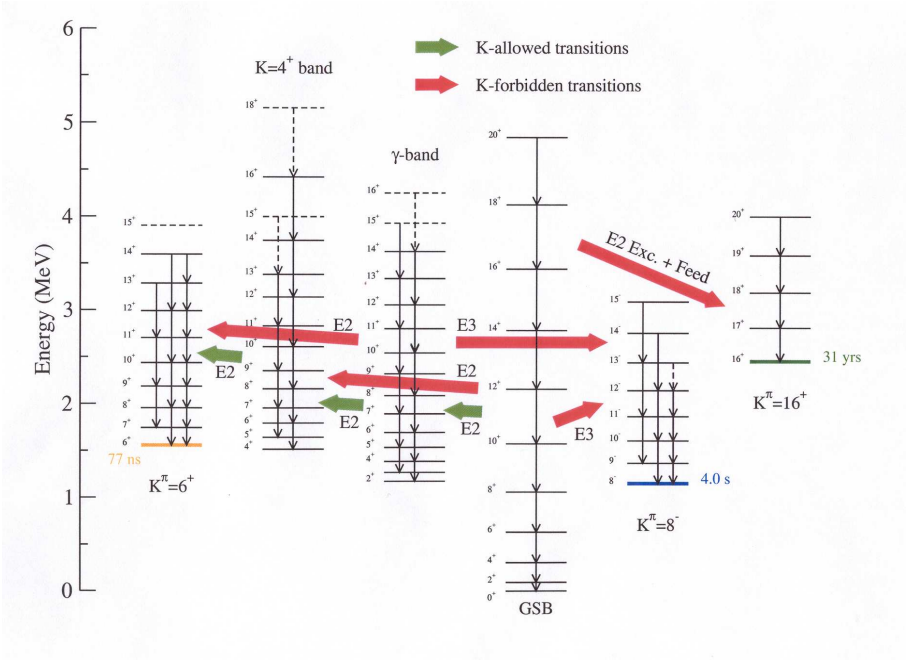

Figure 1: Primary Coulomb excitation paths to high-K isomer bands in ^{178}Hf. The green arrows show schematically the important K-allowed pathways and the red arrows the important K-forbidden pathways populating the isomer bands.

or 4^+ bands, even with unrealistically large values of the interband matrix elements. The only viable paths for populating the 8^-_1 band are by $E3$ transitions from the ground band and the $K = 2^+_\gamma$ band. The $E3$ matrix elements connecting the ground and γ bands to the 8^- bands were fit to the data assuming a spin-dependent intrinsic $E3$ matrix element with $\Delta K = \lambda$ for connections to both the ground and γ bands. Two matrix elements were fixed at upper limits of $< 8^-_8 \,\|E3\|\, 6^+_0 >= 9.3 \times 10^{-6}$ eb$^{3/2}$ and $< 8^-_8 \,\|E3\|\, 8^+_0 >= 2.0 \times 10^{-3}$ eb$^{3/2}$, derived from branching ratios of the isomer decay [22] and the known half-life of the isomer, 4.0(2) s [20]. The most effective direct excitation paths for the $K = 8^-$ band are from the $8^+, 10^+$, and 12^+ ground band states to the 11^-, 12^-, and 13^- states. The $B(E3)$ values connecting the 8^- band to the ground and γ bands are as large as 3 Weisskopf units for the dominant transitions.

Prior Coulomb excitation studies of the 8^-_1 band[5][6] measured only the delayed isomer decay. The present analysis has the advantage of fitting the population pattern of prompt in-band γ-ray yields up to spin 17^-, rather than only the isomer cross sections. It should be noted that for both of the earlier experiments there is a significant contribution to the total cross section beyond the safe scattering angle, where Coulomb-nuclear interference will be significant. The present measurement of the Coulomb excitation cross section as a function of scattering angle allowed selection of orbits where Coulomb-nuclear interference is negligible.

