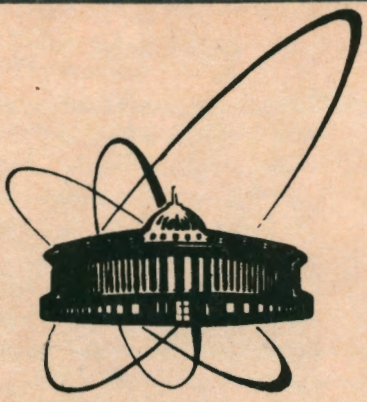

объединенный
институт
ядерных
исследований
дубна

E4-92-183

V.O.Nesterenko, Ph.N.Usmanov[1], A.A.Okhunov[2],
C.Fahlander[3]

THE NONADIABATIC BEHAVIOUR OF $E2(\gamma \rightarrow gr)$ TRANSITIONS IN ^{166}Er

Submitted to "Journal of Physics G"

[1]Department of Physics, Moscow State University, Moscow, Russia
[2]Institute of Nuclear Physics, Academy of Science of the Uzbekistan, Tashkent, Uzbekistan
[3]The Svedberg Laboratory, Uppsala University, Box 533, S-751 21 Uppsala, Sweden

1992

1 Introduction

An almost complete set of reduced E2 matrix elements for the ground and γ bands up to spin 14^+ and 12^+ , respectively, has recently been measured for ^{166}Er in a Coulomb excitation experiment [1]. In total 44 E2 matrix elements have been determined in a model-independent way. Some of them clearly show a nonadiabatic behavior (the deviation from the Alaga rule).

The calculations of the E2 matrix elements within four collective models (the symmetric rotor model, the asymmetric rotor model [2] with $\gamma = 10°$ and $\gamma = 12.7°$, the rotation-vibration model [3], and the IBM-1 model [4]), having been performed in [1] show that both the γ deformation and rotation-vibration coupling may be responsible for the strong slope in the $I_\gamma \rightarrow (I-2)_{gr}$ transition (see figure 1 taken from ref. [1]). However, these models failed in explanation of the sudden increase of this $E2$ matrix element.

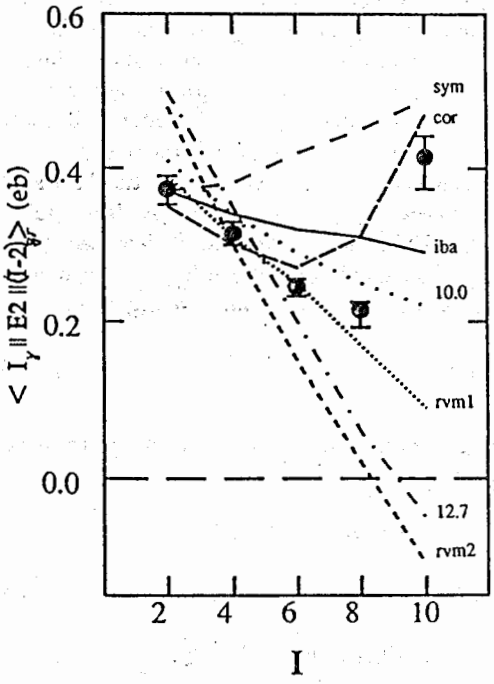

Fig 1: The experimental and calculated values [1] of the $I_\gamma \rightarrow (I-2)_{gr}$ matrix elements in Er^{166}. The calculations were performed within the adiabatic approximation (adi), the symmetric rotor model (sym), asymmetric rotor model [2] (10.0 and 12.7 label $\gamma = 10°$ and $\gamma = 12.7°$ versions, respectively), rotational-vibrational model [3] (versions rvm1 and rvm2), IBA-1 model [4](iba) and phenomenological model [5 – 9] (cor).

