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Review

Reflections on the science and impact of Bent Herskind

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Abstract Bent Herskind was a *Gamma-Ray Grand Master*, who helped trigger the modern revolution in γ-ray spectroscopy, opening the door to new vistas in nuclear structure physics. His story is a remarkable one and the contributions he made to the field in terms of its scientific richness and to the development of ever more powerful detector systems, were unique. The enthusiasm and excitement he put into everything were infectious and the brilliance of his insights was compelling. His legacy will live on, not only in the significant discoveries that he made, but also in the way he instilled his deep commitment to unravelling nature's secrets in this quest and the pleasure of physics discovery with his close collaborators. This review article summarises his career and highlights some of his scientific achievements in which the authors had the privilege to collaborate with him.

1 Introduction and early years at NBI

In the present work a number of the scientific and technical innovations of Bent Herskind, who passed away on the 7^{th} December 2021, only seven days before of his 90^{th} birthday, have been selected to illustrate how he helped revolutionise the field of nuclear structure physics and γ-ray spectroscopy. These contributions are based upon presentations given at a special session *"The Science and Impact of Bent Herskind (1931–2021)"* during the 2022 *Shapes and Symmetries in Nuclei: from Experiment to Theory* conference held at IJCLab Orsay, France.

It is not easy to summarise the brilliant and far reaching career of Bent, however the "*In Memoriam*" article by Geirr Sletten, Thomas Døssing, Silvia Leoni and Lee Riedinger [1] is an excellent testament to Bent's work. Bent started his career in 1956 as a research associate at the Niels Bohr Institute (NBI) in Copenhagen, Denmark, and then moving to the new Risø Tandem Accelerator Laboratory (NBITAL) outside Roskilde in 1962, see Fig. 1. He was fascinated by the research being done by the NBI scientists led by Aage Bohr and Ben Mottelson, the future Nobel laureates, and while initially working on the development of new electronics modules and their implementation into novel experiments, soon became deeply involved in all aspects of the program including the analysis and physics interpretation of the new data. He began designing and performing his own experiments, first exploring the properties of deformed nuclei [2] and then delving into the new arena of high-spin physics inspired and encouraged by Aage and Ben [3,4]. He was promoted to the position of Research Associate in 1966, had a sabbatical year at the University of Wisconsin-Madison in the USA in 1967 and was subsequently appointed "Lektor" at the NBI in 1971. He obtained his Ph.D. from the University of Copenhagen in 1974.

In the late 1960's and early 70's, Aage and Ben predicted the different phases that may be expected in deformed nuclei as a function of increasing angular momentum and excitation energy all the way up to the fission limit. While admitting their picture was highly conjectural they confidently stated *"...with the ingenious experimental approaches that are being developed, we may look forward with excitement to the detailed spectroscopic studies that will illuminate the behaviour of the spinning quantised nucleus"*[3]. It is clear Aage and Ben were thinking about their many interactions with Bent when they wrote this sentence! Bent was at the vanguard and always trying to collect as much multi γ-ray coincidence data as possible. His endeavours in this regard were rewarded with a new unit being named after him. If you

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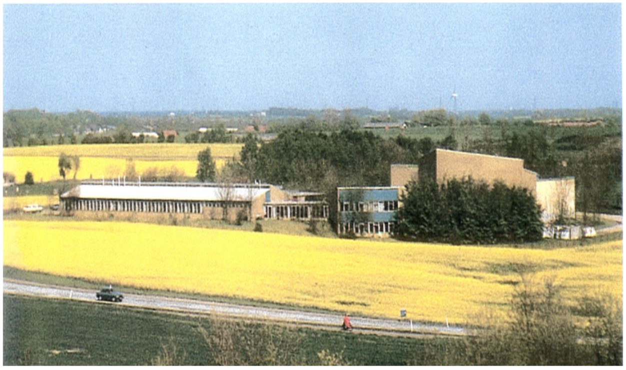

Fig. 1 The Tandem Accelerator Laboratory NBITAL of the Niels Bohr institute at Risø (Roskilde, Denmark)

were fortunate to collect 100 data tapes in an experiment then you had a *"Herskind"*.

In the late 1970's and early 80's Bent and the NBI high-spin group, formed a mighty alliance with groups from the University of Liverpool (Peter Twin, John Sharpey-Schafer, Paul Nolan et al.) and the University of Manchester (John Lisle, Bob Chapman et al.) to create the first escape-suppressed Germanium detector arrays, TESSA [5,6], at the NBITAL and then Daresbury (UK) accelerators, which revolutionised the field of nuclear structure physics [6].

Bent, and the NBI group, continued to be at the epicentre of detector developments in European collaborations in the 80's and in the 90's, (e.g. TESSA, ESSA30 see Fig. 2, Nordball [7], EUROBALL [8–11]). The same was true with regard to the interpretation of the extraordinary physics discoveries being made. Memorable workshops, one three months long(!), were held in the 1980's and 90's both at NBITAL (see Fig. 3) and at the NBI in Copenhagen, with Bent playing a conductors role in so many of these historic discussions, which moved our field forward at a breakneck backbending pace, see for example Ref. [12]. Such was the extent of his influence and popularity, that Bent was not only invited to present his latest findings at major international conferences decade after decade, but also he was invited to spend many research intensive summers, and extended periods, at leading centres and laboratories throughout the world during his career.

High resolution γ-ray spectroscopy continues to be one of the most powerful tools to study the structure of atomic nuclei and has seen many further major scientific advances in recent decades [6,13–15]. This is set to continue with the even more powerful γ-ray tracking spectrometers [16], AGATA [15,17,18] in Europe and GRETA [19,20] in the USA. Figure 4 shows the evolution of γ-ray spectrometers over the years and their increase in resolving power.

In 2004 Bent, with Peter Twin, was awarded the Lise Meitner Prize for Nuclear Science by the European Physical Society "*For their pioneering development of experimental tools, methods of analysis and experimental discoveries concerning rapidly spinning nuclei, in particular the discovery of superdeformed bands.*"

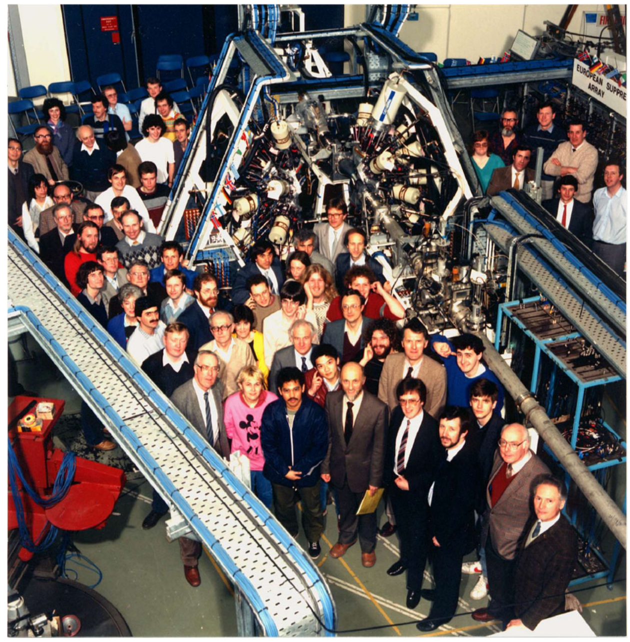

Fig. 2 The European collaboration ESSA30 at Daresbury Laboratory in 1987. Bent would later be instrumental in bringing even larger collaborations successfully together within Europe

