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TEMPERATURE DEPENDENCE OF THE ISOVECTOR DIPOLE RESPONSE FOR ASYMMETRIC SPHERICAL NUCLEI: A KINETIC-THEORY APPROACH

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Semiclassical approach based on the solution of the Vlasov kinetic equation for finite two-component systems with a moving surface is generalized for the study of the isovector dipole resp of excited neutron-rich spherical nuclei. The temperature effects are taken into account through the collision integral in the relaxation time approximation. It is shown that, by taking into account the dynamical surface effects, it is possible to obtain an exact treatment of the centre of mass motion for isovector dipole excitations of neutron-proton asymmetric systems. It is found that the width of giant dipole resonance grows with the temperature increase in the approximation of rare collisions between nucleons.

Introduction

The study of the properties of the giant dipole resonances in hot nuclei is of great interest in the nuclear collective dynamics. The special attention is devoted to the behaviour of the width of the dipole resonance with temperature increase [1 - 8]. For the study of the temperature dependence of the giant dipole resonance, the kinetic approach can be used.

In the paper [9] the isovector dipole excitations in cold neutron-proton asymmetric nuclei were studied within semiclassical approach [10 - 12], based on the solution of the Vlasov kinetic equation for finite two-component systems with a moving surface. In [9], in contrast to paper [13], the exact solution of the kinetic equation with taking into account the separable residual interaction was used. It was shown that, by taking into account the particle-surface coupling effects, it is possible to obtain an exact treatment of the centre of mass motion associated with isovector dipole excitations of neutron-proton asymmetric systems.

In this paper the semiclassical approach of the paper [9] is extended to the study of the isovector dipole response of hot neutron-rich spherical nuclei. The temperature effects are taken into account through the collision integral in the relaxation time approximation. Furthermore, the boundary condition has an additional term, caused by the thermal collisions in the surface region of hot system [14]. We find the collective response function of isovector dipole vibrations. With the help of obtained function we study the temperature dependence of the dipole strength distribution.

The isovector dipole response function of hot system

The analytical expression for isovector dipole response function $\tilde{R}(\omega)$ of a cold collisionless Fermi-system was obtained in the paper [9] within kinetic approach. Before extending this kinetic approach for the case of the hot systems, we review the general formalism. For a two-component system of interacting nucleons considered as a spherical container with a free moving surface one may write

$$R_q(\theta, \varphi, \omega) = R + \delta R_q(\theta, \varphi, \omega). \quad (1)$$

Here q = n (neutrons), p (protons), R is the equilibrium radius, $\delta R_q(\theta, \varphi, \omega)$ - the dynamical change of the equilibrium radius.

It was assumed that the isovector dipole excitations of this system can be described by the phase-space distribution function $\delta\tilde{n}_q(\vec{r}, \vec{p}, \omega)$, given by the linearized Vlasov equation with boundary conditions at the moving surface. We studied the response of our system on the isovector dipole external field of the following type

$$V_q(\vec{r}, t) = \beta\delta(t) a_q r Y_{10}(\theta). \quad (2)$$

Here $a_q = \frac{2Z}{A}$ at $q = n$ (neutrons) and $a_q = -\frac{2N}{A}$ at $q = p$ (protons), such that the external field $V_q(\vec{r}, t)$ generates the motion of the protons and neutrons against each other.

In order to take into account the main effects of the mean field change inside the system, it was assumed that they can be reduce to the separable residual interaction between the nucleons of the following type

$$u_{qq'}(\vec{r}, \vec{r}') = \kappa_{qq'} \sum_M r r' Y_{1M}(\theta, \varphi) Y^*_{1M}(\theta', \varphi') \quad (3)$$

with the strength parameters $\kappa_{qq'}$

$$\kappa_{nn} = \kappa_{pp} = \frac{40\pi}{9A} \frac{\varepsilon_F}{R^2} (F_0 + F_0'),$$

$$\kappa_{np} = \kappa_{pn} = \frac{40\pi}{9A} \frac{\varepsilon_F}{R^2} (F_0 - F_0'). \quad (4)$$

Here F_0' and F_0 are isovector and isoscalar parameters Landau, respectively, and ε_F is the Fermi energy of nuclear matter.

