Heavy-ion reactions and the Nuclear Equation of State

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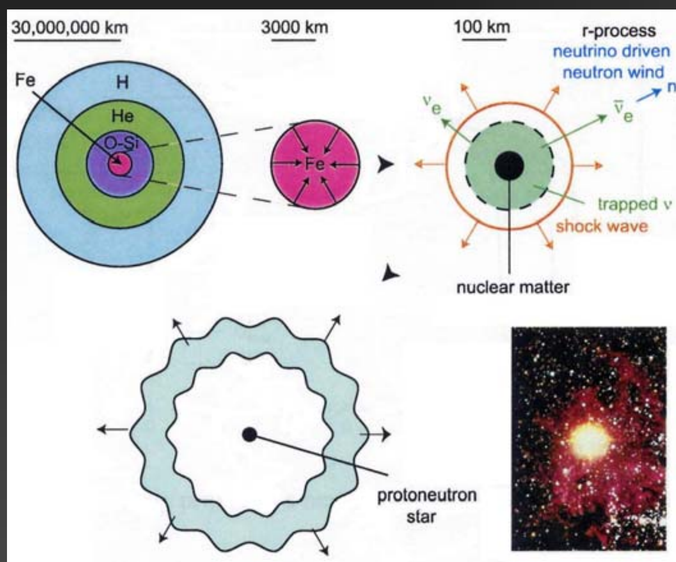
Studying Nuclear Equation of State (EOS)

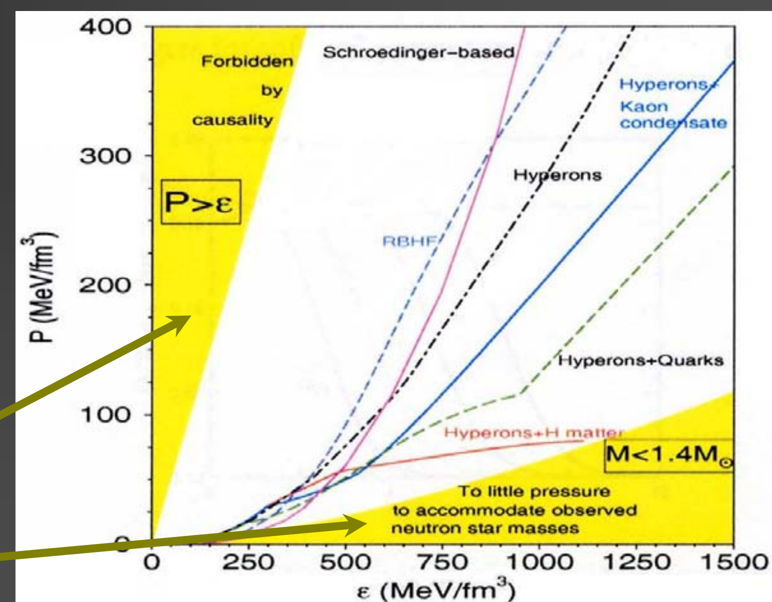
Nuclear Physics : Understanding the dynamics of heavy ion collisions and the structure of nuclei far from stability

Astrophysics : Understanding the dynamics of supernovae collapse and the structure of neutron star

Host of nuclear EOS employed in astrophysical modelling of neutron star & supernova explosion



Still leaves a wide range of possibilities !

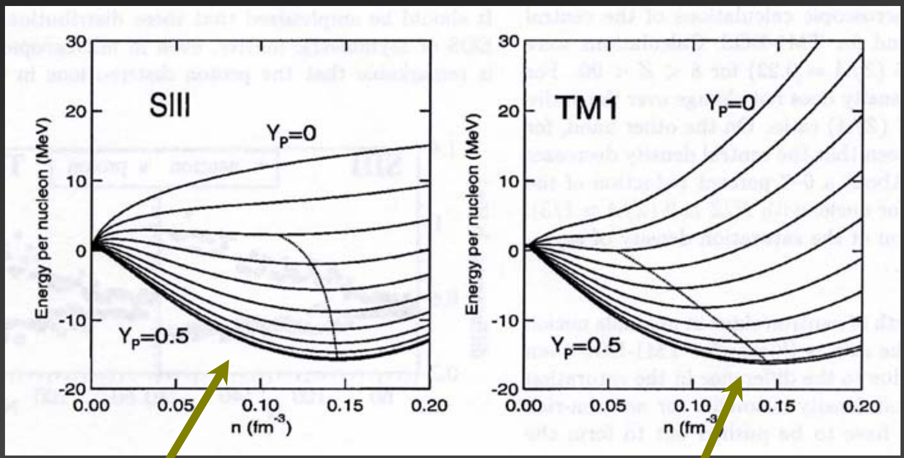


Some are excluded by causality & some by known masses of existing neutron stars

F. Weber, IoP publishing, Bristol (1999)

EOS of asymmetric (N/Z > 1) nuclear matter

K. Oyamatsu, RIKEN Review 26, (2000), 136



Skyrme Hartree-Fock calcn. & Relativistic mean field calcn describes reasonably well the properties of stable symmetric nuclei. However, the EOS of asymmetric nuclear matter shows distinct differences

$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$E_{sym}(\rho) = E_{sym}(\rho_0)u^\gamma, \quad u = \rho/\rho_0$$

$$E_{sym}(\rho_0) \approx 30 \text{ MeV}$$

$$P_{sym}(\rho,\delta) = \rho^2 \frac{\partial E_{sym}}{\partial \rho}\delta^2$$

$$= \rho_0 E_{sym}(\rho_0)\gamma u^{\gamma+1}\delta^2$$

Symmetry term dominates the pressure in asymmetric nuclear matter (imp for neutron star)

Studying Nuclear Equation of State (EOS) Using Heavy Ions

- Direct excess to supernova core or neutron star impossible

- High temperature & density can be achieved in <u>intermediate</u> energy heavy ion collision.

  (At relativistic energies : T ~ 150 - 200 MeV, $\rho \sim (10 - 20)\, \rho_o$)

- Coupled with the possibility of neutron rich beams, very asymmetric nuclear matter (N/Z > 1) can be probed.

- The largely unconstrained density dependence of the asymmetry term in the EOS is sensitive to many observables in heavy ion collisions

Observables sensitive to the asymmetry term in the EOS ?

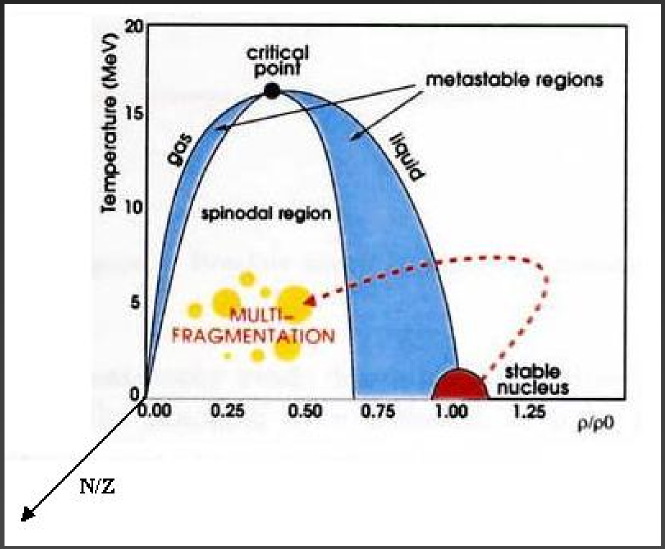
Moderate density ($\rho < 1.5\ \rho_o$) :

Fragment isotope distribution, isotopic & isobaric yield ratios
Isospin distillation/fractionation, relative n & p densities
Isospin diffusion
Nuclear stopping & N/Z equilibration
Pre-equilibrium emission
Particle - particle correlation
Light cluster production

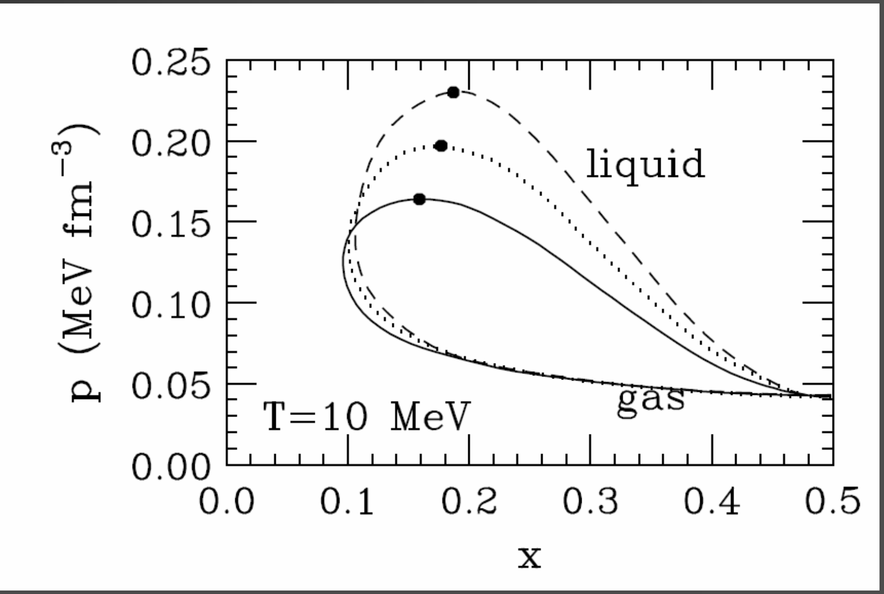
High density ($\rho > 1.5\ \rho_o$) :

