Superdeformed quasicontinuum feeding of the superdeformed yrast band in ^{132}Ce

F. Farget,* D. Santos, M. Asghar, C. Foin, J. Genevey, A. Gizon, J. Gizon, and J. A. Pinston
Institut des Sciences Nucléaires, IN2P3-CNRS, Université Joseph Fourier, F-38026 Grenoble, France

C. W. Beausang, A. J. Boston, S. A. Forbes, D. T. Joss, P. J. Nolan, E. S. Paul, A. T. Semple, and J. N. Wilson
Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 3BX, United Kingdom

R. M. Clark, K. Hauschild, N. J. O'Brien, C. Parry, and R. Wadsworth
Department of Physics, University of York, Heslington, York Y01 5DD, United Kingdom

J. Simpson
CCLRC, Daresbury Laboratory, Daresbury WA4 4AD, United Kingdom

B. M. Nyako and L. Zolnai
Institute of Nuclear Research, H-4001 Debrecen, Hungary
(Received 5 January 1998)

A superdeformed (SD) quasicontinuum in ^{132}Ce is experimentally characterized from rotational ridges in γ-γ correlation matrices. Evidence for a partial feeding of the SD yrast rotational band through highly deformed states is given. The evolution of the rotational transition strength as a function of the angular frequency is shown. A weak rotational damping is inferred. [S0556-2813(98)02207-9]

PACS number(s): 21.10.Re, 21.10.Ma, 21.60.Ev, 23.20.Lv

The superdeformed (SD) bands observed in nuclei of $A\sim130$ mass region present particular features, as they are associated with a less deformed shape of the nucleus ($\beta\simeq0.4$) and they are populated over a larger spin range leading to a higher total intensity than observed in the other mass regions. In this region of mass, the ^{132}Ce plays an important role as a reference for the other nuclei in the neighborhood. Indeed, it is in this particular nucleus that has been observed for the first time a SD band [1] and more recently the first excited SD bands in this mass region [2]. Furthermore the SD cerium nuclei seem to have a different behavior than the SD neodinium nuclei concerning the deexcitation of the SD band, being closer to that found in the $A\sim150$ and $A\sim190$ mass regions, showing a huge fragmentation in the decay out process.

Although the observation of a rotational SD quasicontinuum in the $A\sim150$ mass region has preceded the observation of the discrete SD rotational bands [3], most of the experimental results concern the discrete SD bands. The study of the nondiscrete SD excited states allows us to learn about the highly collective excitations of a fermionic system at nonzero temperature, where rotational transition strength becomes fragmented due to the residual interaction which mixes close-lying states, leading to a damping of the rotational motion. The rotational dynamics of a warm nucleus with a high density of states may be described by three different contributions, all of them depending on the excitation energy (U): (i) the damping width of the excited states (Γ_μ), related to their half-lives ($\tau\simeq\hbar/\Gamma_\mu$), (ii) the dispersion in the angular frequency $\Delta(\hbar\omega)$, mainly due to the dispersion in the contribution to the alignment of single particles, (iii) the residual interaction (V) between single particle states, of which the strength depends on the mean separation of states [4]. One defines, as a collective yield, the rotational damping width $[\Gamma_{\rm rot}(I)]$ as the dispersion of the rotational strength at the angular momentum (I) over different rotational partners at angular momentum ($I-2$). A review of this problem in which the quasicontinuum spectrum has been analyzed by statistical fluctuation methods for normally deformed and SD nuclei can be found in Ref. [5]. Specifically in the second minimum of the potential well, important contributions to the quasicontinuum features have been made in the $A\sim150$ [6–8] and in the $A\sim190$ [9] mass regions. In this paper we try to illustrate the main trends of this complex phenomenon, by a simple treatment of the data, showing the effect of a strong deformation at very high angular momentum on the γ-decay flow process of the SD rotational quasicontinuum in ^{132}Ce and its linking with the discrete superdeformed yrast band, in a region of mass still unexplored on this point. The experiments were performed with the gamma array of second generation EUROGAM in its two versions, phase I (42 Compton-suppressed large volume Ge detectors) and phase II (30 phase I type detectors plus 24 Compton-suppressed clover Ge detectors) [10], at the Nuclear Structure Facility at Daresbury and at the Centre de Recherches Nucléaires at Strasbourg, respectively. In both experiments, the nucleus ^{132}Ce was produced in the ^{100}Mo(^{36}S, $4n$) reaction, with a 155 MeV ^{36}S beam impinging on a self-supporting ^{100}Mo thin target of 615 μg/cm^2. The qualitative difference between the first and second generation of γ arrays resides in the possibility to get high fold ($f\geqslant3$) Compton-suppressed γ coincidences. In the first experiment, a total of 7×10^8 events with suppressed fold $\geqslant3$ were collected, while in the phase II experiment 10^9 events with a suppressed fold $\geqslant5$ were obtained for the same time of measurement.

