High Density Behavior of the Nuclear EoS and Properties of Massive Neutron Stars

Partha Roy Chowdhury

Department of Physics, University of Calcutta
92, A.P.C. Road, Kolkata-09, India

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Nuclear EoS and Symmetry Energy

Introduction:

- The nuclear Equation of state (EoS) $\varepsilon = f(\rho, X)$ is the description of energy per nucleon $E/A = \varepsilon$ of NM as a function ρ and asymmetry parameter X.

- Nuclear EOS can be used to obtain the bulk properties of NM: Energy density (ξ), Pressure (P), Velocity of sound (v_s), Incompressibility (K) for NM.

- Nuclear symmetry energy and then beta equilibrium proton fraction are calculated using EoS for X=0 and X=1.

What is importance of EoS for dense matter?

- Matter at densities up to $9\rho_0$ (ρ_0=2.5 ×10^{14} g/cc) and $4\rho_0$ may be present in the interior of NS and in the core collapse of type II SN respectively.

- The EoS describes the **relationship between pressure (P) and density (ρ)** for cold matter. $P=f(\rho)$ governs the compression achieved in SN and NS as well as their internal structure and many basic properties.

What is the role of experiments?

It is important to test these extrapolations with laboratory measurements. Nuclear collisions provide the only means to compress nuclear matter to high density within a laboratory environment.

What is Nuclear Symmetry Energy (NSE) ?

NSE: Energy required per nucleon to change the SNM to PNM

The analytical expression of NSE comes from Taylor series expansion of EoS of IANM about X=0:

$E_{sym}(\rho)$

$$\varepsilon(\rho, X) = \varepsilon(\rho, 0) + \tfrac{1}{2}\, \partial^2 \varepsilon(\rho, X)/\partial X^2|_{X=0}\, X^2 + O(X^4)$$

Neglecting higher order terms: $E_{sym}(\rho) \approx \varepsilon(\rho,1) - \varepsilon(\rho,0)$

This represents a penalty levied on the system as it departs from the symmetric limit of N=Z. **$E_{sym}(\rho)$ is positive (repulsive) up to 2-3ρ_0.**

Why the determination of Pressure is uncertain?

Role of NSE in Neutron Rich Environment

$E_{sym}(\rho)$ determines how the energies of nuclei and nuclear matter depend on the difference (X) between neutron and proton densities. Due to its repulsive nature, light nuclei have nearly equal numbers of protons and neutrons so that $E_{sym}(\rho) \approx 0$ (SNM).

To know the ρ-dependence of $E_{sym}(\rho)$, one must consider how the EOS depends on the difference between the n and p concentration.

$E_{sym}(\rho)$ in pure neutron matter gives rise to an additional source of Pressure

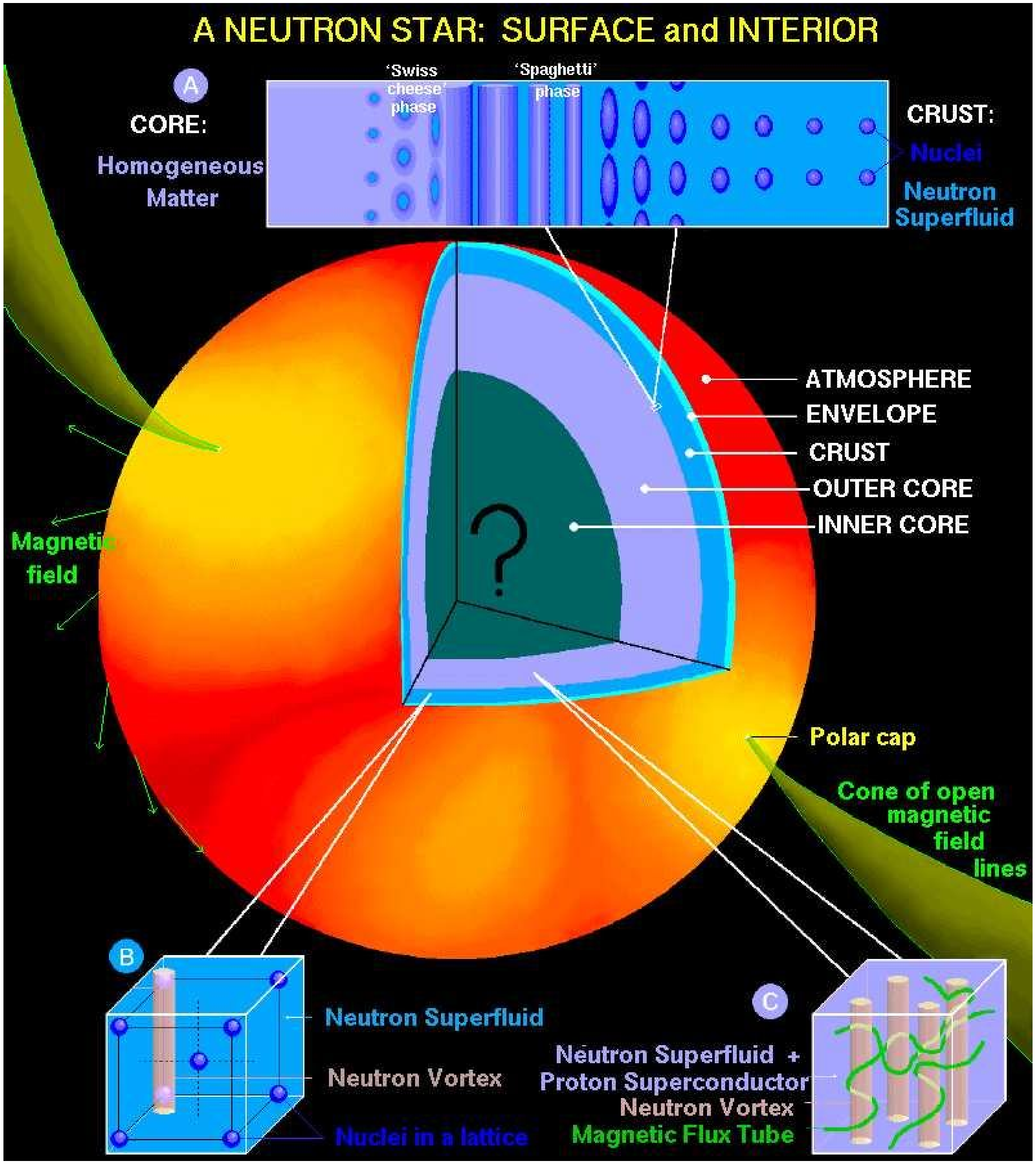
$\mathbf{P_{sym}} = \rho^2\, \partial \mathbf{E_{sym}}(\rho)/\partial\rho|_{s/\rho}$ (depends on the NSE)

makes the determination of Pressure UNCERTAIN!!

Urgent need for accurate determination of density dependence of $E_{sym}(\rho)$.

Application to Astrophysics: Neutron Star

In the outermost part of the solid crust a lattice of ^{56}Fe is present, since it is the most stable nucleus. Inside the interior at increasing density, the electron chemical potential starts to play a role, and β-equilibrium implies the appearence of more and more neutron-rich nuclei.



A section (schematic) of a NS

Figure courtesy:

J.M. Lattimer and M. Prakash, *Science 23 April 2004:Vol. 304. no. 5670, pp. 536 - 542*

Aim of the Present Work

Part I

(I) EoS for SNM using isoscalar part of M3Y effective NN interaction,

(II) EoS for IANM adding isovector part of same NN interaction.

then apply the above EoS's to determine:

(III) Nuclear Symmetry Energy (NSE)

(IV) Proton fraction x_β regarding URCA process in neutron star

Part II

(V) Constraints at saturation density (ρ_o): Slope (L), curvature (K_{sym}) parameters of NSE, Isospin dependent part K_{asy} and K_τ of isobaric incompressibility K(X).

Part III

(VI) The various properties of static & rotating NSs using the present EoS.

The metric used for rotating neutron star:

$$ds^2 = -e^{(\gamma+\rho)}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{(\gamma-\rho)} r^2 \sin^2\theta\, (d\phi - \omega dt)^2 .$$

where the gravitational potentials γ, ρ, α, and ω are functions of polar coordinates r and θ only.

Equation of State for IANM

Assuming interacting Fermi gas of neutrons and protons, the kinetic energy per nucleon ε_{kin} turns out to be

$$\varepsilon_{kin} = [3\hbar^2 k^2_F / 10m]F(X), \quad \text{with } F(X) = [(1 + X)^{5/3} + (1 - X)^{5/3}] / 2$$

The EoS for IANM:

$$E/A = \varepsilon = [3\hbar^2 k^2_F / 10m]F(X) + C\,(1 - \beta\, \rho^{2/3})\, \rho\, J_v / 2 \qquad \textbf{... (1)}$$

where $J_v = J_{v00} + X^2 J_{v01} = \iiint [t_{00}^{M3Y} + t_{01}^{M3Y} X^2] d^3s$ considering energy variation of zero range potential to vary with ε^{kin}.

Isoscalar and isovector components of the effective interaction

- The density dependent M3Y interaction potential is used for isoscalar and isovector part:

$$v_{00}(s,\rho,\varepsilon) = t_{00}^{M3Y}(s,\varepsilon)\, g(\rho,\varepsilon), \qquad v_{01}(s,\rho,\varepsilon) = t_{01}^{M3Y}(s,\varepsilon)\, g(\rho,\varepsilon)$$

- Isoscalar t_{00}^{M3Y} and isovector t_{01}^{M3Y} components of M3Y interaction supplemented by zero range potential representing the single nucleon exchange term are given as

$$t_{00}^{M3Y} = 7999\frac{\exp(-4s)}{4s} - 2134\frac{\exp(-2.5s)}{2.5s} - 276(1-\alpha\varepsilon)\delta(s)$$

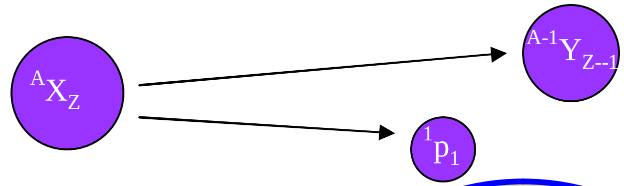
$$t_{01}^{M3Y} = -4886\frac{\exp(-4s)}{4s} + 1176\frac{\exp(-2.5s)}{2.5s} + 228(1-\alpha\varepsilon)\delta(s)$$

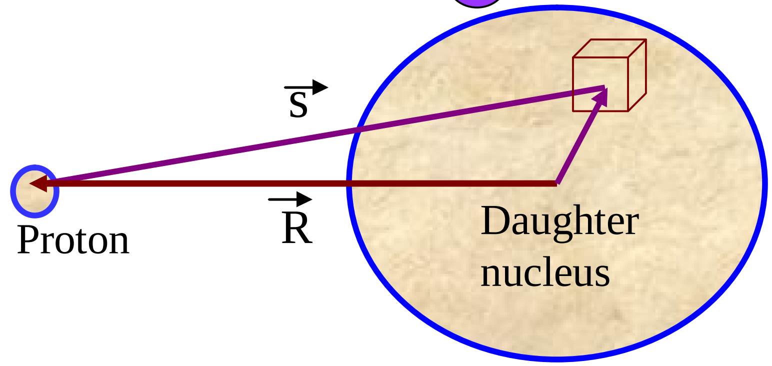
where the energy dependence parameter $\alpha = 0.005$ MeV^{-1}.

$g(\rho, \varepsilon) = C\,[\,1-\beta(\varepsilon)\,\rho^{2/3}]$ accounts Pauli blocking effects.

Spontaneous emission of single proton

from a single nucleus is possible if the released energy $Q_p > 0$: $Q_p = [\, M(^{A}X_{Z}) - M(^{A-1}Y_{Z-1}) - M(^{1}P_{1})\,]c^2$ (MeV)





- Single Folded nuclear interaction energy using DDM3Y : $V_N(R) = \int v(|r-R|)\, \rho(r)\, d^3r$
- The total interaction energy:

$$E(R) = V_N(R) + V_C(R) + \hbar^2\, l(l+1) / (2\mu r^2)$$

- The WKB action integral from turning points R_a to R_b is $K = (2/\hbar)\int[2\mu\,(E(R) - E_v - Q)]^{1/2} dR$

The zero point vibration energy $E_v \propto Q$.

The decay half life of spherical proton emitters:
$T = [\, h\ln 2 / 2E_v\,].[1+\exp K]$

The half lives are very sensitive to Q.

Parent nuclei	2nd T.P R_a (fm)	3rd T.P. R_b (fm)	Our Folding Model Calc $\log_{10}{}^{T}$ (s)	Expt $\log_{10}{}^{T}$ (s)
^{105}Sb	6.61	134.30	1.95 (46)	2.049
^{145}Tm	6.47	56.27	-5.18 (6)	-5.409
^{147}Tm	6.46	88.65	0.94 (4)	0.591
^{147}Tm*	7.19	78.97	-3.41 (5)	-3.444
^{150}Lu	6.51	78.23	-0.63 (4)	-1.180
^{150}Lu*	7.24	71.79	-4.40 (15)	-4.523
^{155}Ta	6.62	57.83	-4.70 (6)	-4.921
^{156}Ta	7.27	94.18	-0.41 (7)	-0.620
^{156}Ta*	6.60	90.30	1.61 (10)	0.949
^{161}Re	7.51	79.33	-3.48 (7)	-3.432
^{161}Re*	6.70	77.47	-0.64 (7)	-0.488

Barrier Penetration of a particle trapped in a potential E (R)

