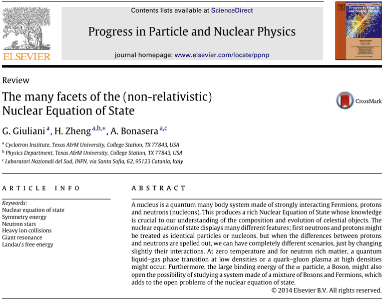
Iso-Vector Giant Dipole Resonance Mode within the Constrained Molecular Dynamics Approach

Gianluca Giuliani

ASY-EOS 2015, Piazza Armerina, Italy, March 2015

Table of contents


Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp

Review

The many facets of the (non-relativistic) Nuclear Equation of State

G. Giuliani [a], H. Zheng [a,b,*], A. Bonasera [a,c]
[a] Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA
[b] Physics Department, Texas A&M University, College Station, TX 77843, USA
[c] Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy

ARTICLE INFO

Keywords:
Nuclear equation of state
Symmetry energy
Neutron stars
Heavy ion collisions
Giant resonance
Landau's free energy

ABSTRACT

A nucleus is a quantum many body system made of strongly interacting Fermions, protons and neutrons (nucleons). This produces a rich Nuclear Equation of State whose knowledge is crucial to our understanding of the composition and evolution of celestial objects. The nuclear equation of state displays many different features; first neutrons and protons might be treated as identical particles or nucleons, but when the differences between protons and neutrons are spelled out, we can have completely different scenarios, just by changing slightly their interactions. At zero temperature and for neutron rich matter, a quantum liquid–gas phase transition at low densities or a quark–gluon plasma at high densities might occur. Furthermore, the large binding energy of the α particle, a Boson, might also open the possibility of studying a system made of a mixture of Bosons and Fermions, which adds to the open problems of the nuclear equation of state.

- Iso-Vector Giant Dipole Resonance (IVGDR) and Neutron Skin Thickness (NST) calculations within Mean Field (Boltzmann-Nordheim-Vlasov Equation) and Constrained Molecular Dynamics (CoMD) approaches
- Slope and Curvature of the Nuclear Symmetry Energy
- Test Our NEOS

NEOS for Asymmetric Nuclear Matter:

$$\frac{E}{A}(\rho,\alpha) = (1+\frac{5}{9}\alpha^2)\tilde{\epsilon}_f\tilde{\rho}^{2/3} + (1+c_1\alpha^2)\frac{A_1}{2}\tilde{\rho} + (1+c_2\alpha^2)\frac{B_1}{1+\sigma}\tilde{\rho}^{\sigma}$$

$\tilde{\epsilon}_f = \frac{3}{5}T_f$, $\alpha = \frac{\rho_n-\rho_p}{\rho}$ neutron-proton concentration. $A_1, B_1, \sigma \Leftarrow$ Equilibrium Conditions for Symmetric Nuclear Matter:

$$\begin{aligned}
\frac{E}{A}|_{\rho=\rho_0} &= -15MeV \\
P|_{\rho=\rho_0} &= \rho^2\frac{\partial(\frac{E}{A})}{\partial\rho}|_{\rho=\rho_0} = 0 \\
K|_{\rho=\rho_0} &= 9\frac{\partial P}{\partial\rho}|_{\rho=\rho_0}
\end{aligned}$$

The Symmetry Term:

$$\frac{E}{A}(\rho,\alpha) - \frac{E}{A}(\rho,0) = (\frac{5}{9}\tilde{\epsilon}_f\tilde{\rho}^{2/3} + c_1\frac{A_1}{2}\tilde{\rho} + c_2\frac{B_1}{1+\sigma}\tilde{\rho}^{\sigma})\alpha^2 = S(\rho)\alpha^2$$

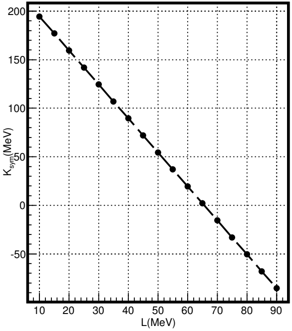
Density Dependence, Slope (L) and Curvature K_{sym}