*Present address: GSI, Planckstraße 1, D-64291 Darmstadt, Germany.

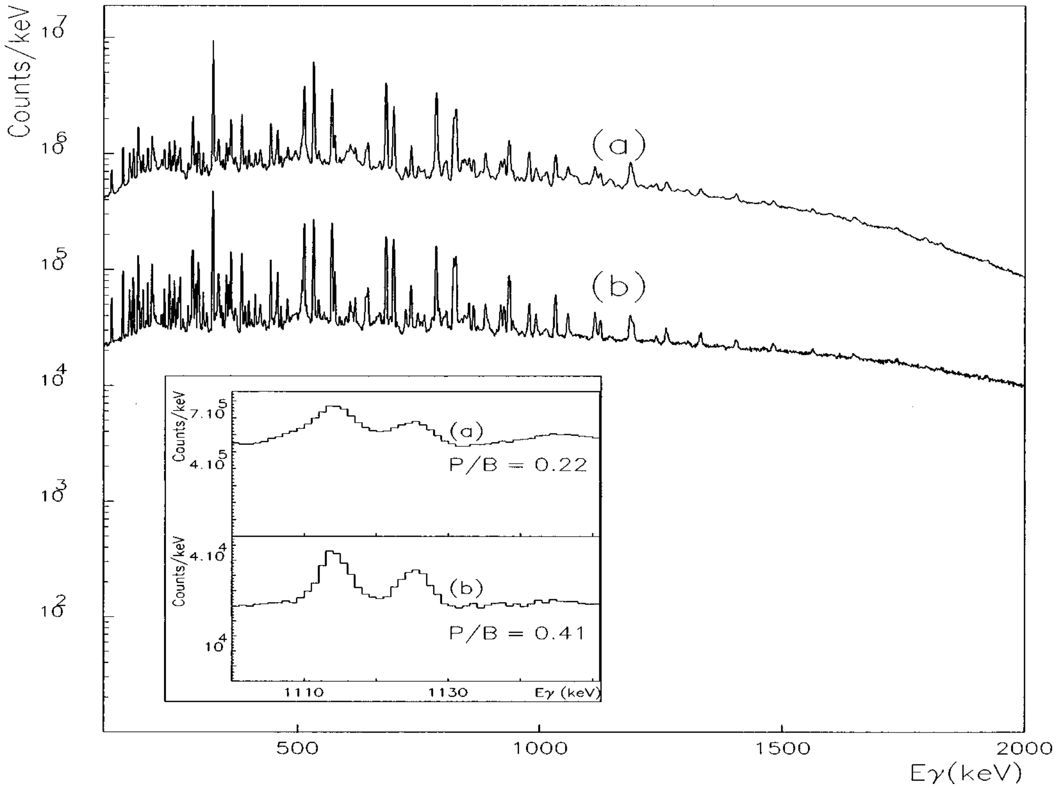

FIG. 1. Projection from 100 to 2000 keV of the matrix twofold conditioned by the yrast SD band of ^{132}Ce (a) compared to (b) the projection of the same matrix with the background removed by the local method (see text). In inset is compared parts of these projections around a SD photopeak energy 1125 keV. It is shown that the method proposed in this work improves the peak/background ratio from 0.22 to 0.41 at this γ energy.

To determine the rotational character of the quasicontinuum transitions coming from the deexcitation of the evaporation residue, the γ-γ correlation matrices and the angular distribution have been analyzed. Indeed, in two-dimensional matrices, discrete transitions between rotational states give rise to a regular grid of photopeaks, whereas quasicontinuum transitions form ridges parallel to the main diagonal [11], of which the valley in between is characteristic of the effective moment of inertia of the nucleus. A method [12] was developed to enhance the rotational ridges in the γ-γ correlation matrices, which allows to see the structure of ridges up to high order (fourth and fifth) in the projection on the perpendicular to the main diagonal of the matrix. This method is a generalization of the widely used ''Copenhagen method'' [13], treating the matrix in a local way by defining for each of its points a square neighborhood sufficiently large to have a good reference of the local background but small enough to avoid in the same square the presence of the other photopeak coincidences coming from the same rotational band. The side length of the neighborhood is chosen by optimizing the peak-to-background ratio in the total projection. In the particular case described here, the side of the neighborhood was 50 channels (1 keV/channel). The projection on the resulting matrix is compared to the projection of the raw matrix on Fig. 1. The peak to background ratio is improved by a factor of 2, and a clearer ridge structure appears. As the method is not well adapted to preserve all the quasicontinuum spectrum, it is not possible to compare quantitatively total intensities between discrete and quasicontinuum contributions in one matrix, but the qualitative evolution of the ridges as a function of the angular frequency may be analyzed.