The Dubna group is known to succeed in the description of the nonadiabatic

effects in $E2(\gamma \rightarrow gr)$ transitions in the framework of the phenomenological model where the Coriolis coupling between γ and ground bands through the one 1^+ state (interpreted as a "scissors" mode) is taken into account [5 – 9]. This model uses the band head energies, moments of inertia, matrix elements of the Coriolis coupling as well as some basic E2 matrix elements as parameters fitted so as to reproduce the experimental data for the spectrum and electromagnetic transitions. In some sense the model takes into account (through their parameters) the $\gamma-$ deformation. Figure 1 shows that the model [5 – 9] succeeds in the description of the experimental data.

From the physical point of view the main idea of the model [5 – 9] about the Coriolis coupling between γ and ground bands through the one 1^+ state seems to be rather reasonable. But it is apparent that the energy excitation interval 2-5 MeV embracing the"scissors" mode has to include a large number of 1^+ states. Therefore, it is rather attractive to perform the microscopic investigation of this problem, taking into account all the 1^+ states in this energy interval and not using any free parameters. This is just the main aim of the present paper. We do not take here into account the $\gamma-$ deformation since this would result in rather cumbersome calculations. Of course, in this case we should not wait for the nice description of the experimental data from the very beginning. Nevertheless, as is seen below, such a consideration results in some interesting conclusions about the rule of the Coriolis coupling in the nonadiabatic behavior of $E2(\gamma \rightarrow gr)$ transitions.

Also an interesting question arises: What 1^+ states will contribute mostly to the nonadiabatic effects, those from the "scissors" mode region or the lowest ones? In the former case the new way of manifestation of the "scissor" mode appears. Although the 1^+ states in the energy interval of the "scissors" mode have been investigated very carefully within the microscopic models (see the review article [10] and refs. therein), the problem mentioned above has not been considered before on a microscopic footing and is also the aim of our investigation.

2 The model

The Hamiltonian of the model is written as a sum of the rotational, intrinsic and Coriolis interaction terms:

$$H = H_{rot} + H_{intr} + H_{cor}, \tag{1}$$

where in the familiar notation

$$H_{rot} = \frac{h^2}{2J} \cdot (I^2 - I_3^2), \tag{2}$$

$$H_{cor} = -\frac{h^2}{2J} \cdot (I^+ j^- + I^- j^+). \tag{3}$$

$$H_{intr} = H_{sp} + H_{pair} + H_{mm}, \tag{4}$$

In eq. (4) H_{sp} is the Woods - Saxon potential, H_{pair} is the monopole pairing and H_{mm} is the quadrupole isoscalar and isovector interaction with $\lambda\mu = 22$ and 21 [11].

The wave function of the Hamiltonian (1) has the form

$$\mid I^\pi M\rho >= \sum_{K\nu} b^{I\rho}_{\nu K} \cdot \mid I^\pi MK\nu >, \tag{5}$$

where $b^{I\rho}_{\nu K}$ are the Coriolis mixing coefficients; M and K are the angular momentum projections in the laboratory and intrinsic systems, respectively; ρ and ν are additional quantum numbers. Further [12]

$$\mid I^\pi MK\nu >= \sqrt{\frac{2I+1}{16\pi^2(1+\delta_{K,0})}} \cdot (D^I_{MK} + (-1)^{I+K} D^I_{M-K} R_i) \cdot \Psi_\nu(K^\pi), \tag{6}$$

where R_i is the operator of rotation by an angle π around the second intrinsic axis and $\Psi_\nu(K^\pi)$ is a one-phonon state:

$$\Psi_g(K^\pi) = Q^\dagger_g \mid > \tag{7}$$

where $\mid >$ is the RPA ground state, $g = \lambda\mu\nu, \mu = K, \nu$ is the number of the state with given $\lambda\mu$.

