Nuclear symmetry energy in density-dependent relativistic Hartree-Fock theory: the role of Fock terms and tensor force

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Outline

Symmetry Energy in Nuclear Matter

- Equation of state isospin asymmetric nuclear matter

$$E_b(\rho_b,\delta) = E_0(\rho_b) + E_S(\rho_b)\delta^2 + \mathcal{O}(4), \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

- Empirical parabolic law: ☼ *I. Bombaci and U. Lombardo, Phys. Rev. C* **44**, *1892 (1991).*

$$E_S(\rho_b) = \frac{1}{2}\frac{\partial^2 E_b(\rho_b,\delta)}{\partial\delta^2}\bigg|_{\delta=0}, \quad L = 3\rho_0 \frac{\partial E_S(\rho_b)}{\partial\rho_b}\bigg|_{\rho_b=\rho_0}, \quad K_{\text{sym}} = 9\rho_0^2 \frac{\partial^2 E_S(\rho_b)}{\partial\rho_b^2}\bigg|_{\rho_b=\rho_0}.$$

- Important to understand
  - Information about nuclear structure:
    fission properties, density distribution, collective excitation, etc.
  - Information about neutron star:
    mass-radius relation, crust-core transition density, cooling rate, etc.
  - Information about heavy ion reaction mechanism: isospin diffusion, DR(n/p), etc.

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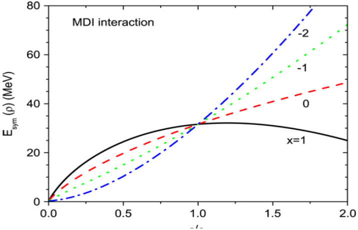
- Density-dependent uncertainty, esp., at supra-saturation densities.

  Ingredients of effective nuclear interaction:
  momentum-dependence, exchange term, tensor force, SRC, ...

L.W.Chen,et al,Phys.Rev.L 94(2005)032701



The Relativistic Hartree-Fock (RHF) Theory

Including the exchange terms and the π-meson

1. In-medium effects not considered explicitly: ☼ *A. Bouyssy:PRL1985,PRC1987*
   ☹ Failed on incompressibility of nuclear matter
2. With the nonlinear self-couplings of the σ-field: ☼ *P. Bernardos:PRC1993*
   ☹ Inconsistency, Broken chiral symmetry
3. Nonlinear self-interaction of scalar field with zero-range limit: ☼ *S. Marcos:JPG2004*
   ☹ Complicated exchange contributions, Violating Pauli Principle
4. Density-dependent meson-nucleon couplings: ☼ *H. L. Shi:PRC1995*
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5. Density-dependent relativistic Hartree-Fock (DDRHF) theory: ☼ *W. H. Long:PLB2006*
   ☺ Quantitative descriptions comparable with RMF without dropping the exchange terms
6. Inclusion of ρ-tensor couplings in DDRHF theory: ☼ *W. H. Long:PRC2007*
   ☺ Enhanced *np* correlations, Better conserved relativistic symmetry ☼ *Long:PRC2010, Liang:EPJA2010*

- DDRHF Effective Interactions : PKO1, PKO2, PKO3, PKA1

Improved Isospin Related Nuclear Structure Descriptions

Fock terms:

→ Improved β and E dependence for the effective mass

☼ *W. H. Long et al., PLB* ***640****, 150 (2006).*

Exchange diagrams in isoscalar channels:

→ Self-consistent description of spin-isospin excitation

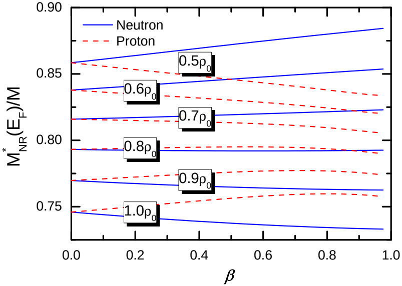
☼ *H. Z. Liang, N. Van Giai, J. Meng, PRL* ***101****,122502 (2008).*

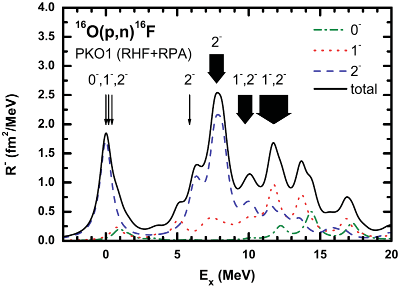
☼ *H. Z. Liang, P. W. Zhao, J. Meng, PRC* ***85****, 064302 (2012).*

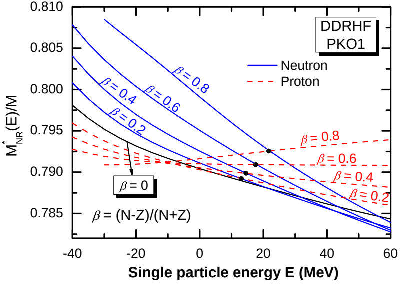
→ Significant contributions in the symmetry energy

☼ *B. Y. Sun et al., PRC* ***78****, 065805 (2008).*

☼ *L. J. Jiang et al., PRC* ***91****, 025802 (2015).*







Scalar and Vector effective masses in DBHF: ☼ *Z. Y. Ma et al., Phys. Lett. B* ***604****, 170 (2004).*

Motivations: Why Symmetry Energies in DDRHF Theory

1. What is the behavior of the symmetry energy at high densites?

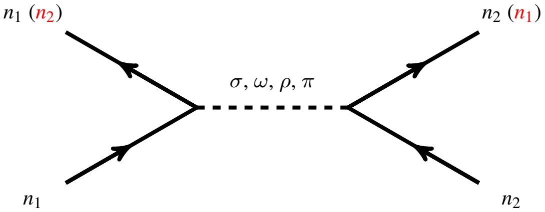
2. What is the role of the Fock terms in symmetry energy of nuclear matter?

3. What is the role of the tensor force in symmetry energy of nuclear matter?

4. Can we find a way to improve RHF EDF from constraints of symmetry energy?

RHF Lagrangian Density

- Relativistic Hartree & Fock (RHF): meson & photon exchanges



Hartree (Fock)

σ: Scalar I

ω: Vector γ^μ

ρ: Vector γ^μ, Tensor $\sigma^{\mu\nu}$

π: Pseudo-Vector $\gamma^\mu\gamma^5$

- RHF Lagrangian density: Nucleon (ψ), Hyperon Λ (ψ_Λ), Mesons (σ, ω, ρ, π)

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_M + \mathcal{L}_\Lambda + \mathcal{L}_I + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\pi \\
&= \bar{\psi}\left[i\gamma^\mu\partial_\mu - M\right]\psi + \bar{\psi}_\Lambda\left(i\gamma^\mu\partial_\mu - M_\Lambda - g_{\sigma\text{-}\Lambda}\sigma - g_{\omega\text{-}\Lambda}\gamma^\mu\omega_\mu\right)\psi_\Lambda \\
&\quad + \bar{\psi}\left[-g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma^\mu\vec{\tau}\cdot\vec{\rho}_\mu + \frac{f_\rho}{2M}\sigma_{\mu\nu}\partial^\nu\vec{\rho}^\mu\cdot\vec{\tau} - \frac{f_\pi}{m_\pi}\gamma_5\gamma^\mu\partial_\mu\vec{\pi}\cdot\vec{\tau}\right]\psi \\
&\quad + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu \\
&\quad - \frac{1}{4}\vec{R}^{\mu\nu}\cdot\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^\mu\cdot\vec{\rho}_\mu + \frac{1}{2}\partial^\mu\vec{\pi}\cdot\partial_\mu\vec{\pi} - \frac{1}{2}m_\pi^2\vec{\pi}\cdot\vec{\pi},
\end{aligned}
$$

with $\Omega^{\mu\nu} \equiv \partial^\mu\omega^\nu - \partial^\nu\omega^\mu, \vec{R}^{\mu\nu} \equiv \partial^\mu\vec{\rho}^\nu - \partial^\nu\vec{\rho}^\mu$.