Collective flow
Subthreshold particle production

Multifragmentation reaction (Probing the low density dependence)

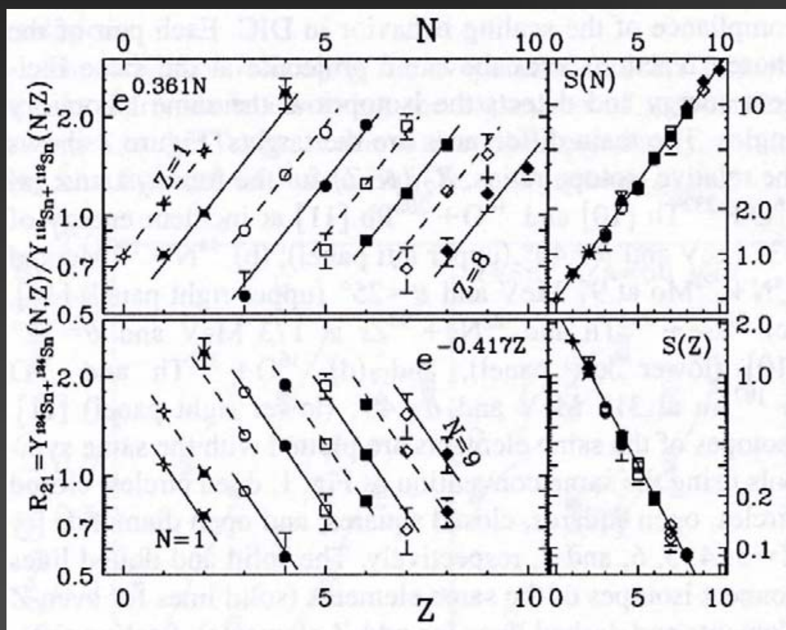


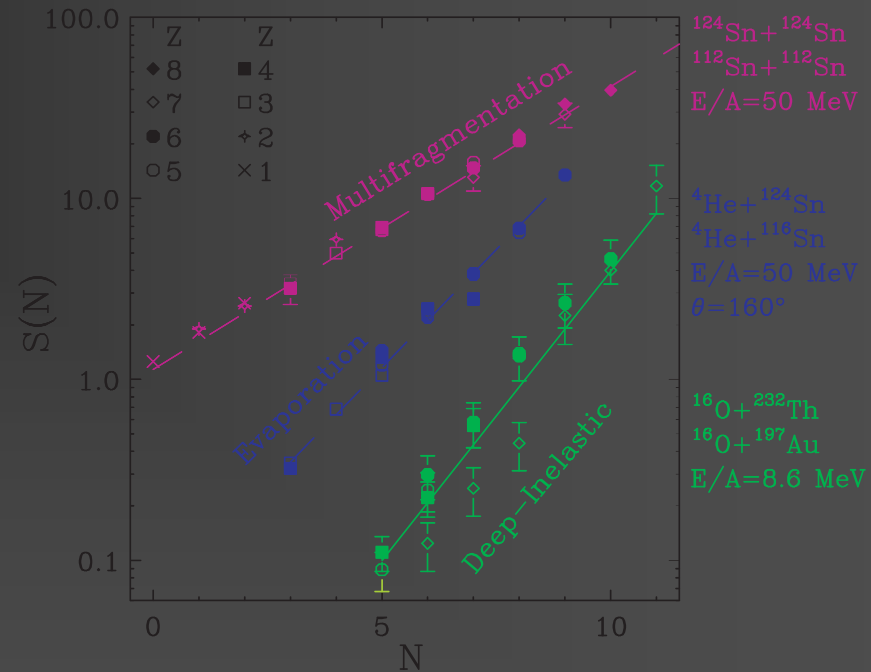
Mueller & Serot
PRC 1995



Isoscaling in multifragmentation reaction

M.B. Tsang et al, Phys. Rev. Lett 68 (2001) 5023
M.B. Tsang et al, Phys. Rev. C 64 (2001) 041603 (R)



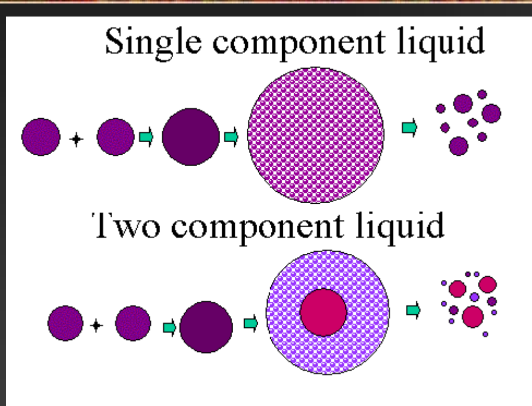


$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C\exp(N\alpha + Z\beta),$$

$$S(N) = R_{21}(N,Z)/\left(\hat{\rho}_p\right)^Z$$

Isospin fractionation / distillation, relative n & p densities

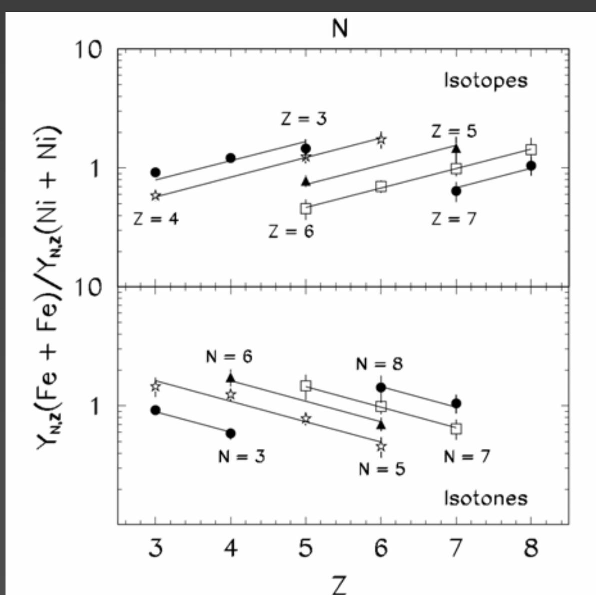
D. V. Shetty et al, Phys. Rev. C 68 (2003) 021602(R)

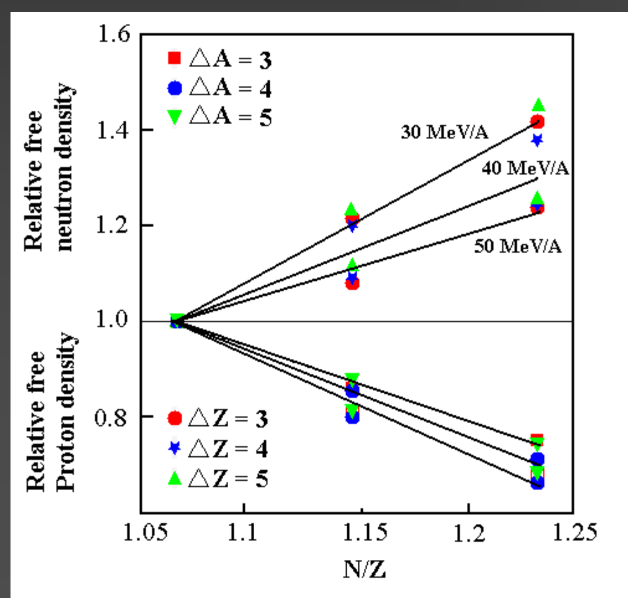


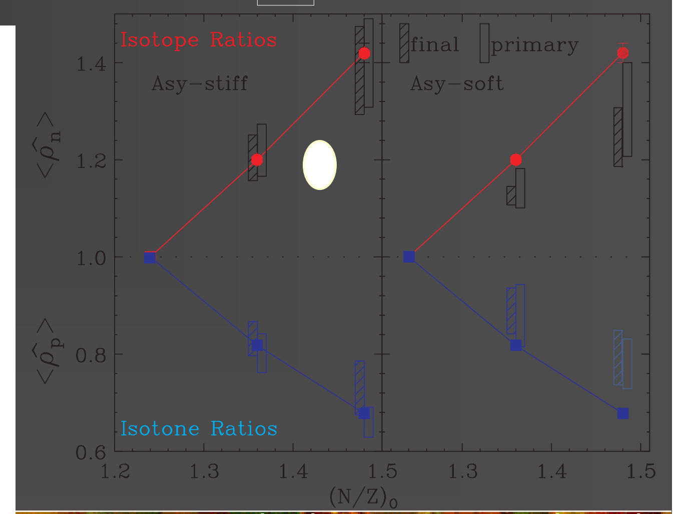
$$Y(N,Z) \propto V \rho_n^N \rho_p^Z Z_{N,Z}(T) A^{3/2} e^{B(N,Z)/T}$$

$$\frac{Y(N+k,Z)/Y^{Ni+Ni}(N+k,Z)}{Y(N,Z)/Y^{Ni+Ni}(N,Z)} = \left(\frac{\rho_n}{\rho_n^{Ni+Ni}}\right)^k$$

$$\frac{Y(N,Z+k)/Y^{Ni+Ni}(N,Z+k)}{Y(N,Z)/Y^{Ni+Ni}(N,Z)} = \left(\frac{\rho_p}{\rho_p^{Ni+Ni}}\right)^k$$





