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ROTATION OF SUPERDEFORMED EVEN-EVEN NUCLEI

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Starting from the microscopic Hamiltonian of the nucleus we derived an equation to describe the rotation and quadrupole vibrations of even-even axially symmetrical nuclei, having arbitrary deformation β. In case of small β it reduces to the Bohr - Mottelson equation with $\gamma \sim 0$. Such an equation is used for calculations of vibrational-rotational energies of superdeformed nuclei.

Introduction

A lot of papers (see e.g. [1 - 14]) are devoted to investigation of spectra of superdeformed nuclei, which are characterized by the quadrupole deformation parameter $\beta_0 \sim 1$. Their energy levels are usually calculated in the framework of the cranked shell model [10]. But the familiar cranking model deals only with static deformation of the nuclei and do not take into consideration any relation of the rotation and vibrations of the nuclear shape. At the same time, this relation is described by the Bohr-Mottelson equation [15, 16]. Most explicitly the dependence of the rotation of normally deformed nuclei ($\beta_0 \sim 0.2 - 0.3$) on β-vibrations is revealed in the Davydov - Chaban model [16, 17]. But its application to superdeformed nuclei faces with difficulty that the Bohr - Mottelson equation is derived assuming small deviations of the nuclear shape from the sphere, when $\beta << 1$ (see [15, 16]). Therefore their generalization to the case of arbitrary deformations is very actual.

A set of independent collective variables, useful for description of the rotating deformed nuclei, has been proposed by Dzyublik [18] which was discussed later in [19 - 24]. The kinetic energy operator for all A nucleons of the nucleus has been expressed in terms of new collective variables in the same paper [18]. Supplementing this kinetic energy operator by a potential energy of the nucleus we can obtain the microscopic Hamiltonian of the nucleus. It was shown in [19], that the Bohr-Mottelsson equation follows from such microscopic Hamiltonian when $\beta << 1$, if we neglect the intrinsic motion of the nucleus and its coupling to rotation. Hence it is natural to generalize the Bohr-Mottelson equation to the case of arbitrary β, starting from the same microscopic Hamiltonian [18, 19] and treating the nucleus as a set of nucleons but not as a liquid drop.

Collective Hamiltonian

Following [18, 19], we shall specify first the collective nuclear coordinates. As usually [15 - 19], two coordinate frames are introduced with the origins coinciding with the center of mass of the nucleus. One of them x, y, z is the laboratory coordinate system and another ξ, η, ζ is the moving one with the axes directed along the principal axes of the inertia tensor of the nucleus. Then the projections of the Jakobi vectors of the nucleons $\boldsymbol{q}_i$ on these axes obey the following constraints

$$\sum_{i=1}^{A-1} q_{i\xi} q_{i\eta} = \sum_{i=1}^{A-1} q_{i\xi} q_{i\zeta} = \sum_{i=1}^{A-1} q_{i\eta} q_{i\zeta}, \tag{1}$$

where A is the number of nucleons in the nucleus.

Rotation of the nucleus is identified with rotation of the coordinate frame ξ, η, ζ whose orientation with respect to x, y, z is determined by the Euler angles $\theta = \{\theta_1, \theta_2, \theta_3\}$. Equation (1) is formally considered as the orthogonality condition for three vectors $\boldsymbol{A}_\xi = \{q_{1\xi}, q_{2\xi}, ..., q_{A-1,\xi}\}$, $\boldsymbol{A}_\eta = \{q_{1\eta}, q_{2\eta}, ..., q_{A-1,\eta}\}$ and $\boldsymbol{A}_\zeta = \{q_{1\zeta}, q_{2\zeta}, ..., q_{A-1,\zeta}\}$ in an abstract $(A - 1)$-dimensional space with basis orts e_1, e_2, ..., e_{A-1}. Such notion enabled us [18] to introduce an independent set of variables. Three of them are defined as the lengths of these vectors:

$$a = \sqrt{\sum_i q_{i\xi}^2}\,,\quad b = \sqrt{\sum_i q_{i\eta}^2}\,,\quad c = \sqrt{\sum_i q_{i\zeta}^2}\,. \tag{2}$$

