Dependence of E1 Radiative Strength Function on Neutron Excess in Heavy Nuclei

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Abstract. The electric dipole radiative strength function (isovector dipole response) of neutron-rich spherical nuclei is studied using a semiclassical method based on the Landau-Vlasov kinetic equation for finite two-component systems. It is shown that, by taking into account the surface degree of freedom, it is possible to obtain an exact treatment of the centre of mass motion. It is also shown that a prescription used to subtract the spurious strength in RPA calculations gives the correct semiclassical strength function for the systems with fixed surface. We focus on the influence of the neutron excess on the isovector dipole strength distribution.

INTRODUCTION

The radiative strength functions (RSF) are an important constituent to calculate capture cross sections, gamma-ray production spectra, isomeric state populations and competition between emission of gamma-rays and particles [1]. The expressions of dipole RSF in the approximation of an symmetric nucleus (with the same numbers of neutrons N and protons Z) is used as a rule in practical calculations. This leads to an underestimate of a total width of the RSF as well as to a distortion of the RSF shape, specifically in the range of gamma-ray energies close to the neutron separation energy (the pygmy dipole resonance region). In this work the electric dipole RSF of neutron-rich spherical nuclei is studied using a semiclassical method based on the solution of the Landau-Vlasov kinetic equation for finite two-component systems. This semiclassical approach to nuclear excitations has been derived in paper [2]. By taking into account the surface degrees of freedom the approach of [2] has been extended to include a coupling between the motion of nucleons and surface vibrations in heavy nuclei [3]. A semiclassical study of the isovector dipole excitations in neutron-proton asymmetric finite systems is given in [4-6].

In present contribution the semiclassical approach of [2-6] is used for the study of the collective isovector dipole excitations in neutron-rich spherical nuclei. The dipole response function is discussed by using different approximations. A correct description of the centre of mass (c.m.) motion is vital when evaluating the dipole response of neutron-proton asymmetric finite systems. We tackle the problem of separating the spurious c.m. excitation from the physically interesting intrinsic excitation by using a solution of the linearized Vlasov equation for finite systems with moving surface, which is well suited to describe c.m. motion [7]. The calculations of the dipole response are made also by using the semiclassical approach with fixed surface which is modified by a prescription for the separation of the c.m. motion like that one used in the RPA calculations [8,9].

SEMICLASSICAL APPROACH

We are interested in the isovector dipole response function, which is determining in the following way [10]

\[ \hat{R}(\omega) = \sum_{q=n,p} \hat{R}_q(\omega) = \]
\[ = \frac{1}{\rho} \sum_{q=n,p} a_q \int d\vec{r} Y_{l0}(\hat{r}) \hat{\rho}_q(\hat{r},\omega), \]

(1)
where \( \delta \rho_q(\vec{r}, \omega) \) - the Fourier transform with respect to time of the density change of neutrons and protons induced by the external field of the form

\[
V_q(\vec{r}, t) = \beta \delta(t) a_q Y_{10}(\hat{r})
\]

(2)

with \( a_q = 2Z/A \) at \( q = n \) (neutrons) and \( a_q = -2N/A \) at \( q = p \) (protons), so the external field \( V_q(\vec{r}, t) \) generates the motion of the protons and neutrons against each other. We put in Eq. (1) a tilde over the moving-surface response function to distinguish it from the untilded fixed-surface one. In the moving-surface approximation the density change is defined as [7]

\[
\delta \rho_q(\vec{r}, \omega) = \frac{2}{R} \left[ \int d\rho \rho^q(\vec{r}, \tilde{p}, \omega) + \delta(r-R) \rho^q_0 \delta R_0(\theta, \varphi, \omega) \right]
\]

(3)