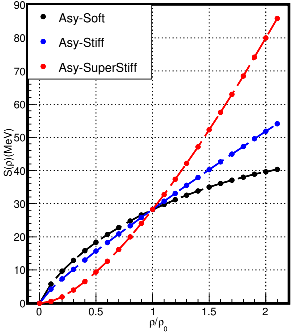
$$\begin{aligned}
S(\rho) &= \frac{5}{9}\tilde{\epsilon}_f\tilde{\rho}^{2/3} + c_1\frac{A_1}{2}\tilde{\rho} + c_2\frac{B_1}{1+\sigma}\tilde{\rho}^{\sigma} \\
L(\rho) &= 3\rho_0\frac{\partial S(\rho)}{\partial\rho} = 3(\frac{10}{27}\tilde{\epsilon}_f\tilde{\rho}^{-1/3} + c_1\frac{A_1}{2} + c_2\frac{B_1\sigma}{1+\sigma}\tilde{\rho}^{\sigma-1}) \\
K_{sym}(\rho) &= 9\rho_0^2\frac{\partial^2 S}{\partial\rho^2} = 9(-\frac{10}{81}\tilde{\epsilon}_f\tilde{\rho}^{-4/3} + c_2\frac{B_1\sigma(\sigma-1)}{1+\sigma}\tilde{\rho}^{\sigma-2}) \\
S(\rho_0) &= S = \frac{5}{27}\tilde{\epsilon}_f - \frac{10}{81}\frac{\tilde{\epsilon}_f}{\sigma} + \frac{L(\rho_0)}{3} - \frac{K_{sym}(\rho_0)}{9\sigma}
\end{aligned}$$

c_1 and c_2 by fixing $S(\rho)$ and $L(\rho)$ values at ρ_0.

Second order phase transition in a Neutron Star (PPNP paper)

$K = 200 MeV \Longrightarrow A_1 = -356 MeV, B_1 = 303 MeV, \sigma = \frac{7}{6}$
$S(\rho_0) = S = 28.3 MeV, L = 50 \pm 40 MeV \Longrightarrow K_{sym} = -85.5 \div 194.5 MeV$



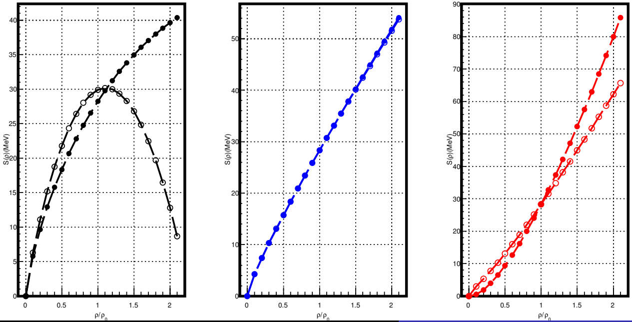


L=14.4 MeV $c_1 = 0.564, c_2 = 0.832$ - Asy-Soft
L=72 MeV $c_1 = 0.08315, c_2 = 8.581 \cdot 10^{-3}$ - Asy-Stiff
L=96.6 MeV $c_1 = -0.359, c_2 = -0.343$ - Asy-SuperStiff

Comparing Symmetry Terms - Form Factors

(B.-A. Li, L-W Chen, C. M. Ko Phys. Rep. 464 (2008) 113-281, V. Baran, M. Colonna, V.Greco, M. Di Toro Phys. Rep. 410 (2005) 335-466, M. Papa and G. Giuliani, Eur. Phys. J. A 39, 117-124 (2009))

- Asy-Soft: $S(\rho) = \frac{5}{9}\tilde{\epsilon}_f \tilde{\rho}^{2/3} + (482 - 1638\rho)\frac{\rho}{2}$ (V. Baran et al Phys. Rev. C 88 044610 (2013))
- Asy-Stiff: $S(\rho) = \frac{5}{9}\tilde{\epsilon}_f \tilde{\rho}^{2/3} + \frac{C}{2}\tilde{\rho}, C = 32MeV$
- Asy-SuperStiff: $S(\rho) = \frac{5}{9}\tilde{\epsilon}_f \tilde{\rho}^{2/3} + \frac{C}{2}\frac{2\tilde{\rho}^2}{1+\tilde{\rho}}, C = 32MeV$



- Same $S_0 = 28.3 MeV$ and L=14.4, 72, 96.6 MeV values
- Different behaviors as a function of the density (except for the Asy-Stiff case)
- S, L and K_{sym} are differently related - Asy-SuperStiff:

$$S = \frac{5}{27}\tilde{\epsilon}_f - \frac{10}{81}\frac{\tilde{\epsilon}_f}{\sigma} + \frac{L}{3} - \frac{K_{sym}}{9\sigma}$$

$$S = \frac{1}{9}(L + K_{sym})$$

- Different K_{sym} values

L(MeV)	$K^{(1)}_{sym}$(MeV)	$K^{(2)}_{sym}$(MeV)
14.4	179.1	-402
72	-22.5	-24
96.6	-109	47

