SCISSORS MODE IN THE γ-SOFT NUCLEUS ^{134}Ba

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In this study the scissors mode is investigated for γ -soft nucleus ^{134}Ba. Calculations have been made using Quasiparticle Random Phase Approximation method. With the selection of suitable separable effective isoscalar and isovector forces, rotational invariance is restored for the description of the M1 modes. Our calculations show that, results obtained here are in a good agreement with the experimental data. In this work, contribution of $\Delta K=0$ branch of $I^{\pi}=1^{+}$ states to scissors mode region has been investigated, as well. Calculations show that most of the M1 transitions have $\Delta K=1$ character.

I. INTRODUCTION

Recently, great success has been achieved in the measurement of nuclear excitations with low multipolarity [1]. One of them is the observation of strong low-lying magnetic dipole excitations in deformed nuclei, which are frequently referred to as a scissors mode. The study of these excitations gives valuable information about nuclear structure and nucleon-nucleon forces at low energy. In a geometrical picture [2] the scissors mode is visualized as a counter rotational oscillation of the deformed proton body against the deformed neutron body in the intrinsic frame of reference. This mode was first observed in high-resolution electron scattering experiments in Darmstadt [3]. A series of subsequent nuclear resonance fluorescence (NRF) experiments (see e.g., Refs [4]) established the systematic of this common mode in deformed even-even nuclei at excitation energies around *3 MeV*. The remarkable features of the scissors mode obtained from experimental results are the quadratic dependence of the summed B(M1) values on the ground state deformation parameter δ and the strong fragmentation of the M1 strength about the pairing gap up to *4 MeV* excitation energy [5-8]. Properties of scissors mode have been investigated for deformed nuclei in detail. Recently the scissors mode was observed in ^{196}Pt [9]. This was the first observation of the scissors mode in a deformed nucleus with a soft triaxiallity. After than this mode else has been obtained for nucleus from another wide region of γ-soft triaxiallity for ^{134}Ba [10]. In spite of the nature of scissors mode is an open question in nuclei near shell closures where the simple geometrical picture of a scissors-like motion of deformed proton and neutron bodies breaks down. There were only some more experiments else for nucleus from these regions [11]. Unfortunately explicit parity determination is not upper degree in those experiments. Therefore, only with the advent of the new generation of experimental facility with improved detection characteristics it is possible to investigate in detail the fine structure of the M1 response [12]. Earlier, the scissors mode calculations for ^{134}Ba [13] had been made using RPA method. In that work, the broken symmetry of the nuclear Hamiltonian is reached by adding to it only some effective isoscalar forces [13]. However, here certain difficulties immediately arise when the isovector quadrupole coupling constant is chosen. Generally, an isovector dependence of effective forces can arise from the breaking of rotational invariance by the isovector term in the mean-field potential.

Based on these observations the aim of the present work is to investigate the nature of the scissors mode of nucleus ^{134}Ba using RPA method, where broken rotational invariance restored adding effective isoscalar and isovector forces [8]. This approach is self- consistent, since the coupling constants and matrix elements of the effective interactions are, in turn, connected with the characteristics of the deformed field. This method of restoring broken symmetries successfully has been applied to the well deformed and spherical nuclei were restored rotational or transitional invariance [8,14-17]. Here we also investigate the contribution $\Delta K=0$ branch of $I^{\pi}=1^{+}$ states to the scissors mode region.

II. THEORY

A detailed description $I^{\pi};K=1^{+};1$ states generated by the isovector spin-spin interactions in rotational invariant Quasiparticle Random Phase Approximation (QRPA) was given in Ref [8]. There, by the selection of suitable separable effective isoscalar and isovector forces, rotational invariance is restored for the description of the M1 modes for $\Delta K=1$ branches without introducing any additional parameters. In this approximation, the model Hamiltonian of the system can be written

$$H = H_{sqp} + h_0 + h_1 + V_{\sigma\tau} \quad (1)$$

where H_{sqp} is the quasiparticle Hamiltonian with pairing interactions, h_0 and h_1 describe the effective isoscalar and isovector interactions restoring the rotational invariance of the quasiparticle Hamiltonian which are important only for $\Delta K=1$ branch of the 1^{+} states.

