Unified Modeling of Intermediate Energy Heavy-ion Reaction and Supernova Matter

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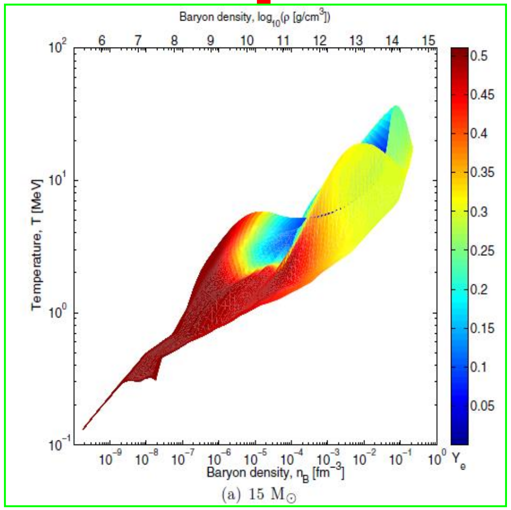
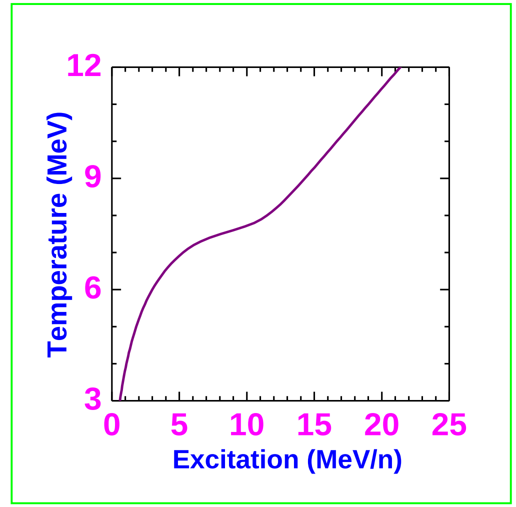
Plan of the Talk:-

- Introduction
- Nuclear Statistical Equilibrium Model of Supernova Matter
- Excitation Correction
- Results
- Summary

Connection between Intermediate energy Heavy Ion Reaction and Supernova:-





Ref: Fischer et. al., AJPS. 194, 39 (2011)

Ref: S. Mallik et. al., PRC. 91, 034616 (2015)

Similarities:-

	Supernova	Heavy ion reaction
Temperature	~ 1-10 MeV	~ 2-10 MeV
Density	~ $10^{-4}\rho_0$ -$0.3\rho_0$	~ $0.2\rho_0$ -$0.4\rho_0$
Proton Fraction	0.1-0.4	0.4-0.6

Differences :-

Size	~ 100 km	~ fm
Time	~ ms-s	~ 100 fm/c
Charge	Neutral	Positive

Nuclear Statistical Equilibrium (NSE) model of supernova matter & HI collisions:-

Basic Assumption:- **Statistical equilibrium** of different clusters and free nucleon gas at given **Temperature (T)**, **Baryonic density (ρ_B)** and **Proton fraction (y_p)**.

❖ Abundances are obtained from phase space calculation (using grand-canonical ensemble method).

$$\rho_{Z,N} \propto e^{\beta\mu_N N + \beta\mu_Z Z}\, \omega_{Z,N}$$

Ref: C. B. Das , S. Das Gupta et al. , Phys. Rep. 406 (2005) 1
S. Mallik and G. Chaudhuri, Phys. Lett. B 727 (2013) 282

- Inclusion of electron screening (SN only).
- Inclusion of mean field of free nucleon gas.

  (calculated by meta-modeling technique of the EoS)
- Replacement of cluster functional from simple liquid drop model to realistic meta-modeling EoS (SLY5 parameters).
- Inclusion of exact excitation correction.
- Consideration of nuclei beyond drip line