Others should be angles to determine the orientation of the vectors A_ξ, A_η, A_ζ in the abstract space. For this aim we introduced [18, 19] the moving frame with orts e'_1, e'_2, ..., e'_{A-1} rotating in the abstract space. The vectors A_ξ, A_η, A_ζ are directed as follows

$$\mathbf{A}_\xi = a\mathbf{e}'_{A-3}\,,\quad \mathbf{A}_\eta = b\mathbf{e}'_{A-2}\,,\quad \mathbf{A}_\zeta = c\mathbf{e}'_{A-1}\,. \tag{3}$$

Then as intrinsic angular variables we choose some of the generalized Euler angles which determine the orientation of the frame $\{e'_i\}$ with respect to $\{e_i\}$.

The kinetic energy of the nucleus may be expressed in new variables [18, 19]

$$T = \frac{m}{2}\Big\{\dot a^2 + \dot b^2 + \dot c^2 + a^2 \sum_{k\neq A-3} \Omega_{A-3,k}^2 + b^2 \sum_{k\neq A-2} \Omega_{A-2,k}^2 + c^2 \sum_{k\neq A-1} \Omega_{A-1,k}^2 - 4bc\Omega_{A-2,A-1}\omega_\xi - \\ - 4ac\Omega_{A-1,A-3}\omega_\eta - 4ab\Omega_{A-3,A-2}\omega_\zeta + \left(b^2+c^2\right)\omega_\xi^2 + \left(a^2+c^2\right)\omega_\eta^2 + \left(b^2+a^2\right)\omega_\zeta^2\Big\}, \tag{4}$$

where m is the mass of the nucleon, $\vec\omega = \{\omega_\xi, \omega_\eta, \omega_\zeta\}$ is the angular velocity of the nuclear rotation, Ω_{ik} is the angular velocity for intrinsic rotation in the plane (e'_i, e'_k) of the abstract space. A simple procedure of quantization T gives the following result for the kinetic energy operator [18 - 22]

$$\hat T = -\frac{\hbar^2}{2m}\Big\{\frac{\partial^2}{\partial a^2} + \frac{\partial^2}{\partial b^2} + \frac{\partial^2}{\partial c^2} + \left(\frac{2a}{a^2-b^2} + \frac{2a}{a^2-c^2} + \frac{A-4}{a}\right)\frac{\partial}{\partial a} + \\ + \left(\frac{2b}{b^2-a^2} + \frac{2b}{b^2-c^2} + \frac{A-4}{b}\right)\frac{\partial}{\partial b} + \left(\frac{2c}{c^2-a^2} + \frac{2c}{c^2-b^2} + \frac{A-4}{c}\right)\frac{\partial}{\partial c} - \\ - \sum_{k=1}^{A-4}\left(\frac{1}{a^2}\hat j_{A-3,k}^2 + \frac{1}{b^2}\hat j_{A-2,k}^2 + \frac{1}{c^2}\hat j_{A-1,k}^2\right) - \frac{b^2+c^2}{\left(b^2-c^2\right)^2}\left(\hat I_\xi^2 + \hat j_{A-2,A-1}^2\right) - \\ - \frac{c^2+a^2}{\left(c^2-a^2\right)^2}\left(\hat I_\eta^2 + \hat j_{A-1,A-3}^2\right) - \frac{a^2+b^2}{\left(a^2-b^2\right)^2}\left(\hat I_\zeta^2 + \hat j_{A-3,A-2}^2\right) - \\ - \frac{4bc}{\left(b^2-c^2\right)^2}\hat I_\xi \hat j_{A-2,A-1} - \frac{4ac}{\left(a^2-c^2\right)^2}\hat I_\eta \hat j_{A-1,A-3} - \frac{4ab}{\left(a^2-b^2\right)^2}\hat I_\zeta \hat j_{A-3,A-2}\Big\}, \tag{5}$$

where $\hat I_\xi$, $\hat I_\eta$, $\hat I_\zeta$ are the spin projections (in units $\hbar$) on the axes ξ, η, ζ; $\hat j_{ik}$ are the infinitesimal operators of rotation in the planes (e'_i, e'_k) of the moving frame in the abstract space. Below we shall analyze only the collective motion neglecting both the intrinsic rotation and the Coriolis coupling. It corresponds to neglecting of all term containing Ω_{ik} in (4).

