Perspectives of NUCLEAR DYNAMICS & THERMODYNAMICS with Radioactive Ion Beams

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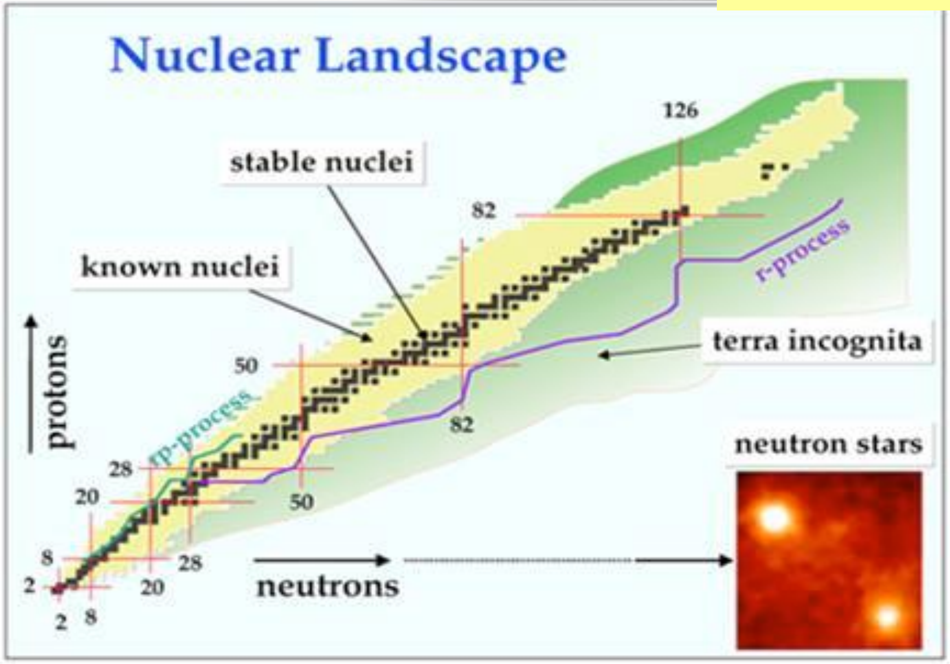
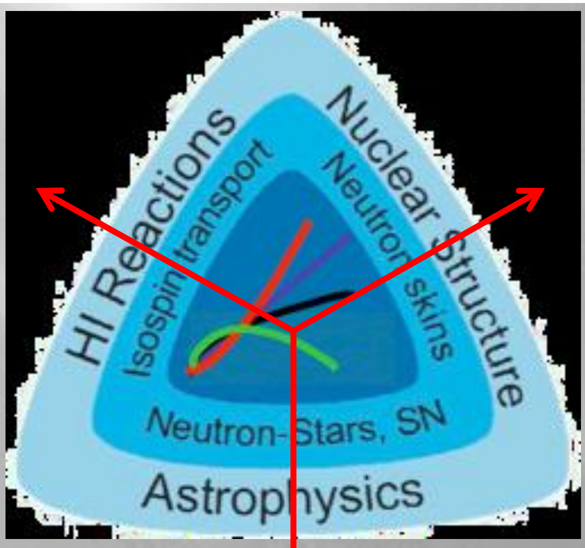
III European Radioactive Ion Beam Conference 2012

Why exotic beams?

More info needed on asymmetric nuclear matter





Isospin asymmetric nuclear matter is present in

- **nuclei**, especially those far away from the stability line

&

- in **astrophysical systems** (neutron stars)

A deep understanding of the **properties of isospin-rich nuclear matter** is necessary for both nuclear physics & astrophysics

Some of these properties are not well constrained.

In particular:

- the **density & temperature dependence of the symmetry energy** is still an important source of uncertainties.
- the **Level density parameter evolution** with **isospin** and **temperature**
- the **effect of isospin** on the **Limiting Temperature**

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NEOS and Symmetry Energy

Bethe-Weizsäcker Binding Energy formula.

$$B(N,Z)= \underbrace{a_v A}_{\text{volume}} - \underbrace{a_s A^{2/3}}_{\text{surface}} - \underbrace{a'_s (N-Z)^2/A}_{\text{Symmetry Energy}} - \underbrace{a_c Z(Z-1)/A^{1/3}}_{\text{Coulomb}} + \underbrace{a_p \Delta(N,Z)/A^{1/2}}_{\text{Pairing}}$$

Pairing

$$\Delta = \begin{cases} 1 & \text{even-even} \\ 0 & \text{odd masses} \\ -1 & \text{odd -odd} \end{cases}$$

In reality an Extended Liquid Drop Model is needed to consider two terms of **Symmetry Energy**: a Volume and a Surface term: **$Csym(A)=a'_s = C_v + C_s A^{-1/3}$**

At T=0 a good aproximation is the **parabolic form** in term of the **asymmetry parameter I**

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho, I=0) + \frac{E_{sym}}{A}(\rho) \times I^2$$

symmetric matter

$$\text{with } I = \delta = \frac{\rho_n - \rho_p}{\rho} = \frac{N-Z}{A}$$

Many measurement performed but better constrained if **I** can vary on a larger range:

importance of RIBs

The importance of isospin in NEOS

MAIN GOAL: Understand the **isospin dependence of <u>in-medium nuclear effective interactions</u>**, extract the **isospin dependence** of thermal, mechanical and transport properties of **asymmetric nuclear matter** playing important roles in nuclei, neutron stars and supernovae.

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

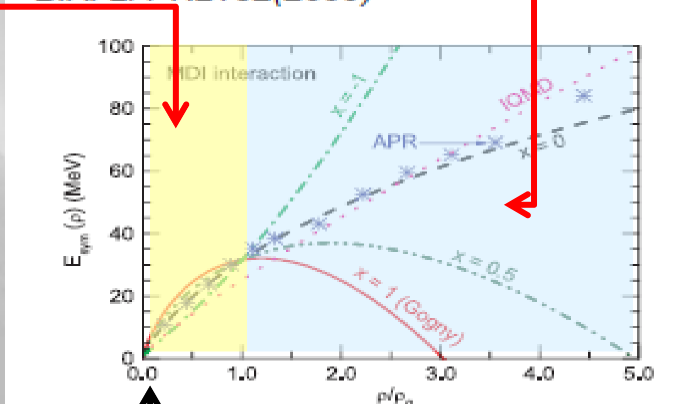
Symmetry energy

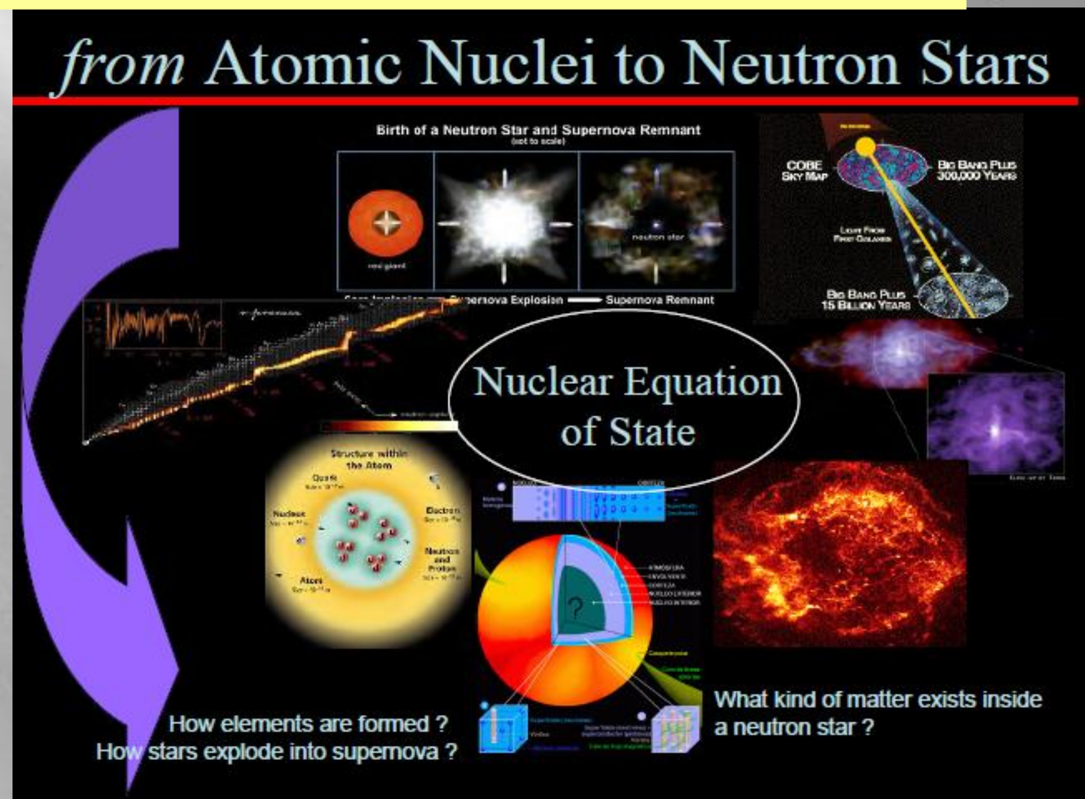
- **Low densities** → Effects on neutron skin structure
- **High density region** → Supernovae dynamics & neutron star properties

Low & intermediate energy HIC

High energy HIC

B.A. Li PRL102(2009)





Density dependence → $E_{sym}(\rho) = S(\rho) = a_4 + p_0(\rho-\rho_0) + \Delta K(\rho-\rho_0)^2$

NEOS & Symmetry Energy

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The symmetry energy can be divided in a Kinetic contribution (due to Pauli correlations) and a potential contribution (isovector part of effective nuclear interactions)

$$\frac{E_{sym}}{A}(\rho) = \overbrace{\frac{\varepsilon_F(\rho)}{3}}^{\text{Kinetic part}} + \overbrace{\frac{C}{2}F(\rho/\rho_0)}^{\text{Potential part}}$$

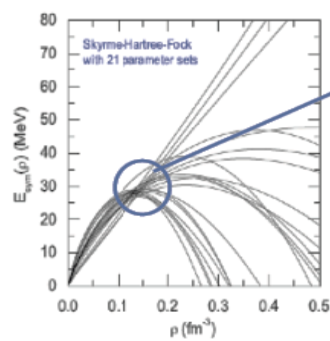
Commonly used approximations using mean field theory:

$$\frac{E_{sym}}{A}(\rho) = \frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

γ and **L** define the asy-stiffness of the EOS and permit the comparison between different approximation formulas

