Impact of Fock Terms on Nuclear Symmetry Energy and Related Physics

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Outline

Symmetry Energy in Nuclear Matter

- Equation of state isospin asymmetric nuclear matter

$$E_b(\rho_b,\delta) = E_0(\rho_b) + E_S(\rho_b)\delta^2 + S_4(\rho_b)\delta^4 + \mathcal{O}(4), \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$$

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

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

- Important to understand
  - nuclear structure: fission properties, density distribution, collective excitation, etc.
    - ☼ *B. A. Brown, Phys. Rev. Lett.* **85**, *5296 (2000).*
    - ☼ *M. Centelles, X. Roca-Maza, X. Viñas et al., Phys. Rev. Lett.* **102**, *122502 (2009).*
    - ☼ *A. Tamii, I. Poltoratska, P. von Neumann-Cosel et al, Phys. Rev. Lett.* **107**, *062502 (2011).*
  - nuclear astrophysics: NS's radius, crust-core transition density, cooling rate, etc.
    - ☼ *C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett.* **86**, *5647 (2001).*
    - ☼ *A. W. Steiner, M. Prakash, J. M. Lattimer et al., Phys. Rep.* **411**, *325 (2005).*
  - heavy ion reactions: isospin diffusion, DR(n/p), etc.
    - ☼ *V. Baran, M. Colonna, V. Greco, and M. Di Toro, Phys. Rep.* **410**, *335 (2005).*
    - ☼ *B. A. Li, L. W. Chen, and C. M. Ko, Phys. Rep.* **464**, *113 (2008).*

Symmetry Energy in Nuclear Matter

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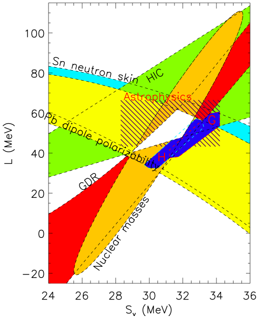
Information of symmetry energy is needed to improve the nuclear many-body models

Ingredients of effective nuclear force:
momentum-dependence, exchange term, tensor force, short range correlation, ...



☼ *J. M. Lattimer, Y. Lim, ApJ* **771**, *51 (2013).*

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*
   ☹ Lacking rearrangement effect

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7. RHF model with bare nucleon-nucleon interaction: ☼ *J. N. Hu:PLB2010*
   ☺ The role of the form factor and short-range correlation ☼ *Hu:EPJA2010, Wen:PTP2010*
8. Self-consistent tensor interaction within DDRHF theory: ☼ *L. J. Jiang:PRC2015*
   ☺ A unified and self-consistent treatment of both the nuclear tensor and spin-orbit interactions

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- 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

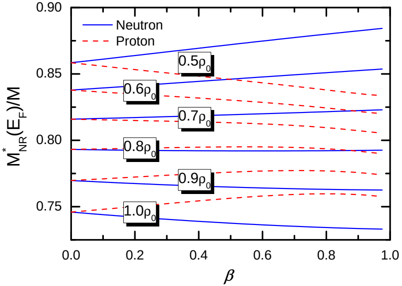
☼ *H. Z. Liang, N. Van Giai, J. Meng, PRL **101**, 122502 (2008).*

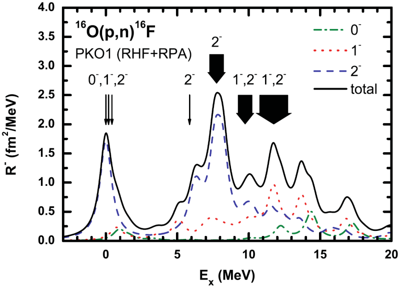
☼ *H. Z. Liang, P. W. Zhao, J. Meng, PRC **85**, 064302 (2012).*

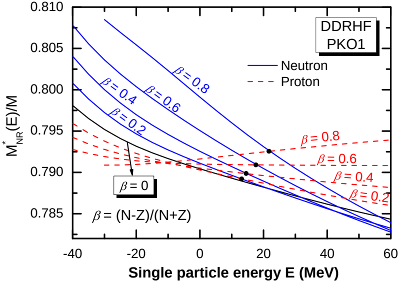
→ Significant contributions in the symmetry energy

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

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

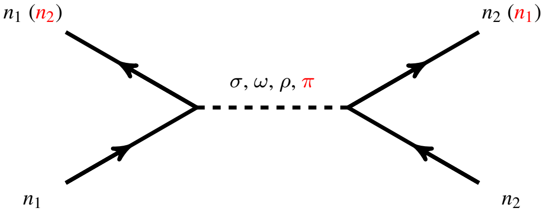






Effective masses in DBHF: ☼ *Z. Y. Ma: PLB2004* BHF vs RHF: ☼ *A. Li: PRC2016*

- 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,

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

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

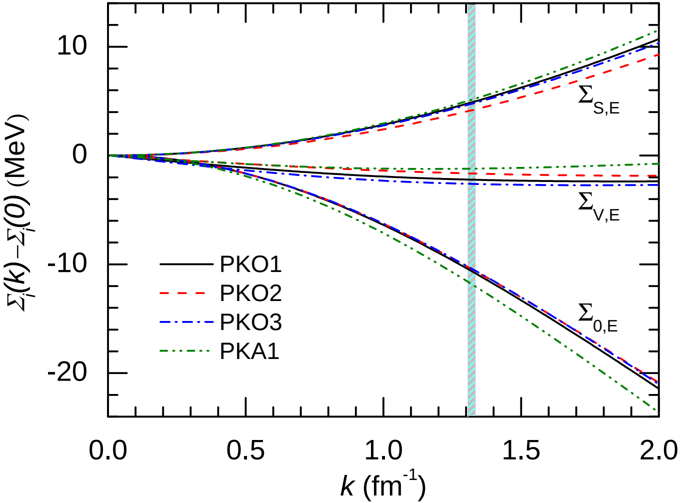
- Self-energies in nuclear matter from variation: $\Sigma(p) = \Sigma_S(p) + \gamma_0\Sigma_0(p) + \boldsymbol{\gamma}\cdot\hat{\boldsymbol{p}}\Sigma_V(p)$

