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The Rotational Quadrupole Moment of continuum-states at high-spin in ^{164}Yb

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The lifetime of the unresolved transitions forming the rotational quasi-continuum spectra has been measured in ^{164}Yb using the Doppler shift attenuation method. The valley structure in $E_{\gamma_1} \times E_{\gamma_2}$ spectra was analysed using a new technique, based on fluctuation patterns, which provided for the first time experimental lifetimes for rotational damped transitions. The present results show, as predicted by the rotational damping model, that the collectivity persists for highly excited bands. In particular, agreement is found between the experimental results, for discrete and damped transitions, and the predictions corresponding to Q_t = 5.5 eb, for the entire interval of γ-ray energies studied.

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1. Introduction

The damping of rotational motion has been extensively studied for normally deformed nuclei analysing the quasi-continuum of γ-ray spectra. In particular, progess in this field has been made using $E_{\gamma_1} \times E_{\gamma_2}$ coincidence matrices in which one can select different regions where the contribution from regular rotational bands (undamped) is separated from that of strongly interacting bands (damped). In fact, strongly correlated in-band γ-transitions produce a ridge structure, parallel to the main diagonal, while the valley region is mainly filled by damped γ-transitions among levels of strongly interacting bands (damped motion) [1]. The characteristic feature of the damped regime of the rotational motion is that the decay from a state at spin I populates a large number of states at I-2 and consequently the correlation between consecutive in-bands transitions are lost.

The lastest developments for the investigation of the rotational damping problem are based on fluctuation analysis techniques applied to the ridge and valley regions of the $E_{\gamma_1} \times E_{\gamma_2}$ spectra [1]. Using these techniques one could establish first the important role played by the residual interaction and second that the rotational band mixing seems to be configuration dependent [2,3].

In spite of the progress made in this field, one of the basic assumptions of the rotational damping model, namely that the warm nucleus is still strongly collective with a quadrupole moment Q_t of the same order of that of the cold regular bands, has never

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been experimentally verified. To test this assumption, measurements of lifetimes of the damped transitions are necessary. So far, the fractional Doppler shifts of discrete bands, of 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 spectra have been measured [4].

However, by focusing only on these parts of the spectra it was not possible to deduce the value of Q_t for damped transitions. In fact, due to their high energy, the damped transitions forming the high energy edge of the one dimensional bump are fully Doppler shifted. In contrast, the analysis of the lower energy damped transitions forming the valley should provide a value for Q_t. Unfortunately the spectral shape of the valley, being continuous and flat does not allow to apply in a simple way the DSAM technique and a new method, based on a covariance analysis of spectra at different angles, was developed.