Λ hyperon participates only in the interactions propagated by the isoscalar mesons.

RHF Energy Functional in Momentum Representation

- Energy functional in momentum representation: energy density in nuclear matter

$$\varepsilon = \frac{1}{\Omega}\langle\Phi_0|H|\Phi_0\rangle = \varepsilon_k + \sum_\phi \left(\varepsilon_\phi^D + \varepsilon_\phi^E\right),$$

with kinetic energy density ε_k, direct (ε_ϕ^D) and exchange (ε_ϕ^E) terms of the potential energy density,

$$\varepsilon_k = \sum_{p,s,\tau} \bar{u}(p,s,\tau)\left(\boldsymbol{\gamma}\cdot\boldsymbol{p} + M_\tau\right)u(p,s,\tau), \quad \text{with} \quad \tau_n = \frac{1}{2},\ \tau_p = -\frac{1}{2},\ \tau_\Lambda = 0,$$

$$\varepsilon_\phi^D = +\frac{1}{2}\sum_{p_1,s_1,\tau_1}\sum_{p_2,s_2,\tau_2} \bar{u}(p_1,s_1,\tau_1)\Gamma_\phi u(p_1,s_1,\tau_1)\frac{1}{m_\phi^2}\bar{u}(p_2,s_2,\tau_2)\Gamma^\phi u(p_2,s_2,\tau_2),$$

$$\varepsilon_\phi^E = -\frac{1}{2}\sum_{p_1,s_1,\tau_1}\sum_{p_2,s_2,\tau_2} \bar{u}(p_1,s_1,\tau_1)\Gamma_\phi u(p_2,s_2,\tau_2)\frac{1}{m_\phi^2+\boldsymbol{q}^2}\bar{u}(p_2,s_2,\tau_2)\Gamma^\phi u(p_1,s_1,\tau_1),$$

where ϕ represents σ-S, ω-V, ρ-V, ρ-T, ρ-VT, and π-PV couplings,

$$\Gamma_{\sigma\text{-S}} = ig_\sigma \text{ or } ig_{\sigma\text{-}\Lambda}, \qquad \Gamma_{\omega\text{-V}} = g_\omega\gamma_\mu \text{ or } g_{\omega\text{-}\Lambda}\gamma_\mu, \qquad \Gamma_{\rho\text{-V}} = g_\rho\gamma_\mu\vec{\tau},$$

$$\Gamma_{\rho\text{-T}} = \frac{f_\rho}{2M}q^\nu\sigma_{\mu\nu}\vec{\tau}, \qquad \Gamma_{\rho\text{-VT}} = \Gamma_{\rho\text{-V}} \text{ or } \Gamma_{\rho\text{-T}}, \qquad \Gamma_{\pi\text{-PV}} = \frac{f_\pi}{m_\pi}\boldsymbol{q}\cdot\boldsymbol{\gamma}\gamma_5\vec{\tau}.$$

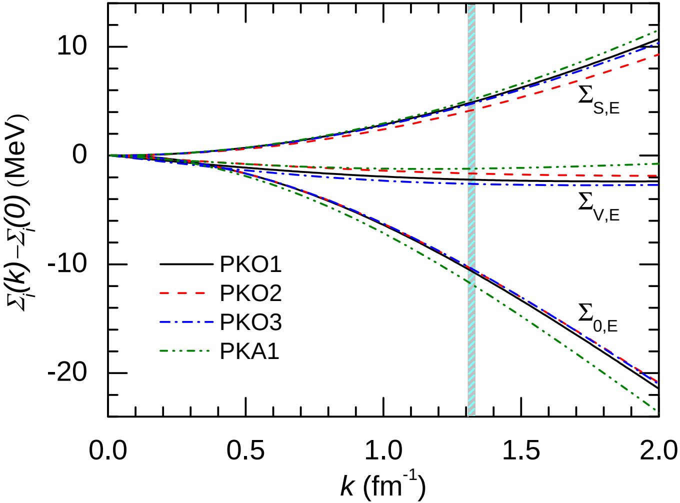
- Self-energies in nuclear matter from variation: $\Sigma(p) = \Sigma_S(p) + \gamma_0\Sigma_0(p) + \boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}\Sigma_V(p)$

$$\Sigma(p)u(p,s,\tau) = \frac{\delta}{\delta\bar{u}(p,s,\tau)}\sum_{\sigma,\omega,\rho,\pi}\left[\varepsilon_\phi^D + \varepsilon_\phi^E\right].$$

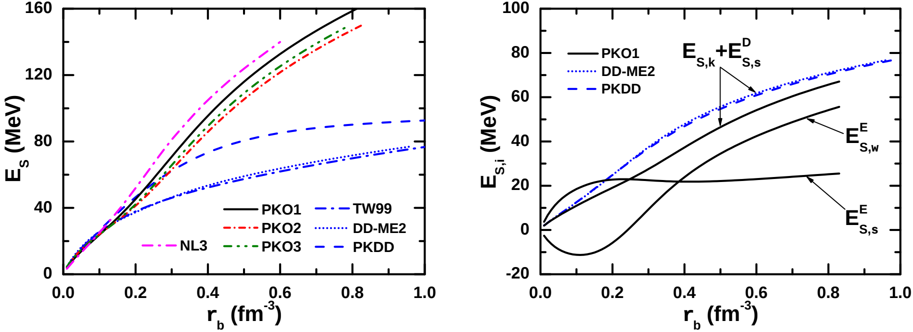
Momentum Dependence of Nucleon Self-Energy

Where does momentum dependence of the potential energy come from?

1. Range of *NN* force
2. Intrinsic *k*-dependence of *NN* interaction
3. Fock term



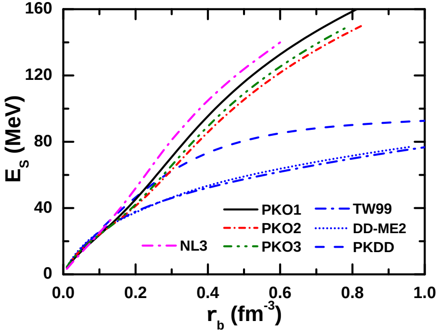
Symmetry Energy — Correlation with Neutron Star Radius

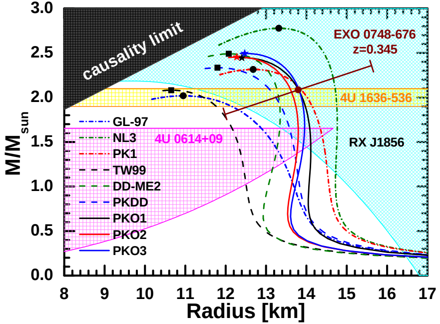


☼ *B. Y. Sun, W. H. Long, J. Meng, and U. Lombardo, Phys. Rev. C* **78**, *065805 (2008).*