Fig. 3 A "Nuclear Structure at High-Spin Workshop" group photo taken at the NBITAL Risø Tandem Accelerator Laboratory in 1981

2 Warm nuclei at high spin

Rotational bands represent one of the most direct manifestations of symmetry breaking in many-body systems, making it possible to define an intrinsic reference system and a deformation. As Phil Anderson wrote in 1972, in a famous paper discussing spontaneous symmetry breaking in science, referring to the unified model introduced by Aage Bohr and

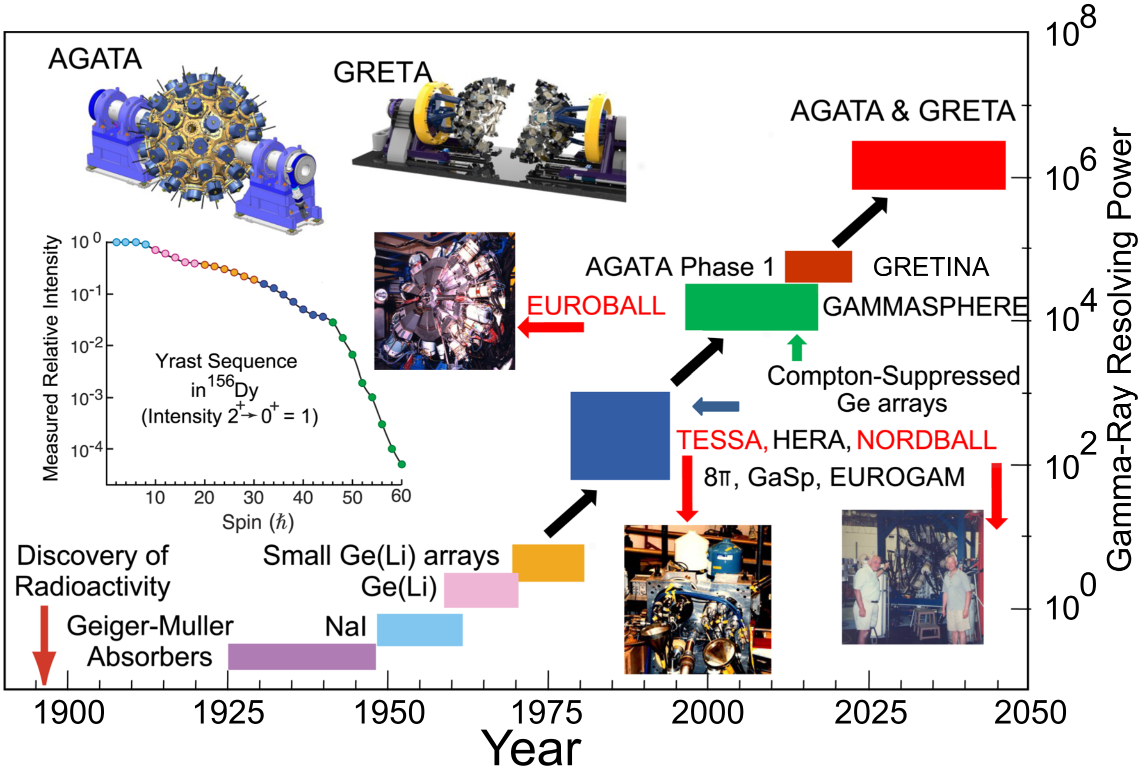

Fig. 4 The progression of gamma-ray *"microscopes"* and their resolving power through the decades. Bent Herskind played a leading role in this evolution, in particular for TESSA, NORDBALL and EUROBALL. The gamma-ray resolving power is a measure of the ability to observe the faint emissions from rare and exotic nuclear states and is directly related to the observable intensity of the gamma-ray signals from an excited nucleus. The insert shows the ratio of the intensity of the transitions along the yrast line (connecting the lowest energy states at the various spins) to the intensity of the $2^+ \rightarrow 0^+$ transition in a typical rare-earth nucleus (^{156}Dy) as a function of spin. Updated from [21]

Ben Mottelson, *"it is fascinating to think that it was not until a couple of decades ago that nuclear physicists stopped thinking of the nucleus as a featureless, symmetrical little ball and realised that... it can become football-shaped or plate-shaped. A macroscopic body of that shape would have such-and-such a spectrum of rotational and vibrational excitations, completely different in nature from those which would characterise a featureless system. When we see such a spectrum, even not so separated, and somewhat imperfect, we recognise that the nucleus is, after all, not macroscopic; it is merely approaching macroscopic behaviour"* [22].

The characterisation of the rotational behaviour of nuclei, and in particular the interplay between single-particle and collective degrees of freedom lay at the heart of the investigation of the exceptional group of theoretical and experimental physicists that gathered around Aage and Ben at the NBI in Copenhagen and at the NBITAL laboratory in Risø. During the 70's extraordinary results were obtained in a variety of deformed nuclei, concerning the dependence of rotational motion on angular momentum, in particular with the identification of the yrast line up to high angular momentum, and with the discovery of backbending [21,23]. Towards the end of that decade, with the advent of new powerful detectors, it became possible to start investigating in detail a new dimension of rotational collective motion, namely its evolution with internal energy above the yrast line. This research exploited the fact that the energy of rotational bands $E(I)$, and the associated transition energies $E_\gamma(I)$, display a regular dependence on angular momentum I. In the simplest case of a well defined prolate deformation, $E(I) = \hbar^2 I(I+1)/2\mathcal{J}$ and $E_\gamma(I) = 2\hbar^2 I/\mathcal{J}$, where $\mathcal{J}$ denotes the moment of inertia [24].

In collaboration with the group at the Lawrence Berkeley National Laboratory, USA, Bent studied the γ-ray cascades produced in nuclei excited by fusion-evaporation reactions. Making use of NaI detector arrays, they produced one-dimensional spectra associated with high multiplicity events, which displayed a low-energy bump of quadrupole character, superimposed on a featureless exponential tail of statistical nature. This led to the conclusion that the $\gamma-$flow proceeds down to the ground state (yrast line) through a large number of stretched E2 transitions between excited configurations [25].

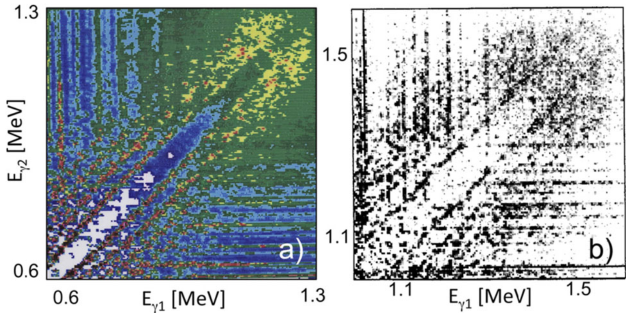

Fig. 5 $\gamma-\gamma$ coincidence matrices of ^{168}Yb (0.6−1.3 MeV region) (**a**) and ^{143}Eu (1.0−1.6 MeV region) (**b**) [24]. They were obtained in experiments with the EUROGAM I array and NORDBALL, respectively. In both cases a pronounced ridge-valley pattern is observed, corresponding to normal deformed (**a**) and superdeformed (**b**) configurations