γ<1 Asysoft, γ>1 Asystiff

Slope and curvature of $E_{sym}(\rho)$



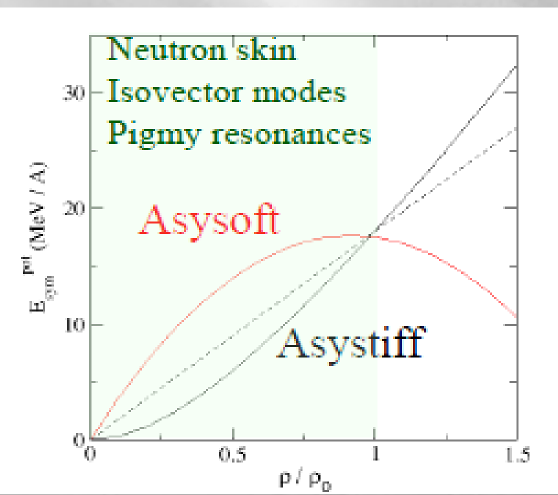
$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

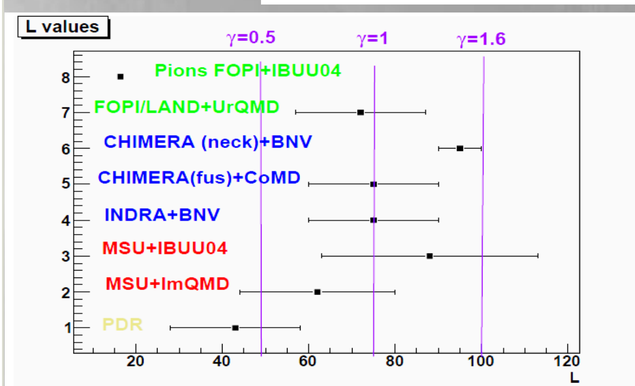
$S_0 = E_{sym}(\rho_0)$ strength

$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho_0} = \left(\frac{3}{\rho_0}\right) p_0$ slope

$K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\right|_{\rho_0}$ curvature

S_0, L and K_{sym} relevant to neutron stars, neutron skins, nuclear collective motion (GMR, GDR, PDR), …



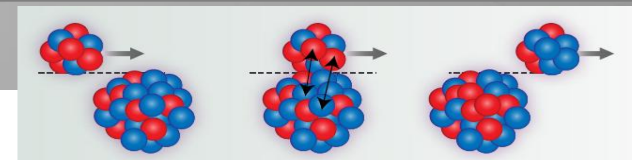


Difficult to give the asy-stiffness of the EOS in view of the presently existing data.

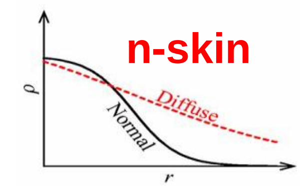
Many measurement have been performed on systems in a range close to **isospin symmetry - stability**.

Many more needed to be performed with new RIBs at low, intermediate and high energy with up to date **performing devices** (isotopic resolution (e.g. **FAZIA**), high performing correlators (e.g. **FARCOS**) etc.)

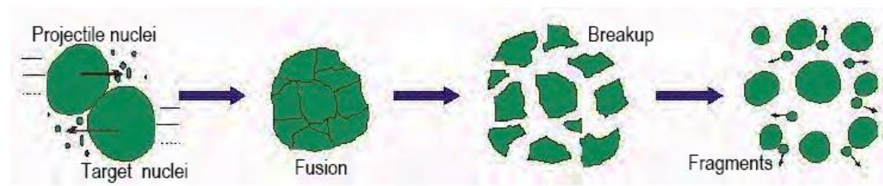
Observables sensitive to E_{sym}

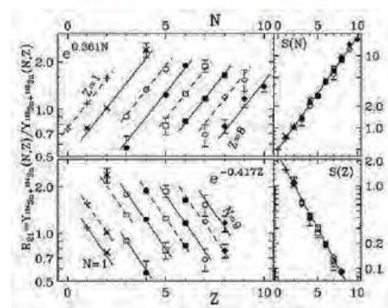


- **Subsaturation densities (**medium & Fermi energies**)**
  - Competition between reaction mechanisms: **fusion** versus **deep inelastic**
  - **Isospin diffusion**
  - **Isospin distillation**: Isospin contents of light fragments
  - **Neck fragmentation** (at Fermi energies)
  - **Neutron skin**
  - **Pre-equilibrium** emission and **N/Z** of **fast nucleon** emission
  - **Particle-particle** correlation
  - **Cluster** emission/preformation
  - Nuclear structure at **drip lines**
  - **Pigmy** resonancies
- ➢ neutron star formation and crust



Studying density dependence of symmetry energy :
Multifragmentation





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

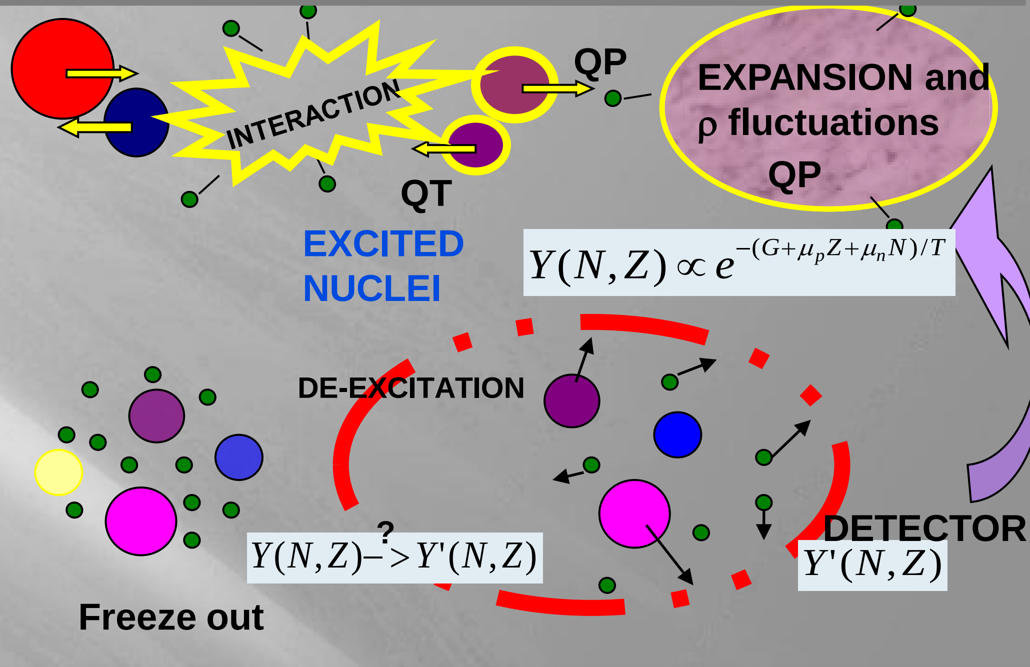
α – Scaling parameter

C_{sym} – Symmetry energy

- **Supersaturation densities (**high energies**)**
  - N,p collective flow
  - Meson production
- ➢ neutron star mass-radius relation
- ➢ transition to a deconfined phase
- ➢ formation of black holes

What info from Nuclear Collisions ?

- Heavy-ion reactions with **neutron rich nuclei**, **from low up to relativistic energies**, can be used to study the **properties** of the **symmetry term** of the nuclear interaction in a **wide range** of **densities** → Heavy-ion collisions provide the **only means** to **compress/expand** nuclear matter in a terrestrial laboratory.
- Nuclear reactions are modeled by solving **transport equations** based on **mean field theories**, with **correlations** included via **hard nucleon-nucleon elastic and inelastic collisions** and via **stochastic forces**
- **Stochasticity** is essential in order to get distributions as well as to allow for the growth of **dynamical instabilities**.



So far these **properties** were studied with **stable beams**.
With availabilities of **radioactive beams** those studies can be extended.

Study of the **nuclear matter properties** under constraint, particularly the **density dependence** of the **symmetry term.**

- **Dynamical studies** → microscopic properties like **viscosity, transport properties, symmetry term, in medium n-n cross section…**
- **Thermodynamics and de-excitation of hot nuclei** → macroscopic properties like the **level density parameter,** the **limiting T,** the **E^*_{max},** the **Coulomb barrier…**

In both cases the **simulated excited (hot) fragments** must be **de-excited** before comparing with experiment. **reaction time 10^{-22} –10^{-21} s; detection time 10^{-8} -10^{-7} s**

NEOS & Symmetry Energy

First determination of Csym: at T=0 and $\rho=\rho_0$ from binding energy fits using LD mass formulas

$$E_{sym}(N,Z) = C_{sym}(A)\frac{(N-Z)^2}{A}$$

Bulk term only (Bethe-Weizsacker)

$$C_{sym}(A) = C_{sym} \approx 32\ \text{MeV}$$

Bulk + surface terms (Myers &Swiatecki, Moller&Nix)

$$C_{sym}(A) = c_v + c_s A^{-1/3}$$

Accepted values of C_{sym} : 28-32 MeV

Can we access Csym at finite Temperature?

It can be studied through well characterized nuclear sources

S. Wuenschel,…S.Yennello. Phys. Rev. C 79, 061602(R) (2009)

Isoscaling of fragments	Isobaric Yield Ratio	m-scaling of fragment yields
-> statistical fragment production, same T	-> Modified Fisher Model **	-> Landau free energy approach***
$Y(N,Z)$	$Y(A,I),\quad I=\frac{N-Z}{A}$	$Y(A,Z)$
$R_{21}(N,Z)=\frac{Y_2(N,Z)}{Y_1(N,Z)}= C\exp(\alpha N+\beta Z)$	$R(I+2,I,A)=\frac{Y(I+2,A)}{Y(I,A)}$	for mirror nuclei:
$\frac{C_{sym}}{T}=\frac{\alpha}{4\left[\left(\frac{Z}{A}\right)_1^2-\left(\frac{Z}{A}\right)_2^2\right]}$ *	$\frac{C_{sym}}{T}\approx-\frac{A}{8}\{\ln R(3,1,A)-\ln R(1,-1,A)-c\}$	$\frac{C_{sym}}{T}=\frac{1}{4}\ln\left(\frac{Y_2}{Y_1}\right)$

* M.B.Tsang et al. Phys.Rev.Lett 86, 5023 (2001)

** R.W. Minich et al. Phys. Lett. B 118, 458 (1982)

*** R. Tripathi et al. (2010)

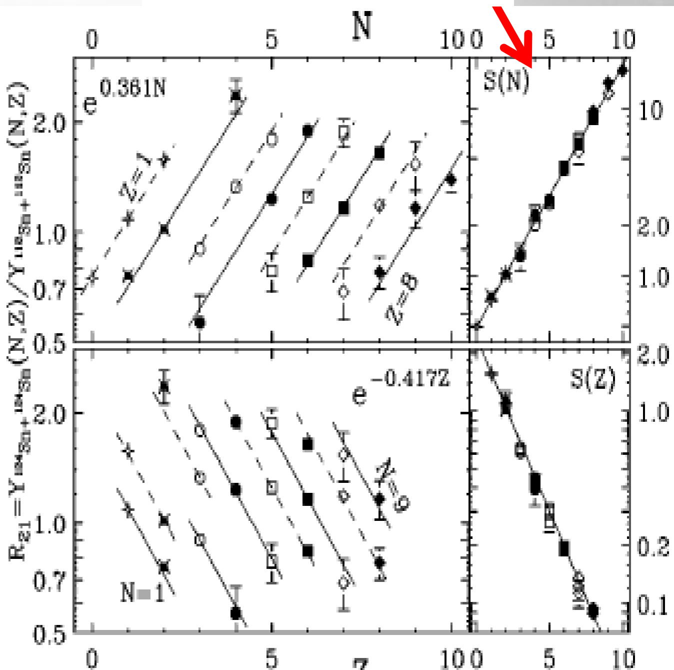
P. Marini talk @ ASY-EOS 2010
Isoscaling, SMM & the symmetry energy: connecting the dots

Symmetry Energy & ISOSCALING

Compact representation

Ratios to amplify the signal

$S(N) = R_{21} \cdot \exp(-\beta Z)$



Universal scaling law: isoscaling

M.B. Tsang et al., PRC 64 (2001) 041603.

isoscaling formulae

$$\frac{Y_2(N,Z)}{Y_1(N,Z)} = C\exp\left[\alpha N + \beta Z\right]$$

$$S(N) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \exp -\beta Z$$

$$S(Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \exp -\alpha N$$

Isoscaling

if statistical reaction mechanisms and close T in both systems.