The reduced probability of $E\lambda$ transition between the states (5) is written as [12]

$$B(E\lambda, I^\pi_\rho \rightarrow I'^{\pi'}_{\rho'}) = \frac{1}{(2I+1)} \mid < I'^{\pi'}_{\rho'} \| E\lambda \| I^\pi_\rho > \mid^2 \tag{8}$$

In our case the reduced matrix element entering into expression (8) may be written as

$$< I^+_\gamma \| E2 \| I^+_{gr} >= \sqrt{2I_{gr}+1} \cdot (M(E2)_{Q_0} + M(E2)_{1^+} + M(E2)_\gamma), \tag{9}$$

where

$$M(E2)_{Q_0} = \sqrt{\frac{5}{16\pi}} eQ_0 \cdot \{ \sum_{\rho=gr,\gamma} b^{I_{gr}}_\rho b^{I_\gamma}_\rho C^{I_\gamma K_\rho}_{I_{gr}K_\rho;20} + \sum_{\nu=1}^{N} b^{I_{gr}}_{1^+_\nu} b^{I_\gamma}_{1^+_\nu} C^{I_\gamma 1}_{I_{gr}1;20} \}, \tag{10}$$

$$M(E2)_{1^+} = \sqrt{2} \cdot \sum_{\nu=1}^{N} L^{E2}_{1^+_\nu} \{ b^{I_{gr}}_{gr} b^{I_\gamma}_{1^+_\nu} C^{I_\gamma 1}_{I_{gr}0;21} - b^{I_{gr}}_{1^+_\nu} b^{I_\gamma}_{gr} C^{I_\gamma 0}_{I_{gr}1;2-1} \}, \tag{11}$$

$$M(E2)_\gamma = \sqrt{2} \cdot L^{E2}_\gamma \{ b^{I_{gr}}_{gr} b^{I_\gamma}_\gamma C^{I_\gamma 2}_{I_{gr}0;22} + b^{I_{gr}}_\gamma b^{I_\gamma}_{gr} C^{I_\gamma 0}_{I_{gr}2;2-2} \}. \tag{12}$$

In (10)-(12) L^{E2}_g is the matrix element of the E2 transition between the one-phonon state g and the ground state, Q_0 is the quadrupole moment calculated by microscopic way [11]. The operator of $E\lambda\mu$ transition has the form

$$\hat{p}(E\lambda\mu) = ee^\tau_{eff} r^\lambda (Y_{\lambda\mu} + (-1)^\mu Y_{\lambda-\mu})(1+\delta_{\mu,0})^{-1}, \tag{13}$$

where the effective charge $e^{\tau}_{eff} = (1+\tau)/2 + e_{eff}$ is fitted so as to describe the experimental $B(E\lambda)$ values, $\tau = -1$ for neutrons and 1 for protons.

The parameters of the Woods-Saxon potential were taken from ref. [13] and the single-particle spectrum from the bottom of the potential well up to +5 MeV was included. The parameters of the pairing interaction were chosen so as to reproduce the experimental pairing energies. The γ-vibrational $K^{\pi} = 2^+$ state and 30 $K^{\pi} = 1^+$ states (all 1^+ states with excitation energies up to 5 MeV) have been calculated within the RPA using the isoscalar and isovector quadrupole interaction with $\lambda\mu = 22$ and 21, respectively. The strength constants of the isoscalar quadrupole interaction $\kappa_0^{(22)}$ and $\kappa_0^{(21)}$ have been adjusted so as to describe the experimental energy of the $K^{\pi} = 2^+$ state and to put the first solution of the secular equation for 1^+ states to be zero. As is shown in ref. [14], the latter condition together with the use of the surface type of radial dependence of the quadrupole interaction is sufficient to extract spurious admixtures caused by the violation of the rotation invariance of the Hamiltonian. This is just the case in our calculation, where the derivative of the spherical Woods-Saxon potential is used as the radial dependence of the quadrupole interaction. The strength constants of the isovector interaction fulfil the condition ($\kappa_1^{(\lambda\mu)} = -1.5\kappa_0^{(\lambda\mu)}$) to reproduce the energy of the isovector giant quadrupole resonance. We also use $e_{eff} = 0.02$ to correctly describe the experimental value of $B(E2, 0^+0_{gr} \rightarrow 2^+2_{\gamma})$. The moment of inertia is the same for all the bands and its value has been fitted to describe the energies of the 2^+, 4^+ and 6^+ members of the ground band using the prescription [15].