In this equation \( \rho_0 \) is the equilibrium density distribution of nucleons, \( \delta R_q(\theta, \varphi, \omega) \) is the equilibrium radius change \( R \) induced by the external field. We will assume below that the neutron and proton equilibrium radii coincide \( R_q = R \), where \( q = n, p \). The second term in Eq.(3) is zero in the fixed-surface approximation. The change of the neutron and proton distribution functions \( \delta \rho^q_0(\vec{r}, \tilde{p}, \omega) \) is the solution of the linearized Vlasov equation with boundary condition at the moving surface [6]. This solution can be obtained at the different approximations. If the change of the mean field inside the system is neglected, then the approximation corresponds to the gas of the non-interacting nucleons, moving in the container with free moving neutron and proton surfaces. This approximation gives the single-particle response function \( \tilde{\rho}^q_0(\omega) \). When we obtain the response function \( \tilde{\rho}^q_0(\omega) \), we have neglected the mean field change inside the system. To take into account the main effects of this change, we will assume that they can be reduce to the separable residual interaction between the nucleons of the following type

\[
u_{qq'}(\vec{r}, \vec{r}') = \kappa_{qq'} \sum_n p' p Y_{1m}(\vec{r}) Y^{*}_{1m}(\vec{r}')
\]

(4)

with the strength parameters \( \kappa_{qq'} \) given by [6]

\[
\kappa_{nn} = \kappa_{pp} = \frac{40\pi}{9R^2} \left( \sum_q a^2_q A_q / \varepsilon_F^2 \right)^{-1} \left( F_0 - F'_0 \right).\]

Here, \( F_0 ', F_0 \) are isovector and isoscalar parameters Landau, respectively,

\[
\varepsilon_F^2 = \varepsilon_F \left( 1 + \tau_q - \frac{Z - N}{A} \right)^{2/3},\]

(6)

where \( \varepsilon_F \) is the Fermi energy of nuclear matter, \( \tau_q = 1 \) at \( q = n \) and \( \tau_q = -1 \) at \( q = p \). Within the fixed-surface theory, and assuming a simplified residual interaction of separable form (4), the dipole response function of a spherical nucleus described as a system of \( A \) interacting nucleons contained within a cavity of radius \( R \) can be found as [5,6]

\[
R_q(\omega) = \frac{R_q^0(\omega)}{1 - R_q^0(\omega) \left\{ \frac{\kappa_{qq'} \kappa_{ww'} - \kappa_{ww'} \kappa_{qq'}}{\alpha_{qq'}^2 \alpha_{ww'}^2} \right\}} \left[ 1 - \kappa_{ww'} (\alpha_{qq'}^2 + \alpha_{ww'}^2) - R_q^0(\omega) R_q^e(\omega) \right].
\]

(7)

where \( q \neq q' \). The single-particle response function in the fixed-surface approximation \( R_q^0(\omega) \) is analogous to the single-particle response function of the quantum theory and, for a square-well type of mean field, it is given explicitly in [4].

Within the moving-surface theory, the collective response function can be written as

\[
\tilde{R}(\omega) = R(\omega) + \tilde{S}(\omega)
\]

(8)

with \( R(\omega) \) still given by Eq. (7), while \( \tilde{S}(\omega) \) represents the moving-surface contribution. With the simple interaction (4) the function \( \tilde{S}(\omega) \) can be evaluated explicitly [6].

In order to obtain accurate results in the pygmy dipole resonance region, it is vital to treat the centre of mass (c.m.) motion correctly. It is shown that the spurious c.m. motion is exact separated from the collective response function (8) due to including dynamical surface effects. The calculations of the collective dipole response are performed also by using the semiclassical approach which is modified by an approximate prescription for the separation of the c.m. motion like that one used in the RPA calculations [8,9].

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As a result expression for modified response function $R_M(\omega)$ without the c.m. motion has the following form

$$R_M(\omega) = R(\omega) - \frac{R_{v,v}(\omega)}{R_{s,s}(\omega)}, \quad (9)$$

where $R_{v,v}(\omega)$ ($R_{s,s}(\omega)$) is response function of isovector (isoscalar) dipole moment on the c.m. motion.

