Rotational Quadrupole Moment of Thermally Excited High Spin States in ^{164}Yb

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The lifetime of the unresolved γ transitions forming the rotational quasicontinuum spectrum has been measured for ^{164}Yb using the Doppler shift attenuation technique. The fractional Doppler shifts of transitions along the diagonal valley of $E_{\gamma_1} \times E_{\gamma_2}$ spectra are extracted for the first time using a new technique based on the fluctuation patterns of counts. The rotational collectivity was found to persist with full strength also when the rotational bands are strongly mixed. For the high spin ($I > 20\hbar$) and energy ($0 < E_{\rm ex} < 2$ MeV) regions there is agreement between the discrete and the damped transitions and with $Q_t \approx 5.5\ e$ b. [S0031-9007(98)07073-2]

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Several studies of the rotational quasicontinuum for normally deformed nuclei in the rare earth region have been made in the last few years employing two different techniques, one based on the shape analysis of the "ridge-valley" structure in $E_{\gamma_1} \times E_{\gamma_2}$ spectra [1], and the other on a fluctuation analysis method [2]. These studies have shown that the rotational motion is carried by regular rotational bands at low excitation energy, while at higher excitation energy, where the level density is high, rotational bands are strongly mixed. By comparing the experimental data with predictions of the rotational damping model [3], one has learned that the mixing among rotational bands is strongly governed by a residual interaction including high multipole terms, and that the mixing is configuration dependent [4–6].

In spite of the progress made recently in this field, one of the basic assumptions behind the rotational damping model, namely, that the warm nucleus is strongly collective with a quadrupole moment Q_t of the same order as that of the cold regular rotational bands, has never been experimentally verified. To test this assumption, lifetime measurements of the damped transitions are necessary.

So far, lifetimes of discrete high spin states have been measured by employing the Doppler-shift attenuation method [7]. In addition, the fractional Doppler shifts of the regular bands forming ridge structures in $E_{\gamma_1} \times E_{\gamma_2}$ spectra, and of the unresolved high energy rotational transitions forming the upper edge of the $E2$ bump in one-dimensional (1D) spectra, have been measured [8,9]. However, only for the ridges and for the discrete lines has it been possible to deduce the value of Q_t, since the high energy transitions at the edge of the $E2$ bump were found to be fully shifted and consequently no sensitivity to the value of the quadrupole moment was obtained.

To deduce the quadrupole moment in the region of strongly mixed bands we have developed and employed for the first time a method, based on the *fluctuation pattern* of counts of unresolved transitions in the diagonal valley of $E_{\gamma_1} \times E_{\gamma_2}$ spectra. By focusing on the valley, we select damped transitions in the cleanest way, excluding transitions which display the energy correlations characteristic of regular rotational bands. A Doppler shift analysis of the fluctuation patterns is made through a covariance analysis of shifted counts in the valley. The new method is described in some detail below, and the obtained results, providing the first measured value of the Q_t in the continuum, are discussed. Furthermore, the results are compared to simulations based on realistic band mixing calculations presently available for the ^{168}Yb nucleus in the same mass region [10].

The fusion reaction ^{30}Si(150 MeV) + ^{138}Ba $\Rightarrow$ ^{168}Yb was used to populate the compound residues ^{163,164,165}Yb after xn evaporations. The experiment was carried out at the Institut de Recherches Subatomiques of Strasbourg using the Vivitron tandem accelerator and the multidetector system EUROGAM II [11]. Two runs were made, one with a backed ^{138}Ba target of 225 μg/cm^2 evaporated on a Pb backing of 9 mg/cm^2, the other using a stack of two targets each evaporated on a thin Au foil of $\approx 580\ \mu g/cm^2$. The total thickness of the ^{138}Ba was 450 $\mu g/cm^2$. The initial velocity of the residual nuclei in the middle of the target was calculated to be $v/c = 1.8\%$. A total of 220 and 120 M triple and higher-fold events (with an average Ge fold of 5) were collected in the thin and backed target experiments, respectively. Energy-dependent time gates on the Ge time signal were used to suppress background from neutrons. Ungated 2D matrices, employed in the following analysis, contain mainly transitions of the nucleus ^{164}Yb at $E_\gamma > 900$ keV. In fact, the intensity of the known discrete transitions of ^{164}Yb relative to that of all the residual nuclei is $\approx 70\%$ at $28\hbar$ ($E_\gamma \approx 900$ keV) and increases at higher spins. The calculated maximum angular momentum is $63\hbar$. The ungated 2D matrix, measured with the unbacked target, is shown in panel (a) of Fig. 1 for γ-transition energies in the interval of interest.