The $K^\pi = 16^+$ band– The observed population of the 16^+ isomer band was unexpected. The intrinsic in-band quadrupole moment has been measured to be $< K\,|E2|\,K >= \sqrt{5/16\pi}eQ_o = 2.27(3)$ [23] and 2.6(3) eb [24], consistent with the 2.16(1) eb ground band intrinsic moment. The observed Coulomb excitation cross sections to the 19^+ member of the $K = 16^+$ band in the prompt $\gamma - \gamma - \gamma$ cube imply that this state is connected to the ground band by $B(E2)$ values that are the order of one Wiesskopf unit in strength. Moreover calculated yields indicated that γ-decay feeding from the GS band must dominate the population of the yrast 16^+ band. The dominant γ-ray feeding branches from the ground band have energies of 1.3 to 1.7 MeV that lie in the background of the Doppler-broadened

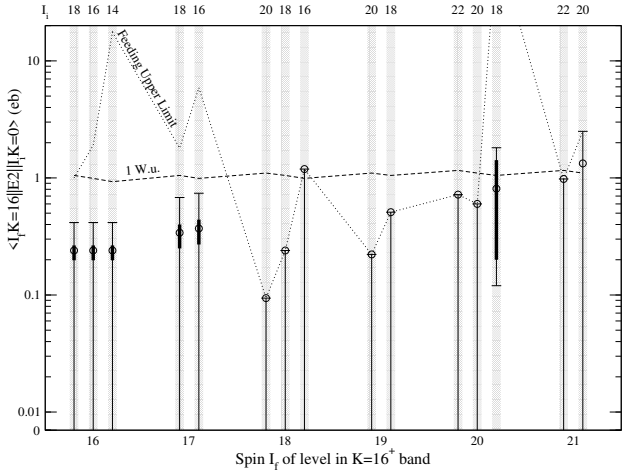

Figure 2: Best fit E2 matrix elements connecting the ground band states to the $K = 16^+$ band states

1.3 MeV ^{136}Xe peak. This, coupled with the dearth of gates in the γ-γ-γ cube for decays to low spin levels obscures observation of the feeding; the predicted feeding strength is below the experimental sensitivity. Deexcitation transitions in ^{136}Xe were observed in coincidence with 16^+ band transitions in a Hf-Hf-Xe cube, and upper limits were set for ^{135}Xe excitation, implying that transfer reactions do not contribute significantly to population of this isomer.

In summary, this first experiment showed that three distinctly different mechanisms primarily populate the $6^+, 8^-$ and 16^+ isomer bands: multiple-step excitation, direct K-forbidden excitation and direct K-forbidden γ-decay feeding, respectively. The data for all three isomer bands are consistent with a rapid increase with spin of the K-mixing in the ground band.

^{178}Hf Beam Activation

The unexpected observation of Coulomb excitation of the $K = 16^+$ band stimulated a second Coulomb excitation study employing activation to enhance sensitivity for detecting the 31 year $K = 16^+$ isomer. A 858 MeV ^{178}Hf beam from ATLAS was Coulomb excited by a stack of five 1 mg/cm^2 Ta target foils and the scattered Hf ions were collected by catcher foils[4]. The beam intensity was monitored both electrically and by using a silicon detector to observe Rutherford scattering at forward angles from a sixth Ta foil. The beam species and sputtering of the target foils were both monitored by using a Ge γ-ray detector to observe the ^{178}Hf deexcitation γ-rays due to Coulomb excitation of the beam in the Ta Faraday cup. The activation experiment used 1.7(2) pmC of ^{178}Hf beam. The K=16^+ isomer activity, ≥ 138 days after activation, was measured off-line using two large Clover Ge detectors in close geometry to observe coincident γ-rays in both the $K = 8^-$ and the ground band decay paths.

The measured excitation function between 700 and 858 MeV for populating the 31 yr $K = 16^+$ isomer follows Coulomb excitation predictions using the final set of $E2$ matrix elements. The isomer cross sections are an order of magnitude greater than the measured cross section for populating the 19^+ state in the first experiment due to direct transitions between the ground band and $K = 16^+$ isomer bands states below 19^+. The analysis of both experiments included a constraint that the matrix elements must satisfy the upper limits for γ-ray feeding transitions measured by the Hf(Xe,Xe)Hf experiment.

Figure 2 shows the final set of E2 matrix elements between the ground band and $K = 16^+$ band states derived from both experiments. The measured upper limits for ground band to isomer band γ-ray feeding are shown. The broad black bars correspond to the diagonal errors while the narrow black lines show the estimated range of the correlated errors. The circles correspond to the final set of matrix elements used in the comparison. Since there are more unknowns than data, the correlated

errors are large. Note that the $E2$ matrix elements increase from below up to slightly above the Weisskopf estimate with increasing ground band spin implying a large breakdown of the K selection rule for these $\Delta K - \lambda = 14$ transitions.