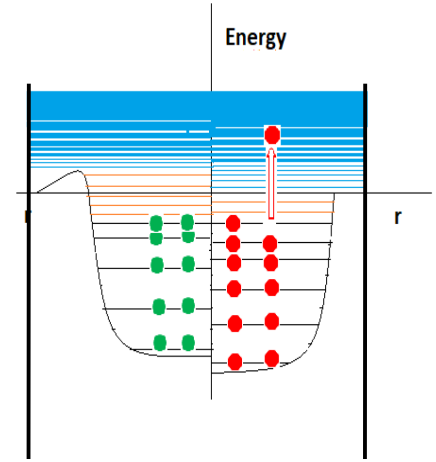
Excitation Correction in NSE model:-

Nucleon in the continuum

- Part of highly excited cluster
- Free particle

Double counting

$$g(T) \approx \int_0^\infty \rho'(A,E)e^{-E/T}dE$$



Existing Methods of Solution

- Upper cut at separation energy
- Upper cut at binding energy
- Limiting internal temperature

Difficult to justify theoretically

Isolated nuclear contribution after gas subtraction

$$\ln Z_{cluster}^{\mu_n,\mu_z,T} = \ln Z_{cluster+gas}^{\mu_n,\mu_z,T} - \ln Z_{gas}^{\mu_n,\mu_z,T}$$

Ref: D. L. Tubbs and S. E. Koonin, APJ 232 ,L59 (1979)

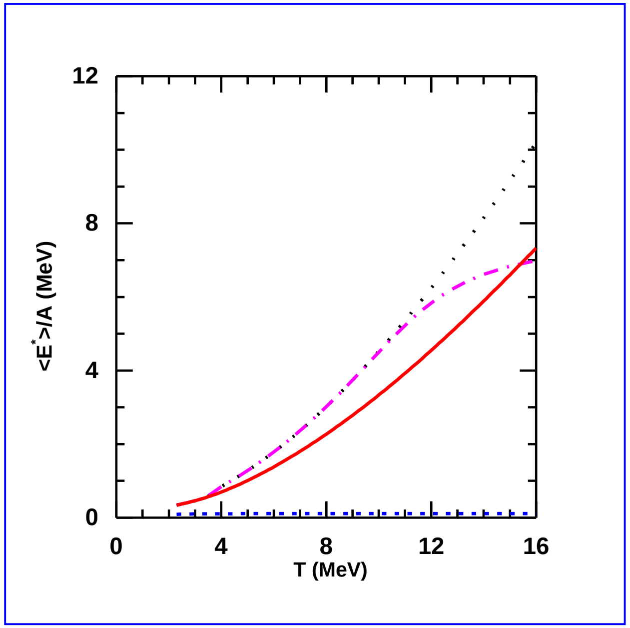
P. Bonche, S. Levit and D. Vautherin, Nucl. Phys. A 427, 278 (1984)