Furthermore, in this approach it was taken into account the particle-surface coupling effects. Due to this fact the isovector dipole strength distribution of cold systems does not contain excitations caused by the centre of mass motion [9].

To extend the semiclassical approach of the paper [9] for the description of hot systems, we take into account collisions between nucleons. For this, in the right side of Vlasov equation we introduced the collision integral in the relaxation time approximation [15, 16]

$$\delta I_q\left[\delta n_q(\vec{r},\vec{p},t),T\right]=-\frac{\delta n_q(\vec{r},\vec{p},t)}{\tau(T,\omega)}. \qquad (5)$$

Here $\tau(T,\omega)$ is the effective temperature-dependent relaxation time [16]

$$\frac{\hbar}{\tau(T,\omega)}=\gamma(T,\omega)=\left(T^2+\left(\frac{\hbar\omega_{col}}{2\pi}\right)^2\right)/const, \qquad (6)$$

where $\gamma(T,\omega)$ is the collision width of collective mode, $\hbar\omega_{col}$ the energy of collective excitation. The constant in Eq. (6) is proportional to the nucleon-nucleon scattering cross section. In some works this constant is related to the nucleon-nucleon scattering cross section in the medium [17], whereas in others – with scattering cross section of free nucleons [18]. According to the suggestions in these papers, the value of constant is defined in the range from 4,07 MeV to 7,36 MeV.

The collision integral (5) in the relaxation time approximation can be used in the rare collisions approximation, when $\omega_{col}\tau(T,\omega)\gg 1$.

In the paper [14] it was shown that the boundary condition has an additional term, caused by the thermal collisions between nucleons in the surface region of the hot system. So, the boundary condition for hot system for dipole vibrations can be written in the following way

$$\left.[\delta n_q(\vec{r},\vec{p}_\perp,p_r,\omega)-\delta n_q(\vec{r},\vec{p}_\perp,-p_r,\omega)]\right|_{r=R}=$$
$$=-2p_r\frac{dn_q^0(\varepsilon,T)}{d\varepsilon}i\left(\omega+\frac{i}{\tau_T(T)}\right)\delta R_q(\theta,\varphi,\omega), \qquad (7)$$

where p_r is the radial momentum, $n_q^0(\varepsilon,T)$ are the equilibrium distribution functions; $\tau_T(T)$ is the thermal relaxation time which is defined through

$$\frac{\hbar}{\tau_T(T)}=\hbar\gamma_T(T)=T^2/const. \qquad (8)$$

The equilibrium distribution function is taken in the Thomas Fermi approximation

$$n_q^0(\varepsilon,T)=\left[1+\exp\left(\frac{\varepsilon-\varepsilon_F^q}{T}\right)\right]^{-1}. \qquad (9)$$

The Fermi energy of the neutron (proton) system is given by

$$\varepsilon_F^q=\varepsilon_F\left(1+\tau_q\frac{N-Z}{A}\right)^{2/3}, \qquad (10)$$

where $\tau_q=1$ at $q=n$ (neutrons) and $\tau_q=-1$ at $q=p$ (protons).

Solving the kinetic equation with boundary conditions at the moving surface, we can obtain the following analytic expression of the collective response function [12]

$$\tilde{R}(\omega,T)=\sum_{q=n,p}\tilde{R}_q(\omega,T)=$$
$$=\frac{1}{\beta}\sum_{q=n,p}\int d\vec{r}a_q rY_{10}(\theta)\delta\tilde{\rho}_q(\vec{r},\omega,T), \qquad (11)$$

where $\delta\tilde{\rho}_q(\vec{r},\omega,T)$ is the Fourier transform with respect to time of the density change of neutrons and protons that is induced by the external field $V_q(\vec{r},t)$. In the moving-surface approximation the density change $\delta\tilde{\rho}_q(\vec{r},\omega,T)$ is defined as

$$\delta\tilde{\rho}_q(\vec{r},\omega,T)=\frac{2}{h^3}\int d\vec{p}\delta\tilde{n}_q(\vec{r},\vec{p},\omega,T)+$$
$$+\delta(r-R)\rho_q\delta R_q(\omega,T)Y_{10}(\theta), \qquad (12)$$

with ρ_q being the neutron ($q=n$) and proton ($q=p$) equilibrium densities.