In summary the activation experiment has shown that the $B(E2)$ values coupling the ground band to the $K = 16^+$ isomer band states are the order of a Weisskopf single particle unit implying massive violation of the K selection rule.

Nuclear Structure Implications

There is a considerable body of work on the decay properties of isomeric states. The present work has made the first measurements of the electromagnetic properties of rotational band states built on isomeric states providing an opportunity to use such high-K isomer data to probe nuclear structure.

The microscopic structure of the isomers in ^{178}Hf has been inferred from $|g_K - g_R|$ measurements, plus the known excitation energies, to comprise both 2 quasiparticle and 4 quasiparticle configurations, and this are consistent with theoretical predictions. The $K = 6^+$ isomer is attributed to a 2 quasi-proton excitation while the two $K = 8^-$ states are a mixture of proton and neutron 2-quasiparticle configurations. The $K = 16^+$ and 14^- isomers are 4-quasiparticle configurations involving coupling of a 2-quasiproton with a 2-quasineutron configuration. Thus the $|K = 16^+\rangle$ is a coupling of the neutron and proton 2-quasiparticle $K = 8^-$ configurations. There should be two $|K = 14^-\rangle$ states from a coupling of the $|K = 6^+\rangle$ and $|K = 8^-\rangle$ configurations built from both proton and neutron 2-quasiparticle excitations; only one has been observed. The excitation energy of the $K = 16^+$ isomer band head is about 1 MeV lower than the next low-lying 16^+ state illustrating the unusually strong binding of this 4 quasiparticle isomer configuration as well as the underlying 2 quasiparticle isomeric configurations.

It is usual to express the partial decay widths Γ_p for isomers in terms of a hindrance factor $F_W = \frac{\Gamma_{WU}}{\Gamma_p}$ where Γ_{WU} is the Weisskopf single-particle estimate for the applicable multipolarity. The reduced hindrance, $f_\nu = (F_W)^{\frac{1}{\nu}}$, is the hindrance per degree of K forbiddeness, where the K forbiddenness factor $\nu = |\Delta K - \lambda|$. Table 1 shows a sample of the hindrance and reduced hindrance factors for the band heads and for one higher-spin rotational band member of the $K = 6^+, 8^-$, and 16^+ isomeric bands.

	$I^\pi_i \rightarrow I^\pi_f$	λ	ν	Hindrance $F_W=\Gamma_{WU}/\Gamma_{Exp}$	Reduced Hindrance $f_\nu= (F_W)^{1/\nu}$ [$\nu = \Delta K - \lambda$]
$K=6^+ \rightarrow$ gsb	$6^+ \rightarrow 4^+$	E2	4	8.5×10^4	17.1
	$12^+ \rightarrow 12^+$	E2	4	8.7	1.7
$K=8^- \rightarrow$ gsb	$8^- \rightarrow 8^+$	E1	7	1.9×10^{13}	79(1)
	$8^- \rightarrow 6^+$	M2	6	$>1.7\times10^{13}$	>160
	$9^- \rightarrow 6^+$	E3	5	9	1.55
	$12^- \rightarrow 12^+$	E3	5	0.13	0.66
$K=16^+ \rightarrow$ gsb	$16^+ \rightarrow 18^+$	E2	14	3.4	1.09
	$16^+ \rightarrow 16^+$	E2	14	3.4	1.09
	$17^+ \rightarrow 16^+$	E2	14	1.5	1.03
	$20^+ \rightarrow 18^+$	E2	14	0.37	0.93
$K=16^+ \rightarrow K=8^-$	$16^+ \rightarrow 13^-$	E3	5	1.3×10^9	66(1)
	$16^+ \rightarrow 12^-$	M4	4	2.8×10^7	72(2)
	$16^+ \rightarrow 11^-$	E5	3	4.5×10^6	165(5)

