Static Electric Quadrupole Moments in the Ground State and $K = 4^-_1$ Bands in ^{168}Er

P. Thakur, M. S. Behra[a], R. Dogra[b], A. K. Bhati, and S. C. Bedi

Physics Department, Panjab University, Chandigarh - 160 014, India
[a] Inter University Consortium - DAEF, Calcutta Centre, Calcutta - 700 091, India
[b] SBS College of Engg. & Tech. Ferozepur -152001, India

Reprint requests to Dr. A. K. Bhati; E-mail: akbhati@pu.ac.in

Z. Naturforsch. **57 a,** 591–594 (2002); received April 2, 2002

Presented at the XVIth International Symposium on Nuclear Quadrupole Interactions, Hiroshima, Japan, September 9-14, 2001.

The time differential perturbed angular correlation (TDPAC) technique has been used to study the nuclear quadrupole interactions of the first excited state of ground state rotational band (2^+, 80 keV, $T_{1/2}$ = 1.88 ns) and the band head of the $K = 4^-_1$ band (4^-, 1094 keV, $T_{1/2}$ = 120 ns) in the ^{168}Er nucleus of a polycrystalline Er host. At room temperature we obtained the electric quadrupole interaction frequencies $\omega_0(K = 0)$ = 457(15) Mrad/s and $\omega_0(K = 4)$ = 69(2) Mrad/s, respectively, for the 2^+ and 4^- isomeric states of ^{168}Er. The ratio of the spectroscopic quadrupole moments, i. e. $Q_s(K = 4)/Q_s(K = 0)$ = 0.69(3), is independent of any model approximation and the electric field gradient at ^{168}Er in the host metal.

Key words: Hyperfine Interactions; TDPAC Technique; Quadrupole Moments.

1. Introduction

^{168}Er is a deformed even-even nucleus in the middle of the deformed nuclei region and is a good test case for the collective model [1]. Nuclear spectroscopic studies have provided a complete level scheme grouped into about 41 rotational bands assigned as collective rotational bands and 2-quasiparticle rotational bands. It has encouraged various theoretical approaches to predict the collectivity and the particle nature of excited states. The electromagnetic properties are derived from γ-transition probabilities, branching ratios etc., but direct information about the nature of the states and the shape of the nucleus in equilibrium is provided by the static nuclear electromagnetic moments. g-factor measurements have been carried out for the ground state (g. s.) rotational band, 2^+ γ-vibrational band and the lowest negative parity $K = 4^-$ band [2, 3]. The deviation of g (2^+vib.) from g (2^+rot.) have been explained in terms of different proton and neutron deformation. The g-factor measurements have confirmed that the lowest negative parity 1094 keV state has the mixed configurations $\{\nu 7^+/2[633] \otimes \nu 1^-/2[521]\}$ (70%) and $\{\pi 7^-/2[523] \otimes \pi 1^+/2[411]\}$ (30%). The quadrupole moments for the g. s. band and the γ-band have been derived from Coulomb excitation data (B(E2) values). The systematics has shown that the measured quadrupole moments of 2^+ γ-vibrational states in even-even Er nuclei are insensitive to the various theoretical model predictions [2]. The model independent measurements of the quadrupole moments of some of the other states, i. e. 2^+ (g. s. band) and 4^- ($K = 4^-_1$ band) can be carried out using the Time Differential Perturbed Angular Correlation (TDPAC) technique.

The sufficiently long relaxation time of the hyperfine field of Er and the short time resolution of BaF_2 scintillators make it possible to observe the quadrupole precession of the 2^+ (E = 80 keV, $T_{1/2}$ = 1.88 ns) and 4^- (E = 1094 keV, $T_{1/2}$ = 120 ns) nuclear states in the paramagnetic phase of Er metal.