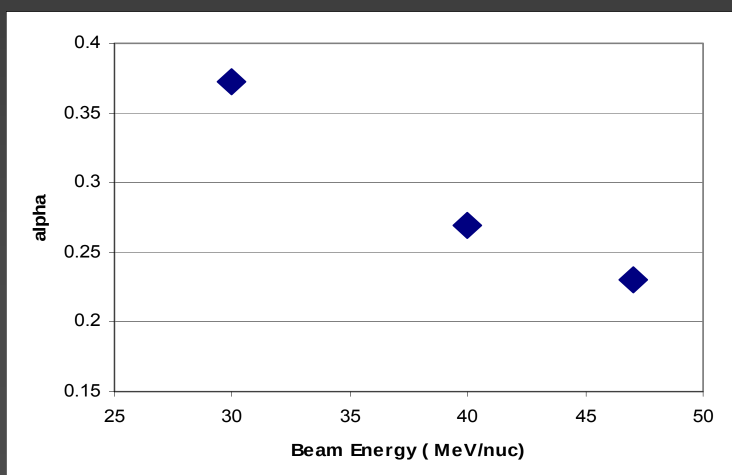


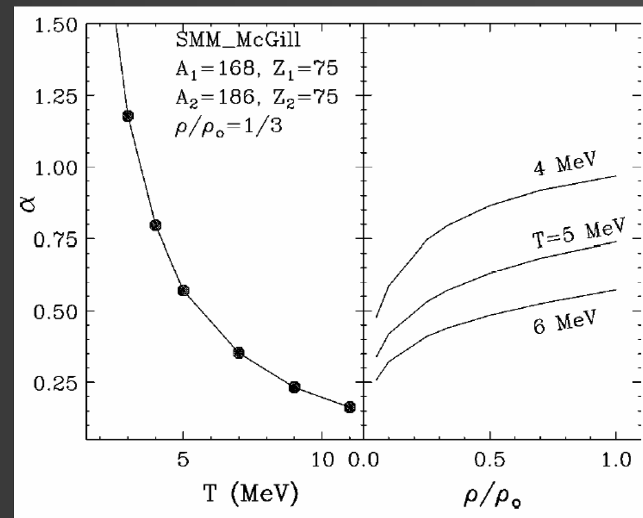
W.P. Tan et al, Phys. Rev. C 64 (2001) 051901 (R)

Temperature dependence of the scaling parameter α

$^{58}Fe + ^{58}Fe$ / $^{58}Ni + ^{58}Ni$

	30 MeV	40 MeV	47 MeV
α	0.372	0.269	0.23
β	-0.395	-0.372	-0.32

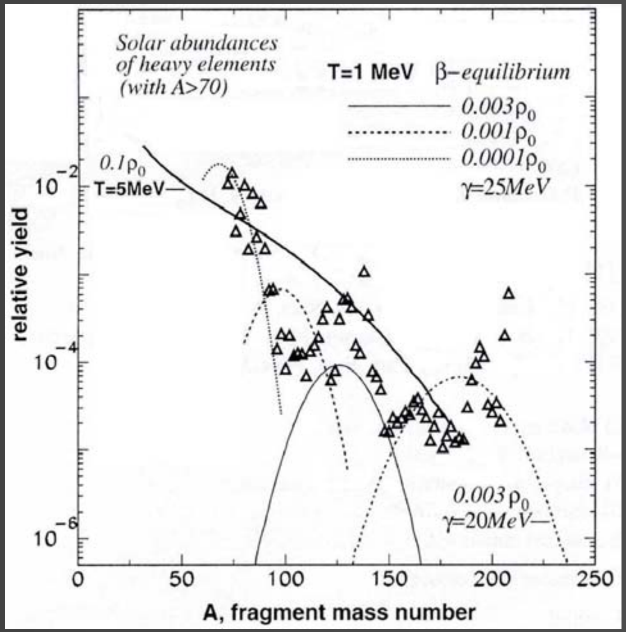




Tsang PRC64, 054615 (2002)

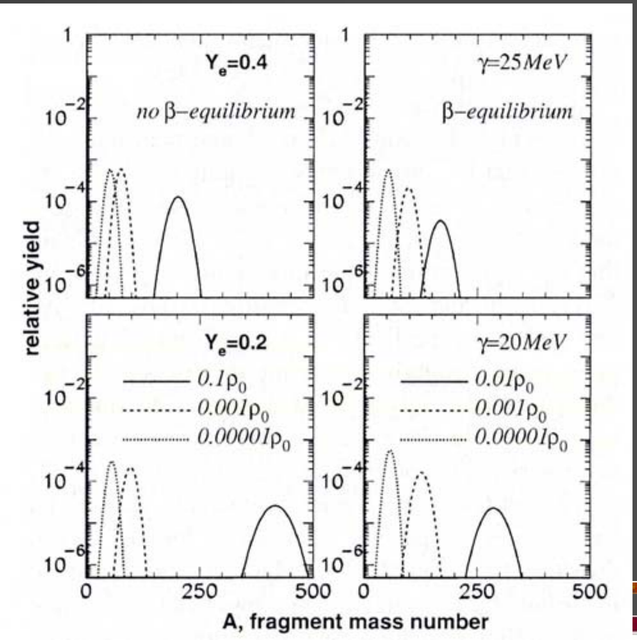
$$\alpha T = 4C_{sym}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

Formation of hot neutron rich nuclei in supernova explosion



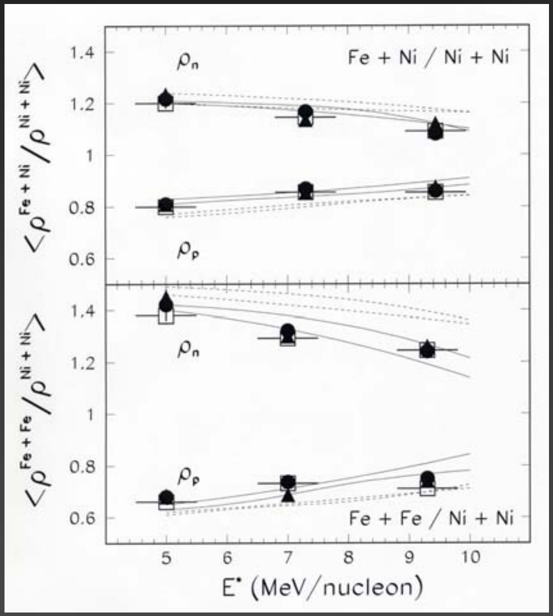
During supernova II type explosion the thermodynamical conditions of stellar matter between the protoneutron star & the shock front correspond to nuclear liquid-gas coexistence region. Neutron rich hot nuclei can be produced in this region which can influence the dynamics of the explosion contribute to the synthesis of heavy elements

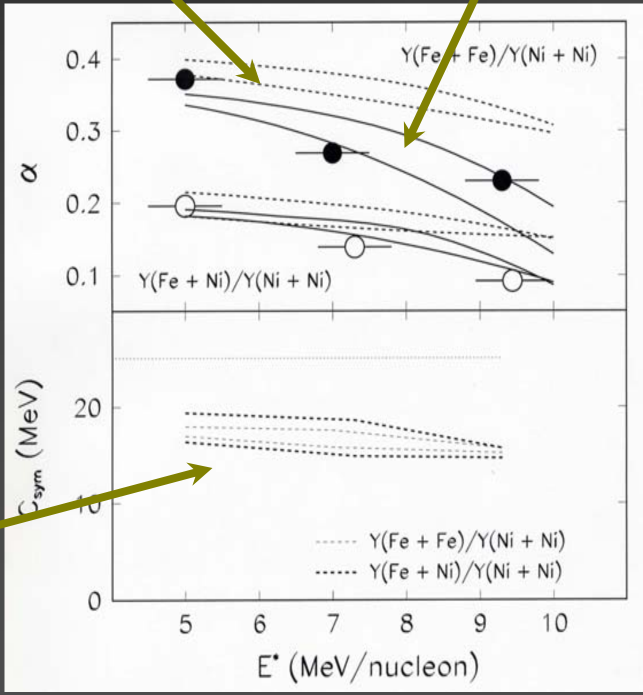
A slight decrease in the symmetry energy co-efficient can shift the mass distribution to higher masses



A. Botvina et al, Phys. Lett. B 584 (2004) 233

Symmetry energy and the fragment yield distribution in Multifragmentation reaction



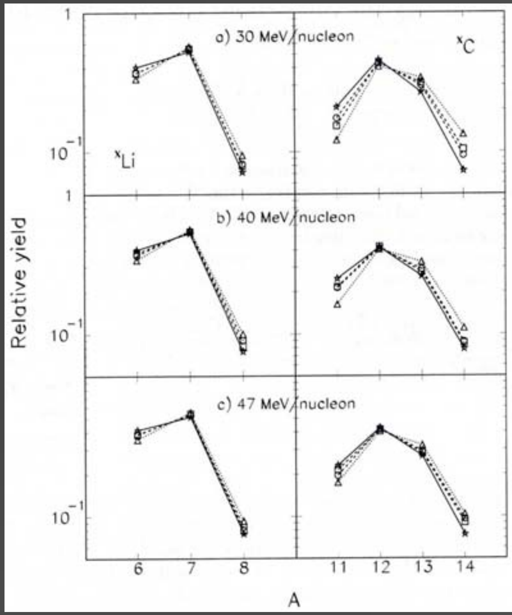


Secondary fragments

Primary fragments

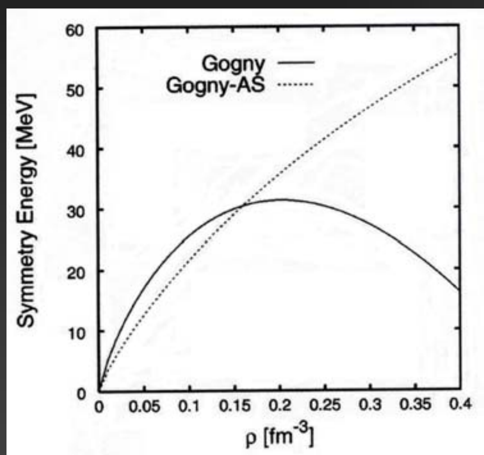
Symmetry energy of the primary fragments are significantly lower

