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Date: 2023-06-18T00:00:00+00:00

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Full Text

Preamble

Nuclear Science and Techniques 24 (2013) 030502

Symmetry Energy Dependence of the Pygmy and Giant Dipole Resonances in an Isospin-Dependent Quantum Molecular Dynamics Model

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Abstract

The Isospin-dependent Quantum Molecular Dynamics (IQMD) model has been applied to investigate the Pygmy Dipole Resonance (PDR) and Giant Dipole Resonance (GDR) in Ni isotopes via Coulomb excitation. By Gaussian fitting to the photon emission spectra, the peak energies and strengths of PDR and GDR are extracted. Their sensitivities to impact parameter, incident energy, and the symmetry energy are discussed. Through comparison of the energy-weighted sum rule (EWSR) with experimental data and other calculations for ^{68}Ni, the parameters of the density dependence of symmetry energy in IQMD are constrained. Additionally, the N/Z dependence of PDR and GDR parameters in Ni isotopes is investigated, revealing that the EWSR increases linearly with N/Z.

Key words: Pygmy dipole resonance, Giant dipole resonance, Energy-weighted sum rule, Symmetry energy

2 Model and Methods

Over the past decades, extensive work has been conducted on Pygmy Dipole Resonance (PDR) and Giant Dipole Resonance (GDR), both experimentally and theoretically. PDR and GDR represent classic collective modes of nuclei, which can be interpreted as the vibration of valence neutrons against the nuclear core (PDR) or neutrons against protons (GDR), respectively.

Numerous studies have demonstrated that PDR plays a crucial role in neutron-capture rates in the r-process, nucleosynthesis, radiative neutron-capture cross sections on neutron-rich nuclei, and the photodisintegration of ultra-high-energy cosmic rays. Recently, the correlation between PDR and symmetry energy has also been investigated. In the present work, we apply the Isospin-dependent Quantum Molecular Dynamics (IQMD) model to study PDR and GDR in Ni isotopes.

This section introduces the model and formulae used in our calculations, as well as the method for selecting valence neutrons.

2.1 Isospin-Dependent Quantum Molecular Dynamics Model

The Isospin-dependent Quantum Molecular Dynamics model, based on the QMD model, is a type of transport model that has been extensively applied in heavy-ion collision dynamics. In our IQMD model, the mean field can be expressed as:

$$U = U_{\text{Skyrme}} + U_{\text{Coulomb}} + U_{\text{Yukawa}} + U_{\text{sym}} + U_{\text{MDI}}$$

where U_{Skyrme}, U_{Coulomb}, U_{Yukawa}, U_{sym}, and U_{MDI} represent the Skyrme potential, Coulomb potential, Yukawa potential, symmetry potential, and Momentum Dependent Interaction (MDI), respectively.

The Skyrme potential is given by:

$$U_{\text{Skyrme}} = \alpha \left(\frac{\rho}{\rho_0}\right) + \beta \left(\frac{\rho}{\rho_0}\right)^{\sigma}$$

where ρ_0 is the saturation nuclear density ($\rho_0 = 0.16\,\text{fm}^{-3}$) and ρ is the nuclear density. The parameters $[\alpha, \beta, \sigma]$ that represent the equation of state are listed in Table 1 . In the table, S(M) denotes the soft EOS (with MDI), while H(M) denotes the hard EOS (with MDI).

Table 1 Parameters $[\alpha, \beta, \sigma]$ for different EOS

K (MeV)	α (MeV)	β (MeV)	σ (MeV)

The Coulomb potential can be written as:

$$U_{\text{Coulomb}} = \frac{e^2}{2} \sum_{i,j\neq i} \frac{Z_i Z_j}{r_{ij}} \text{erf}\left(\frac{r_{ij}}{2\sqrt{L}}\right)$$

where r_{ij} represents the relative distance between two nucleons, and L is the Gaussian wave-packet width for nucleons, for which a constant value $L = 2.16\,\text{fm}^2$ is used.

