γ−γ energy correlations in 167,168Hf observed with two compton-suppression spectrometers

de Voigt, MJA; Janssens, RVF; Sakai, H; Aarts, HJM; van der Poel, CJ; Arciszewski, HFR; Scherpenzeel, DEC

Published in: Physics letters b

DOI: 10.1016/0370-2693(81)90261-6

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date: 1981

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 19-02-2019
\( \gamma - \gamma \) ENERGY CORRELATIONS IN \(^{167,168}\text{Hf}\) OBSERVED WITH TWO COMPTON-SUPPRESSION SPECTROMETERS

M.J.A. de VOIGT, R.V.F. JANSSENS and H. SAKAI
Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands

and

Fysisch Laboratorium, University of Utrecht, The Netherlands

Received 29 May 1981

The \( \gamma - \gamma \) energy correlation matrix obtained from \(^{159}\text{Tb}^{(14}\text{N}, \text{xn})\) 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.) \( \gamma \)-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 \( \gamma \)-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 \( \gamma \)-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 \( \gamma \) rays dominate including the first band crossings occurring in \(^{167}\text{Hf}\) and \(^{168}\text{Hf}\) \([4]\). New irregularities are observed at higher frequencies in the q.c. \( \gamma \)-ray spectrum which can be interpreted as being due to band crossings which involve bands based on \( n_{11/2} \) and high-
Fig. 1. Contour plot of the symmetrized $\gamma-\gamma$ 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 $\omega_{C1}, \cdots, \omega_{C4}$ (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 ro-
tational frequency. This can be ascribed to an increasing
collective moment of inertia.

The final nuclei were excited by bombarding a
≈3 mg 159Tb target with 95 MeV 14N ions from the
Groningen 280 cm AVF cyclotron. The coincidences
were recorded between two Compton suppression
spectrometers which were placed at ±90° with respect
to the beam axis and each central detector ≈10 cm
from the target. One spectrometer consisted of a
NaI(T1) shield with 30 cm diameter × 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 60Co source, was 11. The sec-
ond spectrometer consisted of a 110 cm^3 Ge(Li) de-
tector surrounded by a 25 cm diameter × 23 cm length
NaI(T1) crystal; the solid angle was 70 msr and the
average suppression factor 8.

The generated energy correlation matrix shows al-
ready pronounced regular structures without any cor-
rection for energy uncorrelated events, but with sub-
traction of time uncorrelated (random) events. Energy
uncorrelated events are defined as those which are
caused by coincidences between signals due to non-
photo effects in both Ge-detectors (i.e. Compton—
Compton and photo-Compton effects). For improve-
ment 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 efficien-
cy of the two spectrometers P1 = P2 ≈ 0.6:

\[ \Delta N_{ij} = N_{ij} - \bar{N}_{ij} \]

\[ = N_{ij} - (1 - P_1 P_2) \sum_k N_{ik} \sum_l N_{lj} / \sum_{l'k'} N_{l'k'}. \]

Here \( N_{ij} \) denotes the total number of coincidences
between \( \gamma \)-rays in channel \( i \) of one detector and in chan-
nel \( j \) of the other detector. \( \bar{N}_{ij} \) 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 approxima-
tively 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 ad-
ded to the ones on the right and vice versa in order to
obtain symmetric pictures in figs. 1 and 2.

The features in fig. 1 due to the discrete yrast-band
transitions in \( ^{167,168}Hf \) are immediately apparent. The
rotational character of the gsβ is reflected by the ab-
sence 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 ir-
regularities in the rotational bands i.e. bandcrossings.
The known [4] first bandcrossing in \( ^{168}Hf \) causes coin-
cidences between \( \gamma \) rays of about the same energy of
\( E_\gamma \approx 450 \) keV and also of \( E_\gamma = 522 \) keV. They are in-
dicated in fig. 1 as \( \omega_{11} \) and \( \omega_{12} \). The same feature oc-
curs in \( ^{167}Hf \) at \( E_\gamma \approx 660 \) keV indicated in fig. 1 as
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 \((E_\gamma = E_{\omega2})\) 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 \(\gamma\)-ray spectrum due to \((n, n')\) reactions on Ge and Al at \(E_\gamma = 596, 692\) 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 \(\mathcal{O}_c\) 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:

\[
E(I) \approx \frac{\hbar^2}{2} \mathcal{O}_c (I - I_a)^2 + E_{I_a}.
\]

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

\[
\Delta E_\gamma = \frac{4}{\hbar^2} \frac{d^2 E}{dI^2} \mathcal{O}_c = 8\hbar^2/2 \mathcal{O}_c.
\]

The difference in energies of subsequent \(\gamma\) rays in the cascades \(\Delta E_\gamma\) 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 \(\gamma\)-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 \(\mathcal{O}_c\) is not possible at all frequencies one clearly observes a smooth decrease of \(W\) as function of \(\omega\) (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 \(2\mathcal{O}_c/\hbar^2\) deduced according to (3) are given in fig. 3 as a function of the rotational frequency. The fluctuations seen in fig. 3 reflect the uncertainties in the deduced values. However, the general trend of a rather continuous increase of \(\mathcal{O}_c\) with increasing rotational frequency seems apparent. At the highest frequencies \(\hbar \omega > 0.5\) MeV \(\mathcal{O}_c\) 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 \(\mathcal{O}_c\) 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 \(\approx 80\hbar\) in the 185 MeV \(^{40}\)Ar + \(^{124}\)Sn system of ref. [6] and \(\approx 45\hbar\) 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 $n\ell_{11/2}$ [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 $\nu\ell_{13/2}$ [633] 7/2 and the [642] 5/2 orbitals and also between the $\nu\ell_{7/2}$ [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 $\approx 0.55$ 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 $\gamma$-ray spectra.

The authors would like to thank Drs. G.A.P. Engelbertink, J.F.W. Jansen and J. Lukasiak for assistance in the experiment.

References