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NEW STRUCTURES IN ^{178}HF AND COULOMB EXCITATION OF ISOMERS

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A 985 MeV ^{178}Hf beam was Coulomb excited by a ^{208} Pb target at the ATLAS accelerator of Argonne National Laboratory. Gammasphere and the CHICO particle detector recorded particle-γ coincidence data. The aim was to populate and determine the mechanism of previously observed Coulomb excitation of the $K^\pi = 6^+$ ($t_{1/2}$ = 77 ns) ,8^- (4 s) and 16^+ (31 y) isomer bands. New rotational bands were identified including an aligned band which appears to mix with the ground-state band (GSB) and the γ-vibrational band above $\sim 12\ \hbar$ of angular momentum. Newly observed γ-decay transitions into the three isomer bands may elucidate the K-mixing which allows Coulomb excitation of these isomer bands, but direct decays from the GSB into the 16^+ isomer band have not yet been confirmed.

1. Introduction

Axial symmetry in deformed nuclei leads to conservation of the K quantum number, the projection of the total angular momentum on the symmetry axis. This forbids electromagnetic (EM) transitions in cases where ΔK is greater than the multipole number λ of the transition and leads to K-isomerism with a half-life of $> 10^{15}$ years in the longest-lived known case[1]. The decay rates of K-forbidden transitions are usually described by the "hindrance" $F \equiv \tau_{\text{meas}}/\tau_{s.p.}$, where τ_{meas} and $\tau_{s.p.}$ are the measured and single-particle estimates, respectively, of the excited states' lifetime.

In ^{178}Hf, Coulomb excitation of $K^\pi = 6^+$ ($t_{1/2} = 77$ ns), 8^- ($t_{1/2} = 4$ s) and 16^+ ($t_{1/2} = 31$ y) isomers and the rotational sequences built on them have been observed multiple times[2,3,4]. Several attempts have been made to explain the violations of K-conservation in these experiments, but direct evidence in terms of highly K-forbidden γ-ray transitions have been elusive. Rotational mixing in the low-K rotational bands was proposed[4] by deductive arguments to introduce high-K components into the nominally $K = 0$ and $K = 2$ structures, which would allow Coulomb excitation of the high-K isomer bands. Calculations which reproduced the observed yields of rotational states above the isomers indicated that EM excitations to levels just above the isomer are important. It was argued that an abrupt onset of K-mixing in the isomer bands just above the band heads was unlikely, indicating that there must be high-K admixtures in the GSB and the γ-vibrational band, which become important at $I \sim 12\ \hbar$. Multiple steps through successively higher-K bands was dismissed as a possibility by Coulomb excitation calculations, which predicted negligible strength after more than a few interband transitions.

An earlier ^{178}Hf(^{136}Xe,^{136}Xe)^{178}Hf Coulomb excitation experiment implied γ-ray branches of the order of 1% or less from the highest observed states in the GSB to the 16+ isomer band, which followed from a fit of ∼W.u. strength E2 matrix elements that would be required to reproduce the observed intensity of the isomer's rotational sequence. The present experiment sought to use a high-Z ^{208}Pb target to provide unprecedented statistics to directly detect these 14-times K-forbidden γ-decay transitions.

2. Experiment

A 985 MeV ^{178}Hf beam was Coulomb excited by a 0.5 mg/cm^2 ^{208}Pb target. Gammasphere and CHICO, Rochester's parallel plate avalanche counter, were used to trigger on two-particle plus γ-ray (ppγ) coincidence events. The scattering kinematics were reconstructed using CHICO, and event-by-event Doppler-shift corrections were applied to the prompt γ-ray energies. Approximately 10^9 usable ppγ events were recorded. Data sets were constructed from the forward-scattered events in γ-ray single- (γ), double- ($\gamma\gamma$) and triple-coincidence ($\gamma\gamma\gamma$) sets. The previously known level scheme was extended using these data sets, and many new states were added, extending the known GSB to spin $26\hbar$ and adding many other previously unidentified states.