In this purpose, the projections perpendicular to the main diagonal of a matrix twofold conditioned by the SD-yrast band for an average rotational frequency $\hbar\omega = 0.65$, 0.75, and 0.85 MeV have been built and are shown in Fig. 2. These projections correspond to different but overlapping γ energy slices of 400 keV width, ranging from 1.1 to 1.9 MeV. The ridges shown in Fig. 2(b) are the result of a sum of slices set on the SD discrete transitions observed in the respective 400 keV energy intervals. The ridges shown in Fig. 2(a) are the sum of the slices set in between all the ND and SD known discrete transitions. To be certain that no contribution to the ridges arises from any unknown discrete transition, the matrix was sliced perpendicularly to the main diagonal from 1.1 to 1.9 MeV, into cuts of 20 keV width. Any cut that showed a photopeak was rejected from the sum.

The fifth order ridge observed in Fig. 2(b) for the lower rotational frequencies, reflects the large number (19) of transitions constituting the yrast SD band, and thus the high probability to observe coincidences between nonconsecutive transitions. In Table I the intensity ratios between the high order ridges and the first order ridge are shown, for both types of ridges (discrete and quasicontinuum). The intensity ratio of 0.9 between the second and the first ridge of discrete transitions is correlated to the high intraband multiplicity of the events associated with the SD yrast band. The ridge pattern formed by the quasicontinuum transitions is shown in Fig. 2(a). Ridges are observed up to the third order for the average rotational frequency $\hbar\omega =$ 0.65 MeV. This shows

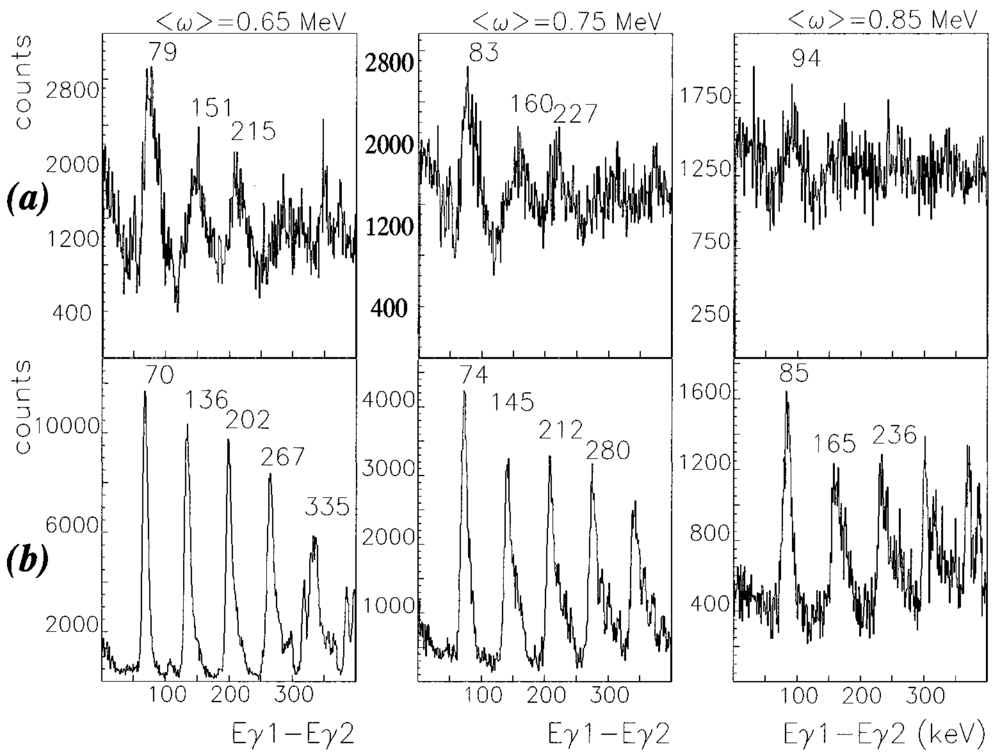

FIG. 2. Evolution of rotational ridges of the matrix twofold conditioned by the yrast SD band of ^{132}Ce as a function of the rotational frequency. (a) Projections of slices perpendicular to the main diagonal set in between all SD transitions and normal transitions known. (b) Projections of slices perpendicular to the main diagonal set on discrete SD transitions. The average rotational energy is taken to be half of the average γ energy corresponding to each slice, following the cranking approximation.

