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The Extended Gaussian Overlap for the Interacting Boson Model Hamiltonian

Uogólnione przybliżenie gaussowskie dla hamiltonianu oddziałujących bozonów

Обобщенное приближение гауссовского перекрытия для гамильтониана модели взаимодействующих бозонов

Dedicated to Professor
Stanisław Szpikowski on occasion
of his 60th birthday

1. INTRODUCTION

In the present paper we propose an unitary approximate transformation of the IBM hamiltonian to the Bohr-Mottelson model (BMM) collective space. The Interacting Boson Model [1] has been successful in providing a systematic interpretation of collective excitations over a wide range of nuclei but conceptually it is quite different from geometrical models based on BMM. A few various attempts [2-5], therefore, have been made to find relations between both approaches. However, in all cases either a restricted boson hamiltonian has been exactly transformed, e.g. [2], to the BMM space or the Hollstein-Primakoff [6] expansion has been finally used. The last case leads to an infinite order differential form which, in practice, must be restricted up to the second order terms. In addition, it is not quite clear if the Hollstein-Primakoff series is appropriately well convergent to apply such a procedure.

Taking into account these results we propose the approximate transformation of the IBM hamiltonian

$$\begin{aligned} H = {} & \varepsilon_s s^+ s + \varepsilon_d \sum_m d_m^+ d_m + \frac{u_0}{2} s^+ s^+ s s \\ & + \frac{1}{2} \sum_L c_L \sqrt{2L+1} \left[(d^+ d^+)^L (\tilde{d}\tilde{d})^L \right]^0 \\ & + \frac{u_2}{\sqrt{5}} s^+ s (d^+ \tilde{d})^0 + \frac{v_0}{2} \left\{ (d^+ d^+)^0 s s + s^+ s^+ (\tilde{d}\tilde{d})^0 \right\} \\ & + \frac{v_2}{\sqrt{2}} \left\{ \left[(d^+ d^+)^2 (\tilde{d} s)^2 \right]^0 + \left[(d^+ s^+)^2 (\tilde{d}\tilde{d})^2 \right]^0 \right\} \end{aligned} \tag{1}$$

where $d_m^+ (s^+)$ stands for quadrupole (monopole) boson creation operator and $\tilde{d}_m = (-)^m d_{-m}$, to the BMM collective space making u se of the Generator Coordinate Method with Gaussian Overlap Approximation (GCM + GOA)[6, 7]. As it will be shown later, the hamiltonian of noninteracting bosons is transformed exactly in this method and the interaction modifies only the BMM mass parameters and the collective potential energy.

2. TRANSFORMATION TO THE BMM COLLECTIVE SPACE

Within the Generator Coordinate Method the collective subspace is defined uniquely by a choice of the generating function $|q\rangle$. In our case, to obtain the six-dimensional harmonic oscillator space (natural for the monopole + quadrupole collective models) we assume $|q\rangle$ in the form of rotating coherent state parametrized by Euler angles $\omega = (\omega_1, \omega_2, \omega_3)$, shape parameters β and γ and the collective variable α corresponding to the monopole degree of freedom:

$$|q\rangle \equiv |\omega \alpha \beta \gamma\rangle = \hat{R}(\omega) \, |\alpha \beta \gamma\rangle \tag{2}$$

where

$$|\alpha\beta\gamma> = \exp\left[-\frac{\alpha^2+\beta^2}{4}\right] \times$$

$$\times \exp\left[\frac{\alpha}{\sqrt{2}} s^+ + \frac{\beta}{\sqrt{2}}\cos\gamma\, d_0^+ + \frac{\beta}{2}\sin\gamma\,(d_2^+ + d_{-2}^+)\right]|0> \qquad (3)$$

$\hat{R}(\omega)$ is the rotation operator in the laboratory frame. The generating function (2) fulfils all conditions for the extended Gaussian Overlap Approximation [7, 8]. It can be proved easy representing $|q>$ in cartesian coordinates:

$$q_{00} = \frac{\alpha}{\sqrt{2}}$$

$$q_{2\mu} = \frac{\beta}{\sqrt{2}}\left[\cos\gamma\, D^{(2)}_{\mu 0}(\omega) + \frac{\sin\gamma}{\sqrt{2}}\left(D^{(2)}_{\mu 2}(\omega) + D^{(2)}_{\mu -2}(\omega)\right)\right] \qquad (4)$$

