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Hadron in Nucleus

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STRUCTURE CHANGES OF THE NUCLEON IN NUCLEAR MATTER

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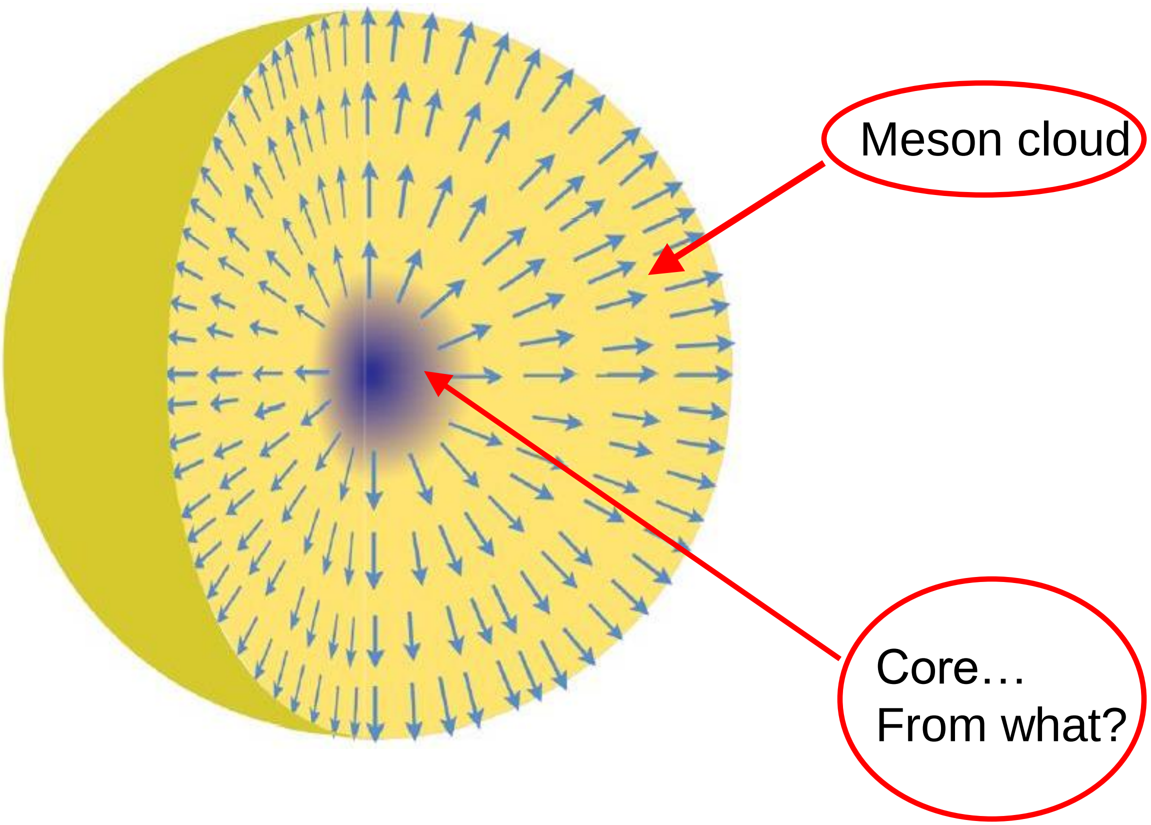
Content

- Topological models and soliton
- Medium modifications
  - "Outer shell" modifications
  - "Inner core" modifications
- Nuclear matter
  - Symmetric matter
  - Asymmetric matter
- Summary
- Outlook

Topological models and soliton

Structure

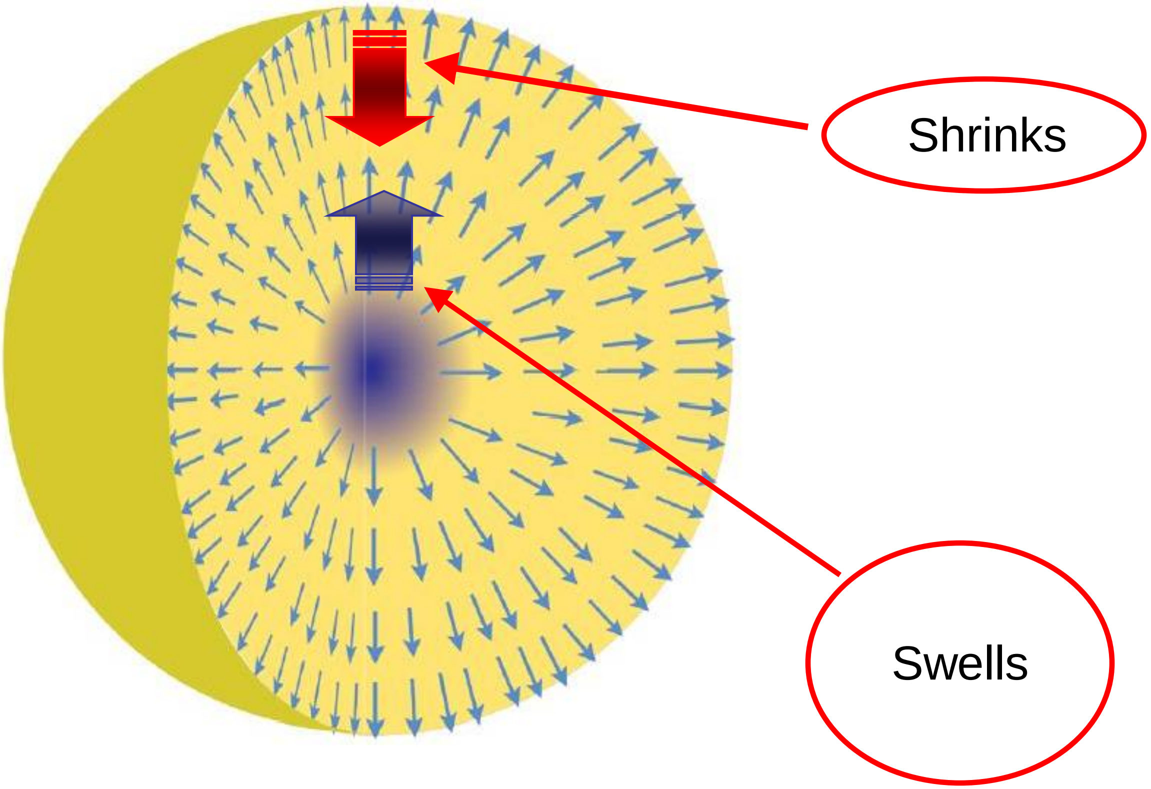
- What is a nucleon and, in particular, its core?
- At large number of colors it still has the mesonic content



Topological models and soliton

Stabilization

- Soliton has finite size and finite energy
- One needs at least two contrterms in the effective Lagrangian