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

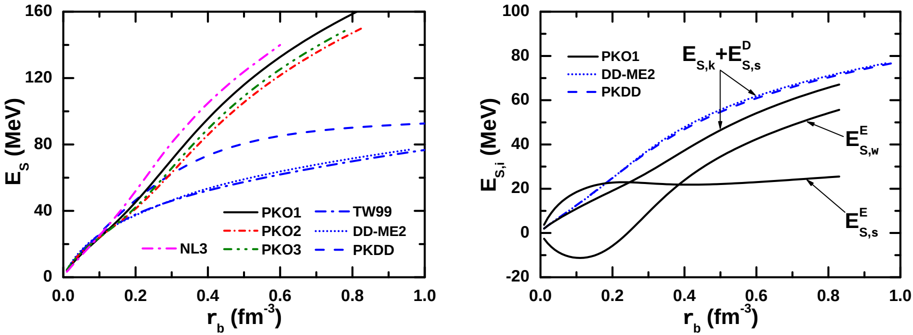
Momentum Dependence of Nucleon Self-Energy

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



Impact of Fock Terms on Nuclear Symmetry Energy



☼ *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).*

Nuclear Tensor Interaction: Relativistic Formalism

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 from (isovector) π and ρ- meson exchange ☼ *T. Otsuka et al., PRL **95**, 232502 (2005).*

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

☼ *H.Z. Liang et al., PRL **101**(2008)122502; H.Z. Liang et al., PRC **85**(2012)064302.*

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

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).*

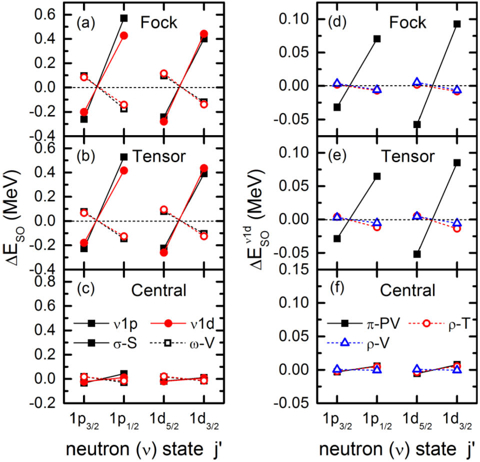
Second-Order Irreducible Tensor S_{12} for π-PV, σ-S:

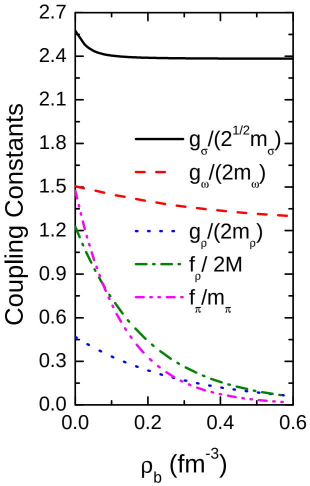
$$S_{12} = 3\left(\gamma_0 \boldsymbol{\Sigma}_1 \cdot \boldsymbol{q}\right)\left(\gamma_0 \boldsymbol{\Sigma}_2 \cdot \boldsymbol{q}\right) - \left(\gamma_0 \boldsymbol{\Sigma}_1\right) \cdot \left(\gamma_0 \boldsymbol{\Sigma}_2\right) \boldsymbol{q}^2$$

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

→ Much distinct tensor effects are found in the isoscalar rather than the isovector.

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) $\nu 1p_{1/2}$	$\nu 1d_{5/2}$	$\nu 1d_{3/2}$	$\nu 1f_{7/2}$	$V^{T,\omega}_{j\gtrless j'}$ $(10^{-1}$MeV) $\nu 1p_{1/2}$	$\nu 1d_{5/2}$	$\nu 1d_{3/2}$	$\nu 1f_{7/2}$
$\nu 1p_{3/2}$	−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

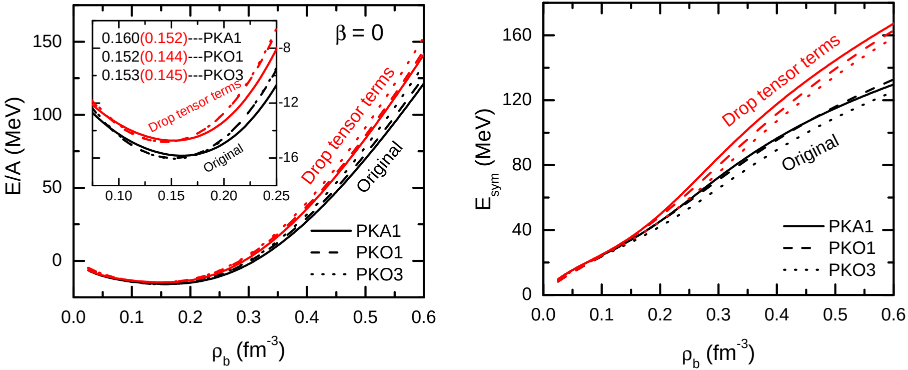
☼ *L. J. Jiang, S. Yang, B. Y. Sun, W. H. Long, and H. Q. Gu, Phys. Rev. C* **91***, 034326 (2015).*

