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$\gamma-\gamma$ ENERGY CORRELATIONS IN ^{167,168}Hf OBSERVED WITH TWO COMPTON-SUPPRESSION SPECTROMETERS

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The $\gamma-\gamma$ energy correlation matrix obtained from ^{159}Tb(^{14}N, xn) reactions at 95 MeV exhibits a low-intensity central valley with smoothly decreasing width when the rotational frequency increases, indicating an increasing collective moment of inertia. Enhanced intensities in the valley at $\hbar\omega$ = 0.42 and 0.52 MeV are observed for the first time in the HF isotopes and are interpreted as due to band crossings which may involve $i_{13/2}$, $f_{7/2}$ neutron and $h_{11/2}$ proton or higher orbitals.

Many studies of the quasi-continuum (q.c.) γ-ray spectrum of highly excited nuclei have already been carried out to obtain nuclear structure information at high rotational frequencies. It has been well established that with increasing frequency a large fraction of the total angular momentum can be generated by the alignment of individual nucleonic spins along the axis of collective rotation. Rotational bands based upon aligned quasiparticles have been observed in several nuclei as well as their crossings with the ground-state-rotational bands, known as the first backbending in the plot of the moment of inertia versus rotational frequency. Such anomalies in the regular bandstructures are interesting because they reveal the nature of the quasiparticles which constitute the crossing bands.

Several groups have started searches for possible second and higher bandcrossing phenomena. Although the second backbending has been established by now [1,2] it occurs at such a high rotational frequency that the signifying transitions are very difficult to observe as discrete peaks in the γ-ray spectrum. Recently a new method has been proposed [3] to isolate energy correlated cascades from a background of uncorrelated events. Such correlations are expected to be strong for yrast-like quasi-continuous cascades in rotational nuclei. The technique is to record coincidences between one or more pairs of γ-ray detectors and to construct the $\gamma-\gamma$ energy correlation matrix. Ge(Li) detectors offer high resolution but the number of full-energy coincidences amount only to 1–2% of the total number of events. This value may be increased to $\approx$25% with large collimated NaI(Tl) detectors, but at the expense of energy resolution. This quantity is of importance for the observation of details in the correlation matrix such as an absence of coincidence events along the diagonal $E_{\gamma 1} \approx E_{\gamma 2}$ (the central valley) signifying collective rotation or enhanced intensity in the valley due to band crossing. Compton suppression spectrometers offer both good energy resolution and a superior fraction photo-photo energy coincidence ($\approx$36%).

In the present work the correlation matrix exhibits clearly the known features in the energy region where discrete γ rays dominate including the first band crossings occuring in ^{167}Hf and ^{168}Hf [4]. New irregularities are observed at higher frequencies in the q.c. γ-ray spectrum which can be interpreted as being due to band crossings which involve bands based on $\pi h_{11/2}$ and high-