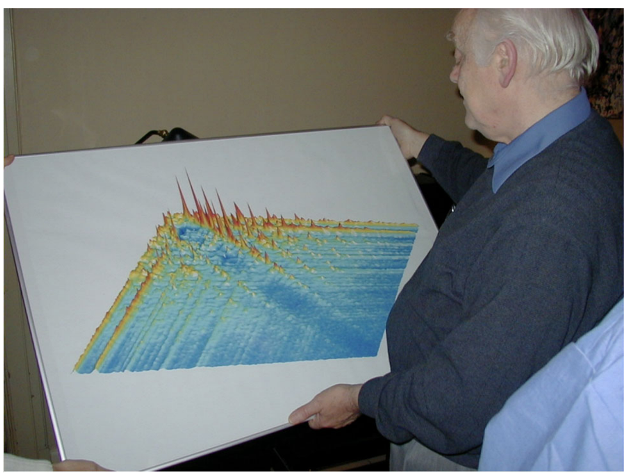

Fig. 6 Bent Herskind looking at a 3D representation of the $E_{\gamma 1} - E_{\gamma 2}$ correlations measured in ^{168}Yb. This image was chosen as a gift upon his retirement in 2002, as it is particularly representative of his scientific activity

These studies represented the beginning of quasi-continuum $\gamma-$ray spectroscopy [24,26]. The new technique of $E_{\gamma 1} - E_{\gamma 2}$ correlations in two-dimensional spectra was then introduced, together with dedicated techniques for background subtraction [27]. Well-defined "ridges" parallel to a "valley" around the diagonal $E_{\gamma 1} = E_{\gamma 2}$ were a clear signature of rotational decay taking place along bands with a moment of inertia that could be deduced from the ridge separation, allowing in particular the identification of superdeformed configurations (see Figs. 5 and 6).

At the same time, these spectra demonstrated that the correlations between energy transitions in the quasi-continuum are weaker than those expected for regular rotational bands. In fact, the central valley showed only a rather weak depression, characterised by a width Γ_{rot}, the "rotational damping" width (see Figs. 7, 8, 9, 10, 11).

The interpretation of these results required a close and intense collaboration between experimentalists and theorists.

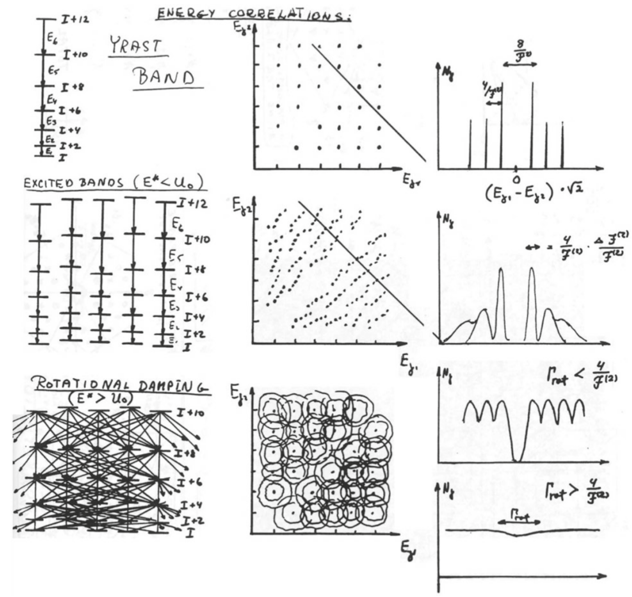

Fig. 7 In the Autumn of 1989, an extended workshop about "Nuclear physics in the era of new spectroscopy" was organised at the NBI in Copenhagen. On that occasion, Bent presented his study of rotational damping based on correlations between transition energies

It was proposed that rotational damping sets in with increasing excitation energy above yrast because the intrinsic states on which rotation bands are mixed by residual interaction, leading to complex compound states. A given intrinsic state is then spread over many compound states, and over an energy interval characterised by a damping width Γ_{CN}. The intrinsic states react in different ways to Coriolis and centrifugal forces, and as a consequence the compound states resulting from the coupling at a given spin I do not populate a single state at spin $I-2$, but a distribution of them, characterised by the rotational damping width Γ_{rot}. This width is a measure of the loss of coherence in the rotational motion and depends on the distribution of frequencies of the intrinsic states $\Delta\omega$ and on the width of the compound states Γ_{CN}. The main theoretical result is that one can identify two different regimes, depending on whether Γ_{CN} is smaller or larger than $2\hbar\Delta\omega$. In the first one, Γ_{rot} is equal to $2(2\hbar\Delta\omega)$; in the second one (motional narrowing) Γ_{rot} is equal to $2(2\hbar\Delta\omega)^2/\Gamma_{CN}$ [28]. The quantities Γ_{CN} and $\Delta\omega$ have a different dependence on the angular momentum I and on the excitation energy above yrast U, so that the rotational damping width depends in a complex way on I and U.

In order to compare these theoretical expectations with data, Bent made a masterful use of the correlation technique, extending it to higher dimensions, considerably enhancing the sensitivity to rotational correlations [31]. An example is shown in Fig. 8. Each tilted rotational plane, defined by the equation

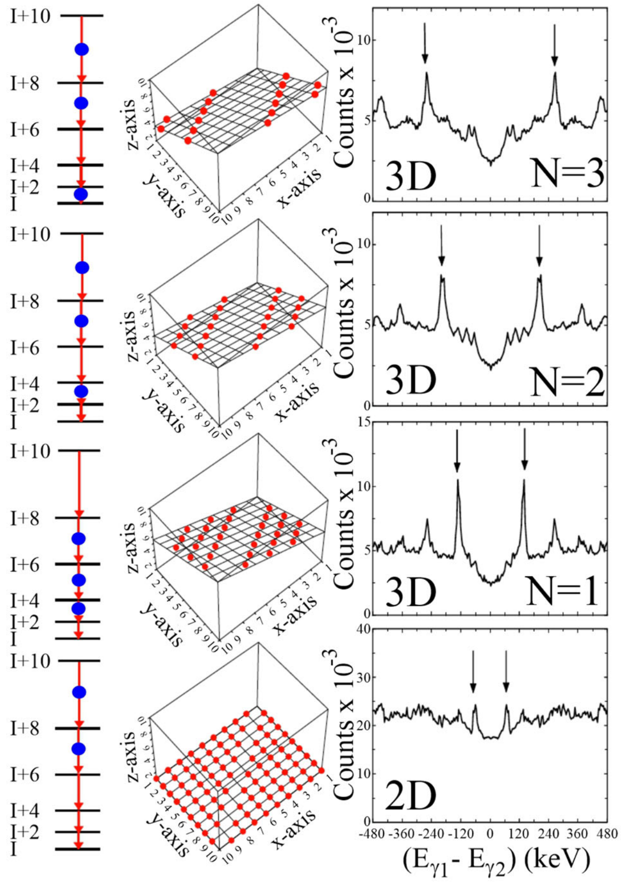

Fig. 8 The left part of the figure shows a schematic illustration of the rotational correlation patterns forming ridges in both the 2D (bottom) and 3D tilted rotational planes defined by Eq. (1), with N=1, 2 and 3. The coincidence combinations selected by the different planes are indicated by circles in the rotational cascades shown in the left hand side of the figure. The right part of the figure shows the corresponding perpendicular cuts taken at the average transition energy $E_\gamma = 900$ keV. Ridge structures are indicated by arrows. Adapted from [29]

$$E_{\gamma 1} - E_{\gamma 3} = N \times (E_{\gamma 3} - E_{\gamma 2}) \pm \delta/2 \qquad (1)$$

with N=1, 2, 3,..., selects different types of coincidences along rotational bands. For example, the N = 1 rotational plane contains only rotational structures corresponding to three consecutive γ-ray transitions in a regular cascade, the N = 2 plane the contributions from four consecutive transitions with the last but one missing, and so on. All planes are produced with a thickness δ of the order of 20 keV, corresponding to the dispersion in the second moment of inertia. This assures that all the rotational correlations satisfying Eq. (1) are included in one of the planes. The coincidences carrying rotational energy correlations form ridges in both 2D and 3D spectra. By cutting out slices of the 3D cube, centered at tilted rotational planes, the ridges are picked out and are much enhanced compared with those visible in the 2D