The coordinates a, b, c determine the shape of the inertia ellipsoid which can be identified with the shape of the nucleus having only quadrupole deformation. Such coordinates are related to much more familiar coordinates ρ, β, γ:

$$a = \frac{\rho}{\sqrt{3}}\exp(\beta\cos(\gamma + 2\pi/3)),$$

$$b = \frac{\rho}{\sqrt{3}}\exp(\beta\cos(\gamma - 2\pi/3)), \tag{6}$$

$$c = \frac{\rho}{\sqrt{3}}\exp(\beta\cos\gamma),$$

where $\rho = (a^2 + b^2 + c^2)^{1/2}$ means a nuclear hyper-radius; β and γ are the quadrupole deformation and unaxiality parameters respectively. New variables vary in the intervals

$$0 \le \rho < \infty, \quad -\infty < \beta < \infty, \quad 0 \le \gamma \le \pi/6, \tag{7}$$

where the deformation parameter $\beta > 0$ describes a prolate shape and $\beta < 0$ an oblate one.

Possible deviations of ρ from ρ_0 describe the density vibrations. Putting $\rho = \rho_0$, we shall express now the collective part of the kinetic energy operator in terms β, γ and three Eulerian angles θ. In general it is cumbersome expression therefore we restrict ourselves by the axially symmetrical nuclei with $\gamma \sim 0$. The most simple way to solve this task is to write down first the classical kinetic energy in terms of β, γ and then to quantize it.
It is easily seen that for $\gamma \approx 0$

$$T_{abc} \equiv \frac{m}{2}(\dot{a}^2 + \dot{b}^2 + \dot{c}^2) = \frac{m\rho_0^2}{6}\left[\left(\frac{1}{2}e^{-\beta} + e^{2\beta}\right)\dot{\beta}^2 + \frac{3}{2}e^{-\beta}\beta^2\dot{\gamma}^2\right]. \tag{8}$$

Then the kinetic energy operator for the collective motion of the nucleus takes the form

$$\hat{T} = -\frac{\hbar^2}{2B(\beta)}\frac{1}{g(\beta)}\frac{\partial}{\partial\beta}g(\beta)\frac{\partial}{\partial\beta} + \frac{\hbar^2\alpha(\beta)}{6B(\beta)\beta^2}\left(\hat{I}_\xi^2 + \hat{I}_\eta^2\right) + \frac{\hbar^2}{2B_\gamma(\beta)\beta^2}\left[-\frac{1}{\gamma}\frac{\partial}{\partial\gamma}\left(\gamma\frac{\partial}{\partial\gamma}\right) + \frac{\hat{I}_\zeta^2}{4\gamma^2}\right], \tag{9}$$

where we used the following notations:

$$B_\gamma(\beta) = B(0)e^{-\beta}, \quad B(\beta) = B(0)f(\beta), \quad B(0) = \frac{m\rho_0^2}{2}, \quad f(\beta) = \frac{1}{3}\left(e^{-\beta} + 2e^{2\beta}\right),$$

$$g(\beta) = \frac{1}{3\sqrt{3}}\frac{\beta^2 e^{-3\beta/2}\left(e^{-\beta} - e^{2\beta}\right)^2}{\left(e^{-\beta} + 2e^{2\beta}\right)}, \quad \alpha(\beta) = \frac{3}{2}\beta^2\left(e^{-\beta} + 2e^{2\beta}\right)\frac{\left(e^{-\beta} + e^{2\beta}\right)}{\left(e^{-\beta} - e^{2\beta}\right)^2}. \tag{10}$$

Here $B(\beta)$ and $B_\gamma(\beta)$ are the mass parameters for β- and γ-vibrations respectively. When $\beta \to 0$ they tend to the same constant value $B(0)$, as in the Bohr - Mottelson model [15, 16].