Topological models and soliton

Skyrme model

[T.H.R. Skyrme, Pros.Roy.Soc.Lond. A260(1961)]

- Nonlinear chiral effective meson (pionic) theory)

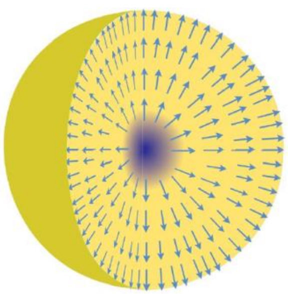
$$\mathcal{L} = \frac{F_\pi^2}{16}\mathrm{Tr}\left(\partial_\alpha U\right)\left(\partial^\alpha U^+\right) + \frac{1}{32e^2}\mathrm{Tr}\left[U^+\partial_\alpha U, U^+\partial_\beta U\right]^2$$

Shrinks

Swells

- Hedgehog soliton (nontrivial mapping)

$$U = \exp\left\{\frac{i\bar{\tau}\,\bar{\pi}}{2F_\pi}\right\} = \exp\left\{i\bar{\tau}\,\bar{n}F(r)\right\}$$



Topological models and soliton

Original Lagrangian in use

[G.S. Adkins *et al.* Nucl. Phys. B228 (1983)]

$$\mathcal{L}_{\text{free}} = \frac{F_\pi^2}{16}\mathrm{Tr}\left(\partial^\alpha U\right)\left(\partial_\alpha U^+\right) + \frac{1}{32e^2}\mathrm{Tr}\left[U^+\partial_\alpha U, U^+\partial_\beta U\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\mathrm{Tr}\left(U + U^+ - 2\right)$$

- Nontrivial mapping
- It has topologically nontrivial solitonic solutions (in separated different topological sectors) with the corresponding conserved topological number A
- Nucleon is quantized state of the classical soliton-skyrmion

$$U = \exp\{i\bar{\tau}\,\bar{\pi}/2F_\pi\} = \exp\{i\bar{\tau}\,\bar{n}F(r)\}$$

$$B^\mu = \frac{1}{24\pi^2}\varepsilon^{\mu\nu\alpha\beta}Tr(L_\nu L_\alpha L_\beta) \qquad L_\alpha = U^+\partial_\alpha U$$

$$A = \int d^3 r B^0$$

$$H = M_{cl} + \frac{\bar{S}^2}{2I} = M_{cl} + \frac{\bar{T}^2}{2I},$$

$$|\,S = T, s, t >= (-1)^{t+T}\sqrt{2T+1}D^{S=T}_{-t,s}(A)$$

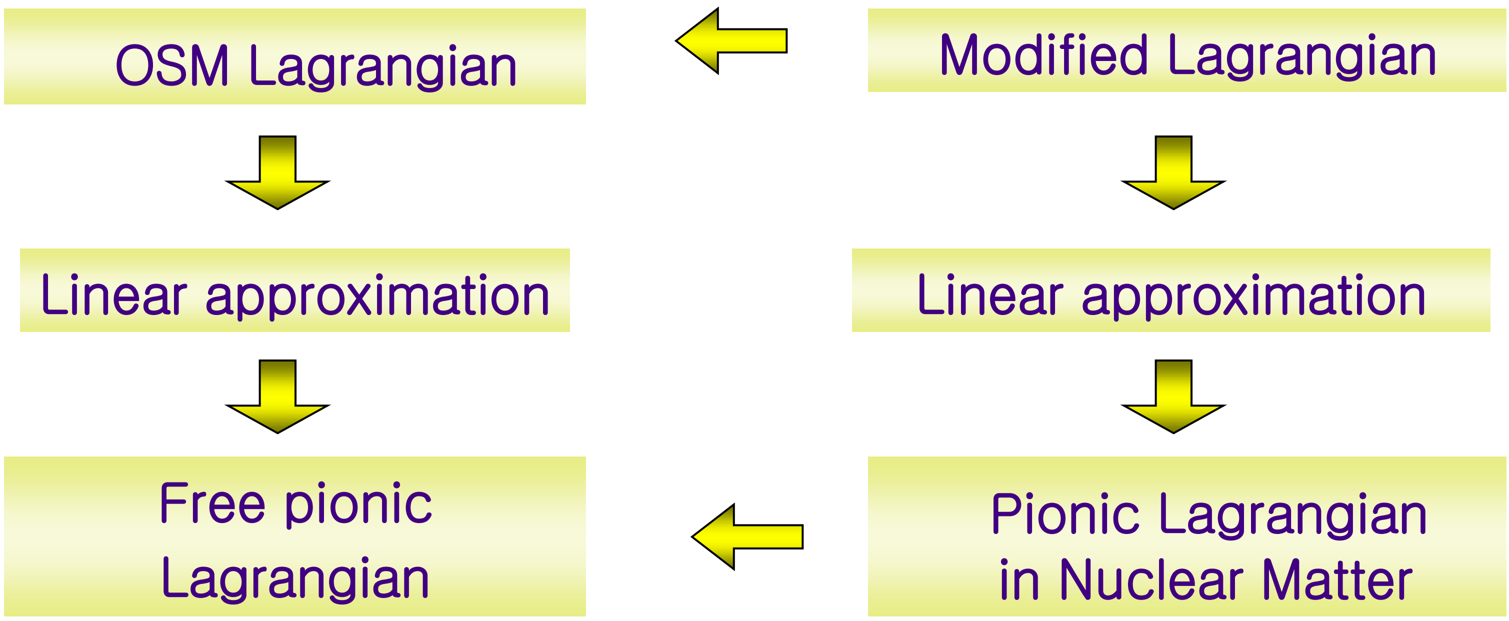
Medium modifications

- What happens in a medium?
- One should be able to describe the possible phenomena

  - Deformations
  - Mass change
  - Swelling or shrinking
  - Effective NN interactions
  - Etc.