Hindrance factors of up to 1.9×10^{13} and reduced hindrance factors the order of 100 occur for the isomer band heads imply that K is a remarkably good quantum number for these band heads. By contrast, the transitions from these three isomeric bands to the ground band are not hindered at higher spin implying massive breakdown of K. Note that the $K = 16^+$ band to ground band transitions should be doubly forbidden since, in addition to K hindrance, the one-body electromagnetic operator does not connect a 4-quasiparticle to 0-quasiparticle configurations. This implies that there must be large admixtures of 2-quasiparticle configurations involved. The K mixing must be associated with 2-quasiparticle components in the structure of the ground band at high spin, not the isomer bands, in

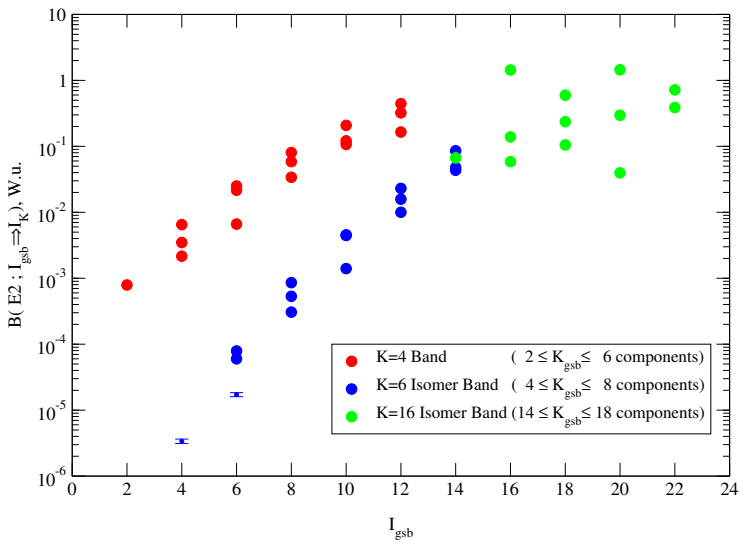

Figure 3: The $B(E2 : I^+_{gsb} \rightarrow I^+_K)$ values, in Weisskopf units $[0.0295\mathrm{e}^2b^2]$, versus ground band spin.

that the $I^\pi = 16^+[K = 16^+]$ to $I^\pi = 12^-[K = 8^-]$ transition is highly hindered implying K is a good quantum number for these states, whereas the transitions from these same states to the ground band, that is, $I^\pi = 16^+[K = 16^+]$ to $I^\pi = 14^+[gsb]$ and $I^\pi = 12^-[K = 8^-]$ to $I^\pi = 12^+[gsb]$, show essentially no hindrance due to the K selection rule.

In deformed rotational nuclei, the Coriolis force causes the nucleon angular momentum in high-j and low-Ω orbitals to decouple from the deformation axis and align along the rotation axis at high rotational frequencies, where the rotation axis is perpendicular to the deformation axis. This leads to the well-known band-crossing phenomena where the Coriolis force breaks a pair of high-j nucleons which then couple to form a 2-quasi-particle configuration aligned along the rotation axis. The lowest rotation-aligned 2-quasiparticle configuration crosses the ground band at spin $\sim 16^+$ and the γ-band at $\sim 8^+$. Such rotation alignment breaks the axial symmetry leading to K mixing. The high-K isomers are formed from configurations with individual quasinucleons having large projections Ω along the deformation axis. These large-Ω orbits are rigid against rotation alignment and thus high-K isomeric bands should have good K. Thus one may anticipate that the breakdown of the K selection rule is related to rotation alignment effects in the ground band. Walker et al[25] observed in ^{174}Hf a $K = 14^+$, 4μsec isomer that decays to the yrast band 14^+ and a nearby 2-quasiparticle band with reduced hindrance factors of about 5 which they ascribe to the role of Coriolis band mixing. Chowdhury[26] ascribed the K breakdown in ^{182}Os to softness in the triaxiality degree of freedom in this nucleus that allows barrier penetration between the rotation-aligned and deformation-aligned configurations. Sun et al[27] have suggested that significant softness to the triaxiality will occur in ^{178}Hf, thus both mechanisms for K violation could be playing a role. Both of these prior results of K breakdown for decays to the aligned 2-quasiparticle states are consistent with the present evidence for ^{178}Hf.