The Yukawa potential can be expressed as:

$$U_{\text{Yukawa}} = V_y \sum_{i,j\neq i} \frac{1}{r_{ij}} \left[\exp\left(-\frac{m_y r_{ij}}{\hbar}\right) \text{erfc}\left(\frac{r_{ij}}{2\sqrt{L}} - \frac{m_y\sqrt{L}}{\hbar}\right) - \exp\left(\frac{m_y r_{ij}}{\hbar}\right) \text{erfc}\left(\frac{r_{ij}}{2\sqrt{L}} + \frac{m_y\sqrt{L}}{\hbar}\right)\right]$$

where $V_y = 0.0024\,\text{GeV}$ and $m_y = 0.0024\,\text{GeV}/c^2$.

The symmetry potential can be written as:

$$U_{\text{sym}} = C_{\text{sym}} \frac{\rho}{\rho_0} \left(2\delta_i \frac{\rho_n - \rho_p}{\rho} + \gamma \left(\frac{\rho}{\rho_0}\right)^{\gamma-1} \left(\frac{\rho_n - \rho_p}{\rho}\right)^2\right)$$

where C_{sym} is the strength of symmetry energy at saturation density, γ is the symmetry energy stiffness coefficient, and the symbol “+” applies to neutrons while “–” applies to protons.

The MDI can be expressed as:

$$U_{\mathrm{MDI}} = \delta \sum_{i,j\neq i} \frac{1}{\rho_0} \frac{p_{ij}^2}{2m} \ln \left[\epsilon \left(\frac{p_{ij}}{p_F} \right)^2 + 1 \right] \exp \left(-\frac{r_{ij}^2}{2L} \right)$$

where $\delta = 1.57\,\mathrm{MeV}$ and $\epsilon = 500\,c^2/\mathrm{GeV}^2$.

2.2 Formalism and Method

The dipole moment of GDR in coordinate space and momentum space can be defined as follows [26,27]:

$$\mathbf{D}_{\mathrm{GDR}}^{\mathrm{coord}}(t) = \frac{N}{A}\mathbf{R}_p(t) - \frac{Z}{A}\mathbf{R}_n(t)$$

$$\mathbf{D}_{\mathrm{GDR}}^{\mathrm{mom}}(t) = \frac{N}{A}\mathbf{P}_p(t) - \frac{Z}{A}\mathbf{P}_n(t)$$

where $\mathbf{R}_p(t)$ and $\mathbf{R}_n(t)$ represent the Center of Mass (CM) of protons and neutrons in coordinate space, respectively, while $\mathbf{P}_p(t)$ and $\mathbf{P}_n(t)$ represent the CM of protons and neutrons in momentum space, respectively.

By Fourier transformation of the second time derivative of $\mathbf{D}_{\mathrm{GDR}}(t)$:

$$\frac{d^2\mathbf{D}_{\mathrm{GDR}}(t)}{dt^2} \xrightarrow{\text{Fourier}} \mathbf{D}_{\mathrm{GDR}}(\omega)$$

one obtains the photon emission probability for energy $E_\gamma = \hbar\omega$ as:

$$P(E_\gamma) \propto |\mathbf{D}_{\mathrm{GDR}}(\omega)|^2$$

Similarly, the dipole moment of PDR in coordinate space and momentum space can be defined as:

$$\mathbf{D}_{\mathrm{PDR}}^{\mathrm{coord}}(t) = \frac{N_v}{N_v + Z_c}\mathbf{R}_c(t) - \frac{Z_c}{N_v + Z_c}\mathbf{R}_{vN}(t)$$

$$\mathbf{D}_{\mathrm{PDR}}^{\mathrm{mom}}(t) = \frac{N_v}{N_v + Z_c}\mathbf{P}_c(t) - \frac{Z_c}{N_v + Z_c}\mathbf{P}_{vN}(t)$$

where $\mathbf{R}_c(t)$ and $\mathbf{R}_{vN}(t)$ represent the CM of the isospin-symmetric core and the valence neutrons in coordinate space, respectively, while $\mathbf{P}_c(t)$ and $\mathbf{P}_{vN}(t)$ represent the CM of the isospin-symmetric core and the valence neutrons in momentum space, respectively. The photon emission probability of PDR can then be obtained analogously.

In PDR calculations, a key challenge is selecting the valence neutrons in the simulation. In our approach, we identify neutrons with the farthest distance from the CM of all nucleons as valence neutrons in the initial state, then extract their oscillation characteristics during the subsequent dynamical evolution.