The expression of the collective response function for a cold Fermi-system was obtained in [9]. Similarly, taking into account the temperature effects, we can write the collective response function of a hot Fermi-system with the moving-surface approximation in the following form

$$\tilde{R}(\omega,T)=R(\omega,T)+\tilde{S}(\omega,T). \qquad (13)$$

The collective dipole response function in the fixed-surface approximation, $R(\omega,T)=\sum_{q=n,p} R_q(\omega,T)$, reads [13]

$$R_q(\omega,T)=\frac{R_q^0(\omega,T)\left(1-\kappa_{nn}\dfrac{R_{q'}^0(\omega,T)}{a_{q'}^2}+\kappa_{np}\dfrac{R_{q'}^0(\omega,T)}{a_n a_p}\right)}{1-\kappa_{nn}\left(\dfrac{R_n^0(\omega,T)}{a_n^2}+\dfrac{R_p^0(\omega,T)}{a_p^2}\right)+(\kappa_{nn}^2-\kappa_{np}^2)\dfrac{R_n^0(\omega,T)}{a_n^2}\dfrac{R_p^0(\omega,T)}{a_p^2}}, \tag{14}$$

where $q\neq q'$. The function $R_q^0(\omega,T)$ in (14) is the zero-order response function in the fixed-surface approximation [10], see also equation (18) in [13]. Such zero-order approximation corresponds to the gas of the non-interacting nucleons, moving in the container with fixed neutron and proton surfaces. The zero-order response function in the fixed-surface approximation $R_q^0(\omega,T)$ is analogous to the single-particle response function of the quantum theory.

The function $\tilde{S}(\omega,T)$ in equation (13) represents the moving-surface contribution

$$\tilde{S}(\omega,T)=-\frac{1}{\beta}\frac{R^2}{1-\kappa_{nn}\left(\dfrac{R_n^0(\omega,T)}{a_n^2}+\dfrac{R_p^0(\omega,T)}{a_p^2}\right)+(\kappa_{nn}^2-\kappa_{np}^2)\dfrac{R_n^0(\omega,T)}{a_n^2}\dfrac{R_p^0(\omega,T)}{a_p^2}}\times$$
$$\times\sum_{\substack{q=n,p\\ q\neq q'}}\left[\chi_q^0(\omega,T)\left(1-\kappa_{nn}\frac{R_{q'}^0(\omega,T)}{a_{q'}^2}+\kappa_{np}\frac{R_{q'}^0(\omega,T)}{a_n a_p}\right)-\chi_q^0(0)\times\right. \tag{15}$$
$$\left.\times\left(\kappa_{nn}\frac{R_q^0(\omega,T)}{a_q^2}+\kappa_{np}\frac{R_{q'}^0(\omega,T)}{a_n a_p}-(\kappa_{nn}^2-\kappa_{np}^2)\frac{R_n^0(\omega,T)}{a_n^2}\frac{R_p^0(\omega,T)}{a_p^2}\right)\right]\delta R_q(\omega,T).$$

Here the function $\chi_q^0(\omega,T)$ characterizes the particle surface pressure that is induced by the external field

$$\chi_q^0(\omega,T)=-\frac{a_q}{m\tilde{\omega}(T)\omega_T(T)}\chi_q(\omega,T), \tag{16}$$

$$\chi_q(\omega,T)=\frac{3A_q}{4\pi}\frac{m\tilde{\omega}(T)\omega_T(T)}{R^2}-\frac{m^2\tilde{\omega}^3(T)\omega_T(T)}{R^2}\frac{R_q^0(\omega,T)}{a_q^2}, \tag{17}$$

$$\chi_q^0(0)=-\frac{3A_q}{4\pi}\frac{a_q}{R^2}, \tag{18}$$

$$\tilde{\omega}(T)=\omega+i\gamma(T,\omega),\quad \omega_T(T)=\omega+i\gamma_T(T), \tag{19}$$

where $A_q=N$ at $q=n$ and $A_q=Z$ at $q=p$, m is the nucleon mass.

The analytic expressions of the amplitudes of motion of the neutron and proton surfaces $\delta R_q(\omega,T)$ in equation (15) have the same form as for the cold system (see equation (15) in [9]) with replace ω by $\tilde{\omega}(T)$.

