Isovector giant dipole resonance in Relativistic Thomas-Fermi formalism

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Introduction

Symmetry energy plays a crucial role in study of nuclear structure. As we know, only in the light mass region the nucleus with the same number of proton and neutron are stable, but as the mass number increases the stability of the nucleus favor for a more asymmetric system. So symmetry energy plays a vital role in the nuclear structure. There is no direct way to measure the symmetry energy in a precise manner, so we need indirect way like giant resonance to the measure the symmetry energy. Also various theoretical models give a wide range of uncertainty in estimation of symmetry energy (J) and its slope (L). Symmetry energy has not only central role in finite nuclei but it has a significant role in infinite nuclear matter system. Giant dipole resonance is one of the most powerfull probe to study the nuclear structure physics. Specifically Isovector modes of the giant resonance gives an unique way to study the symmetry energy, because this mode of the giant resonance concerned to the vibration of proton and neutron in out of phase. We can put constraint on the nuclear symmetry energy coefficient by measuring the isovector giant dipole excitation energy.

Theoretical Formalism

For the calculation of the excitation energy of the isovector giant dipole resonance we have used the semi-classical method like Thomas-Fermi formalism [1]. As the excitation of the giant resonance varies very smoothly with the mass number, so it reasonable to use the semi-classical formalism to study the giant resonance. For the present propose the interaction between the meson and nucleon is given by the Hamiltonian density

$$\mathcal{H} = \sum_i \varphi_i^\dagger \Big[- i\vec{\alpha}\cdot\vec{\nabla} + \beta m^* + g_v V_0 + \frac{1}{2} g_\rho R_0 \tau_3 \Big]\varphi_i + \frac{1}{2}\Big[(\vec{\nabla}\phi_0)^2 + m_s^2 {\phi_0}^2\Big] - \frac{1}{2}\Big[(\vec{\nabla}V_0)^2 + m_v^2 {V_0}^2\Big] - \frac{1}{2}\Big[(\vec{\nabla}R_0)^2 + m_\rho^2 {R_0}^2\Big]. \quad (1)$$

Here, we have consider only the uncharged and symmetric nucleus for the simplicity of the problem. In the semi-classical formalism the density is the basic variable. The Hamiltonian in the density form will be

$$\mathcal{H} = \mathcal{E} + g_v V\rho + g_\rho R\rho_3 + e\mathcal{A}\rho_p + \mathcal{H}_f, \quad (2)$$

The well know scaling formalism [2, 3]is used to calculate the excitation energy of the giant resonance. We have scaled the proton density like

$$\rho_{n\lambda} = \rho_n(x, y, z - \frac{\lambda}{2}), \quad (3)$$

and the neutron density

$$\rho_{p\lambda} = \rho_p(x, y, z + \frac{\lambda}{2}). \quad (4)$$

The double derivative of the scaled Hamiltonian with respect to the scaling parameter gives the restoring force.

$$\frac{\partial^2 E_\lambda}{\partial\lambda^2} = \int dr \Big[\frac{\partial^2 e_{n\lambda}}{\partial\lambda^2} + \frac{1}{2} g_v (\frac{\partial\rho_\lambda}{\partial\lambda} V_{0\lambda} + \rho_\lambda \frac{\partial^2 V_{0\lambda}}{\partial\lambda^2} + 2\frac{\partial\rho_\lambda}{\partial\lambda}) + \frac{1}{4} g_\rho (\frac{\partial^2\rho_{3\lambda}}{\partial\lambda^2} R_{0\lambda} + \frac{\partial^2 R_{0\lambda}}{\partial\lambda^2}(\rho_{3\lambda}) + 2\frac{\partial\rho_{3\lambda}}{\partial\lambda}\frac{\partial R_{0\lambda}}{\partial\lambda}) + \frac{1}{2} g_s (\frac{\partial^2\rho_{s\lambda}}{\partial\lambda^2}\phi_{0\lambda} + \rho_{s\lambda}\frac{\partial^2\phi_{0\lambda}}{\partial\lambda^2} + 2\frac{\partial\rho_{s\lambda}}{\partial\lambda}\frac{\partial\phi_{0\lambda}}{\partial\lambda})\Big] \quad (5)$$

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In calculating the mass parameter of the nucleus we assumed the nucleus as an incompressible fluid of nucleons. The collective velocity and the velocity of the nucleons in the center of mass frame are connected though the continuity equation.

$$\frac{\partial \rho_{n\lambda}}{\partial t} + (\vec{\nabla}.\vec{\vartheta})\rho_{n\lambda} + \vec{\vartheta}_n.\vec{\nabla}\rho_{n\lambda} = 0 \qquad (6)$$

$$\frac{\partial \rho_{n\lambda}}{\partial t} + (\vec{\nabla}.\vec{\vartheta})\rho_{n\lambda} + \vec{\vartheta}_n.\vec{\nabla}\rho_{n\lambda} = 0 \qquad (7)$$

In assumption of the incompressible fluid the i.e. $\vec{\nabla}.\vec{\vartheta} = 0$.

$$\vec{\vartheta}_n = -\frac{\dot{\lambda}}{2}\hat{k}, \vec{\vartheta}_p = -\frac{\dot{\lambda}}{2}\hat{k} \qquad (8)$$

The mass parameter is given by the formula

$$B = \left[\frac{\partial^2}{\partial \dot{\lambda}^2}\int T_\lambda dr\right]_{\lambda=\dot{\lambda}=0} \qquad (9)$$

$$B = \left[\frac{\partial^2}{\partial \dot{\lambda}^2}\int \frac{1}{2}m(\rho_{n\lambda}{\vartheta_n}^2 + \rho_{p\lambda}{\vartheta_p}^2)dr\right]_{\lambda=\dot{\lambda}=0} = \frac{1}{4}m\int \rho dr = \frac{mA}{4} \qquad (10)$$

The excitation energy can be calculated by using the formula

$$E_X{}^s = \sqrt{\frac{C_m}{B_m}} \qquad (11)$$

Results and discussion

In table I we have given the excitation energy of the some symmetric nuclei and compared with other theoretical model like RPA and experimental data. Our results are not exactly matched with the experimental data. This discrepancy is due to the various assumption we have taken for the simplicity of the calculation. Here we have taken the Hamiltonian for the uncharged and symmetric nuclei that means the proton and neutron densities are equal. The most important assumption is that we have not taken the enhancement factor into account, which is an important to estimate the isovector giant dipole excitation energy. As we know from the sum rule approaches the potential energy operator does not commute with the Hamiltonian so we need an enhancement factor. In the non-relativistic formalism like Skyrme the enhancement factor(K) is connected with the effective mass. But in the relativistic formalism how to calculate the K it is not clear. Conceptually the origin of the effective mass in non-relativistic and relativistic formalism are very different.

TABLE I: Our theoretical result are compared with RRPA and experimental data.

nuclei	RTF(NL3)	RRPA	Expt.
^{16}O	28.94	24	23.25
^{40}Ca	25.66	19.57	20.00
^{56}Ni	24.02	–	–
^{100}Sn	21.05	—	–

Conclusion

Semi-classical approximation is a good approximation for calculation of collective excitation like giant isovector resonance. This formalism more simple and less time consummating than the well know RPA method. Our formalism is still under constructions and we have to extend it to more practical case like asymmetric nuclear case.

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