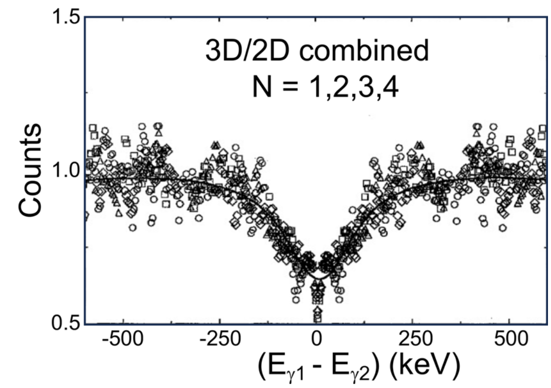

Fig. 9 Spectra of ^{163}Tm obtained dividing perpendicular cuts, 60 keV wide, taken on 3D tilted rotational planes with N=1,2,3,4 by the cut taken on the 2D spectrum at the average transition energy $(E_{\gamma 1} + E_{\gamma 2})/2 =$ 960 keV. The FWHM of the valley gives an experimental estimate of Γ_{rot}. From [30]

spectrum. The width of the central valley gives an indication of the value of Γ_{rot} (see Fig. 9).

A more precise determination of Γ_{rot} was made possible by detailed theoretical investigations of the damped rotational spectra, based on rotational bands obtained according to the cranking model and mixed by a residual interaction [33]. The calculations identified two components in the spectra produced by two consecutive transitions: a narrow one, whose width is related to Γ_{CN} as $\Gamma_{nar} = 2\Gamma_{CN}$, and a broader one, which is instead related to Γ_{rot} as $\Gamma_{wide} = \sqrt{2}\Gamma_{rot}$ [34] (see Fig. 10a)). The comparison of the line shape of experimental $\gamma - \gamma$ spectra with simulated spectra in the nuclei ^{163}Er and ^{168}Yb (see Fig. 10b) and d)) led to values of 200 keV for Γ_{rot} and of 20 keV for Γ_{CN} at $U \approx 2$ MeV in the spin region $I = 30 - 40\hbar$ (see Fig. 10c)) [32,35]. A parallel investigation was carried out by the Berkeley group (of which Bent Herskind was a "great collaborator at times, as well as a great competitor at other times" [36]) with different simulation codes, and led to comparable results. The analysis of $\gamma - \gamma$ spectra from the decay of excited superdeformed states in ^{194}Hg could instead be interpreted as an example of motional narrowing [37]. These spectra display very narrow ridges parallel to the diagonal, which account for most of the E2 strength coming from unresolved bands. Due to shell effects, the value of $\Delta\omega$ is predicted to be particularly small, so that theoretically one expects the condition for motional narrowing, $\Gamma_{CN} > 2\hbar\Delta\omega$ to be fulfilled for values of U larger than about 1.2 MeV, when the intrinsic states start to be mixed by the residual interaction. The fluctuation analysis described below confirmed that the ridges are indeed formed by a large number of rotational bands. The superdeformed quasicontinuum of the nucleus ^{194}Hg then appears as the realization of a chaotic system, in which collective properties are preserved [38]. The analysis of ^{194}Hg is a striking example of the insight provided by the studies of Bent and collabo-

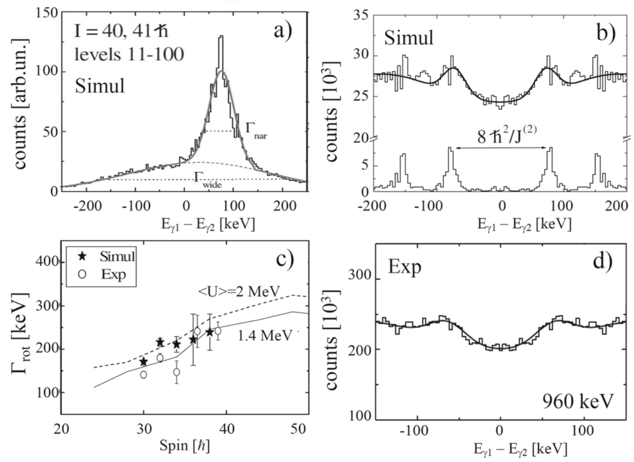

Fig. 10 **a** Projection on the $E_{\gamma 1} - E_{\gamma 2}$ axis of the strength function for two consecutive E2 γ-rays, obtained by microscopic cranked shell model calculations of ^{163}Er at spin I= $40\hbar$ and $41\hbar$, excluding the decay along the cold lowest-lying non-interacting bands. The simulated spectrum is well fitted by the full drawn line, which contains a wide and a narrow Gaussian distribution of width $\Gamma_{wide} = \sqrt{2}\Gamma_{rot}$ and $\Gamma_{nar} = 2\Gamma_{CN}$, respectively. **b** 60 keV wide projections on $E_{\gamma 1} - E_{\gamma 2}$ of simulated matrices of ^{163}Er, at the average transition energies $< E_\gamma >$ = 960 keV. The spectrum obtained from the cold non-interacting bands is shown on the bottom of the panel, while the spectrum obtained from interacting bands is shown on the top of the panel. The latter should be compared with the experimental spectrum shown in **d**. The interpolation of the damped spectra by the two-component distribution is given by the solid lines. **c** The experimental values of Γ_{rot} in ^{163}Er are shown by open circles. They are compared with the values deduced from damped simulated spectra (full stars), and with cranked shell model predictions at two different excitation energies [1.4 MeV (solid line) and 2 MeV (dashed line)]. Adapted from [32]

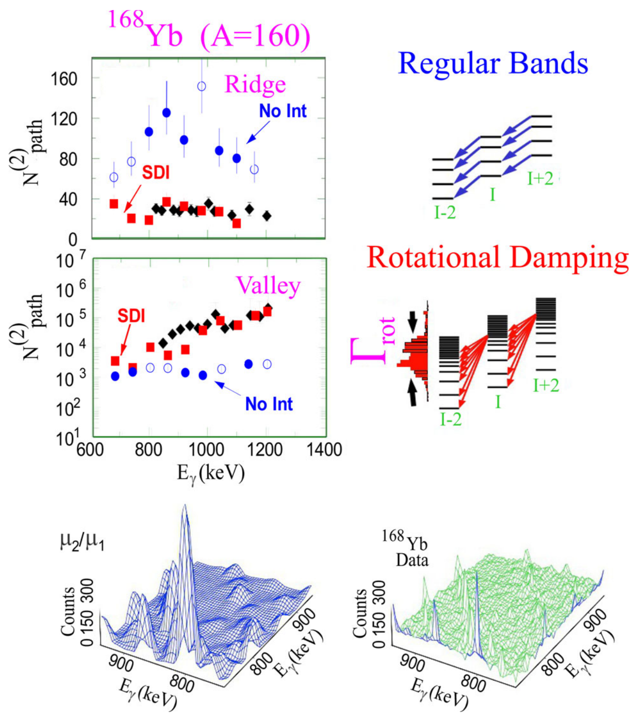

Fig. 11 Bottom panels: Examples of spectral distributions employed in the statistical analysis of γ-coincidence spectra, i.e., a γ-γ coincidence matrix (from the decay of ^{168}Yb, in green), and the corresponding second moment fluctuation spectrum μ_2/μ_1 (in blue). Top panels: Number of paths obtained by applying the fluctuation analysis to the experimental γ-γ coincidence spectrum (black diamonds), considering the ridge region, populated by regular discrete bands, and the valley, populated by damped transitions along interacting bands. Experimental data are compared with the results of simulations based on non-interacting bands (in blue) or on bands interacting by a surface $\delta-$interaction (labeled SDI, in red). Adapted from Refs. [24,48]

