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Quasicontinuum ridges in ^{173,174}W

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A strong quasicontinuum ridge with a spacing of 58.1 ± 0.3 keV was observed in ^{173}W and ^{174}W when populated at high spin. The ridge is a factor of 4 times more intense than that of the sum of discrete bands over the same range of rotational frequencies. The strength of the ridge may be due to the large number of nearly degenerate proton orbitals lying above the $Z = 73$ gap occurring at a deformation $\beta_2 \approx 0.3$. [S0556-2813(96)05310-1]

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The analysis of quasicontinuum ridges in E_γ-E_γ correlation arrays was originally applied to study then unresolved rotational bands in deformed rare-earth nuclei [1]. These ridges arise from coincidences of adjacent γ-ray transitions depopulating regularly spaced yet unresolved rotational bands in which the transition energy E_γ is sharply correlated to the spin via the relation $E_\gamma = (\hbar^2/\mathcal{J})(2J-1)$. With the advent of second and third generation γ-ray spectrometers, yrast and near yrast bands have been resolved up to spins of approximately $40\hbar$ in this mass region. However, the γ-ray flux through these discrete bands at high rotational frequencies is usually only a small fraction of the total flux in the reaction channel, and furthermore, generally only a faint ridge is seen in the E_γ-E_γ correlation array. The major part of the γ-ray flux is believed to be in damped rotational bands in which the sharp correlation of transition energy with spin is destroyed by rotational damping [2]. Such damped cascades do not contribute to a sharp ridge. In this work we report the observation of a very strong quasicontinuum ridge associated with the population of ^{173}W and ^{174}W at high spin.

High-spin states of ^{173}W and ^{174}W were populated in the reaction ^{150}Nd(^{30}Si,xn) at a bombarding energy of 178 MeV. The Si beam was delivered by the MP tandem of the Tandem Accelerator Superconducing Cyclotron (TASCC) facility at Chalk River Laboratories. The target comprised a stack of two self-supporting, isotopically enriched ^{150}Nd target foils each of thickness 500 μg cm^{-2}. This reaction formed the compound nucleus ^{180}W* with a grazing angular momentum of $82\hbar$ and an excitation energy of 98 MeV. The 8π spectrometer, which incorporates 20 Compton-suppressed HPGe detectors, recorded γ-γ and higher fold coincidences. The instrument also includes 71 BGO scintillation detectors which in this experiment were used to provided sum-energy and fold K information for each event. Approximately 4×10^8 γ-γ coincidence events with a BGO fold of $K > 9$ were collected during the experiment.

The data set was sorted off line into E_γ-E_γ coincidence matrices with triple and quadruple coincidence events unfolded into double coincidences. In order to better isolate high-spin events, cuts were made such that only events with a fold in the BGO detectors of $K > 16$ were considered. This left 65% of the original data of which 40% corresponded to ^{173}W and 28% to ^{174}W. Several other evaporation residues including ^{172}W and isotopes of tantalum and hafnium were identified but weakly populated.

In order to analyze the ridge structure, we must account for the discrete-line spectra of all reaction channels in the rotational frequency range of interest. Discrete-line coincidences were first analyzed with the computer program ESCL8R [4] which allows for the interactive construction of level schemes based on a background-subtracted [3] E_γ-E_γ correlation array. Seven discrete rotational bands were observed in ^{173}W with spins as high as $(69/2)\hbar$. This includes five bands which were known previously in ^{173}W [5] but which we have extended to considerably higher spins. In ^{174}W four discrete bands, of which three were known previously [6], were seen to high spin. The program ESCL8R was used to perform a least squares fit to the energies and intensities of individual coincidences based on our level schemes for the seven nuclei populated, as well as for several unassigned bands. With this information we were able to subtract these discrete coincidences, thereby generating a correlation array which is well suited for ridge analysis.