The Hamiltonian of the nucleus will be

$$\hat{H} = \hat{T} + V(\beta, \gamma). \tag{11}$$

The Schrődinger equation

In order to find the solution of the Schrődinger equation

$$\hat{H}\Psi(\beta,\gamma,\theta)=E\Psi(\beta,\gamma,\theta) \tag{12}$$

we shall neglect the dependence of the quantities $f(\beta)$, $B_\gamma(\beta)$ and $\alpha(\beta)$ on β, putting $\beta=\beta_0$, where β_0 determines minimum of the effective potential $W_0(\beta)$ given below. Then the wave function factorizes:

$$\Psi(\beta,\gamma,\theta)=g^{-1/2}(\beta)\varphi(\beta)\,|\,IMK>\chi(\gamma), \tag{13}$$

where the function

$$|\,IMK>=\sqrt{\frac{2I+1}{16\pi^2(1+\delta_{0K})}}\left(D^I_{KM}(\theta)+(-1)^I D^I_{-KM}(\theta)\right), \tag{14}$$

describes rotation of the axially symmetrical rigid rotator with spin I, its projection M on the axis z and projection K on the symmetry axis ζ of the rotator. Besides, $D^I_{KM}(\theta)$ are the Wigner functions depending on the Euler angles. The function $\varphi(\beta)$, describing β-vibrations, satisfies the equation

$$\left\{-\frac{\hbar^2}{2B}\frac{\partial^2}{\partial\beta^2}+W_I(\beta)-\varepsilon_I\right\}\varphi_I(\beta)=0, \tag{15}$$

where we put $B=B(\beta_0)$. The effective potential energy is

$$W_I(\beta)=W_0(\beta)+\frac{\hbar^2\alpha}{6B\beta^2}I(I+1), \tag{16}$$

where

$$W_0(\beta)=C\beta_0^2\left(\frac{\beta_0^2}{2\beta^2}-\frac{\beta_0}{\beta}\right)+C_0, \tag{17}$$

where the constant C_0 determines position of the normal or superdeformed potential well. We introduce the following notations:

$$\zeta=\frac{\beta}{\beta_{00}},\quad \beta_{00}=\sqrt[4]{\frac{\hbar^2}{BC}},\quad \omega=\sqrt{\frac{C}{B}},\quad \mu=\frac{\beta_{00}}{\beta_0},$$

$$Z=\mu^{-3},\qquad l=\frac{1}{2}\left[\sqrt{1+\frac{4}{\mu^4}+\frac{4\alpha}{3}I(I+1)}-1\right], \tag{18}$$

where the parameter β_{00} stands for the amplitude of β-vibrations in the ground state of β-oscillator, and μ is the softness parameter (see also [16, 17]). Then we can rewrite equation (15) as

$$\left\{\frac{\partial^2}{\partial\zeta^2}-\frac{l(l+1)}{\zeta^2}+\frac{2Z}{\zeta}+2\varepsilon\right\}\varphi(\zeta)=0. \tag{19}$$

We see that (19) is formally the equation for the radial part of the wave function of a charged particle bound in the Coulomb potential. This enables one to write down the energies as

$$\varepsilon_{ln_\beta}=-\frac{\hbar\omega}{2}\frac{Z^2}{n^2}+C_0, \tag{20}$$

where $n=n_\beta+l+1$; and n_β = 0, 1, 2 ... indicates the number of phonons for β-vibrations. Note that n and l are not integers.

The function $\chi(\gamma)$, describing γ-vibrations, satisfies the equation

$$\left\{\frac{\hbar^2}{2B_\gamma\beta_0^2}\left[-\frac{1}{\gamma}\frac{\partial}{\partial\gamma}\left(\gamma\frac{\partial}{\partial\gamma}\right)+\frac{\hat{I}_\zeta^2}{4\gamma^2}\right]+\frac{1}{2}\beta_0^2C_\gamma\gamma^2-\varepsilon_\gamma\right\}\chi(\gamma)=0. \tag{21}$$