Centre of mass motion

When we consider the isovector dipole vibrations of neutron-proton asymmetric nuclei, the coupling with isoscalar vibrations appears [19]. As a consequence, the spurious excitations, caused by the centre of mass motion, can arise in the isovector dipole strength distribution. In [9] it was shown that in this approach due to the coupling between the motion of nucleons and surface vibrations, the isovector dipole strength distribution of cold systems does not contain the spurious excitations. Such statement remains correct for the hot system with taking into account the collisions between nucleons. Really, let’s consider the centre-of-mass response determined by

$$\delta\tilde{R}_{c.m.}(\omega,T)=\sum_{q=n,p}\int d\vec{r}\,rY_{10}(\theta,\varphi)\delta\tilde{\rho}_q(\vec{r},\omega,T). \tag{20}$$

After some transformations, analogously to the case of cold system [9], the expression of the centre-of-mass response for hot system can be written as

$$\delta \tilde{R}_{c.m.}(\omega, T) = 0. \quad (21)$$

Thus, the isovector dipole excitations of hot asymmetric systems don't contain the spurious excitations caused by the centre of mass motion.

The quantitative estimation of spurious effects is shown in Fig.1. In this figure we represent the numerical calculations of the strength function associated with the found response function (13) that is defined as

$$S(E,T) = -\frac{1}{\pi}\operatorname{Im}\tilde{R}(E,T), \quad (22)$$

where $E = \hbar\omega$.

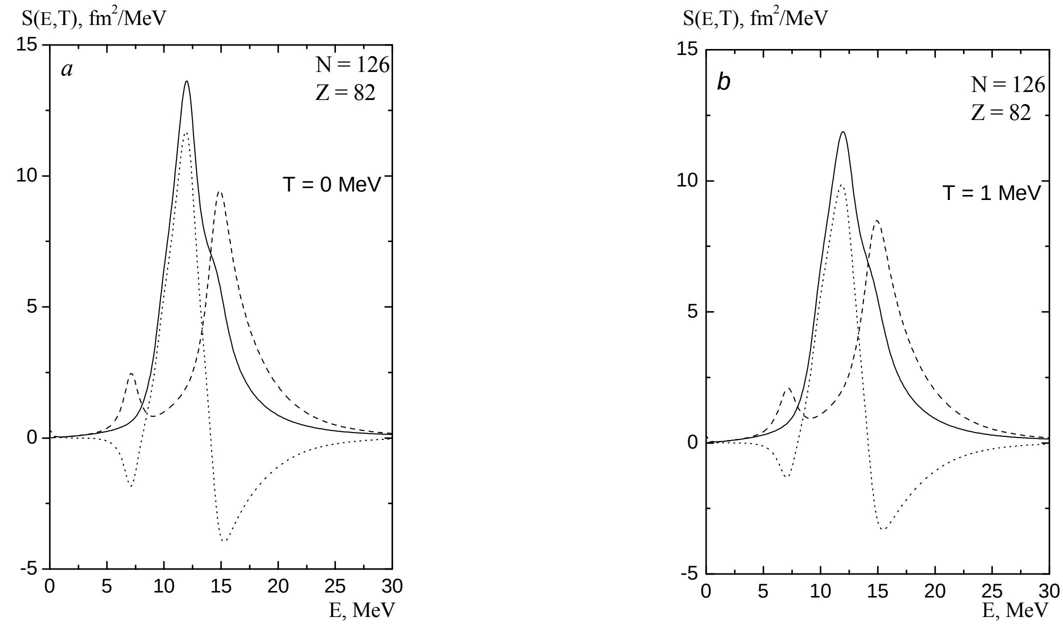

Fig. 1. The isovector dipole strength function (22) with taking into account collisions between nuclei for cold asymmetric system (*a*) and for hot asymmetric system (*b*). The solid line – the collective dipole strength function with the moving-surface approximation, see (13). The dashed line – the collective dipole response in the fixed-surface approximation, see (14). The dotted line – the moving-surface contribution to the dipole response, see (15).