The fraction of Energy-Weighted Sum Rule (EWSR) contained in the PDR relative to that in the GDR region can be expressed as:

$$\mathrm{EWSR}\% = \frac{\mathrm{EWSR}_{\mathrm{PDR}}}{\mathrm{EWSR}_{\mathrm{GDR}}}$$

where $\mathrm{EWSR}_{\mathrm{PDR}}$ and $\mathrm{EWSR}_{\mathrm{GDR}}$ are the EWSR values for PDR and GDR, respectively.

Fig.1 Time evolutions of the root-mean-square radii and binding energy for sample stable nuclei of ^{68}Ni using soft EOS with MDI.

3 Results and Discussions

In low-energy transport model simulations, stability verification of the nucleus is always essential. To this end, we must select stable nuclei during initialization. For example, Fig.1 shows the time evolution of root-mean-square radii and binding energy for some stable nuclei. Clearly, both quantities remain stable before 400 fm/c.

Using these stable nuclei in Coulomb excitation simulations with IQMD, we obtain photon emission spectra. Here, ^{197}Au is chosen as the target, and only the GDR or PDR spectrum from collective motion of nucleons inside the projectile (Ni isotopes) is calculated. By Gaussian fitting to the spectra, peak energies and strengths can be extracted, and their sensitivities to impact parameter, incident energy, and symmetry energy strength can be investigated.

The sensitivities of these parameters to impact parameter are shown in Fig.2. The peak energies and strengths of both GDR and PDR do not change significantly as the impact parameter increases from 16 fm to 26 fm. Since this variation in impact parameter only modestly affects the Coulomb excitation, the result is reasonable.

Fig.2 Impact parameter dependence of GDR and PDR parameters. Calculations use $E_{\mathrm{in}} = 600$ MeV/nucleon, $C_{\mathrm{sym}} = 32$ MeV, $\gamma = 1$, and soft EOS without MDI for ^{68}Ni.

Fig.3 Incident energy dependence of GDR and PDR parameters for ^{68}Ni. Calculations use $b = 24$ fm, $\gamma = 1$, $C_{\mathrm{sym}} = 32$ MeV, and soft EOS without MDI.

Figure 3 [Figure 3: see original paper] shows the incident energy dependence of GDR and PDR parameters for ^{68}Ni. As incident energy increases, both the peak energies and strengths of GDR and PDR decrease. With higher incident energy, the projectile traverses the target's Coulomb field more rapidly, reducing Coulomb excitation and thus decreasing projectile excitation.

Fig.4 C_{sym} dependence of GDR and PDR parameters for ^{68}Ni. Calculations use $E_{\text{in}} = 600$ MeV/nucleon, $b = 24$ fm, $\gamma = 1$, and soft EOS without MDI.

Figure 4 shows the symmetry energy strength C_{sym} dependence of GDR and PDR parameters for ^{68}Ni. As C_{sym} increases, the GDR peak energy increases while the PDR peak energy decreases, and both GDR and PDR strengths decrease.

Fig.5 γ dependence of GDR and PDR parameters for ^{68}Ni. Calculations use $E_{\text{in}} = 600$ MeV/nucleon, $b = 24$ fm, $C_{\text{sym}} = 35.2$ MeV, and soft EOS without MDI.

The γ dependence of GDR and PDR parameters for ^{68}Ni is shown in Fig.5. As γ increases, the GDR peak energy decreases while the PDR peak energy increases, and both GDR and PDR strengths increase.

Symmetry energy is crucial in nuclear physics and astrophysics. Previous studies have identified PDR as a useful probe for investigating symmetry energy. Here, we examine the relationship between PDR and symmetry energy. In our IQMD model, the symmetry energy can be written as:

$$E_{\text{sym}}(\rho) = \frac{1}{2}\left(\frac{\hbar^2}{3m}\right)\left(3\pi^2\rho\right)^{2/3} + C_{\text{sym}}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

where the first term is the kinetic energy contribution and the second term is the potential contribution, with γ being the symmetry energy stiffness coefficient. We investigate the relationship between the two parameters C_{sym} and γ in the symmetry energy formula and the PDR parameters.