Here we followed the methods and notations of Ref.[8]. According to Ref.[8] the rotational invariance of the single-quasiparticle Hamiltonian can be restored with the aid of a separable isoscalar and isovector effective interaction of the form

$$h_0 = -\frac{1}{2\gamma_0}\sum_{\mu}[H_{sqp} - V_1, J_\mu]^+[H_{sqp} - V_1, J_\mu] \quad (2)$$

$$h_1 = -\frac{1}{2\gamma_1}\sum_{\mu}[V_1, J_\mu]^+[V_1, J_\mu] \quad (3)$$

where, V_1 is the isovector part of nuclear potential and J_ν are the spherical components of the total angular momentum for the $K^\pi=1^+$ excitations. Here, γ_0 and γ_1 are the coupling parameters. $V_{\sigma\tau}$ isovector spin-spin interactions that generated the 1^+ states in the deformed nuclei have the form

$$V_{\sigma\tau} = \frac{1}{2}\chi_{\sigma\tau}\sum_{i\neq j}\vec{\sigma}_i\vec{\sigma}_j\vec{\tau}_i\,\vec{\tau}_j \quad (4)$$

where, $\vec{\sigma}$ and $\vec{\tau}$ are the Pauli matrices that represent the spin and the isospin, respectively.

Due to the symmetries of the effective restoring forces, spin- spin interactions and the magnetic dipole operator, the most characteristic quantity of 1^+ state is the reduced *M1* transition probability, which can be written in the form [8]

$$B(M1, 0^+ \to 1_i^+) = = \frac{3}{4\pi}\left| R_p(\omega_i) + \sum_{\tau}(g_s^\tau - g_l^\tau)R_s^\tau(\omega_i)\right|^2 \mu_N^2 \quad (5)$$

Here g_s and g_l are the spin and orbital gyromagnetic ratios of the free nucleons, respectively.

The energy-weighted sum rules for *M1* transitions are given as

$$2\sum_i \omega_i B(M1, 0^+ \to 1_i^+) = [\vec{\mu}^+, [H, \vec{\mu}]]_{RPA} \quad (6)$$

In the RPA, right-hand side of the this sum rule can be obtained

$$[\vec{\mu}^+, [H, \vec{\mu}]]_{RPA} = \frac{3}{4\pi}[\gamma_p + \sum_{\tau}(g_s^\tau - g_l^\tau)\delta^\tau - \frac{(\gamma_p - \gamma_l^p)^2}{\gamma - \gamma_1} - \frac{\gamma_l^{p\,2}}{\gamma_1}]\mu_N^2 \quad (7)$$

where

$$\gamma_\tau = 2\sum_{\mu}{}^{(\tau)}\varepsilon_\mu L_\mu^2 j_\mu^2 ;$$

$$\delta_\tau = 2\sum_{\mu}{}^{(\tau)}\varepsilon_\mu L_\mu^2 j_\mu s_\mu .$$

Since the effective forces h_0 and h_1 are not commutative with the $J_{\pm 1}$ operators besides the H_{sqp} part of the Hamiltonian, they also contribute to the sum rules (7). In this formula, the last two, which represent the contributions of the isoscalar and isovector effectively restoring forces to the sum rule, are important.

Another important quantity of the orbital 1^+ states is excitation energies. In order to establish the average energy of the M1 strength below *4 MeV* we use the energy weighted and not energy weighted sum rules,

$$\overline{\omega} = \frac{\sum_i \omega_i B(M1, \omega_i)}{\sum_i B(M1, \omega_i)} \quad . \quad (8)$$

III. RESULTS AND DISCUSSION

In numerical calculations, the experimental value of deformation parameter $\delta=0.161$ of the ^{134}Ba were taken from the ref.[18]. The Nilsson single-particle energies were obtained from Warsaw deformed Wood-Saxon potential [19]. All energy levels from the bottom of the potential well to *6 MeV* were considered for neutrons and protons. The pair-interaction constants Δ and λ were chosen in accordance with Soloviev [20]. For the strength parameter of the isovector spin -spin interactions we used $\chi_\sigma=40/A$ *MeV*, which has been obtained from magnetic moments calculations. To show important restoration broken symmetry we present here result of calculation obtained without any restoration, result taken from ref [21] where restored only broken isoscalar forces and result of calculation obtained using restored broken isoscalar and isovector forces of the mean field potential. The calculated 1^+ excitation energies and the corresponding *B(M1)* values are shown in Fig.1. As can be seen in Fig. 1 calculations made without any restoration gives for scissors mode summed *B(M1)* $= 4.163\,\mu_N^2$ strength with *8* levels.

The results obtained using only isoscalar restoring forces taken from Ref.[21] give summed $B(M1) = 0.49\,\mu_N^2$ with only *2* levels (in Ref[21], the level obtained at the energy *E=395 keV* hase not been interpreted as scissors mode level). Despite the fact that the results above give the scissors mode like distribution, they are not in agreement with the experimental results.

According to Ref.[8] using isoscalar and isovector restoring forces to restoration the broken rotational invarians, we obtain the sum $\sum_i B(M1; 0_1^+ \to 1_i^+) = 0.60\mu_N^2$ with *10* levels, where ratio *l/s>1*. These levels can be interpreted as a scissors mode. Comparison this result with the results above we observe that the consideration of the isoscalar and isovector restoring forces causes the splitting of the states with large *B(M1)* strengths and fragments the M1 strength into more levels.