rators concerning the transition between order and chaos in warm rotating nuclei (see e.g. [33,39–41], and see [24,42,43] for more recent work). This represents a particular and valuable viewpoint on a vast topic of great interest in the field of nuclear physics (see e.g. [44,45] and refs. therein).

Bent and collaborators also introduced a new type of statistical analysis of quasi-continuum spectra. This was the study of the fluctuations in the number of counts, which depend on the finite number of paths available for the nucleus to decay, weighted by their population probability. This technique was mostly used by Bent and collaborators on data taken by ESSA30 and NORDBALL and required an elaborate treatment to remove the background associated with Compton scattering events [46]. The resulting fluctuation spectrum enhances the original ridge-valley features: strong fluctuations are observed along the ridges, revealing a limited number of discrete bands in the region close to yrast, whereas small fluctuations are found along the valley, pointing to the existence of a large number of bands in the warm regime of fragmented decay. After the contribution from known discrete bands was removed, the moments of the fluctuation spectrum were determined making use of a code developed at the NBI. These moments provide information both on the number of discrete bands not experimentally resolved, and on the large number of transitions available in the region of damped rotational motion. The comparison of fluctuations in experimental and simulated data provided information about the internal excitation energy threshold between the region of cold rotational bands and the region of damped rotational motion. To this purpose, detailed simulation codes of the γ-decay flow were devised [33,47,48]. They included the competition between statistical and collective transitions based on the theoretical calculations of interacting rotational bands. A result of this for ^{168}Yb is shown in Fig. 11. The theoretical results based on non-interacting bands greatly overestimate the number of paths measured in the ridges, while the opposite is true in the valley. Adopting instead a surface delta interaction with a reasonable coupling constant, the experimental data are well reproduced in both regions, showing the overall consistency of the model [48,49].

In conclusion, the seminal work carried out by Bent has led to major advances in the understanding of the physics of warm, rotating nuclei. This fascinating topic continues to pose significant challenges to nuclear spectroscopy. In particular, a complete description of the transition between order and chaos still remains to be accomplished, and a significant step forward in this direction could be made by performing complete γ-ray spectroscopy into the region of rotational damping. By pinning down the fragmentation of the gamma-decay strength as a function of spin, details of the two-body residual interaction and of many-body dynamics will be highlighted. This is expected to be within reach in various regions of mass, owing to the increased detection sensitivity of the new tracking arrays, AGATA and GRETA, and the advent of intense stable and radioactive beams.

3 Quest for Jacobi shapes

One of the many scientific curiosities of Bent Herskind was the shape evolution of rotating nuclei, including hot nuclei. At sufficiently high temperatures the quantum shell effects in atomic nuclei gradually decrease and eventually vanish. Therefore, with increasing spin, the deformation of a hot nucleus undergoes the centrifugal stretching: changing from spherical to a flat oblate shape, rotating, in classical terms, along the symmetry axis. With increasing rotation, the flatness increases, until at some limiting spin the fission of the nucleus occurs. In some cases, however, the shape evolution is expected to proceed in a different way: the deformation of the nucleus becomes oblate, but, at a certain critical spin, the nucleus abruptly assumes a triaxial shape, and at even larger spin values it becomes prolate with a large elongation, rotating perpendicular to the deformation axis. Such shape changes, referred to as Jacobi transitions, had originally been predicted for gravitating stellar bodies by C.G.J. Jacobi in the 19^{th} century [50].

Jacobi-type shape transitions have also been predicted to appear in atomic nuclei by theoretical models based on the Liquid Drop Model [51], especially the Lublin-Strasbourg Drop (LSD) model [52]. They should primarily be observed in light nuclei, where high values of the rotation frequencies are reached before the nucleus starts to fission. For example, for nuclei with A $\approx$ 46 the Jacobi transition is expected to occur above spin $28\hbar$, cf. Figure 12 showing the potential energy surfaces calculated for ^{46}Ti nucleus at different spins.[1] As can been seen in this figure, at spin $24\hbar$ a distinct minimum of the potential energy (indicated by a red cross) is visible. This minimum corresponds to an oblate ($\gamma = 60°$) shape with rather small deformation parameter $\beta = 0.3$. For I = 28, the minimum is still oblate, but more shallow and β increases to 0.4. For I = 30, the minimum rapidly becomes triaxial ($\gamma \approx 30°$) and is well elongated ($\beta = 0.6$), what is the sign for the occurrence of the Jacobi shape transition. And for I = 34 the minimum becomes almost prolate ($\gamma \approx 0°$) with very large elongation ($\beta \approx 0.9$).

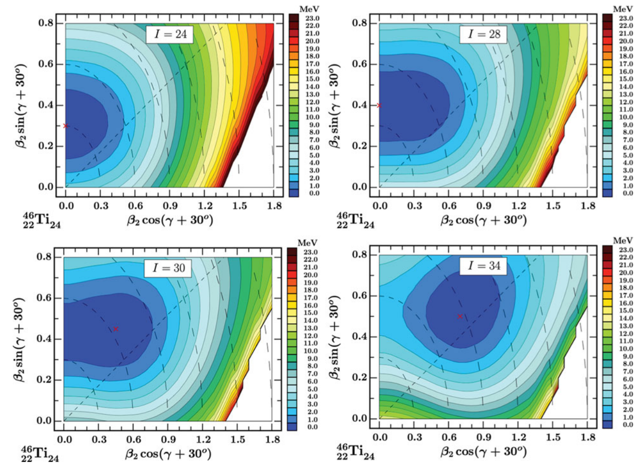

Fig. 12 Potential energy surfaces for ^{46}Ti at spins I = 24, 28, 30 and 34, calculated using the LSD model within an ensemble of 5-dimensional deformation spaces. The graphical representation corresponds to choosing as coordinates the two deformation variables β and γ. The total energies are minimised over the remaining higher order deformation parameters α_{40}, α_{60}, α_{80}

It was demonstrated over many years, that a good probe of the shapes of hot nuclei is the strength function of the Giant Dipole Resonance (GDR) [53]. This is because the GDR couples to the quadrupole degrees of freedom of these nuclei, and the frequencies of oscillations along major nuclear axes are inversely proportional to the lengths of them. Hence, the GDR strength function, being a single Lorentzian for a spherical nucleus, splits into two or more components when it becomes deformed. The size of the splitting (energy difference between the low and high energy component) can be a measure of the nuclear deformation. The top panel of Fig. 13 presents calculated [54] effective GDR strength functions in the spin region of the predicted Jacobi shape transition for the nucleus ^{46}Ti. As can be seen, the nuclear Jacobi shape can be exhibited by a GDR strength function with a distinct low energy component (around 10 MeV) and a bump on the high energy side ($\approx$ 25 MeV).