It can be studied through well characterized nuclear sources

Wuenschel,…S.Yennello. Phys. Rev. C 79, 61602(R) (2009)

The comparison between two reactions is necessary:
Measurement of the **Production yield** of a **given isotope** produced in two reactions leading to a nuclear system with **similar mass** but **different isospin.**

R_{21}=Y2(N,Z)/Y1(N,Z)

Hypothesis: yield ratio is independent of secondary decay → α and β do not change if we measure secondary (cold) fragments
→ drawback: THIS IS NOT CONFIRMED IN ALL MODELS!

- Very **model-dependent** analyses (fragment formation)
- **Secondary decays** may distort sensitivity to **Esym(ρ)**

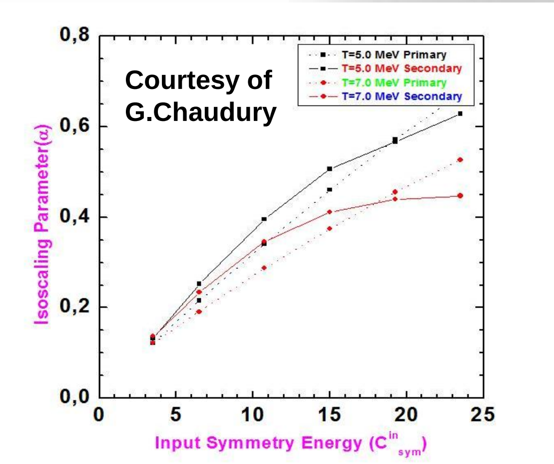
Hot fragment Csym in the formalism (grancanonical)

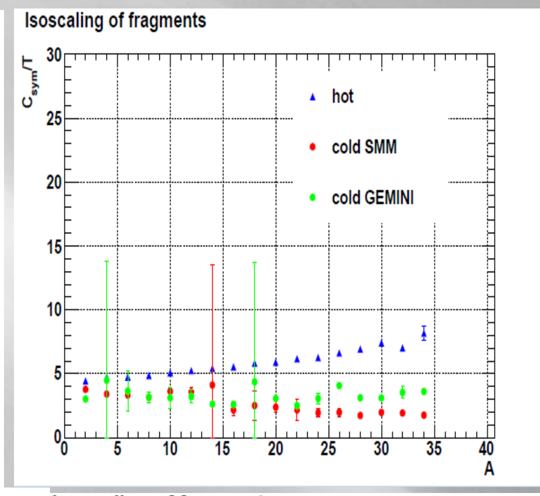
$$4C_{sym}(Z)/T = \alpha / \left[\left(\frac{Z}{\langle A\rangle_1}\right)^2 - \left(\frac{Z}{\langle A\rangle_2}\right)^2\right]$$

If Csym do not depend on Z → $(Z/A)_{frag} = (Z/A)_{source}$

$$4C^{frag}_{sym}/T = \alpha / \left[\left(\frac{Z_{S1}}{A_{S1}}\right)^2 - \left(\frac{Z_{S2}}{A_{S2}}\right)^2\right]$$

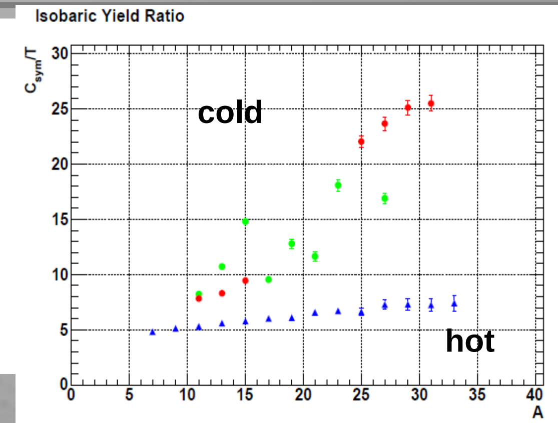
NEOS & Symmetry Energy



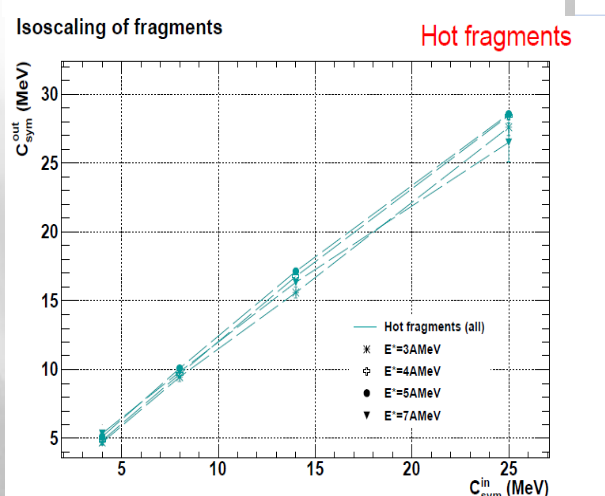


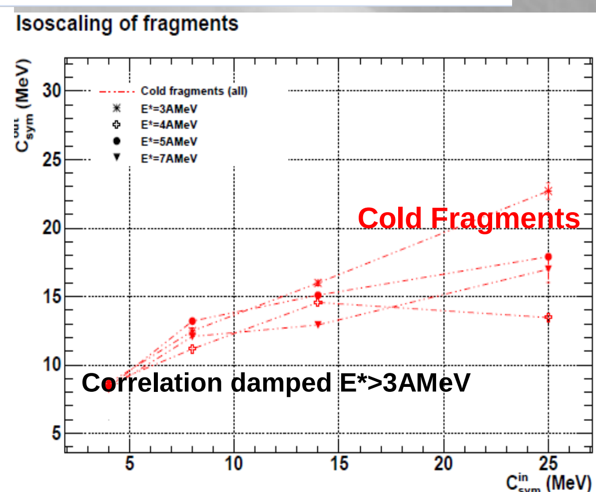
P. Marini talk @ ASY-EOS 2010

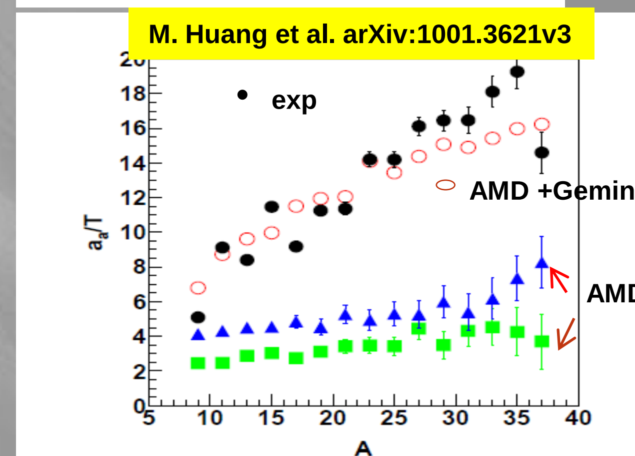
Isoscaling, SMM & the symmetry energy: connecting the dots



Model and analysis dependent



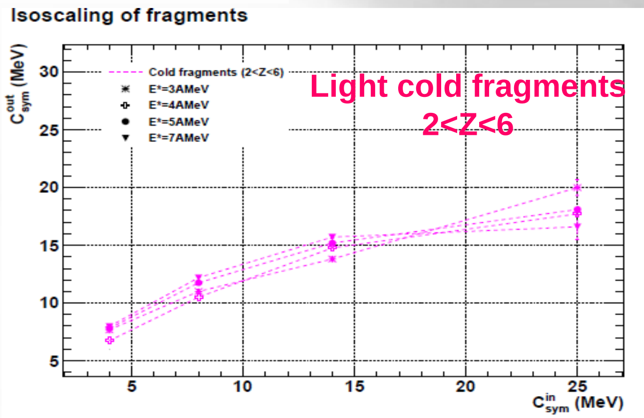


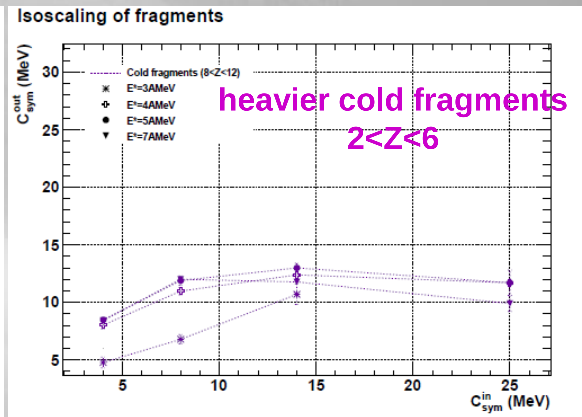


Good values between input and output for E<3AMeV (almost no secondary decay)
Wrong values for E>3AMeV→ damped correlations

Extract information on $\mathbf{E_{sym}}$ starting from **cold fragments -**
effects of **secondary decay** on observables
The importance of these effects will vary according to the observables employed for extraction of the desired information.