Where experiment obtained the total *M1* strength summed over all states, where $J^\pi = 1^+$ is at least tentatively assigned, amounts to $\sum_i B(M1; 0_1^+ \to 1_i^+) = 0.56\mu_N^2$ strength with 6 levels [10] (Fig.1). Due to the low cross sections, firm assignments of spins and parities were not possible for many levels [10]. Although the experiment had been performed in correct spin and parity for only one state, it was assumed that some of the other states were also scissors mode states. So the total strength of the scissors mode in ^{134}Ba presumably does not deviate too much from the value $\sum_i B(M1;0_1^+ \to 1_i^+) = 0.56\mu_N^2$. But for correct determination of scissors mode strength in this region the parity measurement is necessary.

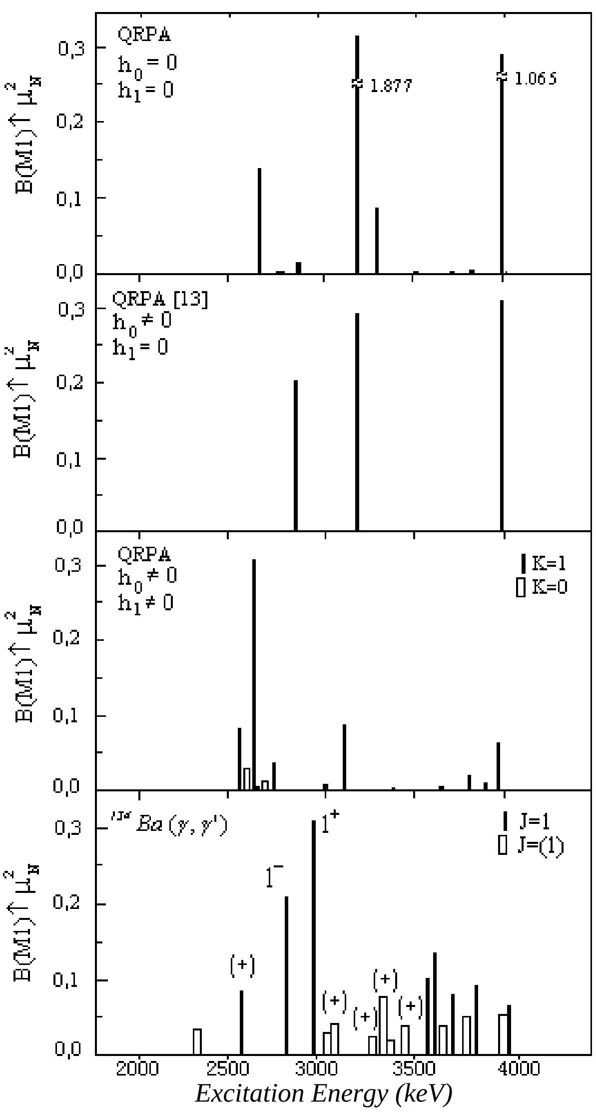

Fig. 1. Spectral distribution of the dipole excitations strength in the ^{134}Ba nucleus

Our theoretical calculations gives for ^{134}Ba several collective 1^+ state (mainly $\Delta K=1$ branch) in the energy interval *2.5- 4 MeV* with an energy centroid $\overline{E} = 2.9$ *MeV*. Also experiment show dipole strength distribution in ^{134}Ba extracted from the measured photon scattering cross sections in the energy range up to *4MeV* with an energy centroid $\overline{E} = 2.987$ *MeV*. As can be seen results obtained in this work are in good agreement with experiment. Comparison results are given in Table 1.

Table1. Comparison RPA calculation with Experimental Results of $I^\pi;K=1^+$; 1 states of ^{134}Ba

RPA Calculations [21]		*RPA Calculation (This Work)*		*Experimental Results [10]*	
$\overline{E}$ (MeV)	$\sum_i B(M1)$ μ_N^2	$\overline{E}$ (MeV)	$\sum_i B(M1)$ μ_N^2	$\overline{E}$ (MeV)	$\sum_i B(M1)$ μ_N^2
3.07	*0.49*	*2.9*	*0.6*	*2.987*	*0.56(4)*

Our results is also in a good agreement with empirical sum rule for the excitations strength of the scissors mode obtained from the *B(E2)* value

$$B(M1)_{sc} = \frac{10.6}{Z^2} B(E2;0_1^+ \to 2_1^+) \qquad (9)$$

This has been formulated in Ref.[22]. From the known *B(E2)* values of ^{134}Ba, using formula (9) we have obtained $B(M1)_{sc}\uparrow = 0.61(2)\,\mu_N^2$, which is in agreement with the our theoretical value and experiment.