The Coriolis matrix elements for the coupling between the γ and 1^+_{ν} bands have the form

$$< 2^+_{\gamma} \mid j^+ \mid 1^+_{\nu} > \equiv < \mid Q_{22i} j^+ Q^+_{21\nu} \mid > = \qquad (14)$$

$$= \sum_{q_1 \geq q_2} j^+_{q_1 q_2} (u_{q_1} u_{q_2} + v_{q_1} v_{q_2}) \cdot \sum_{q_3} (\psi^{221}_{q_1 q_3} \psi^{21\nu}_{q_2 q_3} + \psi^{221}_{q_3 q_2} \psi^{22\nu}_{q_3 q_1})(1 + \delta_{K_1+K_2,1})$$

In (14) u_q and v_q are the Bogoliubov transformation coefficients, $j^+_{q_1 q_2}$ is the single-particle matrix element for the operator $j^+ = j_x + ij_y$. The Coriolis matrix of dimension 32×32 has been diagonalized.

It should be noted that if in the RPA calculations the rotational invariance is restored correctly, the Coriolis interaction between gr band and $K^{\pi} = 1^+$ bands is exactly zero or in other words we have

$$< 1^+_{\nu} \mid j^+ \mid > \equiv < \mid Q_{21\nu} j^+ \mid > = 0. \qquad (15)$$

Indeed, in this case the state $j^+ \mid >$ is the spurious one and, as a result, it should be orthogonal to all the one-phonon states [14,16]. So in the framework of this approach the $K^{\pi} = 1^+$ bands are coupled by the Coriolis interaction with γ band only. In this case, $M(E2)_{Q_0} = 0$ whereas $M(E2)_{1^+}$ and $M(E2)_{\gamma}$ contain the first terms only and influence of the Coriolis coupling should be rather weak which is

confirmed by our calculations presented below. To switch on the coupling of the $K^{\pi} = 1^+$ bands with gr band, we should generalize the approach ,e.g., taking into account γ deformation [2].

3 The results and discussion

In figure 2 the calculated spectrum for the ground, γ and 1^+_1 bands in comparison with the experimental data is presented. Following the above consideration the spectrum of the ground band was calculated in the adiabatic approximation while for the γ and lowest 1^+ bands the Coriolis coupling was taken into account. It is seen that the description of the ground band and of the low-spin members (up to 10^+) of the γ band (only the $E2$ transitions from these levels are considered here) is quite satisfactory.

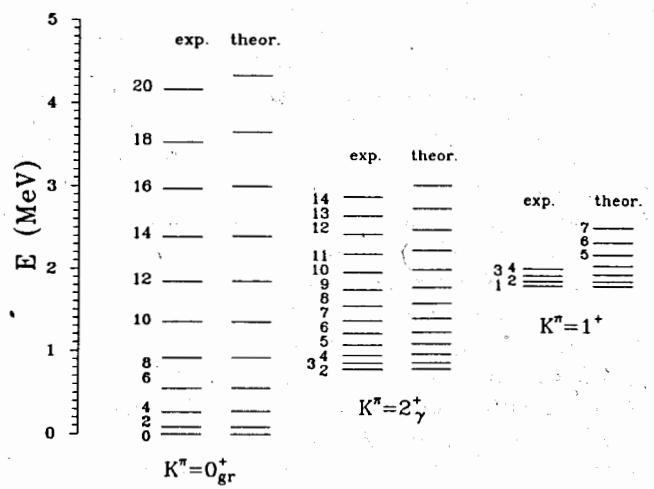

Fig 2: The experimental [1] and theoretical spectrum of the ground, γ and 1^+_1 bands in ^{166}Er.

In table 1 the largest Coriolis mixing coefficients for the γ bands are given. The mixing with the 1^+ states is shown to be noticeable both for the low-lying and

Table 1: The Coriolis mixing coefficients for the γ band.