The wave functions $\chi(\gamma)$ are specified by two quantum numbers n_γ = 0, 1, 2, 3, ... ; and K = 0, 2, 4 ... Their corresponding energies are [16]

$$\varepsilon_\gamma\equiv\varepsilon_{Kn_\gamma}=\hbar\omega_\gamma\left(2n_\gamma+\frac{1}{2}K+1\right),\quad \omega_\gamma=\sqrt{\frac{C_\gamma}{B_\gamma}}. \tag{22}$$

Thus the nuclear energies are

$$E_{lKn_\beta n\gamma}=\varepsilon_{ln_\beta}+\varepsilon_{Kn_\gamma}. \tag{23}$$

Dealing with superdeformed vibrational-rotational band, based on the state with spin I_0^+ and $n_\beta=n_\gamma=K=0$, one must calculate the relative excitation energies

$$\Delta E_{lKn_\beta n_\gamma}=E_{lKn_\beta n_\gamma}-E_{l_0 000}. \tag{24}$$

They are given by

$$\Delta E_{lKn_\beta n_\gamma}=\frac{\hbar\omega}{2\mu^6}\left[\frac{1}{(l_0+1)^2}-\frac{1}{(n_\beta+l+1)^2}\right]+\hbar\omega_\gamma\left[2n_\gamma+\frac{1}{2}K\right] \tag{25}$$

with l_0 associated with I_0 and l with I. Respectively, for the normal bands we must take $I_0^+=0$ for the ground state of even-even nucleus.

Discussion

Equation (12) with the Hamiltonian (9) - (11) describes collective excitations of even-even axially symmetrical nuclei with arbitrary deformation β. Only in the limit $\beta\rightarrow 0$ it reduces to the Bohr - Mottelson equation. Therefore it is most valuable for description of superdeformed nuclei with great values of β. The solution of Eq. (12) given above is obtained nonadiabatically like the

Davydov - Chaban model [16, 17]. It describes complex mixture of the nuclear rotation and longitudinal β-vibrations.

Relative energies of the superdeformed rotational bands of the isotopes ^{190}Hg, ^{192}Hg, ^{194}Hg, ^{192}Pb, ^{194}Pb, ^{198}Po