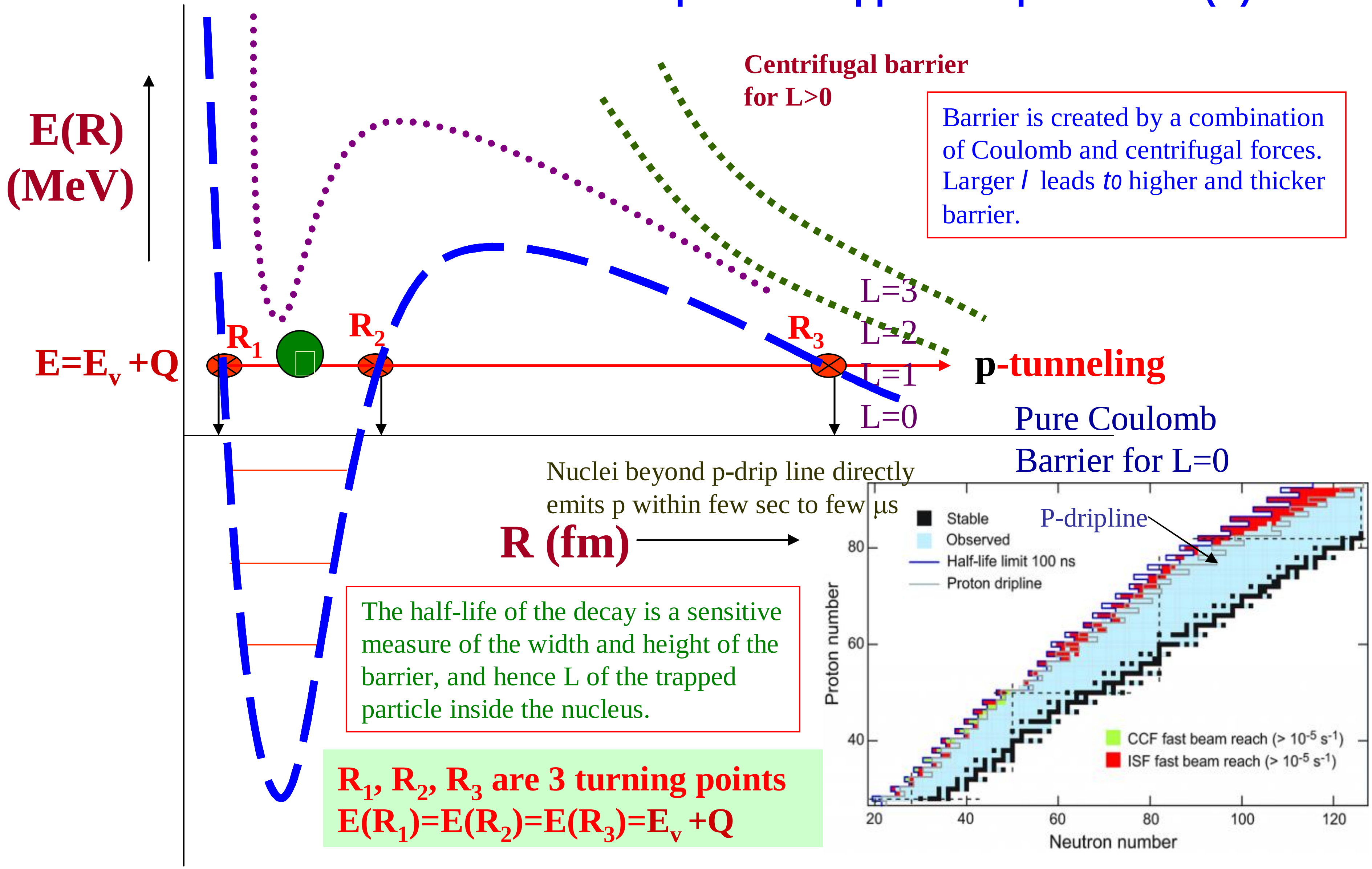


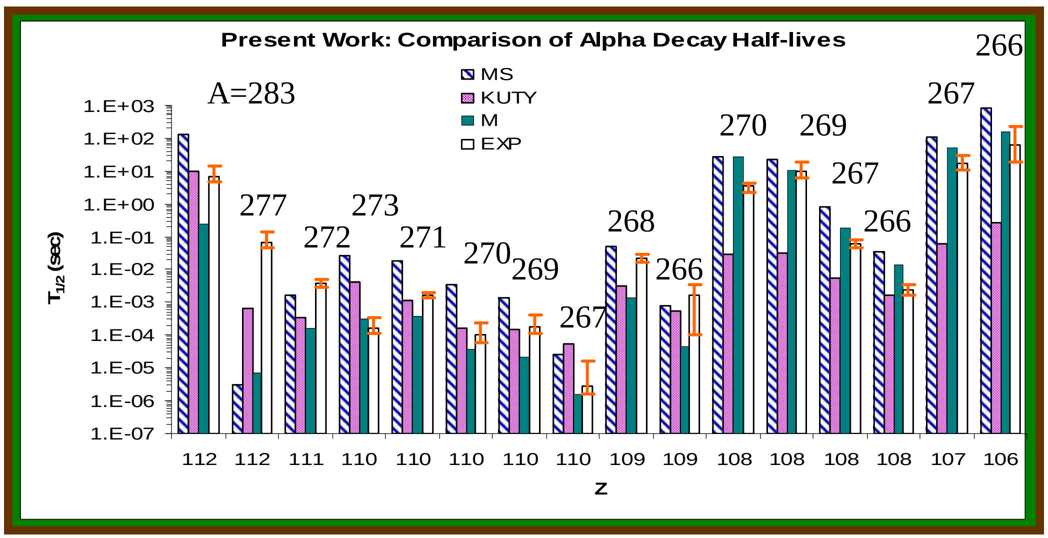
Fig. Total interaction potential E(R) vs. distance between proton and daughter.

The proton drip line defines one of the fundamental limits to nuclear stability.

Results and Discussion

The present method (Double folded DDM3Y nuclear potential within WKB), reproduces the observed data reasonably well.

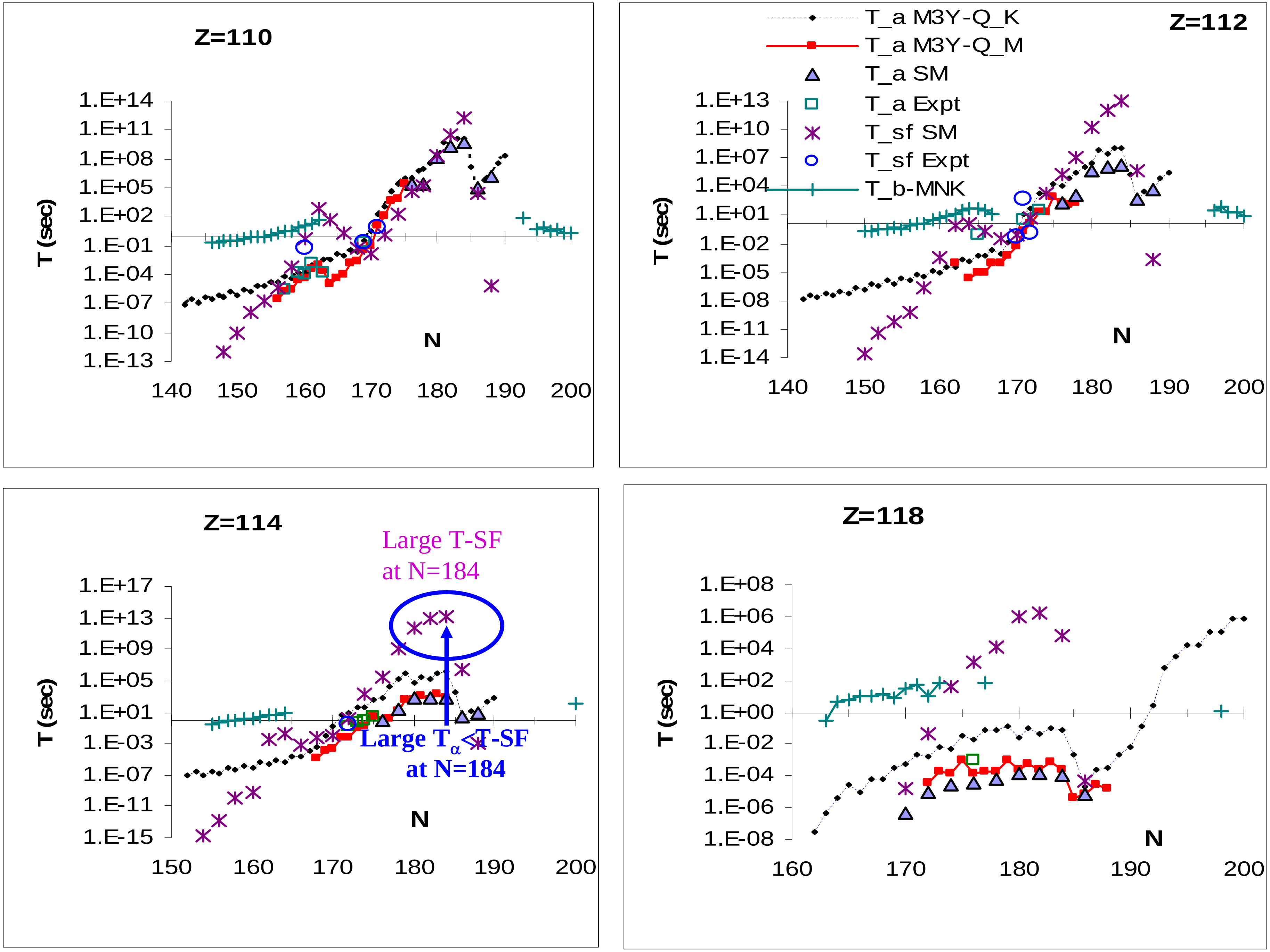
Parent Nuclei Z	A	EXPT Q (MeV)	Theory [M-S] Q (MeV)	Experiment $T_{1/2}$	This work $T_{1/2}$
118	294	11.81 ± 0.06	12.51	(-1.3) 0.89 (+75) ms	(-0.18) 0.66 (+0.23) ms
116	293	10.67 ± 0.06	11.15	(-19) 53 (+62) ms	(-61) 206 (+90) ms
116	290	11.00 ± 0.08	11.34	(-6) 15 (+26) ms	(-5.2) 13.4 (+7.7) ms
114	289	9.96 ± 0.06	9.08	(-0.7) 2.7 (+1.4) s	(-1.2) 3.8 (+1.8) s
114	286	10.35 ± 0.06	9.61	(-0.03) 0.16 (+0.07) s	(-0.04) 0.14 (+0.06) s
112	285	9.29 ± 0.06	8.80	(-9) 34 (+17) s	(-26) 75 (+41) s
112	283	9.67 ± 0.06	9.22	(-0.7) 4.0 (+1.3) s	(-2.0) 5.9 (+2.9) s
110	279	9.84 ± 0.06	9.89	(-0.03) 0.18 (+0.05) s	(-0.13) 0.40 (+0.18) s
108	275	9.44 ± 0.07	9.58	(-0.06) 0.15 (+0.27) s	(-0.40) 1.09 (+0.73) s
106	271	8.65 ± 0.08	8.59	(-1.0) 2.4 (+4.3) min	(-0.5) 1.0 (+0.8) min



Calculated T_α using Q_{KUTY} predicts the long lived SHN around $^{294}110_{184}$, $^{296}112_{184}$, $^{298}114_{184}$ with T_α of the order of 311yrs, 3.10yrs, 17 days respectively. These values are much less than their corresponding T_{SF} (4.48×10^4yrs, 3.09×10^5 yrs, 4.38×10^5 yrs respectively) values.

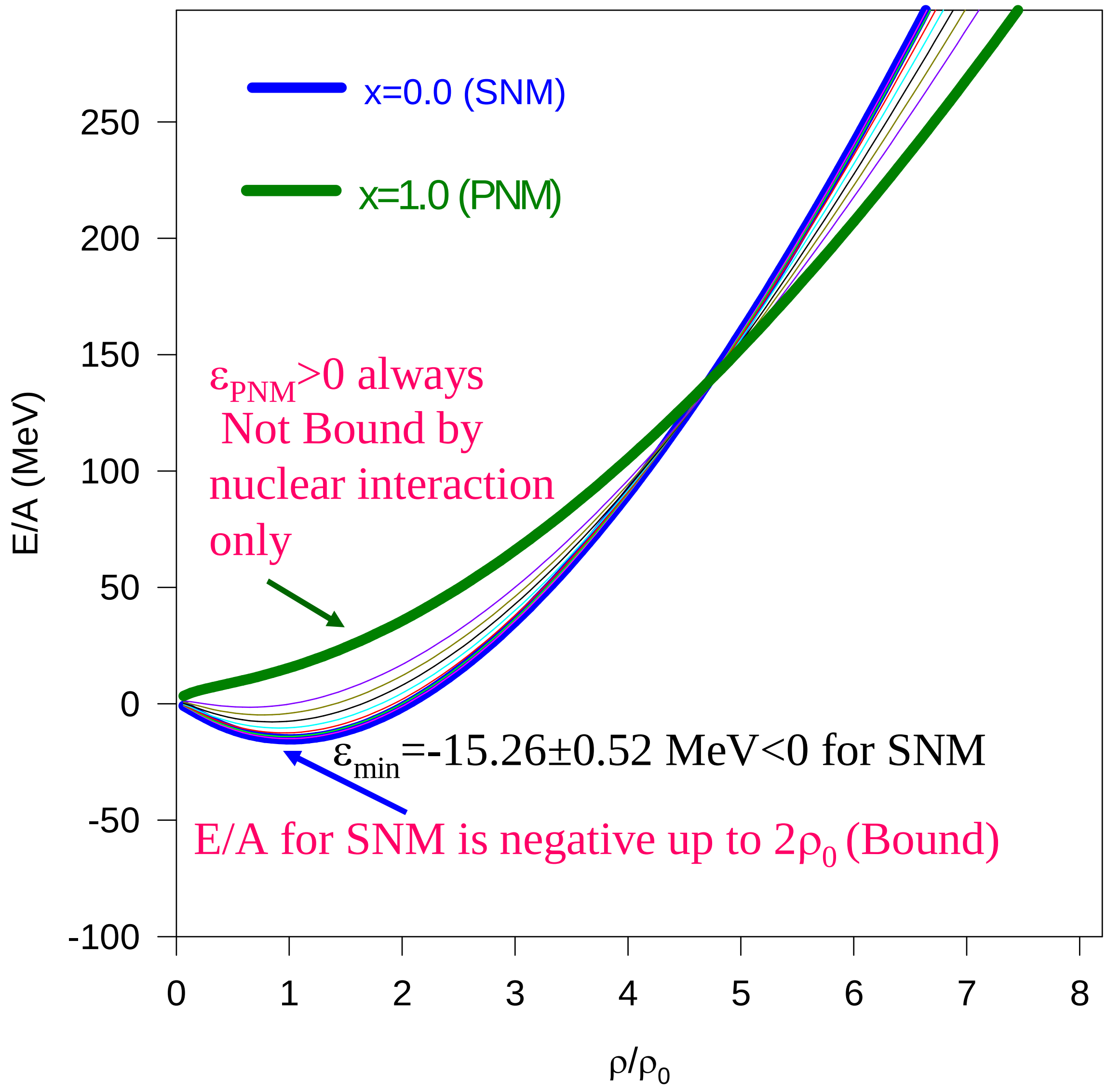
Hence the dominant decay mode of the above nuclei is expected to be alpha emission.

Ref: PRC, CS, DNB Phys. Rev. C 77, 044603 (2008)



Z=110
Z=112
Z=114
Z=118
T_a M3Y-Q_K
T_a M3Y-Q_M
T_a SM
T_a Expt
T_sf SM
T_sf Expt
T_b-MNK
T (sec)
N
Large T-SF
at N=184
Large T$_\alpha$<T-SF
at N=184

E/A=ε of NM with different X as functions of ρ/ρ_0 for present calc.



Cntd…

✓EoS of SNM can be obtained by putting X=0 in EoS of IANM:

$\varepsilon=[3\hbar^2 k^2_F /10m] + C\,(1-\beta(\varepsilon)\,\rho^{2/3})\,\rho\,J_{v00}/2$

✓In saturation condition of SNM $\partial\varepsilon/\partial\rho=0$.

The two eqns. can be solved simultaneously with $\partial\varepsilon/\partial\rho=0$ for fixed values of ε_0 and ρ_0 of SNM to obtain the values of density dependence parameters β and C.

Energy density ξ : $\xi = (\varepsilon + mc^2)\,\rho$

Pressure P : $P = \rho^2 \partial\varepsilon/\partial\rho$

Velocity of Sound v_s : $v_s/c = [\partial P/\partial\varepsilon]^{1/2}$

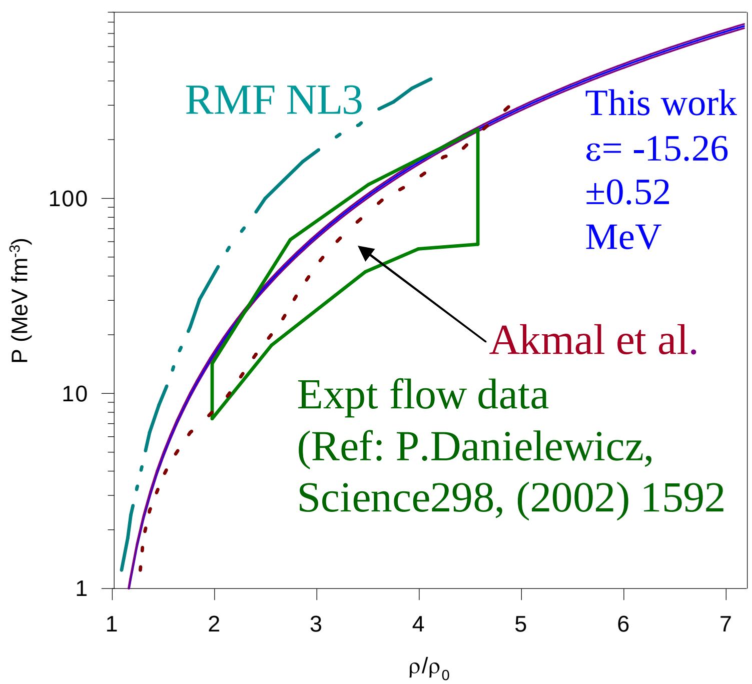
Incompressibility K_0 : $K_0 = 9\,\rho^2\,\partial^2\varepsilon/\partial\rho^2\,|_{\rho=\rho_s}$

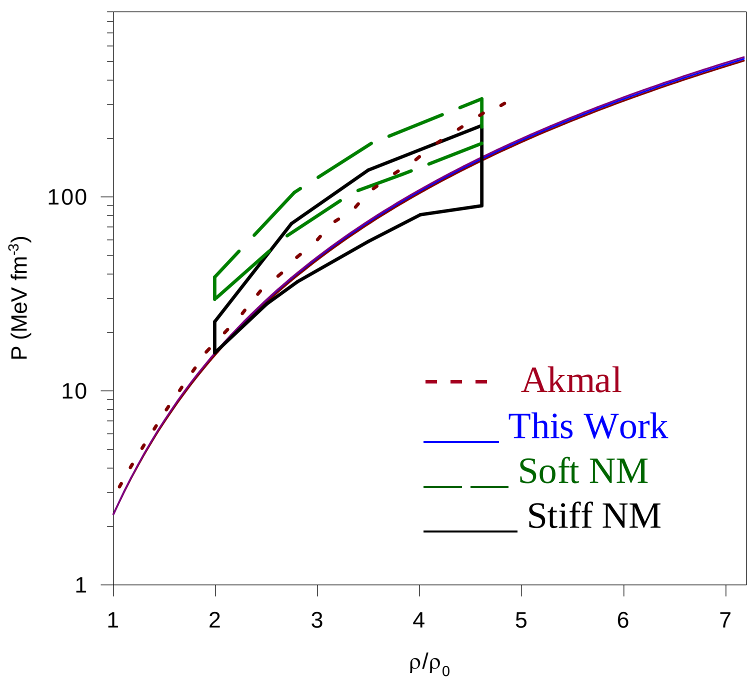
where saturation density ρ_s is defined by :

$\partial\varepsilon/\partial\rho\,|_{\rho=\rho_s}$ is equal to zero (saturation condition for IANM)

The pressure P of **SNM** as a function of ρ/ρ_o is consistent with experimental flow data for SNM

The pressure P of **PNM** : consistent with flow data for PNM with weak (soft NM) and strong (stiff NM) ρ-dependence.