I	$b^{I_\gamma}_{1^+_\nu}$								
	1^+_1	1^+_7	1^+_8	1^+_{11}	1^+_{13}	1^+_{17}	1^+_{22}	1^+_{23}	γ
2	-.0277	-.0137	-.0076	-.0116	.0071	-.0066	.0063	-.0127	.9992
3	-.0426	-.0212	-.0118	-.0180	.-109	-.0105	.0097	-.0181	.9981
4	-.0554	-.0276	-.0153	-.0234	.0142	-.0137	.0127	-.0236	.9968
5	-.0667	-.0334	-.0185	-.0283	.0172	-.0165	.0153	-.0285	.9953
6	-.0768	-.0386	-.0214	-.0327	.0199	-.0191	.0177	-.0330	.9938
7	-.0860	-.0433	-.0241	-.0368	.0223	-.0215	.0199	-.0371	.9922
8	-.0942	-.0476	-.0265	-.0405	.0246	-.0236	.0219	-.0408	.9906
9	-.1017	-.0516	-.0287	-.0439	.0266	-.0256	.0238	-.0443	.9889
10	-.1085	-.0552	-.0307	-.0470	.0285	-.0274	.0255	-.0475	.9873
11	-.1147	-.0586	-.0326	-.0499	.0303	-.0292	.0271	-.0504	.9858
12	-.1205	-.0618	-.0344	-.0526	.0319	-.0307	.0286	-.0532	.9842

high-lying (the "scissor mode" region) states.

It is interesting to compare the collectivity of the 1^+ states from the low-energy and "scissors" mode regions. For this purpose the structure and the $B(E2, 0^+0_{gr} \rightarrow 2^+K)$ values for the lowest and the two most collective 1^+ states from the "scissors" mode region are presented in table 2. The same characteristics for the $\gamma-$ vibrational state are also given. It is seen that the 1^+ states from both the regions are quite collective.

The correlation between the collectivity of the 1^+ states and the Coriolis matrix elements (14) is demonstrated in figure 3. The larger the collectivity of the 1^+ band head the stronger the coupling between this band and the γ band. Indeed, it should be the case since according to (14) the coupling takes place only if the 1^+ state and the γ- vibrational state contain identical quasiparticles in their structures. This is most probable for the collective states and table 2 confirms this assertion. On the other hand, this correlation clearly shows the importance of the residual interaction for the 1^+ states.

It is interesting to compare the collectivity of the 1^+ states from the low-energy and "scissors" mode regions. For this purpose the structure and the $B(E2, 0^+0_{gr} \rightarrow 2^+K)$ values for the lowest and the two most collective 1^+ states from the "scissors" mode region are presented in table 2. The same characteristics for the $\gamma-$ vibrational state are also given. It is seen that the 1^+ states from both the regions are quite collective.

The correlation between the collectivity of the 1^+ states and the Coriolis matrix elements (14) is demonstrated in figure 3. The larger the collectivity of the 1^+ band head the stronger the coupling between this band and the γ band. Indeed, it should

Table 2: The calculated excitation energies (MeV), reduced transition probabilities $B(E2, 0^+0_{gr} \rightarrow 2^+K)$ (Wu), and structure (the main two-quasiparticle components with their contributions in % to the states) of the $K^\pi_\nu = 2^+_1$, 1^+_1, 1^+_{11} and 1^+_{23} states.

K^π_ν E_ν $B(E2)\uparrow$	The main two-quasiparticle components	%	K^π_ν E_ν $B(E2)\uparrow$	The main two-quasiparticle components	%
2^+_1	$nn523\downarrow -521\downarrow$	30	1^+_{11}	$nn532\downarrow -521\downarrow$	20
0.786	$pp411\uparrow +411\downarrow$	28	3.66	$pp402\uparrow -411\uparrow$	16
22	$nn521\uparrow +521\downarrow$	16	1.3	$nn514\downarrow -512\uparrow$	16
	$pp413\downarrow -411\downarrow$	6		$nn523\downarrow -532\downarrow$	10
1^+_1	$nn633\uparrow -642\uparrow$	71	1^+_{23}	$nn521\uparrow -510\uparrow$	58
1.81	$pp514\uparrow -523\uparrow$	9	4.55	$nn512\downarrow -521\downarrow$	9
3.5	$nn512\uparrow -521\uparrow$	8	0.75	$nn523\downarrow -512\downarrow$	8
	$nn624\uparrow -633\uparrow$	2		$pp411\uparrow -420\uparrow$	5