NEOS & Symmetry Energy





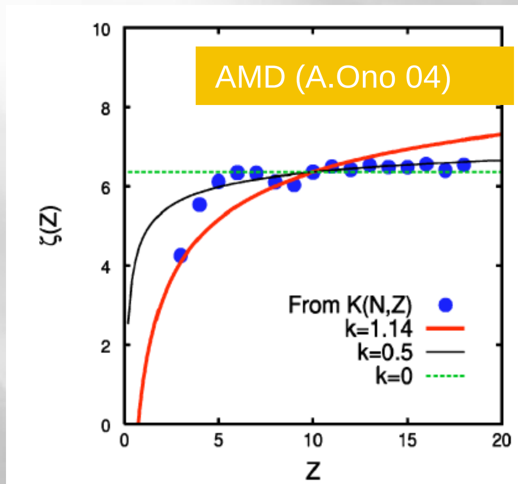
Correlations between *input* and *output* **Csym** are **still present** for very **light** fragments but **washed** out for the **heaviest**

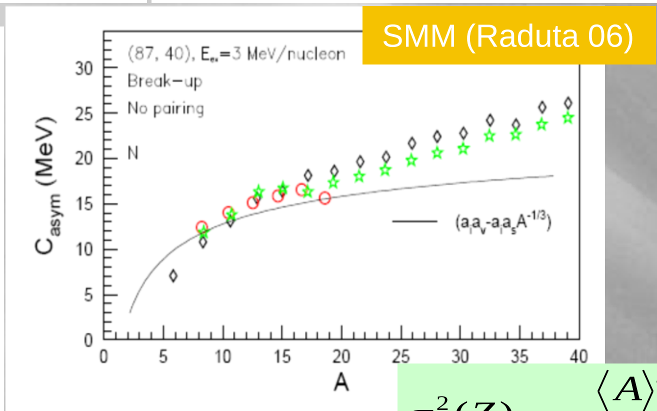
M-scaling

Landau expansion of free energy near the critical point

$$\frac{F}{T} = \frac{1}{2}am^2 + \frac{1}{4}bm^4 + \frac{1}{6}cm^6 - \frac{H}{T}m$$

m (=N-Z)/A: Order parameter
H : External field





$$\sigma_I^2(Z) = \frac{\langle A \rangle T}{2C_{sym}(Z)}$$

One reaction is enough

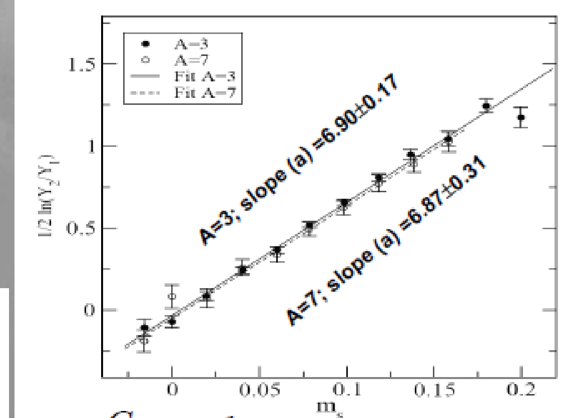
M.Colonna, B.Tsang; Eur. Phys. J. A 30 (2006) 165
Ad.Raduta,F.Gulminelli; PRC75 (2007) 044605

For mirror nuclei yield ratio (ignoring the higher order terms)

$$\frac{1}{2}\ln\left(\frac{Y_2}{Y_1}\right) = am_s$$

Source Isospin

$$\frac{C_{Sym}}{T} \approx \frac{1}{2}a$$



$$\frac{C_{Sym}}{T} \approx \frac{1}{2}a$$

Second method: extract the symmetry energy of the primary fragments with Z and A studying the **width of the mass distribution** for every isotope (under assumption of a gaussian A distribution), which is predicted to be **directly related to Csym** both if fragmentation occurs at **equilibrium** or **out of equilibrium**

secondary decay is even more important and may distort the information

NEOS & Symmetry Energy

Secondary decay effects

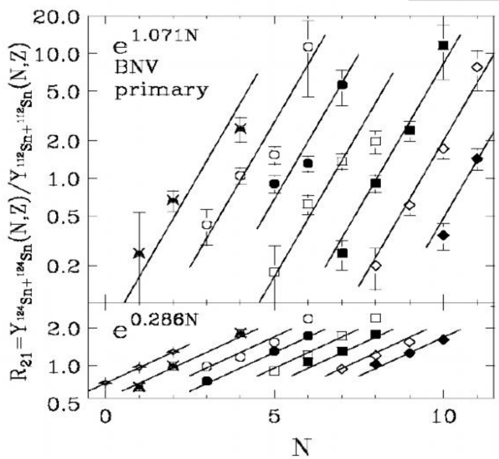
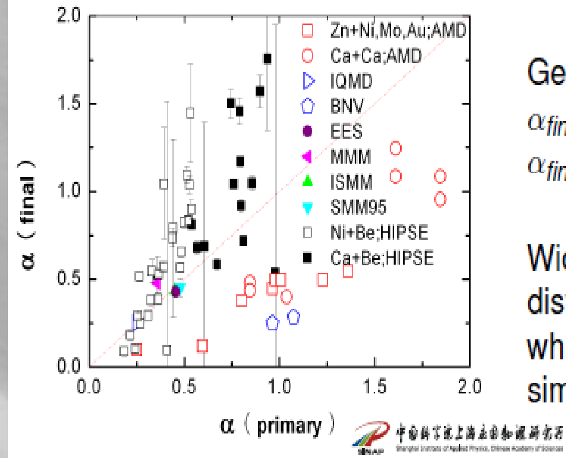


Fig. 5-5. Stochastic transport simulations of $Sn+Sn$ central collisions at $50AMeV$. Isoscaling behaviors: primary fragments (upper curves); after sequential decays (lower curves).

The determination of the symmetry energy from the **dynamical model comparison** is highly **model dependent**, and the assumption of a single form of the symmetry energy at different densities questionable.



Generally

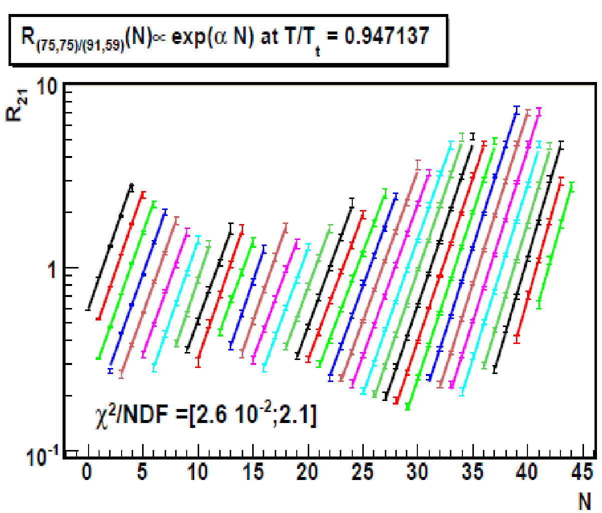
$\alpha_{fin} \geq \alpha_{prim}$ in stat. mod.

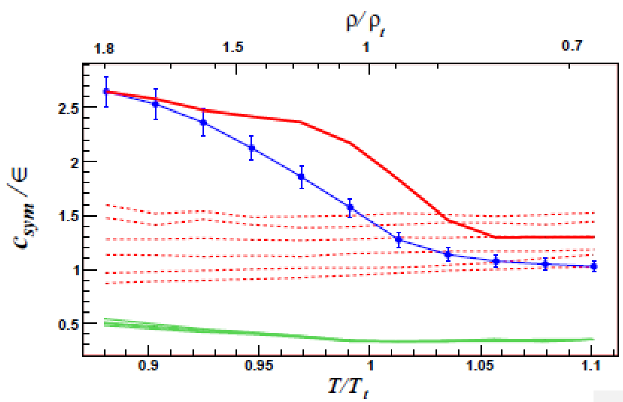
$\alpha_{fin} \leq \alpha_{prim}$ in dyn. mod.

Widths of excited isotopic dist. smaller in Dynamical, while final widths are more similar in both cases.

Isoscaling in the Lattice Gas Model: Z_{max} is promising

α(Zmax) qualitatively is in a better agreement with the input symmetry energy





Input model - $\langle \alpha_{Z=2-7} \rangle\ \Delta(\frac{N}{Z})$ source

dotted: α for Z=2 to 7, $\Delta(\frac{N}{Z})$ fragments

full: α for Z_{max}, $\Delta(\frac{N}{Z})$ fragments

Need to detect and identify Z_{max}
New devices with large angular coverage and good resolution up to high Z→ e.g. FAZIA or $FAZIA_{dem}$+INDRA/ $FAZIA_{dem}$+CHIMERA

G. Lehaut et al. PRL 102, 142503 (2009)

NEOS & Symmetry Energy

Particle emission due to unstable states need to be checked

Prediction of the contributions to the total (final) spectrum due to fragments unstable for particle emission. The spectrum of detected α particle contains about 30% of secondary particles.

These de-excitation of **«hot» fragments** produce a **«staggering» effect** in the isotopic distributions

M. D'Agostino et al. Nucl.Phys.A861(2011)47

At **low energy** we can study effects close to the **multi-fragmentation threshold** (cold produced fragments). The experimental reconstruction of the primary fragment through **correlation techniques of secondary decays** in such moderately excited fragments will allow us to **trace back** the primary fragmentation pattern minimizing the model dependence of the procedure.

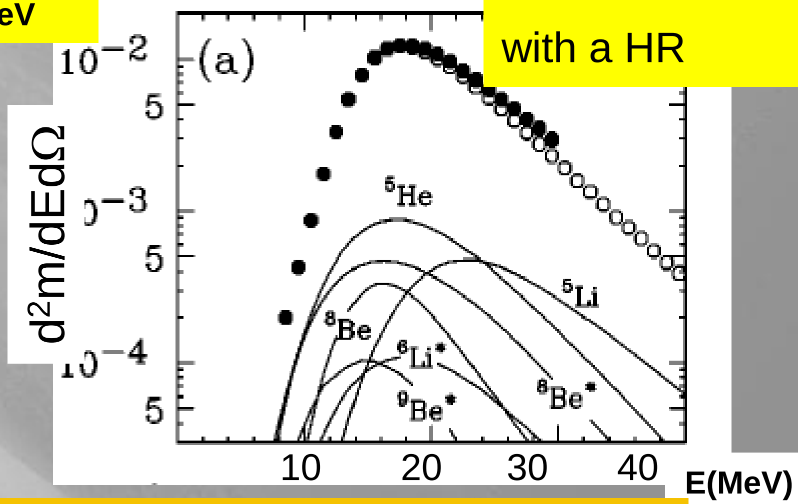
Better knowledge of hot light nuclei:

- **Statistical decay** of hot light nuclei (C -Ca): T_{lim}, E^*_{max} ? control of the secondary decay in multifragmentation (characterization of the freeze-out stage)
- Studying the **decay of isobars** populated at the same E*

