Determination of the Spreading Width for the Collective Transition Strength at Finite Temperature

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The experimentally observed structure of the $E2$ transitions in the quasicontinuum for ^{168}Yb is analyzed. The valley ridge structure along the $E_{\gamma 1}=E_{\gamma 2}$ diagonal in γ-energy correlation spectra has been reproduced by a model simulation in which a spreading of the rotational decay strength Γ_{rot} is introduced in regions of nuclear excitation energy $U > U_0$ where the density of bands with slightly differing moments of inertia and alignment is high. The values of Γ_{rot} and U_0 vary from 75 to 110 keV and from 1.25 to 1.0 MeV, respectively, in the energy range $780 < E_\gamma < 1160$ keV.

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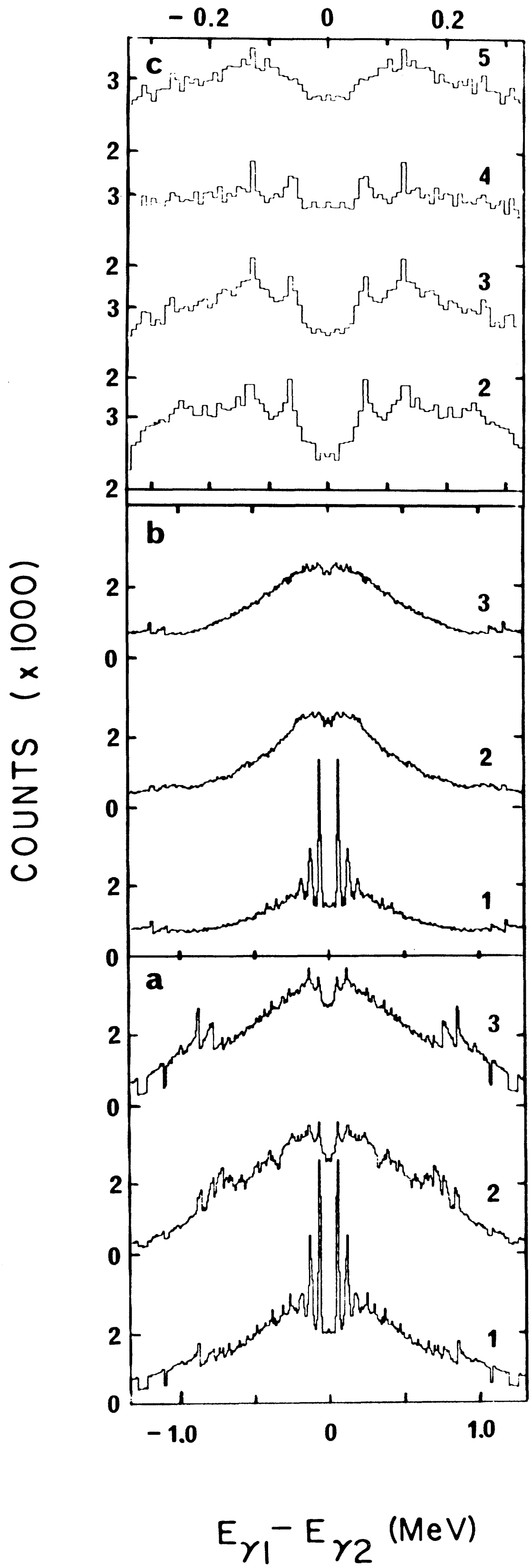
With the advent of new detection systems and larger accelerators, the rotational structure of nuclei can be studied to the highest angular momentum which nuclei can accommodate. Discrete line studies were extended in recent experiments up to about spin $40\hbar$ in several rare-earth nuclei for the yrast sequence and a few low-lying rotational bands. The discrete γ-ray transitions deexciting states with spins of $30\hbar$ or greater only account for a few percent of the total intensity, and most of the collective $E2$ strength is still unresolved forming a large continuum spectrum. Until recently this was believed to be associated with a large number of almost parallel rotational bands above the yrast sequence. Each rotational band would therefore produce a sequence of correlated γ-ray energies given by $E_\gamma = 4\hbar^2(I-i)/2J^{(2)}$, where $J^{(2)}$ is the collective dynamical moment of inertia and i the alignment of the particle angular momentum. Such a correlation is readily shown to exist in experimentally observed discrete-line rotational bands (e.g., Bacelar *et al.*[1] and references therein). Cranking calculations indicate that these correlations persist at higher spins and temperatures.[2]