The effective lifetime (effective since it reflects also the feeding time) of some of the discrete transitions of the yrast band was deduced from the Doppler shift of the centroid position in the forward (46.4°) and backward (−46.4°) angles. The energies, spins, and observed fractional shifts of these transitions are given in Table I, together with the effective lifetimes deduced directly from $F(\tau)$ using the calculated velocity profile of the recoiling nucleus in the target. To extract the intrinsic quadrupole moment Q_t the measured values of $F(\tau)$ are compared to calculated curves associated to different Q_t values (as described below). The analysis for the three transitions in the table gives $Q_t \approx 5.5\ e\,$b (see Fig. 3), which is $\approx 15\%$ lower than the average value deduced for the same transitions in a previous work [12] where a full line shape analysis was performed.

The analysis of unresolved transitions in regular excited rotational bands forming the ridge structure in $E_{\gamma_1} \times E_{\gamma_2}$ spectra was based on the Doppler shift of the ridges in the forward-backward and backward-forward 2D matrices. The matrices were background subtracted by means of the COR procedure [13], thereby removing the coincidences with low lying bands, which extends over the valley as straight "stripes" in the raw spectra [2]. Two sets of spectra obtained from 64 keV wide cuts perpendicular to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal, at $\langle E_\gamma \rangle = 0.5(E_{\gamma_1} + E_{\gamma_2}) = 800$ and 880 keV in the two matrices are shown in Fig. 1(b). The amount of shift can clearly be seen for the ridges but not for the valley characterized by a flat continuous distribution. Values for the fractional shifts of selected intervals of the ridge structures are shown in Fig. 3.

The simplest and most direct way to measure lifetimes of transitions in the damped region is to deduce the fractional Doppler shift from 1D spectra at forward and backward angles, where the spectral shape changes with E_γ, e.g., the upper edge of the $E2$ continuous bump. To extract the size of the shift in the energy interval $1200 < E_\gamma < 1400$ keV of the $E2$ bump of ^{164}Yb, shown in Fig. 1(c), we have used the procedure described in Refs. [8,9]. Applying this method, fractional shifts of ≈ 1 were obtained, as shown by open squares in Fig. 3. Since these high energy transitions of the $E2$ bump are fully shifted, it was not possible from this analysis to obtain a value for the quadrupole moment, but only to extract an upper limit of $\approx 10^{-14}$ s for the effective lifetime of the rotational states in the quasicontinuum.

To measure the nuclear quadrupole moment of the strongly mixed bands, one has to focus on lower transition energies where the values of the fractional shifts are

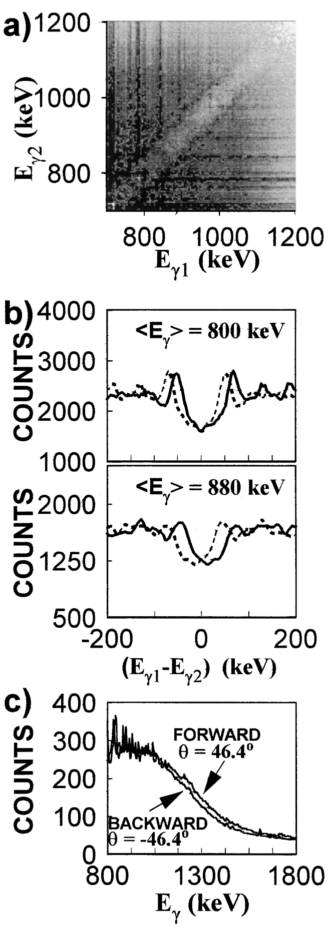

FIG. 1. (a) The 2D matrix measured with the unbacked target shown for the region of interest. (b) The Doppler shift of the ridges in spectra obtained in cuts perpendicular to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal at $\langle E_\gamma \rangle = 800$ and 880 keV in ($E^F_{\gamma_1} \times E^B_{\gamma_2}$), as solid line, and ($E^B_{\gamma_1} \times E^F_{\gamma_2}$), as dotted line, where B and F indicate backward and forward angles, respectively. (c) One-dimensional spectra measured at 46.4° and −46.4°, showing the shift of the $E2$ bump.