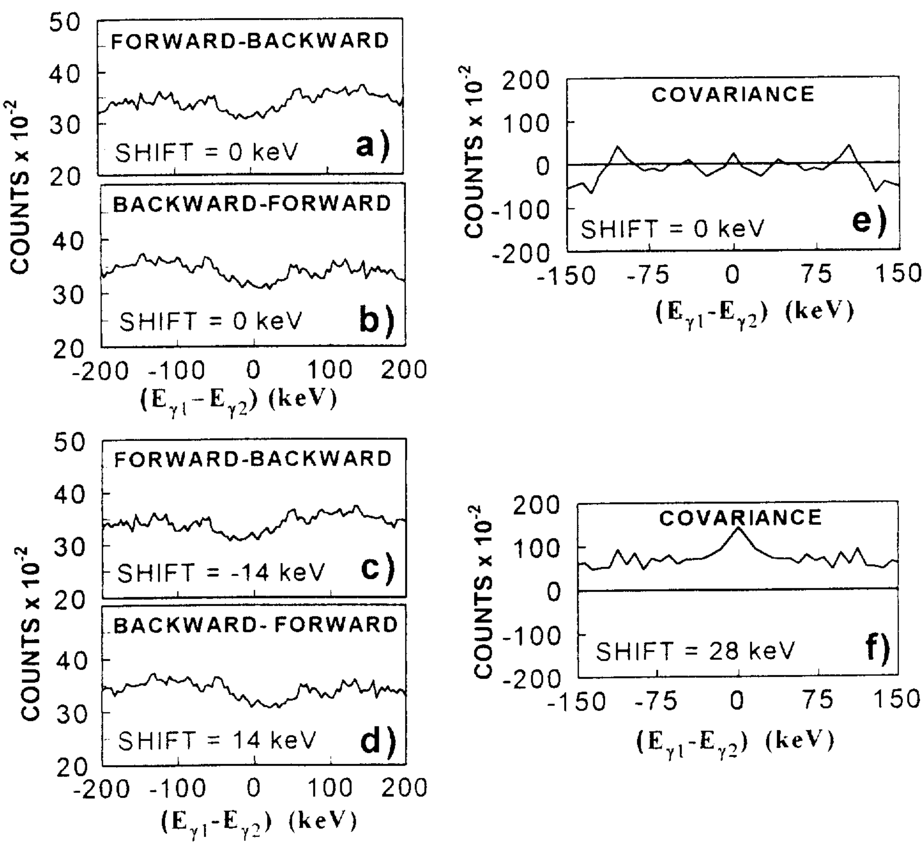

Figure 1. Spectra obtained as perpendicular cuts, 60 keV wide, at $< E_\gamma > = 960$ keV. In particular: *Part a)*: cut on $(E^F_{\gamma_1} \times E^B_{\gamma_2})$; *Part b)*: cut on $(E^B_{\gamma_1} \times E^F_{\gamma_2})$; *Part c)*: cut on $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=-14keV}$; *Part d)*: cut on $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{Shift=+14keV}$; *Part e)*: Covariance μ_{cov} between the spectra of part *a)* and *b)*. *Part f)*: Covariance μ_{cov} between the spectra of part *c)* and *d)*.

2. Experiment and data analysis

The experiment used the reaction ^{30}Si(E_{beam} = 150 MeV)+^{138}Ba and was carried out with the EUROGAM II detector array. The most populated channel was 4n, corresponding to ^{164}Yb. The maximum angular momentum reached for the nucleus ^{164}Yb was calculated to be $63\hbar$. A total of 220 and 120 M triple and higher folds events (with an average Ge fold of 5) were collected in the unbacked and backed target experiments, respectively.

The data were sorted in 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 $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{Shift=N}$, obtained by shifting the counts in channel (X,Y) to channel (X+N, Y-N), each corresponding to a given N integer value. The second set consists of spectra of the type $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=-N}$, obtained by shifting the counts in channel (X,Y) to channel (X-N, Y+N).

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

$$\mu_{2,cov}(A,B) \equiv \frac{1}{N_{ch}} \sum_j (M_j(A) - \tilde{M}_j(A))((M_j(B) - \tilde{M}_j(B)) \qquad (1)$$

The sum is over a region spanning N_{ch} channels (in this case 24) in a two-dimensional window, and $\tilde{M}$ denotes an average spectrum (which in our case is found by the routine STATFIT as a numerical smoothed 3rd order approximation to the 2D spectrum [1]).

To illustrate with an example the method we show in figure 1 perpendicular cuts at $< E_\gamma >$ = 960 keV for $(E^B_{\gamma_1} \times E^F_{\gamma_2})$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})$ (parts a and b of Fig. 1) and for $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{Shift=14keV}$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=-14keV}$ (parts c and d of Fig. 1). The covariance spectrum in the valley region is small (≈ 0, see part e in Fig. 1) before we shift the matrices relative to each other, and has a large value (see part f in Fig. 1) when the relative shift is 28 keV.

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

$$r(A,B) \equiv \frac{\mu_{2,cov}(A,B)}{\sqrt{(\mu_2(A) - \mu_1(A))(\mu_2(B) - \mu_1(B))}} \qquad (2)$$

Here, μ_1 and μ_2 are the first and second moments defined for the same region N_{ch}, and μ_2 is related to the expression for the covariance by $\mu_2(A) = \mu_{2,cov}(A,A)$.