- Not only the ρ meson but all the mesons take part in the isospin properties in the DDRHF theory
  - → In charge of producing the symmetry energy via the Fock channel
  - → Significant contributions from isoscalar σ and ω exchange diagram in the symmetry energy
- Observation limit to neutron star radius imposes a strong constraint on the symmetry energy

Correlation with neutron star radius: ☼ *C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett.* **86**, *5647 (2001).*





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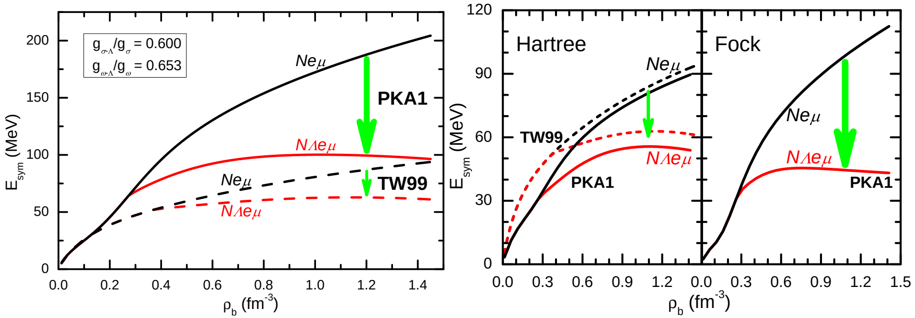
Symmetry Energy — Hyperon effects

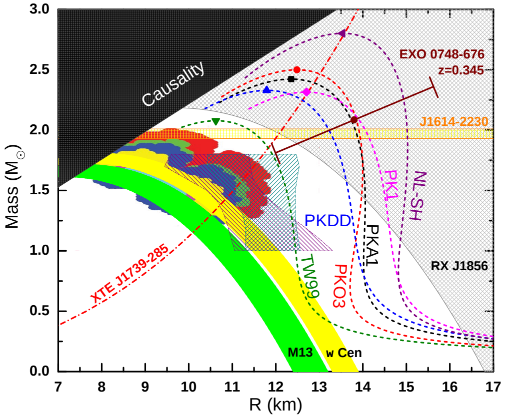


- Softened E_{sym} with hyperons ➞ Reduced R_{max}
- Softened EoSs: The stiffer the EoS is, the greater the effort by Λ to soften the EoS is.
- The Λ-ω couplings in the Fock channel give an attraction even at high densities
  ➞ Extra mass reduction due to the Fock terms

☼ *W. H. Long, B. Y. Sun, K. Hagino, and H. Sagawa, Phys. Rev. C* **85**, *025806 (2012).*

Extra E_{sym} softening due to Fock terms: 2-3 times reduction by Fock terms as Hartree ones do
Fock terms play more significant role in determining the symmetry energy.

Mass-Radius Relations of Neutron Stars

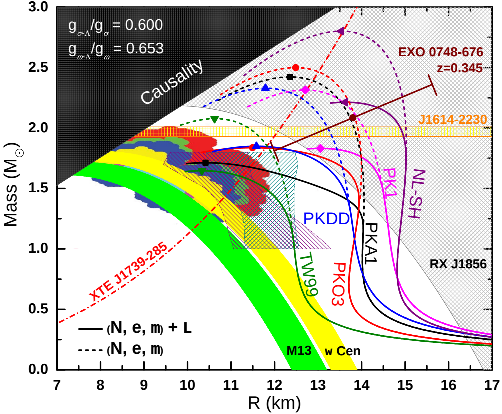


☼ *W. H. Long, B. Y. Sun, K. Hagino, and H. Sagawa, Phys. Rev. C* **85**, *025806 (2012).*

	PKA1	PKO3	PKDD	TW99	PK1	NL-SH
M_{max}	1.713	1.837	1.849	1.647	1.832	2.213
R_{max}	10.425	11.495	11.583	10.333	13.048	13.633
ΔM_{max}	0.710	0.663	0.480	0.431	0.483	0.589
ΔR_{max}	1.929	0.992	0.215	0.299	-0.343	-0.099

- Reduced deviations on EoSs → Vicinal M_{max}
- Softened E_{sym} with hyperons → Reduced R_{max}
- Softened EoSs: The Λ-ω couplings in the Fock channel give an attraction even at high densities → Extra mass reduction due to the Fock terms

Mass-Radius Relations of Neutron Stars — Hyperon effects



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Nuclear Tensor Interaction

Nuclear tensor interaction is identified by the form:

$$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{q})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{q}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \boldsymbol{q}^2$$

Usually thought it is from (isovector) π and ρ- meson exchange

☼ *T. Otsuka, T. Suzuki et al., Phys. Rev. Lett.* ***95****, 232502 (2005).*

- Nuclear structure of ground state: Shell model, SHF+Tensor
  ☼ *T. Otsuka, T. Suzuki et al., Phys. Rev. Lett.* ***95****, 232502 (2005).*
  ☼ *Colò, H. Sagawa, et al., Phys. Lett.****B*** *646 227–231 (2007).*
- Excitation and decay modes: GT、SD，β-decay SHF+Tensor+RPA
  ☼ *C.L. Bai, H. Q. Zhang, H. Sagawa, et al., Phys. Rev. Lett.* ***105*** *072501 (2010).*
  ☼ *F. Minato and C.L. Bai, Phys. Rev. Lett.* ***110*** *122501 (2013).*
- Density dependence of the symmetry energy
  ☼ *C. Xu and B. A. Li, Phys. Rev. C* ***81****, 064612 (2010).*
  ☼ *I. Vidaña, A. Polls, and C. Providência, Phys. Rev. C* ***84****, 062801(R) (2011).*

→ GT and SD in RHF+RPA: significant contribution from $\sigma^E + \omega^E$: central+tensor?

☼ *H.Z. Liang, N.V. Giai, and J. Meng, PRL* ***101****(2008)122502; H.Z. Liang, P.W. Zhao, and J. Meng, PRC* ***85****(2012)064302.*

→ β-decay in RHF+QRPA: ☼ *Z.M. Niu, Y.F. Niu, H.Z.Liang, et al., Phys. Lett.* ***B 723****, 172-176, (2013).*

Relativistic Formalism of Tensors

Relativistic formalism to quantify tensors in Fock diagrams of π-PV, σ-S, ω-V, ρ-T couplings:

☼ *L. J. Jiang, S. Yang, B. Y. Sun, W. H. Long, and H. Q. Gu, Phys. Rev. C* **91**, *034326 (2015).*

$$\mathcal{H}^T_{\pi\text{-PV}} = -\frac{1}{2}\left[\frac{f_\pi}{m_\pi}\bar{\psi}\gamma_0\Sigma_\mu\vec{\tau}\psi\right]_1 \cdot \left[\frac{f_\pi}{m_\pi}\bar{\psi}\gamma_0\Sigma_\nu\vec{\tau}\psi\right]_2 D^{T,\,\mu\nu}_{\pi\text{-PV}}(1,2), \quad (1)$$

$$\mathcal{H}^T_{\sigma\text{-S}} = -\frac{1}{4}\left[\frac{g_\sigma}{m_\sigma}\bar{\psi}\gamma_0\Sigma_\mu\psi\right]_1 \left[\frac{g_\sigma}{m_\sigma}\bar{\psi}\gamma_0\Sigma_\nu\psi\right]_2 D^{T,\,\mu\nu}_{\sigma\text{-S}}(1,2), \quad (2)$$

$$\mathcal{H}^T_{\omega\text{-V}} = +\frac{1}{4}\left[\frac{g_\omega}{m_\omega}\bar{\psi}\gamma_\lambda\gamma_0\Sigma_\mu\psi\right]_1 \left[\frac{g_\omega}{m_\omega}\bar{\psi}\gamma_\delta\gamma_0\Sigma_\nu\psi\right]_2 D^{T,\,\mu\nu\lambda\delta}_{\omega\text{-V}}(1,2), \quad (3)$$

$$\mathcal{H}^T_{\rho\text{-T}} = +\frac{1}{2}\left[\frac{f_\rho}{2M}\bar{\psi}\sigma_{\lambda\mu}\vec{\tau}\psi\right]_1 \cdot \left[\frac{f_\rho}{2M}\bar{\psi}\sigma_{\delta\nu}\vec{\tau}\psi\right]_2 D^{T,\,\mu\nu\lambda\delta}_{\rho\text{-T}}(1,2), \quad (4)$$

where $\Sigma^\mu = \left(\gamma^5, \boldsymbol{\Sigma}\right)$, and D^T (ϕ for σ and π, ϕ' for ω and ρ) read as, $G^{\mu\nu\lambda\delta} \equiv \left(g^{\mu\nu}g^{\lambda\delta} - \frac{1}{3}g^{\mu\lambda}g^{\nu\delta}\right)$

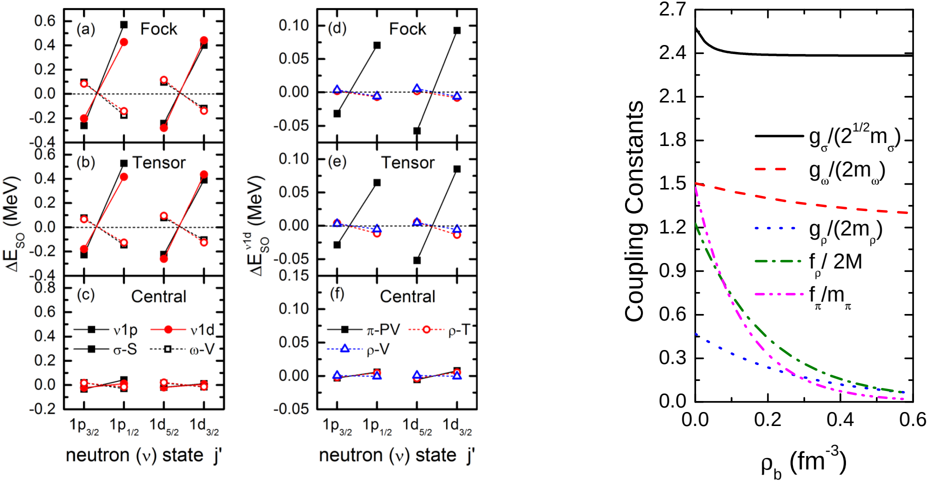
$$D^{T,\,\mu\nu}_{\phi}(1,2) = \left[\partial^\mu(1)\partial^\nu(2) - \frac{1}{3}g^{\mu\nu}m^2_\phi\right]D_\phi(1,2) + \frac{1}{3}g^{\mu\nu}\delta(x_1 - x_2),$$

$$D^{T,\,\mu\nu\lambda\delta}_{\phi'}(1,2) = \left[\partial^\mu(1)\partial^\nu(2)g^{\lambda\delta} - \frac{1}{3}G^{\mu\nu\lambda\delta}m^2_{\phi'}\right]D_{\phi'}(1,2) + \frac{1}{3}G^{\mu\nu\lambda\delta}\delta(x_1 - x_2).$$

Relativistic Formalism of Second-Order Irreducible Tensor S_{12}: For π-PV, σ-S

$$S_{12} = 3\left(\gamma_0\boldsymbol{\Sigma}_1 \cdot \boldsymbol{q}\right)\left(\gamma_0\boldsymbol{\Sigma}_2 \cdot \boldsymbol{q}\right) - \left(\gamma_0\boldsymbol{\Sigma}_1\right)\cdot\left(\gamma_0\boldsymbol{\Sigma}_2\right)\boldsymbol{q}^2$$

Nature of Tensor Force: Spin Dependence



- Tensor feature involved by Fock diagram is evaluated almost completely by the proposed formalism.
- Much distinct tensor effects are found in the isoscalar rather than the isovector.

☼ *L. J. Jiang, S. Yang, B. Y. Sun, W. H. Long, and H. Q. Gu, Phys. Rev. C* **91**, *034326 (2015).*

Nature of Tensor Force: Tensor Sum Rule

- Tensor sum rule: ☼ *T. Otsuka, T. Suzuki et al., Phys. Rev. Lett.* ***95****, 232502 (2005).*

$$(2j_> + 1)\, V^T_{j_> j'} + (2j_< + 1)\, V^T_{j_< j'} = 0$$

$V^T_{j_\gtrless j'}$: Interaction matrix elements of the tensor force components

^{48}Ca PKA1	$V^{T,\sigma}_{j_\gtrless j'}$ (10^{-1}MeV)				$V^{T,\omega}_{j_\gtrless j'}$ (10^{-1}MeV)			
	$\nu 1p_{1/2}$	$\nu 1d_{5/2}$	$\nu 1d_{3/2}$	$\nu 1f_{7/2}$	$\nu 1p_{1/2}$	$\nu 1d_{5/2}$	$\nu 1d_{3/2}$	$\nu 1f_{7/2}$
$\nu 1p_{3/2}$	-1.72	$+0.80$	-1.24	$+0.56$	$+0.27$	-0.13	$+0.21$	-0.10
$\nu 1p_{1/2}$	$+3.43$	-1.60	$+2.48$	-1.11	-0.54	$+0.26$	-0.41	$+0.19$
$\nu 1d_{5/2}$	-1.62	$+1.13$	-1.66	$+1.02$	$+0.27$	-0.19	$+0.28$	-0.18
$\nu 1d_{3/2}$	$+2.44$	-1.69	$+2.50$	-1.53	-0.40	$+0.29$	-0.42	$+0.27$

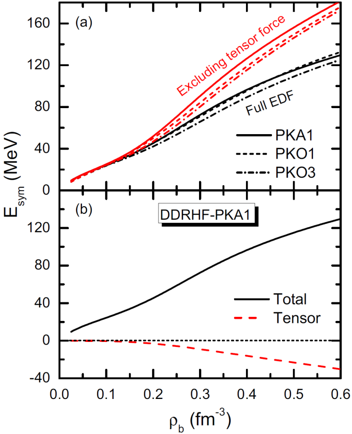
☼ *L. J. Jiang, S. Yang, B. Y. Sun, W. H. Long, and H. Q. Gu, Phys. Rev. C* **91***, 034326 (2015).*

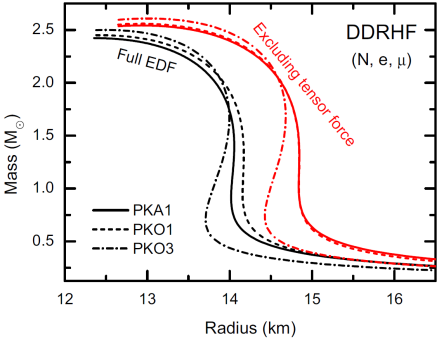
◇ Combined with the contributions in spin-orbit splittings, the relativistic formalism are then confirmed to be of the nature of tensor force.