TABLE I. Measured fractional Doppler shift $F(\tau)$ for some discrete peaks of the yrast band. The effective lifetimes are deduced directly from $F(\tau)$ and the velocity profile of the recoiling nucleus, as discussed in the text.

E_γ (keV)	I ($\hbar$)	$F(\tau)$	τ (10^{-12} s)
780.6	$24^+ \rightarrow 22^+$	0.33 ± 0.01	0.850 ± 0.005
838.4	$26^+ \rightarrow 24^+$	0.35 ± 0.05	0.815 ± 0.005
889.2	$28^+ \rightarrow 26^+$	0.58 ± 0.03	0.500 ± 0.005

expected to be smaller than 1. This cannot be done by studying the shift in 1D spectra because at lower transition energies the one-dimensional $E2$ bump is flat with superimposed contributions from the discrete regular bands [see Fig. 1(c)]. In contrast, one can study the valley structure of the $E_{\gamma_1} \times E_{\gamma_2}$ spectrum, which is mainly populated by damped rotational transitions and almost free of regular rotational bands. Because this region of the spectrum is also flat and continuous, as one can see in Fig. 1(b), we had to develop a new method to extract the Doppler shift attenuation, based on a covariance analysis of the fluctuations of counts in pairs of 2D spectra.

The data were sorted into 2D spectra, namely, $(E^F_{\gamma_1} \times E^B_{\gamma_2})$ and $(E^B_{\gamma_1} \times E^F_{\gamma_2})$, where B and F indicate backward and forward angles, respectively. Two sets of spectra were then constructed. The first consists of spectra of the type $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{\mathrm{shift}=N}$, obtained by shifting the counts in channel (X, Y) to channel $(X + N, Y - N)$, each corresponding to given integer values, $N = 1, 2, 3 \ldots$. The second set consists of spectra of the type $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{\mathrm{shift}=-N}$, obtained by shifting the counts in channel (X, Y) to channel $(X - N, Y + N)$.

The correlations in fluctuations between any two $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{\mathrm{shift}=N}$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{\mathrm{shift}=-N}$ spectra [denoted in the following equation by $M(A)$ and $M(B)$] were evaluated in terms of the covariance of counts, defined as

$$\mu_{2,\mathrm{cov}}(A, B) \equiv \frac{1}{N_{\mathrm{ch}}} \sum_j [M_j(A) - \tilde{M}_j(A)] \times [M_j(B) - \tilde{M}_j(B)]\,. \quad (1)$$

The sum is over a region spanning N_{ch} channels in a 2D 64 keV $\times$ 64 keV window, and $\tilde{M}$ denotes an average spectrum (which in our case is found by the routine STAT-FIT as a numerical smoothed third-order approximation to the 2D spectrum [2]).

To normalize the covariance [5] and thereby determine the degree of correlation between the two spectra, the correlation coefficient $r(A, B)$ was calculated:

$$r(A, B) \equiv \frac{\mu_{2,\mathrm{cov}}(A, B)}{\sqrt{[\mu_2(A) - \mu_1^{(\mathrm{raw})}(A)][\mu_2(B) - \mu_1^{(\mathrm{raw})}(B)]}}\,. \quad (2)$$

Here $\mu_1^{(\mathrm{raw})}$ is the first moment of the raw spectrum, and μ_2 is the second moment of the COR-subtracted spectrum, both defined for the same region N_{ch}, as the covariance. The second moment is related to the covariance by the relation $\mu_2(A) = \mu_{2,\mathrm{cov}}(A, A)$. This analysis requires that μ_2/μ_1 is significantly larger than 1, which is the statistical limit.

A typical example of the correlation coefficient r is shown in Figs. 2(a) and 2(b) as a function of the relative shifts between $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{\mathrm{shift}=N}$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{\mathrm{shift}=-N}$, for the transition energy $\langle E_\gamma \rangle = 880$ keV. In this figure we indicate with arrows the values corresponding to the maximum of the correlation coefficient r and to the full shift position, from which we can deduce the fractional Doppler shift $F(\tau)$. We find an energy region in the valley $800 < E_\gamma < 1000$ keV, where $F(\tau)$ is significantly smaller than 1 and thereby a sensitivity to the value of the quadrupole moment. As can be seen from Fig. 2(c), $F(\tau)$ increases with $\langle E_\gamma \rangle$, as expected.