The data were divided into two ^{178}Hf projectile scattering ranges, $24° \leq \theta_{\rm scat} \leq 31°$ and $35° \leq \theta_{\rm scat} \leq 50°$ for "safe" Coulomb excitation analysis, where nuclear interference is negligible, and $50° \leq \theta_{\rm scat} \leq 85°$, beyond the safe scattering angle of 50°. A peak-to-background ratio of ~ 100 in the prompt ppγ data sets and gated coincidence spectra enabled the observation of γ rays with intensities of $\geq 10^{-4}$ normalized to the GSB $8^+ \rightarrow 6^+$ transition (Figure 1). The Coulomb-excitation yields were measured using the ppγ—pp$\gamma\gamma\gamma$ data, and preliminary fits of sets of matrix elements to the measured γ-ray intensities were made using the rotor model with the coupled-channels semiclassical Coulomb excitation search code GOSIA[5]. The $\theta_{\rm scat} > 50°$ data set was used to build the level scheme and measure γ-decay branching ratios, but was not used to fit EM matrix elements, because of possible systematic errors due to Coulomb-nuclear interference effects.

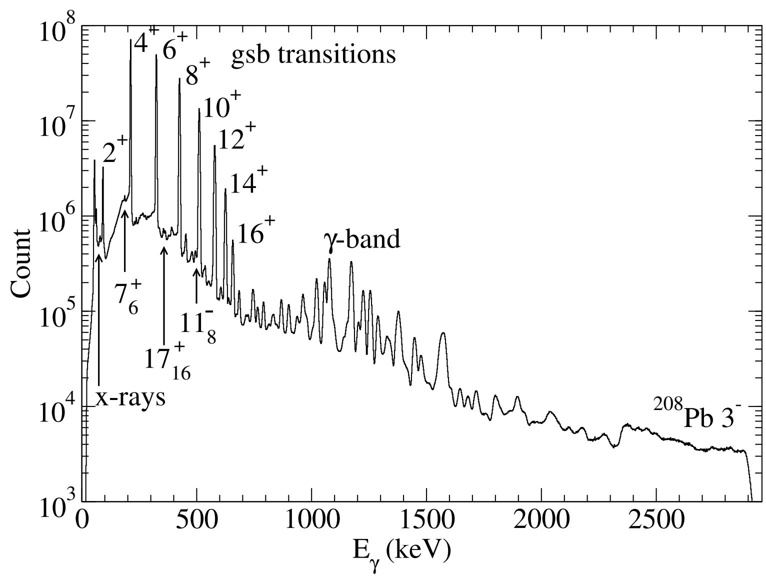

Fig. 1. A p-γ singles spectrum for the projectile scattering angle range $35° \leq \theta_{\rm scat} \leq 50°$. The GSB in-band transitions, decays from the γ-vibrational band, several transitions in the isomer bands and a number of high-E_γ doublets can be seen.

3. Preliminary Results

A partial level scheme was constructed using the γ-ray coincidence data (Figure 2). More than 115 levels in 12 bands and 240 γ ray transitions have been found, while some remain tentative, and more remain to be identified, in particular many negative-parity states. The $K^\pi = 6^+, 8^-$ and 16^+ isomer bands were observed with intensities of $\sim 10^{-3}$ relative to the $8^+_{\rm GSB}$ transition. Two new structures of partic-