that the associated quasicontinuum rotational bands present a smaller number of transitions, but sufficiently high to show a third order ridge. This is consistent with the wide range of spin over which the SD yrast band is fed ($\sim 26\hbar$) [2] as is shown in inset of Fig. 3. The rotational quasicontinuum provides thus a long γ cascade and therefore the observation of high multiplicity events. Indeed, the intensity ratio of 0.6 of the second order ridge relative to the first order one (see Table I) is important compared to other observed values [14]. However, this ratio is lower than the value observed for the SD yrast band. This relative change in the intensity ratio between the first and the second order ridge is related to the higher excitation energy of the quasicontinuum states.

TABLE I. n is the order of the ridge, ΔE is the position of the nth ridge in keV, FWHM its full width at half maximum, and R_n is the ratio of intensity between the nth ridge and the first one. They are displayed for both types of transitions (discrete and quasicontinuum) as well as the associated average of the effective moment of inertia.

	$1.1<E_\gamma<1.5$				$1.3<E_\gamma<1.7$			$1.5<E_\gamma<1.9$		
n	1	2	3	4	1	2	3	1	2	3
Discrete										
$\langle J_{\rm eff}\rangle$	$57.1\hbar^2$ MeV^{-1}				$54.1\hbar^2$ MeV^{-1}			$47.1\hbar^2$ MeV^{-1}		
ΔE (keV)	70	136	202	267	74	145	212	85	165	236
FWHM (keV)	10	10	10	11	12	14	13	15	17	15
R_n	1.0	0.9	0.9	0.8	1.0	0.9	0.8	1.0	0.9	0.6
Continuum										
$\langle J_{\rm eff}\rangle$	$50.1\hbar^2$ MeV^{-1}				$48.2\hbar^2$ MeV^{-1}			$42.6\hbar^2$ MeV^{-1}		
ΔE (keV)	79	151	215		83	160	227	94		
FWHM (keV)	26	30	35		30	34	35	40		
R_n	1.0	0.6	0.4		1.0	0.6	0.5	1.0		

The presence of quasicontinuum SD ridges in the γ-γ matrix strongly correlated to the SD yrast band provides the evidence of a partial feeding of the discrete SD states by a rotational quasicontinuum. These transitions are shown in Fig. 3. This spectrum was obtained with the unfolded substraction [15] taking into account the response function of EUROGAM I to substract the Compton background.

The rotational character of these quasicontinuum transitions may be stressed by the analysis of angular distribution of γ rays. As the EUROGAM I multidetector is composed of six rings of detectors placed at angles 72, 94, 108, 126, and 158 degrees with respect to the beam direction, spectra threefold and twofold conditioned by the superdeformed yrast band of ^{132}Ce have been built for each ring. The resulting twofold conditioned spectra have been substracted to the corresponding threefold conditioned ones. The substraction factor was determined according to the ratio between statistical tails of both type of spectra in the ring placed at the angle 94°. As a result, for each angle a spectrum similar to the one of Fig. 3 is observed, showing a bump of quasicontinuum transitions in coincidence with the SD band. The intensity of this continuum was then measured for each angle. The resulting angular distribution is shown on Fig. 4, in comparison with the angular distribution resulting from the same