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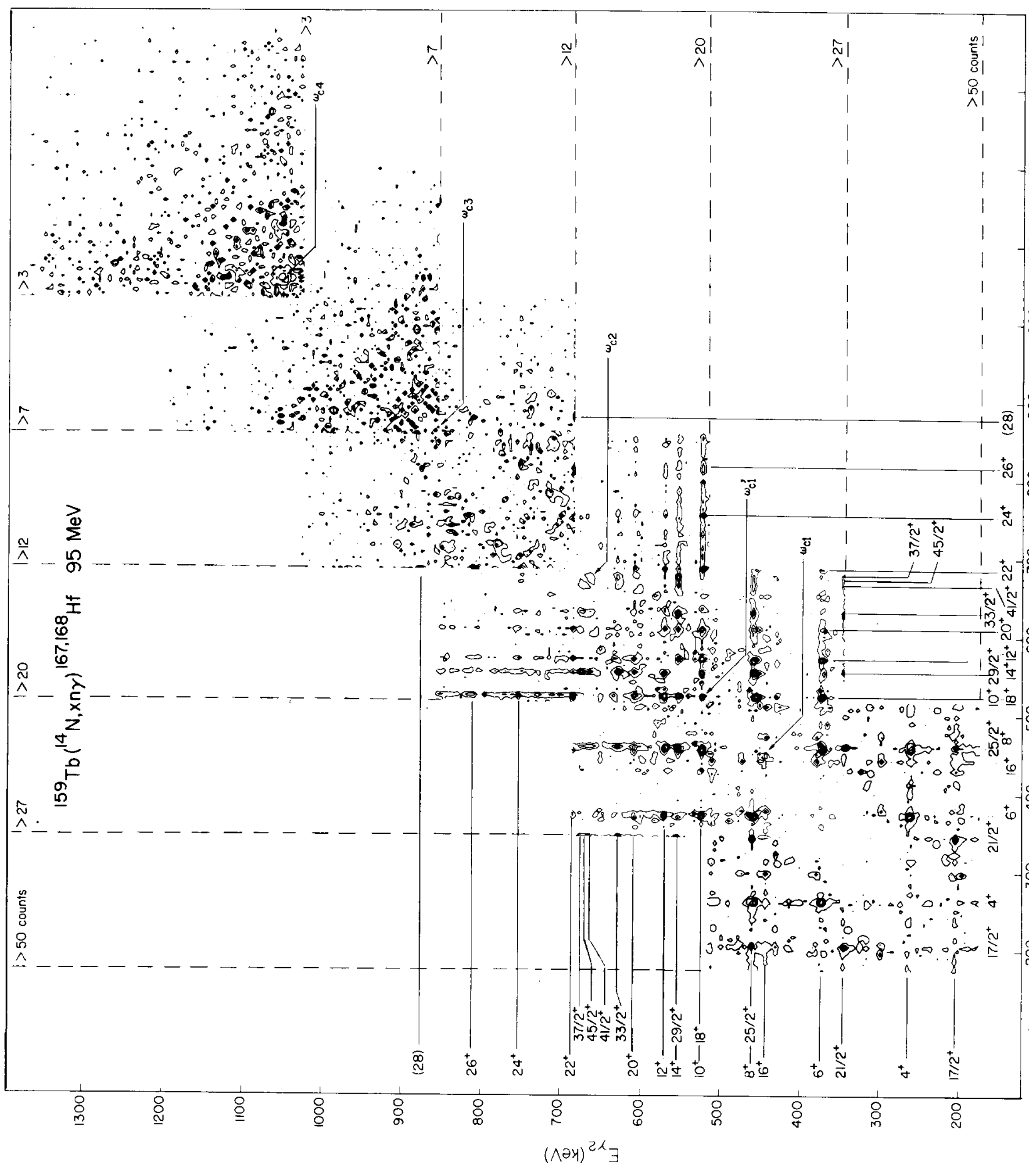

Fig. 1. Contour plot of the symmetrized γ–γ coincidence matrix, corrected with three steps of the iteration procedure (see text). Six different intensity thresholds have been used indicated by the numbers on the right and above. Enhanced intensities in the valley are indicated by $\omega_{c1}, ..., \omega_{c4}$ (see also fig. 2). The known discrete yrast-band transitions in $^{167,168}Hf$ are indicated on the left and below by the spin of the initial level.

er lying orbitals. The width of the central valley in the matrix is seen to decrease smoothly with increasing rotational frequency. This can be ascribed to an increasing collective moment of inertia.

The final nuclei were excited by bombarding a $\approx$3 mg ^{159}Tb target with 95 MeV ^{14}N ions from the Groningen 280 cm AVF cyclotron. The coincidences were recorded between two Compton suppression spectrometers which were placed at $\pm 90°$ with respect to the beam axis and each central detector $\approx$10 cm from the target. One spectrometer consisted of a NaI(T1) shield with 30 cm diameter $\times$35 cm length and a 90 cm^3 HPGe detector as central detector; its solid angle was 120 msr, and the average suppression factor, measured with a ^{60}Co source, was 11. The second spectrometer consisted of a 110 cm^3 Ge(Li) detector surrounded by a 25 cm diameter $\times$ 23 cm length NaI(T1) crystal; the solid angle was 70 msr and the average suppression factor 8.

The generated energy correlation matrix shows already pronounced regular structures without any correction for energy uncorrelated events, but with subtraction of time uncorrelated (random) events. Energy uncorrelated events are defined as those which are caused by coincidences between signals due to nonphoto effects in both Ge-detectors (i.e. Compton–Compton and photo-Compton effects). For improvement of the data they were subtracted according to the method given in ref. [3] but modified by us to take into account explicitly the large photo efficiencies of the two spectrometers $p_1 = p_2 \approx 0.6$:

$$\Delta N_{ij} = N_{ij} - \tilde{N}_{ij}$$

$$= N_{ij} - (1 - p_1 p_2) \sum_k N_{ik} \sum_l N_{lj} \Big/ \sum_{l'k'} N_{l'k'} \, . \qquad (1)$$

Here N_{ij} denotes the total number of coincidences between γ-rays in channel i of one detector and in channel j of the other detector. $\tilde{N}_{ij}$ thus represents the background component which according to ref. [3] also contains part of the correlated events. Therefore the lost number of correlated events was approximately retrieved in an iteration procedure as proposed in ref. [5]. The result after three iteration steps is shown in fig. 1. The matrix is symmetrised, which means that the events located on the left of the diagonal are added to the ones on the right and vice versa in order to obtain symmetric pictures in figs. 1 and 2.