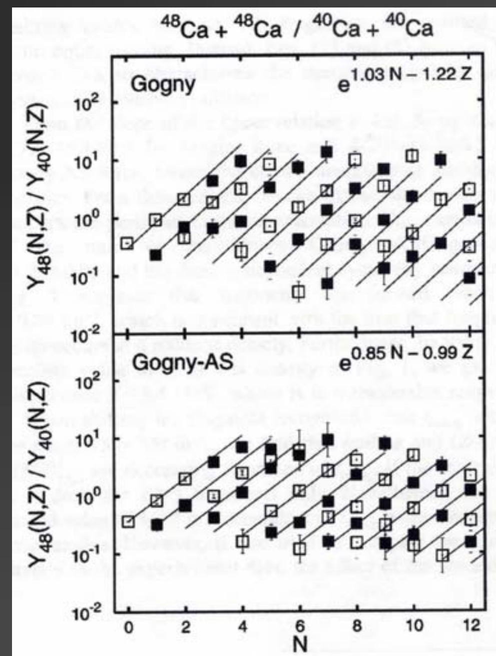
$$\alpha T = 4C_{sym}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$

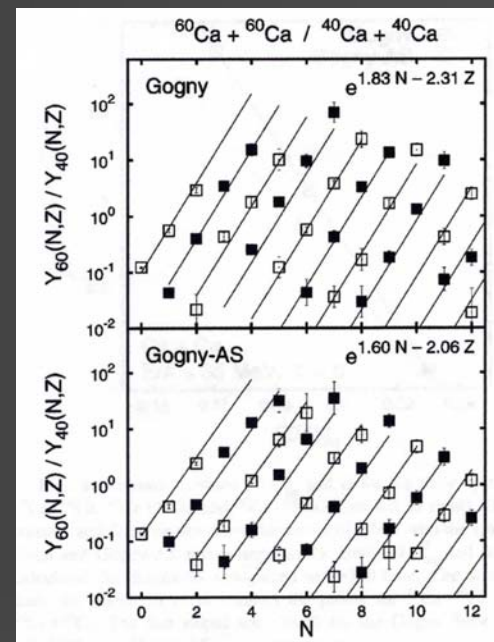


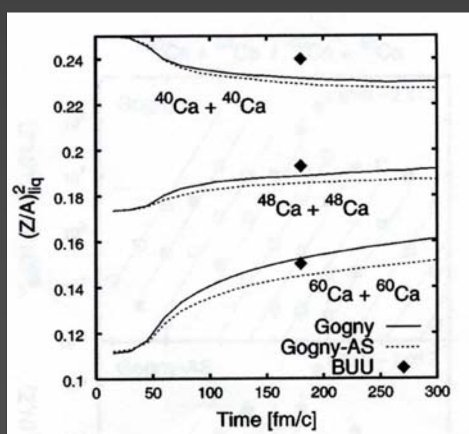
D. V. Shetty et al, (2004)

EOS and dynamical simulation of fragment production (AMD model calculations)





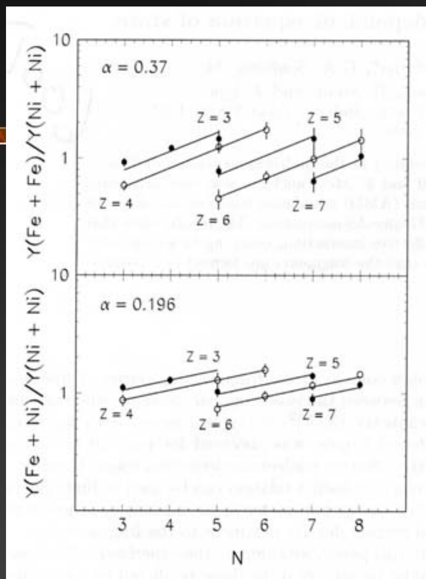


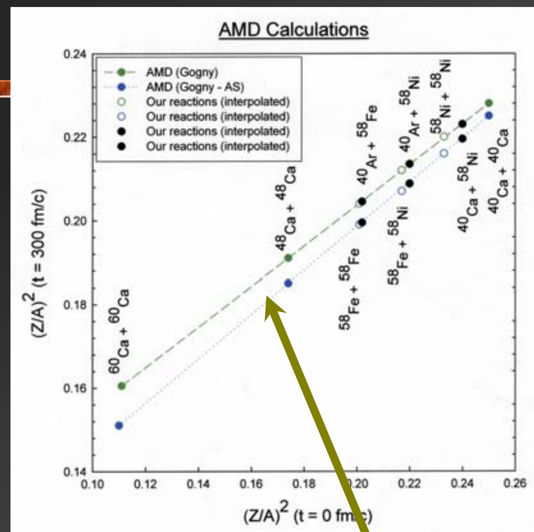


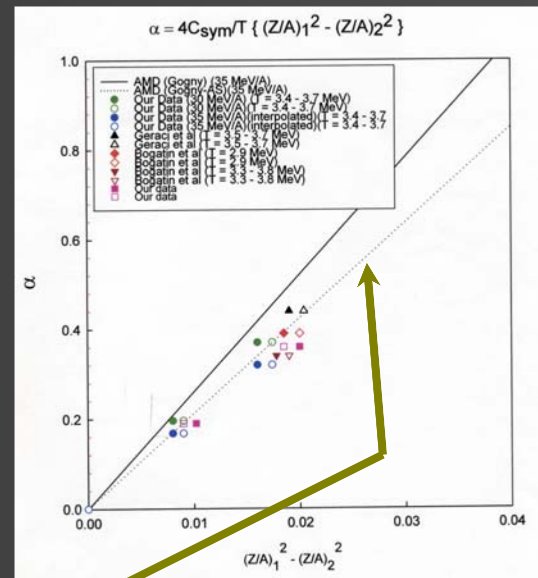
$$V_{\text{Gogny-AS}} = V_{\text{Gogny}} - (1-x)t_3[\rho(\mathbf{r}_1)^{1/3} - \rho_0^{1/3}]P_\sigma \delta(\mathbf{r}_1 - \mathbf{r}_2)$$

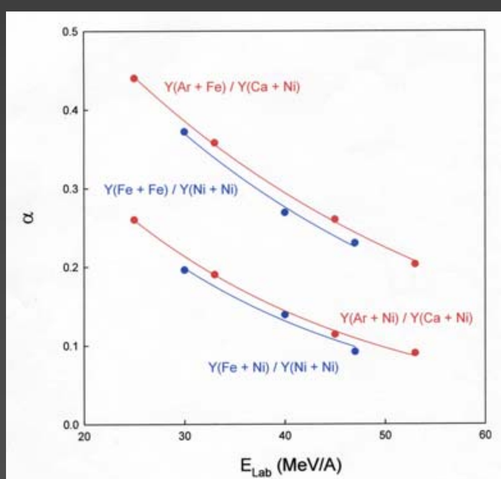
A. Ono et al, Phys. Rev. C 68 (2003) 051601(R)

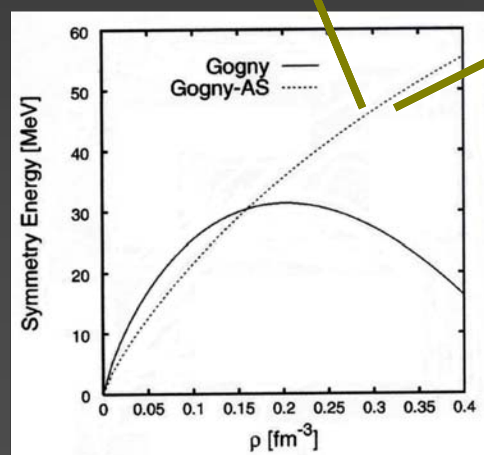
Symmetry energy and the scaling parameter α











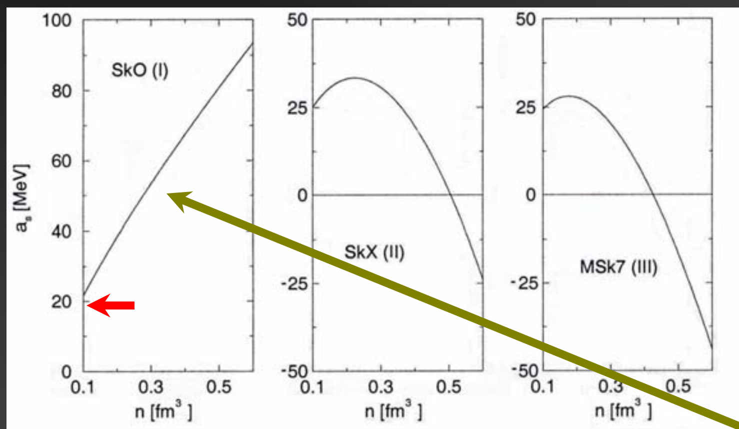
$$\alpha T = 4C_{sym}\left(\frac{Z_1^2}{A_1^2}-\frac{Z_2^2}{A_2^2}\right)$$