The internal generating function (3) is invariant under the transformations of the standard octahedral group d_2:

$$e^{-i\pi\hat{L}_K}|\alpha\beta\gamma> = |\alpha\beta\gamma> \quad , \; K=1,2,3 \qquad (5)$$

and formulas derived in the paper [9], contained in this volume, could be applied in our case. For the boson hamiltonian (1) and the generating function (2) we obtained the metric tensor $g_{\mu\nu}$, the inverse mass tensor $(M^{-1})^{\mu\nu}$, the moment of inertia J_k $(k=1,2,3)$ and the collective potential energy in a form of simple analytical expressions.

The metric tensor forms 6x6 matrix with non-zero components:

$$g_{\omega_K\omega_{K'}} = 2\beta^2\sum_{l=1}^{3} b_{Kl}(\omega)\, b_{K'l}(\omega)\sin^2\left(\gamma - \frac{2l\pi}{3}\right) \qquad (6)$$

where

$$[b_{Kl}(\omega)] = \begin{bmatrix} \sin(\omega_2)\cos(\omega_3) & \sin(\omega_2)\sin(\omega_3) & \cos(\omega_3) \\ \sin(\omega_3) & \cos(\omega_3) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and

$$g_{\alpha\alpha} = \frac{1}{2}\ , \quad g_{\beta\beta} = \frac{1}{2}\ , \quad g_{\gamma\gamma} = \frac{1}{2}\beta^2 . \tag{7}$$

The square root of its determinant, which is known expression for the weight in the definition of the scalar product in the collective quadrupole space, is given by

$$D = \sqrt{|\det[g_{\mu\nu}]|} = \frac{1}{4}\beta^4 |\sin 3\gamma| \sin\omega_2 \tag{8}$$

The collective hamiltonian $\hat{\mathcal{H}}$ [9] contains three terms: the kinetic vibrational energy, the rotational energy and the collective potential:

$$\begin{aligned}\hat{\mathcal{H}} &= -\frac{1}{2D}\sum_{\mu\nu=4}^{6}\frac{\partial}{\partial q^{\mu}} D (M^{-1})^{\mu\nu}\frac{\partial}{\partial q^{\nu}} \\ &\quad + \frac{1}{2}\sum_{k=1}^{3}\mathcal{J}_k^{-1}(\alpha\beta\gamma)\hat{L}'^{2}_{k} \\ &\quad + V(\alpha\beta\gamma)\end{aligned} \tag{9}$$

where $q^4 = \alpha$, $q^5 = \beta$, $q^6 = \gamma$ and $\hat{L}'_k$ denotes the angular momentum operator in the rotating frame.

The inverse mass tensor has six independent components:

$$\begin{aligned}(M^{-1})^{\alpha\alpha} &= \varepsilon_s + \frac{u_0}{2}\alpha^2 + \frac{1}{2}\left(\frac{u_2}{5} - \frac{v_0}{\sqrt{5}}\right) \\ (M^{-1})^{\beta\alpha} &= \frac{v_0}{\sqrt{5}}\alpha\beta - \frac{v_2}{\sqrt{35}}\beta^2\cos 3\gamma \\ (M^{-1})^{\gamma\alpha} &= \frac{v_2}{\sqrt{35}}\beta\sin 3\gamma \\ (M^{-1})^{\beta\beta} &= \varepsilon_d + \frac{1}{2}\left(\frac{u_2}{5} - \frac{v_0}{\sqrt{5}}\right) + \frac{1}{2}\left(\frac{c_0}{5} + \frac{2c_2}{7} + \frac{18c_4}{35}\right) \\ &\quad - \frac{v_2}{\sqrt{35}}\alpha\beta\cos 3\gamma\end{aligned} \tag{10}$$

$$(M^{-1})^{\gamma\beta} = \frac{V_2}{\sqrt{35}}\,\alpha \sin 3\gamma$$

$$(M^{-1})^{\gamma\gamma} = \frac{1}{\beta^2}\Big[\,\varepsilon_d + \frac{1}{2}\Big(\frac{u_2}{5} - \frac{V_0}{\sqrt{5}}\Big) + \Big(-\frac{C_0}{10} + \frac{3C_2}{7} + \frac{6C_4}{35}\Big)\beta^2 + \frac{V_2}{\sqrt{35}}\,\alpha\beta\cos 3\gamma\Big]$$