P. Roy Chowdhury et al; Nucl. Phys. A **811**, 140 (2008)

Nuclear Symmetry Energy (NSE)

Definition of NSE: $E_{sym}(\rho) = \varepsilon(\rho,1) - \varepsilon(\rho,0)$

[Ref: T. Klahn et al., PRC74, 035802 (2006)]

Therefore, putting X=1 (PNM) and X=0 (SNM) in EoS for IANM **Eq.(1)** :

$$E_{sym}(\rho) = (2^{2/3} - 1)3/5\ E_{f0}\ (\rho/\rho_0)^{2/3} + C/2\ \rho(1 - \beta\rho^n)J_{v01}$$ **.....(2)**

where E_{f0} is the Fermi energy for SNM in ground state and J_{v01} is volume integral of isovector part of M3Y interaction.

Therefore, density dependence of symmetry energy is:

$$E_{sym}(\rho) = a_0\rho^{2/3} + a_1\rho + a_2\rho^{n+1} + a_3\rho^{5/3} + a_4\rho^{n+5/3}.$$

Can the symmetry energy becomes negative at high densities?

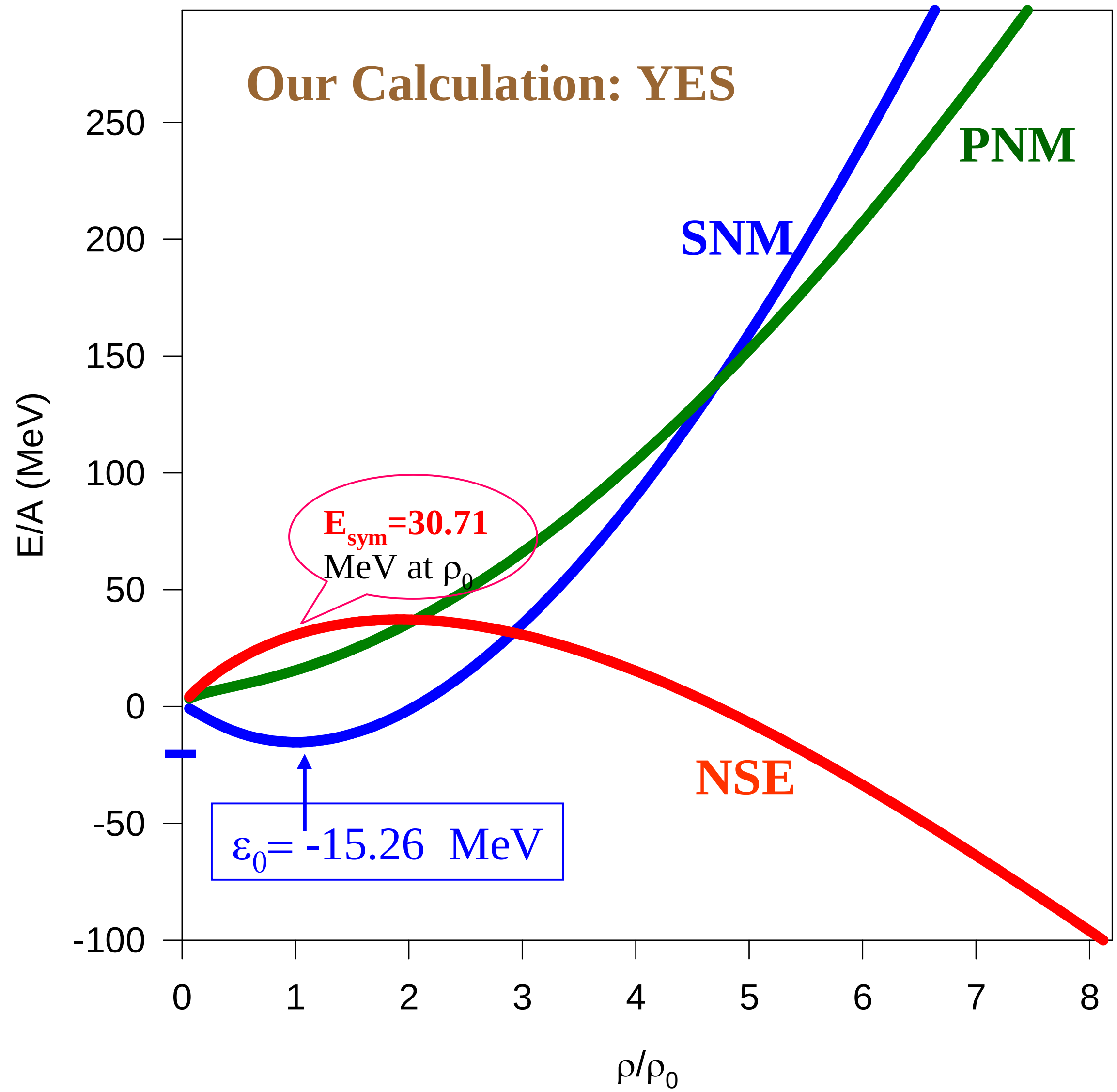
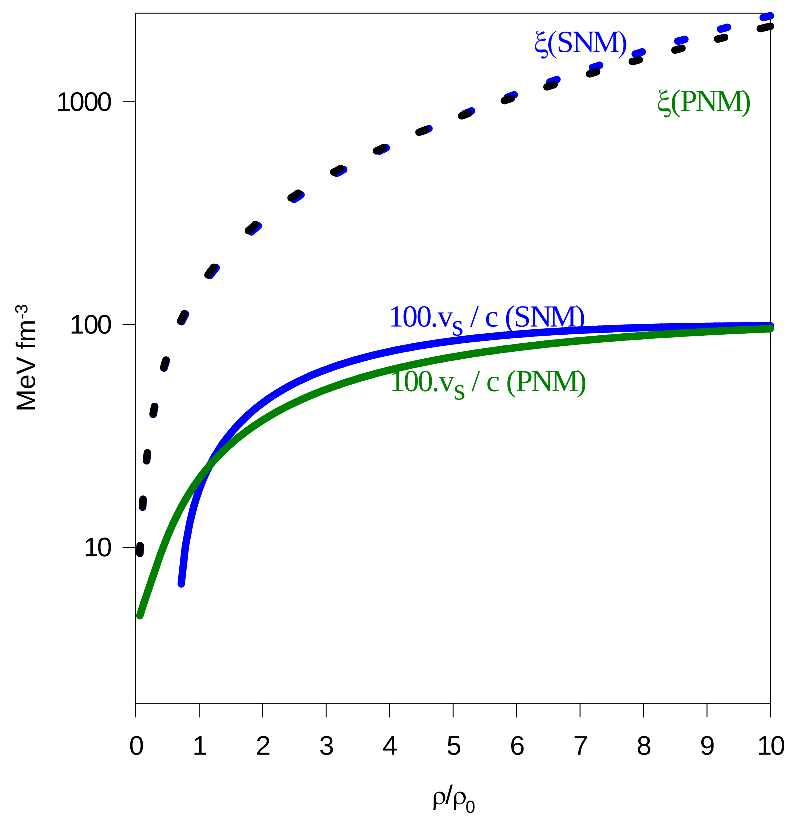


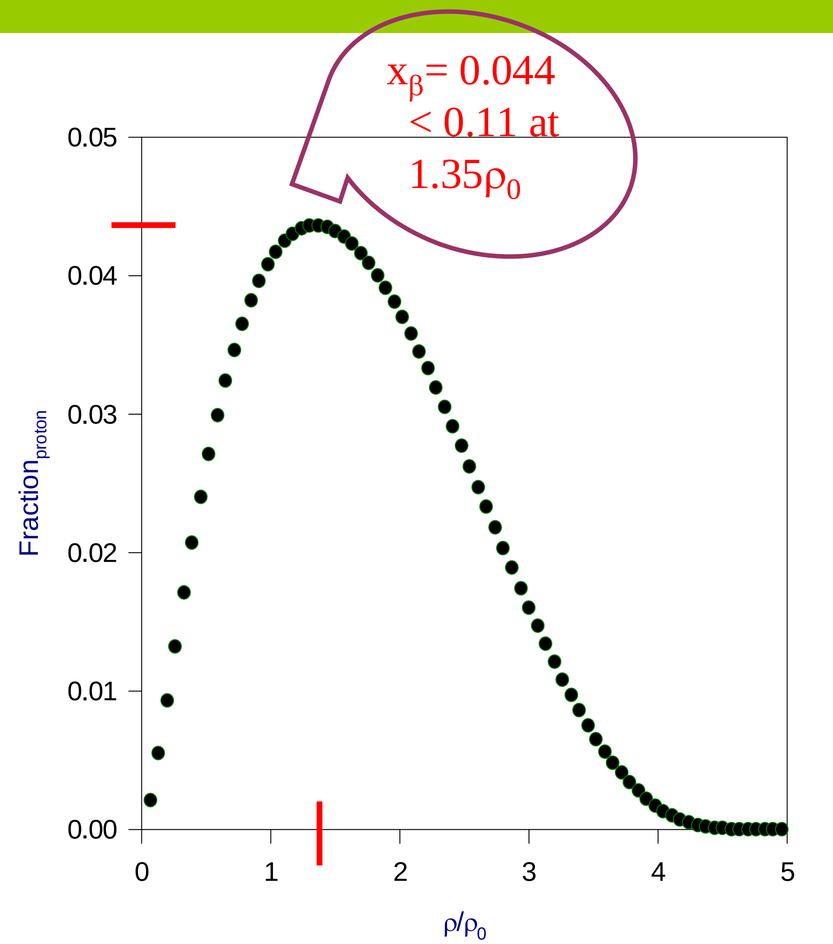
FIG. The energy per nucleon ε = E/A of SNM, PNM & NSE as functions of ρ/ρ_0 using ε_0= -15.26 MeV

At high densities, the energy of pure neutron matter becomes lower than symmetric matter leading to negative symmetry energy

The velocity of sound (in units of $10^{-2}c$) & the energy density (MeV fm^{-3}) ξ of SNM and PNM as functions of ρ/ρ_0 for the present calculations.

The present calculation of x_β using NSE, forbids the direct URCA process inside neutron star core as $x_\beta < 1/9$.





Part II: Isospin dependent bulk properties of IANM

Taylor series expansion about ρ_o gives:

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L/3\ (\rho-\rho_0)/\rho_0 + K_{sym}/18\ [(\rho-\rho_0)/\rho_0]^2 + \text{H.O. terms}$$

where Slope (L) and Curvature (K_{sym}) parameters of NSE at saturation density (ρ_o) characterize the density dependence of the NSE around normal nuclear matter density.

(a) $L=3\rho_o \partial E_{sym}(\rho) / \partial \rho|_{\rho=\rho_o}$ (b) $K_{sym}=9\rho_o^2 \partial^2 E_{sym}(\rho) / \partial \rho^2|_{\rho=\rho_o}$.

Thus L and K_{sym} carry important information on properties of NSE at both high and low densities.

Slope **L can be determined** from measured thickness of neutron skin of heavy nuclei but with large uncertainties in measurements.

[See M. Centelles et al. PRL 102, 122502 (2009), Tsang et al; PRL 102, 122701 (2009)]

From measured excitation energy of GMR, one can relate bulk SE. This correlates to neutron skin thickness S

Isospin dependent part K_{asy} of isobaric incompressibility K(X) can be obtained form Taylor Series Expansion of K(X) about X=0

$$K(X) \approx K_0 + K_{asy} X^2 .$$

K_{asy} can be determined from: $K_{asy} = K_{sym} - 6L$

K_{asy} can be extracted from measured isotopic dependence of the **GMR** in n-rich nuclei (even-A Sn isotopes) [See T. Li et al. PRL 99, 162503 (2007), M.M. Sharma et al. PRC 98, 2562 (1988), M. Centelles et al. PRL 102, 122502 (2009)]

Higher order effects (Q_0) on the K(X): Isospin dependence of incompressibility at ρ_o more accurately characterized by

$$K_\tau = K_{sym} - 6L - (Q_0/K_0)\, L$$

where

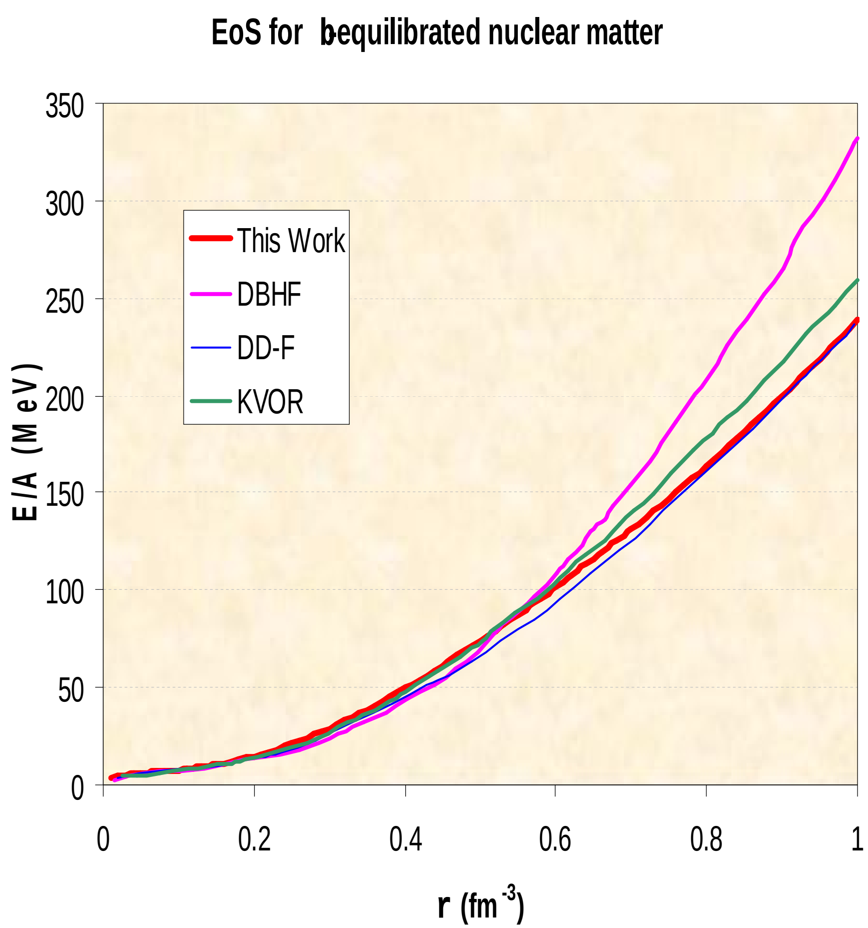
$$Q_0 = 27\rho_o^3\, \partial^3 (\rho,0) / \partial \rho^3 |_{\rho=\rho_o}$$

