Nuclear symmetry energy in relativistic meanfield model constrained by collective excitations

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Our aim

- ✓ Investigate the relation between the nuclear symmetry energy (J) and collective excitations in the framework of relativistic nuclear energy-density functional (RNEDF);
- ✓ Optimize the RNEDF parameters to existing data, and thus, examine the appropriate value of symmetry energy, equation of state (EOS), etc.

Introduction

Symmetry energy can be determined uniquely from the RNEDF Lagrangian of interest. That is,

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + S(\rho)\delta^2 + \mathcal{O}[\delta^4]$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{sym}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \mathcal{O}[(\rho-\rho_0)^3],$$

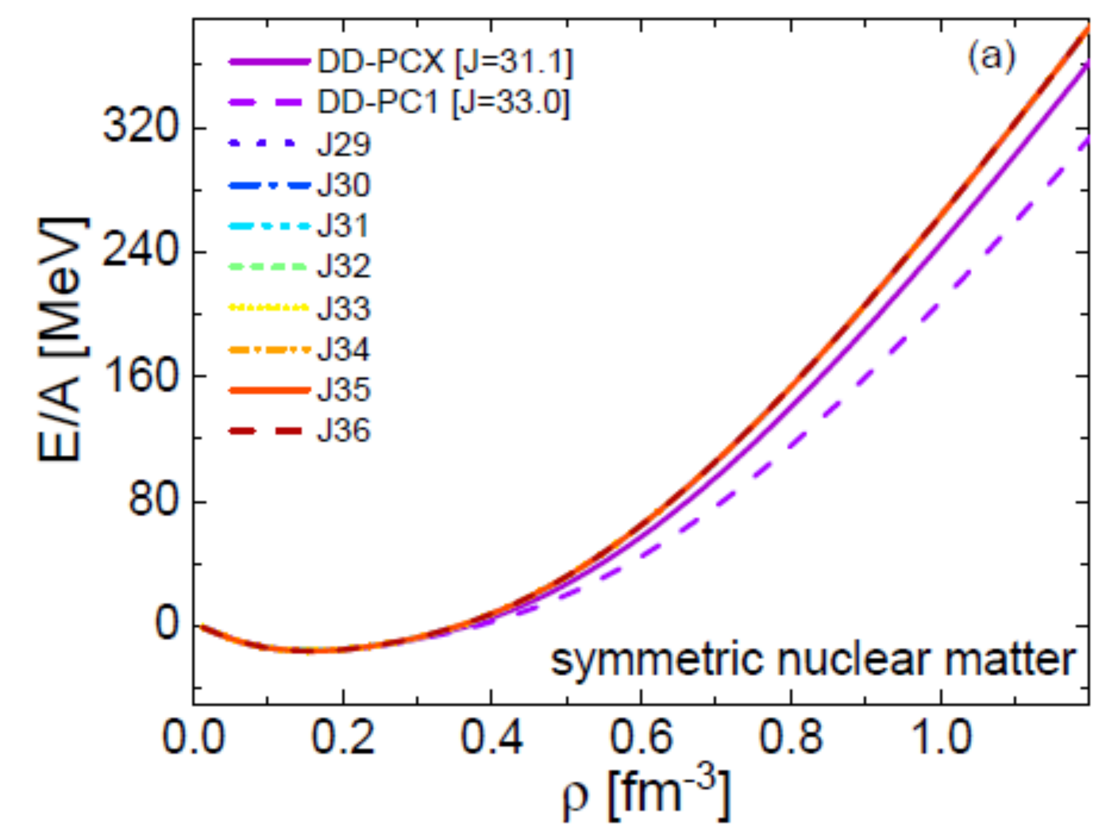
$J \equiv S(\rho_0)$ Symmetry Energy at Saturation

RNEDF Lagrangian

We assume the density-dependent point-coupling (DD-PC) Lagrangian for relativistic meanfield calculation:

$$\mathcal{L} = \bar{\psi}(i\gamma\cdot\partial - m)\psi$$
$$-\frac{1}{2}a_S(\hat{\rho})(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}a_V(\hat{\rho})(\bar{\psi}\gamma^\mu\psi)(\bar{\psi}\gamma_\mu\psi) - \frac{1}{2}a_{TV}(\hat{\rho})(\bar{\psi}\vec{\tau}\gamma^\mu\psi)(\bar{\psi}\vec{\tau}\gamma_\mu\psi)$$
$$-\frac{1}{2}\delta_S(\partial_\nu\bar{\psi}\psi)(\partial^\nu\bar{\psi}\psi) - e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi.$$ (+ residual interactions)

Parameters in DD-PC Lagrangian ⬄ J at saturation density.