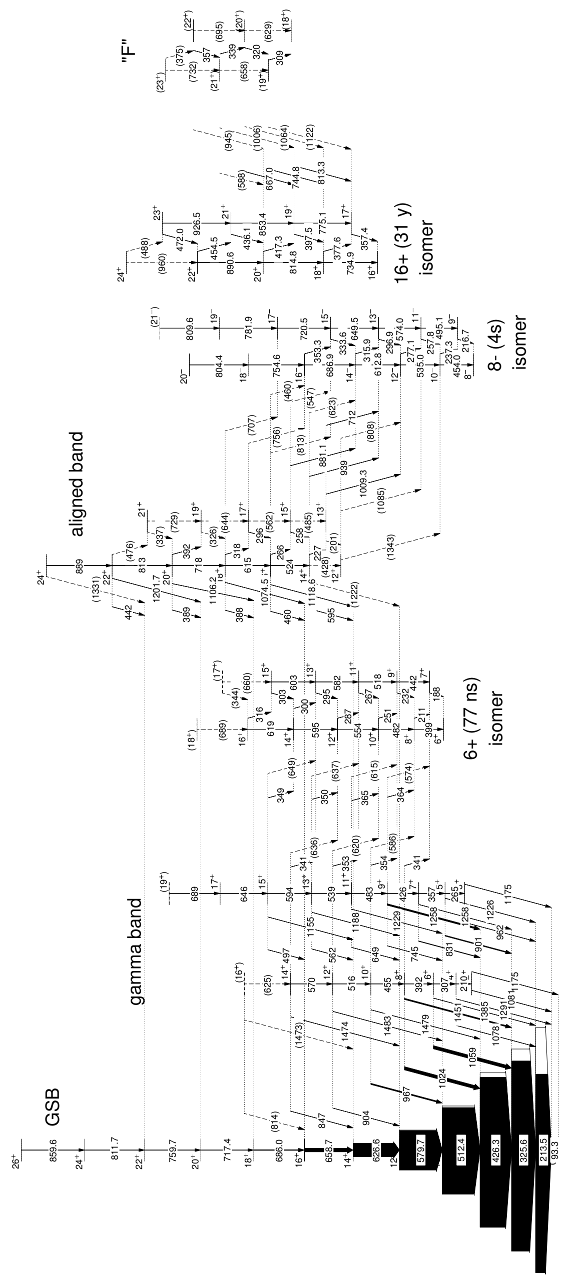

Fig. 2. A partial level scheme constructed from the γ-ray coincidence data. A number of bands have been omitted for clarity, while a large number of transitions remain to be placed.

ular interest to the understanding of population of the isomers are an aligned band and a band "F" which feeds the $K^\pi = 16^+$ states (Figure 2). Spin assignments and a number of γ-ray transitions in the band feeding the $K^\pi = 16^+$ states are tentative.

3.1. *The aligned band*

Transitions were observed from the even-spin signature of the new aligned band to the GSB. The observed signature splitting in the aligned band suggests an interaction between the even-spin states and the GSB. The in-band GSB yields are reproduced by $B(E2)$ values which drop by approximately a factor of 2 from $I = 10\hbar$ to $I = 20\hbar$. These observations are consistent with significant mixing between the aligned and ground-state bands above $I \approx 12\hbar$. The aligned band intersects the γ-band at about spin $10\hbar$. This could corroborate the earlier claim[4] that high-K components entering the wave functions of the *yrast* states are responsible for experimentally observed Coulomb excitation of the high-K bands.

3.2. *The $K^\pi = 6^+$ (77 ns) isomer band*

It was argued in previous work that the observed population of the $K^\pi = 6^+$ rotational states was likely due to contributions from the $K^\pi = 2^+$ γ-vibrational band and the $K^\pi = 4^+$ band, assuming matrix elements extrapolated from measured 6^+ isomer decay branching ratios using the rotor model and Bohr and Mottelson's treatment of K-forbidden transition rates[6].

Significant K-mixing in the γ-vibrational band should be expected because axial symmetry is not preserved in these states. Moreover, mixing in the γ-band has been demonstrated experimentally to be important in populating other quasi-particle states by forbidden excitations, for example by a crossing with an S-band[7] in ^{162}Dy and exciting states in ^{181}Ta where strong population is unexpected because of the change of single-particle states[8].