Medium modifications

- Modification in the mesonic sector modifies the baryonic sector

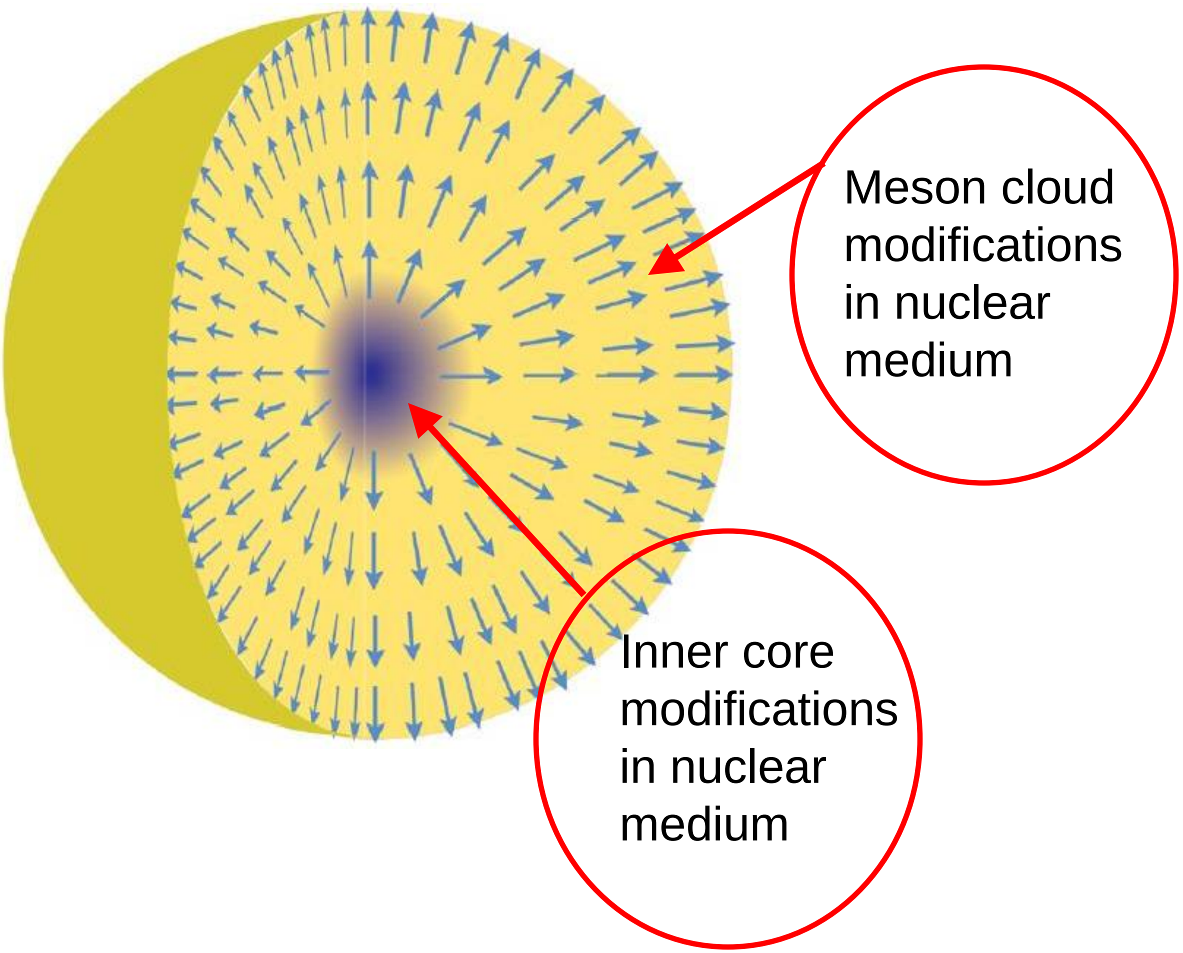


- How to modify the mesonic sector?

Medium modifications

Soliton in Nuclear Medium (structure changes)

- Outer shell modifications plus
- Inner core modifications (in particular, at higher densities)



Medium modifications

“Outer shell” modifications

$$\left(\partial^\mu \partial_\mu + m^2_{\pi^{(\pm,0)}}\right)\vec{\pi}^{(\pm,0)} = 0$$

$$\left(\partial^\mu \partial_\mu + m^2_{\pi^{(\pm,0)}} + \hat{\Pi}^{(\pm,0)}\right)\vec{\pi}^{(\pm,0)} = 0$$

- Three types of pions can be treated separately
- In nuclear matter, one considers three types of polarization operators
- There will be some parameters which correspond to the isospin breaking effects in the surrounding environment

	π-atom	$T_\pi = 50$ MeV
$b_0\ [m_\pi^{-1}]$	- 0.03	- 0.04
$\boxed{b_1\ [m_\pi^{-1}]}$	- 0.09	- 0.09
$c_0\ [m_\pi^{-3}]$	0.23	0.25
$\boxed{c_1\ [m_\pi^{-3}]}$	0.15	0.16
g'	0.47	0.47

Medium modifications

"Outer shell" modifications [U.Meissner *et al.*, EPJ A36 (2008)]

$$\mathcal{L}_2^* = \frac{F_\pi^2}{16}\{\alpha_s^{02}\,\mathrm{Tr}(\partial_0 U \partial_0 U^\dagger) - \alpha_p^0\,\mathrm{Tr}(\partial_i U \partial_i U^\dagger)\},$$

$$\mathcal{L}_{\chi\mathrm{SB}}^* = \frac{F_\pi^2 m_\pi^2}{8}\,\alpha_s^{00}\,\mathrm{Tr}\,(U - 1),$$

- Due to the nonlocality of optic potential the kinetic term is also modified
- Due to energy and momentum dependence of the optic potential parameters following parts of the kinetic term is modified in different form:
  - Temporal part
  - Space part

$$\hat{\Pi} = 2\omega U_{opt} = \chi_s + \vec{\nabla}\cdot\chi_p\vec{\nabla}$$

	π-atom	$T_\pi = 50$ MeV
$b_0\ [m_\pi^{-1}]$	- 0.03	- 0.04
$b_1\ [m_\pi^{-1}]$	- 0.09	- 0.09
$c_0\ [m_\pi^{-3}]$	0.23	0.25
$c_1\ [m_\pi^{-3}]$	0.15	0.16
g'	0.47	0.47

Medium modifications

"Inner core" modifications

[UY & H.Ch. Kim, PRC83 (2011); UY, JKPS62 (2013); UY, PRC88 (2013)]

- May be related to
  - vector meson properties in nuclear matter
  - nuclear matter properties

$$\mathcal{L}_4^* = -\frac{1}{16 e_\tau^{*2}} \mathrm{Tr}\left[L_0, L_i\right]^2 + \frac{1}{32 e_s^{*2}} \mathrm{Tr}\left[L_i, L_j\right]^2$$

$$\boxed{e \to e^* = e\,\gamma^{1/2}(\rho)}$$

Medium modifications

Final Lagrangian

[U.Meissner *et al.*, EPJ A36 (2008); UY, JKPS62 (2013), UY, PRC88 (2013)]

- Separated into two parts

$$\mathcal{L}^* = \mathcal{L}^*_{\rm sym} + \mathcal{L}^*_{\rm asym}$$

  - Isoscalar part

$$\mathcal{L}^*_{\rm sym} = \mathcal{L}^*_2 + \mathcal{L}^*_4 + \mathcal{L}^*_{\chi{\rm SB}}$$