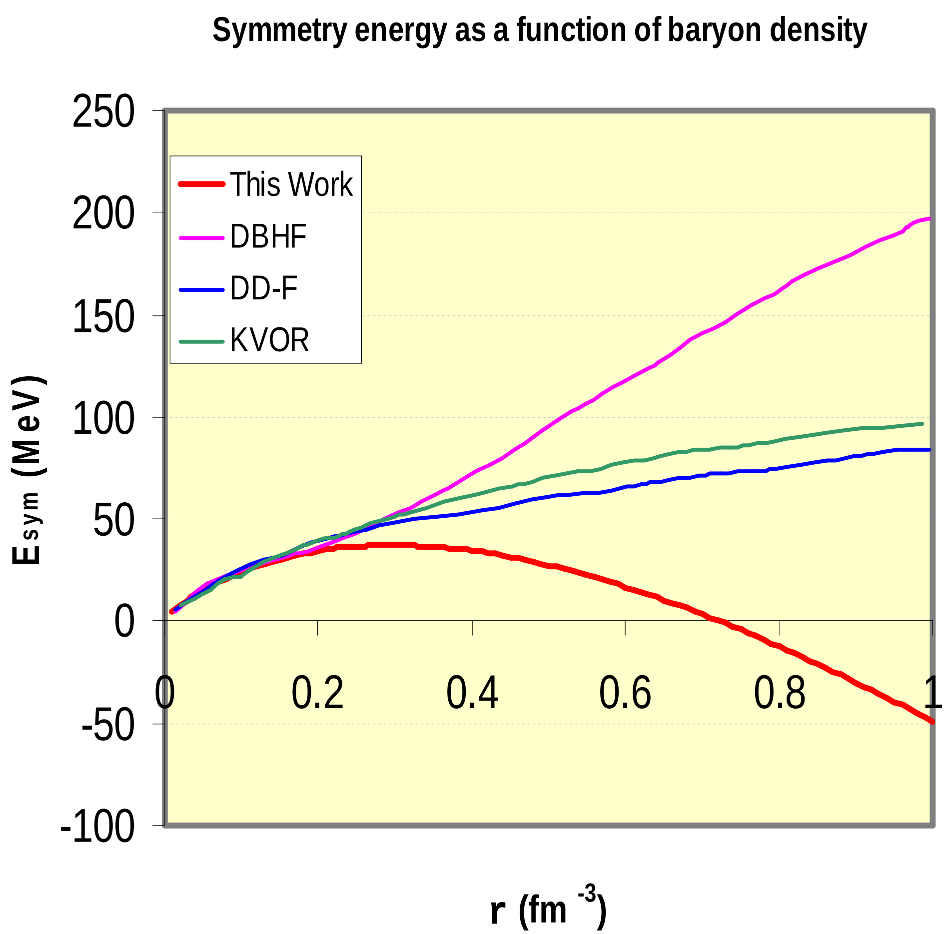
Comparison of the Results of Present Calculations (all in MeV) with Other Models

Model	K_0	$E_{sym}(\rho_0)$	L	K_{sym}	K_{asy}	Q_0	K_τ
This work	274.7 ± 7.4	30.71 ± 0.26	45.11 ± 0.02	-183.7 ± 3.6	-454.4 ± 3.5	-276.5 ± 10.5	**-408.97** ± 3.01
Expt.	--	31.6	75 ± 25	K_τ = -550 (+/-100)TL **-389** (12) MMS			
FSUGold	230.0	32.59	60.5	-51.3	-414.3	-523.4	-276.77
NL3	271.5	37.29	118.2	+100.9	-608.3	+204.2	-697.36
Hybrid	230.0	37.30	118.6	+110.9	-600.7	-71.5	-563.86

Ref: P. Roy Chowdhury et al; Phys. Rev. C **80**, 011305 (2009) (Rapid Comm.)
* MMS is from the work by M. M. Sharma, Nucl. Phys. A**816**, 65 (2009).

Part III: Neutron star matter





The NSE calculated by the phenomenological relativistic mean-field (RMF) models using density-dependent masses and coupling constants (e.g., DD-F,KVOR) and DBHF continue increasing with density and never become negative.

Ref: Partha Roy Chowdhury et al; Phys. Rev. C **81**, 062801(Rapid) (2010)

Results and Discussion

Present NSE is consistent with the recent evidence for a soft NSE at suprasaturation densities and supersoft nuclear symmetry energies is preferred by the FOPI/GSI experimental data on the $\pi+$ /$\pi-$ ratio.

The saturation density (ρ_0) used in DD-F, KVOR, DBHF, and our EOS are 0.1469, 0.1600, **0.1810**, and 0.1533 fm^{-3}, respectively. *So the DBHF uses considerably larger density than measured value of 0.1533* fm^{-3}.

The values of NSE at ρ_0 calculated by DD-F, KVOR, **DBHF,** and our EOS are 31.6, 32.9, **34.4**, and 30.71 MeV, respectively. It is clear that DBHF slightly overestimates the value of NSE at ρ_0 .

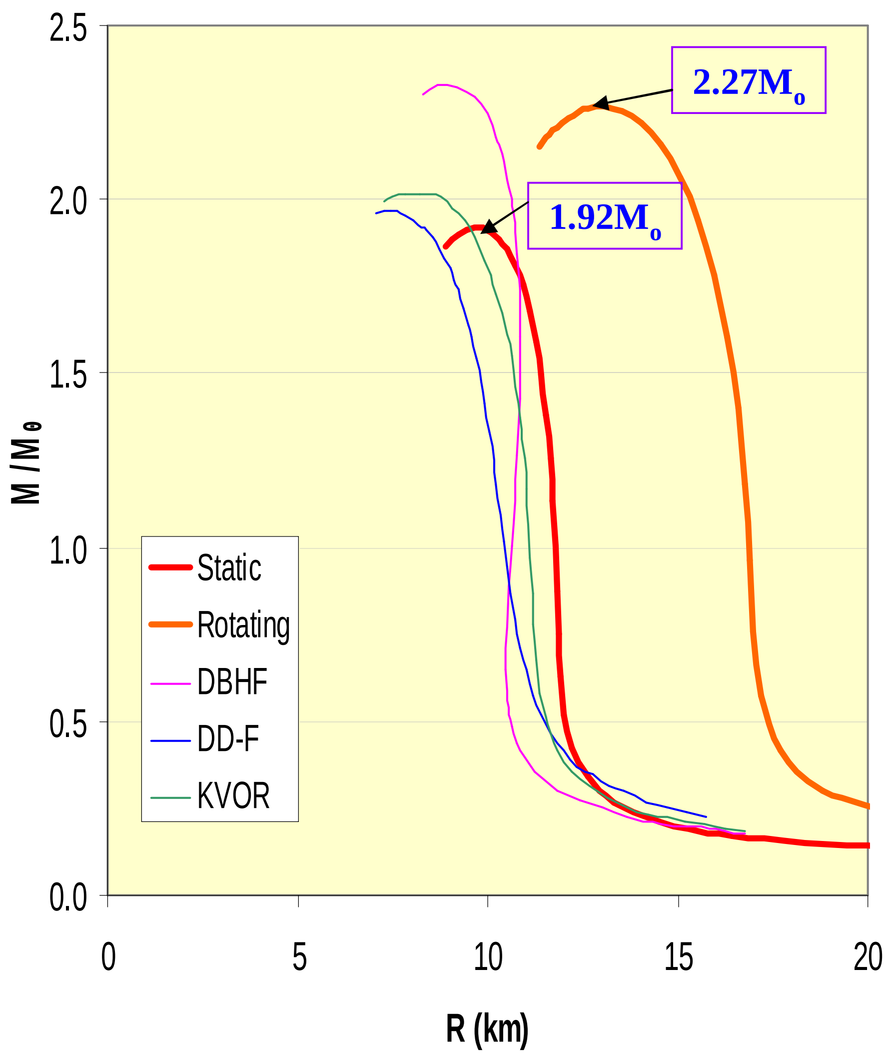
Results and Discussion

In the relativistic DBHF approach, the NSE increases more rapidly with density, indicating a very large proton fraction at higher density. This shows an opposite trend to the NSE function determined from our EOS.

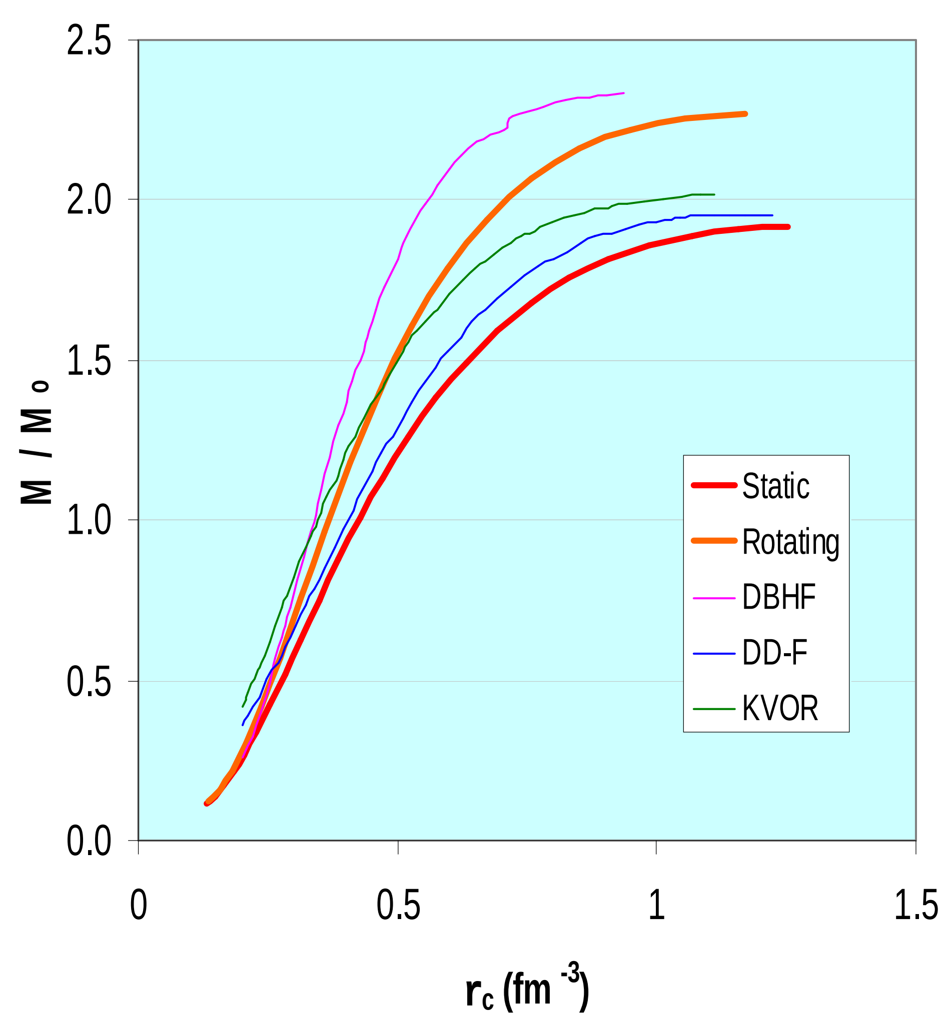
Contrary to the relativistic models like DD-F, KVOR, DBHF, etc., this work does not support the fast cooling via direct nucleon URCA process.

The possibility of fast cooling via direct hyperon URCA or any other processes that enhance neutrino emissivities, such as π- and K^- condensates, may not be completely ruled out here.

Neutrinos emitted in continual Cooper-pair breaking and formation (PBF) processes are an integral part of minimal cooling paradigm as referred in a recent review by Page, Lattimer, Prakash and Steiner in *Astrophys. J. 707:1131-1140,2009*.



Mass-Radius Relation for a sequence of NSs



Mass vs.central density for a sequence of NSs

Ref: Partha Roy Chowdhury et al; Phys. Rev. C **81**, 062801(Rapid) (2010)

Results and discussion: Mass & Radius of the Neutron Star

For the same mass comparatively less central density appears for the rotating stars.

The maximum mass for the static case is about 1.92M_{solar} with radius ~9.7 km and for the rotating case it is about 2.27M_{solar} with radius ~13.1 km.

So a mass higher than 1.92M_{solar} would rule out a static star as far as this EOS is concerned.

The phenomenological RMF models DD-F and KVOR predict maximum mass around twice solar mass for a non-rotating star. The relativistic DBHF model calculates the maximum mass ~2.33M_{solar}.

Summary and Conclusion

Modern constraints from the mass and M-R measurements require stiff EOS at high ρ, whereas flow data from HI collisions seem to disfavor too stiff behavior of the EOS.

The P vs. ρ for present EOS is consistent with the experimental flow data and confirms its high-density behavior.

We are able to describe highly massive compact stars, e.g. the millisecond pulsars PSR B1516+02B with a mass $M = 1.94^{+0.17}_{-0.19}\, M_{solar}(1\sigma)$ and PSR J0751+1807, with a mass $M = 2.1 \pm 0.2 M_{solar}$ (1σ) and $2.1^{+0.4}_{-0.5}\, M_{solar}(2\sigma)$.

The present calculation gives $E_{sym}(\rho_0)$, K_0, L, K_{sym}, K_{asy}, K_τ which are in excellent agreement with recently accepted values..

Thus the DDM3Y effective interaction is found to provide a unified description of alpha and proton radioactivities, properties of nuclear matter and compact star.

Future Projects

- Extend the present EoS to finite temperature considering the chemical potentials for neutron and proton and Fermi distribution functions.
The properties at finite temperature such as the pressure, compressibility, speed of sound and specific heats will be calculated.

List of Publications (Refereed International Journals)

1) "Isospin asymmetric nuclear matter and properties of axisymmetric neutron stars"
Partha Roy Chowdhury et al; Phys. Rev. C **81**, 062801(Rapid) (2010)

2) "Charged and neutral hyperonic effects on the driplines" **P. Roy Chowdhury** et al;
Rom. Rep. Phys**. 62**, 65-98, (2010)

3) "Isospin dependent properties of asymmetric nuclear matter" **P. Roy Chowdhury** et al;
Phys. Rev.C **80**, 011305 (Rapid) (2009)

4) "Isobaric incompressibility of isospin asymmetric nuclear matter"
D.N. Basu, **P. Roy Chowdhury**, C. Samanta; Phys.Rev.C **80**, 057304 (2009)

5) "Search for long lived heaviest nuclei beyond the valley of stability" **P. Roy Chowdhury** et al;
Phys. Rev.C **77**, 044603 (2008)

6) "Lambda hyperonic effect on the normal drip lines" C. Samanta, **P. Roy Chowdhury**, D.N. Basu;
J.Phys.G35, 065101 (2008).

7) "Nuclear half-lives for α-radioactivity of elements with 100 ≤ Z ≤ 130" **P. Roy Chowdhury** et al;
Atomic Data Nuclear Data Tables **94**, 781-806 (2008)

8) "Nuclear equation of state at high baryonic density and compact star constraints"
D.N. Basu, **P. Roy Chowdhury**, C. Samanta; Nucl.Phys. A811, 140 (2008).

9) *"Predictions of alpha decay half lives of heavy and superheavy elements"*
C. Samanta, **P. Roy Chowdhury**, D.N. Basu, Nuclear Physics A 789, (2007) 142–154.

10) *"α decay chains from element 113"* **P. Roy Chowdhury** et al; Physical Review C 75, 047306
(2007).

Contd.

List of Publications (Refereed International Journals)

11) "Quantum tunneling in ^{277}112 and its alpha-decay chain" C. Samanta, D.N. Basu, **P. Roy Chowdhury** J. Phys.Soc.Jap.76, 124201 (2007).

12) *"α decay half-lives of new superheavy elements"* **P. Roy Chowdhury** et al; Physical Review C **73**, (2006) 014612.

13) *"Generalized mass formula for non-strange and hypernuclei with SU(6) symmetry breaking"* C Samanta, **P. Roy Chowdhury,** D N Basu, J. Phys. G: Nucl. Part. Phys. **32**, (2006) 363.

14) "*Reaction mechanisms with loosely bound nuclei ^{7}Li+^{6}Li at forward angles in the incident energy range 14–20 MeV*" **P. Roy Chowdhury** in S. Adhikari *et al.*, Phys. Rev. **C 74**, 024602 (2006).