^{190}Hg			^{192}Hg			^{194}Hg		
$\hbar\omega = 1030$ kev $\mu = 0.105$			$\hbar\omega = 1105$ kev $\mu = 0.098$			$\hbar\omega = 1190$ kev $\mu = 0.092$		
I^π	E_{exp} [30]	E_{theor}	I^π	E_{exp} [31]	E_{theor}	I^π	E_{exp} [30]	E_{theor}
12^+	0.0	0.0	8^+	0.0	0.0	10^+	0.0	0.0
14^+	316.9	314.5	10^+	214.4	210.3	12^+	200.8	200.4
16^+	676.9	672.9	12^+	472.2	463.9	14^+	443.0	442.1
18^+	1079.2	1074.2	14^+	772.3	760.1	16^+	726.2	724.8
20^+	1522.2	1517.2	16^+	1113.7	1098.3	18^+	1049.6	1048.0
22^+	2004.9	2000.7	18^+	1495.3	1477.6	20^+	1412.8	1411.1
24^+	2526.2	2523.2	20^+	1916.4	1897.4	22^+	1814.8	1813.4
26^+	3084.8	3083.2	22^+	2375.2	2356.5	24^+	2255.1	2254.3
28^+	3679.7	3679.4	24^+	2871.2	2854.1	26^+	2732.8	2733.0
30^+	4305.8	4310.0	26^+	3403.3	3389.0	28^+	3247.0	3248.6
32^+	4973.9	4973.4	28^+	3970.7	3960.0	30^+	3796.9	3800.3
34^+	5670.8	5668.0	30^+	4572.4	4566.1	32^+	4381.8	4387.1
36^+	6399.3	6391.9	32^+	5207.3	5205.8	34^+	5000.7	5008.2
38^+	7156.7	7143.5	34^+	5875.4	5878.0	36^+	5652.8	5662.4
40^+	7940.2	7920.9	36^+	6575.5	6581.3	38^+	6337.3	6348.7
42^+	8742.0	8722.3	38^+	7307.0	7314.2	40^+	7053.5	7066.0
			40^+	8069.3	8075.5	42^+	7800.4	7813.3
			42^+	8862.0	8863.6	44^+	8578.2	8589.3
			44^+	9684.9	9677.2	46^+	9385.9	9392.9
			46^+	10538.0	10514.7	48^+	10223.4	10222.9
			48^+	11426.7	11394.7	50^+	11090.5	11078.2
^{192}Pb			^{196}Pb			^{198}Po		
$\hbar\omega = 990$ kev $\mu = 0.105$			$\hbar\omega = 1120$ kev $\mu = 0.096$			$\hbar\omega = 1130$ kev $\mu = 0.098$		
I^π	E_{exp} [31]	E_{theor}	I^π	E_{exp} [30]	E_{theor}	I^π	E_{exp} [30]	E_{theor}
8^+	0.0	0.0	8^+	0.0	0.0	6^+	0.0	0.0
10^+	215.6	215.2	10^+	204.5	204.8	8^+	171.4	170.4
12^+	478.1	474.4	12^+	452.4	451.8	10^+	387.0	385.4
14^+	782.3	776.7	14^+	741.8	740.5	12^+	646.5	644.7
16^+	1127.5	1121.2	16^+	1071.5	1070.2	14^+	949.5	947.6
18^+	1512.3	1506.9	18^+	1441.0	1440.3	16^+	1295.3	1293.5
20^+	1936.2	1932.7	20^+	1850.4	1850.0	18^+	1682.9	1681.4
22^+	2398.4	2397.4	22^+	2298.2	2298.4	20^+	2111.4	2110.7
24^+	2897.4	2899.6	24^+	2783.5	2784.6	22^+	2580.8	2580.2
26^+	3432.7	3437.9	26^+	3306.1	3307.7	24^+	3089.3	3089.0
28^+	4008.0	4010.9	28^+	3864.3	3866.6	26^+	3636.2	3636.0
30^+	4607.7	4617.0	30^+	4458.4	4460.3	28^+	4220.4	4220.0
32^+	5247.7	5254.7	32^+	5088.4	5087.5	30^+	4841.0	4839.7
			34^+	5753.6	5747.1	32^+	5495.9	5494.0
						34^+	6184.7	6181.4
						36^+	6904.8	6900.5
						38^+	7656.9	7650.1

The calculated vibrational-rotational energies are compared in the table with the experiment [30, 31] for superdeformed bands of the isotopes ^{190}Hg, ^{192}Hg, ^{194}Hg, ^{192}Pb, ^{194}Pb, ^{198}Po. Being in the superdeformed state this nuclei have the ratio of the axes $c/a = 2$ [9]. Then $\beta_0 = 0.462$. Only two parameters $\hbar\omega$ and μ were used for fitting. The obtained results are displayed in the table.

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ОБЕРТАННЯ СУПЕРДЕФОРМОВАНИХ ПАРНО-ПАРНИХ ЯДЕР

А.Я. Дзюблик, В.В. Утюж

Стартуючи з мікроскопічного гамільтоніана для нуклонів, ми отримали рівняння, що описує обертання та квадрупольні коливання парно-парних аксіально-симетричних ядер, які мають довільну деформацію β. У випадку маленьких β воно співпадає з рівнянням Бора - Моттельсона з $\gamma \sim 0$. Це рівняння використовується для отримання коливально-обертальних енергій супердеформованих ядер.

ВРАЩЕНИЕ СУПЕРДЕФОРМИРОВАННЫХ ЧЕТНО-ЧЕТНЫХ ЯДЕР

А.Я. Дзюблик, В.В. Утюж

Стартуя из микроскопического гамильтониана для нуклонов, ми получили уравнение, описывающее вращение и квадрупольные колебания четно-четных аксиально-симметричных ядер, которые имеют произвольную деформацию по β. В случае маленьких β оно совпадает с уравнением Бора - Моттельсона с $\gamma \sim 0$. Это уравнение используется для получения колебательно-вращательных энергий супердеформированных ядер.