  - Isovector part

$$\mathcal{L}^*_{\rm asym} = \Delta\mathcal{L}_{\rm mes} + \Delta\mathcal{L}^*_{\rm env}$$

$$\begin{aligned}
\mathcal{L}^*_2 &= \frac{F_\pi^2}{16}\Big\{\alpha_s^{02}\,{\rm Tr}\left(\partial_0 U \partial_0 U^\dagger\right) \\
&\qquad - \alpha_p^0\,{\rm Tr}(\vec{\nabla}U\cdot\vec{\nabla}U^\dagger)\Big\}, \\
\mathcal{L}^*_4 &= -\frac{1}{16e^2\zeta_\tau}\,{\rm Tr}\left[U^\dagger\partial_0 U, U^\dagger\partial_i U\right]^2 \\
&\quad + \frac{1}{32e^2\zeta_s}\,{\rm Tr}\left[U^\dagger\partial_i U, U^\dagger\partial_j U\right]^2, \\
\mathcal{L}^*_{\chi{\rm SB}} &= \frac{F_\pi^2 m_\pi^2}{8}\,\alpha_s^{00}\,{\rm Tr}\left(U-1\right),
\end{aligned}$$

$$\begin{aligned}
\Delta\mathcal{L}_{\rm mes} &= -\frac{F_\pi^2}{32}\sum_{a=1}^{2}(m_{\pi^\pm}^2 - m_\pi^2){\rm Tr}(\tau_a U){\rm Tr}(\tau_a U^\dagger), \\
\Delta\mathcal{L}^*_{\rm env} &= -\frac{F_\pi^2}{32}\sum_{a,b=1}^{2}\varepsilon_{ab3}\frac{\Delta\chi}{m_\pi}{\rm Tr}(\tau_a U){\rm Tr}(\tau_b\partial_0 U^\dagger).
\end{aligned}$$

Medium modifications

Medium functionals and their parameters

[U.Meissner *et al.*, EPJ A36 (2008); UY, JKPS62 (2013), UY, PRC88 (2013)]

- From pionic atoms and pion-nucleon scattering

Nuclear matter stabilization

$$\alpha_s^{00} = 1 + \left(\tilde{b}_0 + \frac{3(3\pi^2\rho/2)^{1/3}}{8\pi^2\eta}\tilde{b}_0^2\right)\frac{\rho}{m_\pi^2},$$

$$\alpha_s^{02} = 1 + \left(\tilde{b}_0 + \frac{3(3\pi^2\rho/2)^{1/3}}{4\pi^2\eta}\left(\tilde{b}_0^2 - \tilde{b}_1^2\right)\right)\frac{\rho}{m_\pi^2},$$

$$\alpha_p^0 = 1 - \frac{2\pi\left(c_0\rho - c_1\delta\rho\right)}{\eta + 4\pi g'\left(c_0\rho - c_1\delta\rho\right)} - \frac{2\pi\left(c_0\rho + c_1\delta\rho\right)}{\eta + 4\pi g'\left(c_0\rho + c_1\delta\rho\right)},$$

$$\Delta\chi = \tilde{b}_1\delta\rho - \frac{2\pi m_\pi}{\eta m_{\mathrm{N}}}c_1\left(\vec{\nabla}^2\delta\rho\right)$$

Asymmetric Matter Properties

- From nuclear matter properties

$$\zeta_\tau = 1 + \zeta_0\rho\,,$$

$$\zeta_s = \frac{1}{2}\left\{\exp\left(-\frac{\gamma_{\mathrm{n},0}\rho + \gamma_{\mathrm{n},1}\delta\rho}{1+\gamma_{\mathrm{d},0}\rho + \gamma_{\mathrm{d},1}\delta\rho}\right) + \exp\left(-\frac{\gamma_{\mathrm{n},0}\rho - \gamma_{\mathrm{n},1}\delta\rho}{1+\gamma_{\mathrm{d},0}\rho - \gamma_{\mathrm{d},1}\delta\rho}\right)\right\}$$

Medium modifications

Nucleon in nuclear matter

- Isoscalar mass

$$m_{\rm N}^{S*} = M_{\rm NP}^{*} + \frac{3}{8\Lambda^{*}} + \frac{\Lambda^{*}}{2}\left(a^{*2} + \frac{\Lambda_{\rm env}^{*2}}{\Lambda^{*2}}\right)$$

- Isovector mass

$$\Delta m_{\rm np}^{*} = a^{*} + \frac{\Lambda_{\rm env}^{*}}{\Lambda^{*}}$$

- Mass of the nucleon

$$m_{\rm n,p}^{*} = m_{\rm N}^{S*} - \Delta m_{\rm np}^{*} T_3,$$

Nuclear matter

Origin of the binding-energy-formula terms in present model

$$\varepsilon(A,Z) \;=\; -a_V + a_S\,\frac{(N-Z)^2}{A^2} + \ldots,$$

- Volume term
  - Infinite and asymmetric nuclear matter
- Asymmetry term
  - Isospin asymmetric environment
- Surface and Coulomb terms
  - Nucleons in a finite volume
- Finite nuclei properties
  - Local density approximation

Nuclear matter

Volume term and Symmetry energy

- At infinite nuclear matter approximation the binding energy formula takes form

$$\varepsilon(\lambda,\delta) = -a_V(\lambda) + \varepsilon_S(\lambda)\delta^2 + O(\delta^4)$$
$$\equiv \varepsilon_V(\lambda) + \varepsilon_A(\lambda,\delta),$$

  - λ is normalized nuclear matter density
  - β is asymmetry parameter
  - a_S is symmetry energy

- In our model
  - Symmetric matter

$$\varepsilon_V(\lambda) = \tfrac{1}{2}[m_{\rm p}^*(\lambda,0) + m_{\rm n}^*(\lambda,0)] - m_{\rm N}^{\rm S}$$
$$= m_{\rm N}^{{\rm S}*}(\lambda,0) - m_{\rm N}^{\rm S},$$

  - Asymmetric matter

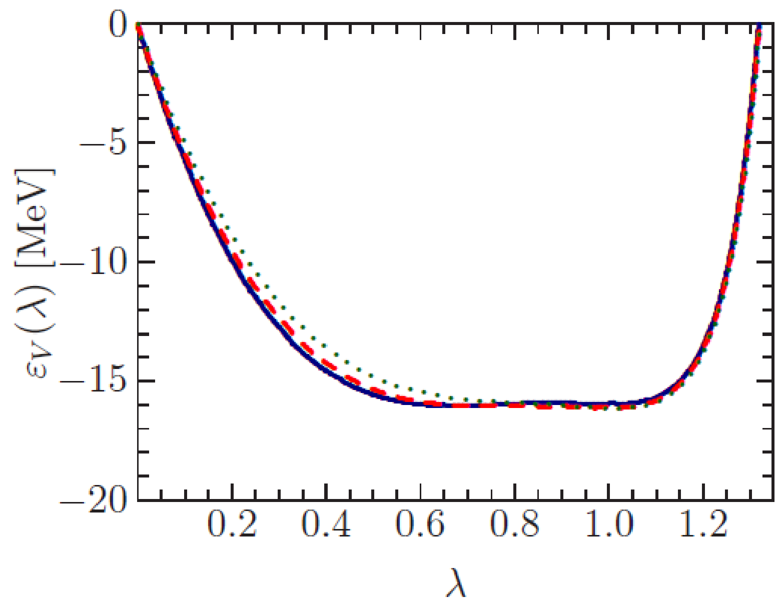
$$\varepsilon(\lambda,\delta) = \frac{Zm_{\rm p}^*(\lambda,\delta) + Nm_{\rm n}^*(\lambda,\delta)}{A} - \frac{Zm_{\rm p} + Nm_{\rm n}}{A}$$