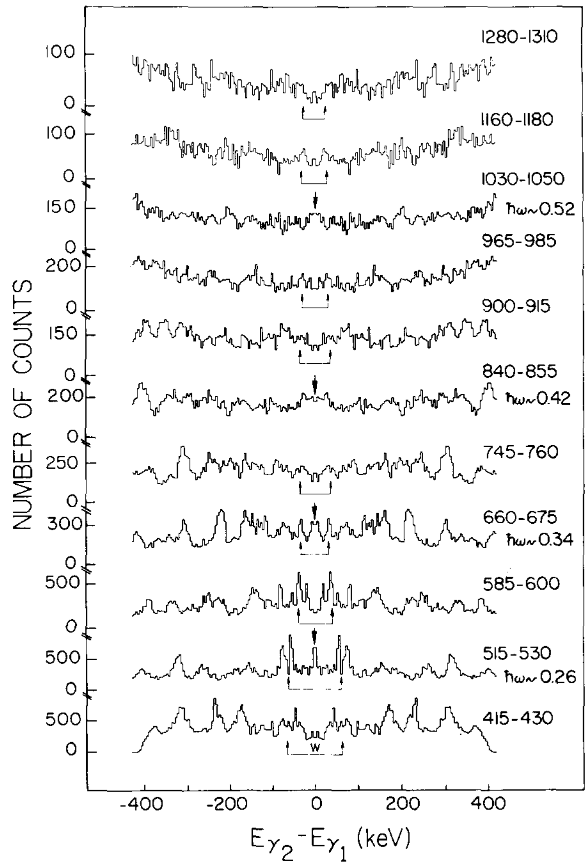

Fig. 2. Cuts through the energy correlation matrix perpendicular to the diagonal $E_{\gamma 1} = E_{\gamma 2}$. The energy region over which is summed is indicated in keV. The enhanced intensities in the valley found at four rotational frequencies are indicated by an arrow and the frequency on the right. The estimated width of the central valley is indicated by W, determined by the average positions of the first few peaks along the valley (in the low-energy region known as due to transitions in ^{167}Hf and ^{168}Hf).

The features in fig. 1 due to the discrete yrast-band transitions in ^{167,168}Hf are immediately apparent. The rotational character of the gsb is reflected by the absence of counts along the 45° diagonal ($E_{\gamma 1} = E_{\gamma 2}$) valley. This valley can be traced up to at least 1000 keV. Enhanced intensity in the valley is caused by irregularities in the rotational bands i.e. bandcrossings. The known [4] first bandcrossing in ^{168}Hf causes coincidences between γ rays of about the same energy of $E_\gamma \approx 450$ keV and also of $E_\gamma = 522$ keV. They are indicated in fig. 1 as ω_{c1} and ω'_{c1}. The same feature occurs in ^{167}Hf at $E_\gamma \approx 660$ keV indicated in fig. 1 as

ω_{c2}. Those enhanced intensities in the central valley also show up clearly if one projects the intensities in e.g. 20 keV wide slices perpendicular to the 45° diagonal ($E_{\gamma 1} = E_{\gamma 2}$) as shown in fig. 2. Besides the above mentioned irregularities at $\hbar\omega$ = 0.26 and 0.33 MeV enhanced intensities in the valley are seen at $\hbar\omega \approx 0.42$ and 0.52 MeV (see figs. 1 and 2). Those intensities are not due to e.g. neutrons because the strongest lines in the γ-ray spectrum due to (n, n′) reactions on Ge and Al at E_γ = 596, 692 and 1014 keV, respectively, are not observed in the coincidence spectra and in the matrix.

The width of the valley can be related to the collective moment of inertia $\mathcal{J}_c$ which in the quasi-continuum (above $E_\gamma \approx 0.8$ MeV) may represent an average over many rotational bands if they all satisfy approximately the relation:

$$E(I) \approx \hbar^2/2\mathcal{J}_c (I - j_a)^2 + E_{j_\alpha} . \tag{2}$$

Here j_a represents the angular momentum of aligned particles and E_{j_a} the corresponding energy contribution. The second derivative thus yields:

$$\Delta E_\gamma = 4\, d^2E/dI^2|_{j_a, \mathcal{J}_c} = 8\hbar^2/2\mathcal{J}_c . \tag{3}$$