If the rotational transition energies in the continuum between about 0.75 and 1.4 MeV, often referred to as the "$E2$ bump," follow these trends the γ-ray energy correlations are expected to show characteristic patterns in two-dimensional coincidence spectra, in which there will be a valley along the $E_{\gamma 1}=E_{\gamma 2}$ diagonal bounded by ridges on either side.[3] The separation of the ridges is given by $W = 8\hbar^2/2J^{(2)}$. In the past the direct observation of the ridge-valley structure has been obscured by the presence of a large Compton background associated with the Ge detector response. From such measurements the presence of the structure has been inferred by use of a statistical background-subtraction technique,[3] but a quantitative estimate of the intensity within the ridge structure proved difficult. In recent measurements the Compton background has been suppressed by surrounding each Ge detector with a large scintillator (NaI or bismuth germanate) operated in anticoincidence to suppress Compton-scattered events.[4] Since the small residual background is rather flat it is a simple operation to unfold the response functions of the detectors and to observe true γ-ray intensities in two-dimensional coincidence spectra. Such procedures have recently been carried out by Love *et al.*,[5] who found that the ridge structure at higher γ-ray energies, where the continuum predominates, is only a few percent of the total intensity, and that the $B(E2)$ strength spreads over an energy range much greater than 15 keV.

The data discussed in this Letter were obtained by observation of γ-ray coincidences with suppressed Ge detectors (TESSA 2) for the reaction ^{124}Sn(^{48}Ca,xn), the 200-MeV ^{48}Ca beam being obtained from the tandem Van de Graaff at the Daresbury Laboratory. The TESSA 2 array also provided total cascade energy and fold information. The two-dimensional coincidence spectrum selected with fold >15 was predominantly associated with the $4n$ channel (^{168}Yb, 66%) but contained also smaller contributions from the $3n$ channel (^{169}Yb, 13%) and the $5n$ channel (^{167}Yb, 21%). The discrete-line analysis of the same data is discussed elsewhere.[1] Figure 1 shows a number of cuts taken at constant $E_{\gamma 1}+E_{\gamma 2}$ from the two-dimensional coincidence spectrum. The ridge structure is found to be weak and



the valley is seen to be very shallow particularly at higher γ-ray energies in accordance with Ref. 5.

Attempts to explain the uncorrelated intensity by simply introducing a spread in moments of inertia require an unreasonably large range of values to wash out the ridge-valley structure. The influence of large fluctuations in the γ degree of freedom has recently been investigated by Hamamoto and Onishi[6] and found to make only a small contribution to the filling of the valley.

It is therefore necessary to propose a mechanism for perturbing the $E2$ rotational energy correlations. We consider a model in which the spreading of the rotational quadrupole decay strength is due to the progressive damping of the rotational pattern with increasing temperature.[7] At a few megaelectronvolts above the yrast line the level density is so high that the unperturbed bands that carry the rotational decay become considerably mixed by a weak residual interaction. For parallel bands the diagonalized states at neighboring values I and $I-2$ of the angular momentum have the same rotational structure, and the main part of the collective decay pattern continues to follow rotationallike bands. The introduction of differences in alignment of the unperturbed bands causes the collective quadrupole decay strength from a diagonalized state of angular momentum I to spread over an interval $\Gamma_{\rm rot}$ of final states of angular momentum $I-2$. This spreading width of the rotational strength is predicted to decrease with excitation energy U above the yrast line as $1/U$ for U greater than a few megaelectronvolts.[7]

Following the basic concepts of this model a simulation code is developed to describe the γ-deexcitation process, such that an average width $\Gamma_{\rm rot}$ of the electronic quadrupole decay strength and a critical energy U_0, below which no damping is present as a result of lower level density, can be extracted. At every step in the deexcitation process from an entry population in the (E,I) plane, the relative probabilities of noncollective (statistical) and collective stretched quadrupole transitions are calculated. The transition strengths for the statistical transitions are determined as decay rates from the initial state to all available final states by the