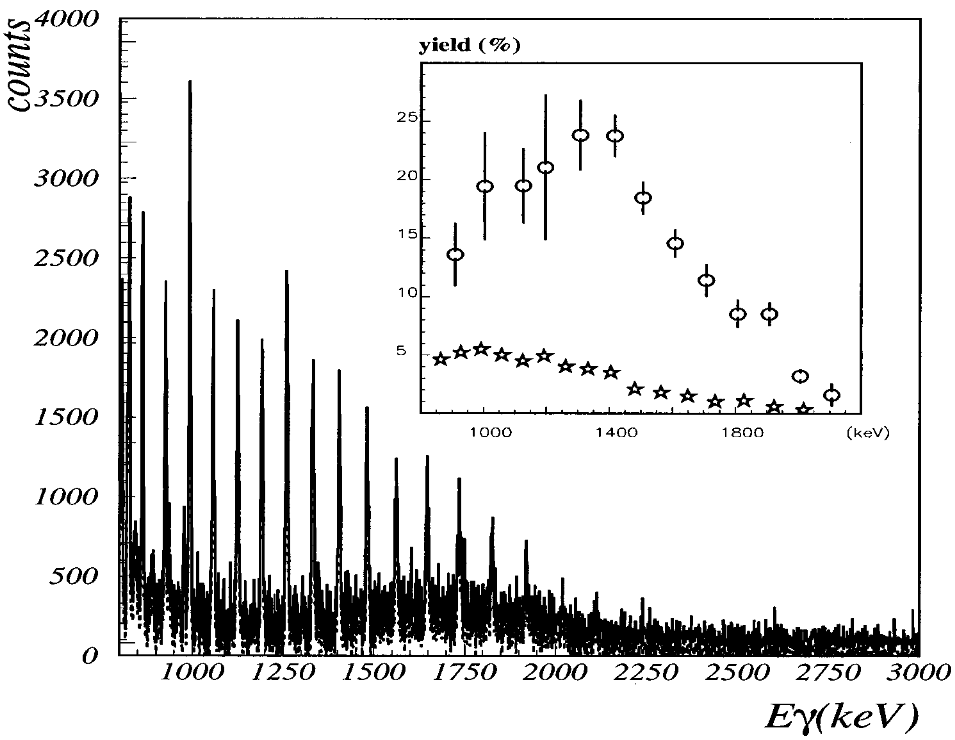

FIG. 3. Spectrum threefold conditioned by the yrast superdeformed band of ^{132}Ce. The substracted background was a twofold conditioned spectrum by the same transitions. Both spectra were normalized with respect to their statistical tails, i.e., $E_{\gamma}>2.2$ MeV. The inset shows the intensity of the superdeformed continuum (open circles) in the $4n$ channel, as a percentage of the total yield intensity. It is compared to the intensity of the yrast superdeformed band (stars). Error bars take into account statistical and background substraction fluctuations.

spectra, for the $2^+ \rightarrow 0^+$ stretched quadrupolar transition. The asymmetry parameters resulting of the fit from the data show that the main component of these transitions is of stretched quadrupolar character.

To estimate the percentage of this particular feeding with respect to the entire SD quasicontinuum in the $4n$ channel, the intensities of the quasicontinuum first order ridges defined by 70 keV$<\Delta E_{\gamma}<$90 keV in two different matrices have been compared: one of them conditioned by the $4n$ channel and requiring at least two transitions deexciting the normally deformed (ND) yrast states and the other strongly correlated to the SD yrast transitions as explained above. The intensity of the quasicontinuum in the $4n$ channel picked up in this way is displayed and compared to the intensity of the SD yrast band in the inset of Fig. 3. After normalization of the total statistics in both matrices relative to the intensity of the $2^+ \rightarrow 0^+$ transition observed in each matrix, the intensity ratio between the two ridges for γ energies ranging from 1.1 to 1.9 MeV is estimated to be 30%. This result indicates that a minimum value of at least 30% of the total rotational quasicontinuum is decaying toward the SD yrast band in this range of γ energies.

This particular feeding by a SD quasicontinuum reveals the existence of links between the quasicontinuum structure and the SD yrast one. These linking transitions may be produced by a gradual approach of both structures. This gradual approach would trigger at an angular momentum $I_c(U)$, a function of the intrinsic excitation energy (U), the transitions