The first experimental indication of the existence of Jacobi shapes was the work of Kicińska-Habior and the group in Seattle [56] based on inclusive experiments, in which they studied the decay of ^{45}Sc nuclei formed in reactions at different projectile energies. They observed a broad hump around an energy of 25 MeV in the experimentally extracted GDR function, and an increase in the intensity of this hump with increasing beam energy (and thus with increasing average spin of the ^{45}Sc compound nucleus). This suggested the

[1] This figure was created using the Virtual Access facility MeanField4Exp (https://meanfield4exp.ifj.edu.pl) funded by the European Union's Horizon Europe Research and Innovation Program EURO-LABS under Grant Agreement No 101057511.

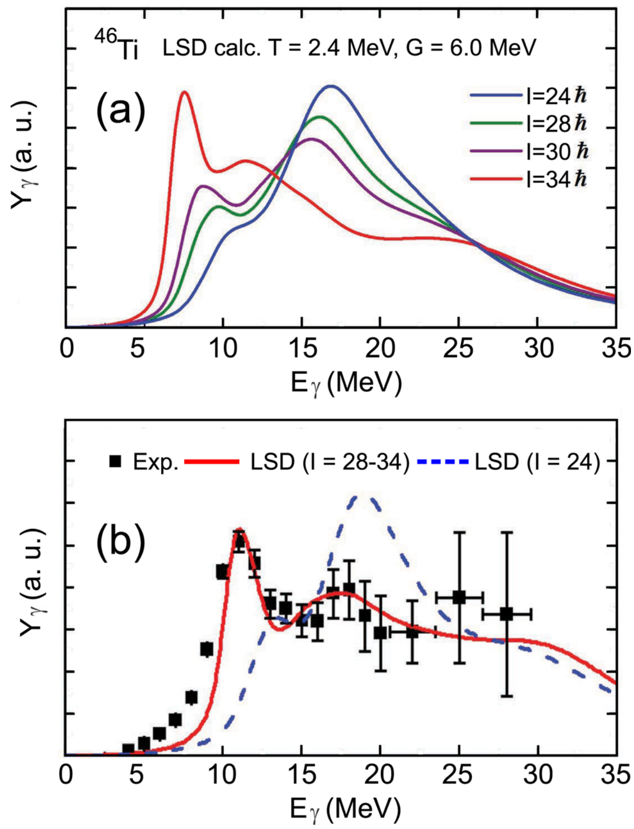

Fig. 13 **a** The calculated effective GDR strength functions at the temperature 2.4 MeV and 4 spins for the ^{46}Ti nucleus, averaged using the shape probability distributions corresponding to the potential energy surfaces from Fig. 12. **b** Experimentally extracted GDR strength function (black squares) with LSD model predictions for two spin regions: I = 24 (dashed blue line), where the equilibrium deformation is oblate; and I = 28–34 (solid red line), where triaxial deformation occurs. Adapted from [55]

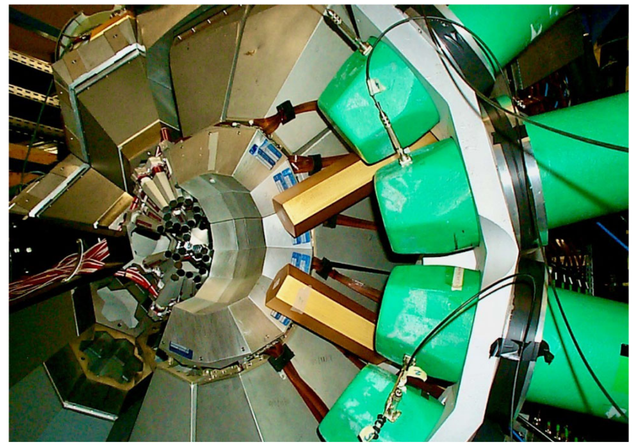

Fig. 14 The experimental setup at IReS Strasbourg in 2002. The aluminium cans house EUROBALL escape suppressed Germanium detectors and the BGO inner ball detectors. The green detectors are the large BaF_2 detectors from the HECTOR array, and the smaller gold detectors are the BaF_2 crystals from the HELENA multiplicity filter

existence of very large deformations of the decaying compound nucleus. However, they did not observe the distinct low energy component.

It was the idea, among others, of Bent, that in order to identify without any doubt the Jacobi shape transition, one should perform more exclusive experiments, in order to avoid potential background from non-fusion reactions. Following this idea, a series of exclusive experiments were performed on the γ decay of the ^{46}Ti compound nucleus, using the HECTOR array [57] for high energy γ rays developed within the Copenhagen-Milano-Krakow collaboration. In the first experiments, at NBITAL Risø, the spin selection was based on filters applied to the γ multiplicity measurements in the HELENA array [57]. Later, at IReS (presently IPHC) Strasbourg, addition experimental refinements took place, in which for the first time it was used the combination of high-resolution ball of Ge detectors EUROBALL [9], the BGO inner ball of EUROBALL merged with the HELENA BaF_2 detectors, both acting as the efficient γ multiplicity filter, and the high-efficiency detector system for high-energy γ-rays HECTOR. This allowed filters to be placed on discrete transitions associated with a specific final nucleus, select the high-spin events and under such condition to measure the high-energy γ-rays from the GDR decay (see Fig. 14).

These exclusive experiments, in which both gating on high γ multiplicity events and discrete transitions in the residual nuclei of interest were used, resulted in the first clean evidence for the existence of the Jacobi shape transition in atomic nuclei [55]. The low-energy (at $\sim$10 MeV) component of the GDR strength function extracted from the measured high-energy gamma-ray spectrum function, is clearly present for data corresponding to higher spins (I $\geq$ 30), see bottom panel of Fig. 13. The experimental results are also satisfactorily reproduced by the LSD model calculations. Soon after these pioneering studies, further evidence was provided by a group from India for other light nuclei: ^{47}V [58], ^{31}P [59] and ^{43}Sc [60].

Another interesting outcome of these experiments was the world-first observation of a preferential feeding of the highly deformed states in a cold residual nucleus ^{42}Ca by the low-energy component of the GDR decaying from the hot ^{46}Ti possessing a Jacobi shape [61]. Such an effect of GDR gamma-decay on the population of the SD bands was postulated by Bent already in 1987 in the paper analysing the SD band in ^{152}Dy [62]. However the experimental evidence for such an effect had been, until this experiment, very scarce and contradicting. E.g. for ^{149}Gd no enhancement, but rather diminishing of the SD band intensity, when gating on