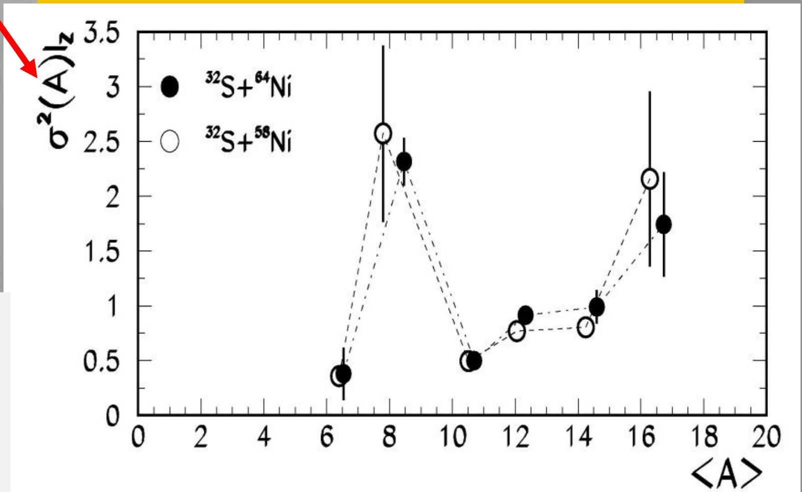
R.Charity et al PRC63(2001)024611

^{60}Ni+^{100}Mo 11 A.MeV

α-particles in coincidence with a HR

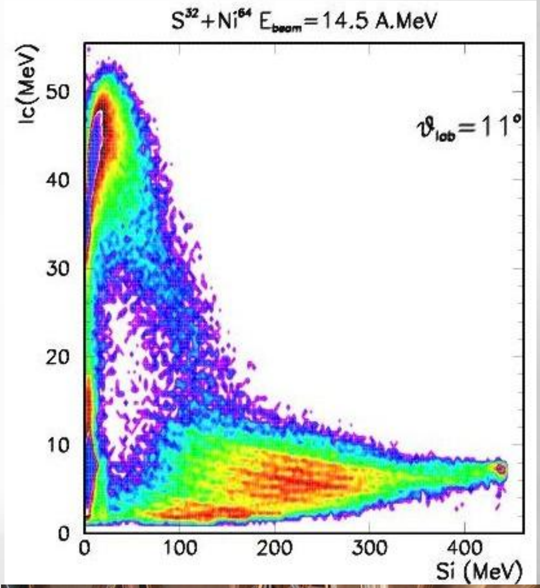


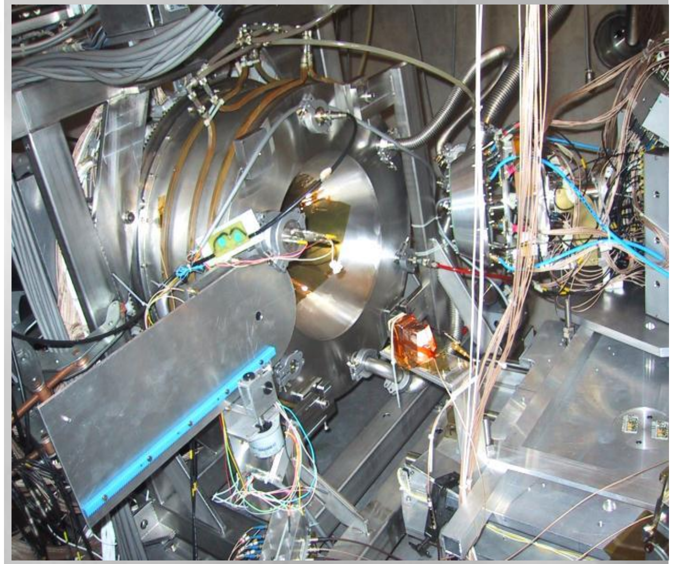
GARFIELD @ ALPI 14.5 AMeV

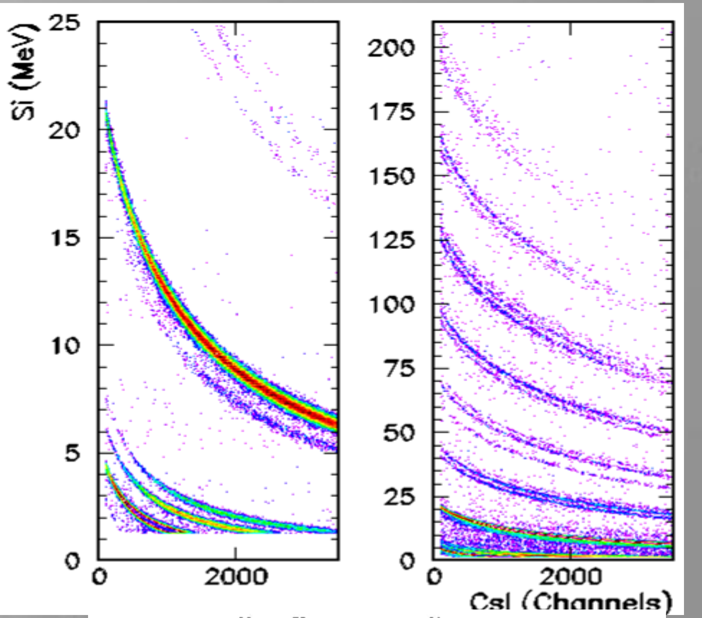


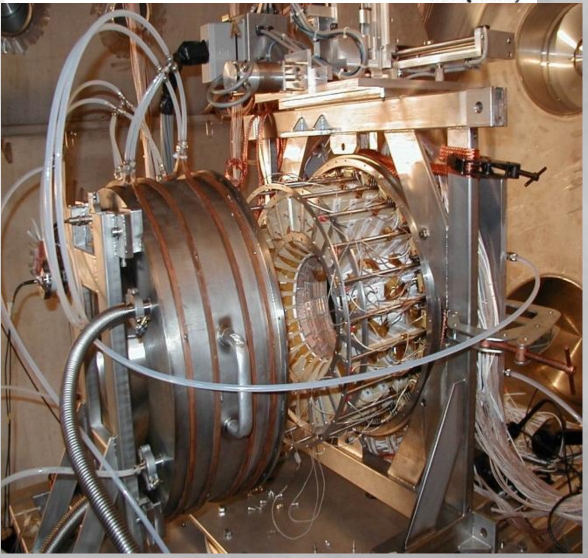
Experiments with n-rich/poor systems at low energy: euroRIB'12

$^{32}S+^{58}Ni$, ^{64}Ni 14.5MeV/A (N/Z=1., 1.22, 1.05)





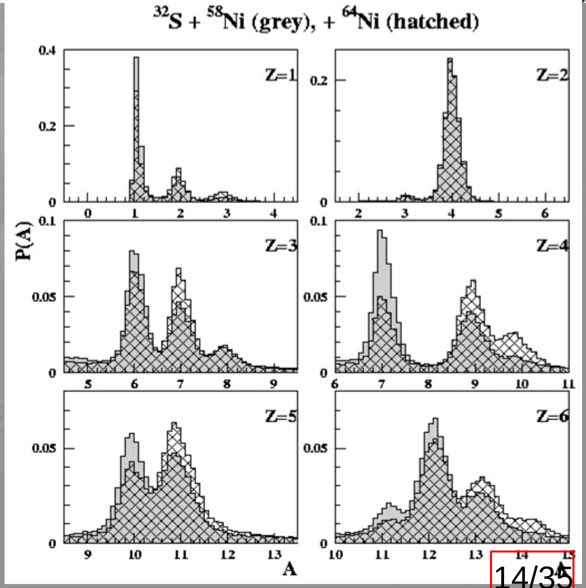




What info from the liquid part of the caloric curve?

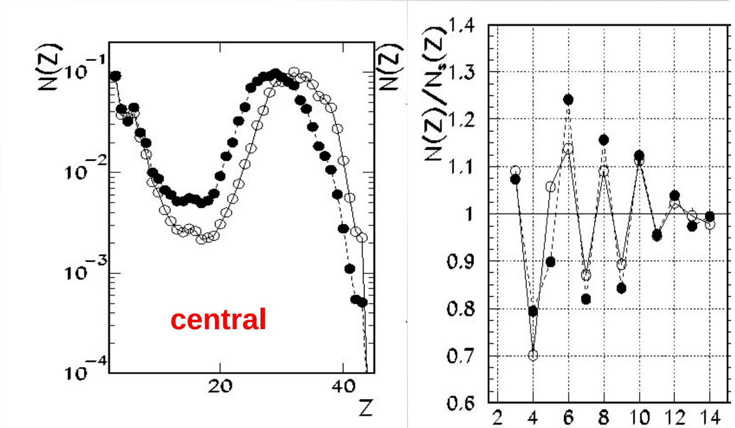
E_P/A_P < 25 A MeV A_{P+T}~100

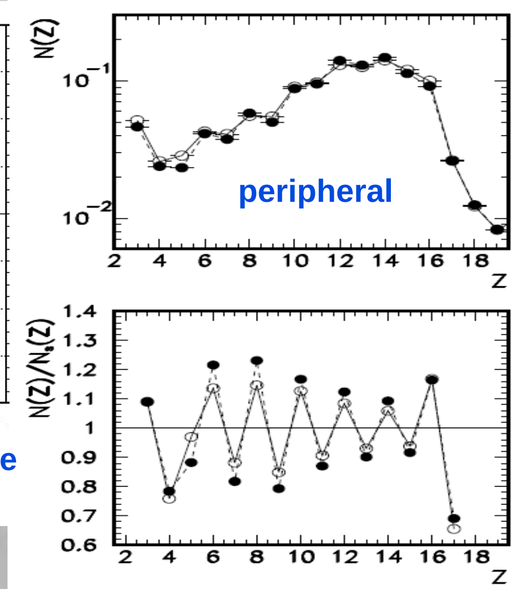
- very low threshold : Ion gasChamber (ΔE)
- High granularity: 400 ΔE-E telescopes ϑ ≈4°-150°
- Mass identification in the Ring Counter (PSA in Silicon) (1<=Z<=12) ϑ ≈20°
- Digital electronics
- LCP mass discrimination from CsI (Z<=4) on the whole solid angle

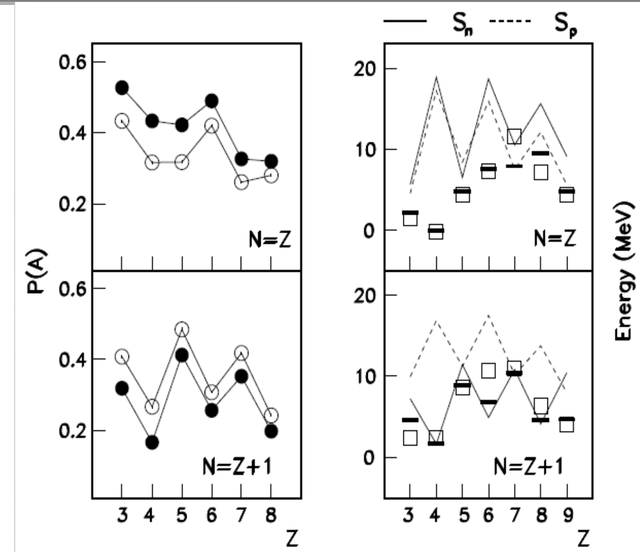


nucl-ex&garfield collab.