◇ The tensors are involved naturally by the Fock diagrams and quantified by the relativistic formalism without introducing any additional free parameters.

Tensor Effects — Nuclear Matter

☼ *L. J. Jiang, S. Yang, J. M. Dong, and W. H. Long, Phys. Rev. C* **91**, *025802 (2015).*





→ Smaller proton fraction and larger ρ^{DU}

→ Smaller NS radius due to tensor force

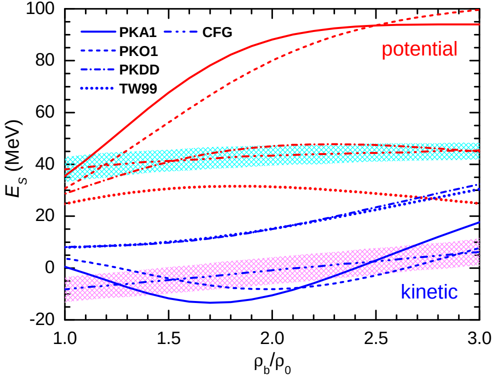
- Softer E_S due to tensor effects
- Tensor effects enhance with increasing density

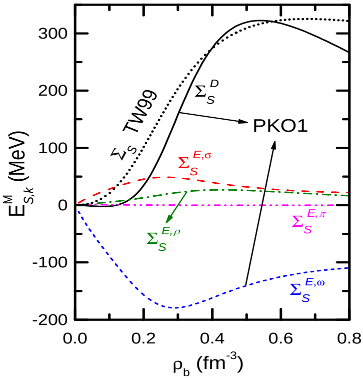
Tensor Effects: Responsible for the uncertainty of E_S at supranuclear densities

☼ *C. Xu and B. A. Li, Phys. Rev. C* **81**, *064612 (2010); I. Vidaña et al., Phys. Rev. C* **84**, *062801(R) (2011).*

Tensor Effects — Kinetic Symmetry Energy

☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, arXiv:1411.6274, accepted by J. Phys. G.*





		TW99	PKDD	PKO1	PKA1	BHF
	kin	8.0	8.1	3.7	0.5	-1.0
J	$T=0$	51.0	50.8	38.8	42.4	44.2
	$T=1$	-26.2	-22.1	-8.1	-5.7	-9.0

☼ *Or Hen et al., Phys. Rev. C* **91***, 025803 (2015).*

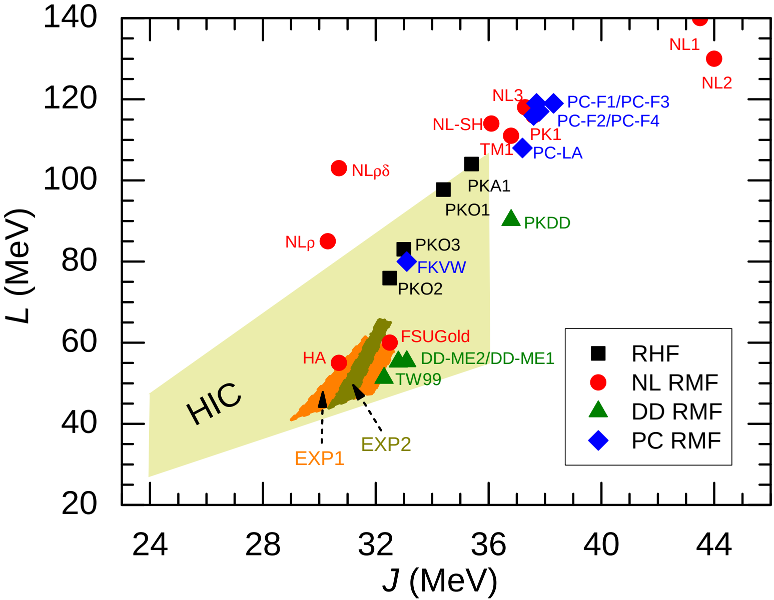
☼ *I. Vidaña et al., PRC* **84***, 062801(R) (2011).*

Short Range Correlation?

$$E_\omega^T \leftrightarrow \int p_1 dp_1 p_2 dp_2 \left\{ \left[\left(P_1^2 + p_2^2 + \frac{1}{6} m_\omega^2 \right) \Phi_\omega - p_1 p_2 \Theta_\omega \right] \hat{P}_1 \hat{P}_2 + \left(\frac{1}{4} m_\omega^2 \Theta_\omega - p_1 p_2 \right) (\hat{M}_1 \hat{M}_2 - 1) \right\}$$

Difference of $E_{S,k}$ between RMF and RHF: mainly due to the exchange term of ω-coupling

Properties of $E_S(\rho_b)$ at saturation density: J and L

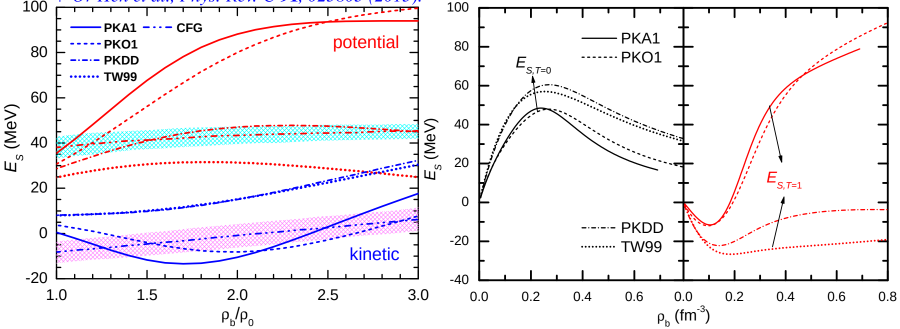


☼ *EXP1: J. Lattimer, Astrophys. J. 771, 51 (2013); EXP2: J. Lattimer, Eur. Phys. J. A 50, 40 (2014).*

Potential Symmetry Energy

$$E_S(\rho_b) = E_{S,k} + E^D_{S,T=0} + E^E_{S,T=0} + E^D_{S,T=1} + E^E_{S,T=1}$$

☼ *Or Hen et al., Phys. Rev. C* ***91****, 025803 (2015).*



☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, arXiv:1411.6274, accepted by J. Phys. G.*

		TW99	PKDD	PKO1	PKA1	BHF
	kin	5.9	5.0	-34.5	-69.6	14.9
L	$T=0$	62.2	78.2	67.5	71.3	69.1
	$T=1$	-12.8	7.0	64.8	103.2	-17.5

☼ *I. Vidaña et al., PRC* ***84****, 062801(R) (2011).*

Large model dependence in kinetic and T=1 potential parts: Significant $E_S^{E,\sigma+\omega}$