◇ 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).*



Effects of Fock terms to E_S: Soften due to tensor part; Stiffen due to central part

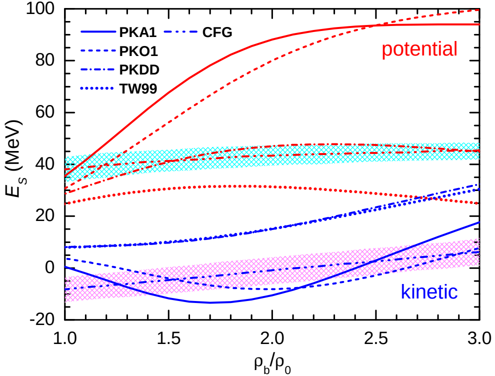
$$E_{\sigma}^{T} = + \frac{1}{2} \frac{1}{(2\pi)^4} \frac{g_{\sigma}^2}{m_{\sigma}^2} \sum_{\tau_1,\tau_2} \delta_{\tau_1,\tau_2} \int p_1 dp_1 p_2 dp_2 \hat{P}_1 \hat{P}_2 \left[\left(p_1^2 + p_2^2 - \frac{1}{3} m_{\sigma}^2 \right) \Phi_{\sigma} - p_1 p_2 \Theta_{\sigma} \right].$$

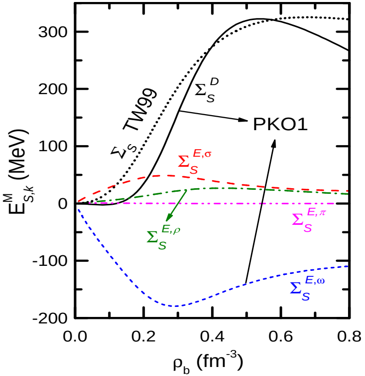
Tensor Effects: Responsible for the uncertainty of E_S at supranuclear densities

☼ *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, BYS, Wen Hui Long, J. Phys. G* **42**, *095101 (2015);* *BYS et al., EPJConf* **117**, *07011 (2016).*





		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).*
☼ *A. Rios et al., Phys. Rev. C* **89**, *044303 (2014).*
☼ *I. Vidaña et al., PRC* **84**, *062801(R) (2011).*

Short Range Correlation?

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

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

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.*

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

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

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

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

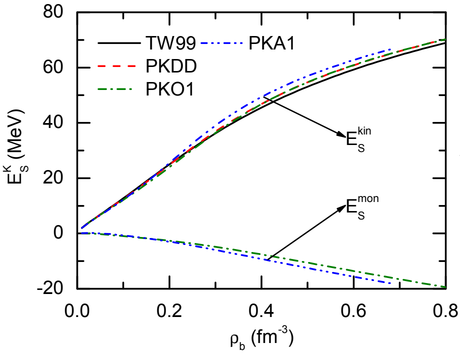
$$E_S^{\text{mon}}(\rho_b) = \frac{k_F k_F^*}{6E_F^*}\frac{\partial \Sigma_V}{\partial k}\Big|_{k=k_F} + \frac{k_F M_F^*}{6E_F^*}\frac{\partial \Sigma_S}{\partial k}\Big|_{k=k_F} + \frac{k_F}{6}\frac{\partial \Sigma_0}{\partial k}\Big|_{k=k_F},$$

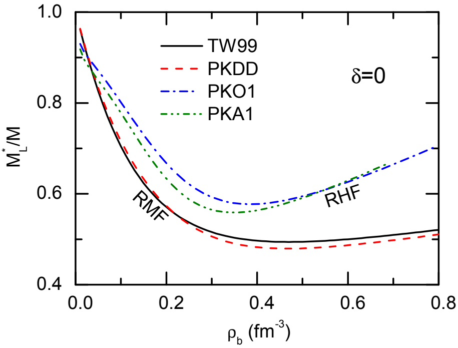
- k-dependenct contribution and Landau mass:

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

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

Impact of Landau Mass





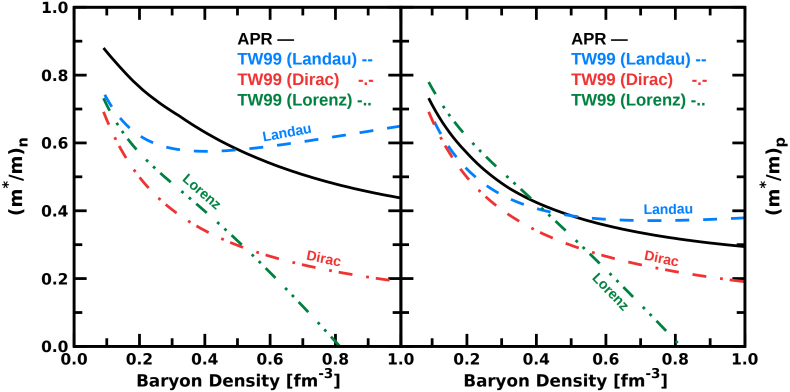
Neutrino emission from neutron stars:

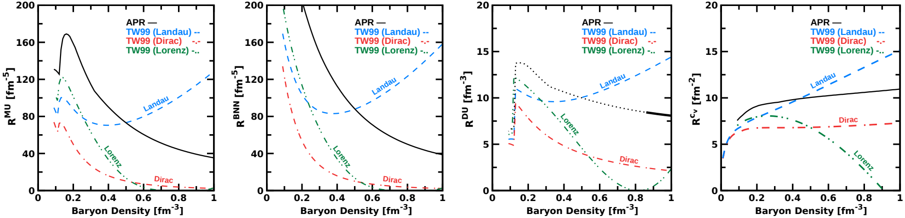
$$M_R^* = M_{NR}^* + \epsilon = M_g^* = M_L^*$$

- 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).*

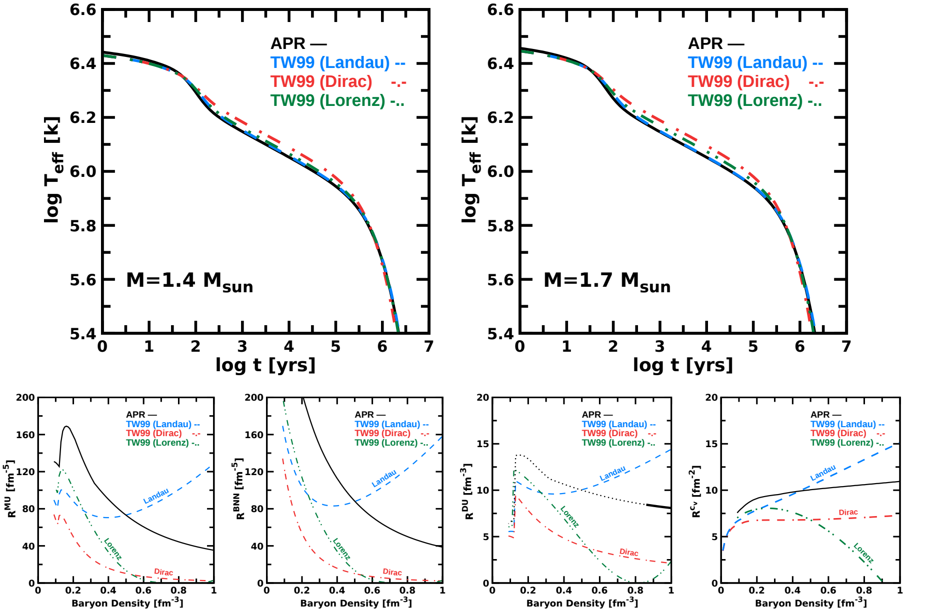
Rotation Effects: ☼ *N. B. Zhang et al.*