Average Excitation per nucleon:-

Studied Nucleus: ^{56}Ni

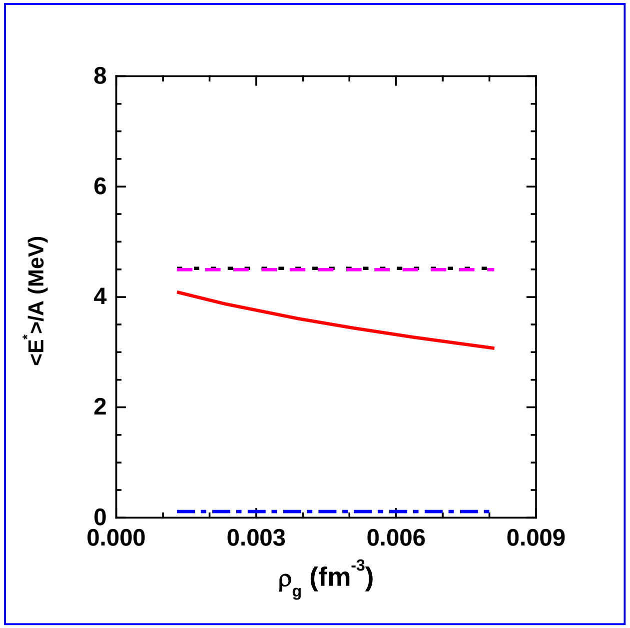
Temperature Dependence

$\rho_B = 0.3\ \rho_0$



Free Nucleon Density Dependence

T=10 MeV



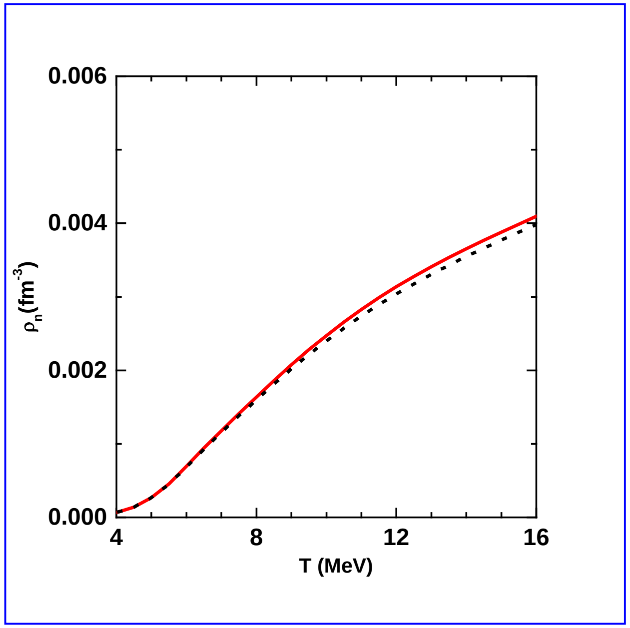
Black dotted line → E_{upper}=Infinity
Blue dash dotted line → $E_{upper}=S_n$
Magenta dashed line → E_{upper}=B
Red solid line → Calculation from proposed method

Effect of excitation correction in NSE model:-

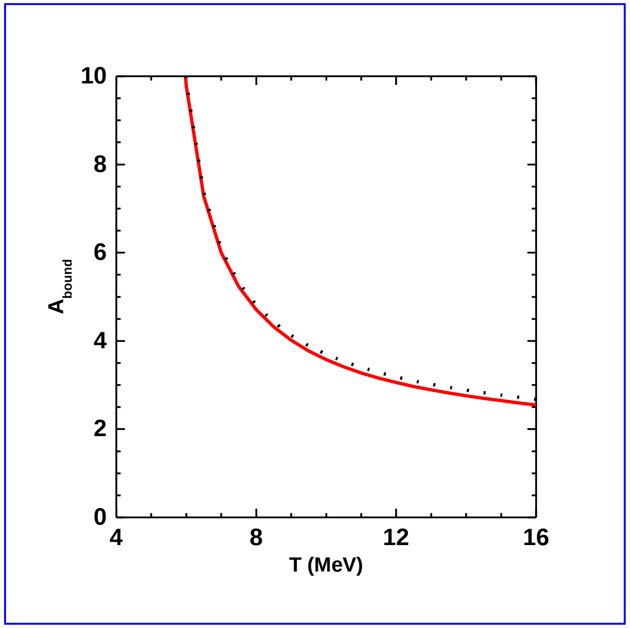
1. Neutron gas density:-

$$A_{bound} = \frac{\sum_{A>1} A\rho(A,Z)}{\sum_{all A} \rho(A,Z)}$$

y_p=0.5 ρ_B= 0.3 ρ_0



2. Bound Mass:-



Black dotted line → Without excitation correction
Red solid line → With excitation correction

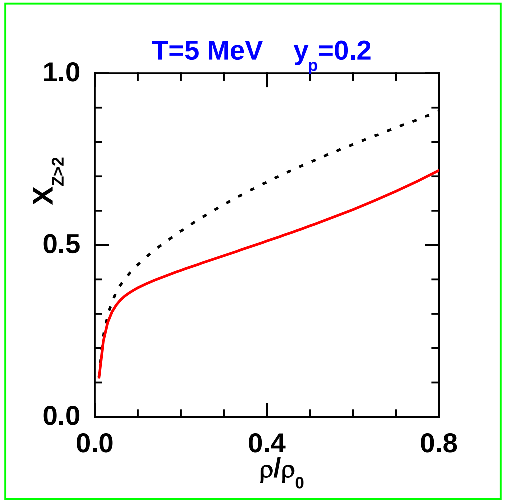
➢ Heavy cluster production is less, effect of excitation correction is not very significant for observables like A_{bound} and ρ_n.