Stiff E_S in RHF: Too strong T=1 ☹

Self-energy decomposition of $E_S(\rho_b)$

- Symmetry Energy from HVH theorem ☼ *B. J. Cai, L. W. Chen, Phys.Lett. B 711 (2012) 104 – 108.*

$$E_b + \rho_b \frac{\partial E_b}{\partial \rho_b} = \varepsilon_F \xrightarrow[\text{to asymmetry}]{\text{expansion}} E_S(\rho_b) = \frac{1}{4}\frac{d}{d\delta}\left[\sum_\tau \tau \varepsilon_F^\tau(\rho_b, \delta, k_F^\tau)\right]\Big|_{\delta=0}$$

$$\frac{d\varepsilon_F^\tau}{d\delta}\Big|_{\delta=0} = \frac{\tau k_F}{3}\left(\frac{\partial \varepsilon}{\partial k}\right)\Big|_{k=k_F} + \frac{\partial \varepsilon_F^\tau}{\partial \delta}\Big|_{\delta=0}, \quad \Longrightarrow E_S(\rho_b) = \overbrace{\boxed{E_S^{\text{kin}}(\rho_b) + E_S^{\text{mon}}(\rho_b)}}^{\partial k} + \overbrace{\boxed{E_S^{\text{1st}}(\rho_b)}}^{\partial \delta}$$

- Kinetic part, k-dependence of self-energy, δ-dependence of self-energy:

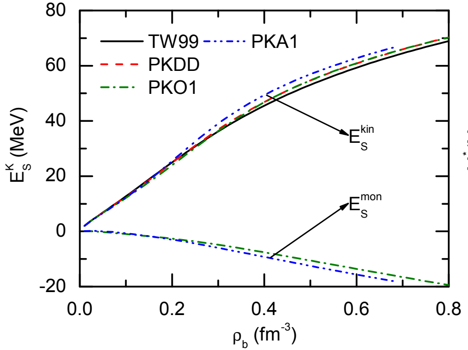
$$E_S^{\text{kin}}(\rho_b) = \frac{k_F k_F^*}{6E_F^*}, \qquad E_S^{\text{1st}}(\rho_b) = \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_b + E_S^{1st,E}$$

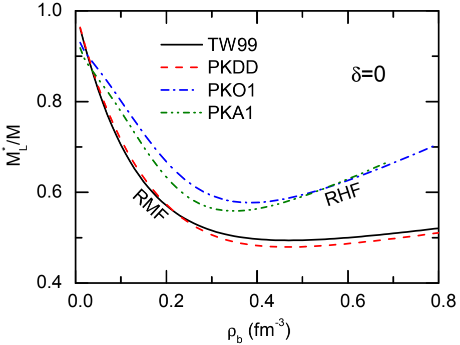
$$E_S^{\text{mon}}(\rho_b) = \frac{k_F k_F^*}{6E_F^*}\frac{\partial \Sigma_V}{\partial k}\Big|_{k=k_F} + \frac{k_F M_F^*}{6E_F^*}\frac{\partial \Sigma_S}{\partial k}\Big|_{k=k_F} + \frac{k_F}{6}\frac{\partial \Sigma_0}{\partial k}\Big|_{k=k_F},$$

- k-dependenct contribution and Landau mass:

$$\boxed{E_S^K = E_S^{\text{kin}} + E_S^{\text{mon}} = \frac{k_F^2}{6M_L^*}}$$

- The negative E_S^{mon} due to the k-dependence of self-energies in RHF, lead to larger M_L^*





More reasonable M_L^* at ρ_0 in RHF compared to empirical data, thus more reasonable E_S^K in RHF

☼ *GQR: P.-G. Reinhard, Nucl. Phys. A649, 305c (1999).*

☼ *β-decay: T. Marketin et al., Phys. Rev. C 75, 024304(2007).*

Neutrino emission from neutron stars:

$$M_R^* = M_{NR}^* + \epsilon = M_g^* \neq M_L^*$$

- Non-Relativistic: Landau Mass ☼ *D.G. Yakovlev et al., Phys. Rep.* ***354****, 1 (2001).*
- Relativistic: Dirac Mass ☼ *L.B. Leinson, A. Pérez, Phys. Lett. B* ***518****, 15 (2001).*

Possible Ways to Improve RHF EDF

- Inclusion of δ-meson coupling channel
- E_S, L, $E_{S,k}$ and $E_{S,pot}$ constraints in fitting process
- New density dependence of meson-nucleon coupling constants
- Correction of interaction vertex with the form factor
- SRC: a high-momentum tail for the nuclear momentum distribution

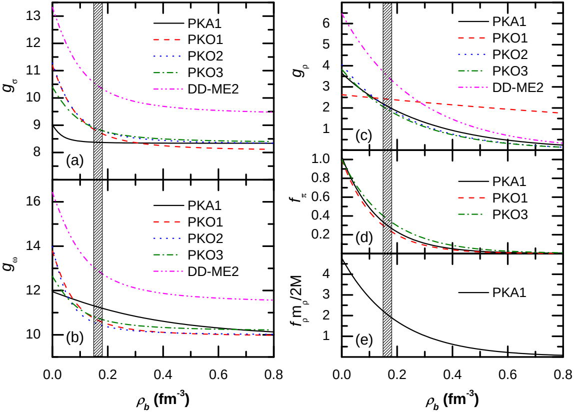
Meson-Nucleon Coupling Constants
medium effects

☼ *R. Brockmann & H. Toki:PRL1992*

$$g_i(\rho_b) = g_i(0)e^{-a_i\xi}, \quad i = \rho, \pi;$$
$$g_i(\rho_b) = g_i(\rho_0)f_i(\xi), \quad i = \sigma, \omega,$$

where $\xi = \rho_b/\rho_0$ with $\rho_b = \sqrt{j^\mu j_\mu}$, and

$$f_i(\xi) = a_i \frac{1 + b_i(\xi + d_i)^2}{1 + c_i(\xi + d_i)^2}$$



Summary and Outlook

- The effects of exchange terms: isoscalar channel σ and ω Fock terms

  ☼ *B. Y. Sun et al., PRC* ***78****(2008)065805; W. H. Long et al., PRC* ***85****(2012)025806.*

- Without introducing any additional free parameters, the DDRHF approach is a natural way to reveal the tensor effects on the nuclear matter system.

  ☼ *L. J. Jiang et al., PRC* ***91****(2015)034326; L. J. Jiang et al., PRC* ***91****(2015)025802.*

- The inclusion of the Fock terms in the CDF theory reduces the kinetic part of the symmetry energy and enhances the Landau mass.

  ☼ *Q. Zhao, B. Y. Sun, W. H. Long, arXiv:1411.6274, accepted by J. Phys. G.*

- Isospin related properties in RHF EDFs could be improved by constraining precisely each components of the symmetry energy.

Collaborators

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Thank you for your attention!