FIG. 1. Cuts taken from the two-dimensional coincidence spectra at (a),(c) $(E_{\gamma 1}+E_{\gamma 2})/2 = 970$ keV and (b) 1130 keV. In all cases the cuts are of width 56 keV. Spectrum 1 is obtained from simulations with $\Gamma_{\rm rot}=0$ and spectrum 3 with values of $\Gamma_{\rm rot}$ and U_0 corresponding to the resulting best values given in Table I. Spectrum 2 is obtained from the unfolded and efficiency-corrected experimental data. (c) shows the central region of spectra 2 and 3 of (a) in addition to simulations with $\Gamma_{\rm rot}$ and U_0 equal to 150 keV and 1.0 MeV (spectrum 4) and 75 keV and 0.5 MeV (spectrum 5) to illustrate the sensitivity.

following formulas[8,9]:

$$T(E1;i \to f) = C_1(r)(E_i - E_f)^{r+1}\rho(U_f)/\rho(U_i),$$

$$T(E2;i \to f) = C_2(E_i - E_f)^6\rho(U_f)/\rho(U_i).$$

U is the excitation energy above yrast and $\rho(U)$ is the level density at fixed angular momentum, $\rho(U)$ being given by[10]

$$\rho(U) = \text{const}(gU)^{-2}\exp[2(aU)^{1/2}].$$

Here g ($=6$ MeV^{-1}) represents the single-particle level density and the parameter a is taken as $A/8$ MeV^{-1} in accordance with the work of Bohr and Mottelson.[11] Since the $E1$ statistical γ rays are in the tail of the distribution of the giant dipole resonance, the value of r in (1) is taken to be 5 (instead of 3) following the prescription given by Anderson *et al.*[11] and Bollinger and Thomas.[12] The coefficients $C_1(r)$ and C_2 are chosen to reproduce the experimental values for the total transition rates at $U_i = 6.44$ MeV.[11] A $B(E2)$ value of 400 Weisskopf units was used for calculating in-band transition rates in accordance with theoretical expectations ($Q_0 \approx 7$ $e \cdot$b) and measured feeding times in the continuum.[13]

The introduction of a spreading width affects the $E2$ collective transitions in two respects. Firstly, there is a range of possible transition energies related to the magnitude of the width Γ_{rot}. Secondly, since the transition probabilities are weighted by $(E_i - E_f)^5$, higher transition energies are favored, leading to a rotational cooling of the nucleus compared to the situation in the absence of a spreading width. The spreading width was maintained at a constant value for all energies above the yrast line greater than the critical value U_0, Γ_{rot} being made to fall rapidly to zero for $U < U_0$. The extracted value of Γ_{rot} therefore represents an average over the full temperature range above U_0 and gives no information on the U dependence.

Moments of inertia ($J^{(2)}$) and alignments (i) for rotational bands were selected by a Monte Carlo method from Gaussian distributions. The parameters used for these distributions were $\bar{J}^{(2)} = 70\hbar^2$ MeV^{-1}, $\sigma(J^{(2)}) = 16\hbar^2$ MeV^{-1}, and $\bar{i} = 3\hbar$, $\sigma(i) = 3\hbar$. The values of $J^{(2)}$ were chosen to reproduce the observed distance between the ridges for $E_\gamma > 1$ MeV and the width of the ridge structure (16 keV) in the two-dimensional spectra. The entry population ($0 < U < 7$ MeV, $40\hbar < I < 56\hbar$) used in the simulation is chosen in accordance with "cascade" calculations with the fold restrictions imposed on the experimental data[14] taken into account.

Each cascade terminates through a number of yrast transitions known[1] in ^{168}Yb, but no side bands have been included. A pictorial representation of a typical simulated decay path is shown in Fig. 2.