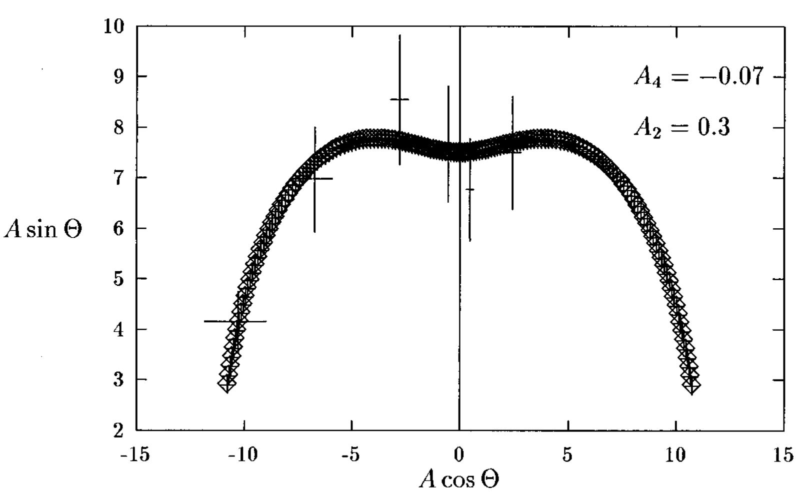

FIG. 4. Angular distribution in polar coordinates of the quasicontinuum in coincidence with the superdeformed yrast band of ^{132}Ce (crosses). The given asymmetry parameters are extracted from the fit of experimental points (diamonds).

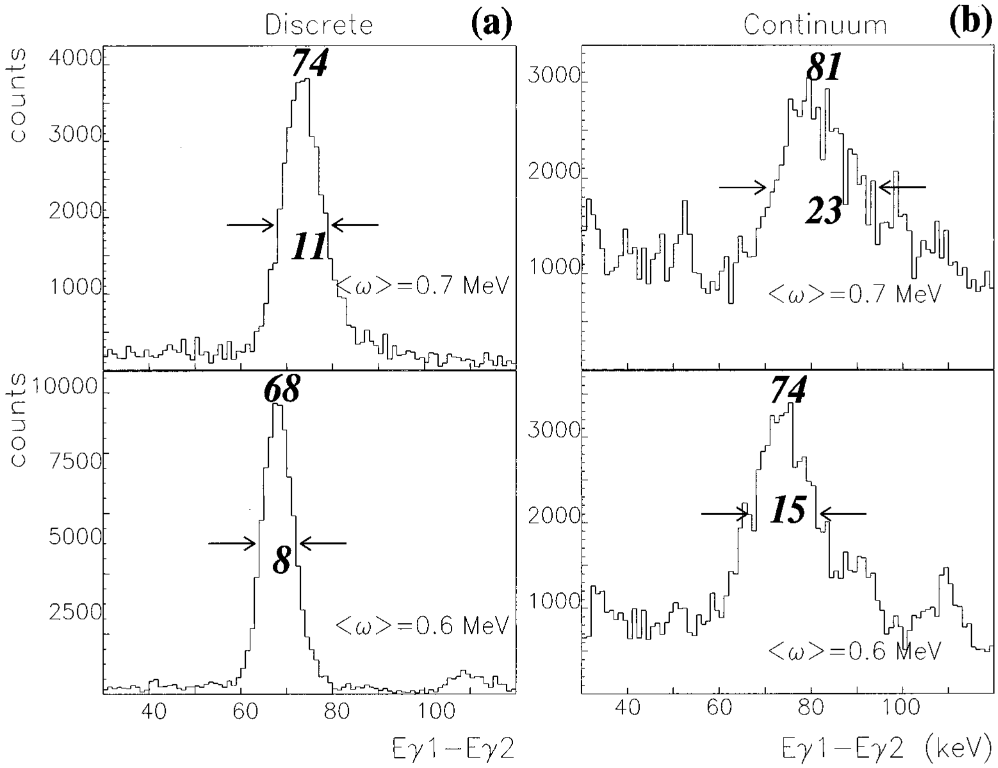

FIG. 5. Evolution of the first order ridge coming from (a) the discrete and (b) the quasicontinuum bands as a function of the rotational frequency. Centroids and FWHM of ridges are indicated on the figure in keV units.

linking the highly deformed quasicontinuum to the discrete SD states via a selective mechanism in which the similar deformed wave functions interact in a region of high density states.

The position of the first order ridges ΔE_γ is related to the effective moment of inertia by the relation $J_{\rm eff}=4/\Delta E_\gamma$. This effective moment of inertia is an average of the dynamical moment of inertia $J^{(2)}$ that gives a local information about the changes in the nuclear structure due to the evolution of the alignment (smooth changes) and eventually the crossing between the single particle states (abrupt changes). The values of the effective moment of inertia associated with the discrete and quasicontinuum rotational motion are given in Table I. The rotational quasicontinuum presents a slight but systematic deformation difference with respect to the discrete SD bands, whereas the discrete excited SD bands show roughly the same deformation as the SD yrast band [16].