Quantization of RHF Hamiltonian

- System Hamiltonian ($\phi = \sigma^{\rm S}, \omega^{\rm V}, \rho^{\rm V}, \rho^{\rm VT}, \rho^{\rm T}, \pi^{\rm PV}$):

$$H = \int d\boldsymbol{x}\bar{\psi}\left(-i\boldsymbol{\gamma}\cdot\boldsymbol{\nabla} + M\right)\psi + \frac{1}{2}\int d\boldsymbol{x}d\boldsymbol{x}'\bar{\psi}(\boldsymbol{x})\bar{\psi}(\boldsymbol{x}')\Gamma_\phi D^\phi\psi(\boldsymbol{x}')\psi(\boldsymbol{x}),$$

with interaction vertices $\Gamma_\phi(x,x')$ and meson propagators $D_\phi\left(\boldsymbol{x},\boldsymbol{x}'\right)$ **Retardation effects neglected**

$$D_\phi\left(\boldsymbol{x},\boldsymbol{x}'\right) = \frac{1}{4\pi}\frac{e^{-m_\phi|\boldsymbol{x}-\boldsymbol{x}'|}}{|\boldsymbol{x}-\boldsymbol{x}'|}, \qquad D_\phi\left(1,2\right) = \frac{1}{m_\phi^2+\boldsymbol{q}^2} \quad \text{where} \quad \boldsymbol{q} = \boldsymbol{p}_2 - \boldsymbol{p}_1.$$

- Self-energies Σ in nuclear matter: Four-momentum of nucleon: $p = (E(p), \boldsymbol{p})$

$$\Sigma(p) = \Sigma_S(p) + \gamma_0\Sigma_0(p) + \boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}\Sigma_V(p).$$

- Dirac equation in nuclear matter:

$$\left(\boldsymbol{\gamma}\cdot\boldsymbol{p}^* + M^*\right)u(p,s,\tau) = \gamma_0 E^* u(p,s,\tau),$$

with starred quantities: Relativistic mass-energy relation: $E^{*2} = \boldsymbol{p}^{*2} + M^{*2}$

$$\boldsymbol{p}^* = \boldsymbol{p} + \hat{\boldsymbol{p}}\Sigma_V(p), \qquad M^* = M + \Sigma_S(p), \qquad E^* = E(p) - \Sigma_0(p).$$

- Quantization of the nucleon field: **No-sea approximation**

$$\psi(x) = \sum_{p,s,\tau} u(p,s,\tau)e^{-ipx}c_{p,s,\tau}.$$

- RHF ground state: $|\Phi_0\rangle = \prod_{p,s,\tau} c^\dagger_{p,s,\tau}|0\rangle$, where $|0\rangle$ is physical vacuum state.

Selected CDF Effective Lagrangians

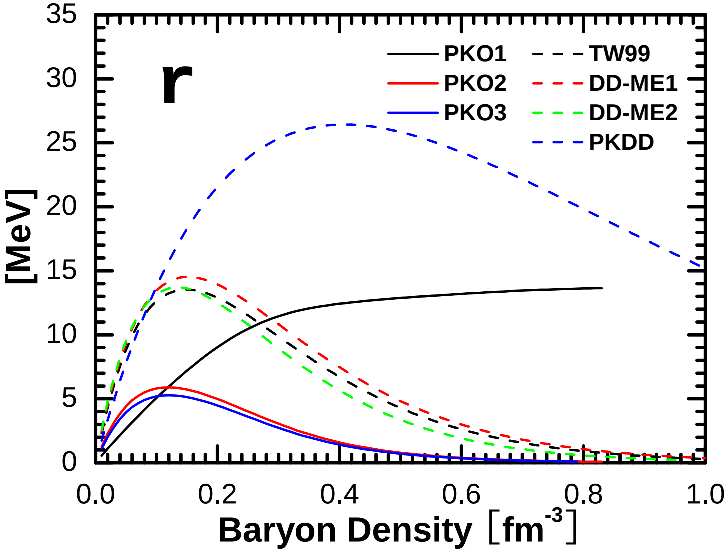
Table: Bulk properties of symmetric nuclear matter at saturation point

	Fock	σ-NL	ω-NL	DD	π-PV	ρ-T	ρ_0 (fm^{-3})	E_B/A (MeV)	K (MeV)	J (MeV)	L (MeV)	Reference
PKA1	✓	×	×	✓	✓	✓	0.160	-15.83	230.0	36.0	104	*Long:2007*
PKO1	✓	×	×	✓	✓	×	0.152	-16.00	250.2	34.4	98	*Long:2006*
PKO2	✓	×	×	✓	×	×	0.151	-16.03	249.6	32.5	76	*Long:2008*
PKO3	✓	×	×	✓	✓	×	0.153	-16.04	262.5	33.0	83	*Long:2008*
NL1	×	✓	×	×	×	×	0.152	-16.43	211.2	43.5	140	*Reinhard:1986*
NL3	×	✓	×	×	×	×	0.148	-16.25	271.7	37.4	118	*Lalazissis:1997*
NL-SH	×	✓	×	×	×	×	0.146	-16.33	354.9	36.1	114	*Sharma:1993*
TM1	×	✓	✓	×	×	×	0.145	-16.26	281.2	36.9	111	*Sugahara:1994*
PK1	×	✓	✓	×	×	×	0.148	-16.27	282.7	37.6	116	*Long:2004*
TW99	×	×	×	✓	×	×	0.153	-16.25	240.3	32.8	55	*Typel:1999*
DD-ME1	×	×	×	✓	×	×	0.152	-16.20	244.7	33.1	56	*Nikšić:2002*
DD-ME2	×	×	×	✓	×	×	0.152	-16.11	250.3	32.3	51	*Lalazissis:2005*
PKDD	×	×	×	✓	×	×	0.150	-16.27	262.2	36.8	90	*Long:2004*

Relatively large values of K and J systematically in RMF with nonlinear self-coupling of mesons (NLRMF)

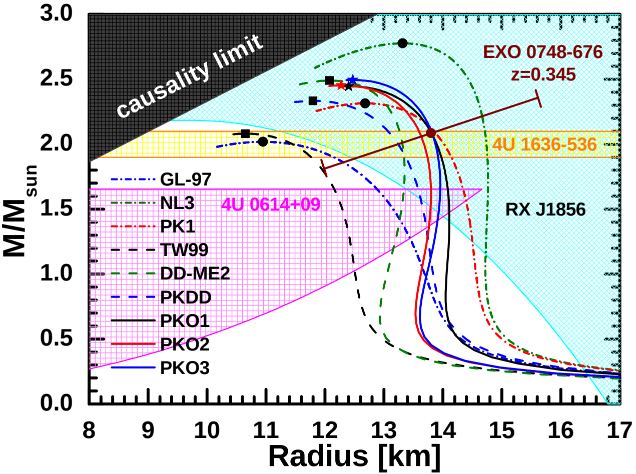
☼ *B. Y. Sun et al., PRC* **78***(2008)065805; W. H. Long et al., PRC* **85***(2012)025806; L. J. Jiang et al., PRC* **91***(2015)025802.*

Symmetry Energy — Contribution from ρ Meson



The Fock terms play an important role in EoSs of asymmetric nuclear matter at high densities.