be the case since according to (14) the coupling takes place only if the 1^+ state and the γ- vibrational state contain identical quasiparticles in their structures. This is most probable for the collective states and table 2 confirms this assertion. On the other hand, this correlation clearly shows the importance of the residual interaction for the 1^+ states.

It should also be noted that the signs of reduced E2 matrix elements $< 0^+_{gr}||M(E2)||1^+_\nu >$ and of the Coriolis coupling matrix elements $< 2^+_\gamma \mid j^+ \mid 1^+_\nu >$ are mainly positive and negative, respectively. It means that the contribution of 1^+ states to the matrix element (9) has to be rather coherent. This will favor the nonadiabatic effects caused by coupling with 1^+ states.

The results of the calculations within the microscopic approach of the reduced E2 matrix elements for the $I_\gamma \rightarrow (I-2)_{gr}$, $I_\gamma \rightarrow (I+2)_{gr}$, $I_\gamma \rightarrow I_{gr}$, $I_\gamma \rightarrow (I-2)_\gamma$, $I_{gr} \rightarrow (I-2)_{gr}$ and $I_{gr} \rightarrow I_{gr}$ transitions in ^{166}Er as well as the experimental data [1] are shown in figure 4. Together with the calculations with the effective charge $e_{eff} = 0.02$ another version is presented where for the $1^+_i \rightarrow 2^+_\gamma$ transitions the value $e_{eff} = 0.3$ was used (to demonstrate the tendency if the collectivity of 1^+ states increases). It is seen that for all the transitions the microscopic calculations give nearly the adiabatic behavior which would be exactly the case if any Coriolis coupling were absent. Such a description is in agreement with the experimental data for all the transitions with the exception of the $I_\gamma \rightarrow (I-2)_{gr}$ one. In latter case, the calculations provide only a slight hint of the deep minima which takes place in the experimental data. Thus, as was assumed before, the microscopic approach presented here fails to describe the nonadiabatic behavior of the $I_\gamma \rightarrow (I-2)_{gr}$ transitions.

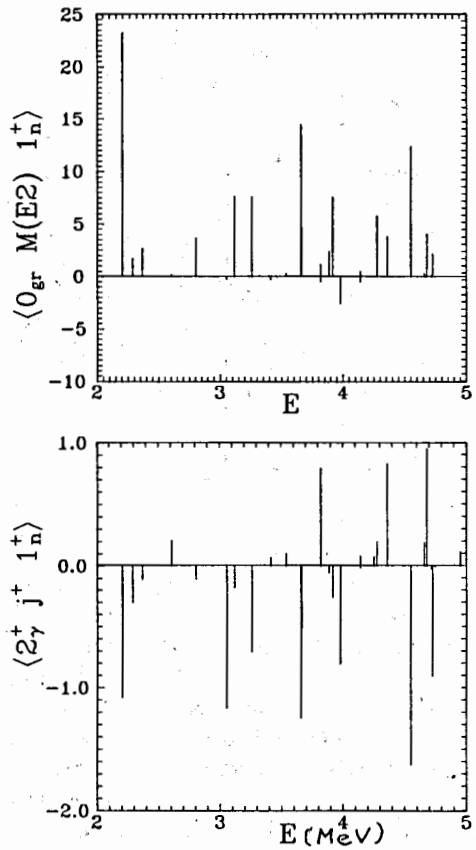

Fig 3: The calculated reduced E2 matrix elements $< 0^+_{gr}||M(E2)||1^+_\nu >$ and Coriolis coupling matrix elements $< 2^+_\gamma \mid j^+ \mid 1^+_\nu >$ in ^{166}Er.