2. Experimental Details and Results

The ^{168}Tm ($T_{1/2}$ = 90 days) activity, decaying to ^{168}Er, was obtained through the reaction

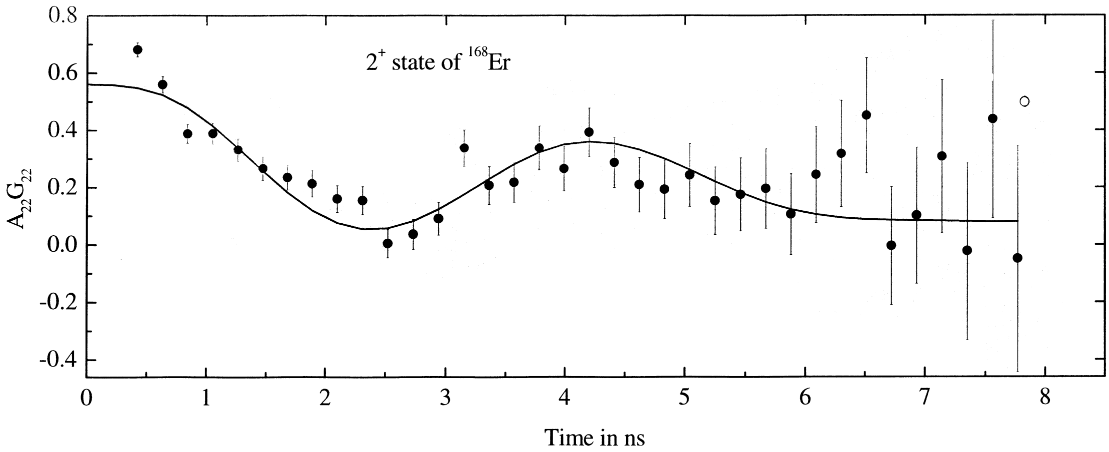

Fig. 1. Spin rotation TDPAC Spectra of the 2^+ state in ^{168}Er.

^{168}Er$(p,n)^{168}$Tm using a 12 MeV proton beam on the cooled natural Er metal target at the Variable Energy Cyclotron, Kolkata. This energy was chosen to maximise the production of the ^{168}Tm and minimise the production of ^{167}Tm ($T_{1/2}$ = 9.6 d) activity through the $(p, 2n)$ reaction. The Er target with ^{168}Tm activity was used for the TDPAC measurements without any heat treatment of the sample after about 3 months (for the decay of the very weak ^{167}Tm activity).

The TDPAC experiments were carried out with the γ-ray cascades 816 - 80 keV and 448 - 830 keV for the intermediate levels 2^+ (80 keV) and 4^- (1094 keV), respectively. The 80 keV state is the first excited state of the g. s. band, and the 1094 keV is the band- head of the $K = 4^-_1$ band. Two coincidence spectra were recorded simultaneously in three-detector geometry at 180° and 90°, detecting 80 keV, 448 keV γ-rays in a 15 mm × 44 mm BaF_2 crystal and 816 keV, 830 keV γ-rays in 25 mm × 44 mm BaF_2 crystals coupled to XP2020Q PM tubes for the intermediate levels 2^+ and 4^-, respectively. The background subtracted and normalized spectra were used to deduce the ratio function $G_{22}(t)$ as

$$G_{22} = \frac{2}{A_{22}} \frac{C(180°) - C(90°, t)}{C(180°) + 2C(90°, t)}, \quad (1)$$

where $C(\theta, t)$ are the background subtracted and normalised time spectra at the angles 180° and 90°. The following theoretical perturbation expression of $A_{22}G_{22}(t)$ for a polycrystalline sample with spin quantum numbers $I = 2$ and 4

$$A_{22}G_{22}(t) =$$

$$f \sum S_{2n} \cos(n\omega_{01}t) \exp\left[-\frac{1}{2}(n\delta\omega_{01}t)^2\right] \quad (2)$$

$$+ (1-f) \sum S_{2n} \cos(n\omega_{02}t) \exp\left[-\frac{1}{2}(n\delta\omega_{02}t)^2\right]$$

has been used. The values of the coefficients S_{2n} are taken from [4] for $I = 2$ and 4. The experimental $A_{22}G_{22}(t)$ function was least-squares fitted to two-fraction model. It was observed that

(i) the fraction corresponding to the self-implanted nuclei at regular sites experiences a unique axially-symmetric quadrupole interaction, and

(ii) the rest of the fraction $(1 - f)$, for nuclei at irregular sites experiences a very low quadrupole interaction and hence is not sensitive to any distribution.