Symmetric matter

Volume term [UY, JKPS62 (2013)]

- Volume term (binding energy per nucleon) in the binding energy formula can be defined as
  - Model I - solid curve
  - Model II - dashed curve
  - Model III – dotted curve

Model	γ_0 $[m_\pi^{-3}]$	$\gamma_{n,0}$ $[m_\pi^{-3}]$	$\gamma_{d,0}$ $[m_\pi^{-3}]$
I	0.0	1.901	0.070
II	0.5	1.867	0.049
III	1.0	1.840	0.031



Symmetric matter

TABLE I: The volume term coefficient $a_V(1)$ at the normal nuclear matter density $\lambda = 1$ and the compression modulus K_0 of symmetric nuclear matter. Their values are given for the three different sets of parameters. The variational parameters $\gamma_{\mathrm{n},0}$ and $\gamma_{\mathrm{d},0}$ are chosen in such a way that at saturation point $\rho = \rho_0 = 0.15\ \mathrm{fm}^{-3}$ the value of volume energy per nucleon is close to its experimental value, $\varepsilon_V^{\exp} \simeq -16$ MeV.

Model	γ_0 $[m_\pi^{-3}]$	$\gamma_{\mathrm{n},0}$ $[m_\pi^{-3}]$	$\gamma_{\mathrm{d},0}$ $[m_\pi^{-3}]$	$a_V(1)$ [MeV]	K_0 [MeV]
I	0.0	1.901	0.070	15.94	202
II	0.5	1.867	0.049	16.11	218
III	1.0	1.840	0.031	16.12	366

Asymmetric matter

- Asymmetry energy

$$\varepsilon_A(\lambda, \delta) = \varepsilon(\lambda, \delta) - \varepsilon_V(\lambda)$$
$$= m_{\mathrm{N}}^{\mathrm{S}*}(\lambda, \delta) - m_{\mathrm{N}}^{\mathrm{S}*}(\lambda, 0) + [\Delta m_{\mathrm{np}}^*(\lambda, \delta) - \Delta m_{\mathrm{np}}]\frac{\delta}{2}.$$

- Symmetry energy

$$\varepsilon_S(\lambda) = \frac{1}{2}\frac{\partial^2 \varepsilon_A(\lambda, \delta)}{\partial \delta^2}\bigg|_{\delta=0}$$
$$= \frac{1}{2}\frac{\partial^2}{\partial \delta^2}\left(m_{\mathrm{N}}^{\mathrm{S}*}(\lambda, \delta) + \Delta m_{\mathrm{np}}^*(\lambda, \delta)\,\frac{\delta}{2}\right)_{\delta=0}$$

- Symmetry energy coefficients

$$\varepsilon_S(\lambda) = \varepsilon_S(1) + \frac{L_S}{3}(\lambda - 1) + \frac{K_S}{18}(\lambda - 1)^2 + \cdots$$

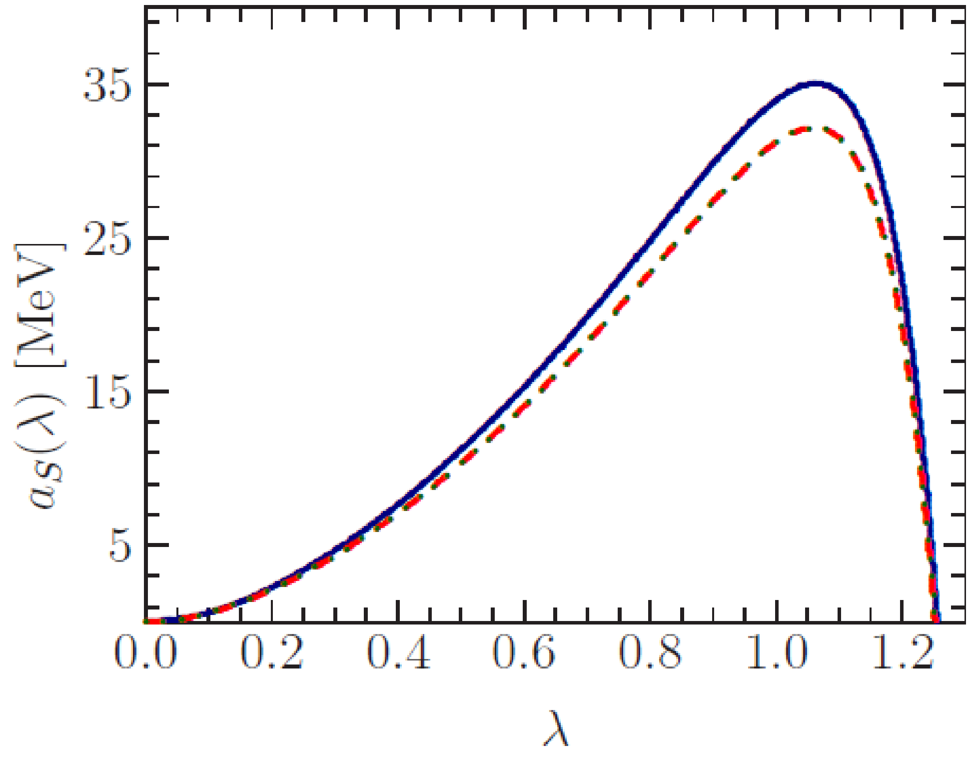
Asymmetric matter

Symmetry energy [UY, JKPS62 (2013)]

- Symmetry energy as function of normalized density

  - Model I - solid curve
  - Model II - dashed curve
  - Model III – dotted curve

Model	$\gamma_{\mathrm{n},1}$ $[m_\pi^{-3}]$	$\gamma_{\mathrm{d},1}$ $[m_\pi^{-3}]$
I	0.830	0.415
II	0.860	0.430
III	0.830	0.374



Asymmetric matter

Symmetry energy [UY, JKPS62 (2013)]

TABLE II: The slope L_S and the curvature K_S of symmetry energy. The variational parameters $\gamma_{\mathrm{n},1}$ and $\gamma_{\mathrm{d},1}$ are chosen in such a way that at normal nuclear matter density $\rho = \rho_0 = 0.15\ \mathrm{fm}^{-3}$ the value of symmetry energy $a_S(1)$ is close to its experimental value, $a_S^{\mathrm{exp}} \approx 32$ MeV. Other parameters $\gamma_{\mathrm{n},0}$ and $\gamma_{\mathrm{d},0}$ are given in Table I.