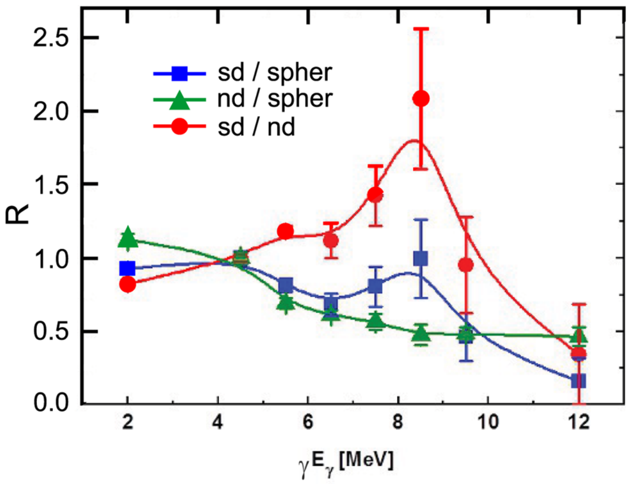

Fig. 15 Ratio of the γ-transition intensities in super-deformed (sd), normally deformed (nd) and spherical (spher) bands in ^{42}Ca, as a function of the high-energy photon from the GDR decay of ^{46}Ti. Adapted from [61]

high-energy γ-rays, was observed [63]. Contrary, for ^{143}Eu it is found that the population of the superdeformed states is enhanced by a factor of ca. 1.6 when a coincidence with a γ-ray with energy $\geq$ 6 MeV is required, in reasonable agreement with the increase of the line shape of the GDR built on a superdeformed configuration [64]. In the experiment presented here the intensities of selected transitions belonging to the sequences of transitions in bands of different deformations in ^{42}Ca were measured, in coincidence with different energy bins in the spectrum of high-energy gamma rays. It turned out (see Fig. 15) that the ratio of the transition intensities in the super-deformed band to the normally deformed band were particularly large, when gated by the high-energy quanta around 8.5 MeV (which after the detector's response correction corresponds to 10 MeV, where the low-energy GDR component of the Jacobi shape is located). This means that the low-energy GDR component feeds more preferentially the super-deformed band over other bands. Such an effect, observed clearly for the first time, suggests that the extreme Jacobi deformation of the hot ^{46}Ti nucleus survived and was preserved over the whole decay process down to the cold super-deformed structures in ^{42}Ca, confirming Bent Herskind's hypothesis [62].

It was also Bent Herskind, who immediately realised, that such a process utilising the low-energy GDR component of the Jacobi shapes and its preferential feeding mechanism, might be a gateway to select extreme shapes of cold rotating nuclei, and may be a useful technique in the quest to find predicted hyper deformed nuclei. This brilliant idea led to a series of proposals and experiments prepared by Bent and collaborators (see e.g. [65,66] and references therein) for the search of nuclear hyper-deformation (cf. Sect. 4).

4 Exploring the extremes of nuclear deformation

One of the most tantalising predictions of nuclear structure models is the existence of extreme nuclear deformations, or so-called "hyperdeformed" (HD) states [67–71]. One of the regions, where these highly elongated ellipsoids with axis ratios close to 3:1, are predicted to manifest themselves, is at very high spin where they become the yrast structures at around 80 $\hbar$ of angular momentum (see Fig. 16). These potential energy minima caused by shell effects are predicted to be stable or quasi-stable over a range of at least 10 $\hbar$ or more in spin. At such extremes, the nucleus will be close to the fission limit, where the barrier height against fission drops to zero. The phenomenon of hyperdeformation is hence constrained by the amount of angular momentum atomic nuclei can support [72], which is predicted to vary strongly with nuclear mass in rare-earth nuclei (mass A = 130 to 160).

The experimental signature of a stable or quasi-stable, highly rotating, hyperdeformed nucleus is expected to be similar to that of superdeformed nuclei, manifesting itself as sequences of regularly-spaced rotational E2 transitions corresponding to a dynamical moment of inertia as high as 100–130$\hbar^2$/MeV, corresponding to transition spacings of 30–40 keV. These sequences could either be detected as a discrete rotational band, or a continuum of rotational bands with very similar moments of inertia. The former would produce a gamma-ray coincidence spectrum of regularly-spaced peaks, while the latter would give rise to characteristic diagonal ridge structures in the corresponding gamma-ray coincidence matrices.

Optimal experimental conditions for populating HD states are thought to consist of (i) searching in the rare-earth region where it was predicted that nuclei might be populated at the highest angular momenta without undergoing fission [72], (ii) symmetric reactions, which were observed previously to significantly enhance the population of superdeformed states [74] and (iii) to study reaction channels that also emit a charged particle (proton or alpha), which might be enhanced at extreme deformations due to the lowering of the Coulomb barrier at the tips of such an elongated shape.

Experimental results on hyperdeformed states have a rather colourful history. The first evidence suggesting the possible observation of a HD band in ^{152,153}Dy populated via *pxn* channels, was published in 1993 by the Chalk River group [75]. However, there was a certain degree of caution concerning the results, including from the authors themselves, partly since these were obtained using the 8π spectrometer from the 2nd generation of arrays. First searches using the EUROGAM, 3rd generation spectrometer, in ^{167,168}Yb nuclei, which were first predicted to exhibit HD minima by complementary theoretical approaches [67,68], yielded no results [76]. Subsequently, the discovery of a HD band in ^{147}Gd using the GAMMASPHERE spectrom-

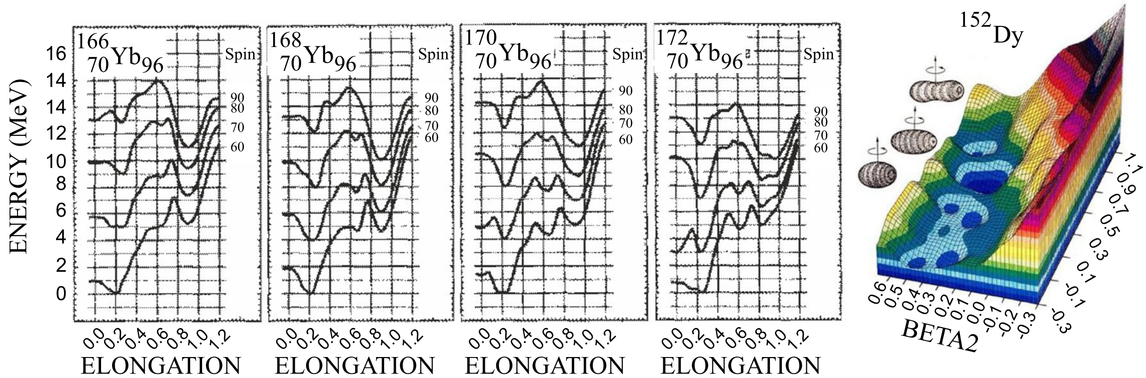

Fig. 16 (Left) Predictions of hyperdeformed minima in the nuclear potential energy at different angular momenta in Yb nuclei. Adapted from [67]. (Right) Representation of the nuclear potential energy as a function of quadrupole deformation parameters β_2 and triaxality γ for the ^{152}Dy nucleus at 80$\hbar$ showing the coexistence of normally deformed, superdeformed and hyperdeformed minima [73]. The left axis is parallel to the $\gamma = 60°$ line and the right axis to the $\gamma = -30°$ line

eter [73] coupled to the microball charged particle detector was announced [77]. However, a follow-up higher-statistics experiment by the same authors could not reproduce the original result, suggesting that the initial observation was not a HD band structure, but was rather a statistical anomaly arising from the elaborate background subtraction procedures [78]. A repeat of the ^{167,168}Yb searches using the full GAMMASPHERE array yielded useful information on the achievable sensitivity of HD searches, but alas no evidence of hyperdeformation was observed [79]. Subsequently, a repeat of the original Chalk River experiment with the GASP [80,81] array at Legnaro could not reproduce the original Chalk River band structure. However, the ridge structures in coincidence with protons were still seen, but assigned to ^{152}Dy [82,83]. In a follow-up experiment with the more powerful EUROBALL III array the previously observed ridges could barely be seen despite the higher statistics [84].