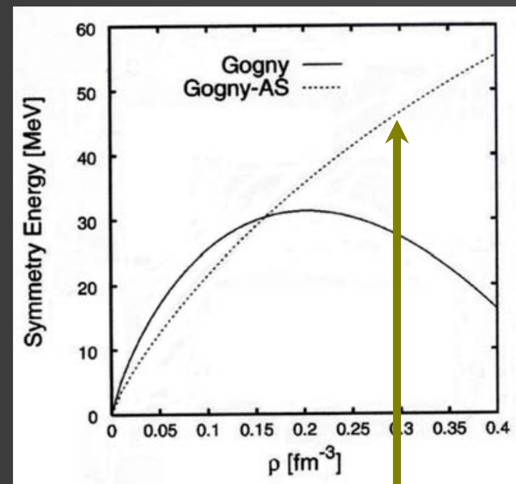
Csym ~ 18 – 20 MeV ; ρ ~ 0.08 fm^{-3}

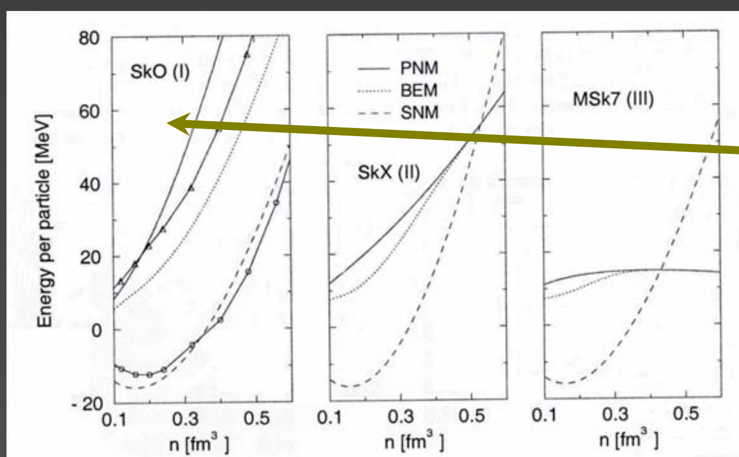
D. V. Shetty et al, Phys. Rev. C 70 (2004) 011601(R)

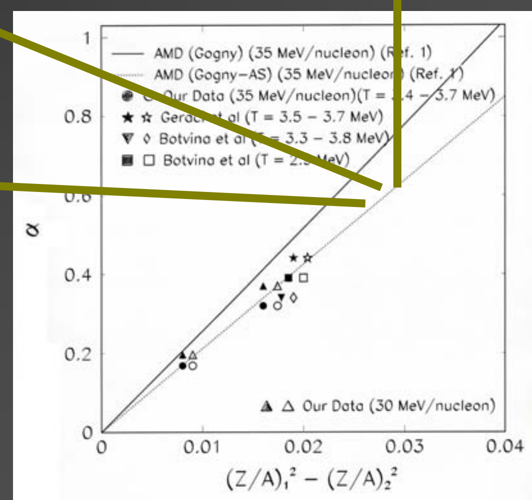
Density dependence of the Symmetry energy

A. Ono et al, Phys. Rev. C 68 (2003) 051601(R)









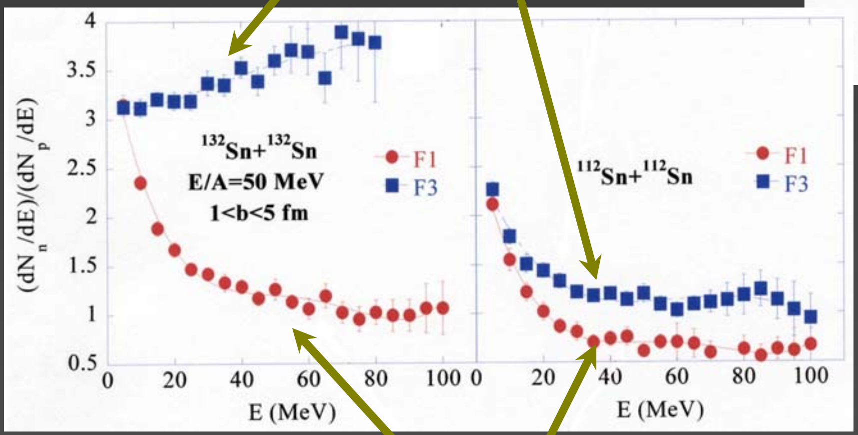
J. Stone et al, Phys. Rev. C 68 (2003) 034324

D. V. Shetty et al, Phys. Rev. C 70 (2004) 011601(R)

EOS and pre-equilibrium emission rate and spectra

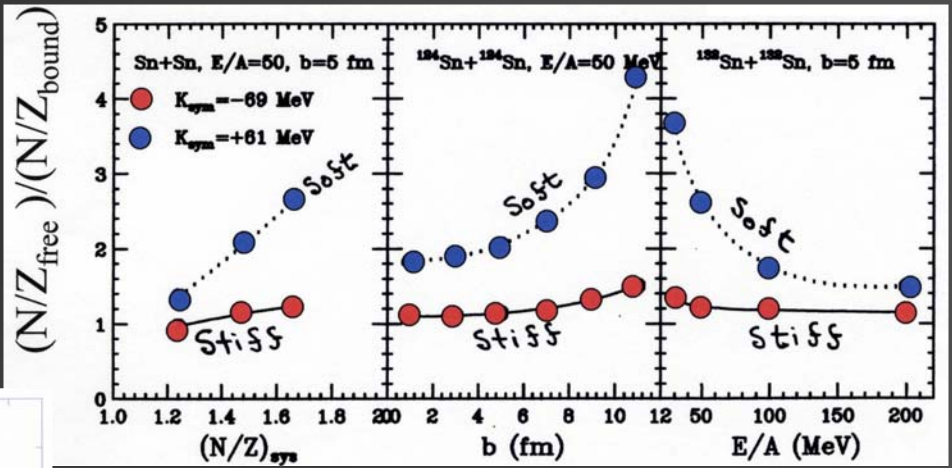
Pre-equilibrium energy spectra

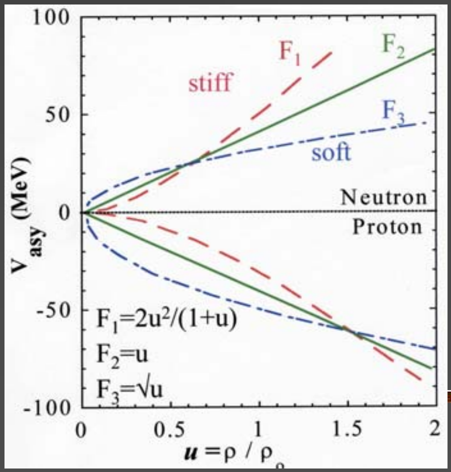
Soft asymmetry term



Stiff asymmetry term

Neutron/Proton emission rate





B.A. Li et al, PRL 85 (2000) 4221

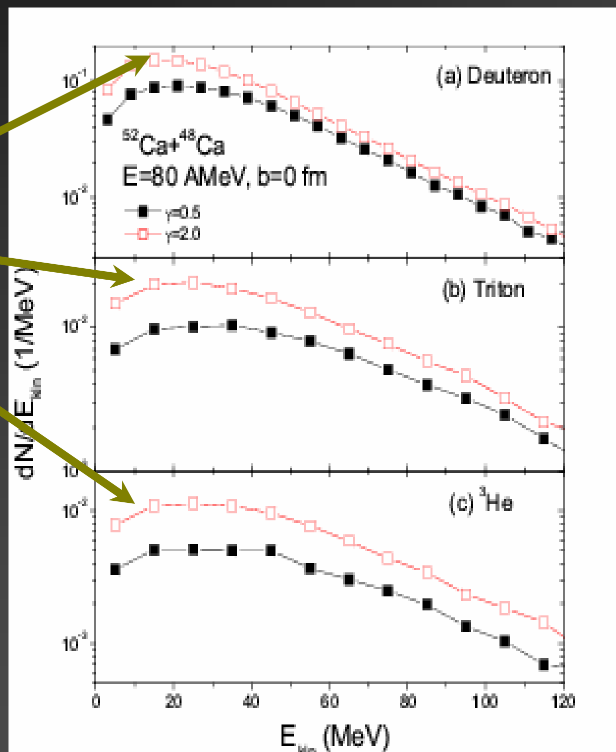
Light Cluster production and EOS

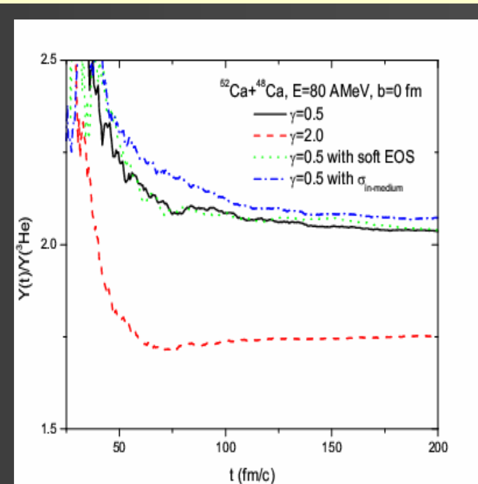
$$E_{sym}(\rho) = E_{sym}(\rho_0)u^{\gamma}, \quad u = \rho/\rho_0$$