Model	$\gamma_{\mathrm{n},1}$ $[m_\pi^{-3}]$	$\gamma_{\mathrm{d},1}$ $[m_\pi^{-3}]$	$a_S(1)$ [MeV]	L_S [MeV]	K_S [MeV]
I	0.830	0.415	33.99	91.75	−3428
II	0.860	0.430	31.21	85.66	−2761
III	0.830	0.374	31.21	76.41	−2800

Medium modifications

Reparametrization [UY, PRC88 (2013)]

- Five medium parameters

$$F_{\pi,t} \to F^*_{\pi,t}, \quad e_t \to e^*_t, \quad m_\pi \to m^*_\pi,$$
$$F_{\pi,s} \to F^*_{\pi,s}, \quad e_s \to e^*_s$$

Core modifications

Shell modifications

- Rearranging

$$1 + C_1\lambda = f_1(\lambda) \equiv \sqrt{\frac{\alpha_p^0}{\zeta_s}},$$

$$1 + C_2\lambda = f_2(\lambda) \equiv \frac{\alpha_s^{00}}{(\alpha_p^0)^2 \zeta_s},$$

$$1 + C_3\lambda = f_3(\lambda) \equiv \frac{(\alpha_p^0 \zeta_s)^{3/2}}{\alpha_s^{02}},$$

$$\Delta\chi = m_\pi^{-1} C_4\, \delta\rho = 0.5 m_\pi^2 C_4 \lambda\delta$$

$$\alpha_s^{02} = 1 + C_5 m_\pi^{-1} \rho,$$

$$\alpha_p^0 = 1 - \frac{4\pi c_0 \rho}{\eta + 4\pi g' c_0 \rho},$$

$$c_0 = C_5 m_\pi^{-3}$$

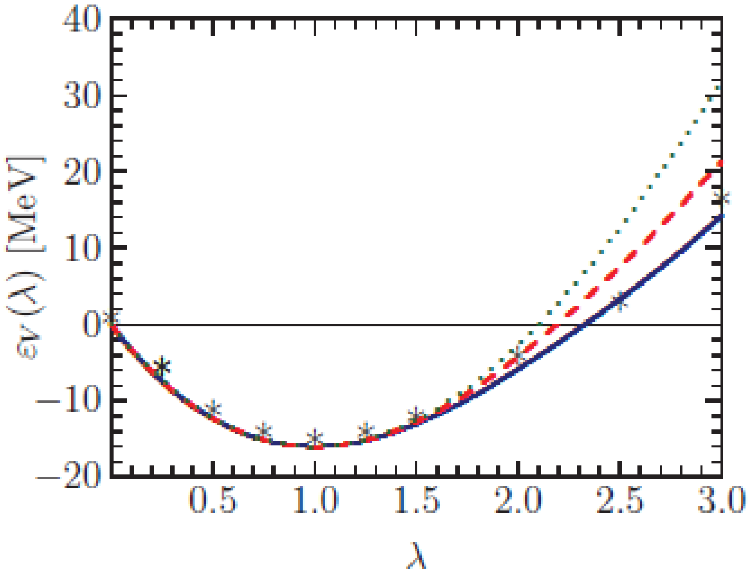
Symmetric matter

After reparametrization [UY, PRC88 (2013)]

- Volume energy

TABLE I. The variational parameters and the coefficients of the volume term at the saturation density ρ_0. Here the isospin-breaking effect in the mesonic sector is ignored, i.e., $\mathcal{M}_- = 0$.

Set	C_1	C_2	C_3	$\varepsilon_V(\rho_0)$ (MeV)	K_0 (MeV)	Q (MeV)
I	−0.279	0.737	1.782	−16	240	−410
II	−0.273	0.643	1.858	−16	250	−279
III	−0.277	0.486	2.124	−16	260	−178



$$K_0 = 9\rho^2 \frac{\partial^2 \varepsilon_V}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

$$Q = 27\lambda^3 \frac{\partial^3 \varepsilon_V(\lambda)}{\partial \lambda^3}\bigg|_{\lambda=1}$$

FIG. 1. (Color online) The volume energy ε_V as a function of normalized density $\lambda = \rho/\rho_0$. The parameters of medium functionals are given in Table I: the solid curve corresponds to Set I, the dashed one to Set II, and the dotted curve to Set III. Akmal-Pandharipande-Ravenhall predictions [68] are marked by stars.

[68] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C 58, 1804 (1998).

Symmetric matter

After reparametrization [UY, PRC88 (2013)]

- Pressure in symmetric matter

$$p = \rho \frac{\partial \tilde{\mathcal{E}}_V(\rho)}{\partial \rho} - \tilde{\mathcal{E}}_V(\rho) = \rho_0 \lambda^2 \frac{\partial \varepsilon_V(\lambda)}{\partial \lambda},$$

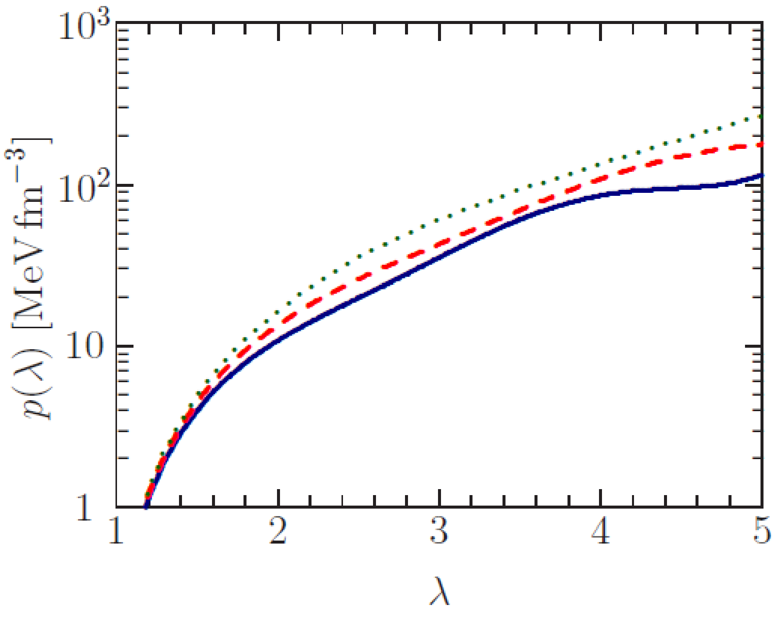
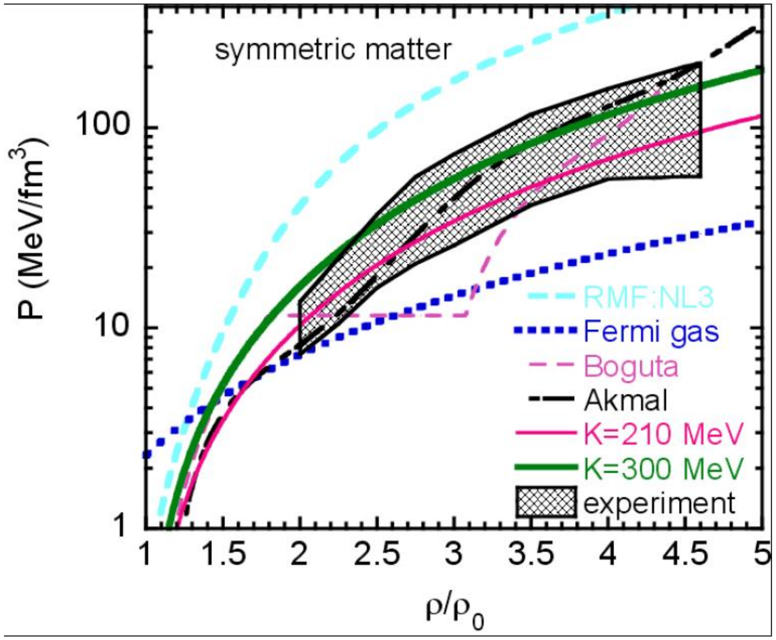