Gates on delayed γ-rays from the 6^+ isomer as well as double gates in the prompt $\gamma\gamma\gamma$ cube (Figure 3) were used to measure the intensities of newly-discovered $\Delta I = -1$ transitions as well as stretched E2 decays (mostly upper limits) feeding the isomer band from the γ band. A fit of the E2 and M1 matrix elements to the feeding transition data assuming the rotor model with a $K = 6$ admixture in the γ-band (Figure 4) reproduced the overall intensity of the observed in-band $K^\pi = 6^+$ yields without any other contribution. This resulted in E2 and M1 reduced transition probabilities of ≈ 3 W.u. and $\approx 10^{-2}$ W.u., respectively. (The Weisskopf estimate is taken in the excitation [upward] direction.) The obvious systematic error in the slope of yield vs. spin indicates that the spin-dependence of the mixing must be considered in order to obtain a good fit. The partial widths of the 6^+ isomer decay branches to the γ band set a limit of 10^{-2} W.u. on the $\langle 6^+_6 || E2 || 4^+_\gamma \rangle$ matrix element,which indicates a rapid increase in the $B(M1)$ and $B(E2)$ values of two orders of magnitude coupling these two bands from $I_{\gamma-\text{band}} = 4\hbar$ to $I_{\gamma-\text{band}} = 8\hbar$.

A complete fit of all EM matrix elements coupling the $K = 0$—6 bands will be necessary to obtain accurate values.

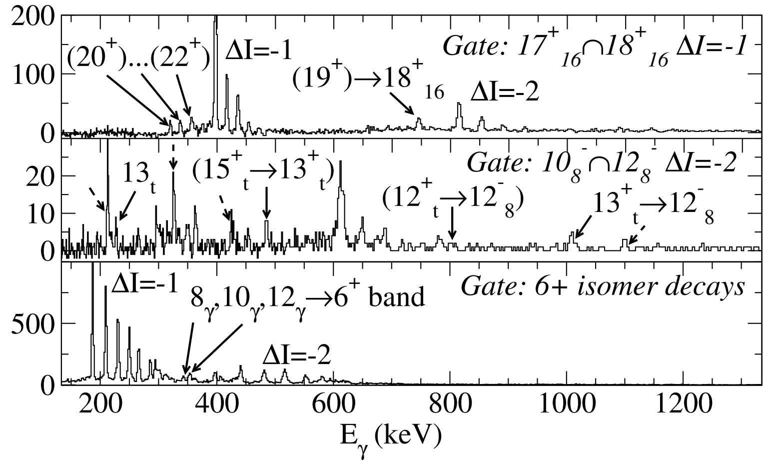

Fig. 3. Resultant spectra from three different gates showing the newly-identified feeding transitions (solid arrows) to the 6^+ (bottom), 8^- (middle) and 16^+ (top) isomer bands. Dashed arrows mark under-subtracted high-intensity transitions.

3.3. *The $K^\pi = 8^-$ (4 s) isomer band*

The aligned band is observed to decay from both signatures into the 8^- isomer band (Figure 2) with an E1 strength of $\sim 10^{-5}$ W.u. reproducing the observed intensities. However, the aligned band does not seem to be responsible for a large fraction of the observed population of the $K^\pi = 8^-$ states, since $B(E3)$ values of $\gg 100$ W.u. would be required to reproduce the observed 8^- band yields. Mixing of the aligned states with the GSB may explain the $B(E3; GSB \to 8^-) \leq 4$ W.u. strength, which was proposed earlier as the mechanism of direct population. These $B(E3)$ values obtained from a previous ^{178}Hf target excitation experiment reproduce the present 8^- band yields.

3.4. *The $K^\pi = 16^+$ (31 y) isomer band*

The previously observed Coulomb excitation yields in the 16^+ isomer band were used to find a self-consistent set of $\langle K^\pi = 16^+ \| E2 \| K^\pi = 0^+ \rangle$ matrix elements which reproduced the observed intensities, without violating the upper limits on unobserved GSB to $K^\pi = 16^+$ branches. The fitted matrix elements represented for example a $\sim 1\%$ $20^+_{\rm GSB} \to 20^+_{16}$ γ-decay branch, which should be observable in the present data, but this transition has not yet been observed. This seems to indicate that some intermediate states mediate the isomer population from the *yrast* line.