Influence of Nucleon Effective Masses

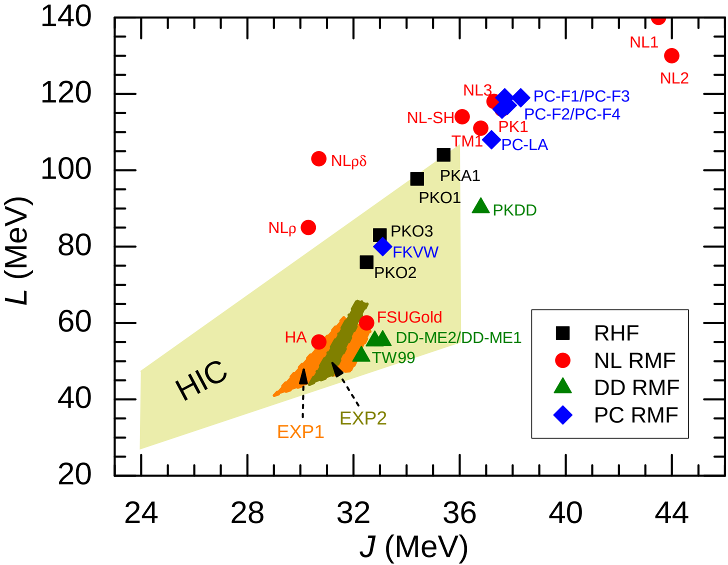




Influence of Nucleon Effective Masses

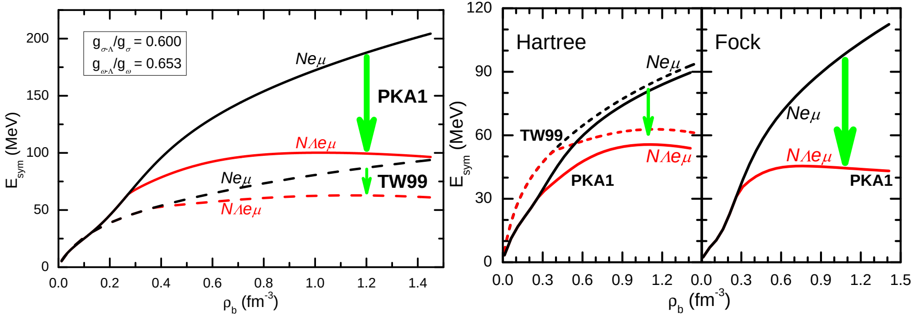


Properties of E_S at Saturation Density: J and L



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

Symmetry Energy — Hyperon effects

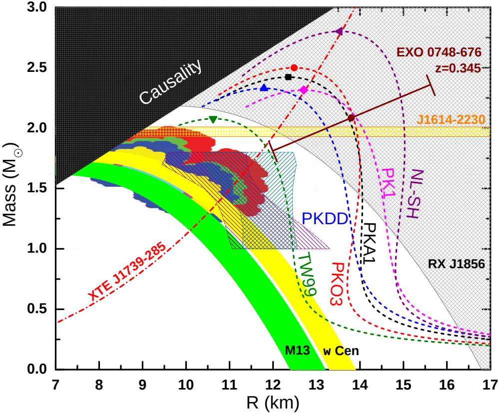


- Softened E_{sym} with hyperons ➞ Reduced R_{max}
- Softened EoSs: The stiffer the EoS is, the greater the effort by Λ to soften the EoS is.
- The Λ-ω couplings in the Fock channel give an attraction even at high densities
  ➞ Extra mass reduction due to the Fock terms

☼ *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.

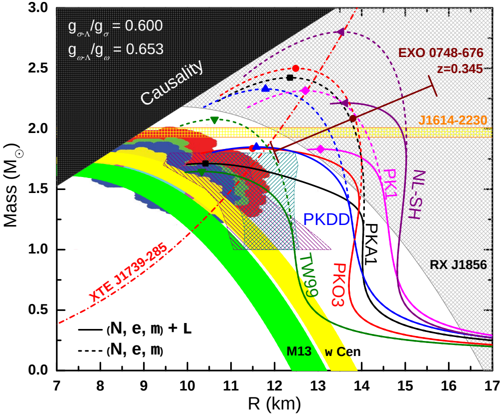


☼ *W. H. Long, B. Y. Sun, K. Hagino, and H. Sagawa, Phys. Rev. C* **85**, *025806 (2012).*

	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
$\Delta M_{\max}$	0.710	0.663	0.480	0.431	0.483	0.589
$\Delta R_{\max}$	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



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

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- 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

Summary and Outlook

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

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

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

- 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 et al., JPG* **42***, 095101 (2015).*

- Influence of theoretical model uncertainties
- Inclusion of δ-meson coupling channel
- New density dependence of meson-nucleon coupling constants
- SRC: a high-momentum tail for the nuclear momentum distribution
- Correction of interaction vertex with the form factor
- Second-order Hartree-Fock theory

Collaborators

Prof. Jie Meng	Peking University, China
Prof. Wen Hui Long	Lanzhou University, China
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Prof. Kouichi Hagino	Tohoku University, Japan
Prof. Hiroyuki Sagawa	University of Aizu, Japan
Dr. Jian Min Dong	IMPCAS, China
Dr. Li Juan Jiang	Lanzhou University, China
Mr. Shen Yang & Mr. Qian Zhao	Lanzhou University, China

Thank you for your attention!

Quantization of RHF Hamiltonian

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

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

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:

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

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.*

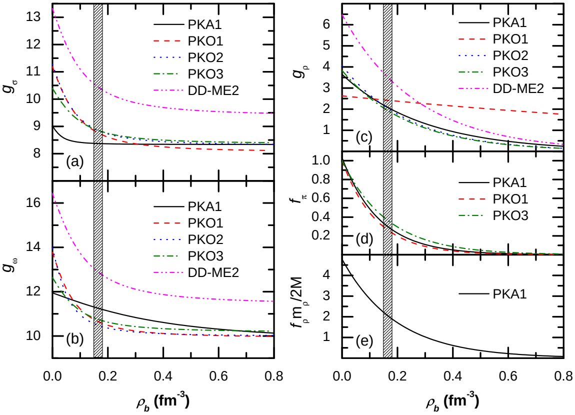
Meson-Nucleon Coupling Constants
medium effects

☼ *R. Brockmann & H. Toki:PRL1992*

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

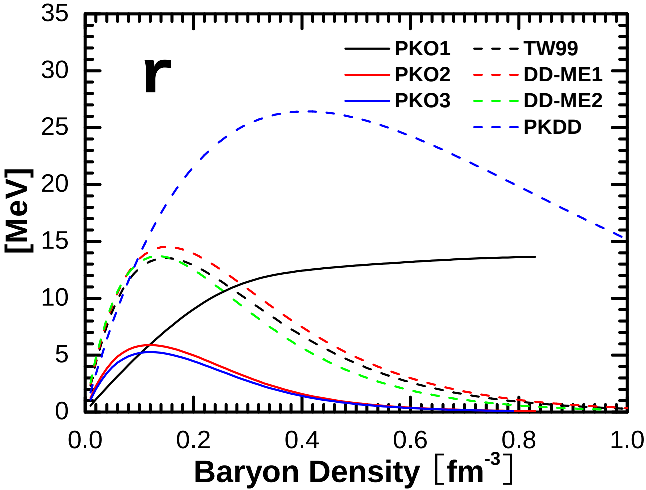
where $\xi = \rho_b/\rho_0$ with $\rho_b = \sqrt{j^\mu j_\mu}$, and