15) **P. Roy Chowdhury**, D.N. Basu**,***"Nuclear matter properties with the re-evaluated coefficients of liquid drop model"* Acta Physica Polonica B Vol. **37,** No. 6 (2006) 1833.

16) D.N. Basu, **P. Roy Chowdhury**, C. Samanta, *"Equation of state for isospin asymmetric nuclear matter using Lane potential"* Acta Physica Polonica B Vol. **37**, No. 10 (2006) 2869.

17) **P. Roy Chowdhury**, D.N. Basu; "Spin-parities and half lives of ^{257}No and its alpha-decay daughter ^{253}Fm", Rom. J. Phys. **51**, 853-857 (2006).

18) C. Samanta, **P. Roy Chowdhury**, D.N. Basu, *"Modified Bethe-Weizsäcker mass formula with isotonic shift,new driplines and hypernuclei"*, American Institute of Physics (Conf. Proc.) 802 (2005) 142.

19) D.N. Basu, **P. Roy Chowdhury**, and C. Samanta**,** *"Folding model analysis of proton radioactivity of spherical proton emitters"*, Physical Review C **72,** (2005) 051601 (Rapid Comm.).

20) **P. Roy Chowdhury** et al; *"Modified Bethe-Weizsacker mass formula with isotonic shift and new driplines"*, Modern Physics Letter A **20**, No.21 (2005) 1605-1618.

THANK YOU

We take a different attitude: we try to predict the bulk properties of nuclear matter, effect of large isospin asymmetry and its link to static & rotating NS structure and properties of finite nuclei using the **effective NN interaction** with the theoretical uncertainty.

Possibility of Direct URCA process in neutron star

From the condition of beta equilibrium in degenerate matter we have chemical potential (μ) of electron $\mu_e = \mu_n - \mu_p = -\partial\epsilon/\partial x$

Beta equilibrium proton fraction (x_β) is determined by:

$$\hbar c(3\pi^2 \rho x_\beta)^{1/3} = 4E_{sym}(\rho)(1-2x_\beta) \quad ...(3)$$

Ref: Lattimer, Pethik, Prakash, Haensel, PRL 66, 2701 (1991)

Hence x_β is entirely determined by NSE.

Using present NSE [**Eq.(2)**], $(x_\beta)_{max}$=0.044 occurs at $\rho=1.35\rho_0$ and goes to zero at $\rho=4.5\rho_0$ for n=2/3.

Is direct URCA possible to occur?

At temperatures sufficiently lower than typical Fermi temp ($T_F \sim 10^{12}$ K), n, p, e must have momenta close to Fermi momenta (P_F).

The condition for momentum conservation for direct URCA is:
$\mathbf{P_{Fp} + P_{Fe} \geq P_{Fn}}$ neglecting the neutrino and antineutrino's momenta.

Using charge neutrality condition $\mathbf{n_p = n_e}$ and $\mathbf{P_F = (1.5\pi^2 n)^{1/3}}$, baryon density= $n = n_n + n_p$ one can find at threshold $\mathbf{n_n = 8n_p} \Rightarrow x = \mathbf{n_p/n = x_{th} = 1/9}$.

From the condition of beta equilibrium in degenerate matter we have chemical potential (μ) of electron $\mu_e = \mu_n - \mu_p = -\partial\epsilon/\partial x$ where ϵ (n, x) =energy per baryon.$\Rightarrow \hbar c\mathbf{(1.5\pi^2 nx)^{1/3}} = 4S_v(n)(1-2x)$.

The density n_{th} at which proton fraction $x = \mathbf{x_{th}} = 1/9$ can be found from $S_v \alpha\ n^q$.in the above relation.

An alternative rapid cooling path: Direct Hyperon URCA

- **The hyperons begin to populate the central region of the star at the density $n \approx 2n_0$, (RBHF calculation) where $n_0 = 0.16\ fm^{-3}$= normal nuclear matter density**. [Ref. H. Huber et al., nucl-th/9711025].

- **Presence of hyperons might lead to direct hyperon URCA even if the proton fraction is too small (<11%).** [M. Prakash et al. Astrophys. J **390**, 1992, L77]

- **Besides the direct nucleon URCA process the most important Direct Hyperon URCA processes (with their inverse at same rate) are :**

$$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e, \quad \Lambda \rightarrow p + e^- + \bar{\nu}_e,$$

$$\Sigma^- \rightarrow n + e^- + \bar{\nu}_e, \quad \Xi^- \rightarrow \Lambda + e^- + \bar{\nu}_e.$$

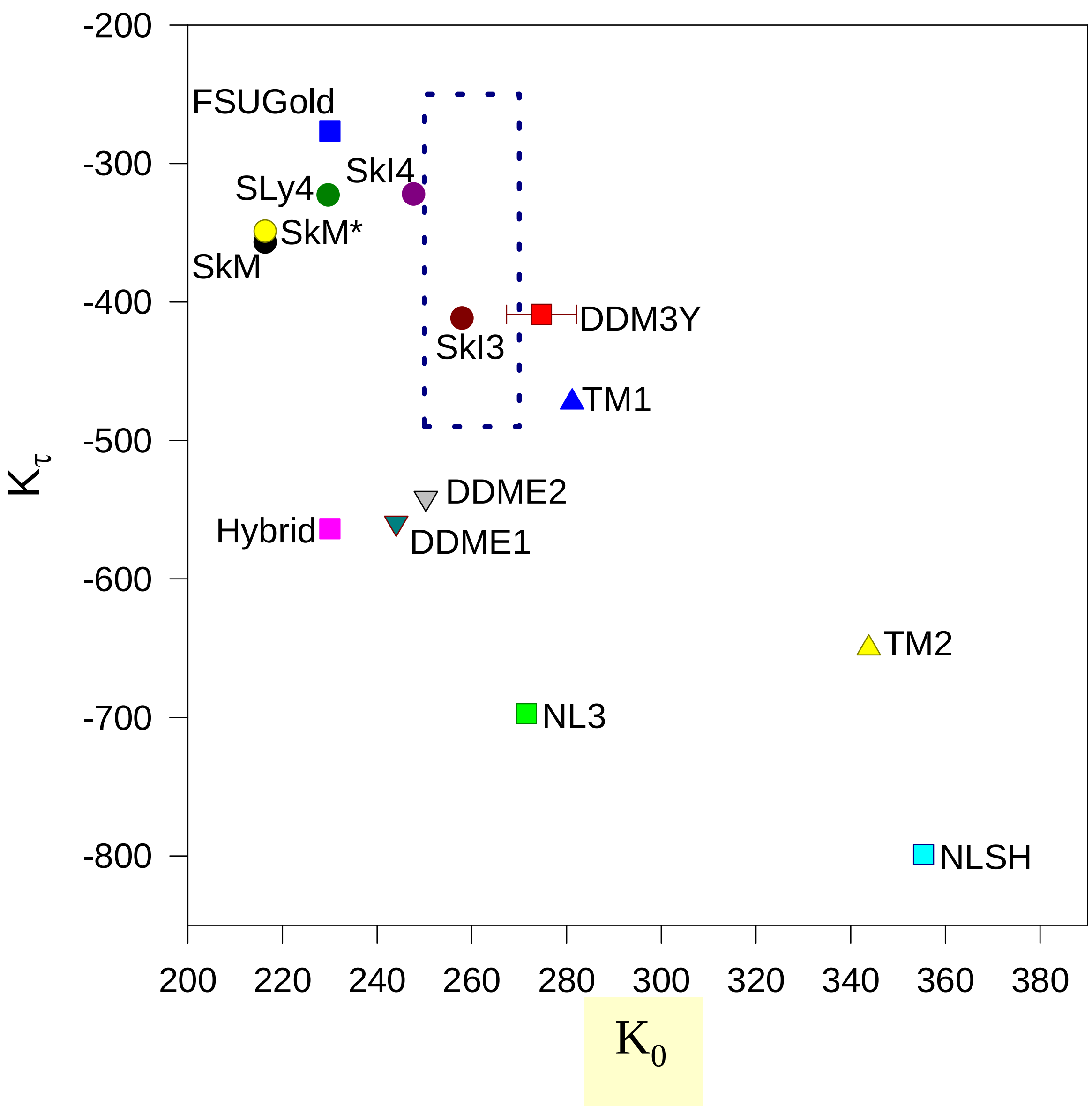


FIG. K_τ is plotted against K_0 for present calc.& compared with other predictions.

Recent accepted values of K=250-270 MeV and K_τ = -370 ±120 MeV

Although both DDM3Y & SkI3 are within the above region, unlike DDM3Y the L value for SkI3 is 100.49 MeV much above the acceptable limit of 45-75 MeV

Isoscalar and isovector components of the effective interaction

- The central part of the effective interaction between two nucleons 1 and 2 can be written as:

  $$v_{12}(s) = v_{00}(s) + v_{01}(s)\, \tau_1.\tau_2 + v_{10}(s)\, \sigma_1.\sigma_2 + v_{11}(s)\, \sigma_1.\sigma_2\, \tau_1.\tau_2$$

  where τ_1, τ_2 are the isospins, σ_1, σ_2 are the spins and s is the distance between nucleons 1, 2.

- For spin symmetric nucleons $\mathbf{v}_{10}$ and $\mathbf{v}_{11}$ do not contribute
  Z-component of Isospins (I_z) of protons and neutrons are +1 and -1.
  $\tau_n.\tau_p = \tau_p.\tau_n = -1$ and $\tau_n.\tau_n = \tau_p.\tau_p = +1$.

- For SNM only the first term, the isoscalar term, contributes.
  For IANM the first two terms the isoscalar and the isovector (Lane) terms contribute.

- The n-n and p-p interactions are $\mathbf{v}_{nn} = \mathbf{v}_{pp} = \mathbf{v}_{00} + \mathbf{v}_{01}$
  The n-p and p-n interactions are $\mathbf{v}_{np} = \mathbf{v}_{pn} = \mathbf{v}_{00} - \mathbf{v}_{01}$

Effective NN interaction potential

- The density dependent M3Y interaction potential is used for isoscalar and isovector part:

$$v_{00}(s,\rho,\varepsilon) = t_{00}^{M3Y}(s,\varepsilon)\, g(\rho,\varepsilon), \qquad v_{01}(s,\rho,\varepsilon) = t_{01}^{M3Y}(s,\varepsilon)\, g(\rho,\varepsilon)$$

- Isoscalar t_{00}^{M3Y} and isovector t_{01}^{M3Y} components of M3Y interaction supplemented by zero range potential representing the single nucleon exchange term are given as

$$t_{00}^{M3Y} = 7999\frac{\exp(-4s)}{4s} - 2134\frac{\exp(-2.5s)}{2.5s} - 276(1-\alpha\varepsilon)\delta(s)$$

$$t_{01}^{M3Y} = -4886\frac{\exp(-4s)}{4s} + 1176\frac{\exp(-2.5s)}{2.5s} + 228(1-\alpha\varepsilon)\delta(s)$$

where the energy dependence parameter $\alpha = 0.005$ MeV^{-1}.

$g(\rho, \varepsilon) = C\,[\,1-\beta(\varepsilon)\,\rho^{2/3}]$ accounts Pauli blocking effects.

Symmetric and isospin asymmetric nuclear matter calculations

For a single neutron interacting with rest of nuclear matter with isospin asymmetry X, the interaction energy per unit volume at s is:

$$\rho_n v_{nn}(s) + \rho_p v_{np}(s) = \rho_n [v_{00}(s) + v_{01}(s)] + \rho_p [v_{00}(s) - v_{01}(s)]$$

$$= [v_{00}(s) + v_{01}(s)X]\rho$$

Similarly, for the case of proton the interaction energy per unit volume

$$= [v_{00}(s) - v_{01}(s)X]\rho$$

- Asymmetric nuclear EOS can be applied to study the pure neutron matter with isospin asymmetry X=1.

- The bulk properties of neutron matter such as the nuclear incompressibility (K_o), the energy density (ξ), the pressure (P) and the velocity of sound in nuclear medium can be used to study the cold compact stellar object like neutron star.

Kinetic & Potential energy of a nucleon in symmetric nuclear matter

- K.E. /A = $[\,{}_0\int^{kF} (\hbar^2 k^2/2m)(4d^3p/h^3)\,] \,/\, [\,{}_0\int^{kF} 4d^3p/h^3\,]$
- $= (3/10)\, \hbar^2 k_F^{\,2}/2m$

- P.E. / A = $(1/2) \int {}_0\int^{kF} \{ \int {}_0\int^{kF} v(s)\, (4d^3p_2/h^3)\, d^3s\}\, (4d^3p_1/h^3)\, d^3r$

$/ \,[\, \int {}_0\int^{kF} (4d^3p_1/h^3\,) d^3r]$

$= \int {}_0\int^{kF} v(s)\, (4d^3p_2/h^3)\, d^3s$

$= (1/2) \int v(s) d^3s \;\; {}_0\int^{kF} (4d^3p/h^3)$

$= (1/2)\, \rho \int v(s) d^3s$ since $\rho = {}_0\int^{kF} (4d^3p/h^3)$

$= (1/2)\, \rho\, g(\rho,\varepsilon\,)\, J_v$ where $J_v = \int t^{M3Y}(s,\varepsilon\,) d^3s$

Contd…..

Calculations with weak energy dependence

$$\varepsilon = [3\hbar^2 k^2_F / 10m] + C\,(1-\beta\rho^n)\,\rho\, J_{v00}/2$$

$$\partial\varepsilon/\partial\rho = \hbar^2 k^2_F / 5m\rho + C\,[1-(n+1)\,\beta\rho^n]\, J_{v00}/2$$

Using: 1. $\partial\varepsilon/\partial\rho = 0$ at $\rho=\rho_0$ 2. $\varepsilon = \varepsilon_0$ at $\rho=\rho_0$

where saturation energy per nucleon = ε_0 and the saturation density = ρ_0

$$\beta = \rho_0^{-n}\,[1-p]/[(3+1)-(n+1)p]$$

where $p = 10m\varepsilon_0 / \hbar^2 k^2_{F0}$

$$C = -2\hbar^2 k^2_{F0} / [\,5m\rho_0\, J^0_{v00}\,\{1-(n+1)\,\beta\rho_0^n\}]$$

where $J^0_{v00} = J_{v00}$ at $\varepsilon = \varepsilon_0$

Calculations with kinetic energy dependence

$$\varepsilon = [3\hbar^2 k^2_F / 10m] + C\,(1-\beta\rho^n)\,\rho\, J_{v00}/2$$

$$\partial\varepsilon/\partial\rho = \hbar^2 k^2_F / 5m\rho + C\,[1-(n+1)\,\beta\rho^n]\, J_{v00}/2$$
$$-\alpha J_{00} C\,(1-\beta\rho^n)[\hbar^2 k^2_F / 10m]$$

where α=0.005/MeV and J_{00} =-276MeV

Using: 1. $\partial\varepsilon/\partial\rho = 0$ at $\rho=\rho_0$ 2. $\varepsilon = \varepsilon_0$ at $\rho=\rho_0$

where saturation energy per nucleon = ε_0

and the saturation density = ρ_0

$$\beta = \rho_0^{-n}[(1-p)+\{q-(3q/p)\}] / [(3+1)-(n+1)p+\{q-(3q/p)]$$

where $p = 10m\varepsilon_0 / \hbar^2 k^2_{F0}$ and $q = 2\alpha\varepsilon_0 J_{00} / J^0_{v00}$

$$C = -2\hbar^2 k^2_{F0} / 5m\rho_0 J^0_{v00}[1-(n+1)\,\beta\rho_0^n-\{q\hbar^2 k^2_{F0}\,(1-\beta\rho_0^n)/10m\varepsilon_0\}]$$

where $J^0_{v00} = J_{v00}$ at $\varepsilon^{kin} = \varepsilon^{kin}_0$

SNM Energy density, Pressure and Velocity of Sound

Energy density ξ : $\xi = (\varepsilon + mc^2)\,\rho$

Pressure P : $P = \rho^2\, \partial \varepsilon / \partial \rho$

Velocity of Sound v_s : $v_s/c = [\partial P/ \partial \xi]^{1/2}$

Incomressibility K_0 : $K_0 = k_F^2\, \partial^2 \varepsilon / \partial k_F^2 |_{\rho=\rho_0}$

since $k_F^3 = 1.5\pi^2\rho$: $K_0 = 9\, \rho^2\, \partial^2 \varepsilon / \partial \rho^2 |_{\rho=\rho_0}$