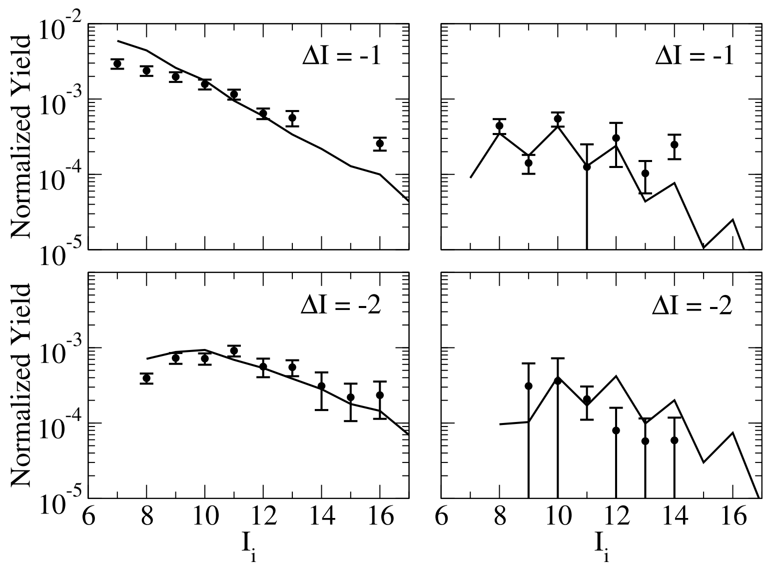

Fig. 4. Experimental γ-decay yields (points) for $K^\pi = 6^+$ in-band (left frames) and γ-band to 6^+ band transitions (right frames). The result of a fit of $\langle K^\pi = 6^+ \mid E2 \mid \gamma - \text{band}\rangle$ and $\langle K^\pi = 6^+ \mid M1 \mid \gamma - \text{band}\rangle$ matrix elements is shown (lines).

A new band "F" feeding the rotational states built on the 16^+ isomer has been found, and tentative spin assignments have been made based on the assumptions of positive parity and weak stretched E2 transitions into the isomer band (Figure 2). As in the case of the 8^- band, the population of the feeding band appears to be too weak to explain a significant fraction of the observed $\sim 10^{-4}$—10^{-3} isomer band intensity.

4. Conclusions

Coulomb excitation of a ^{178}Hf beam on a ^{208}Pb target has resulted in nearly complete spectroscopy of the states in the *yrast* domain. A newly-identified aligned band may play an essential role in explaining the population of K-forbidden states electromagnetically from the ground state by forming a highly-mixed *yrast* line. The importance of the γ-band in Coulomb excitation of the isomers now appears to be greater than was previously claimed, possibly explaining the $K^\pi = 6^+$ isomer band population entirely via K-mixing that increases dramatically with spin as it crosses the aligned band.

The preliminary analysis is consistent with the earlier claim that rotational mixing in the low-K bands above spin $I \approx 12\hbar$ is responsible for Coulomb excitation of the high-K structures. It may be possible to reproduce the observed γ-ray yields of the GSB and the new aligned band using model calculations or a two-state approximation, resulting in some estimate of the amplitudes of high-K admixtures in the wave functions of the nominally low-K rotational states. While the 8^- isomer band yields are reproduced by the $\langle I_{K^\pi=8^-} \| E3 \| I_{\mathrm{GSB}} \rangle$ matrix elements obtained in an earlier experiment, more direct evidence is being sought to support this proposed direct Coulomb excitation path.

A new rotational sequence feeding the $K^\pi = 16^+$ band has been established with tentative spin-parity assignments. A study of the γ-ray angular correlations may be required in order to determine the spin-parity assignments of the feeding band states. The structure of the new band has not been determined, but its $\sim 10^{-4}$ decay intensity suggests that it does not contribute a large fraction of the Coulomb excitation cross section of the isomer band. The population of the $K^\pi = 16^+$ levels via Coulomb excitation is difficult to understand as more restrictive upper limits on $GSB \rightarrow K = 16$ decays are being established. Ongoing analysis and placement of γ-ray transitions may clarify the elusive electromagnetic paths to this isomer.

Acknowledgements

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