Let us assume that the ^{178}Hf ground band structure can be described in terms of basis states having good I and K, and that the K mixing in the isomer bands is small, as indicated by the large hindrance factors for electromagnetic transitions between the high-K isomer bands. Then the measured K forbidden electromagnetic transition matrix elements can be used to determine the K distribution and its spin dependence for the ground band. Figure 3 shows the three strongest measured $B(E2 : I_{gsb} \rightarrow I_{isomer})$ values, expressed in Weisskopf units, versus ground band spin for the $K = 4^+, 6^+$, and 16^+ isomeric bands from the present work. The data shown with error bars are from the known

decay of the $K = 6^+$ isomer band head. The $B(E2)$ values can be used as a direct measure of the $2 \leq K \leq 6$ admixture from the $< K = 0^+ \,|E2|\, K = 4^+ >$ values, the $4 \leq K \leq 8$ admixture from the $< K = 0^+ \,|E2|\, K = 6^+ >$, and the $14 \leq K \leq 18$ admixture from the $< K = 0^+ \,|E2|\, K = 16^+ >$ values. The enhancement above ground-state spin 16 is comparable to the maximum that might be expected implying that the K admixtures are very large at such spin. The data are fit best assuming that the increase with spin of the E2 matrix elements is according to the band mixing model[19]. The roughly exponential increase of the K admixture with ground band spin correlates with the increase in rotation alignment of the ground band providing evidence that the breakdown of the K quantum number is associated with the Coriolis effect acting on the ground band. A similar rapid spin-dependent increase in E2 strength for the $K = 16^+$ band is observed for coupling to the gamma band consistent with the band crossing occurring at lower γ-band spin. The strength of the E3 transitions connecting the ground and γ bands to the $K = 8_1^-$ band also exhibits a similar spin dependence for the ground and γ-bands. Rotation alignment effects eventually will be manifested at much higher angular momenta in the high-K isomer bands; the evidence given above suggests that rotation alignment effects are small at spins relevant to this experiment.

This is the first case where the K distribution of the ground band has been measured. These K distributions can be compared with model predictions to ascertain the relative roles of rotation alignment and softness to triaxial deformation leading to the breakdown of the K quantum number in ^{178}Hf. The above results demonstrate that Coulomb excitation of high-K states is a powerful probe of nuclear structure and of the role of the Coriolis force on the breakdown of the K quantum number.

Stimulated Depopulation of K=16$^+$ Isomer

Evaluation of the feasibility of stimulated depopulation of the $K = 16^+$ isomeric state depends crucially on knowledge of the electromagnetic matrix elements to all nearby high-spin states. The present Coulomb excitation study has determined that the $E2$ matrix elements connecting the ground band to the $K = 16^+$ band are of the order of a Weisskopf unit presumably due to the interaction between the ground band and the rotation-aligned 2 quasiparticle configuration. These measured enhanced $E2$ matrix elements provide a viable path for stimulated depopulation of the $K = 16^+$ isomer. Other rotation-aligned 2-quasiparticle bands, including the gamma band, existing at higher excitation energies will have comparable enhanced $E2$ and $E3$ matrix elements to the isomer. However, these higher lying rotation aligned bands will play a reduced role in Coulomb excitation due to their higher excitation energy. The probability for Coulomb exciting the ground and gamma bands from the $K = 16^+$ bandhead probably will be of the order of $\leq 1\%$ of the isomer in-band rotational levels.

The 2573 keV $K = 14^-$ isomeric band head, which is only 126 keV above the $K = 16^+$ isomer, as well as the 15^- and 16^- states in this band can be Coulomb excited by allowed $E3$ transitions from the isomer with a probability that is $\leq 1\%$ of the isomer rotational band, providing another viable depopulation mechanism. A presumed second low-lying $K = 14^-$ state, in addition to other higher lying high-spin 4 quasiparticle configurations, can be excited by K-allowed transitions contributing to the depopulation of the isomer by Coulomb excitation.

The transitions between the $K = 16^+$ isomer and the $K = 8_1^-$, 8_2^- bands are strongly inhibited by the K selection rule showing that K is a well conserved quantum number at moderate spins in these strongly deformation-aligned 2 quasiparticle bands. That is, these transitions do not provide a viable path for significant stimulated depopulation of the $K = 16^+$ isomer. The present work has not observed any state that could mediate depopulation of the $K = 16^+$ isomer claimed by the Collins et al work [7][8].