The isovector dipole strength function (22) with taking into account collisions between nucleons for cold asymmetric system (Fig. 1, *a*) and for hot asymmetric system at the temperature T = 1 MeV (Fig. 1, *b*) is shown. The collective dipole strength function for the system with moving boundary is shown by the solid curve, see Eq. (13). It has a giant resonance structure in the energy region of the giant dipole resonance in the nucleus ^{208}Pb. To demonstrate that the found dipole strength doesn't contain the spurious centre-of-mass response, the collective dipole response in the fixed-surface approximation is also shown in Fig. 1 by the dashed curve, see Eq. (14). We can see that the fixed-surface collective response has two resonances. The high-energy resonance describes the giant dipole resonance in the nucleus ^{208}Pb. The low-energy resonance displays the spurious mode at the energy around 7 MeV. The position of this mode is defined by the isoscalar Landau parameter F_0. The dotted curve represents the moving-surface contribution to the dipole response, see Eq. (15). We may see on Fig. 1 that due to including dynamical surface effects in the dipole response, the spurious centre-of-mass strength is exactly canceled. So our dipole strength distribution with moving surfaces for the hot systems doesn't contain the spurious centre-of-mass response.

Temperature dependence of the dipole strength function

The strength function (22) describes the strength distribution of the isovector dipole excitations. The numerical calculations of the strength function were performed for the system with the numbers of neutrons N = 126 and protons Z = 82 like that is in nucleus ^{208}Pb. We used the following values of the nuclear parameters: $r_0 = 1{,}12$ fm, $m = 1{,}04$ MeV × × (10^{-22}s)^2/fm^2 and $\varepsilon_F = 40$ MeV. The phenomenological values of the surface symmetry energy $Q = 75$ MeV and the Landau parameters $F_0' = 1{,}25$ and $F_0 =$ = -0,42 were taken from [20]. The value of constant in Eqs. (6) and (8) was put 5,6 MeV, in order to describe the experimental width of dipole strength distribution at temperature $T = 0$ MeV.

In Fig. 2 we display the effect caused by collisions between nucleons. The dashed line represents the moving-surface dipole strength function without taking into account collisions between nucleons. The solid line represents the moving-surface dipole strength function with accounting for collisions through the collision integral in the relaxation time approximation. We can see that the collision effects lead to the increase of width of the isovector dipole resonance. Really, as we can see, the width of the isovector dipole resonance for cold collisionless Fermi-systems (the dashed line) equals 0,8 MeV. This width is caused by the Landau damping. If we take into account collisions between nucleons (solid line), the width of the distribution increases and becomes equal 4 MeV. As we can see, the obtained width is in a good agreement with the experimental width of the dipole distributions for the nucleus ^{208}Pb [21].

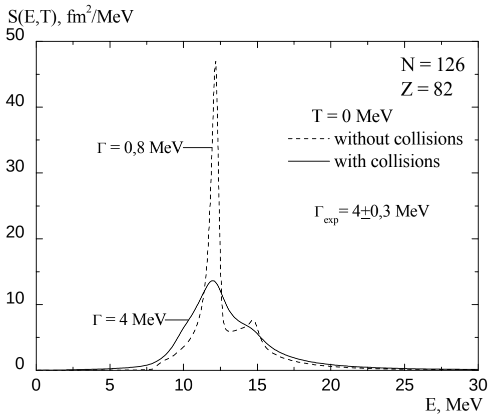

Fig. 2. The collective dipole strength function (22) with the moving-surface for asymmetric system in two approximations: the dashed line – without taking into account collisions between nucleons and the solid line – with taking into account collisions through the collision integral in the relaxation time approximation.

Fig. 3 demonstrates the influence of the neutron excess on the isovector dipole strength distribution. The dipole strength function for the symmetric system of $A = 208$ nucleons with the same numbers of neutrons and protons (the dashed curve) is compared to the one with the neutron numbers $N = 126$ like in the nucleus ^{208}Pb (the solid curve). We can see that the neutron excess also increases the width of the isovector dipole resonance.