E. Yuksel et al, Universe Vol. 7(3), page 71 (2021).

T. OISHI et. Al., "NuSym21 – International Symposium on Nuclear Symmetry Energy", October 2021.

Relativistic QRPA for excitations

We perform the QRPA based on the DD-PC Lagrangian for collective excited states:

$$\hat{\mathcal{H}}\left|\omega\right\rangle = E_\omega\left|\omega\right\rangle,$$
$$\left|\omega\right\rangle = \hat{\mathcal{Z}}^\dagger(\omega)\left|\Phi\right\rangle$$

$$\hat{\mathcal{Z}}^\dagger(\omega) = \frac{1}{2}\sum_{\rho\neq\sigma}\left\{X_{\rho\sigma}(\omega)\hat{\mathcal{O}}^{(J,P)\dagger}_{\sigma\rho} - Y^*_{\rho\sigma}(\omega)\hat{\mathcal{O}}^{(J,P)}_{\sigma\rho}\right\},$$

➔ Matrix QRPA equation:

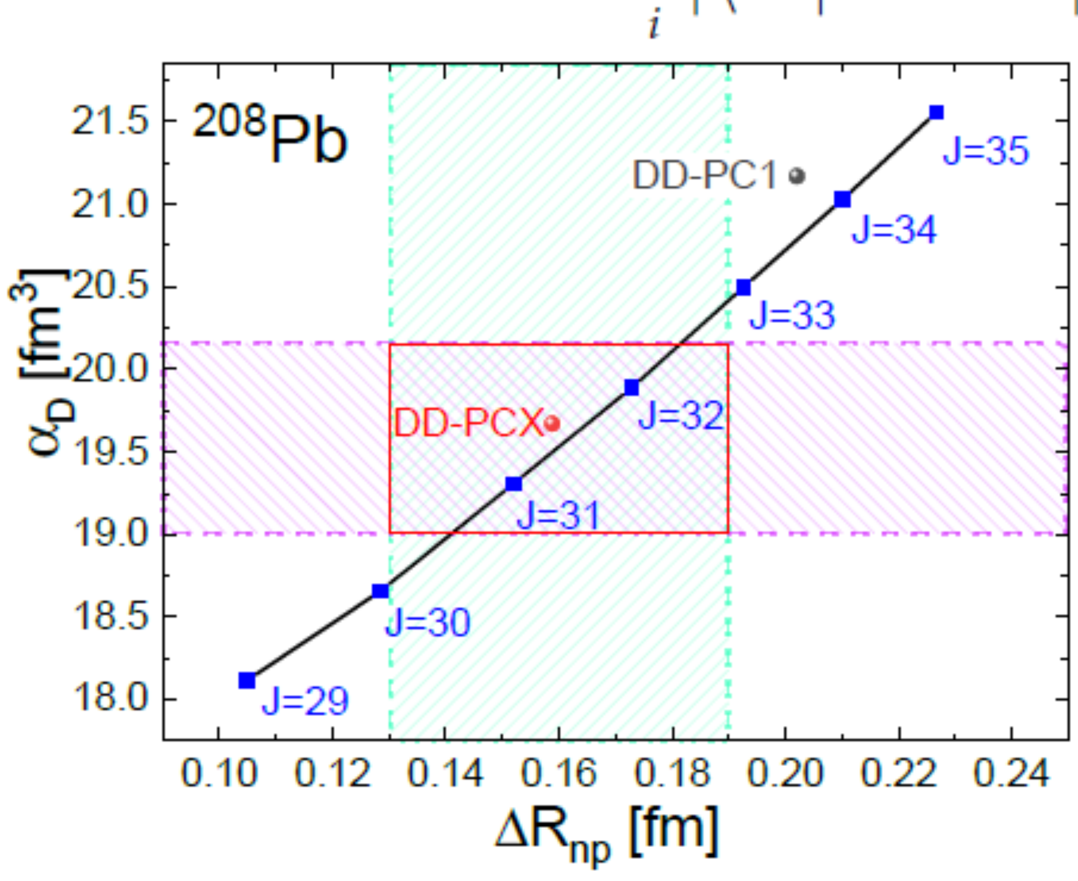
$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix}\begin{pmatrix} X(\omega) \\ Y^*(\omega) \end{pmatrix} = \hbar\omega\begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}\begin{pmatrix} X(\omega) \\ Y^*(\omega) \end{pmatrix},$$

Result 1: Electric dipole mode (E1)

The E1 response and its polarizability is investigated as functions of sym. energy J:

$$\alpha_D = \frac{8\pi e^2}{9}\int_0^\infty E^{-1}S_{E1}(E)dE = \frac{8\pi e^2}{9}m_{-1}(E1),$$

$$S_{E1}(E) = \sum_i\left|\left\langle\omega_i\left|\hat{\mathcal{Q}}^{(\mathrm{IV-E1})}\right|\Phi\right\rangle\right|^2\delta(\hbar\omega_i - E),$$



Conclusion: J=31-32 MeV is found as appropriate from experimental data. The same J value is also suggested from other nuclei's data.