Hamiltonian in the CoMD Framework
M. Papa Phys. Rev. C 87 014001 (2013) - (Symmetry Potential in the CoMD Model in Nuclear Matter and Nuclei)

$$
\begin{aligned}
H &= T + V_{2B} + V_{3B} + V_{Sym} + V_{Surf} + V_{Coul} \\
V_{2B} &= \frac{A_1}{2\rho_0}\bar{S}_V \\
V_{3B} &= \frac{B_1}{(\sigma+1)(\rho_0)^\sigma}(\bar{S}_V)^\sigma \\
V_{sym} &= \frac{T_4}{2\rho_0}F'_k(\bar{S}_V)\tilde{\rho}_A[(1+\frac{\alpha_c}{2})\alpha^2 - \frac{\alpha_c}{2}] \\
V_{sym} &= [c_1\frac{A_1}{2\rho_0}\bar{S}_V + c_2\frac{B_1}{(\sigma+1)(\rho_0)^\sigma}(\bar{S}_V)^\sigma](\frac{\rho_n-\rho_p}{\rho_n+\rho_p})^2
\end{aligned}
$$

$\bar{S}_V$ average overlap integral per nucleon

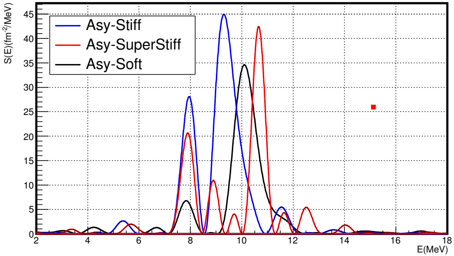
Constraining the NEOS:

$L, K_{sym} \leftrightarrow E_{GDR} = 31.2A^{-1/3} + 20.6A^{-1/6}$ (M. N. Harakeh A. Van Der Woude, Giant Resonances, first ed. Oxford Science Publications (2001))

- t=0 fm/c: protons and neutrons displeased in momentum space
  $\Delta P_z = \frac{E_{GDR}}{A\hbar}$,
  $P_z^n \rightarrow P_z^n - (\frac{Z}{A}\Delta P_z)$
  $P_z^p \rightarrow P_z^p - (\frac{N}{A}\Delta P_z)$
- Time evolution: dipole momentum in coordinate and momentum spaces
  $\mathbf{DR}(t) = \frac{NZ}{A}(\mathbf{R}_p - \mathbf{R}_n)$
  $\mathbf{DK}(t) = \frac{NZ}{A}(\mathbf{K}_p - \mathbf{K}_n)$
- IVGDR strength: $\frac{dP}{dE} \propto |D(E)|^2$

$^{132}Sn \longrightarrow E_{GDR} = 15.26 MeV$

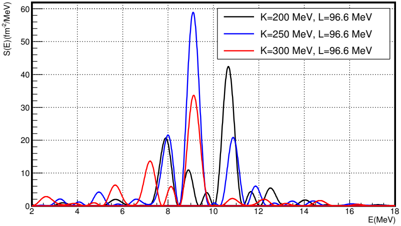
(1): $A_1 = -356 MeV, B_1 = 303 MeV, \sigma = \frac{7}{6}, K = 200 MeV, L = 14.4, 72, 96.6 MeV$

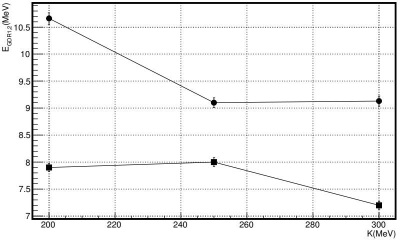


- No Filtering of the Dipolar Signal (P.-G. Reinhard Phys. Rev. E 73 036709 (2006))
- Peaks Around 8 MeV, Pygmy Dipole Resonance Systematics (PDR) $E_{PDR} = 41A^{-1/3} = 8.05 MeV$ (V. Baran et al PRC 88 044610 (2013)))

L(MeV)	E_{GDR}(MeV)
14.4	10.1
72	9.3
96.6	10.66

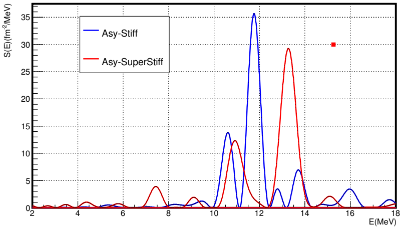
(2): L=96.6 MeV (Asy-SuperStiff), K=200, 250, 300 MeV

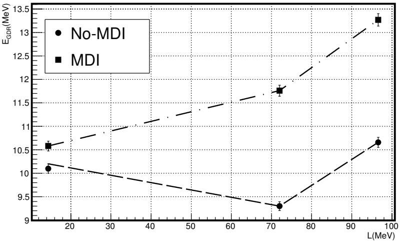




Iso-Scalar and Iso-Vector parts of the NEOS cannot be completely disentangled

Momentum Dependent Potential $U(\mathbf{p}_{i,j}) = \alpha p_{i,j}^2$
(3): K=200 MeV, $m^*/m = 0.7$ - $L = 14.4, 72, 96.6 MeV(A_1, B_1, \sigma)$