The effective moment of inertia associated with these quasicontinuum rotational bands is estimated for a rotational frequency of 0.65 MeV to be $50\hbar^2\ {\rm MeV}^{-1}$. It is interesting to note that assuming the nucleus as a rigid prolate ellipsoid, the moment of inertia associated with the yrast SD states would correspond to a slightly more deformed ellipsoid as for the quasicontinuum bands. However, to give a precise value of the deformation of the nucleus associated with the quasicontinuum transitions, it would be interesting to perform lifetime measurements with a thick target, as it was done in Ref. [17]. The slightly less deformed shape associated with quasicontinuum bands would imply a larger curvature of the corresponding parabolas representating the rotational states $E=(\hbar^2/2J)I(I+1)$ in the (E^*,I) plane than the curvature associated to the SD yrast line. Therefore the relative excitation energy of the quasicontinuum bands with respect to the discrete SD states decreases with decreasing angular momentum. This experimental observation could explain the less extended plateau in the intensity pattern with respect to the nuclei in the mass region $A\sim150$, where a quasicontinuum associated with a more deformed shape of the nucleus has been reported, which inhibits this gradual approach.

The width of the quasicontinuum ridges is correlated to the spread out of the moment of inertia of the rotational bands at nonzero temperatures and the probable existence of rotational damping. The width [full width at half maximum (FWHM)] of the first discrete ridge is 10 keV while the quasicontinuum ridge is 26 keV width at the 0.65 MeV rotational frequency. The higher order ridges show a similar ratio of broadening, between discrete and quasicontinuum ridges ($\frac{10}{26}=0.38$, $\frac{12}{30}=0.40$, and $\frac{15}{40}=0.37$); see Table I. Two contributions are expected to be involved in this phenomenon of broadening of the rotational ridges: (i) the variation of the dynamical moment of inertia, and (ii) the rotational damping associated with the spreading in the rotational frequencies coming from the single-particle alignments and the corresponding widths of these states (Γ_μ). In order to study these two contributions from the experimental data, two slices of the matrix lying between 1100 to 1300 keV and 1300 to 1500 keV have been projected selecting the discrete and the quasicontinuum bands reported as (a) and (b), respectively, in Fig. 5. From this figure it may be inferred that the relative shifts in the average effective moment of inertia $\Delta J_{\rm eff}/J_{\rm eff}$ due to the variation of the average rotational frequency in the discrete band and in the quasicontinuum rotational bands are quite similar: $\Delta J_{\rm eff}/J_{\rm eff}=6/68$ and 7/74, respectively, for a $\Delta\hbar\omega=(0.7-0.6)$ MeV$=0.1$ MeV. However, it is possible to appreciate the more important effect of the damping width on the broadening of the quasicontinuum ridge. Indeed, from Fig. 5, a difference in the discrete ridge width of 37% is observed for a $\Delta\hbar\omega = 0.1$ MeV. This increase in the width of the ridge may be correlated to the associated change in the moment of inertia. An increase of 53% in the ridge width is observed for the quasicontinuum transitions. This increase is related to a weak rotational damping that starts to wash out the rotational correlation, as the rotational frequency, and the excitation energy increase.

It is possible to divide schematically the rotational dynamics of a warm nucleus in three main regimes [4] to understand where the rotational damping (Γ_{rot}), suggested above, starts to influence the deexcitation of the nucleus. In the first regime, near the SD yrast line, the average level spacing between the states which could be mixed by a two-body residual interaction is larger than the damping width Γ_μ of the rotational states. As a consequence near the SD yrast line and up to an excitation energy U_0, only discrete bands are found. At higher excitation energy, two additional regimes may be considered: one regime in which the dispersion of frequency dominates, and the other one, at even higher temperature, where both the increment of the residual interaction with the angular momentum and the increasing damping width contribute together to the rotational damping (Γ_{rot}), producing a mixing of the different rotational states with the consequent dispersion of the rotational intensity. In the specific case of the $A \sim 130$ mass region, following the general expressions to estimate these regimes presented in Ref. [4], a value of $U_0 \simeq 0.8$ MeV is estimated for this delimiting value of excitation energy, taking the level density parameter as $a = A/10$ for the SD well.

At highest rotational frequency ($\hbar\omega \sim 0.75$ MeV) the first as well as the second order quasicontinuum ridge are still well defined showing that the rotational damping is not yet important for these SD excited rotational bands. Only for the highest rotational frequency ($\hbar\omega \sim 0.85$ MeV) does the ridge structure start to be washed out in the background. This weak damping of rotational states confirms a strong matrix element connecting rotational states associated with a strong deformation, preventing them from mixing with single particle excited states.