Even prior to the subtraction of discrete-line coincidences, a clearly defined ridge can be seen in the background-

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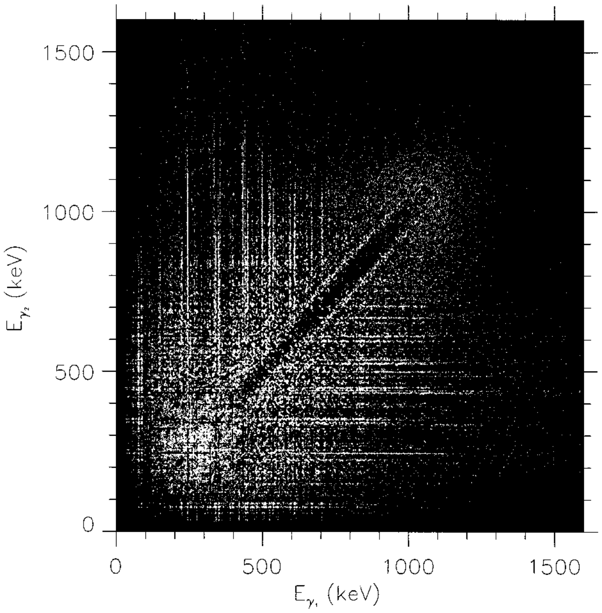

FIG. 1. E_γ-E_γ correlation array for ^{150}Nd(^{30}Si,xn) at 178 MeV. The brightness of each point is proportional to the number of counts in the array element.

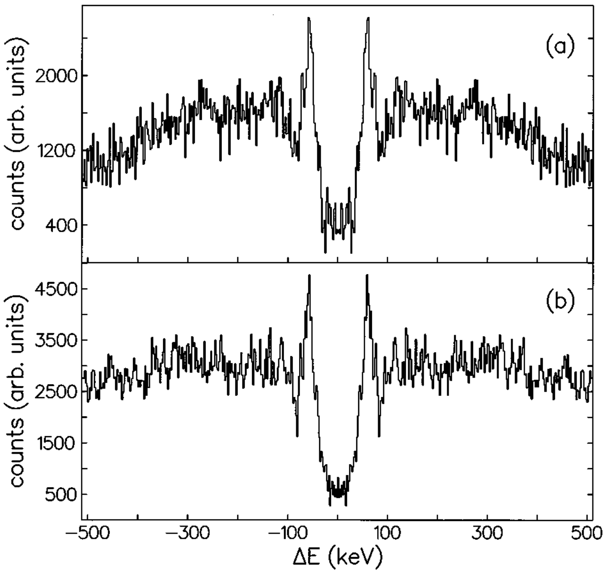

FIG. 2. Projection of the background-subtracted correlation array on the diagonal over the energy ranges 750 keV $\leq (E_{\gamma_1}+E_{\gamma_2})/2 <$ 850 keV (a) and 850 keV $\leq (E_{\gamma_1}+E_{\gamma_2})/2 <$ 950 keV (b).

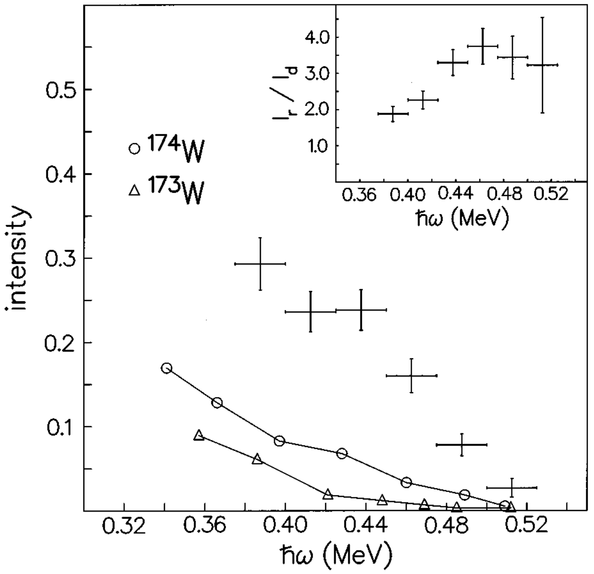

FIG. 3. Intensity of the quasicontinuum ridge and the sum of discrete-line intensities as a function of rotational frequency normalized to the total γ-ray flux populating ^{173}W and ^{174}W. The horizontal error bars for ridge intensities correspond to the frequency range over which the intensity was measured. The discrete-line intensities are calculated from the sum of intensities of transitions composing the discrete bands in each reaction channel following the first alignment. The inset gives the ratio of ridge intensity (I_r) to the total discrete-line intensity into ^{173}W plus ^{174}W (I_d) as a function of rotational frequency.