The difference in energies of subsequent γ rays in the cascades ΔE_γ corresponds to the width of the central valley W as indicated in fig. 2. In this procedure W is measured perpendicular to the diagonal in fig. 1 and is then projected on the horizontal γ-ray energy axis (i.e. W is divided by $\sqrt{2}$). This procedure is identical to that followed in ref. [6]. From this figure it is clear that the determination of W is far from unambiguous because the ridges along the valley contain discrete peaks due to coincidences between, e.g. gsb and q.c. transitions (and remaining Compton events). Although an absolute determination of W and thus of $\mathcal{J}_c$ is not possible at all frequencies one clearly observes a smooth decrease of W as function of ω (see fig. 1). The width has been determined up to $E_\gamma \approx 1000$ keV for 20 keV wide slices through the correlation matrix. The width W equals the distance between the ridges along the central valley. From the low-energy discrete part of the matrix (fig. 1) it appears that W is somewhat smaller for ^{168}Hf than for ^{167}Hf. Therefore average positions of the ridges have been chosen throughout the matrix (see fig. 2). The moments of inertia $2\mathcal{J}_c/\hbar^2$ deduced according to (3) are given in fig. 3 as a function of the rotational frequency. The fluctuations seen in fig. 3 reflect the

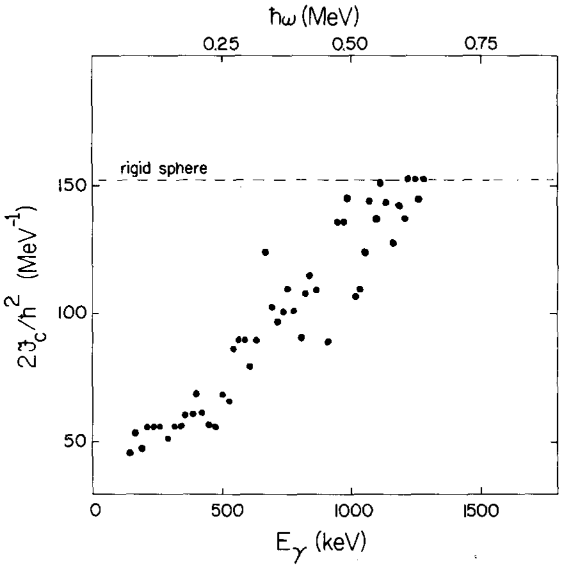

Fig. 3. The derived collective moment of inertia plotted as a function of γ-ray energy and of rotational frequency ($\hbar\omega \approx \frac{1}{2}E_\gamma$). The fluctuations in $2\mathcal{J}_c/\hbar$ are probably due to experimental uncertainties.

uncertainties in the deduced values. However, the general trend of a rather continuous increase of $\mathcal{J}_c$ with increasing rotational frequency seems apparent. At the highest frequencies $\hbar\omega > 0.5$ MeV $\mathcal{J}_c$ approaches the value of the rigid sphere which is about 15% smaller than that of the rigid rotor. In contrast with the present work, a much wider valley width at the highest frequencies was reported in ref. [6]. This implies that $\mathcal{J}_c$ in that case was much smaller than the rigid rotor value (25–50%) as compared to the present case (≈15%). This would mean a smaller particle alignment effect in the present case as compared to ref. [6]. It is not clear at the moment whether the deviation with the result of ref. [6] is due to different nuclear structure or to the maximum input angular momentum of ≈80ħ in the 185 MeV ^{40}Ar + ^{124}Sn system of ref. [6] and ≈45ħ in the present case. Moreover, the determined valley widths at high rotational frequencies should be considered as very tentative in both the present experiment and that of ref. [6].

The crossing frequencies of the various rotational bands can be calculated within the framework of the cranked shell model as is discussed in the preceeding paper [4]. There it is shown that the first bandcrossings in ^{167}Hf and ^{168}Hf are due to the alignment of $i_{13/2}$ neutron orbitals. The same calculation shows that a next crossing of bands in these nuclei occurs at a rotational frequency of $\hbar\omega = 0.45$ MeV due to the interaction between the $\pi h_{11/2}$ [523] 7/2 orbital and its energy conjugate. At about $\hbar\omega = 0.51$ MeV other crossings may occur because of the interaction between the $\nu i_{13/2}$ [633] 7/2 and the [642] 5/2 orbitals and also between the $\nu f_{7/2}$ [523] 5/2 orbital and its energy conjugate. The enhanced intensities in the central valley found at $\hbar\omega = 0.42$ and 0.52 MeV correspond rather well with the calculated ones. This indicates that the higher bandcrossing phenomena involve most likely the $i_{13/2}$ and $f_{7/2}$ neutron and the $h_{11/2}$ proton orbitals. It may be noticed that the presently found irregularity at $\hbar\omega_{c3} = 0.42$ MeV corresponds almost exactly with that of the observed second backbending in ^{158}Er [1] and ^{160}Yb [2], which was ascribed as being due to the $h_{11/2}$ proton orbital. The highest observed irregularity at $\hbar\omega_{c4} = 0.52$ MeV is close to the one observed at ≈ 0.55 MeV in a similar work [6], but employing single detectors.

Although the present paper cannot be conclusive on the specific details of the nuclear structure in ^{167,168}Hf at fast rotations it shows that the presently employed technique reveals details on collective and single-particle motions which remained undiscovered in the discrete γ-ray spectra.

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