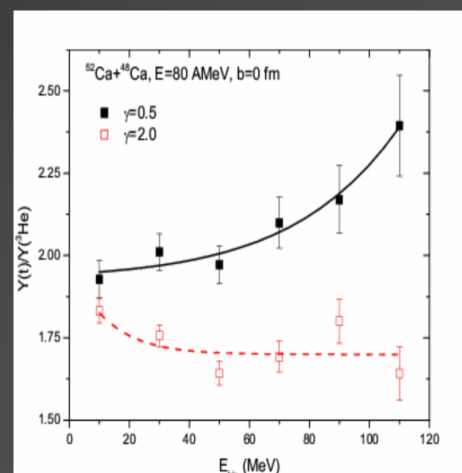
Isobaric yield ratio of t/^{3}He

Asy-Stiff symmetry term

Asy-Soft symmetry term

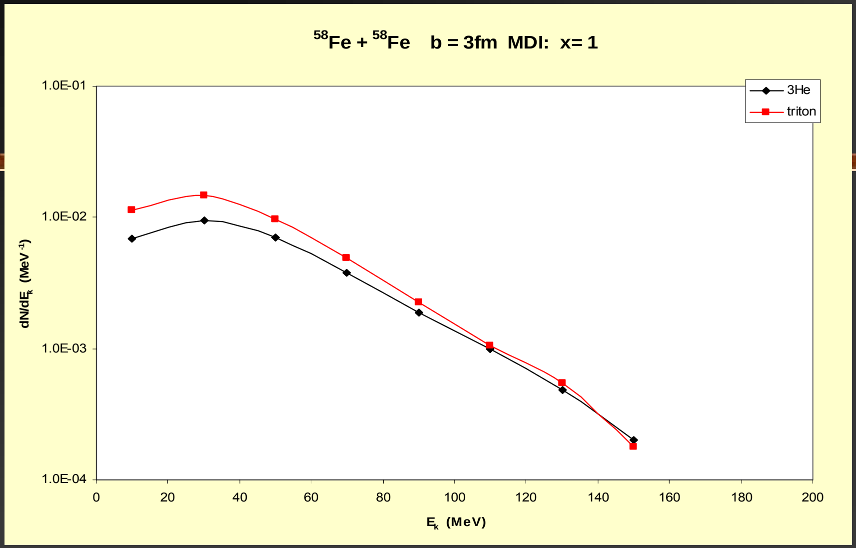


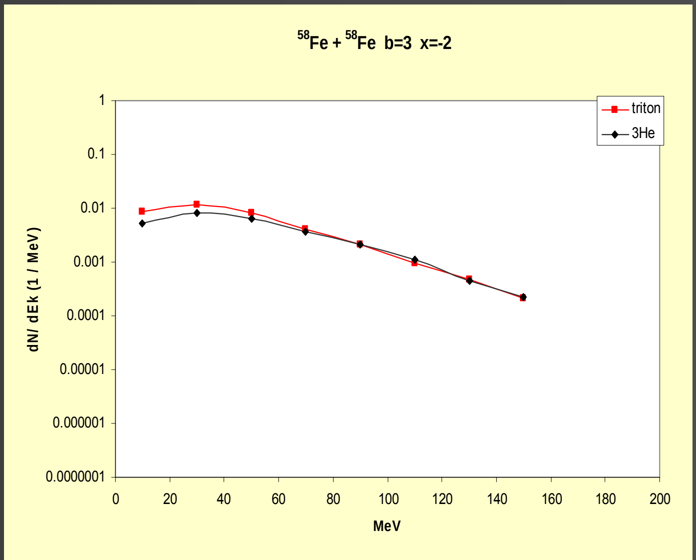


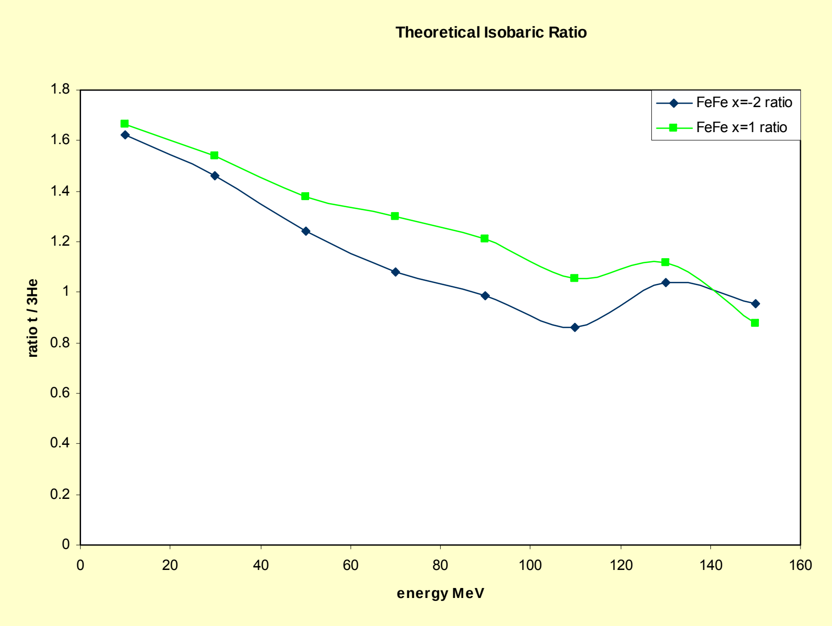


L.W. Chen, Phys. Rev. C 68 (2003) 017601

Preliminary Data



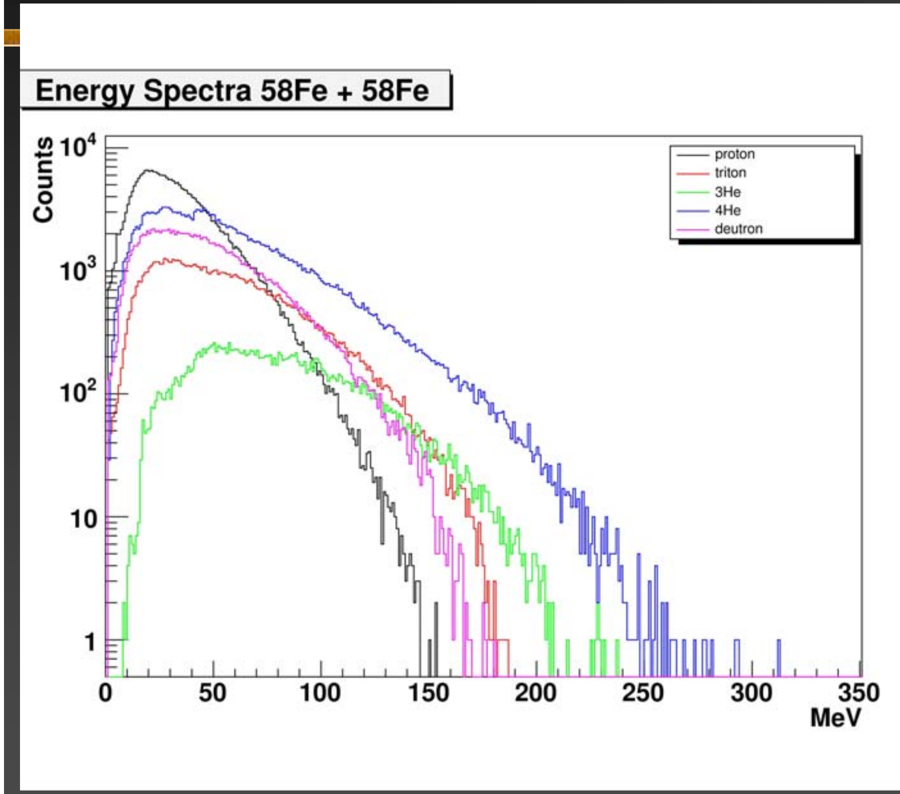


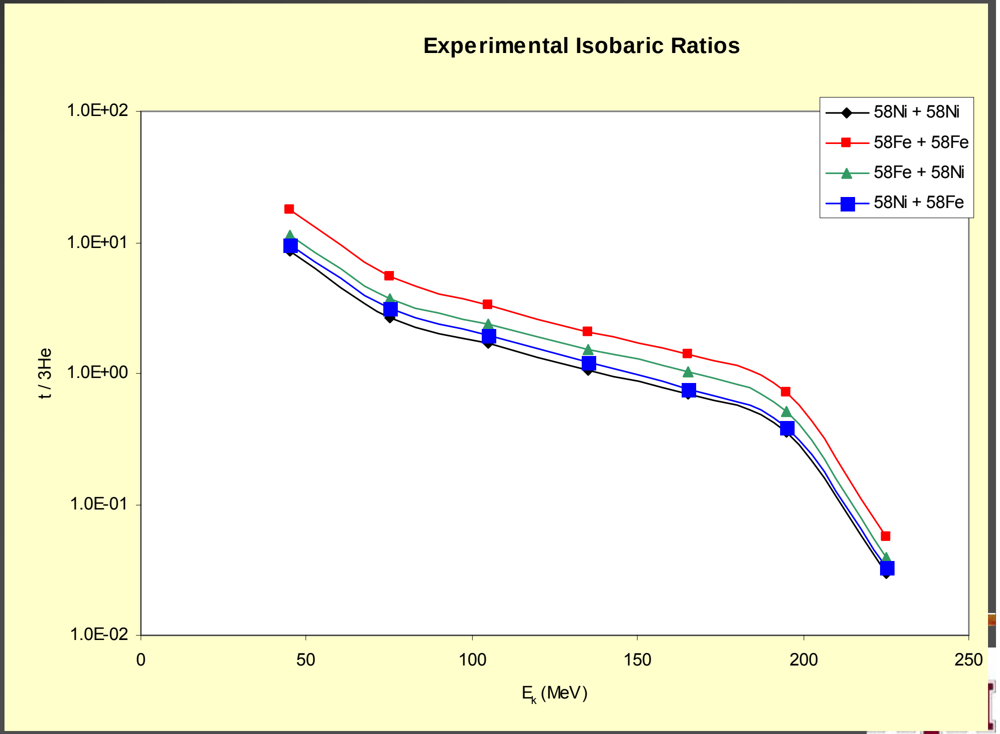


$60^{\circ} < \theta_{cm} < 120^{\circ}$

Preliminary Data

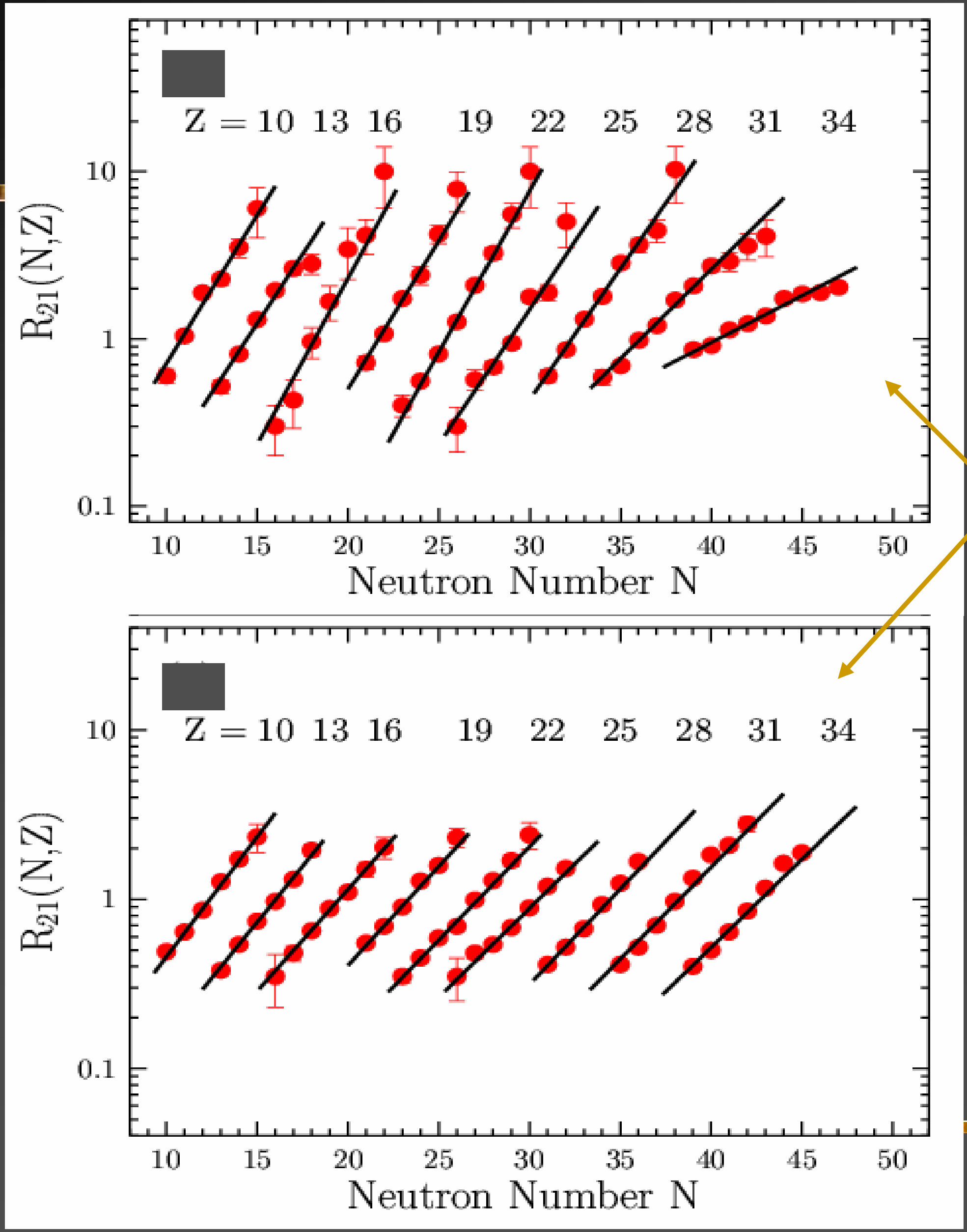
$28.7^o < \theta_{lab} < 45.0^o$





Scaling of Yield Ratios of Heavy Residues :