Experiments with n-rich/poor systems at low energy: $^{32}S+^{58}Ni$, ^{64}Ni 14.5MeV/A (N/Z=1,05, 1.18)





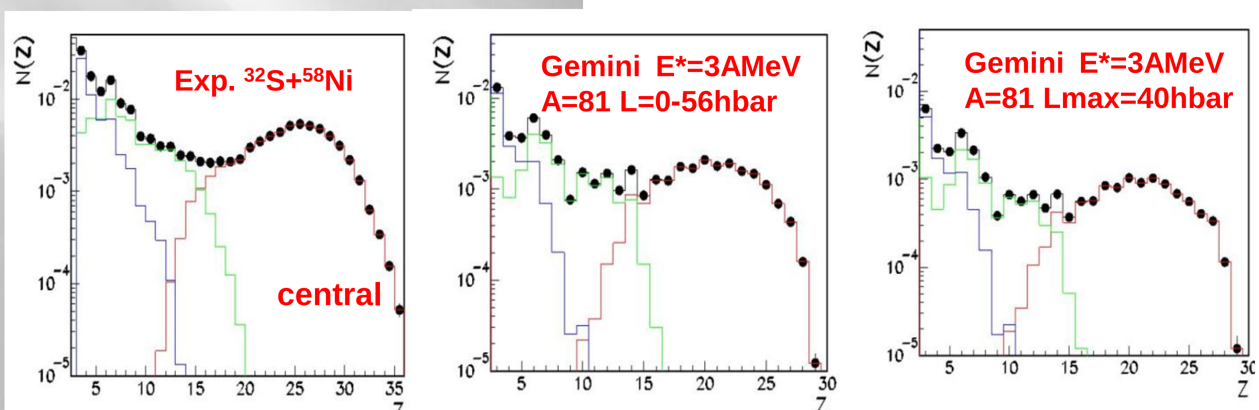


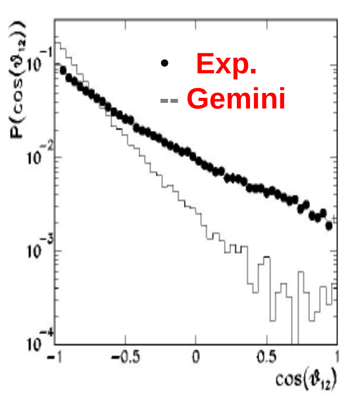
peripheral

More n-rich system → more pronounced U shape
Staggering also in central events

5% of well measured central events: at least 3 fragment (IMF Z≥3).

odd-even staggerings depend on the **whole evaporation chain** and not only on the energy balance of the last evaporation step.





Smallest, second and third largest fragment distributions

Not only sequential decay?
More structure info needed in Multi-fragmentation models for the decay of primary fragments

M. D'Agostino et al. Nucl.Phys.A861(2011)47

NEOS & Symmetry Energy

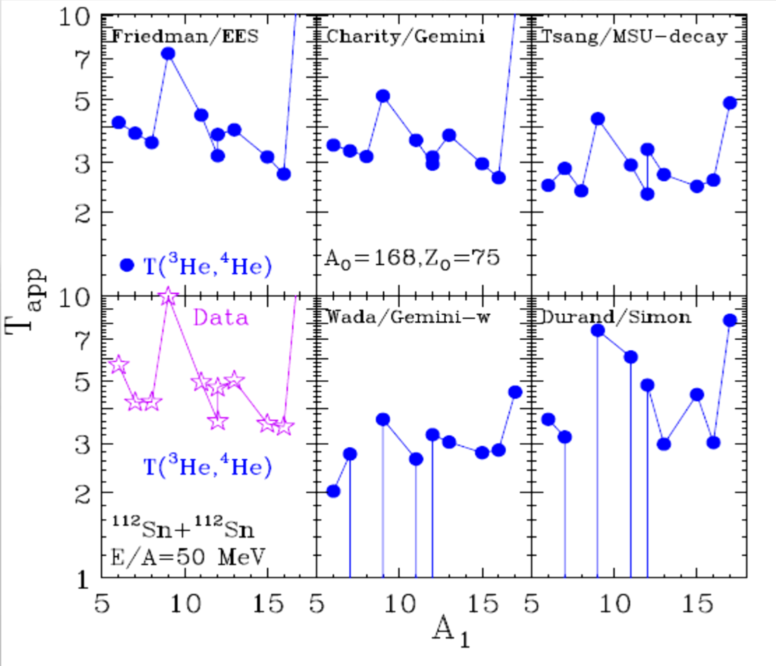
W.P. Tan et al.,Phys.Rev.C69,06130 (2004).

Measurement of the population of unstable states towards particle emission through the method of **correlation functions**

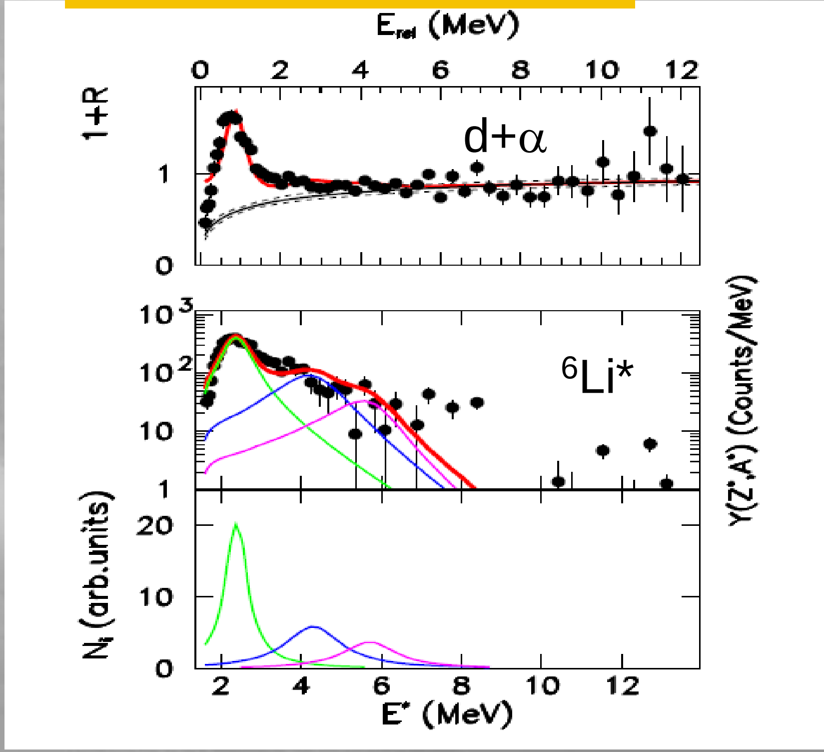
Coulomb background

Breit-Wigner

total (Breit-Wigner Coulomb subtracted)



GARFIELD @ ALPI 14.5 AMeV



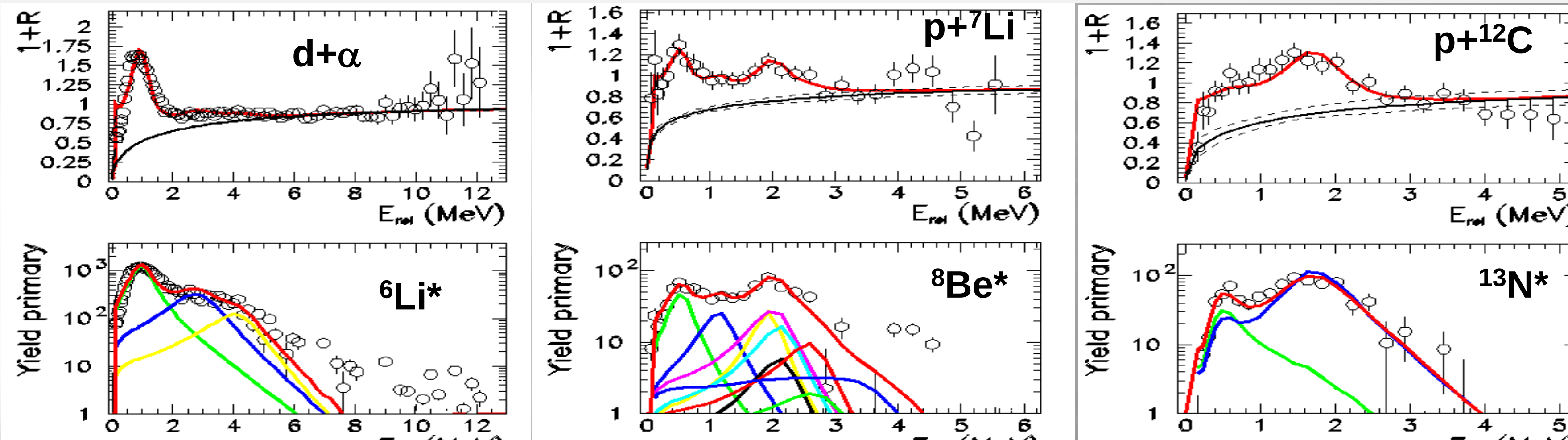
M. D'Agostino et al. Nucl.Phys.A875(2012)139

- Benchmark for the level density through evaporative models **(Gemini,SMM-MSU,ABLA07…)**
- New evaporation code HF (PhD Thesis G.Baiocco Univ. Bologna- Univ. Caen)

B.Tsang et al., in "Dynamics and Thermodynamics with nuclear Degrees of freedom", Springer 2006

NEOS & Symmetry Energy

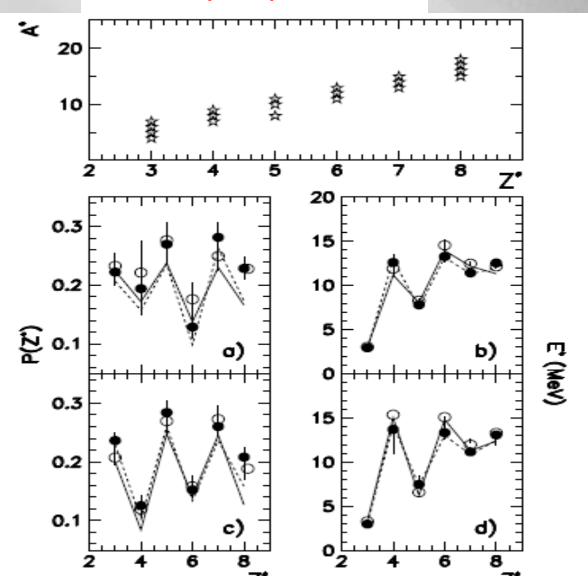
Last decay stadium can be reconstructed through **correlation functions**→ need of **experimental devices** with optimal angular and energy resolution (**GARFIELD+RINGCo, FAZIA, FARCOS etc.**)



E*= 2.2, 4.3, 5.6 MeV

E*=1.8-2.0 MeV

E*=2.3, 3.5 MeV



Primary fragment yields to be reconstructed after Coulomb background subtraction
Up to 23 resonances observed *from Li* to O**

The primary fragments

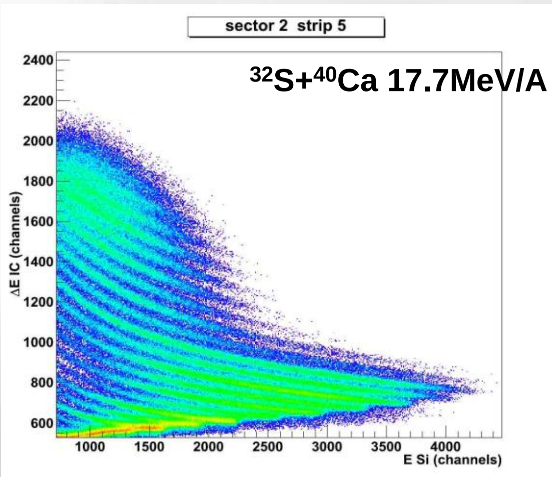
The decay probability is larger and the excitation energy lower for odd Z than for even Z.