Figures 4 and 5 reveal different behaviors for GDR and PDR peak energies: the GDR peak energy increases with C_{sym} but decreases with γ, whereas the PDR peak energy shows the opposite trends. To understand these behaviors, Fig.6 presents symmetry energy versus C_{sym} and γ. Since we employ the Coulomb excitation method, the nucleon density in the projectile remains primarily in the sub-saturation region. The guide lines in Fig.6 show that symmetry energy increases with C_{sym} when γ is fixed at 1 (Fig.6a), and decreases with γ in the sub-saturation region (Fig.6b). Thus, the GDR peak energy exhibits a positive correlation with symmetry energy, while PDR shows an anti-correlation.

Fig.6 E_{sym} versus ρ/ρ_0 for various C_{sym} or γ. (a) γ fixed at 1; (b) C_{sym} fixed at 35.2 MeV.

Fig.7 EWSR versus the derivative of symmetry energy at saturation (L).

Previous studies have established a good correlation between L (the derivative of symmetry energy at saturation) and the fraction of energy-weighted sum rule (in percentage) exhausted by PDR in ^{68}Ni. Different mean-field calculation results for ^{68}Ni are displayed in Fig.7, where solid circles represent those results. From the symmetry energy equation, L can be derived as:

$$L = 3\rho_0 \left. \frac{dE_{\text{sym}}}{d\rho} \right|_{\rho=\rho_0}$$

L increases linearly with either C_{sym} or γ when the other parameter is fixed. Our calculations are shown as open stars, solid stars, and open diamonds, representing L deduced from different C_{sym} values for $\gamma = 1$ (soft EOS without MDI), from different γ values where $C_{\text{sym}} = 35.2$ MeV (soft EOS without MDI), and from different γ values where $C_{\text{sym}} = 35.2$ MeV (soft EOS with MDI), respectively. We find that EOS with MDI yields a higher EWSR fraction compared to EOS without MDI, possibly due to the effective mass reduction by MDI. The curves represent polynomial fits, from which we can estimate the allowed ranges of L and C_{sym} for our IQMD model. The box in the figure shows constraints from experiments and other calculations.

Within this box, C_{sym} and γ in the IQMD model can be constrained from the crossing points of the fitting curves. For the case $\gamma = 1$ with soft EOS without MDI, we obtain $C_{\text{sym}} \in [16.9, 42.9]$ MeV if we adopt $L \in [50.3, 89.4]$ MeV from Ref.[8]. For $C_{\text{sym}} = 35.2$ MeV with soft EOS without MDI, we find $\gamma \in [0.61, 1.22]$ and $L \in [57, 89.4]$ MeV. For $C_{\text{sym}} = 35.2$ MeV with soft EOS with MDI, $\gamma \in [0.78, 1.22]$ and $L \in [66, 89.4]$ MeV. Based on these results, symmetry energy forms that are either too soft or too stiff should be excluded.

Fig.8 EWSR fraction versus N/Z. Calculations use $E_{\text{in}} = 100$ MeV/nucleon, $b = 24$ fm, $C_{\text{sym}} = 32$ MeV, $\gamma = 1$, and soft EOS without MDI.

Finally, we plot the EWSR fraction versus N/Z for our results together with Piekarewicz's calculations in Fig.8. As the neutron-to-proton ratio increases, our results for Ni isotopes show a linear increase. In contrast, Piekarewicz's results for Sn isotopes within the relativistic random phase approximation framework show an initial linear increase followed by a slight decrease.

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4 Conclusion

In this paper, we studied PDR and GDR in Ni isotopes through Coulomb excitation within the IQMD model framework. By Gaussian fitting to the photon spectra, we obtained GDR and PDR parameters including peak energies and strengths. We investigated their sensitivities to impact parameter, incident energy, and symmetry energy. The results demonstrate that GDR and PDR peak energies correlate with symmetry energy, while the EWSR fraction anti-correlates with the derivative of symmetry energy at saturation.

Combining our results with experimental data and other calculations, we constrained the γ coefficient and L parameter for IQMD with different symmetry energy parameters: for soft EOS without MDI, γ lies in the range 0.61–1.22 and L in 57–89.4 MeV; for soft EOS with MDI, γ lies in 0.78–1.22 and L in 66–89.4 MeV. In other words, symmetry energy forms that are too stiff or too soft are excluded by our calculations. Finally, we studied the N/Z dependence of PDR and GDR parameters in Ni isotopes, finding that the EWSR fraction increases linearly with N/Z.

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