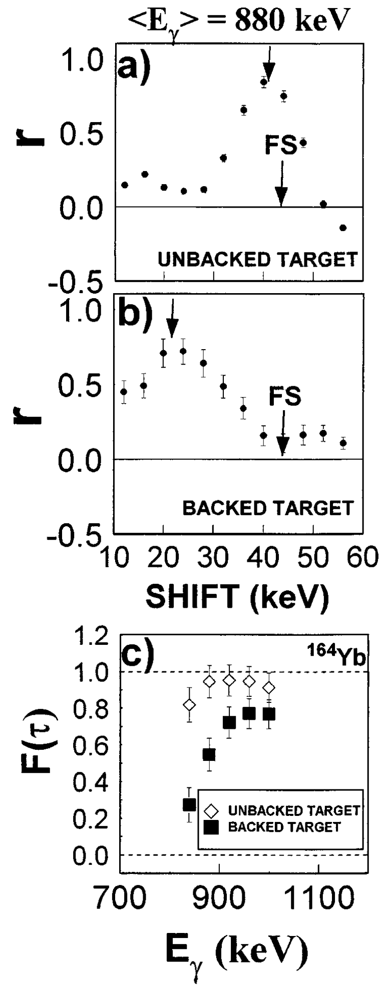

FIG. 2. (a) and (b) Typical examples of the correlation coefficient r, associated to the $\langle E_\gamma \rangle = 880$ keV as a function of the relative shifts between $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{\mathrm{shift}=-N\ \mathrm{keV}}$ and $(E^F_{\gamma_1} + E^B_{\gamma_2})_{\mathrm{shift}=+N\ \mathrm{keV}}$ in the case of the backed and the thin target experiment, respectively. The arrows indicate the values corresponding to the maximum of r and to the full shift (FS) from which we deduce the fractional Doppler shift $F(\tau)$, as shown in (c) for different energies E_γ. The error bars in (c) represent the step for the shift applied to the data in the covariance analysis (± 4 keV).

A stringent test of this new method is obtained by analyzing data for the same reaction but using a thin target. In fact, in the case of thin target data one expects to find $F(\tau) \approx 1$ for all γ-transition energies because the emission from the recoiling nucleus occurs in flight with the maximum velocity. The results of the analysis of the backed and thin target data are shown in Fig. 2(c). In the figure we compare data corresponding to the same average transition energy for a backed and a thin target. Indeed, while the backed target data display partial shifts, the thin target data are in accordance with the full shifts, giving convincing support to the validity of the new method.

The observed Doppler shift attenuation corresponds to effective decay times related to the history of the paths from the entry point to the time of emission of the observed transitions. The γ cascades proceed through the region of rotational damping, where the energy spread of the decay transitions affects the average lifetimes due to the E_γ^5 factor in the $E2$ transition probability. In order to extract the nuclear quadrupole moment Q_t from the measured shifts, the γ cascades from the excited nucleus have been realistically simulated by theoretically calculated cascades including damping, starting from an entry distribution in energy and spin of the residual nucleus [10] and ending at the transition in question. The competition between statistical $E1$ transitions, governed by the tail of the giant dipole resonance, and $E2$ transitions from microscopically calculated rotational bands is simulated. The energies and transition probabilities of the rotational bands mixed by the residual interaction are available for the ^{168}Yb nucleus in great detail and have therefore been used to represent typical decay paths in a deformed nucleus in this same mass region [4].

The intrinsic lifetime τ_i of a state i at spin I and excitation energy U_i was calculated starting from the transition probabilities for $E1$ and $E2$ decay $T(E1, U_i)$ and $T(E2, U_i)$. The simulation program calculates the effective lifetime τ of a transition at spin I as the sum of the lifetimes τ_i of the preceding transitions with spin $J \geq I$, $\tau(I) = \sum_{J \geq I} \tau_i(J)$. Making use of the velocity profile of the recoiling nucleus in the target and backing [7,14,15] the program calculates the velocity of the nucleus at the time τ and then the associated Doppler shift. More details about the simulation procedures can be found in Ref. [10].