$R_{21}(N,Z) = Y_2/Y_1$



- $^{86}Kr+^{124}Sn,^{112}Sn$
  (data inside $\theta_{gr}=6.2^o$)

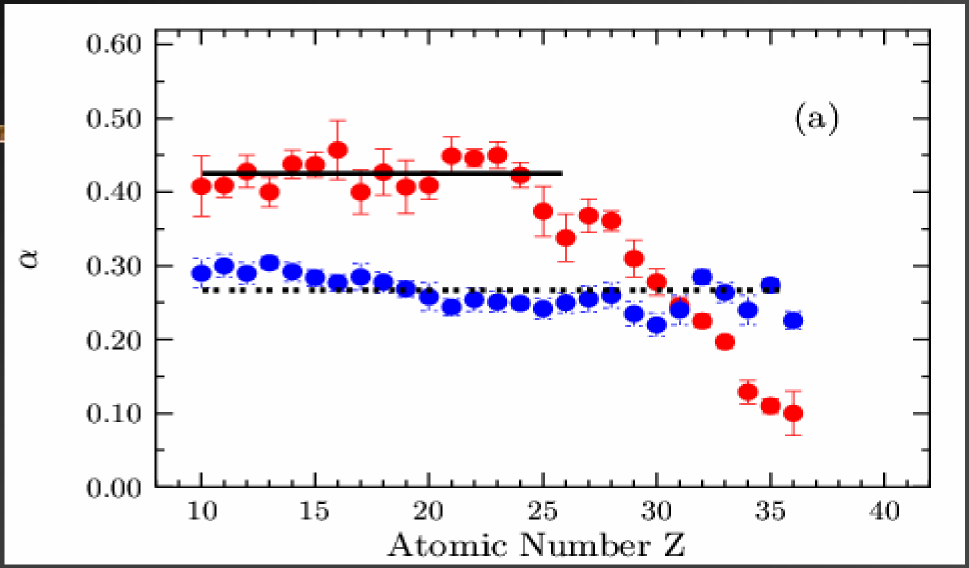
$R_{21} = C \exp(\alpha N)$

- $^{86}Kr+^{64}Ni,^{58}Ni$
  (data outside $\theta_{gr}=3.5^o$)

Isoscaling Parameter α : *

α =0.43

α =0.27



- $^{86}Kr + ^{124}Sn, ^{112}Sn$
- $^{86}Kr + ^{64}Ni, ^{58}Ni$

$$R_{21} = C \exp(\alpha N)$$

$$\alpha = 4 C_{sym}/T \left((Z/A)_1^2 - (Z/A)_2^2 \right)$$

Quasi-projectiles 1: n-poor 2:nrich

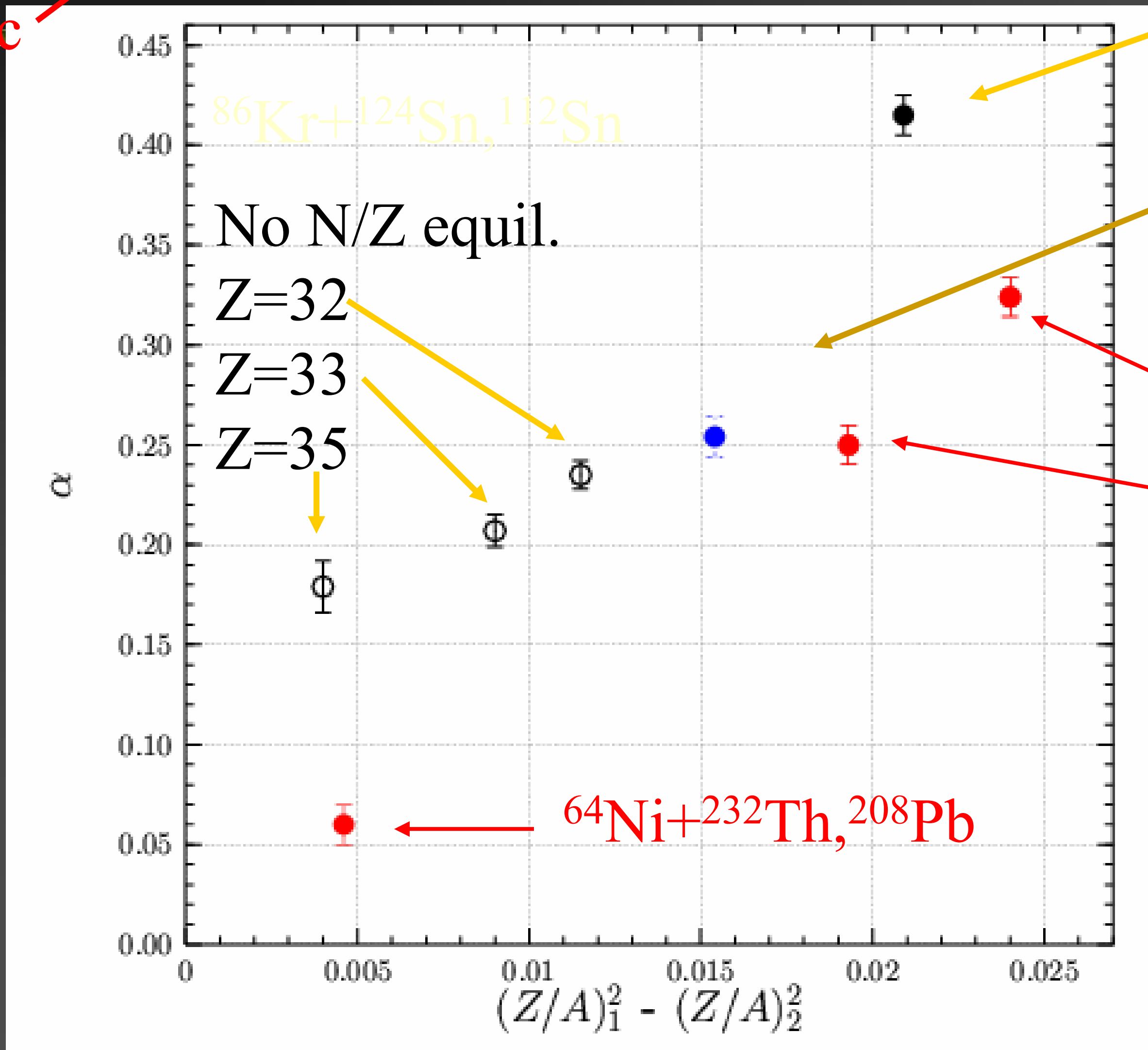
* G.A. Souliotis et al., Phys. Rev. C 68, 024605