Effect of excitation correction in NSE model:-

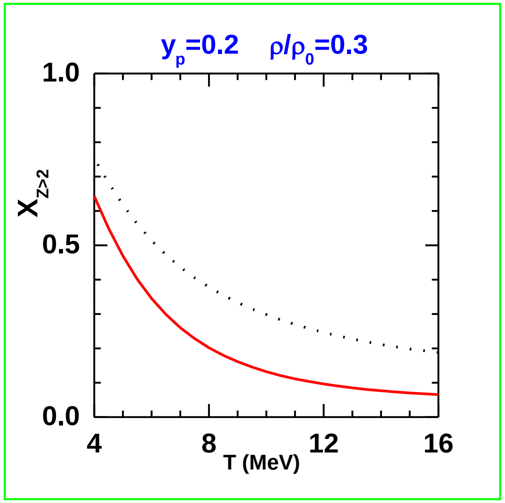
Studied Observable: Charge fraction with Z>2

$$X_{Z>2} = \frac{\sum_{Z>2} Z\rho(A,Z)}{\sum_{Z\geq 0} Z\rho(A,Z)}$$

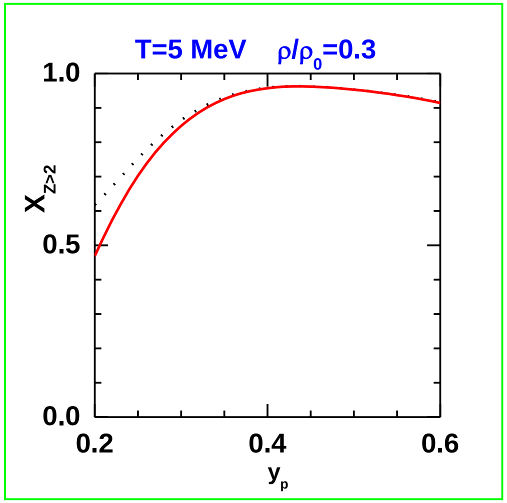
1. Baryonic density dependence:-



2. Temperature dependence:-



3. Proton fraction dependence:-



Black dotted line → Without excitation correction
Red solid line → With excitation correction

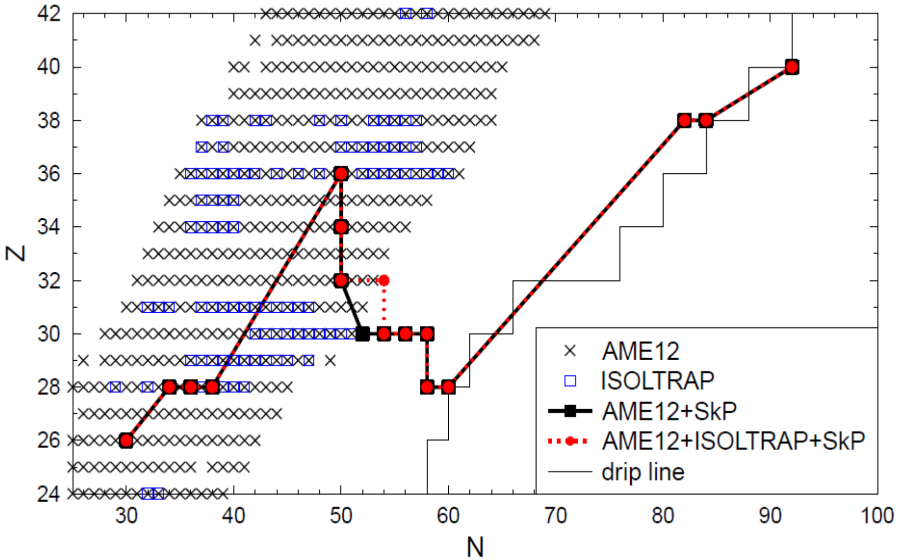
Observable sensitive to excitation correction

Effect of Nuclear Drip line:-

❑ In the inner crust of neutron star (after the drip point, S_n=0) nuclei are immersed in a "free" neutron gas even at T=0 MeV.

❑ The effect increases with increasing T.

❑ If nuclei beyond drip line can be considered as double counting of gas they have to be excluded from the statistical equilibrium.