subtracted tungsten E_γ-E_γ correlation array shown in Fig. 1. The ridge extends from approximately 640 keV to 1100 keV, which corresponds to a rotational frequency range of $\hbar\omega$ = 0.32 MeV to $\hbar\omega$ = 0.55 MeV. Averaged over its length, the ridge spacing (the average energy difference ΔE_γ between adjacent γ rays in the rotational cascades which constitute the ridge) is 58.1 ± 0.3 keV and is nearly constant as can be seen in Fig. 2 where two diagonal slices over different energy regions are shown. The ridge spacing is directly related to the average dynamical moment of inertia of bands which make up the ridge by the relation $\mathcal{J}^{(2)}=4/\Delta E_\gamma$, yielding a value of $68.8\hbar^2$ MeV^{-1}. This value is indicative of normal deformation (β_2 = 0.3) in this mass region. The ridge is considerably broader than can be accounted for by the resolution of the HPGe detectors. Unfolding the intrinsic detector resolution, the full width at half maximum (FWHM) of the ridge in the rotational frequency interval from 0.375 MeV to 0.425 MeV is 24.8 ± 2.8 keV while the FWHM in the frequency interval between 0.425 MeV and 0.475 MeV is 25.8 ± 3.6 keV. This width is significantly narrower than rotational damping widths measured in rare-earth nuclei in this mass region ($\Gamma_{\rm rot}$ = 75–110 keV in ^{168}Yb [7]), suggesting that the ridge width arises solely from the dispersion of $\mathcal{J}^{(2)}$ and rotational alignments among bands comprising the ridge. In the limit of a constant and equal alignment for all bands, the ridge width corresponds to a dispersion in the dynamical moment of inertia $\mathcal{J}^{(2)}$ of $12.4\hbar^2$ MeV^{-1}.

Considering the apparent strength and rotational frequency range of the ridge, it is likely that both reaction channels leading to ^{173}W and ^{174}W contribute to the ridge's intensity. With the method outlined by Love *et al.* [8] we have calculated the intensity of the ridge relative to the discrete-line rotational bands as a function of rotational frequency. The ridge intensity scaled to the flux terminating in the ground state of ^{173}W and ^{174}W is shown in Fig. 3. The ridge intensity is measured in the background-subtracted correlation array with discrete lines subtracted as described above. Formally the background subtraction procedure oversubtracts the ridge since a component of the two-dimensional (2D) correlation has a projection on the singles spectra. However, this effect is small as it is spread over the entire array. This is supported empirically by a measurement of the ridge intensity over carefully selected slices in the unsubtracted correlation array.

The intensity of the low-frequency portion of the ridge represents approximately 25% of the total flux into ^{173}W and ^{174}W as can be seen in Fig. 3. This is more intense than the strong ridges seen in ^{130}Ce [8] and much more intense than ridges generally seen in rare-earth nuclei. One can see that the ridge is also very strong when compared to the discrete-line intensity at a given rotational frequency as shown in the inset plot in Fig. 3; the ridge intensity is up to 4 times greater than the sum of discrete-line intensities in ^{173}W and ^{174}W. In contrast, a similar intensity measurement of the ridge associated with the population of ^{167}Hf and ^{168}Hf when populated at high spins gives a ratio of approximately 1:1 at similar rotational frequencies [9].