Our observations suggest that only at the highest average rotational frequency reported here does the rotational continuum lie at an excitation energy where the rotational damping starts to wash out the rotational features. From this observation, following the model cited above [4], it is possible to estimate the excitation energy of this rotational continuum at high angular momentum ($I \sim 50\,\hbar$) to be about 1.7 MeV.

In conclusion, the superdeformed rotational quasicontinuum features in the region of mass $A \sim 130$ have been explored by the study of different γ-γ correlation matrices. It has been shown experimentally that the SD yrast band in ^{132}Ce is fed by a highly deformed quasicontinuum of transitions with a quadrupolar character. From an analysis of the effective moment of inertia, it is suggested that these transitions correspond to a slightly less deformed shape of the nucleus than for the SD yrast band. A possible scenario, based on the deformation associated to the SD quasicontinuum transitions, to explain the difference in the plateau intensity pattern of SD bands in the $A \simeq 130$ mass region with respect to the other mass regions has been presented. We have also analyzed the effect of the rotational damping in the SD well of ^{132}Ce. From experimental results it was shown that the rotational damping related to SD states is weak, and appears to be relevant only for the highest rotational frequency.

Two of us (F.F. and D.S.) are grateful to B. Haas and J.P. Vivien for enlightening discussions. This work was supported in part by the exchange program between CNRS and the Hungarian Academy of Science by the Hungarian scientific Research Fund, OTKA under Contract No. 20655. The EUROGAM project was supported by grants from the EPSRC (U.K.) and IN2P3 (France). Five of us (C.F., A.G., J.G., J.A.P., D.S.) acknowledge support from the exchange program between CNRS and the Royal Society. Two of us (A.T.S. and J.N.W.) acknowledge financial support from EPSRC during the course of this work, and K.H. acknowledges support from the University of York. One of us (D.S.) thanks the Institute for Nuclear Theory at the University of Washington for its hospitality and the Department of Energy for partial support during the completion of this work.

[1] P.J. Nolan, A. Kirwan, D.J.G. Love, A.H. Nelson, D.J. Unwin, and P.J. Twin, J. Phys. G **11**, L17 (1985).
[2] D. Santos *et al.*, Phys. Rev. Lett. **74**, 1708 (1995).
[3] B.M. Nyakó, J.R. Cresswell, P.D. Forsyth, D. Howe, P.J. Nolan, M.A. Riley, J.F. Sharpey-Schaffer, J. Simpson, N.J. Ward, and P.J. Twin, Phys. Rev. Lett. **52**, 507 (1984).
[4] B. Lauritzen, T. Dossing, and R. A. Broglia, Nucl. Phys. **A457**, 61 (1986).
[5] T. Dossing, B. Herskind, S. Leoni, A. Bracco, R.A. Broglia, M. Matsuo, and E. Vigezzi, Phys. Rep. **268**, 1 (1996).
[6] T. Dossing and E. Vigezzi, Nucl. Phys. **A587**, 13 (1995).
[7] K. Schiffer, B. Herskind, and J. Gascon, Z. Phys. A **332**, 17 (1989).
[8] S. Leoni, B. Herskind, T. Dossing, A. Ataç, and M. Piiparinen, Phys. Rev. Lett. **76**, 3281 (1996).
[9] R.G. Henry *et al.*, Phys. Rev. Lett. **73**, 777 (1994).
[10] F. Beck, Prog. Part. Nucl. Phys. **28**, 443 (1992).
[11] B. Herskind, T. Dossing, D. Jerrestam, K. Schiffer, S. Leoni, J. Lisle, R. Chapman, F. Khazaie, and J.N. Mo, Phys. Lett. B **276**, 4 (1992).
[12] F. Farget, Ph.D. thesis, Université Joseph Fourier, Grenoble, 1996.
[13] B. Herskind, J. Phys. (Paris), Colloq. **41-10**, 106 (1980).
[14] J.P. Vivien *et al.*, Phys. Lett. B **278**, 407 (1992).
[15] D.C. Radford, I. Ahmad, R. Holzmann, R.V.F. Janssens, and T.L. Khoo, Nucl. Instrum. Methods Phys. Res. A **258**, 111 (1987).
[16] R.M. Clark *et al.*, Phys. Rev. Lett. **76**, 3510 (1996).
[17] I.Y. Lee, H. Xie, C. Baktash, W.B. Gao, J.D. Garrett, N.R. Johnson, F.K. McGowan, and R. Wyss, Nucl. Phys. **A554**, 485 (1993).