Nuclear collisions can compress nuclear matter to densities achieved within neutron stars and within core-collapse supernovae. These dense states of matter exist momentarily before expanding. We analyzed the flow of matter to extract pressures in excess of 10**34 pascals, the highest recorded under laboratory-controlled conditions. These densities and pressures are achieved by inertial confinement; the incoming matter from both projectile and target is mixed and compressed in the high-density region where the two nuclei overlap. Participant nucleons from the projectile and target, which follow small impact parameter trajectories, contribute to this mixture by smashing into the compressed region, compressing it further. The observables sensitive to the EOS are chiefly related to the flow of particles from the high-density region in directions perpendicular (transverse) to the beam axis. This flow is initially zero but grows with time as the density grows and pressure gradients develop in directions transverse to the beam axis. The pressure can be calculated in the equilibrium limit by taking the partial derivative of the energy density e with respect to the baryon (primarily nucleon) density. The pressure developed in the simulated collisions is computed microscopically from the pressure-stress tensor Tij, which is the nonequilibrium analog of the pressure. Different theoretical formulations concerning the energy density would lead to different pressures (that is, to different EOSs for nuclear matter) in the equilibrium limit, in these simulations, and in the actual collisions. Analyses of EOS-dependent observables: The comparison of in-plane to out-of plane emission rates provides an EOS-dependent experimental observable commonly referred to as elliptic flow. The sideways deflection of spectator nucleons within the reaction plane, due to the pressure of the compressed region, provides another observable. This sideways deflection or transverse flow of the spectator fragments occurs primarily while the spectator fragments are adjacent to the compressed region. Experimentally, one distinguishes spectator matter from the projectile and the target by measuring its rapidity y, a quantity that in the nonrelativistic limit reduces to the velocity component vz along the beam axis. We have analyzed the flow of matter in nuclear collisions to determine the pressures attained at densities ranging from two to five times the saturation density of nuclear matter. We obtained constraints on the EOS of symmetric nuclear matter that rule out very repulsive EOSs from relativistic mean field theory and very soft EOSs with a strong phase transition, but not a softening of the EOS due to a transformation to quark matter at higher densities. Investigations of the asymmetry term of the EOS are important to complement our constraints on the symmetric nuclear matter EOS. Both measurements relevant to the asymmetry term and improved constraints on the EOS for symmetric matter appear feasible; they can provide the experimental basis for constraining the properties of dense neutron-rich matter and dense astrophysical objects such as neutron stars.

References:

- G.R. Satchler and W.G. Love, Phys. Reports 55 (1979) 183 and references therein.
- A.M. Kobos, B.A. Brown, R. Lindsay and G.R. Satchler, Nucl. Phys. A 425 (1984) 205.
- C. Samanta, Y. Sakuragi, M. Ito and M. Fujiwara, Jour. Phys. G 23 (1997) 1697.
- D.N. Basu, Int. Jour. Mod. Phys. E 14 (2005) 739.
- P. Roy Chowdhury and C. Samanta, Acta Phys. Pol. B 37 (2006) 1833.
- D.N. Basu, P. Roy Chowdhury and C. Samanta, Acta Phys. Pol. B 37 (2006) 2869.

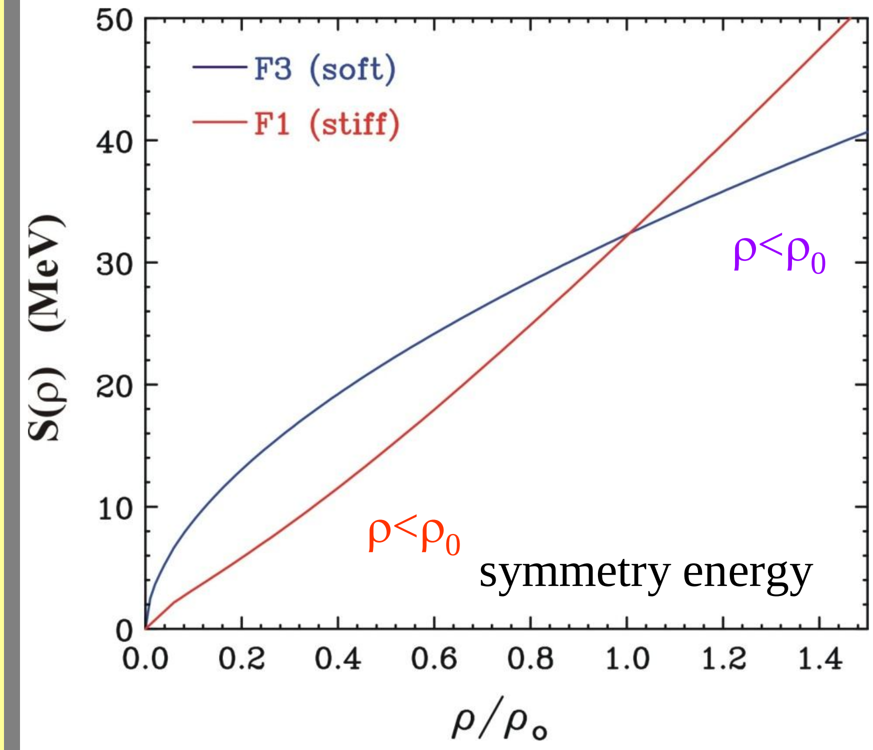
If we use the alternative definition of $E_{sym}(\rho)=1/2[\partial^2\varepsilon(\rho,X)/\partial X^2]_{X=0}$ the expression for $E_{sym}(\rho)$ remains almost same.
[Ref: R.B. Wiringa et al., PRC38, 1010(1988)]

The present calculation gives $E_{sym}(\rho_0)=30.71\pm 0.26$ MeV. This is in reasonable agreement with the presently accepted value of $E_{sym}(\rho_0)$ $\approx$30 MeV.
[DNB, PRC, CS, Nucl. Phys. A811, 140 (2008)]

Probes of the symmetry energy

$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$; $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

- To maximize sensitivity, reduce systematic errors:
  - Vary isospin of detected particle
  - Vary isospin asymmetry $\delta=(N-Z)/A$ of reaction.
- Low densities ($\rho<\rho_0$):
  - Neutron/proton spectra and flows
  - Isospin diffusion
- High densities ($\rho\approx 2\rho_0$) :
  - Neutron/proton spectra and flows
  - π^+ vs. π^- production



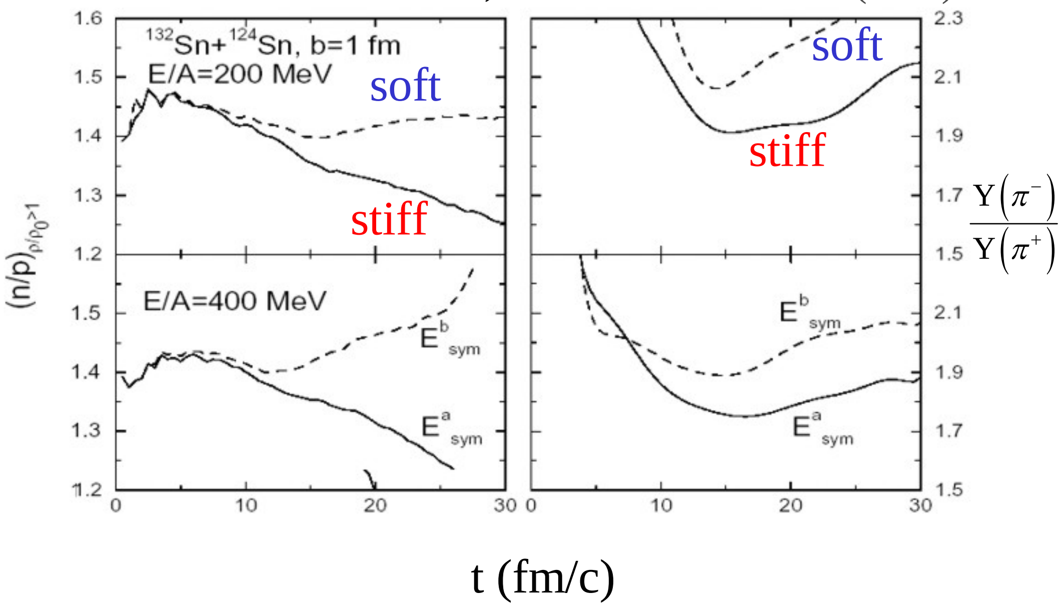
Why choose to measure Isospin Diffusion, n/p flows and pion production?

- Supra-saturation and sub-saturation densities are only achieved ***momentarily***
- Theoretical description must follow the reaction dynamics self-consistently from contact to detection.
- Theoretical tool: transport theory:
  - The most accurately predicted observables are those that can be calculated from $f(\vec{r}, \vec{p}, t)$ i.e. flows and other average properties of the events that are not sensitive to fluctuations.
- Isospin diffusion and n/p ratios:
  - Depends on quantities that can be more accurately calculated in BUU or QMD transport theory.
  - May be less sensitive to uncertainties in (1) the production mechanism for complex fragments and (2) secondary decay.

High density probe: pion production

- Larger values for ρ_n/ρ_p at high density for the soft asymmetry term (x=0) causes stronger emission of negative pions for the soft asymmetry term (x=0) than for the stiff one (x=-1).
- π^- / π^+ means $Y(\pi^-)/Y(\pi^+)$
  - In delta resonance model, $Y(\pi^-)/Y(\pi^+) \approx (\rho_n/\rho_p)^2$
  - In equilibrium, $\mu(\pi^+)-\mu(\pi^-)=2(\mu_p-\mu_n)$
- The density dependence of the asymmetry term changes ratio by about 10% for neutron rich system.

Li et al., arXiv:nucl-th/0312026 (2003).



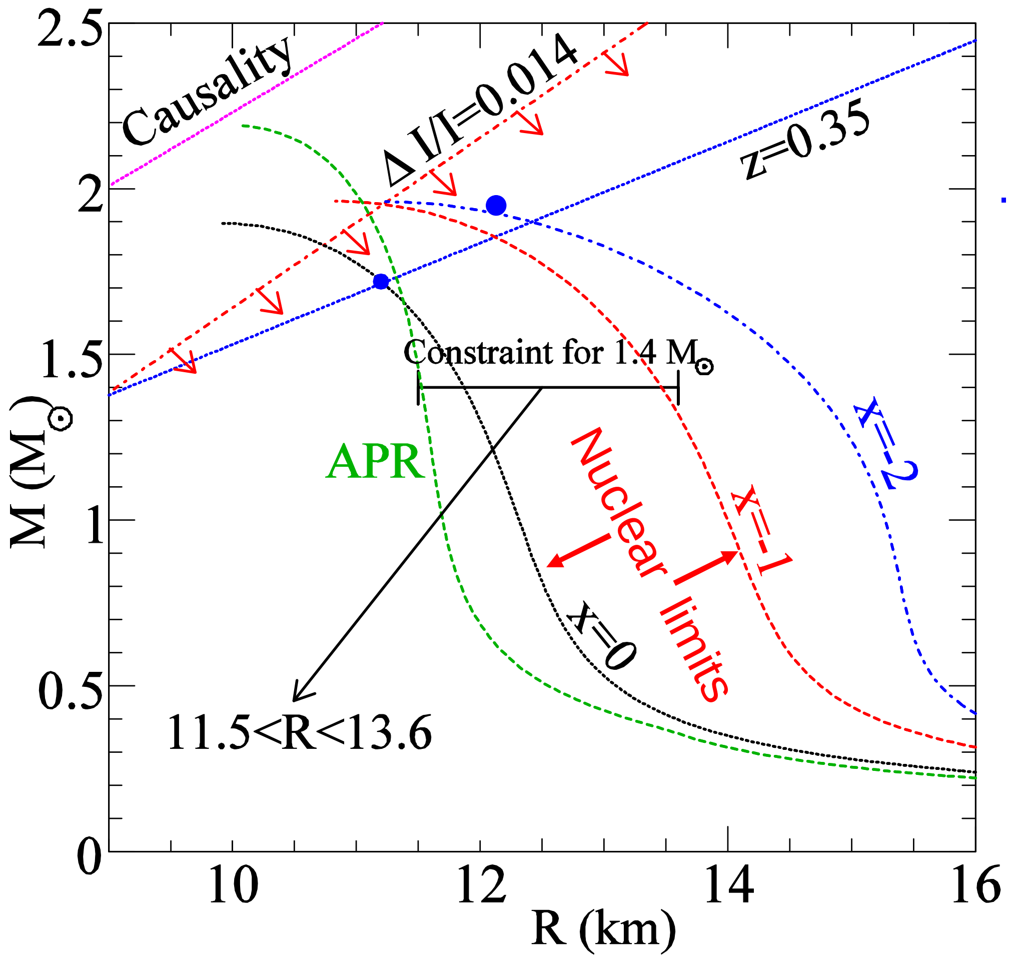
- This can be explored with stable or rare isotope beams at the MSU/FRIB and RIKEN/RIBF.
  - Sensitivity to $S(\rho)$ occurs primarily near threshold in A+A

Summary and Outlook

- Heavy ion collisions provide unique possibilities to probe the EOS of dense asymmetric matter.
- A number of promising observables to probe the density dependence of the symmetry energy in HI collisions have been identified.
  - Isospin diffusion, isotope ratios, and n/p spectral ratios provide some constraints at $\rho \leq \rho_{0,}$.
  - π^+ vs. π^- production, neutron/proton spectra and flows may provide constraints at $\rho \approx 2\rho_0$ and above.
- The availability of fast stable and rare isotope beams at a variety of energies will allow constraints on the symmetry energy at a range of densities.
  - Experimental programs are being developed to do such measurements at MSU/FRIB, RIKEN/RIBF and GSI/FAIR

Constraining the radii of NON-ROTATING neutron stars

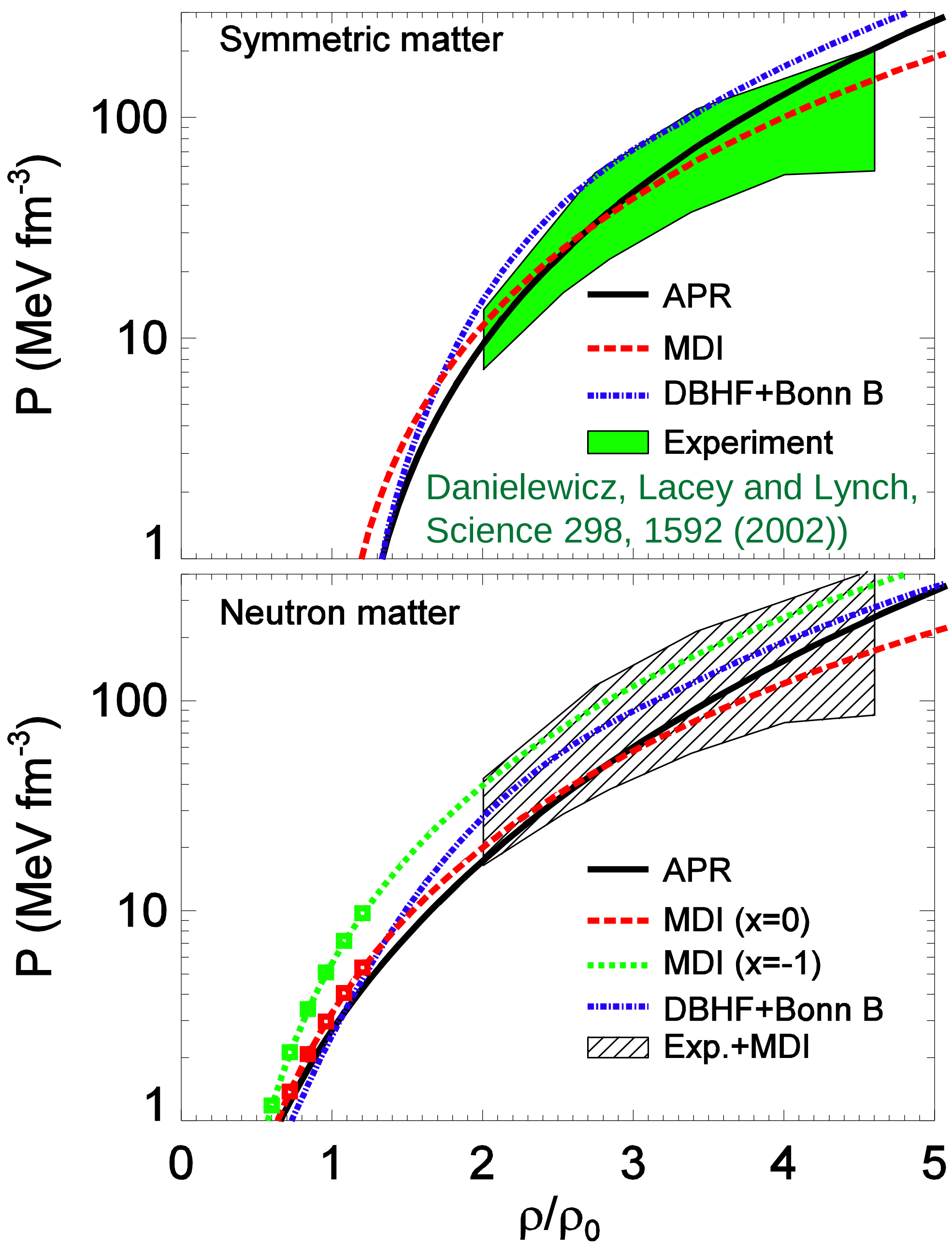
Bao-An Li and Andrew W. Steiner, Phys. Lett. B642, 436 (2006)



APR: K_0=269 MeV.