A typical example of the correlation coefficient r is shown in Fig. 2a as a function of the relative shift 2N between $(E^B_{\gamma_1} \times E^F_{\gamma_2})_{Shift=N}$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=-N}$, for the transition energy $< E_\gamma >$=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, from which we can deduce the fractional Doppler shift $F(\tau)$. For the valley region, we find $F(\tau) < 1$, which means that this method is sensitive to the value of the quadrupole moment. Furthermore $F(\tau)$ increases with $< E_\gamma >$, as expected.

A stringent test for this new method was obtained analysing data for the same reaction but using an unbacked target. In fact, in such a case one expects to find all transitions fully shifted (F(τ) $\approx$ 1) because the γ-ray emission occurs from the recoiling nucleus at maximum velocity. The results of the analysis of the backed and unbacked target data are shown in Fig. 2a and 2b. In the figure we are comparing data corresponding to the same average transition energy for a backed and a thin target. Indeed, while the backed target data correspond to partial shift, the thin target data correspond to full shift. This result gives a stronger support to the new method. In figure 2 (right panel), the experimental data are shown together with the results of the simulations for three different values of Q_t (5.5, 6.6 and 7.6 eb) [2]. The simulations are based on levels and E2 transition probabilities calculated with the band mixing model [5]. In this figure the results obtained for the analysis of some discrete lines and of the ridge structure [6] are also shown. One can see that both the data associated to the regular rotational motion (discrete transitions and ridges) and those associated to the rotational damped motion (valley) are rather well described by the curve corresponding to Q_t = 5.5 eb.

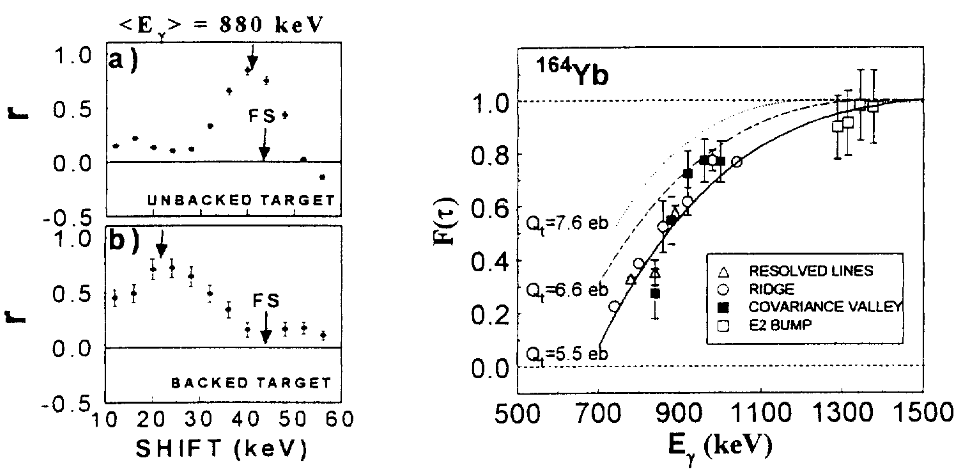

Figure 2. **Left part** : *Part a) and b)* show a tipical example of the correlation coefficient r, associated to the $< E_\gamma > = 880$ keV as a function of the relative shifts between $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=-NkeV}$ and $(E^F_{\gamma_1} \times E^B_{\gamma_2})_{Shift=+NkeV}$ in the case of the thick and thin target experiment, respectively. The arrows indicate the values corresponding to the maximum of r (r_{max}) and to the full shift (FS) from which one deduces the fractional Doppler shift F(τ)= r_{max}/FS. **Right part** : The measured fractional Doppler shifts are shown for some discrete transitions and for different parts of the quasi-continuum spectra. The lines represent the expected theoretical values for Q_t=5.5, 6.6 and 7.6 eb, as obtained from simulated spectra.

3. Conclusion

A new method based on the covariance analysis of spectra measured at forward and backward angles has been developed and has allowed to measure for the first time the quadrupole moment for continuous E2 γ-transitions of a warm rotating nucleus. The results indicate that with increasing excitation energy the nucleus conserves the same collectivity as it has for the regular rotational motion at low excitation energy. This gives a strong support not only to the model of rotational damping but also to the previous findings concerning this subject.

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