This confirms the conclusions [1] that for the description both the Coriolis coupling and γ deformation should be taken into account. Indeed, the γ deformation results in mixing of the ground and γ bands. The corresponding enhancement of the Coriolis coupling should improve the description of this nonadiabatic behavior. Maybe, the experimental data [1] will turn out to be a rather interesting test for the γ deformation in ^{166}Er.

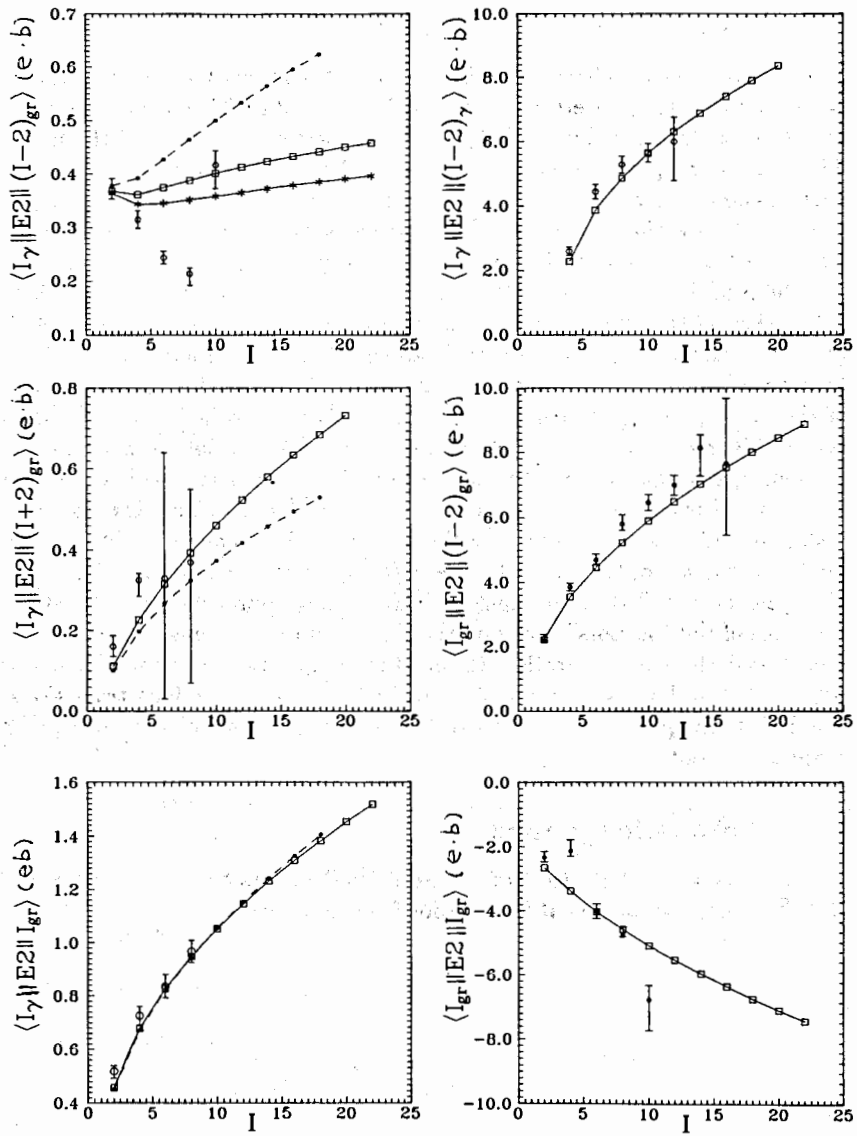

Fig 4: The reduced E2 matrix elements for the $I_\gamma \to (I-2)_{gr}$, $I_\gamma \to (I+2)_{gr}$, $I_\gamma \to I_{gr}$, $I_\gamma \to (I-2)_\gamma$, $I_{gr} \to (I-2)_{gr}$ and $I_{gr} \to I_{gr}$ transitions in ^{166}Er:
●- adiabatic case, o- experimental data [1],
□- microscopic calculations with $e_{eff} = 0.02$,
∗- microscopic calculations with $e_{eff} = 0.3$
for $1^+_\nu \to 2^+_\gamma$ transitions.