**STRENGTH DISTRIBUTION IN NEUTRON-RICH NUCLEI**

The strength distribution of the isovector dipole excitations is given by the strength function, which is defined as [10]

$$S(\omega) = -\frac{1}{\pi} \text{Im} \tilde{R}(\omega). \quad (10)$$

The numerical calculations of the strength function for the system with the numbers of neutrons $N=126$ and protons $Z=82$ like that in nucleus $^{208}$Pb were performed. For numerical calculations we used the following values of the nuclear parameters: $r_0 = 1.12$ fm, $m = 1.04$ MeV$(10^{-22}$s$^2$/fm$^2$, $\varepsilon_F = 40$ MeV. For the surface symmetry energy $Q$, the Landau parameters $F_0$ and $F_0'$ we used the following phenomenological values: $Q = 75$ MeV, $F_0 = -0.42$ and $F_0' = 1.25$ [12].

In Fig. 1 the single-particle dipole strength function for the system with the numbers of neutrons $N=126$ and protons $Z=82$ is shown. We can see that the single-particle strength distribution in the fixed-surface approximation without the c.m. motion and in the moving-surface approximation are in reasonable agreement.

In Fig. 2 the collective dipole strength function is shown in the same approximations as in Fig. 1. The fixed-surface response with the c.m. motion (the dotted curve) displays the spurious mode at the energy around 7 MeV. On the other hand the moving-surface response (the solid curve) as well as the fixed-surface response without the c.m. motion (the dashed curve) have not the strength in this energy region. They have a giant resonance in the energy region of the GDR in the nucleus $^{208}$Pb. The results of the both calculations are in reasonable agreement. The latter semiclassical approach maybe useful to make more sophisticated calculations with allowance for memory effects in the nucleon collisions [11].

**FIGURE 1.** Single-particle dipole strength function for the system with the numbers of neutrons $N=126$ and protons $Z=82$ (like in nucleus $^{208}$Pb). The dotted and dashed curves show the single-particle response evaluated in the fixed-surface approximation, respectively, with the c.m. motion and without one. The solid curve gives the single-particle response in the moving-surface approximation.

**FIGURE 2.** Collective dipole strength function for the system with the numbers of neutrons $N=126$ and protons $Z=82$ (like in nucleus $^{208}$Pb). The dotted and dashed curves show the collective response evaluated in the fixed-surface approximation, respectively, with the c.m. motion and without one. The solid curve gives the moving-surface response.

Figure 3 demonstrates the influence of the neutron excess on the isovector dipole strength distribution. Collective dipole strength function in the moving-surface approximation for the symmetric system of $A=208$ nucleons with the same numbers of neutrons and protons (the dashed curve) is compared to the one for the system with the neutron numbers $N=126$ like in the nucleus $^{208}$Pb (the solid curve). One can see that the neutron excess leads to the strength in the pygmy
dipole resonance region. However, in the present approximation we cannot reproduce a pygmy resonance. To this end we should include effects of neutron skin in our semiclassical approach.

![Graph](image)

**FIGURE 3.** Collective dipole strength function in the moving-surface approximation for the system with the numbers of nucleons $A=208$ at two values of the neutron numbers: $N=104$ (the dashed curve) and $N=126$ (the solid curve).

In Fig. 4 we display the dipole strength function using different approximations for the system with the numbers of neutrons $N=126$ and protons $Z=82$. One can see that taking into account only the residual interaction inside system (dashed line in Fig. 4) lead to the displacement of the giant resonance structure of the strength function to the higher energy region. While taking into account dynamical effects induced by the surface energy potential has the opposite effect (the dash-dot line in Fig. 4). So due to the surface symmetry potential the spurious c.m. excitation is separated from the dipole intrinsic excitations. Moreover, it plays an essential role in the structure of the giant dipole resonance.

It is found that the neutron excess leads to increase the width (or to decrease the collectivity) of the isovector giant dipole resonance due to a strengthening of the Landau damping. An additional low-energy strength appears at the values of the asymmetry parameter $I=(N-Z)/A$ like that one in nucleus $^{208}$Pb. Surface effects are essentially implicated in the isovector giant dipole resonance. The approach can allow to improve the reliability of the dipole RSF in the wide range of energy from zero to the giant dipole resonance region.

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**REFERENCES**