The inverse moment of inertia $\mathcal{J}^{-1}$ is a simple function of the collective variables α, β and γ :

$$\mathcal{J}_K^{-1} = (\mathcal{J}_K^{(B)})^{-1}\Big[\,\varepsilon_d + \frac{1}{2}\Big(\frac{u_2}{5} - \frac{V_0}{\sqrt{5}}\Big) + \Big(-\frac{C_0}{10} + \frac{3C_2}{7} + \frac{6C_4}{35}\Big)\beta^2 + \frac{4}{7}(C_4 - C_2)\beta^2 \times \sin^2\Big(\gamma - \frac{2K\pi}{3}\Big) + \frac{V_2}{\sqrt{35}}\,\alpha\beta\cos\Big(\gamma - \frac{2K\pi}{3}\Big)\Big] \tag{11}$$

where

$$\mathcal{J}_K^{(B)} = 4\beta^2 \sin^2\Big(\gamma - \frac{2K\pi}{3}\Big) \tag{12}$$

represents Bohr's inertia. For fixed $\alpha = \alpha_0$ and small β deformations one can expand (11) in the Taylor series and obtain

$$\mathcal{J}_K \approx \mathcal{J}_K^{(B)} B\Big[1 + \frac{2\sqrt{2}}{35}\,\frac{B_3}{B}\,\beta\cos\Big(\gamma - \frac{2K\pi}{3}\Big)\Big] \tag{13}$$

where

$$B = \varepsilon_d + \frac{1}{2}\Big(\frac{u_2}{5} - \frac{V_0}{\sqrt{5}}\Big)$$

$$B_3 = \frac{V_2}{2\sqrt{2}}\,\alpha_0$$

This case corresponds to the expansion of the classical kinetic energy containing third order terms in the collective velocity [10]:

$$T' = \frac{1}{2}B\sum_{\mu}\dot{\alpha}_{\mu}^{*}\dot{\alpha}_{\mu} + B_3\sum_{\mu\nu\lambda}\begin{pmatrix}2&2&2\\ \mu&\nu&\lambda\end{pmatrix}\dot{\alpha}_{\mu}\dot{\alpha}_{\nu}\dot{\alpha}_{\lambda} \tag{14}$$

The parameter B_3 is uniquely determined by the interaction strength between s and d bosons.

The collective potential is given by the expectation value of H (1) and so-called zero-point energy ε_0:

$$\begin{aligned} V(\alpha\beta\gamma) &= \langle\alpha\beta\gamma|\, H\,|\alpha\beta\gamma\rangle - \varepsilon_0 \\ &= -\frac{\varepsilon_s}{2} - \frac{5\varepsilon_d}{2} + \left(\frac{\varepsilon_s}{2} - \frac{u_0}{2} - \frac{u_2}{4}\right)\alpha^2 \\ &+ \frac{u_0}{8}\alpha^4 + \left(\frac{\varepsilon_d}{2} + \frac{u_2}{20} - \frac{c_0}{10} - \frac{c_2}{2} - \frac{9c_4}{10}\right)\beta^2 \\ &+ \frac{1}{8}\left(\frac{c_0}{5} + \frac{2c_2}{7} + \frac{18c_4}{35}\right)\beta^4 + \left(\frac{v_0}{4\sqrt{5}} + \frac{u_2}{20}\right)\alpha^2\beta^2 \\ &- \frac{v_2}{2\sqrt{35}}\alpha\beta^3\cos 3\gamma . \end{aligned} \tag{15}$$

For pure quadrupole case ($\alpha = \alpha_0$) the potential (15) relates to the potential analysed in the chapter 4 of [10]:

$$V'(\beta\gamma) = \frac{1}{2}\mathcal{C}_2\beta^2 - \frac{\sqrt{2}}{\sqrt{35}}\mathcal{C}_3\beta^3\cos 3\gamma + \frac{1}{5}\mathcal{C}_4\beta^4 \tag{16}$$

with coefficients:

$$\mathcal{C}_2 = \varepsilon_d - \frac{c_0}{2} - c_2 - \frac{9c_4}{5} + \frac{v_0}{2\sqrt{5}}\alpha_0^2 + \frac{u_2}{10}(\alpha_0^2 - 1)$$

$$\mathcal{C}_3 = \frac{v_2}{2\sqrt{2}}\alpha_0$$

$$\mathcal{C}_4 = \frac{5}{8}\left(\frac{c_0}{5} + \frac{2c_2}{7} + \frac{18c_4}{35}\right).$$