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



Symmetry Energy — Contribution from ρ Meson

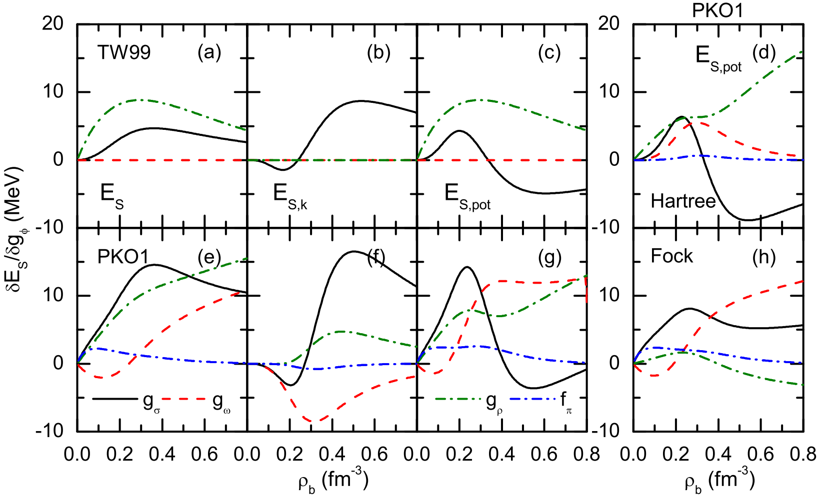
☼ *B. Y. Sun, W. H. Long, J. Meng, and U. Lombardo, Phys. Rev. C* **78**, *065805 (2008).*



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

Influence of Theoretical Model Uncertainties

Enhancing the interaction between nuclear experiment and theory through information and statistics: ☼ *D. G. Ireland, W. Nazarewicz, J. Phys. G* **42**, *030301 (2015).*



☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, J. Phys. G.* **42**, *095101 (2015).*

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).*

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

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

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

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

where $\Sigma^\mu = \left(\gamma^5, \boldsymbol{\Sigma}\right)$, and D^T (ϕ for σ and π, ϕ' for ω and ρ) read as,

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

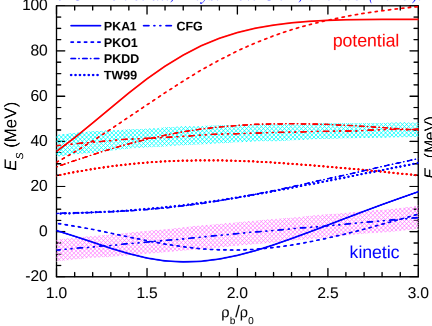
$$D^{T,\,\mu\nu\lambda\delta}_{\phi'}(1,2) = \left[\partial^\mu(1)\partial^\nu(2)g^{\lambda\delta} - \frac{1}{3}G^{\mu\nu\lambda\delta}m^2_{\phi'}\right]D_{\phi'}(1,2) + \frac{1}{3}G^{\mu\nu\lambda\delta}\delta(x_1 - x_2).$$

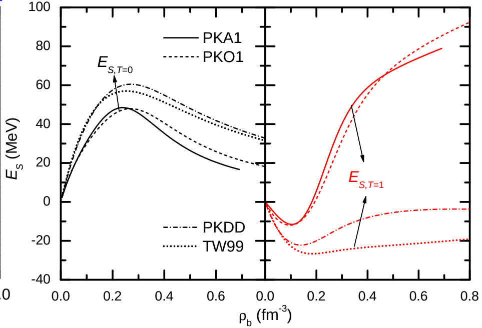
$$G^{\mu\nu\lambda\delta} \equiv \left(g^{\mu\nu}g^{\lambda\delta} - \frac{1}{3}g^{\mu\lambda}g^{\nu\delta}\right)$$

Potential Symmetry Energy in DDRHF Theory

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

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





☼ *Qian Zhao, Bao Yuan Sun, Wen Hui Long, J. Phys. G* ***42****, 095101 (2015).*

		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

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 ☹

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

Effective Mass in RHF Theory

- Definition of the Effective Mass:

$$\frac{M_\tau^*}{M} = 1 - \frac{dU_\tau(k,\epsilon(k))}{d\epsilon_\tau} = k\frac{dk}{d\epsilon_\tau} = \left[1 + \frac{M}{k}\frac{dU_\tau}{dk}\right]^{-1}$$

- Non-relativistic Mass: Shrödinger equivalent potential U_e^τ

$$E - mass: \frac{\bar{M}}{M} = \left[1 - \frac{\partial U^\tau}{\partial \epsilon^\tau}\right], \quad K - mass: \frac{\tilde{M}}{M} = \left[1 + \frac{M}{k}\frac{\partial U^\tau}{\partial k}\right]^{-1}$$

$$\frac{M_{NR}^*}{M} = \frac{\bar{M}}{M}\cdot\frac{\tilde{M}}{M} = \left[1 - \frac{\Sigma_0}{M}\right]\left[1 + \left(\frac{M^*}{k}\frac{\partial \Sigma_S}{\partial k} + \frac{E^*}{k}\frac{\partial \Sigma_0}{\partial k} + \frac{k^*}{k}\frac{\partial \Sigma_V}{\partial k} + \frac{\Sigma_V}{k}\right)\right]^{-1}$$