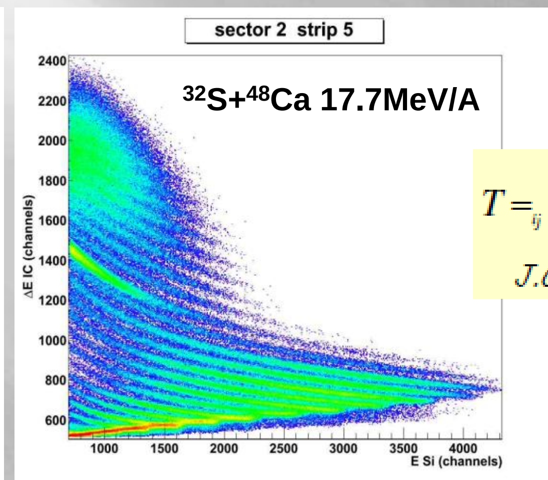
Isotopes reconstruction by the correlation function technique in two data set ($^{32}S+^{58}Ni$ and $^{32}S+^{64}Ni$ at 14.5 MeV/n). From the primary yields one can calculate the **average decay proabilities** and the **excitation energy** for every parent nucleus.

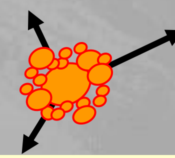
Experiments with n-rich/poor systems at low energy: $^{32}S+^{40}Ca$, ^{48}Ca, ^{48}Ti 17.7MeV/A (N/Z=1., 1.22, 1.05)

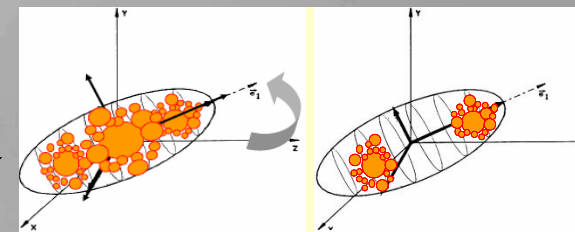
GARFIELD + RING Counter: **Central collisions**: we expect that close to the multifragmentation threshold, the produced fragments will be relatively **cold**. The experimental reconstruction through **correlation techniques of secondary decays** in such moderately excited fragments will allow us to **trace back the primary fragmentation pattern** minimizing the model dependence of the procedure.

Analysis in progress







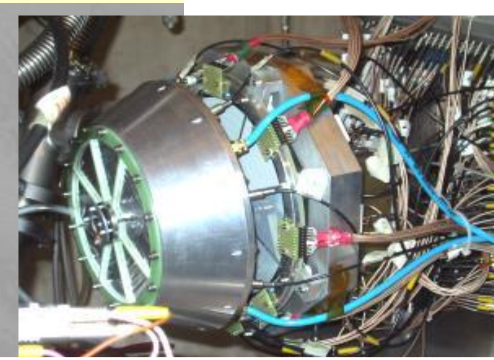


$$T_{ij} = \sum_{k=1}^{M} p_i^{(k)} p_j^{(k)} w^{(k)} \quad (i,j=1,3)$$

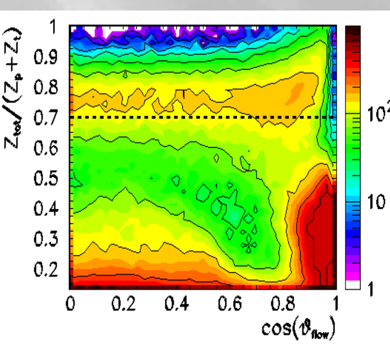
J.Cugnon,NPA(1985)

Sorting the events:

- **Peripheral collisions**: many sources,
- **Central collision** one source



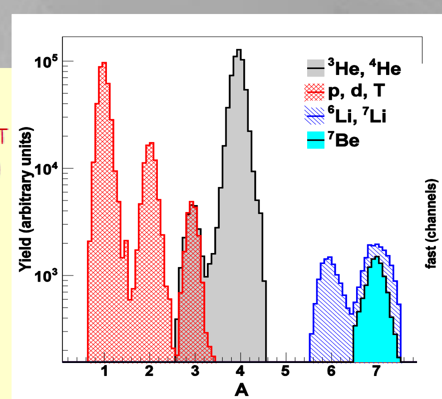
Level densities at low excitation energy are known to exhibit **important isotopic** and **odd-even effects**, resulting in **staggering effects** in different isotopic observables.

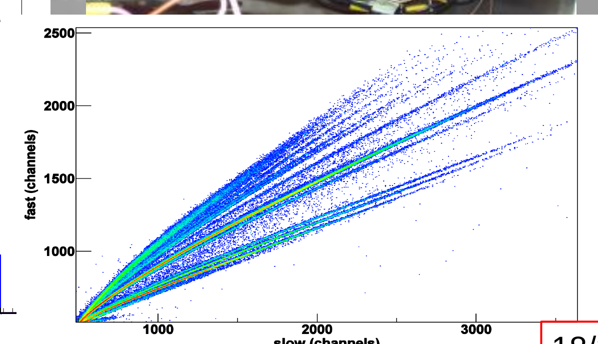


PCA analysis;

For events where Ztot >70% Z_{P+T} and θ_{flow} >60 ° (central collisions)

1. Comparison with models, source characterization ($Z, A, \varepsilon^*, T, \rho$)
2. Isotope analysis for different classes of events





NEOS & Symmetry Energy

Recently, Natowitz & co-workers have shown that the **symmetry energy at very low densities ((0.01 - 0.05)ρ_0)** can be explained by quantum statistical calculation that includes **cluster correlation in nuclear medium**. At densities higher than **0.2-0.3ρ_0** the many body correlation disappears and the symmetry energy follows the dependence predicted by the **mean field** calculations.

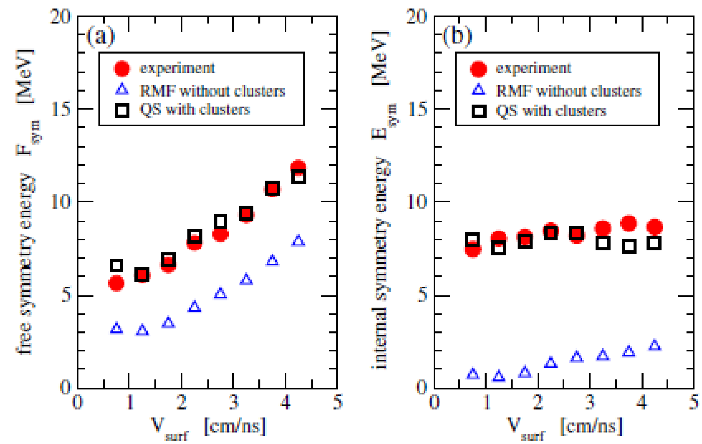
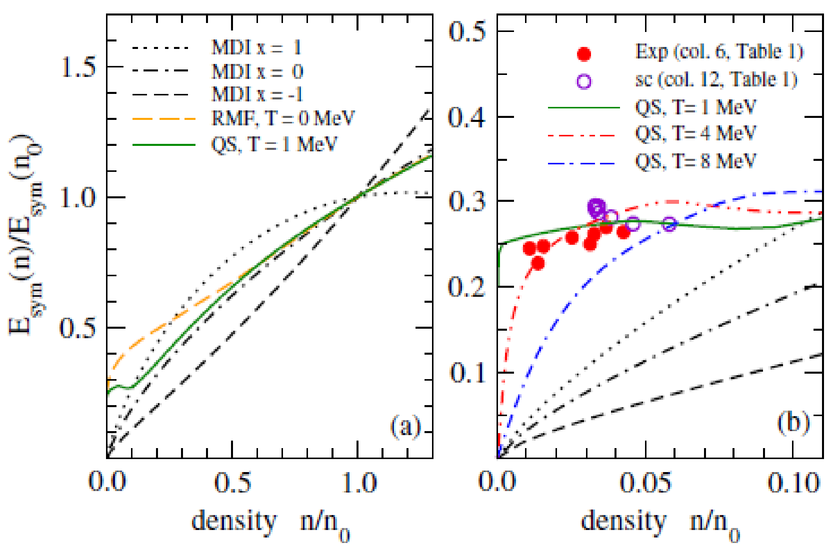


FIG. 1 (color online). Free (a) and internal (b) symmetry energy as a function of the surface velocity. Experimental results are compared with results of theoretical calculations neglecting cluster formation (RMF) and including cluster formation (QS).

^{64}Zn on ^{92}Mo and ^{197}Au at 35 MeV



New data from heavy-ion collisions can be used to extract the free symmetry energy and the internal symmetry energy at **subsaturation densities** and **temperatures below 10 MeV**. Conventional theoretical calculations of the symmetry energy based on mean-field approaches fail to give the correct low-temperature, **low-density limit** that is governed by correlations, in particular, by the **appearance of bound states**. A recently developed quantum-statistical approach that takes the **formation of clusters** into account predicts symmetry energies that are in very good agreement with the experimental data.