For integer spin, the quadrupole interaction frequency ω_0 is given by

$$\omega_0 = \frac{3eQ_S V_{ZZ}}{4I(2I-1)\hbar}, \quad (3)$$

where Q_S is the spectroscopic quadrupole moment and V_{ZZ} the principal component of the diagonalized electric field gradient (EFG) tensor. The exponential factor takes care of the small Gaussian distribution of the EFG. The amplitude S_{2n} for the different frequency components was fixed in the least squares fitting of the data. For the 2^+ state, the solid line shown in Fig. 1 represents a fitted quadrupole interaction pattern with the parameters ω_{01} = 467(15) Mrad/s and

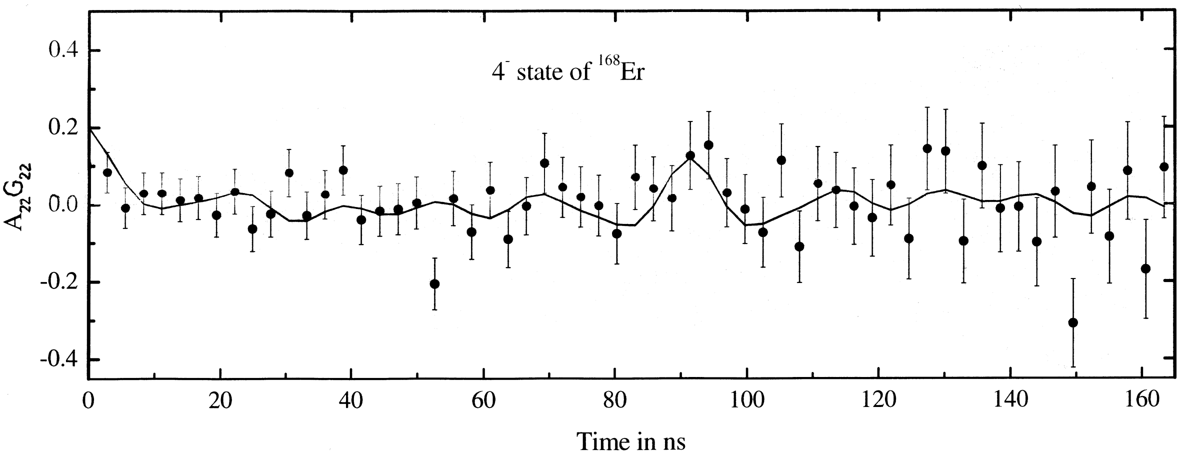

Fig. 2. Spin rotation TDPAC Spectra of the 4^- state in ^{168}Er.

ω_{02} = 120(8) Mrad/s corresponding to the fractions f and $(1 - f)$ respectively. The fraction (f) and field distribution (δ) at a regular site are observed to be 80% and 0.12, respectively. The value of the effective anisotropy A_{22} is not known. The fitted fraction f simply shows that the major fraction is experiencing a unique EFG at regular sites. In case of the 4^- state, the solid line shown in Fig. 2 corresponds to the interaction frequencies ω_{01} = 69(2) Mrad/s and ω_{02} = 12(7) Mrad/s corresponding to the fractions f and $(1 - f)$, respectively. The fraction (f) and field distribution (δ) at a regular site are fixed at 80% and 0.12, respectively, as observed in case of the 2^+ state.

2.1. Discussion

The Coulomb excitation studies were carried out in even-even Er nuclei to get insight into the electromagnetic properties of the excited state [5]. It is observed that the average intrinsic quadrupole moment of the first excited states is 7.63(6) b, and the shape is expected to be prolate [6]. In the Coulomb excitation only the ground and gamma-band transitions could be excited, and no information could be obtained about the states in other bands. It is observed that the quadrupole collectivity is the dominant feature of low-lying states in the ^{168}Er nucleus. A reduction in the collectivity in the γ-band has been observed for the states around 8^+. The identification and the structure of the negative parity bands were obtained through particle scattering [7] and transfer reactions [8, 9]. The (d, d') reaction [6] has shown the non-collective nature and confirmed the dominant two-quasiparticle configuration of the K^π = 4_1^- band, i. e., $\{\nu 7^+/2[633]\otimes\nu 1^-/2[521]\}$ (70%) and $\{\pi 7^-/2[523]\otimes\pi 1^+/2[411]\}$ (25%). The measured quadrupole interaction frequencies in our case can be used to derive the spectroscopic quadrupole moments and their ratios for the 2^+ (80 keV) and 4^- (1094 keV) states, i. e. $Q_S(I = 4)/Q_S(I = 2) = 0.69(3)$. This factor is independent of the EFG at the nucleus and any theoretical approximation. It is interesting to note the reduction of the quadrupole moment of the 4^- state. Further, if we assume K to be a good quantum number and define Q_S as the projection of the intrinsic quadrupole moment Q_0 along the symmetry axis, then from the Bohr-Mottelson formula