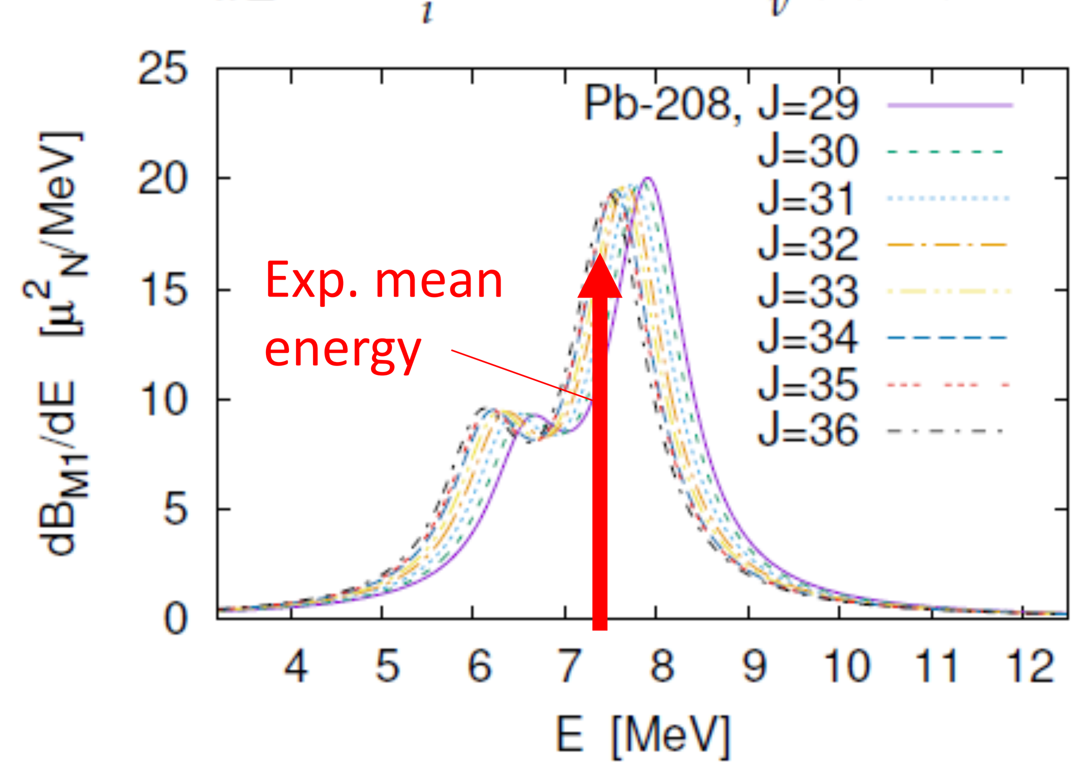
More details ➔ E. Yuksel et al, Universe Vol. 7(3), page 71 (2021).

Result 2: Magnetic dipole mode (M1)

We calculate the M1 response with various J:

$$\hat{\mathcal{Q}}^{(\mathrm{IV-M1})}_\nu = \sqrt{\frac{3}{4\pi}}\mu_N\sum_{k\in A}\left(g_l^{(\mathrm{IV})}\hat{l}_\nu(k) + g_s^{(\mathrm{IV})}\hat{s}_\nu(k)\right)\hat{\tau}_3(k),$$

$$\frac{dB_{M1}}{dE} = \sum_i\delta(E-\hbar\omega_i)\sum_\nu\left|\left\langle\omega_i\left|\hat{\mathcal{Q}}^{(\mathrm{IV-M1})}_\nu\right|\Phi\right\rangle\right|^2.$$



Conclusion: M1 response is finitely sensitive to the sym. energy J. J=31-32 MeV is again found as appropriate.

More details of M1 QRPA ➔ [1] G. Kruzic et al, Phys, Rev, C 102, 044315 (2020); [2] E. Yuksel et al, Universe Vol. 7(3), 71 (2021).

Summary

The nuclear E1 and M1 excitations are investigated as functions of nuclear symmetry energy J in the RNEDF framework. The J=31-32 MeV and its corresponding DD-PC Lagrangian are found as the best option with respect to the experimental data.

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