The same incompressibility for symmetric nuclear matter of K_0=211 MeV for x=0, -1, and -2

Partially constrained EOS for astrophysical studies



What if a Violation of the $1/r^2$ Law Were Observed?

Extra dimension at short length or a new Boson?

$$F(r) = G\frac{m_1 m_2}{r^{2+\epsilon}}.$$

String theorists have published TONS of papers on the extra dimension

Arkani-Hamed, N., Dimopoulos, S. & Dvali, G. Phys Lett. B 429, 263–272 (1998).

J.C. Long et al., Nature **421**, 922-925 (2003); *C.D. Hoyle, Nature* **421,** 899–900 (2003)

In terms of the gravitational potential

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}].$$

Repulsive Yukawa potential due to the exchange of a new boson proposed in the super-symmetric extension of the Standard Model of the Grand Unification Theory, or the fifth force

Yasunori Fijii, Nature 234, 5-7 (1971); G.W. Gibbons and B.F. Whiting, Nature **291**, 636 - 638 (1981)

The neutral spin-1 gauge boson U is a candidate, it can mediate the interaction among dark matter particles, e.g., Pierre Fayet, PLB675, 267 (2009), C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, PRL, 92, 101301 (2004).

Some thoughts and observations

Bao-An Li et al. Phys. Rep. **464**, 113 2008, arXiv:0908.1922 [nucl-th]

- The high-density behavior of the nuclear symmetry energy relies on the short-range correlations and the in-medium properties of the short-range tensor force in the n-p singlet channel.

- The FOPI/GSI pion data indicates a super-soft symmetry energy at high densities

- NS can be stable even with a super-soft symmetry energy if one considers the possibilities of extra-dimensions, new bosons and/or a 5th force as proposed in string theories and super-symmetric extensions of the Standard Model

- It may not be that crazy to think about a super-soft and/or even negative symmetry energy at supra-saturation densities.

Why is the symmetry energy so uncertain especially at high densities?

Based on the Fermi gas model (Ch. 6) and properties of nuclear matter (Ch. 8) of the textbook: *Structure of the nucleus by M.A. Preston and R.K. Bhaduri*

$$\begin{aligned} E_{sym} &= E_{sym}^{kin} + E_{sym}^{pot1} + E_{sym}^{pot2} \\ &= \frac{1}{3}t(k_F) + \frac{1}{6}\frac{\partial U_0(k)}{\partial k}\Big|_{k_F} k_F + \frac{1}{\pi^2}\int_0^{2^{\frac{1}{3}}k_F} U_{sym}(k)k^2 dk \end{aligned}$$

Kinetic Isoscalar Isovector

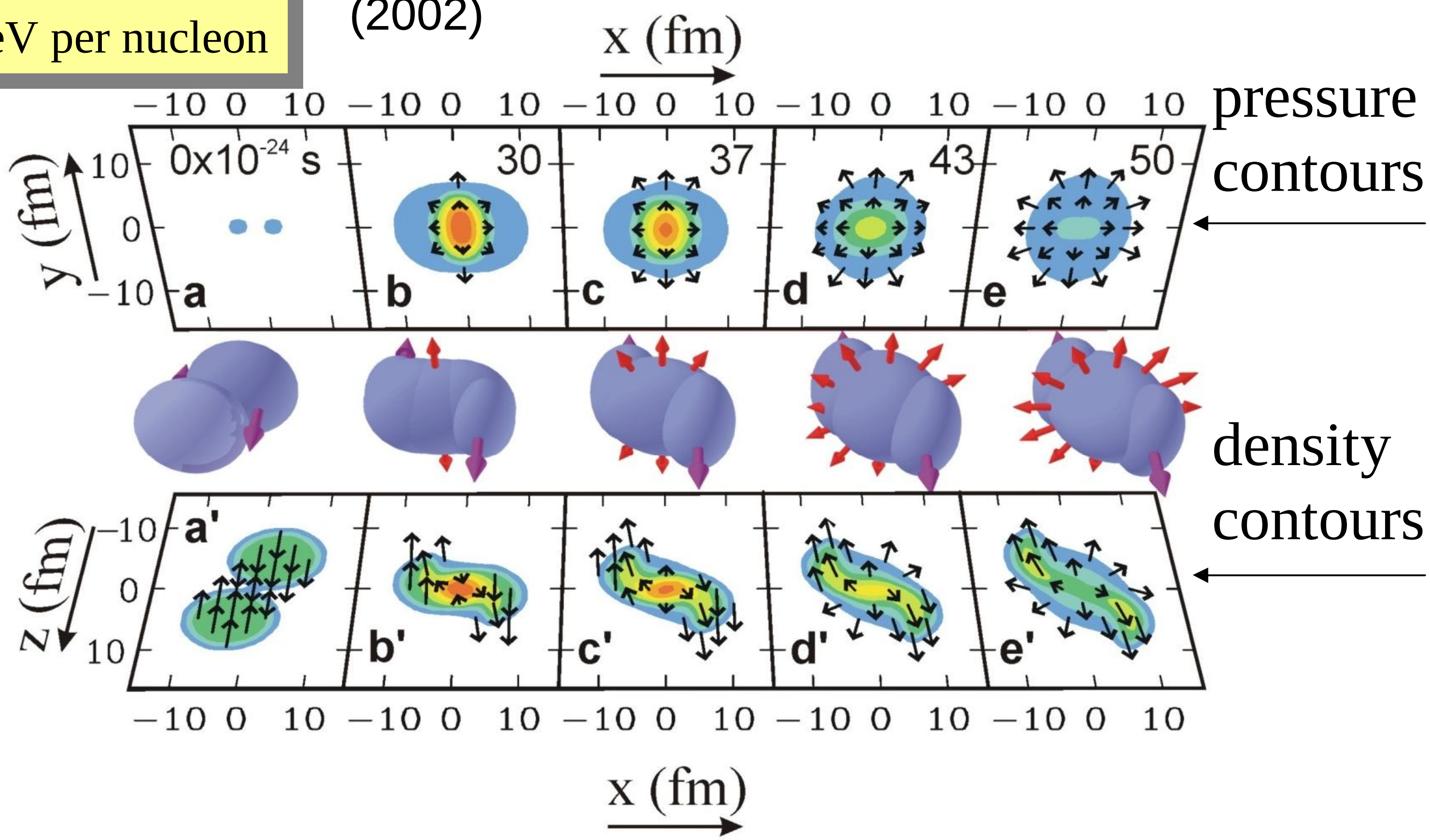
$$\begin{aligned} U_0 &= \frac{1}{2}(U_n + U_p) \quad \text{(Isoscalar single particle potential)} \\ U_{sym} &= \frac{1}{2\delta}(U_n - U_p) \quad \text{(Isovector or Lane potential)} \end{aligned}$$

Constraining the EOS at high densities by nuclear collisions

$^{197}Au+^{197}Au$ collisions

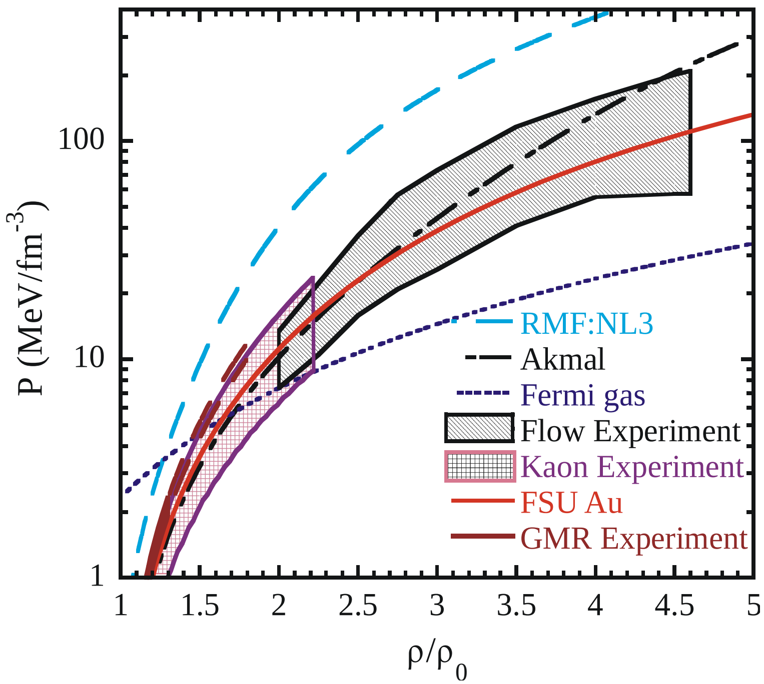
E/A = 2 GeV per nucleon

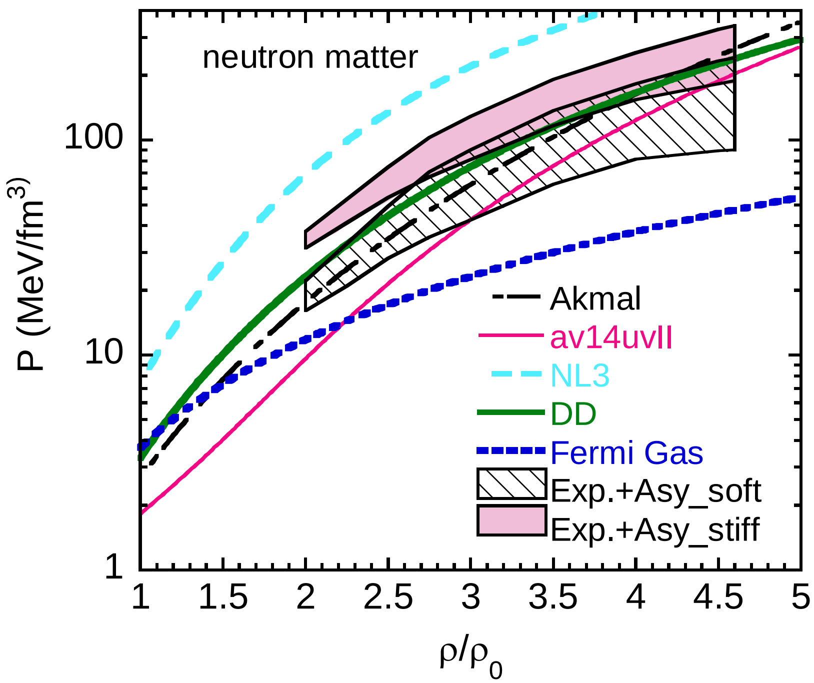
Ref: Danielewicz, Lacey, Lynch, Science **298**, 1592 (2002)



- Two observable consequences of the high pressures that are formed:
  - Nucleons deflected sideways in the reaction plane.
  - Nucleons are "squeezed out" above and below the reaction plane. .

Constraints from collective flow on EOS at $\rho > 2\,\rho_0$.





Ref: Danielewicz, Lacey, Lynch, Science **298**, 1592 (2002)

$E/A\,(\rho, X) = E/A\,(\rho,0) + X^2 \cdot E_{sym}(\rho)$

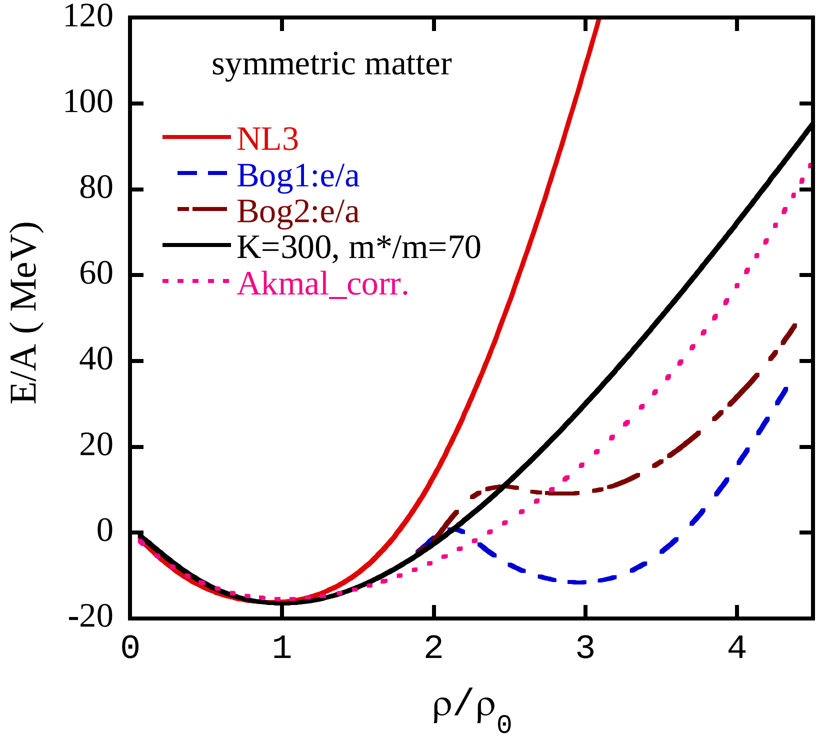
$X = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$ for PNM

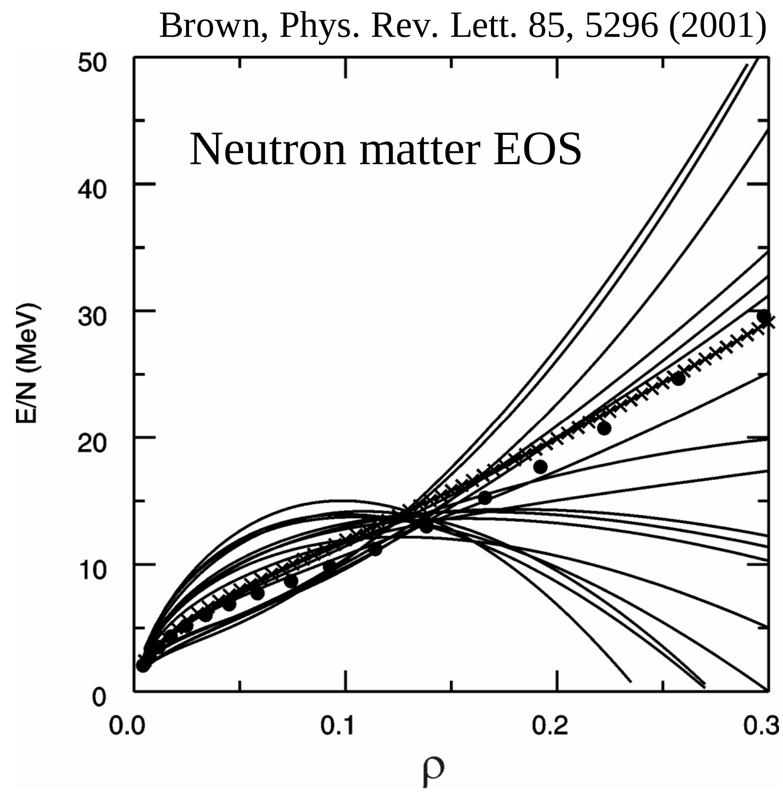
- Flow confirms the softening of the EOS at high density.
- **NSE dominates the uncertainty (e.g. Pressure) in PNM-EOS.**