Ref: Kreim et. al., Int. Jour. Mass Spectroscopy 349, 63 (2013)

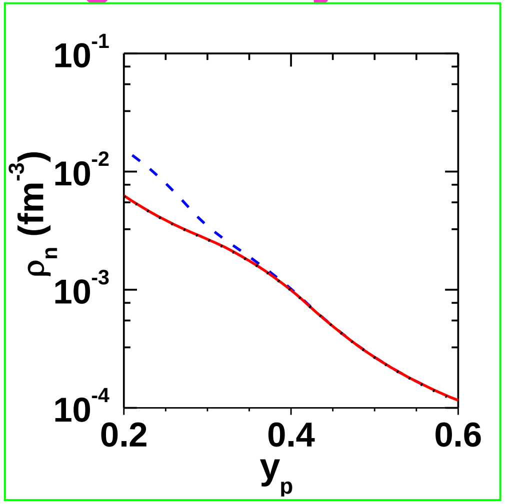
Similar to S_n cut for symmetric matter

To verify this, one has to include them and apply gas subtraction.

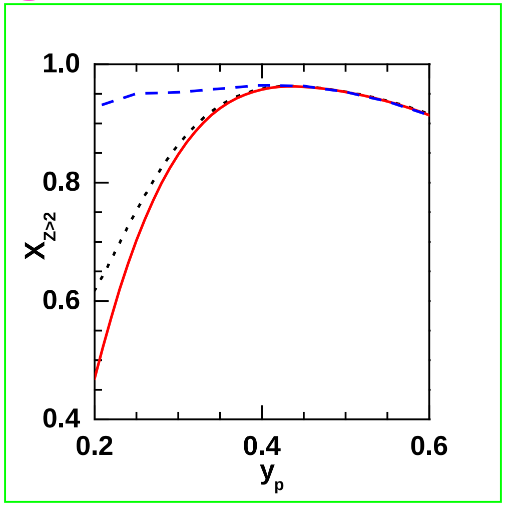
Effect of Nuclear Drip line:-

Temperature (T)=5 MeV   Baryonic Density(ρ_B)= 0.3 ρ_0

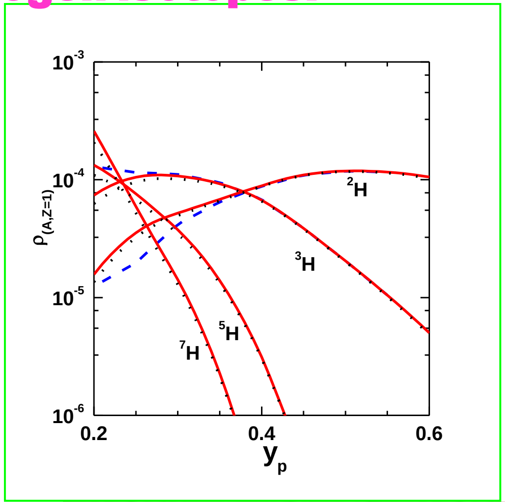
1. Neutron gas density:-



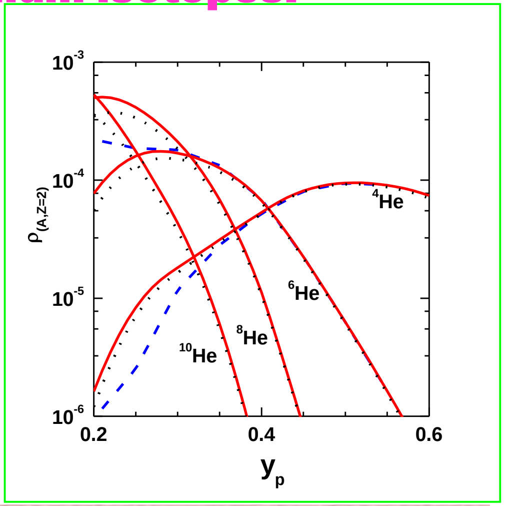
2. Charge fraction with Z>2:-



3. Hydrogen isotopes:-



4. Helium isotopes:-



Blue dashed line → Nuclei inside drip line only (With excitation correction)
Black dashed line →All nuclei (Without excitation correction)
Red solid line →All nuclei (With excitation correction)

Conclusions:-

- Unified treatment of intermediate energy heavy ion reaction and supernova matter has been proposed .
- An exact analytical excitation correction has been introduced.
- Inclusion of excitation correction significantly modifies charge fraction of bound nuclei.
- Nuclei beyond drip-line also modify the results for systems with lower proton fractions even at low temperature.
- In-medium correction can be added by fitting heavy ion reaction data.

The work is in progress…….

Thank you….