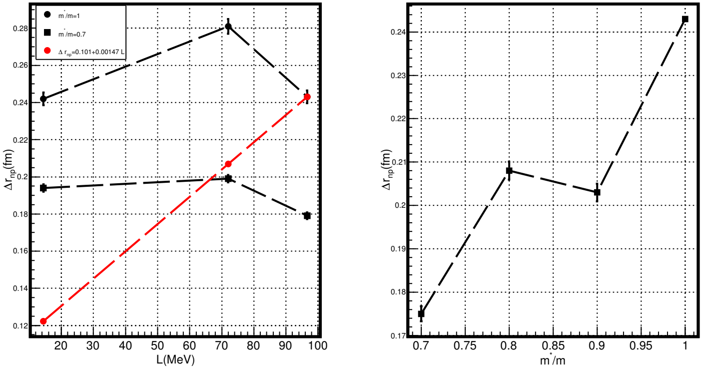




- Oscillation Energy Distributions Sensitive to the Effective Mass
- Improvement of the Sensitivity to the L parameter
- Increasing as L Increases

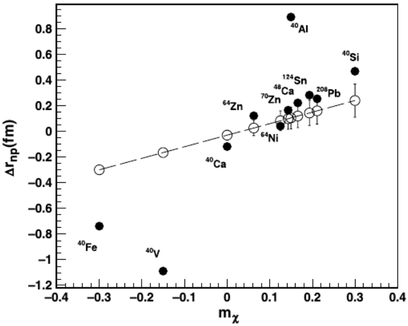
- $\Delta r_{np} = \langle R_n^2 \rangle^{\frac{1}{2}} - \langle R_p^2 \rangle^{\frac{1}{2}}$
- Dependence and connection with collective modes (IVPDR): Non-Relativistic and Relativistic mean field calculations

[B. Alex Brown Phys. Rev. Lett. 85 (2000),R. J. Furnstahl Nucl. Phys. A 706 (2002); C. J. Horowitz, J. Piekarewicz Phys. Rev. Lett. 86 (2001),X. Roca-Maza et al, Phys. Rev. Lett. 106 (2011)]

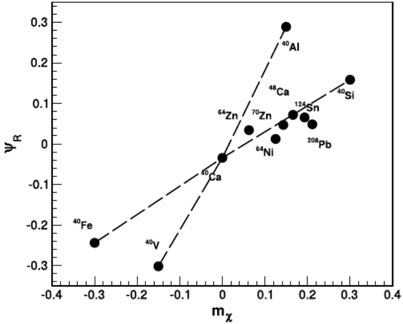


A=40 Isotopes Calculations - Neutron-Proton concentration Dependence

- $\Delta r_{np} = (0.90 \pm 0.15) m_\chi + (-0.03 \pm 0.02)$ fm
- Odd-Even staggering effect ^{40}V(odd-odd), ^{40}Fe(even-even); ^{40}Al(odd-odd), ^{40}Si(even-even)



Geometrical effects: $\Psi_R = \frac{\langle R_n^2\rangle - \langle R_p^2\rangle}{\langle R_n^2\rangle + \langle R_p^2\rangle} =^{+1, m_\chi=1}_{-1, m_\chi=-1}$



- Approximately linear relation for systems having the same mass - A=40
- Sensitivity on whether the nuclei are odd-odd or even-even
- Fixing A and varying m_χ, $\Longrightarrow a_a$ coefficient (similar to the IAS method)
- N=Z system: $\Delta r_{np}(^{40}Ca) \approx -0.12 fm \Leftrightarrow \Psi_R(^{40}Ca) \approx -0.035$

remove Coulomb effects $\Psi_R(^{40}Ca) = \Psi_0$: $\Psi_R' = |\Psi_R - \Psi_0|$

Conclusions:

- A Symmetry Potential Term having a 2+3 body dependence has been suggested. The comparison with other Symmetry Terms shows the dependence of the L and K_{sym} parameters on the details of the NEOS
- The CoMD model is suitable to perform collective modes calculations to constrain the NEOS
- Calculations for the ^{132}Sn nucleus reveal that IVGDR mode and NST constrain the symmetry term, however effective mass plays a role to reproduce experimental results

Outlook:

- Calculations for further S and L values (in progress)
- IVPDR, IVGDR for Tin Isotopes and other nuclei (EWSR, $N-Z/A$ dependence, Surface Effects)
- Comparisons with Dynamical (MD), Transport Models (Landau-Vlasov) and available experimental data