A curious aspect of the observed quasicontinuum ridge is the apparent absence of a secondary ridge (a ridge formed by coincidences between two γ rays in a cascade separated by a third) in the diagonal slices shown in Fig. 2. The in-band transition probability for the bands which constitute the ridge is related to the intensities of the primary and secondary ridges. Although the background fluctuations are large and the secondary ridge should be broader than the primary ridge by a factor of $\sqrt{2}$, the intensity of the secondary ridge is clearly significantly less than that of the primary ridge. In the diagonal slice from 850 keV to 949 keV it could be argued that the broad structure whose centroid is located at ΔE_γ of approximately 126 keV is the secondary ridge. Bounds on the secondary ridge intensity were measured by fitting a peak of proper width at the position ΔE_γ equal to twice that of the primary ridge. From the diagonal slice from 850 keV $\leqslant (E_{\gamma_1}+E_{\gamma_2})/2 <$ 950 keV we deduced a value for the in-band transition probability of 0.51 ± 0.27. Because of the narrow width of the first ridge, we ascribe the low probability for in-band transitions to a strong decay-out probability to lower-lying bands rather than to a rotational damping effect. A calculation of the average number of transitions per band is precluded by the large error in the above measurement as this value depends exponentially on the in-band transition probability. However, taking into account the primary ridge intensity, the in-band decay probability and the fact that E_γ-E_γ correlation techniques are not sensitive to bands of length less then 2, it is clear that the majority of the flux flowing into ^{173}W and ^{174}W is through this ridge.

The high intensity of this ridge as compared to other rare-earth nuclei suggests that it may be related to the detailed orbital configurations of ^{173}W and ^{174}W. There is a large shell gap at moderate deformation at $Z = 73$ delimited by the down-sloping π [660] Nilsson intruder orbitals as seen in the unpaired energy-level diagram shown in Fig. 4. In the above calculation a deformation parameter of $\beta_2 = 0.30$ was determined by performing a total Routhian surface (TRS) calculation assuming the occupation of a single $N = 6$ proton intruder orbital. At this deformation the π $[660]\frac{1}{2}^+$ orbital crosses the Fermi surface at a rotational frequency of $\hbar\omega = 0.25$ MeV, leaving the remaining valence proton to occupy one of many possible $N = 4$ and $N = 5$ orbitals above the $Z = 73$ gap. These orbitals are nearly degenerate in energy, with eight being within 340 keV of each other close to the Fermi surface. This could yield the large number of nearly degenerate rotational configurations required for the formation of a ridge.

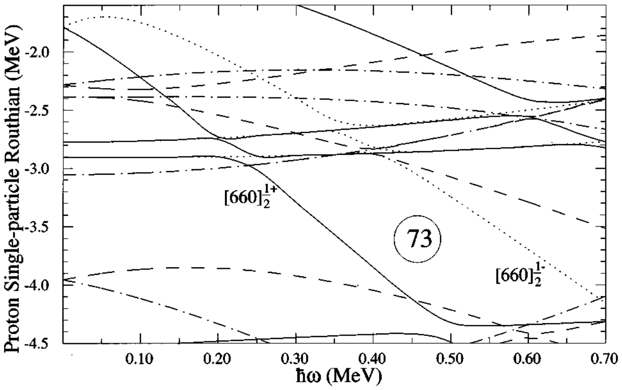

FIG. 4. Proton single-particle levels calculated with deformation parameters obtained from TRS calculations ($\beta_2 = 0.30$). The levels are classified by parity and signature quantum numbers as follows: (+,+1/2) solid lines, (+,−1/2) dotted lines, (-,-1/2) dashed lines, and (−,+1/2) dot-dashed lines.

While this multitude of nearly degenerate orbitals is a necessary condition for the existence of a strong ridge, it is not sufficient. The rotational bands associated with each of the configurations must have similar energy spacings or, equivalently, similar dynamical moments of inertia, $\mathcal{J}^{(2)}$. Referring again to Fig. 4, these $N = 4$ and $N = 5$ orbitals near the Fermi surface have a curvature $d^2e'/d\omega^2$ that is nearly zero, indicating that their contribution to the dynamical moment of inertia of any of these individual orbitals will be small. Since these many configurations differ only in their valence orbital due to the large energy gap present at $Z = 73$, the total dynamical moment of inertia of each configuration should be similar, thereby accounting for the small dispersion in $\mathcal{J}^{(2)}$ of the ridge.

A final requirement for a strong ridge to be formed is that the γ-ray flux must pass rapidly to the region of lower temperature. If this is not the case, rotational damping will destroy the E_γ-spin correlation necessary for the formation of a ridge. Evidently some quality of the reaction or the residual nucleus studied favors rapid cooling; however, more theoretical and experimental work will be required to elucidate this point.

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