FIG. 2: (Color online) The pressure p in symmetric matter as a function of normalized density $\lambda = \rho/\rho_0$. The parameters of medium functionals are given in Table I: the solid curve corresponds to the Set I, the dashed one to the Set II and the dotted curve belongs to the Set III.



Right figure from:

P. Danielewicz, R. Lacey, and W. G. Lynch, Science 298, 1592 (2002).

Asymmetric matter

After reparametrization [UY, PRC88 (2013)]

- Symmetry energy

$$\alpha_s^{02} = 1 + C_5 m_\pi^{-1} \rho,$$

$$\alpha_p^0 = 1 - \frac{4\pi c_0 \rho}{\eta + 4\pi g' c_0 \rho},$$

$$c_0 = C_5 m_\pi^{-3}$$

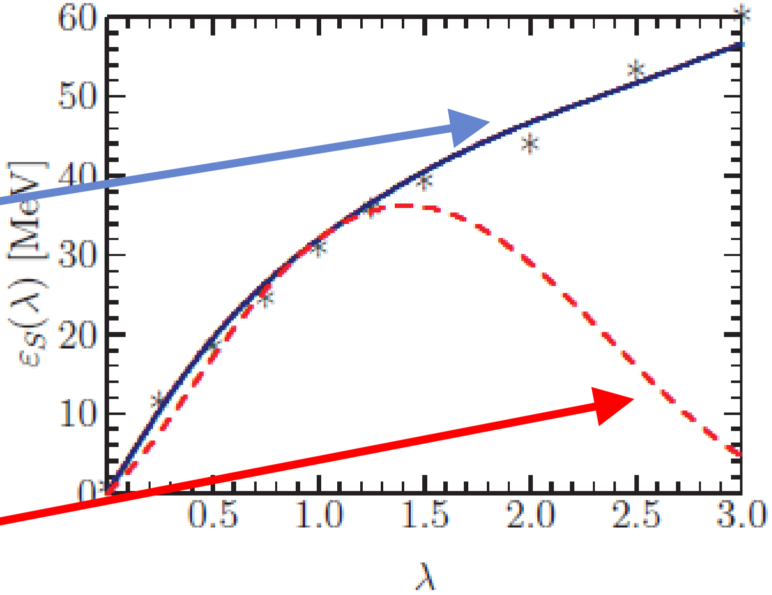


FIG. 3. (Color online) The symmetry energy as a function of normalized density $\lambda = \rho/\rho_0$. The solid curve corresponds to Eq. (49) and to the parameters defined by Set II, while the dashed one corresponds to Eq. (50) and to the parameters defined by Set II (see Tables I and II). APR predictions [68] are marked by stars.

Asymmetric matter

After reparametrization [UY, PRC88 (2013)]

- Symmetry energy coefficients

$$c_0 = C_5 m_\pi^{-3}$$

$$\alpha_p^0 = 1 - \frac{4\pi c_0 \rho}{\eta + 4\pi g' c_0 \rho},$$

$$\alpha_s^{02} = 1 + C_5 m_\pi^{-1} \rho,$$

TABLE II: Three sets of parameters which reproduce the asymmetric matter properties. The variational parameters C_4 and C_5 are chosen in such a way that, at saturation point $p(\rho_0) = 0$, the value of symmetry energy ε_S and its first derivative $L_S/3$ reproduced in the commonly adopted range. Other parameters are defined in Table I and it is used an approximation $\mathcal{M}_- = 0$.

Set	C_4	C_5	$\varepsilon_S(\rho_0)$ [MeV]	L_S [MeV]	K_S [MeV]	K_τ [MeV]	$K_{0,2}$ [MeV]
		C_5 is defined by Eq. (49).					
I	2.367	0.037	32	60	−411	−591	−488
II	2.356	0.036	32	60	−405	−585	−518
II	2.228	0.035	32	60	−418	−598	−557
		C_5 is defined by Eq. (50).					
I	4.249	−0.1370	32	60	−127	−307	−204
II	4.258	−0.1372	32	60	−126	−306	−239
III	4.290	−0.1373	32	60	−124	−304	−263

$$\varepsilon_S(\lambda) = \varepsilon_S(1) + \frac{L_S}{3}(\lambda - 1) + \frac{K_S}{18}(\lambda - 1)^2 + \cdots$$

Asymmetric matter

After reparametrization [UY, PRC88 (2013)]