$$Q_S = Q_0 \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} \quad (4)$$

the ratio $Q_0(4^-)/Q_0\,(2^+)$ can be deduced to be 0.39(2) and deformation parameter $\beta(4^-)/\beta(2^+)$ to have value 0.45(6) by using the relationship

$$Q_0 = \frac{3}{\sqrt{5\pi}} ZR^2(\beta_2 + 0.36\beta_2^2), \quad (5)$$

where Z and R have their usual meaning. (5) is valid in the case of axially symmetric and strongly deformed nuclei. The reduction of the deformation is much greater than expected in this region at low spin values. This drastic change in deformation may be attributed to the shape difference or the K-mixing due to Coriolis interaction. Lifetime measurements of the 5^- member of $K^\pi = 4^-$ band have shown [10] that the intrinsic quadrupole moment (Q_0 = 7.4(4) b) of the $K^\pi = 4^-$ band is comparable to the ground state band (Q_0 = 7.63(6) b). In view of their uncertainties and model dependences, it is useful to assume the deformation or the intrinsic quadrupole moment to be the same in both the g. s. and $K = 4^-$ band. Under this assumption (4) can be solved for the effective value of K for the same value of Q_0 in the g. s. band and the $K^\pi = 4^-$ band. It comes out to be K = 2.9(2). This is smaller than the experimentally observed nature of this isomer, i. e. K = 4 for the configuration $\nu\{7^+/2[633]\otimes 1^-/2[521]\}$ 70% and 25% proton component $\pi\{7^-/2[523]\otimes 1^+/2[411]\}$. It indicates the presence of neutron orbitals of different Ω values, e. g. $\nu 5^+/2[642]$. In N = 100 isotones the maximum hindrance factor for the E1 decay from the $K^\pi = 4^-$ band to the g. s. band is observed in ^{168}Er [9]. The variation of the E1 hindrance factor is analyzed in terms of shape difference or K value difference. Detailed total routhian surface (TRS) calculations are desired to have a clear picture in this regard.

Acknowledgement

This research work was supported by the University Grants Commission through the Inter University Consortium – DAEF, Calcutta Centre, Govt. of India. The help by the Variable Energy Cyclotron Calcutta crew in the irradiation of the sample is gratefully acknowledged.

[1] A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. 2, W. A. Benjamin, New York 1975.
[2] I. After, E. Bondensted, W. Knichel, and J. Schüth, Nucl. Phys. **A 635**, 273 (1998).
[3] A. Furusawa, M. Kanazawa, and S. Hayashibe, Phys. Rev. **C 21**, 2575 (1980).
[4] E. Dafni, R. Bienstock, M. H. Rafailovich, and G. D. Sprouse, At. Data and Nucl. Data Tables **23**, 315 (1979).
[5] S. Raman, C. H. Malarkey, W. T. Milner, C. W. Nestor, and P. H. Stelson, At. Data and Nucl. Data Tables **36**, 1 (1987).
[6] T. J. Humanic, J. X. Saladin, J. G. Alessi, and A. Hussein, Phys. Rev.**C 27**, 550 (1983).
[7] P. O. Tjom and B. Elbek, Nucl. Phys. **A 107**, 385(1968).
[8] D. G. Burke, B. L. W. Maddock, and W. F. Davidson, Nucl. Phys. **A 442**, 424(1985).
[9] D. G. Burke, W. F. Davidson, J. A. Cizewski, R. E. Brown, and J. W. Sunier, Nucl. Phys. **A 445**, 70 (1985).
[10] P. Petkov, W. Andrejtscheff, J. Copnell, and S. J. Robinson, Nucl. Phys. **A 533**, 49(1991).