From this analysis one can conclude the condition for physical behaviour of the potential (16) while $\beta \longrightarrow \infty$: the coefficient $\mathcal{C}_4$ must be positive, i.e. $\frac{c_0}{5} + \frac{2c_2}{7} + \frac{18c_4}{35} > 0$. In the opposite case it leads to nuclear instability. The further conclusion is that the s-d boson interaction is responsible for existence of a static nonzero β deformation. It supports the IBM approximation where the strength of s-d boson interaction classifies nuclei as transitional or rotational ones; for $v_2 = 0$ we get the "vibrational" limit $SU(6) \supset SU(5) \otimes U(1)$.

For the case of vanishing boson interaction the hamiltonian (9) reduces to the six-dimensional harmonic oscillator (with $\varepsilon_s = \varepsilon_d = 1$ it corresponds to the total boson number operator $\hat{N}$) which can be written in the form:

$$\hat{\mathcal{H}}_{BM} = \frac{\varepsilon_s}{2}\left(-\frac{\partial^2}{\partial\alpha^2} + \alpha^2 - 1\right) + \frac{\varepsilon_d}{2}\left(-\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\beta^4\frac{\partial}{\partial\beta} - \frac{1}{\beta^2\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma} + \sum_K \left(\mathcal{J}_K^{(B)}\right)^{-1}\hat{L}_K^2 + \beta^2 - 5\right) \tag{17}$$

where the second term is just the simplest version of the BM collective hamiltonian.

One can easily check that GCM + GOA transformation to the BMM collective space reproduces the exact structure of one boson operators but the interaction is mapped only approximately and, in general, the hamiltonian (9) does not commute with the boson number operator. It makes some difficulties in comparison between IBM and BMM calculations because all fits for the boson model parameters are done only for an effective hamiltonian in which a renormalization of the interaction parameters has remarkable influence on form of the masses and the potential in (9).

3. APPLICATIONS AND DISCUSSION.

In general the IBM effective hamiltonian, which one compares with experimental data, is usually obtained from (1) by subtracting the operator dependent only on the total number of bosons:

$$H_o(\hat{N}) = \left(\varepsilon_s - \frac{u_o}{2}\right)\hat{N} + \frac{u_o}{2}\hat{N}^2 \tag{18}$$

Such a renormalization allows to diminish the number of free parameters by two: ε_s - the single energy of s-bosons and u_o - the interaction strenght between them. Note that for a fixed nucleus the operator (18) can be replaced by a constant number. However, as we mentioned above, the collective masses and potential are strongly dependent on this renormalization, i.e. on values of ε_s and u_o. To overcome this difficulty in general one needs to project the hamiltonian (9) into subspaces with definite number of bosons N:

$$\hat{\mathcal{H}}_N = \hat{P}_N \hat{\mathcal{H}} \hat{P}_N \tag{19}$$

where

$$\hat{P}_N = \frac{1}{2\pi} \int_0^{2\pi} d\Phi \, e^{-i\Phi(\hat{N}-N)} \tag{20}$$

and $\hat{N}$ is given by (17) with $\varepsilon_s = \varepsilon_d = 1$. Because this method is rather cumbersome in practice we use only the first order Kamlah approximate projection [6] of $H_o(\hat{N})$ in order to subtract from hamiltonian (9) a bulk ground state energy connected with the valence nucleon pairs:

$$\hat{\mathcal{H}}_{eff} = \hat{\mathcal{H}} - h_o(\hat{N} - N) \tag{21}$$

where

$$h_o = \frac{\langle\alpha\beta\gamma|H_o(\hat{N})(\hat{N} - \langle\hat{N}\rangle)|\alpha\beta\gamma\rangle}{\langle\alpha\beta\gamma|(\hat{N} - \langle\hat{N}\rangle)^2|\alpha\beta\gamma\rangle} \tag{22}$$

with

$$\langle\hat{N}\rangle \equiv \langle\alpha\beta\gamma|\hat{N}|\alpha\beta\gamma\rangle$$