Cuts taken from the computer-generated two-dimensional spectra at the same values of $(E_{\gamma1} + E_{\gamma2})/2$ together with the experimental data are shown in Fig. 1 for different spreading widths. Extreme values of Γ_{rot} are first discussed. The intense ridge structure for $\Gamma_{\text{rot}} = 0$, as is evident from Fig. 1, is not found in the experimental data. For very large values of Γ_{rot} (>1 MeV) the $E2$ cooling effect is dominant, and the decay path will reach the region of the yrast line after a few transitions only. As a result high-spin discrete transitions associated with yrast and other low-lying bands will become intense and neither the large intensity nor the shape of the "$E2$ bump" in the quasicontinuum will be reproduced. It is, therefore, necessary to focus on intermediate values of Γ_{rot}. Provided $\Gamma_{\text{rot}} > 0.03$ MeV, the critical energy U_0 controls the fraction of the γ-ray decay passing through unperturbed bands which contribute to the intensity of the ridge structures. In contrast, as seen from Fig. 1(c), Γ_{rot} primarily determines the depth of the central valley, and there is, therefore, little correlation between the two quantities. From direct comparisons in the region of the valley-ridge structure between the data and the simulation by a least-squares procedure the values of Γ_{rot} and U_0 given in Table I are obtained. The excellent agreement generally obtained and the sensitivity are illustrated in Fig. 1(c) for the region $(E_{\gamma1} + E_{\gamma2})/2 \sim 970$ keV. The structure at larger values of $E_{\gamma1} - E_{\gamma2}$ in the cut at 970 keV is due to coincidences between low-spin discrete lines and the continuum and are quite well reproduced by the calcu-

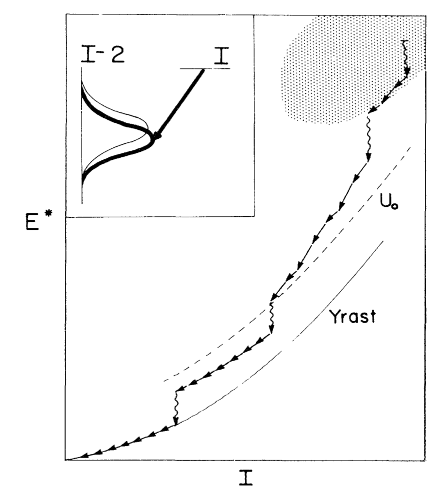


FIG. 2. A typical calculated decay path of statistical dipole (wavy line) and collective stretched $E2$ (straight line) transitions. U_0 is the critical energy at which the spreading width reaches its full value. The inset illustrates the spreading of the rotational $B(E2)$ strength values of Γ_{rot} and U_0 (thin Gaussian curve) and the transition probability (thick Gaussian curve), obtained by weighting the $B(E2)$ distribution by E_γ^5.

TABLE I. Values of Γ_{rot} and U_0 at different γ-transition energies.

E_γ (keV)	Γ_{rot} (keV)	U_0 (MeV)
810	75 ± 20	1.25 ± 0.2
970	75 ± 20	1.1 ± 0.2
1130	110 ± 40	1.0 ± 0.2

lations. However, the fits to the experimental data cannot be quantitative with the restricted parameters used. This applies particularly to the 1130-keV cut, which is just below the edge of the $E2$ bump. The overall shape of the intensity distribution here depends on the form of the entry population. The overall shape from the simulation can be improved further by including an expected increase in proton alignment at high rotational frequencies.[15] However, the inclusion of gradually increasing alignment affects the extracted values of Γ_{rot} and U_0 little, and is included in the estimated errors.

For the first time it has been possible to reproduce the general features of the quasicontinuum and determine both the average spreading width and the critical excitation energy at which damping sets in. The extraction of specific values for Γ_{rot} and U_0 will be important for a quantitative estimate of the residual interaction and spreading in alignment at higher level densities. While the present discussion has been restricted to ^{168}Yb, the observed spreading of the transition strength, which most clearly manifests itself as a marked quenching of the ridge-valley structure at higher rotational frequencies, appears to be a general phenomenon found for all deformed nuclear systems studied so far. This damping mechanism may also explain our inability to observe more discrete-line sequences. With the very sensitive techniques presently available only high-K bands,[16] for which the effective density of states is probably low, have been isolated at more than 1 MeV above the yrast band. For other bands the spreading width mixes the decay paths so effectively that selectivity is much reduced.

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