Mass-Radius Relations of Neutron Stars

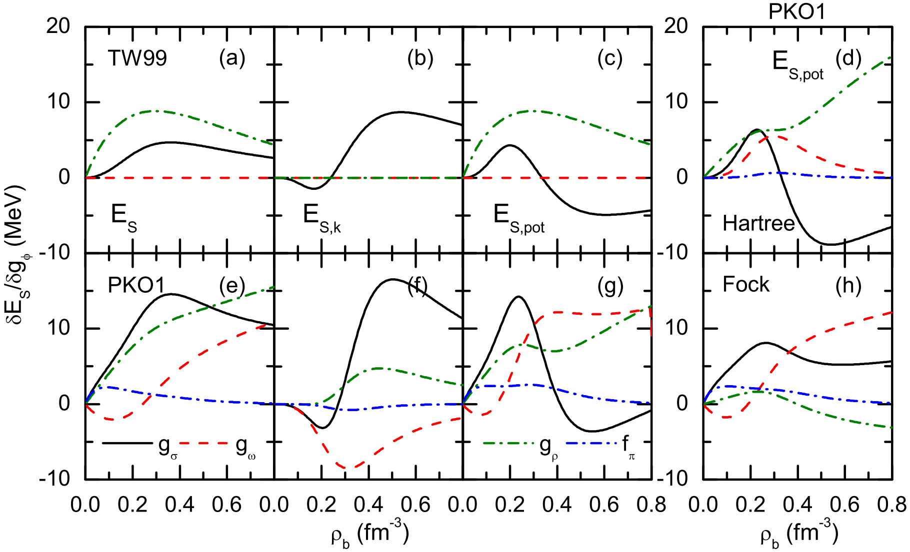


☼ *B. Y. Sun, W. H. Long, J. Meng, and U. Lombardo, Phys. Rev. C* **78**, *065805 (2008).*

	GL-97	NL1	NL3	NL-SH	TM1	PK1	TW99	DD-ME1	DD-ME2	PKDD	PKO1	PKO2	PKO3	關
$M_{\max}$ $(M_\odot)$	2.02	2.81	2.78	2.80	2.18	2.32	2.08	2.45	2.49	2.33	2.45	2.45	2.49	E_0
$\rho_{\max}(0)$ (fm^{-3})	1.09	0.66	0.67	0.65	0.85	0.80	1.10	0.84	0.82	0.89	0.80	0.81	0.78	
$R(M_{\max})$ (km)	10.9	13.4	13.3	13.5	12.4	12.7	10.7	11.9	12.1	11.8	12.4	12.3	12.5	
$R(1.4\,M_\odot)$ (km)	13.3	14.7	14.7	14.9	14.4	14.5	12.4	13.2	13.3	13.7	14.1	13.8	13.9	E_S

Influence of theoretical model uncertainties

☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, arXiv:1411.6274, accepted by J. Phys. G.*



- Zero-Range Tensor Terms in Skyrme EDF

$$V^T = \frac{T}{2}\left\{\left[\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{k}'\right)\left(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}'\right) - \frac{1}{3}\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right)\boldsymbol{k}'^2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2) + \left[\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{k}\right)\left(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}\right) - \frac{1}{3}\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right)\boldsymbol{k}^2\right]\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\right\} + U\left\{\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{k}'\right)\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\left(\boldsymbol{\sigma}_2\cdot\boldsymbol{k}\right) - \frac{1}{3}\left(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right)\left[\boldsymbol{k}'\cdot\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\boldsymbol{k}\right]\right\}$$

T: triplet-even; U: triplet-odd

- Tensor Strength Factors: $\alpha = \alpha_T + \alpha_C$ and $\beta = \beta_T + \beta_C$

$$\alpha_C = \frac{1}{8}\left(t_1 - t_2\right) - \frac{1}{8}\left(t_1x_1 + t_2x_2\right), \qquad \beta_C = -\frac{1}{8}\left(t_1x_1 + t_2x_2\right), \tag{5}$$

$$\alpha_T = \frac{5}{12}U, \qquad \beta_T = \frac{5}{24}\left(T + U\right). \tag{6}$$

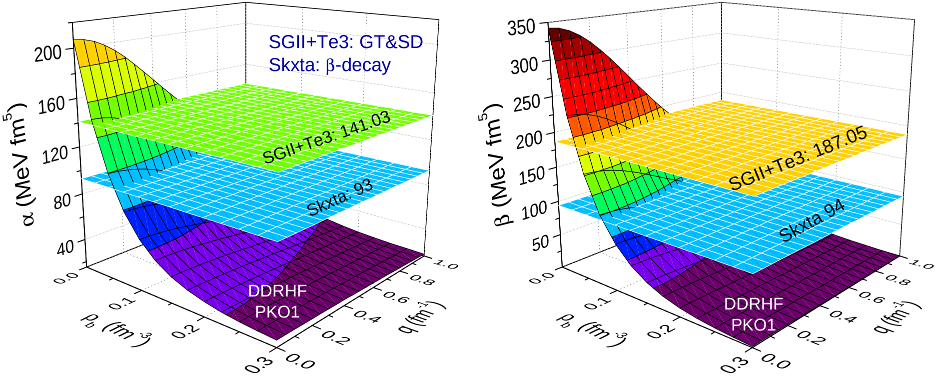
Tensor Strength Factors

Tensor Strength Factors: α and β

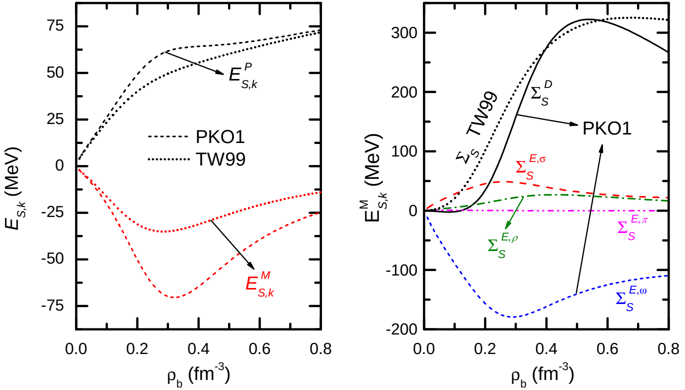
$$\alpha = \frac{5}{12}\left\{\frac{1}{4}\frac{g_\sigma^2}{m_\sigma^2}\frac{1}{m_\sigma^2+\boldsymbol{q}^2} - \frac{1}{8}\frac{g_\omega^2}{m_\omega^2}\frac{1}{m_\omega^2+\boldsymbol{q}^2} + \frac{1}{2}\frac{f_\pi^2}{m_\pi^2}\frac{1}{m_\pi^2+\boldsymbol{q}^2} - \left[\frac{1}{8}\frac{g_\rho^2}{m_\rho^2} - \frac{1}{2}\frac{f_\rho^2}{4M^2}\right]\frac{1}{m_\rho^2+\boldsymbol{q}^2}\right\},$$

$$\beta = \frac{5}{6}\left[\frac{1}{2}\frac{f_\pi^2}{m_\pi^2}\frac{1}{m_\pi^2+\boldsymbol{q}^2} - \left(\frac{1}{8}\frac{g_\rho^2}{m_\rho^2} - \frac{1}{2}\frac{f_\rho^2}{4M^2}\right)\frac{1}{m_\rho^2+\boldsymbol{q}^2}\right]. \tag{7}$$

☼ *L. J. Jiang, S. Yang, B. Y. Sun, W. H. Long, and H. Q. Gu, Phys. Rev. C* **91**, *034326 (2015).*



☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, arXiv:1411.6274.*



- Kinetic energy density:

$$\mathcal{E}_k = \sum_{i=n,p} \frac{1}{\pi^2} \int_0^{k_{F,i}} p^2 dp \left(M\hat{M} + p\hat{P} \right) \equiv \mathcal{E}_k^M + \mathcal{E}_k^P,$$

$\hat{M} = \frac{M}{E^*} + \frac{\Sigma_S^D}{E^*} + \frac{\Sigma_S^{E,\phi}}{E^*}$ with direct term Σ_S^D and exchange term Σ_S^E of the scalar self-energy.

- Difference of $E_{S,k}$ between RMF and RHF: mainly due to the exchange term of ω-coupling