According to the IBM interpretation [1, 11, 12] the vibrational isotope ^{150}Gd does not contain any d-boson admixture in its ground state (or this admixture can be neglected). Then

$$h_o = \varepsilon_s + \frac{u_o}{2}(\alpha^2 + \beta^2) \tag{23}$$

and the single s-boson energy ε_s and u_0 can be estimated within the generalized seniority scheme [6, 13]:

$$\begin{aligned} \varepsilon_s &\approx G\,\Omega = 0.33 \text{ MeV} \\ u_0 &\approx -G = -0.166 \text{ MeV} \end{aligned} \tag{24}$$

where $\Omega = j + 1/2 = 5$ corresponds to 4 valence neutrons on 1 $h_{9/2}$ level (we assume Z = 64 as magic number) and $G \approx \frac{25}{A}$ MeV denotes the usual pairing strength. In the "vibrational" limit of IBM the boson renormalized hamiltonian for ^{150}Gd has the following form:

$$H_{eff} = \varepsilon \sum d_m^+ d_m + \frac{1}{2}\sum_L \tilde{c}_L \sqrt{2L+1}\,[(d^+d^+)^L(\tilde{d}\tilde{d})^L]^0 \tag{25}$$

where [12] $\varepsilon = 0.63$ MeV, $\tilde{c}_0 = -0.0705$ MeV, $\tilde{c}_2 = 0.0095$ MeV, $\tilde{c}_4 = -0.044$ MeV. The corresponding collective hamiltonian is determined by the collective masses:

$$\begin{aligned} (M'^{-1})^{\alpha\alpha} &= -\frac{u_0}{2}\beta^2 \\ (M'^{-1})^{\beta\beta} &= \varepsilon - \frac{u_0}{2}\alpha^2 + \left(\frac{\tilde{c}_0}{10} + \frac{\tilde{c}_2}{7} + \frac{9\tilde{c}_4}{35} - \frac{3}{4}u_0\right)\beta^2 \\ (M'^{-1})^{\gamma\gamma} &= \frac{1}{\beta^2}\left[\varepsilon - \frac{u_0}{2}\alpha^2 + \left(-\frac{\tilde{c}_0}{10} + \frac{3\tilde{c}_2}{7} + \frac{6\tilde{c}_4}{35} - \frac{3}{4}u_0\right)\beta^2\right] \end{aligned} \tag{26}$$

the effective moment of inertia

$$\begin{aligned} \mathcal{J}'_k = \mathcal{J}_k^{(B)} \Big/ \Big[& \varepsilon - \frac{u_0}{2}\alpha^2 + \left(-\frac{\tilde{c}_0}{10} + \frac{3\tilde{c}_2}{7} + \frac{6\tilde{c}_4}{35} - \frac{3}{4}u_0\right)\beta^2 \\ & + \frac{4}{7}(\tilde{c}_4 - \tilde{c}_2)\beta^2 \sin^2\left(\gamma - \frac{2k\pi}{3}\right)\Big] \end{aligned} \tag{27}$$

and the γ-independent potential (Fig. 1) with the minimum at $\alpha_{eq} = \pm 8$, $\beta_{eq} = 0$. The potential is plotted at is equilibrium point in α. The collective masses $M'_{\beta\beta}$ and $M'_{\gamma\gamma}$ and moment of inertia J' (k = 1 or 2) are plotted in Fig. 2 for fixed $\alpha = \alpha_{eq}$ and $\gamma = 0$.