As can be seen in Fig1., the experiment shows the 1^+ state at energy *E=2939 keV* with a relatively large M1 excitation strength of $B(M1;\ 0^+ \to 1^+) = 0.307\,\mu_N^2$. This level is only one level where made correct parity and multipolarity determination. The corresponding excitation obtained from our calculation at energy *E=2612 keV* with $B(M1;\ 0^+ \to 1^+) = 0.305\,\mu_N^2$. Also theory predicts 1^+ state at energy *E=2583 keV*, with excitation strength of $B(M1) = 0.083\,\mu_N^2$, so experiment gives spin one state at energy *E=2571 keV*, with excitation strength of $B(M1)=0.081\,\mu_N^2$ which can be attributed to magnetic dipole transition. According with the results obtained here we can say experimental observed spin one state at energy *E=2571 keV* may have positive parity.

Furthermore, above an excitation energy of *3500 keV* experimentally eight states where observed, four of them with spin assignment *J=1*. Experiment according to Ref. [21] were restored only isoscalar forces and expected that the magnetic dipole excitations above *3500 keV* have a low orbit-to-spin ratio and thus do not belong to the scissors mode. However our rotational invariant RPA calculation predicts three high orbit-to spin ratio *(l/s>1)* levels with summed excitation strength of $B(M1)\uparrow = 0.086\,\mu_N^2$. It has been shown that some of observed strengths in experiment above *3500 keV* are in orbital character. This situation shows that without any correct spin determination it is no right makes any comment.

Here we also made calculation for $\Delta K = 0$ branch of $I^\pi = 1^+$ states. The obtained summed B(M1) value for $\Delta K = 0$ is $B(M1;\ K^\pi = 0^+) = 0.045\,\mu_N^2$ with only two strength (Fig.1). Our results showed that likely the deformed nuclei [23] in γ-soft nuclei, all stronger M1 transitions were $\Delta K = 1$ character. Where $\Delta K = 0$ branch take only *8 %* of all strength.

IV. CONCLUSION

Results obtained here show that using isovector and isoscalar effective forces fragmented the scissors mode of appropriate with fragmentation with deformed rare earth nuclei but gives the scissors mode strength amounts to about *1/5* of the strength in typical deformed nuclei. These results are suitable with experiment. Besides this, our calculations show the important consideration of the isovector restorating forces in calculations. These results point out, the choice of the isoscalar and isovector forces in a self-consistent manner based on the rotational invariance of the Hamiltonian makes it possible to treat the scissors mode more rigorously without any extra quadrupole-quadrupole inteaction parameter and results gained in this case has been found to be in a close proximity to the experimental data.

Recent experiments show that the scissors mode is fundamental excitation mode of γ *-soft* nuclei. Our theoretical calculations give same results and show that above *3500 keV* it is possible to obtain scissors mode levels. Our calculations also show that all stronger magnetic dipole strengths are from $\Delta K=1$.

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γ-SOFT BÖLGƏSINDƏ YERLƏŞƏN ^{134}Ba NÜVƏSININ QAYÇI MOD HƏYƏCANLANMALARI

Məqalədə qayçı modu (scissors mode) səviyyələri γ-soft nüvəsi olan ^{134}Ba nüvəsi üçün tədqiq edilmişdir. Hesablamalar QRPA (Quasiparticle Random Phase Approximation) yanaşması bazasında aparılmışdır. Uyğun izoskalar və izovektor effektiv qüvvətləri secilərək *M1* səviyyələri üçün rotasion invariantlıq bərpa edilmişdir. Məqalədə əldə edilən nəticələr təcrübi nəticələrlə uyğunluq təşkil edir. Bundan başqa $I^{\pi}=1^{+}$ həyəcanlanmaların $\Delta K=0$ budağının qayçı modu bölgəsinə əlavəsi də tədqiq edilmişdir. Hesablamalar *M1* səviyyələrin bir çoxunun $\Delta K=1$ budağına aid olduğunu gostərdi.

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НОЖНИЧНАЯ МОДА СОСТОЯНИЯ ДЛЯ ЯДРА ^{134}Ba ИЗ РЕГИОНА γ- СОФТ

В статье была изучена ножничная мода (scissors mode) состояния для ядра из региона γ-софт ^{134}Ba. Вычисления были произведены в рамках QRPA (Quasiparticle Random Phase Approximation). Для M1 переходов С выбором соответствующих изоскалярных и изовекторных эффективных сил была реставрирована нарушенная ротационная инвариантность. Результаты, полученные здесь, соответствуют данным, полученным из экспериментов. Кроме того, здесь было произведено вычисление для ΔК=0 ветви $I^{\pi}=1^{+}$ возбуждения. Было показано, что большинство из M1 состояний принадлежит ветви ΔК=1.

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