- Pressure in asymmetric matter

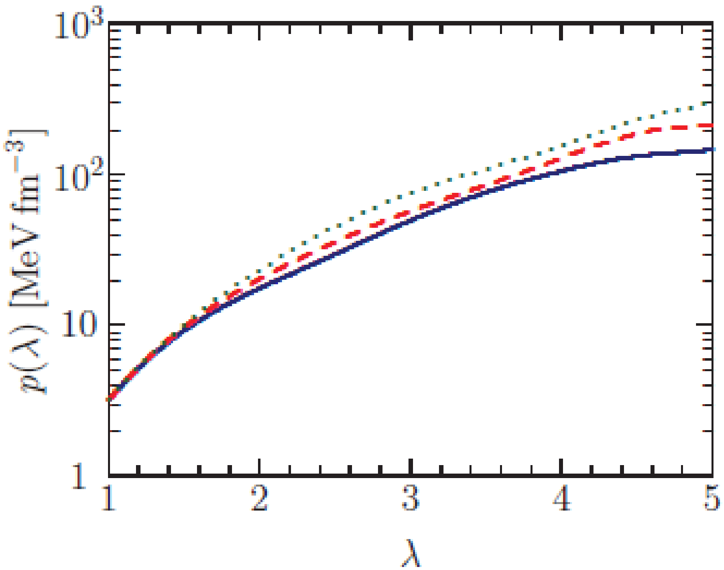
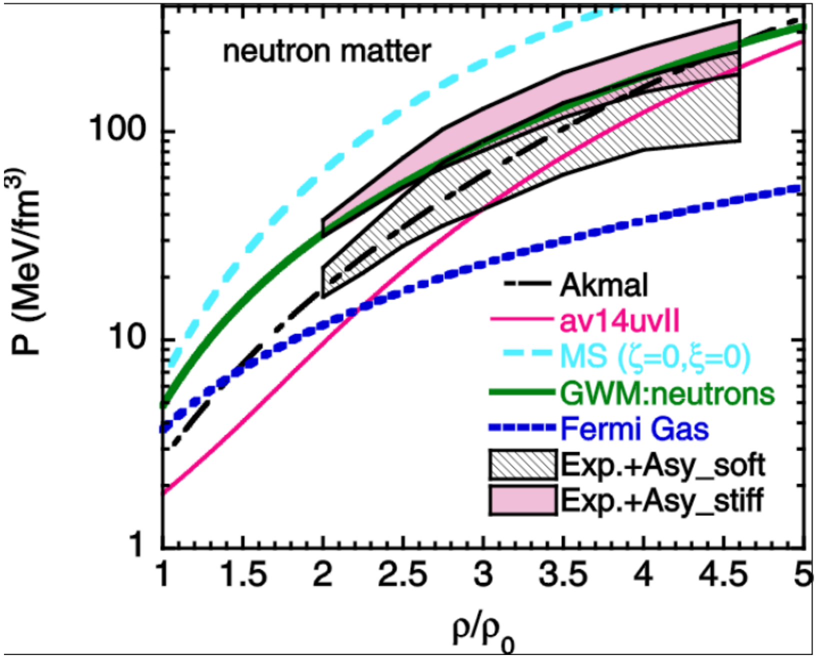


FIG. 4. (Color online) The pressure p in asymmetric matter as a function of normalized density $\lambda = \rho/\rho_0$. The parameters of medium functionals are given in Table II [C_5 is defined by Eq. (50)]: the solid curve corresponds to Set I, the dashed one to Set II, and the dotted curve to Set III.



Right figure from:

P. Danielewicz, R. Lacey, and W. G. Lynch, Science 298, 1592 (2002).

Asymmetric matter

After reparametrization

- Low density behavior of symmetry energy and correlations between coefficients

TABLE III: Correlations of symmetry energy coefficients. The variational parameters C_4 and C_5 are chosen in such a way that, at saturation point $p(\rho_0) = 0$, the value of symmetry energy ε_S and its first derivative $L_S/3$ are reproduced in the commonly adopted range. Other parameters are defined in Table I (see Set II).

C_4	C_5	$\varepsilon_S(\rho_0)$ [MeV]	L_S [MeV]	K_S [MeV]	K_τ [MeV]	$K_{0,2}$ [MeV]	$\varepsilon_S(0.1\text{fm}^{-3})$ [MeV]
1.294	0.132	32	40	−181	−301	−257	25.15
1.168	0.022	32	50	−160	−310	−254	24.15
1.064	−0.069	32	60	−126	−306	−239	23.22
0.978	−0.144	32	70	−80	−290	−211	22.37
0.904	−0.209	32	80	−21	−261	−172	21.57
0.841	−0.264	32	90	50	−220	−119	20.82
0.786	−0.313	32	100	134	−166	−55	20.13

From analysis of GDR (208Pb)

$$23.3 < \varepsilon_S(\rho = 0.1\ \text{fm}^{-3}) < 24.9\ \text{MeV}$$

L. Trippa, G. Colo, and E. Vigezzi, Phys. Rev. C 77, 061304 (2008).

Nuclear matter

After reparametrization [UY, PRC88 (2013)]

- The energy per nucleon in symmetric matter and in neutron matter

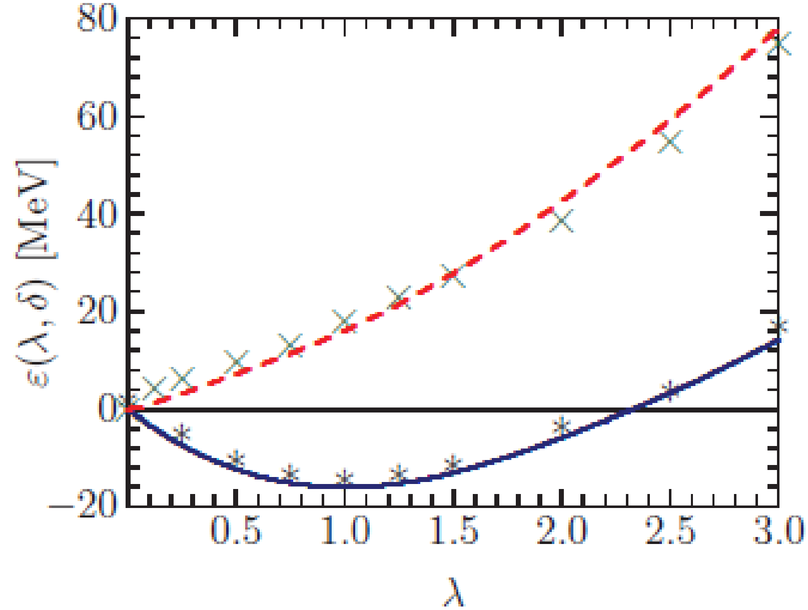


FIG. 5. (Color online) The energy per nucleon $\varepsilon(\lambda, \delta)$ as a function of normalized nuclear matter density $\lambda = \rho/\rho_0$. The parameters are taken from Model II (see the lower part of Table II). The solid curve represents symmetric nuclear matter ($\delta = 0$) while the dashed curve represents neutron matter ($\delta = 1$). For comparison, APR predictions [68] are marked by crosses and stars.

Summary

- Within the applicability range, the model describes
  - the single hadrons properties
    - in separate state
    - in the community of their partners
  - as well as the properties of that whole community at same footing

Outlook

Extensions and applicability of the approach

- Nucleon tomography in nuclear matter
  [H.Ch. Kim, UY, PLB726 (2013), arXiv:1304.5926]
- NN interactions in nuclear matter
- Neutron stars
- Finite nuclei properties
  - Mirror nuclei
  - Exotic nuclei
  - Halo nuclei
- Nucleon-knock out reactions
- Vector mesons in nuclear matter
  [J.H.Jung, UY, H.Ch.Kim, PLB 723 (2013), arXiv:1212.4616]

Thank you for your attention!