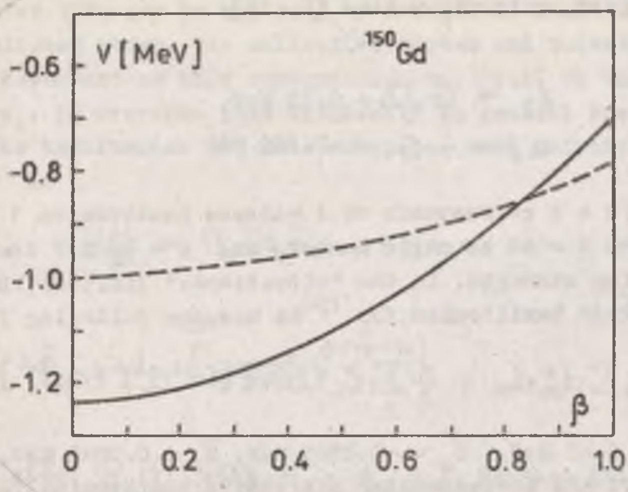

Fig. 1

Because the mass $M'_{\beta\beta}$ is nearly constant and the collective potential nearly parabolic one can estimate the excitation energy of the first β-vibrational state - it is given by $\hbar\omega_\beta \approx 0.69$ MeV (experimental value $E^{exp}_{2^+_1} = 0.633$ MeV).

These are also plotted (dot lines) the collective potential (Fig. 1) and $M'_{\beta\beta}$ (Fig. 2) obtained for the effective hamiltonian proposed by Casten [11]:

$$H_{eff} = \varepsilon \sum_m d^+_m d_m - \varkappa Q \cdot Q \tag{28}$$

where $Q_{2u} = s^+ d_u + d^+_u s + \chi/\sqrt{5}\,(d^+ d)^2_u$ and the effective parameters are: $\varepsilon = 0.45$ MeV, $\varkappa = 0.019$ MeV, $\chi = -0.9$ MeV. We did not plot the mass $M'_{\gamma\gamma}$ and moment of inertia for Castens' case because they are very similar to "vibrational" limit calculations.

In both cases the mass parameters and moments of inertia depend smoothly on deformation parameters. They satisfy the appropriate (for the generalized BMM) boundary conditions [14] and reproduce well the first excited state in the isotope ^{150}Gd. The magnitudes of the boson mass parameters are much smaller than corresponding masses in the cranking model but also the collective

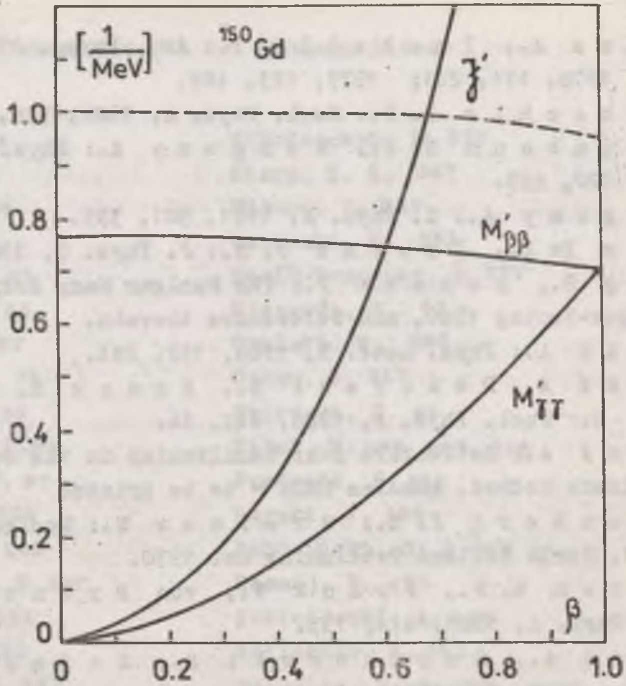

Fig. 2

potential is much softer. For ^{150}Gd the moment of inertia J is very small - it is consistent with interpretation of this nucleus as nearly pure, not deformed vibrator. However, to such a quality of this approximation for the interacting bosons hamiltonian, in general, one needs to fit the parameters of (1) for nuclei throughout the whole periodic table elements with additional conditions implied by the BM model (i.e. positive defined mass tensor and non-negative moment of inertia) and calculate the appropriate masses and potential. It is a purpose of a future publication.

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STRESZCZENIE

W pracy zastosowano metodę współrzędnej generującej wraz z przybliżeniem gaussowskim do wyprowadzenia kolektywnego hamiltonianu w formie operatora różniczkowego drugiego rzędu odpowiadającego hamiltonianowi modelu oddziałujących bozonów.

Р Е З Ю М Е

В работе применен метод генерирующей координаты вместе с гауссовским приближением для выведения коллективного гамильтониана в форме дифференциального оператора второй степени соответствующего гамильтониану модели взаимодействующих бозонов.

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