- Landau Mass: $\epsilon + M = E^* + \Sigma_0$

$$\frac{M_L^*}{M} = k\frac{dk}{d\epsilon^\tau} = k\left[\frac{k^*}{E^*} + \frac{M^*}{E^*}\frac{\partial \Sigma_{S,E}}{\partial k} + \frac{k^*}{E^*}\frac{\partial \Sigma_{V,E}}{\partial k} + \frac{\partial \Sigma_{0,E}}{\partial k}\right]^{-1}$$

- Relativistic Mass:

☼ *W. H. Long et al., Phys. Lett. B 640, 150 (2006).*

$$\frac{M_R^*}{M} = 1 - \frac{d}{d\epsilon}\left[U_e^\tau - \frac{\epsilon^2}{2M}\right], \quad M_R^* = M_{NR}^* + \epsilon = M_g^* \to \text{group mass}$$

HVH theorem and $E_S(\rho_b)$

- Hugenholtz-Van Hove (HVH) theorem: relations between binding energy per nucleon and single-nucleon Fermi energy.
  - HVH theorem: $p = \rho_b^2 \frac{\partial}{\partial \rho_b}\left(\frac{\mathcal{E}}{\rho_b}\right) = -\mathcal{E} + \mu\rho_b, \xrightarrow{\mu=\epsilon_F} E_b + \rho\frac{\partial E_b}{\partial \rho_b} = \varepsilon_F$

    ☼ *L. Satpathy, V. S. Uma Maheswari, R. C. Nayak, Phys. Rep. 319, 85(1999).*
  - RHF approximation with static limit satisfies the thermodynamic $p - \mathcal{E}$ relation with $\mu = \varepsilon_F$ at every density.

    ☼ *Hiroshi. Uechi, Nucl. Phys. A. 501, 813(1989)*
- Single-nucleon potential decomposition of $E_S(\rho_b)$ in non-relativistic framework.

  ☼ *R.Chen, B.J.Cai, L.W.Chen, B.A.Li, X.H.Li and Ch.Xu, Phys. Rev. C. 85, 024305(2012).*

  ☼ *C. Xu, et al, Nucl.Phy.A 865 (2011) 1; R. Chen, et al, Phys.Rev. C 85, 024305 (2012)*
  - Constraining $E_S(\rho_b)$ from neutron-nucleus scattering data.

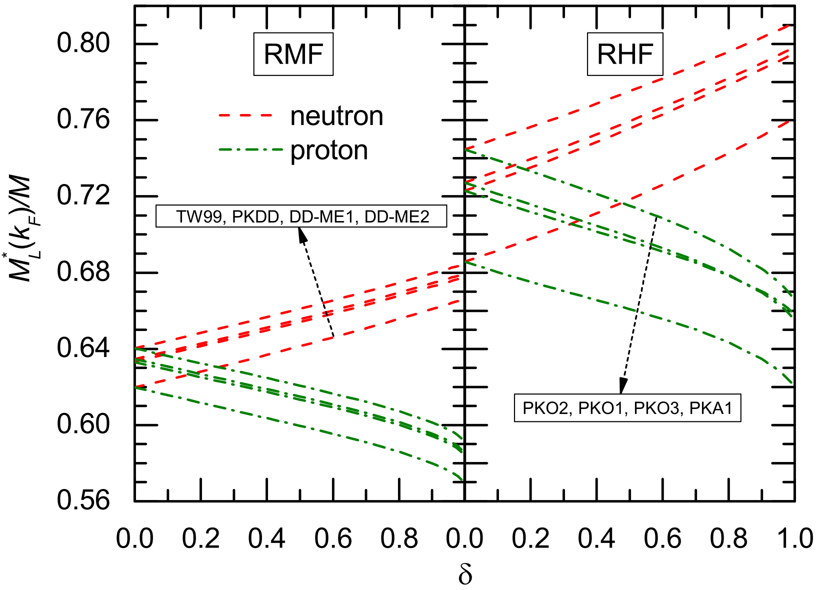
    ☼ *X. H. Li,et al,Phys. Lett. B 721(2013)101-106*
  - Constraining the n-p effective mass splitting from empirical constraints on E_S.

    ☼ *B. A. Li and X. Han, Phys. Lett. B 727(2013)276-281*
- Self-energy decomposition of $E_S(\rho_b)$ in relativistic framework.

  ☼ *B. J. Cai, L. W. Chen, Phys.Lett. B 711 (2012) 104 – 108.*

Examining the effects of momentum-dependent exchange term of self-energy on the symmetry energy in RHF theory.

Isospin Splitting of Landau Mass



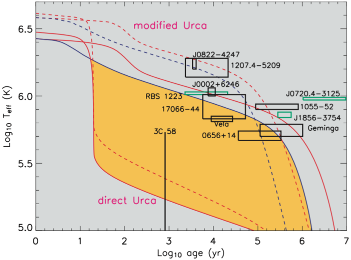
Neutron Star Cooling

Input Physics of Neutron Star Cooling:

1. The Equation of State
2. Nucleon Effective Masses
3. Pairing Correlations
4. The Specific Heat
5. Neutrino Emissivity

☼ *D. Page et al., ApJS* **155**, *623 (2004).*

☼ *D. G. Yakovlev et al., Phys. Rep.* **354**, *1 (2001).*

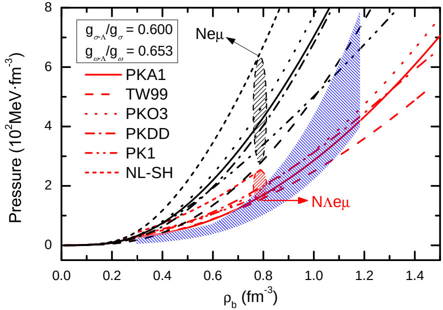


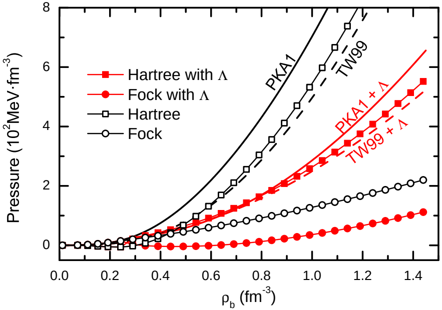
☼ *J. M. Lattimer and M. Prakash*

Specific heat, entropy, and superfluid gaps, and processes such as neutrino emission from particles with energies in the neighborhood of the Fermi energy, depend sensitively on the so-called Landau effective masses of particles.

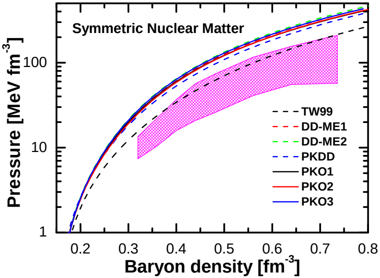
- Direct Urca
  (only proton fraction x $\geq$ 1/9)
  $n \rightarrow p + e^- + \bar{\nu}_e$
  $p \rightarrow n + e^+ + \nu_e$
- Modified Urca
  $n + n \rightarrow p + n + e^- + \bar{\nu}_e$
  $p + p \rightarrow n + p + e^+ + \nu_e$
- Neutrino bremsstrahlung
  $n + n \rightarrow n + n + \nu + \bar{\nu}$
  $p + p \rightarrow p + p + \nu + \bar{\nu}$
  $p + n \rightarrow n + p + \nu + \bar{\nu}$
- Pair break and form (PBF)
  $p \rightarrow p + \nu + \bar{\nu}$
  $n \rightarrow n + \nu + \bar{\nu}$

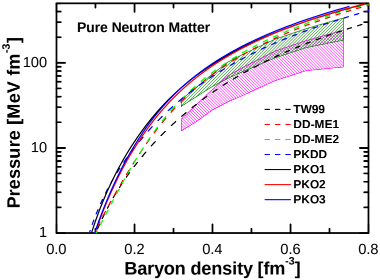
EoS of Neutron Star Matter — Hyperon effects





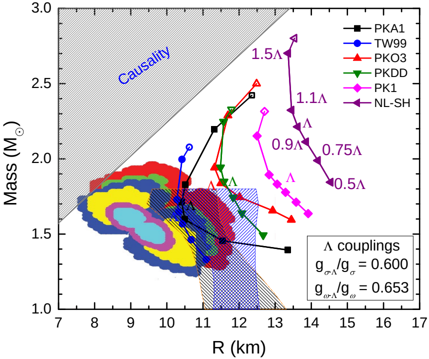
Constraint for cold matter: ☼ *F. Özel, G. Baym, and T. Güver, Phys. Rev.* **D 82**, *101301(R) (2010).*





1. How to reproduce the reported massive NS mass? $1.97 \pm 0.04\ M_\odot$ A stiffer E_0

- Uncertainty of Λ-hyperon coupling strengths
- The neglected Λ-Λ interactions mediated by the strange mesons may contribute additional repulsion to stiffen the EoS
- Inclusion of Σ and Ξ hyperons
- Inclusion of the quark degree of freedom
  ☼ *T. Klähn, et al., Phys. Lett. B* **654**, *170 (2007).*
  ☼ *A. Kurkela, et al., Phys. Rev. D* **81**, *105021 (2010).*
- Recalibrated model with a stiff behavior of E_0
- Rotation effects on increasing the NS mass



Difficulty to an Unified EoS of Neutron Star Matter

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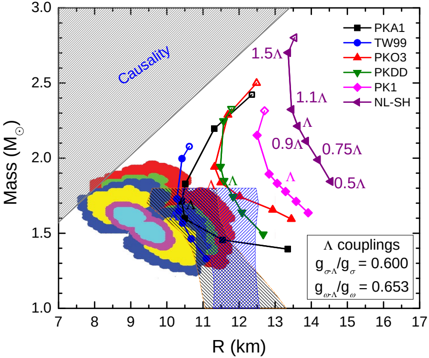
- Recalibrated model with a stiff behavior of E_0
- Rotation effects on increasing the NS mass



2. How to reproduce the small radius of $1.4\, M_\odot$ **NS?** 8.7-12.5 km A softer E_S

- The EoS at density region $3\rho_0 \sim 5\rho_0$ is still too stiff
- Recalibrated EoS model with a soft behavior of E_S around ρ_0 without exotic degrees of freedom
  ☼ *F. J. Fattoyev and J. Piekarewicz, Phys. Rev. C* ***82****, 025805 (2010).*
  ☼ *F. J. Fattoyev, C. J. Horowitz, J. Piekarewicz, and G. Shen, Phys. Rev. C* ***82****, 055803 (2010).*
- Including the Δ resonance and adopting weaker Δ-ω coupling than the one in the nucleonic sector
  ☼ *T. Schürhoff, S. Schramm, and V. Dexheimer, Astrophys. J. Lett.* ***724****, L74 (2010).*