Conclusions

The reduced matrix elements of E2 $gr \to \gamma$ transitions measured in the Coulomb excitation reaction [1] were calculated within the RPA with exact extraction of spurious admixtures caused by the violation of the rotation invariance of the Hamiltonian. The Coriolis coupling between γ and ground bands through the 1^+ states is investigated assuming the γ deformation to be neglected. The microscopic analysis shows that in this case the Coriolis coupling between ground and 1^+- bands is exactly zero. This effect seems to be rather interesting and unexpected.

The model gives the adiabatic behavior for all the transitions which is in agreement with all the experimental data except the nonadiabatic behavior of the $I_\gamma \to (I-2)_{gr}$ transitions. In latter case, both the Coriolis interaction and γ deformation have to be taken into account simultaneously. Recently, the nonadiabatic behavior of the $I_\gamma \to (I-2)_{gr}$ transitions can also be discovered in ^{168}Er [17]. Maybe, this type of E2 transitions can be used as a test for γ deformation in this region of nuclei.

The correlation between the collectivity of 1^+ states and their Coriolis coupling with γ band is demonstrated. Due to this effect 1^+ states from the "scissors" mode region should influence noticeably the nonadiabatic behavior of the E2 transitions. On the other hand, this could be the new way of manifestation of "scissors" mode. It should be noted that the nucleus ^{166}Er is not appropriate for the study of the influence of the "scissors" mode on the $E2(\gamma \to gr)$ transitions since in ^{166}Er the $\gamma-$ vibrational state is very collective and the competition between the strong direct $(2^+_\gamma \to 0^+_{gr})$ and weak indirect (due to the Coriolis interaction) transitions is very small. For this purpose, nuclei with 2^+_γ states of small collectivity (e.g., ^{172}Yb) are more appropriate.

Acknowledgement

The authors are grateful to Profs. V.M.Mikhailov, V.G.Soloviev and I.N.Mikhailov, Drs. R. Nazmitdinov and R.Kulessa for fruitful discussions.

References

1. Fahlander C, Thourslund I, Varnestig B, Backlin A et al 1992 Nucl. Phys. **A537** 183
2. Davydov A S and Filippov G F 1958 Nucl. Phys. **8** 237
3. Faessler A, Greiner W and Sheline R K 1965 Nucl. Phys. **70** 33
4. Arima A and Iachello F Advanc. 1984 Nucl. Phys. **13** 139
5. Mikhailov I N, Usmanov Ph N and Yuldashbaeva E Kh 1987 Yad. Fiz. **45** 646
6. Briancon Ch, Mikhailov I N and Usmanov Ph N 1989 Yad. Fiz. **50** 52
7. Gromov K Ya, Islamov T A and Usmanov Ph N 1989 Izv. Akad. Nauk SSSR, Ser. Fiz. **53** 858
8. Kulessa R et al. 1989 Z.Phys. **A334** 299
9. Mikhailov I N and Usmanov Ph N 1991 Yad. Phys. **54** 1239
10. Faessler A, Nojarov R and Scholtz F G 1990 Nucl. Phys. **A515** 237
11. Nesterenko V O, Soloviev V G and Sushkov A V 1986 Preprint JINR P4-86-115 Dubna
12. Bohr A and Mottelson B R 1974 Nuclear Structure **2** (Benjamin W A Inc. New-York Amsterdam)
13. Gareev F A et al 1976 Part. Nucl. **4** 357
14. Baznat M I and Pyatov N I 1975 Yad. Fys. **21** 708
15. Harris S M 1965 Phys. Rev. **B138** 509
16. Mikhailov V M and Pogosjan V V 1972 Yad. Fys. **16** 289
17. Kotlinski B, Cline D, Backlin A et al 1990 Nucl. Phys. **A157** 365

Received by Publishing Department
on April 23, 1992.