Fig. 4 demonstrates the temperature effects on the isovector dipole strength distribution with moving-surface approximation. It is found that the width of giant dipole resonance grows with the temperature increase in the approximation of rare

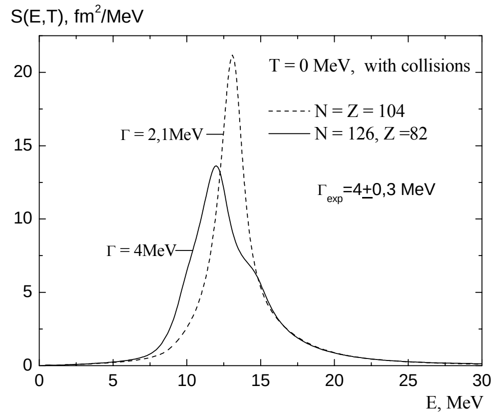

Fig. 3. The collective dipole strength function (22) with the moving-surface approximation for symmetric (N = Z = 104) system (the dashed line) and for asymmetric (N = 126, Z = 82) system (the solid line).

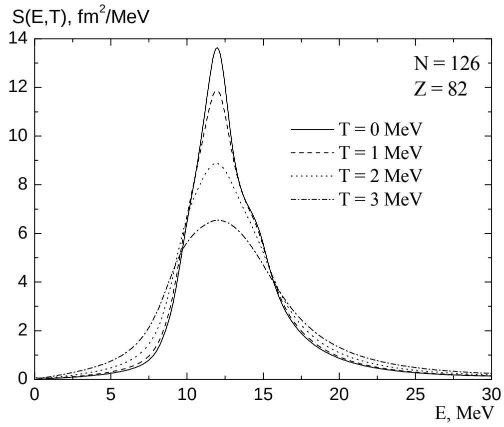

Fig. 4. The collective dipole strength function (22) with the moving-surface approximation at different temperature.

collisions between nucleons. Take note that the main temperature effect in the resonance width is connected with the temperature effects in the collision integral. Both the temperature effects in the equilibrium distribution function and the thermal collision in the surface region do not change essentially the isovector dipole strength distributions.

Conclusions

Semiclassical approach based on the solution of the Vlasov kinetic equation for finite two-component systems with a moving surface is generalized for the study of the isovector dipole response of excited neutron-rich spherical nuclei. The temperature effects are taken into account through the collision integral in the relaxation time approximation. It is shown that, due to the account of the surface degree of freedom, the obtained isovector dipole strength distribution does not contain spurious excitations caused by the centre of mass motion. The analytic expression for isovector dipole response function of hot systems is obtained. It is found that the neutron excess leads to the increase of width (the decrease of collectivity) of the isovector giant dipole resonance due to a strengthening of the Landau damping. Surface effects play the essential role in the structure of the isovector giant dipole resonance. It is found that the width of giant dipole resonance grows with the temperature increase in the approximation of rare collisions between nucleons.

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ТЕМПЕРАТУРНА ЗАЛЕЖНІСТЬ ІЗОВЕКТОРНОГО ДИПОЛЬНОГО ВІДГУКУ АСИМЕТРИЧНИХ СФЕРИЧНИХ ЯДЕР: КІНЕТИЧНИЙ ПІДХІД

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Напівкласичний підхід, що базується на кінетичному рівнянні Власова для скінченних систем із рухомою поверхнею, узагальнено для вивчення ізовекторних дипольних збуджень нагрітих сферичних ядер із надлишком нейтронів. Температурні ефекти враховано в інтегралі зіткнень у наближенні ефективного часу релаксації. Показано, що врахування поверхневих ступенів вільності дозволяє виключити духові збудження, що пов'язані з рухом центра мас. Знайдено, що ширина гігантського дипольного резонансу збільшується з ростом температури в наближенні рідкісних зіткнень між нуклонами.

ТЕМПЕРАТУРНАЯ ЗАВИСИМОСТЬ ИЗОВЕКТОРНОГО ДИПОЛЬНОГО ОТКЛИКА АСИММЕТРИЧНЫХ СФЕРИЧЕСКИХ ЯДЕР: КИНЕТИЧЕСКИЙ ПОДХОД

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Полуклассический подход, основанный на кинетическом уравнении Власова для конечных систем с подвижной поверхностью, обобщается для изучения изовекторных дипольных возбуждений нагретых сферических ядер с избытком нейтронов. Температурные эффекты учитываются в интеграле столкновений в приближении эффективного времени релаксации. Показано, что учет поверхностных степеней свободы позволяет исключить духовые возбуждения, связанные с движением центра масс. Найдено, что ширина гигантского дипольного резонанса увеличивается с ростом температуры в приближении редких столкновений между нуклонами.

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