^{86}Kr, ^{64}Ni data: Isocaling parameter α vs $\Delta(Z/A)^2$:

$\alpha = 4C_{sym}/T\,(\,(Z/A)_1^{\,2} - (Z/A)_2^{\,2}\,)$

Quasi-projectiles : (E/A ~ 25 MeV/u)

- N/Z equilibrated
- negligible pre-eq.



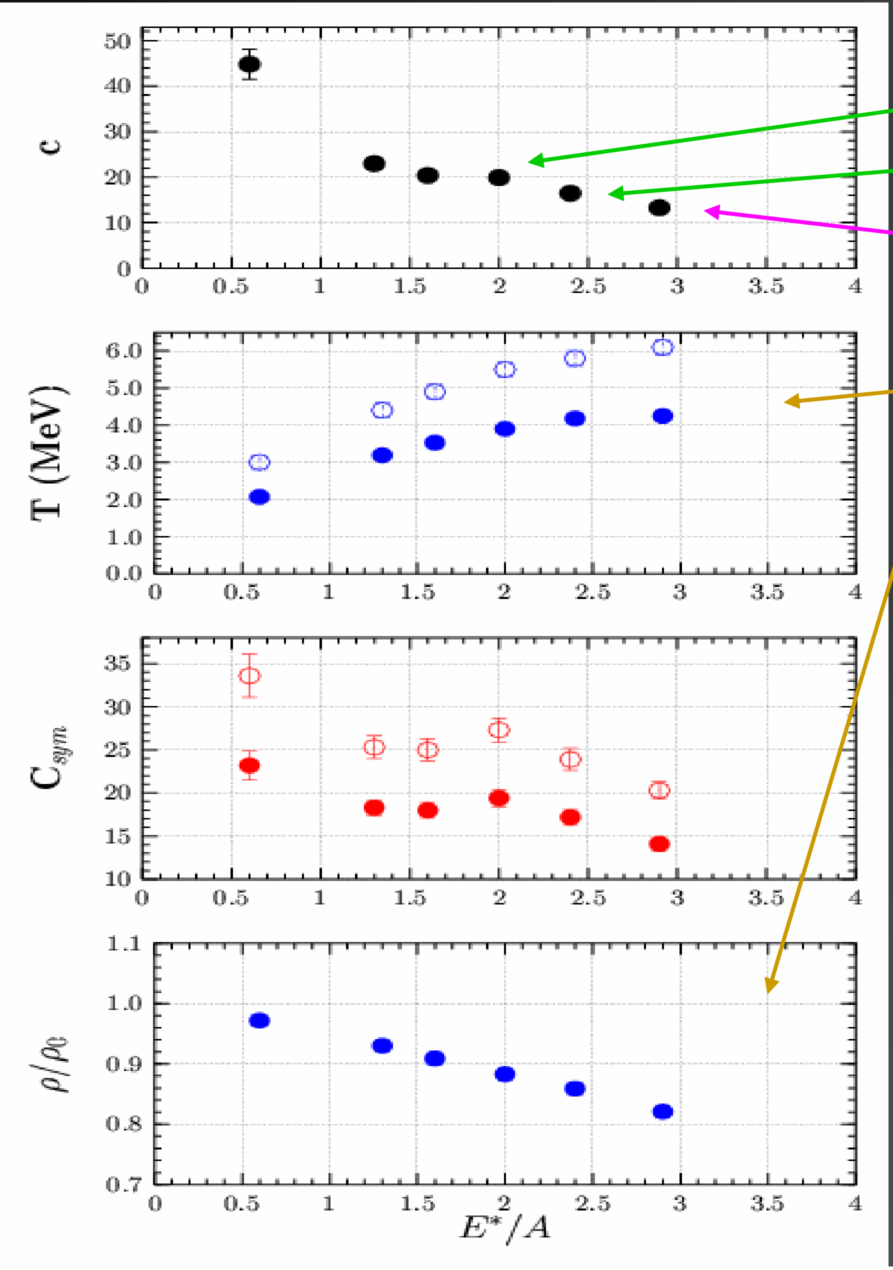
c = 19.9 ±0.8
ε* ≅ 2.0 MeV/u

^{86}Kr+^{64}Ni,^{58}Ni
c = 16.5 ±0.7
ε* ≅ 2.4 MeV/u

^{64}Ni+^{124}Sn,^{112}Sn
^{64}Ni+^{64}Ni,^{58}Ni

c = 13.3±0.7
ε* ≅ 2.9 MeV/u

Variation w.r.t excitation energy:



Data :

$^{86}Kr+^{124,112}Sn$

$^{86}Kr+^{64,58}Ni$

^{64}Ni+ Ni,Sn,Th-Pb

Calculation:
Mononucleus expansion model (L. Sobotka)

$C_{sym} = c\,T / 4$

Heavy Residue Isoscaling and N/Z equilibration

$R_{21} \sim \exp(\alpha N)$

$\alpha = 4\, C_{sym}/T\ \left((Z/A)_1^{2} - (Z/A)_2^{2} \right)$ *

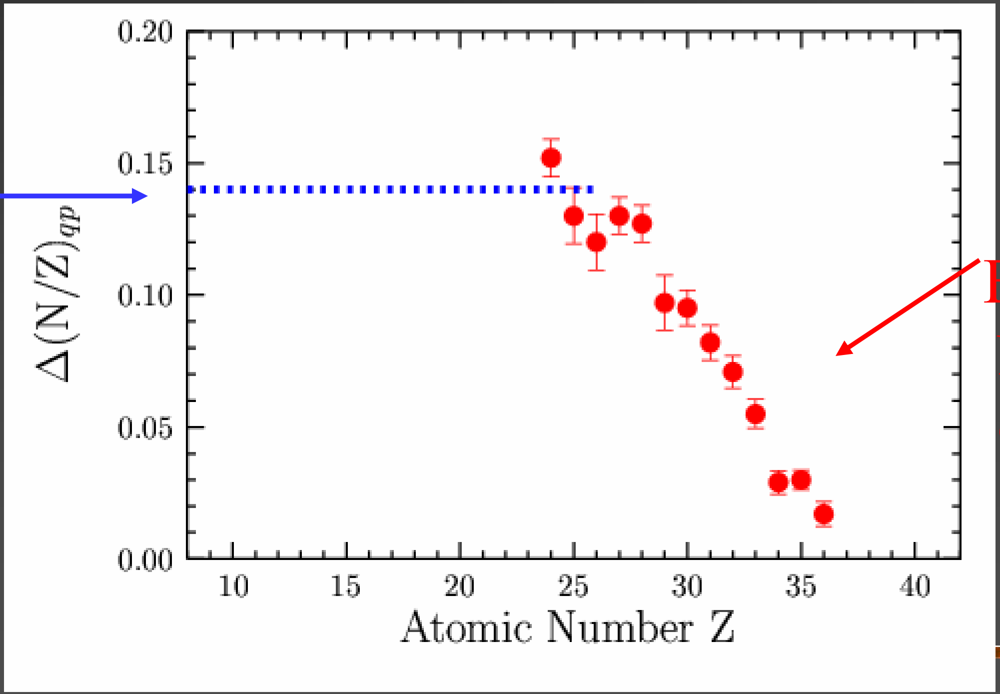
$\alpha = 8\, C_{sym}/T\ (Z/A)^3_{ave}\ \Delta(N/Z)$

	N/Z
$^{86}Kr + ^{124}Sn \Rightarrow [^{210}Rn]$	1.44
$^{86}Kr + ^{112}Sn \Rightarrow [^{198}Rn]$	1.30

For each Z: get **Δ(N/Z)** from **α** and **T** (from ε*) :

$\Delta(N/Z) = 0.14$

N/Z equilibrated quasi-projectile



● $^{86}Kr + ^{124}Sn, ^{112}Sn$

Evolution towards N/Z equilibration of quasi-projectile**

** G.A. Souliotis et al., Phys. Rev. C 68, 024605

Summary

- Intermediate heavy-ion collisions are a window into the nuclear EOS
- Isoscaling of fragment yields may be a discriminatory observable to the symmetry energy dependence