Bent was clearly fascinated by the possibility of discovering and studying HD states. However, before starting an experimental campaign some important preparatory work was performed by the NBI and Bonn groups at the 8π spectrometer, based in the late 1990's, at the 88" cyclotron in Berkeley [85,86]. Here, the symmetric reactions ^{64}Ni+^{64}Ni, ^{74}Ge+^{76}Ge and ^{74}Ge+^{94}Zr were studied at different beam energies to measure precisely the gamma-ray multiplicity and sum-energy distributions of the nuclei produced. This allowed an experimental determination of the amount of angular momentum that these nuclei could support, confronting the theoretical predictions for the first time and allowing selection of the optimal conditions for success.

Following these studies, the Hyper-long hyperdeformed (HLHD) experiment was performed using the EUROBALL IV spectrometer and the DIAMANT [87] charged particle detector, based in IReS Strasbourg in 2002, where Bent led an international collaboration of 76 scientists. The ^{64}Ni + ^{64}Ni $\rightarrow$ ^{128}Ba* fusion reaction was chosen at beam energies of 255 and 261 MeV to reach the highest angular momentum states with ^{64}Ni beams produced by the Vivitron accelerator. The experiment ran for 4 weeks producing a high-fold γ-ray coincidence data set of unprecedented size.

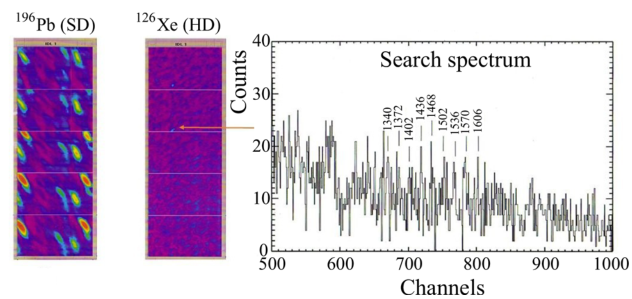

Fig. 17 Visual representation of the statistical significance of candidate bands in the band search space for multiple known superdeformed (SD) bands in ^{196}Pb on the left and HD candidates in ^{126}Xe produced in the ^{48}Ca + ^{82}Se reaction studied with EUROBALL in 2001 on the right. The multiple-gated strongest discrete HD candidate corresponding to the zone of highest statistical significance in the search space (2.3σ) is shown on the far right of this figure

Around the same time, experiments were also carried out at Argonne National Laboratory with the Gammasphere array to search for hyperdeformation in Xe nuclei with the ^{82}Se(^{48}Ca,xn) reaction [88]. This reaction was also used later to search for hyperdeformation with EUROBALL VI, but without success [88].

The data analysis techniques developed and employed by Bent and his group were, and still are, state-of-the-art. The search for discrete rotational structures could be carried out in 3D or 4D coincidence spaces with a full visualisation of the search space, allowing selection of the multiple-gated spectra of interest (see figure 17). The enhancement of either reaction channels or rotational structures themselves could

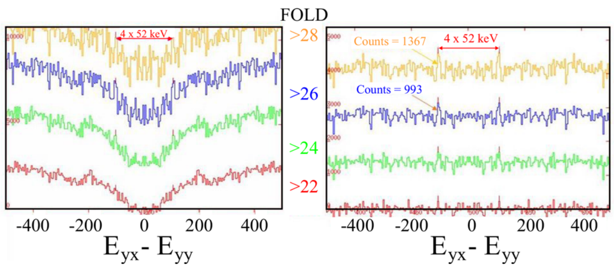

Fig. 18 Ridge spectra as a function of event fold, produced from Bent Herskind's analysis of the rotational planes in the HLHD data set selecting the 2n channel through filtering [89] and charged-particle veto. The right panel shows the difference between the 261 MeV and 255 MeV data for perpendicular cuts to the diagonal at an energy of 1440 keV and width of 102 keV. From [65]

be performed using filtering techniques that abandoned the concept of an analysis "fold", but rather sought to classify which counts to increment in the spectrum according to a figure of merit determined from all the other gamma-rays in the event [89].

Bent pioneered and employed the analysis of the rotational planes in 3D coincident gamma data structures to search for hyperdeformed ridge structures. The ridge pattern when staring down the long diagonal of such a cube would manifest themselves as equidistant tubes with a six-fold "snow-flake" symmetry. When projected cleanly into 2 or 1 dimensions, these would be reduced to the more well-known ridges or DeltaE peak structures (see Fig. 18). The full results of Bent's tour-de-force analysis of this data set can be found in Ref. [65]. The suggestion is that exit channels involving charged particles do indeed provide the best evidence so far of the existence of hyperdeformation.

Although these strong hints of HD structures can be seen in the HLHD data, the signal is not yet sufficiently clear to have the highest degree of confidence. Indeed, it would be fair to say that definitive evidence for the existence of hyperdeformation at very high spin still remains elusive to the present day. Nonetheless, the pioneering approaches and the analysis techniques developed by Bent Herskind will surely

Fig. 19 A photo collage as a tribute to Bent Herskind

prove invaluable when at some point this fascinating topic is revisited using the powerful tracking arrays that will soon come online in their 4π configurations [90].

To summarise from what has been learned, a list of important ingredients for future experimentation on this topic to ensure optimal chances of success, includes: (i) More powerful instrumentation, i.e. the next generation of 4π tracking arrays AGATA and GRETA. (ii) A recoil filter detector [91] that will give the ability to veto fission events by detecting the nuclear recoil from the fusion reaction. (iii) A detector of light charged particles. (iv) Full use of γ-ray calorimetry to select the highest-fold events. (v) Massive data sets acquired at stable beam accelerator facilities which have the necessary beam intensities ($> 10^{11}$ pps). (vi) New and innovative analysis techniques which are essential to fully exploit the rich and complex correlations contained in the high-fold data. The last point, in particular, is an area where Bent made a very significant contribution and was years ahead of his time.

5 Epilogue

Bent officially retired in January 2002 and a celebration workshop at the NBI was held the month before, see centre picture in Fig. 19, but he continued to be extremely active, contributing greatly to the field in both science output and detector developments. In fact, Bent's final email message to his cherished friend, Jerzy Dudek, just a few days before he passed away, gives us further insight into the great man. The note reads:

"Dear Jerzy, Thanks for your last news, even in these difficult days, which have been reasonably OK for me, I will be soon 90 in December, probably. I do not walk well, but avoided COVID-19 and got full vaccination in April. I worked home ca 4–5 h/day until 2 month ago, when I realised that my intensive Data sets from 1998–2005 was finally analysed my way. All the best to you and your impressive work, which I often see on ACADEMIA from USA, Bent."

In this contribution some of the major physics contributions of Bent Herskind have been outlined. What cannot be captured in the written word is the infectious enthusiasm that was always at the heart/nuclear core of any interaction or collaboration with Bent. He was uniquely brilliant in everything he touched and his joy of physics discovery is something we will all remember and cherish forever. He is gone, but his impact and his "Copenhagen" way of doing science will never be forgotten. Thank you dear friend for enriching all our lives. You will live forever in our hearts and minds!

Acknowledgements The authors would like to sincerely thank all our friends and co-collaborators with Bent through the decades, who were involved in collecting and interpreting the data discussed within the present article. It has been and continues to be, as we carry Bent's indomitable spirit forward, a lot of fun! This work has been supported by the State of Florida and by grants from the UK Science and Technology Facilities Council.

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