Conclusions

Considerable advances have taken place both in detector technology and the field of Coulomb excitation that open new opportunities for the study of nuclear isomeric states. These advances have been applied to heavy-ion induced Coulomb excitation of ^{178}Hf resulting in population of the rotational bands built on the $K = 4^+, 6^+, 8^-, 14^-$, and 16^+ isomeric states. The $E\lambda$ matrix elements have been determined for the rotational band states built on these states.

The electromagnetic matrix elements are consistent with massive break down of the K quantum

number at high spin in the ground band which is presumed to be due to Coriolis induced rotation alignment. The $E\lambda$ matrix elements have been used to deduce for the first time the K-distribution for the ground band states. The present work has identified viable Coulomb excitation paths for stimulated depopulation of the $K = 16^+$ isomer in ^{178}Hf. These are by enhanced $E2$ excitation to the rotational aligned components in the ground and gamma bands, and by $E3$ K-allowed transitions to the $K = 14^-$ bands. Transitions to the other high-K bands do not provide viable paths due to strong K-forbiddenness.

Coulomb excitation can unambiguously determine the pathways that can lead to stimulated depopulation of isomeric states. A target sufficiently enriched in the $K = 16^+$ isomer is not available to make the definitive experiment for stimulated depopulation of ^{178m}Hf. However, there are two long-lived nuclear isomers,^{242}Am (5^-, E=48.6keV, $T_{\frac{1}{2}}$=141yr) and ^{180}Ta (9^-, E=75.3keV, $T_{\frac{1}{2}}$=1.2×10^{15}yr), where isomeric targets are available to directly observe stimulated depopulation by Coulomb excitation and these will be studied this year. Such opportunities are of interest both to address fundamental questions of nuclear structure as well as for elucidating the feasibility of using isomer states for energy storage.

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References

[1] S. M. Mullins et al., Phys. Lett. **B393**, 279 (1997); **400** 401 (1997
[2] A.B. Hayes. Ph. D. Thesis, University of Rochester, 2005
[3] A.B. Hayes, D. Cline, C.Y. Wu, et al. Phys. Rev. Lett, **89** 242501(2002)
[4] A.B. Hayes, D. Cline, C.Y. Wu, et al. Unpublished 2004
[5] J. H. Hamilton et al., Phys. Lett. **B112**, 327 (1982).
[6] H. Xie et al., Phys. Rev. **C48**, 2517 (1993).
[7] C.B. Collins et al, Physical. Review. Letters. **82** 695 (1999)
[8] C.B. Collins et al, Physical Review **C61** 054305 (2000)
[9] P. von Neumann-Cosel, A. Richter, Physical Review Letters **84** 2543 (2000)
[10] I. Ahmad et al, Physical Review Letters **87** 072503 (2001)
[11] I. Ahmad et al, Physical Review **C67** 041305 (2003)
[12] B. Schwarzschild, Physics Today 21 May 2004
[13] http://www.phy.anl.gov/gammasphere/index.html
[14] M. W. Simon, D. Cline, C.Y. Wu, et al, Nucl. Instr. Meth **A 452**, 205 (2000).
[15] http://www.pas.rochester.edu/~chico/
[16] D. Cline, Ann. Rev. Nucl. Part. Sci. **36**, 683 (1986).
[17] T. Czosnyka, D. Cline, and C. Y. Wu, Bull. Am. Phys. Soc. **28**, 745 (1983).
[18] D. Cline et al., Nucl. Phys. **A133**, 445 (1969)
[19] A. Bohr and B. R. Mottelson, Nuclear Structure (Benjamin, 1975), Vol. 2.
[20] E. Browne, Nucl. Data Sheets **54**, 199 (1988).
[21] M.B. Smith, P.M. Walker et al Phys. Rev. **C68** 031302 (2003)
[22] J. Van Klinken, et al, Nucl. Phys. **A339**, 189 (1979).
[23] N. Boos et al., Phys. Rev. Lett. **72**, 2689 (1994).
[24] E. Lubkiewicz et al., Z. Phys. **A 355**, 377 (1996).
[25] P.M. Walker et al, Phys. Rev. Lett. **65** 416 (1990)
[26] P. Chowdhury et al Nucl. Phys. **A485** 136 (1988)
[27] Y. Sun, W-R Zhou, et al. Phys. Lett. **B589** 83(2004)