Probing the symmetry energy at high densities

- **Why is the symmetry energy so uncertain at supra-saturation densities? Can the symmetry energy become super-soft or even negative at high densities?**
- **Indications of a super-soft symmetry energy at supra-saturation densities from transport model analyses of the FOPI/GSI experimental data on pion production**
- **Can neutron stars be stable with a super-soft or negative symmetry energy at supra-saturation densities?**
- Ref: Bao An Li et al., Physics Report 464, 113 (2008), arXiv:0908.1922v1 [nucl-th] 13 Aug 2009

EOS: symmetric matter and neutron matter (Review)





$E/A\,(\rho,\delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$

$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$

$$P = \rho^2 \left.\frac{\partial (E/A)}{\partial \rho}\right|_{s/a}$$

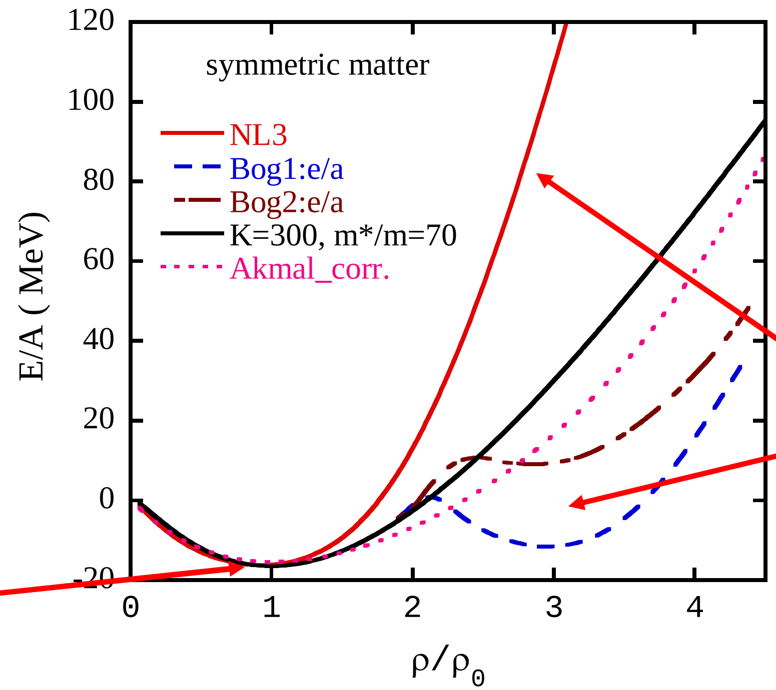
- The density dependence of symmetry energy is largely unconstrained.
- What is “stiff” or “soft” is density dependent

Need for probes sensitive to higher densities: Experimental Status

Constraining the EoS and Symmetry Energy from HI collisions

William Lynch, Yingxun Zhang, Dan Coupland, Pawel Danielewicz,
Micheal Famiano, Zhuxia Li, Betty Tsang
NSCL, Michigan State Univ., USA; GSI, Darmstadt, Germany

- If the EoS is expanded in a Taylor series about ρ_0, the incompressibility, K_{nm} provides the term proportional to $(\rho-\rho_0)^2$. Higher order terms influence the EoS at sub-saturation and supra-saturation densities.



- The curvature K_{nm} of the EOS about ρ_0 can be probed by collective monopole vibrations, i.e. Giant Monopole Resonance.

The solid black, dashed brown & dashed blue EoS's all have K_{nm}=300 MeV.

- To probe the EoS at $3\rho_0$, you need to compress matter to $3\rho_0$.

Experimental Input to EoS and NSE: Summary

- Heavy ion collisions provide unique possibilities to probe the EOS of dense asymmetric matter.
- The availability of fast stable and rare isotope beams at a variety of energies will allow constraints on the symmetry energy at a range of densities.
- Experimental programs are being developed to do such measurements at MSU/FRIB, RIKEN/RIBF and GSI/FAIR

Theoretically, at a given average baryon density, one has to impose

a) Charge neutrality,

b) Beta-equilibrium

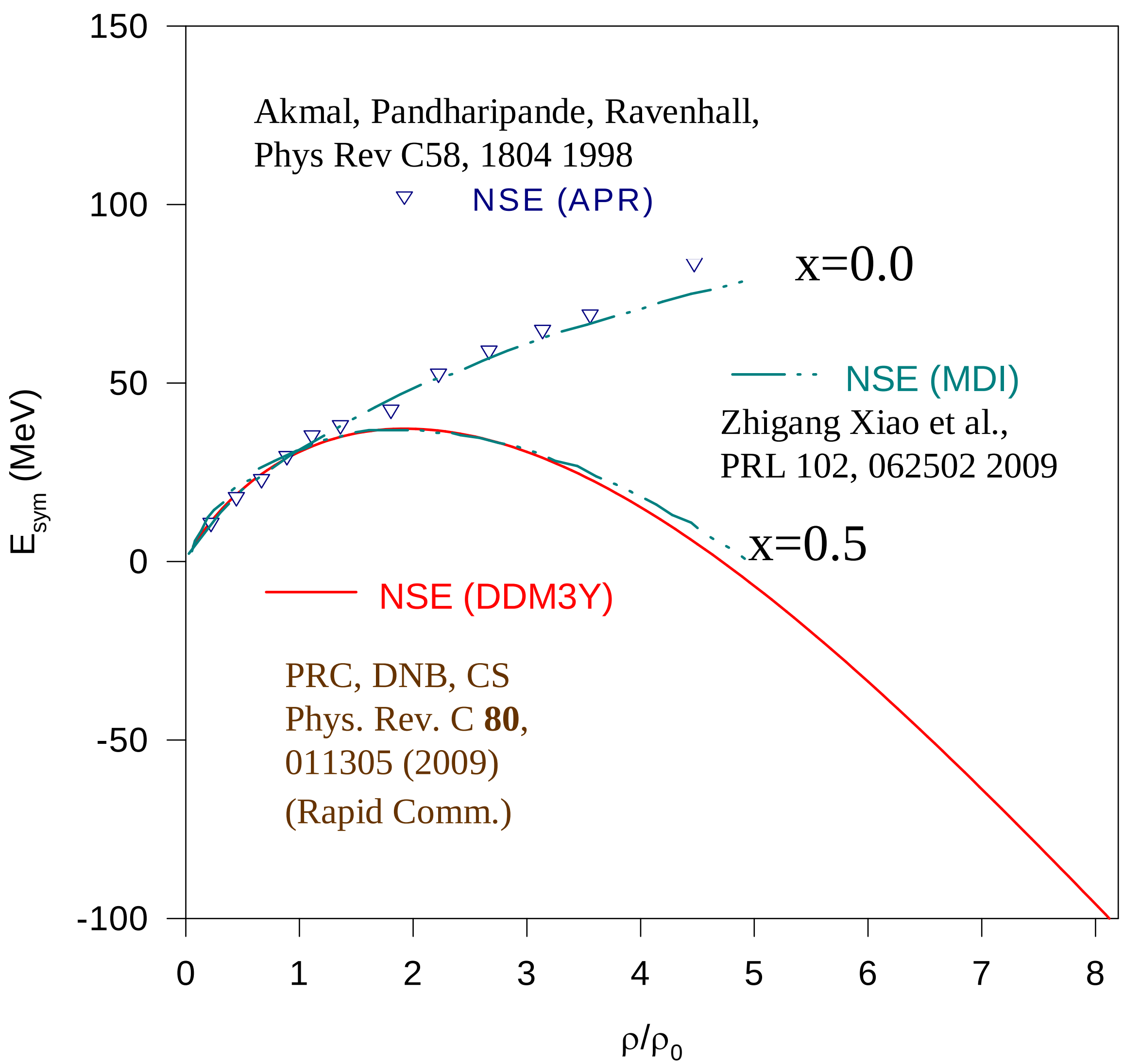
and then mimimize the energy. This fixes A, Z and cell size. At higher density nuclei start to drip. Highly exotic nuclei are then present in the NS crust**.**

There has been a lot of work on trying to correlate the finite nuclei properties (e.g. neutron skin) and Neutron Star structure.

A possibility is to consider a large set of possible EoS and to see numerically if correlations are present among different quantities, like skin thickness vs. pressure or onset of the Urca process.

(see. e.g. Steiner et al., Phys. Rep. 2005).

The present calculation of NSE using DDM3Y interaction (E_{sym}) is compared with those by Akmal-Pandharipande-Ravenhall (APR) and MDI interaction for the variable x=0.0, 0.5 defined in Ref. PRL 102, 062502 (2009)



NSE (APR) and NSE (MDI) with x=0.0 predict stiff NSE.

NSE (MDI) with x=0.5 and Our calc. NSE (DDM3Y) predict soft dependence of NSE on density.

NSE of our calc. becomes supersoft at very high density

Isospin diffusion in peripheral collisions, also probes symmetry energy at $\rho<\rho_0$.

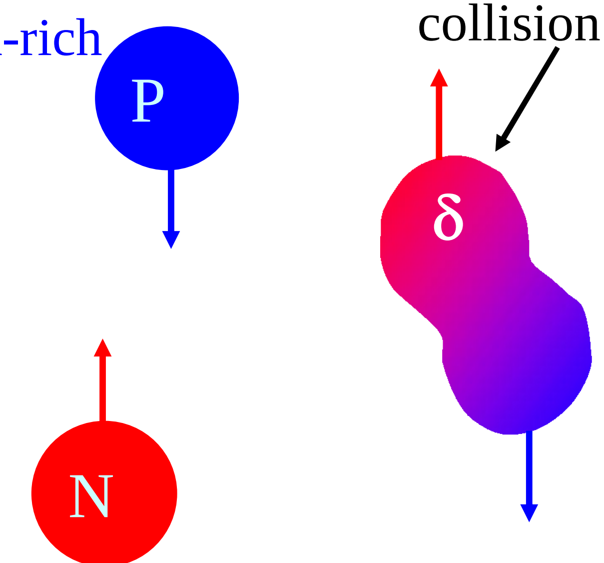
- Collide projectiles and targets of differing isospin asymmetry
- Probe the asymmetry $\delta=(N-Z)/(N+Z)$ of the projectile spectator during the collision.
- The use of the isospin transport ratio $R_i(\delta)$ isolates the diffusion effects:

$$R_i(\delta) = 2 \cdot \frac{\delta - (\delta_{both\_neut.-rich} + \delta_{both\_prot.-rich})/2}{\delta_{both\_neut.-rich} - \delta_{both\_prot.-rich}}$$

- Useful limits for R_i for $^{124}Sn+^{112}Sn$ collisions:
  - $R_i = \pm 1$: no diffusion
  - $R_i \approx 0$: Isospin equilibrium

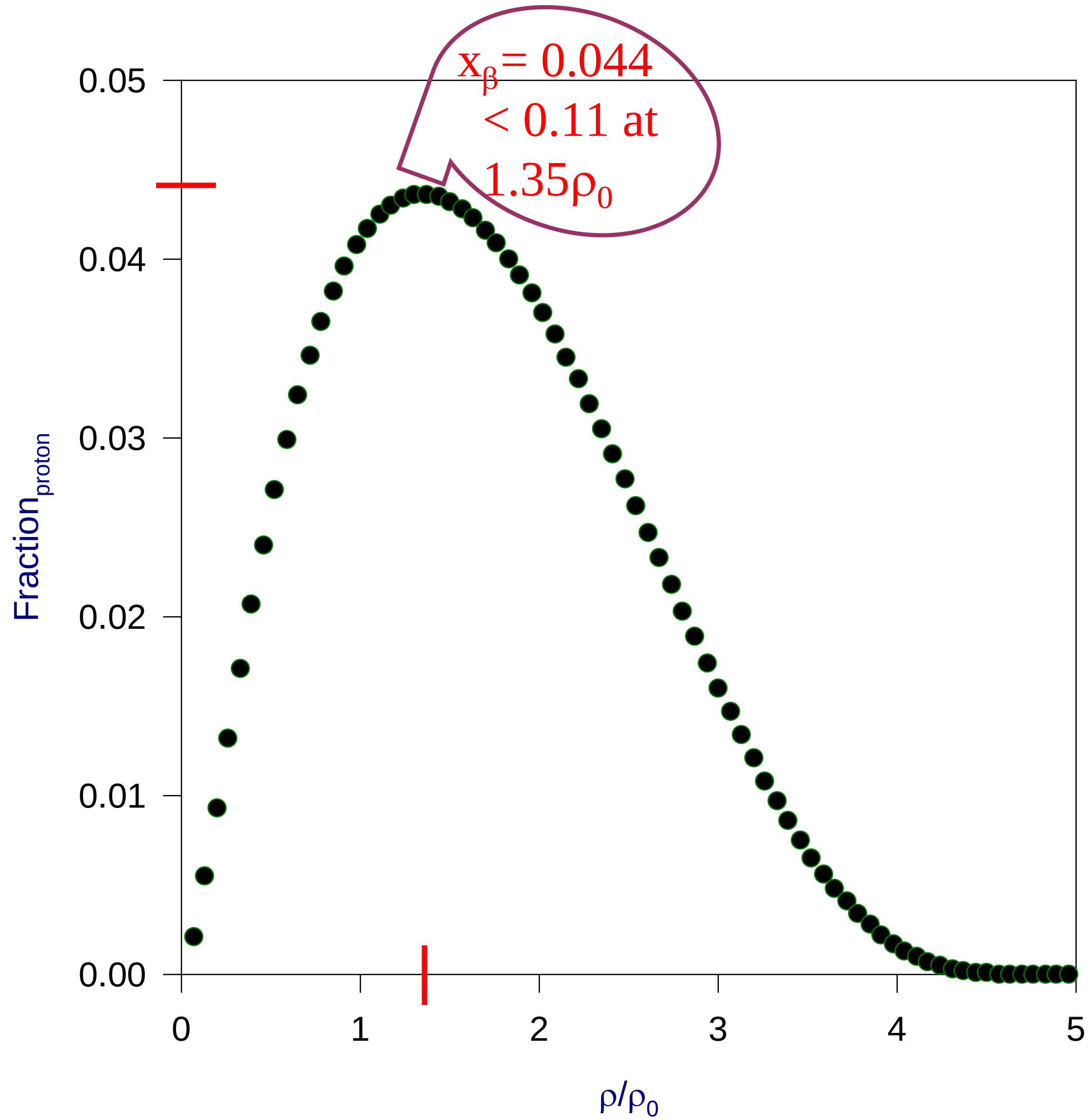
Systems:
- mixed $^{124}Sn+^{112}Sn$
- n-rich $^{124}Sn+^{124}Sn$
- p-rich $^{112}Sn+^{112}Sn$

Example:



The present calculation of x_β using NSE, forbids the direct URCA process inside neutron star core as x_β < 1/9.

FIG.
The beta equilibrium proton fraction calculated with NSE obtained from present work is plotted as a function of ρ/ρ_0.



Our calc. does not support rapid cooling of NS via neutrino emission during direct URCA

Results and Discussions :

According to the present calculation, the incompressibility (K_0) of symmetric nuclear matter is 274.7 MeV using values of ρ_o= 0.1533 fm^{-3}, β=1.5934 fm^{-2}, C=2.2497, ε = -15.26 MeV.

Incompressibility of asymmetric nuclear matter in saturation condition changes (decreases) with the value of asymmetry parameter X .

X	ρ_s (fm^{-3})	K_0 (MeV)
0.0	0.1533	274.7
0.1	0.1525	270.4
0.2	0.1500	257.7
0.3	0.1457	236.6
0.4	0.1392	207.6
0.5	0.1300	171.2

Isospin Asymmetric Nuclear Matter (IANM)

The isospin asymmetry parameter $X=(\rho_n-\rho_p)/(\rho_n+\rho_p)$ with density $\rho=\rho_n+\rho_p$.

Symmetric Nuclear Matter SNM, X=0

↓

Towards asymmetry: Change X from 0

Range of X: $-1 \leq X \leq 1$

For X positive fraction

↓

Isospin Asymmetric Nuclear Matter, $X\neq0$,

contains different no. of n and p ($\rho_n\neq\rho_p$).

↓

Pure Neutron Matter (PNM): X= +1, $\rho_p=0$

Useful to study the bulk properties of the Neutron Star (NS)