In Fig. 3, the experimental data are shown together with the fractional shifts deduced from simulated spectra for three different values of $Q_t = 5.5$, 6.6, and 7.6 e b. One can see that the data are well described by the curve corresponding to $Q_t = 5.5$ e b (or 200 W.u.). For this high spin region, similar values of the quadrupole moment were also found in previous works [12,16], using a different reaction and experimental setup, in which Doppler shifts were deduced for both discrete lines and ridge structures.

An important conclusion can be drawn from this work: the discrete excited bands carry the same rotational collectivity as the yrast band, and this collectivity is also maintained for the thermally excited mixed bands up to around 2 MeV of excitation energy above yrast.

For the mixed bands, the lifetime is not only sensitive to the total Q_t but also to the distribution of the transition energy of the fragmented strength. It has been suggested [17] that a significant part of the strength might not be available for rotational decay, because it is shifted too far up in excitation energy, and thereby down in transition energy. The present measurement shows that the major part of the strength remains concentrated around the average decay energy.

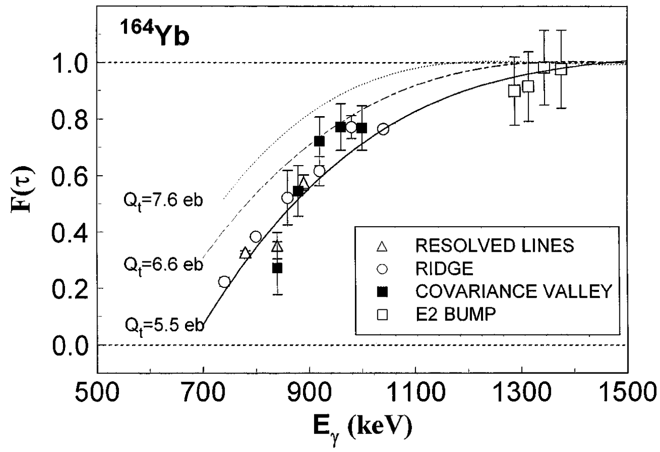

FIG. 3. The measured fractional Doppler shifts for some discrete transitions and for different parts of the quasicontinuum spectra. The lines represent the expected theoretical values for $Q_t = 5.5$, 6.6, and 7.6 e b [corresponding to 200, 300, and 400 W.u. (Weisskopf units), respectively], as obtained from simulated spectra.

In summary, a new method based on a covariance analysis of spectra measured with detectors at forward and backward angles has allowed us to extract for the first time the quadrupole moment of states in a nucleus with excitation energies in the continuum region. The results show that the nucleus conserves its collectivity at increasing excitation energy ($\leq$2 MeV), thus giving strong support to the rotational damping model.

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[1] S. Leoni *et al.*, Nucl. Phys. **A587**, 513 (1995).
[2] T. Døssing *et al.*, Phys. Rep. **268**, 1 (1996).
[3] B. Lauritzen, T. Døssing, and R. A. Broglia, Nucl. Phys. **A457**, 61 (1986).
[4] M. Matsuo *et al.*, Nucl. Phys. **A617**, 1 (1997).
[5] P. Bosetti *et al.*, Phys. Rev. Lett. **76**, 1204 (1996).
[6] R. A. Broglia *et al.*, Z. Phys. A **356**, 259 (1996).
[7] J. C. Bacelar *et al.*, Phys. Rev. Lett. **57**, 3019 (1986).
[8] H. Hübel *et al.*, Phys. Rev. Lett. **41**, 791 (1978).
[9] B. Million *et al.*, Phys. Lett. B **415**, 321 (1997).
[10] A. Bracco *et al.*, Phys. Rev. Lett. **76**, 4484 (1996).
[11] P. J. Nolan, F. A. Beck, and D. B. Fossan, Annu. Rev. Nucl. Part. Sci. **45**, 561 (1994).
[12] H. Xie *et al.*, Nucl. Phys. **A599**, 560 (1996).
[13] O. Andersen *et al.*, Phys. Rev. Lett. **43**, 687 (1979).
[14] L. C. Northcliffe and R. F. Schilling, At. Data Nucl. Data Tables **7**, 233 (1970).
[15] J. F. Ziegler and W. K. Chu, Nucl. Data Tables **13**, 463 (1974).
[16] I. Y. Lee *et al.*, Nucl. Phys. **A554**, 485 (1993).
[17] G. A. Leander, P. Arve, and B. Lauritzen, Phys. Rev. C **37**, 328 (1988).