Transport Properties & Symmetry Energy

Transport equation for the one-body distribution function f,
Stochastic Mean Field (SMF) approach

Chomaz,Colonna, Randrup Phys. Rep. 389 (2004)
Baran,Colonna,Greco, Di Toro Phys. Rep. 410, 335 (2005)

$$\boxed{\frac{df(r,p,t)}{dt} = \frac{\partial f(r,p,t)}{\partial t} + \{f,h\} = I_{coll}[f] + \delta I_{coll}}$$

Residual interaction: Correlations, Fluctuations

The nuclear interaction, contained in the Hamiltonian h, is represented by effective interactions (Skyrme)

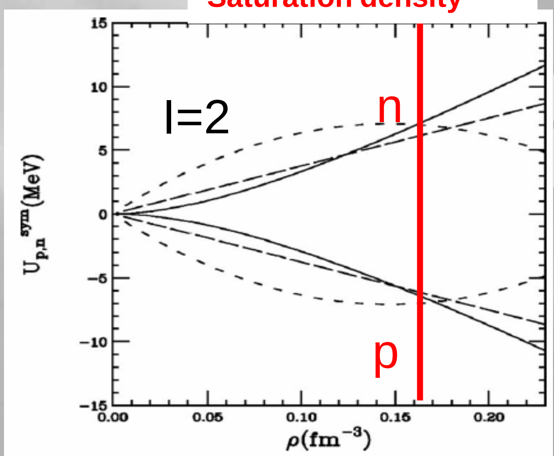
Transport models predict **fluctuations of large amplitude** in the **density matter** during the **dynamic phase** of the collisions

• We can **observe** these **fluctuations** by measuring the **isotopic distributions** in the mid-velocity region

• **Competition** between (incomplete) **fusion** and **deep–inelastic** reactions=> information on the **density behaviour** of the symmetry energy, the **viscosity** and **in medium n-n cross section.**

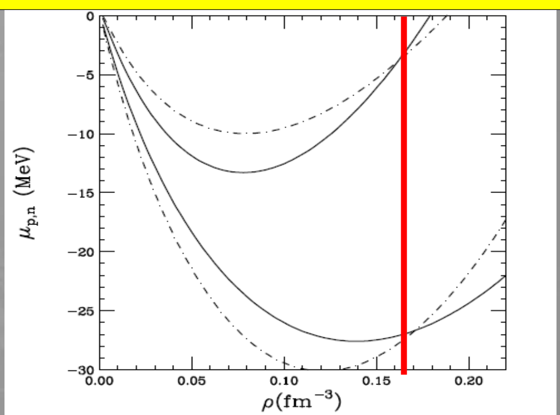
Comparison with theory gives access to **transport properties** such as the dependence of the symmetry term on density

Saturation density

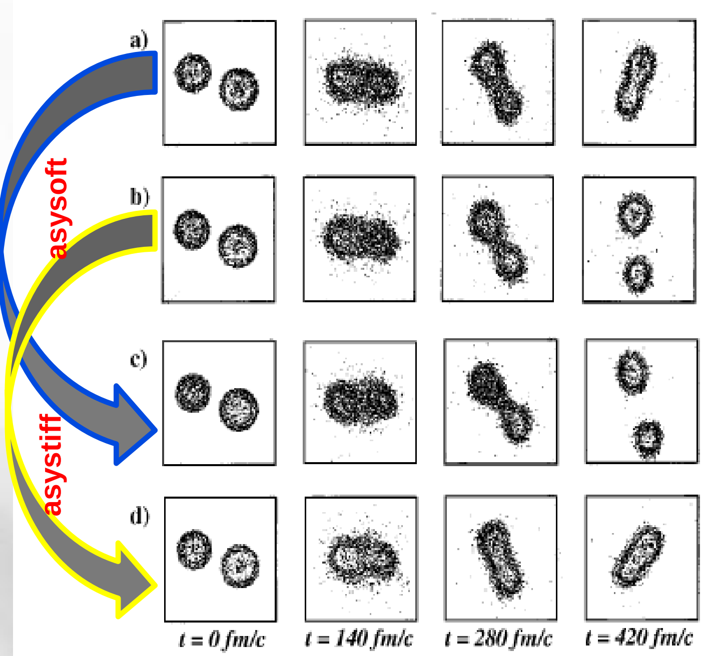


asysuperstiff
asystiff
asysoft

Larger isospin distillation in asysoft case



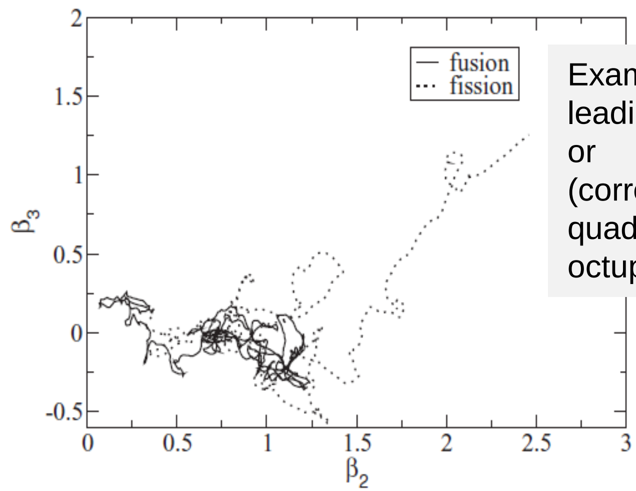
Competition of reaction mechanisms:
fusion versus break-up processes
(deep inelastic and fragmentation)



n-rich
^{46}Ar+^{64}Ni
N_P/Z_P=1.56
N_T/Z_T=1.29

n-poor
^{46}V+^{64}Ge
N=Z

Fig. 5-1. Density plots at different times in a reaction between neutron-rich ions $(a, b : ^{46}Ar + ^{64}Ni)$ and neutron-poor ions $(c, d : ^{46}V + ^{64}Ge)$. (a, c): *asysoft* symmetry term; (b, d): *asystiff*. See text



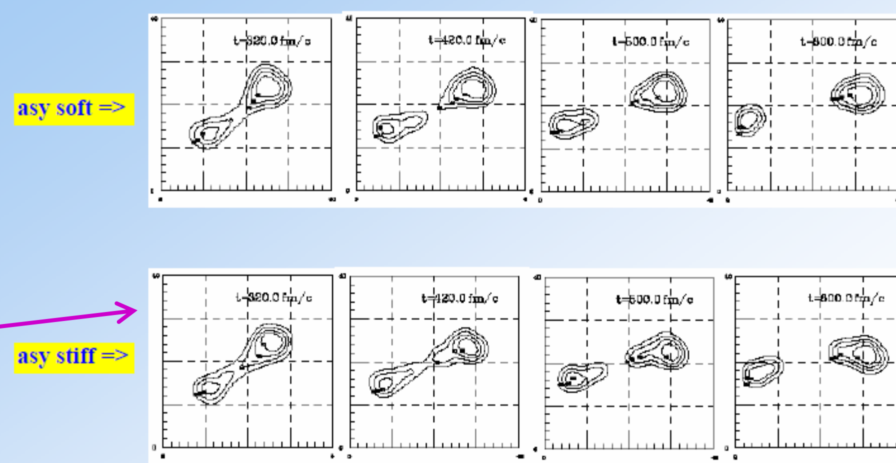
Example of trajectories leading either to **fusion** or to **break-up** (correlations between quadrupole and octupole moments)

n-rich → asysoft →less repulsion **→ fusion**
n-poor→asysoft→more repulsion (larger Coulomb)**→ deep inel**.

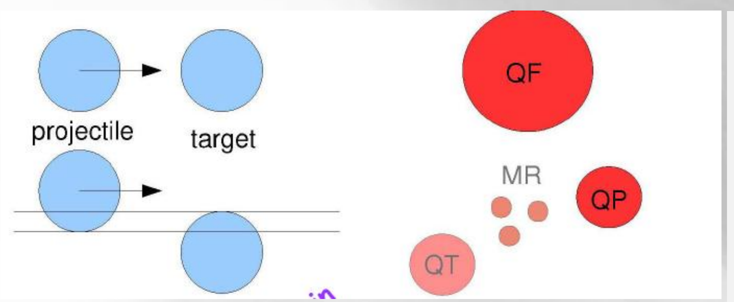
Less repulsion at low density (**neck**) **larger surviving probability**
Presence of the **neck**: observable to constraint the **symmetry energy**

BNV calculation: ^{124}Sn+^{64}Ni @ 10 A.MeV b=7fm

Maria Colonna: stochastic BNV calculations (private communication)



Competition of reaction mechanisms: fusion versus deep inelastic

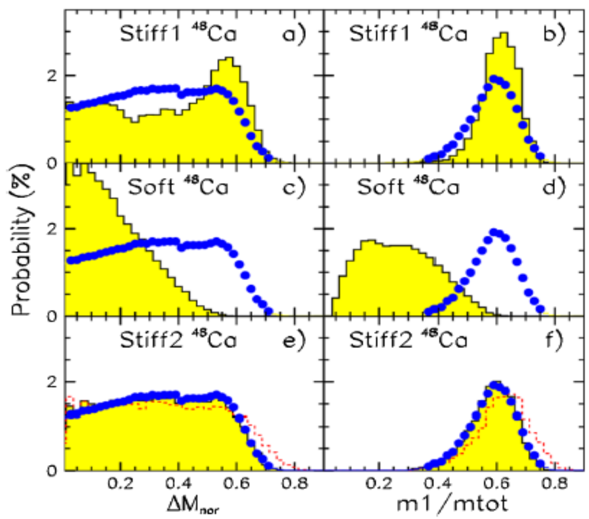


Effect of isospin: amount of **repulsion** existing during the interaction of the 2 surfaces;

n-rich systems → fusion is favoured with **asy-soft** (proton symmetry field **more actractive** → interaction between incoming nuclei **stronger**

n-poor systems → fusion easier with **asy-stiff:** due to **proton skin** (repulsion) **p** are promptly emitted →Coulomb decreases →**fusion enhanced**

Amorini et al. PRL 102(2009)112701

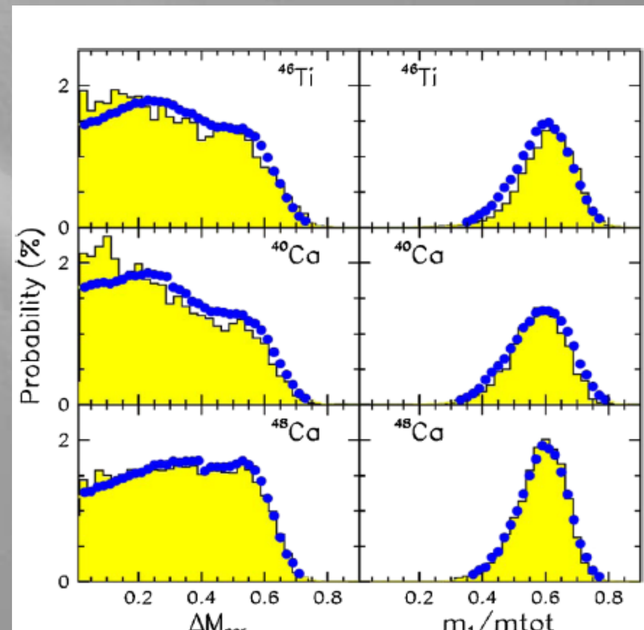


$$\Delta M_{nor} = (m_1 - m_2)/m_{tot}$$

• data two largest fragments

CoMDII+Gemini simulations
3 symmetry energy terms:
γ= 0.5 soft
γ=1.0 stiff2
γ=1.5 stiff1

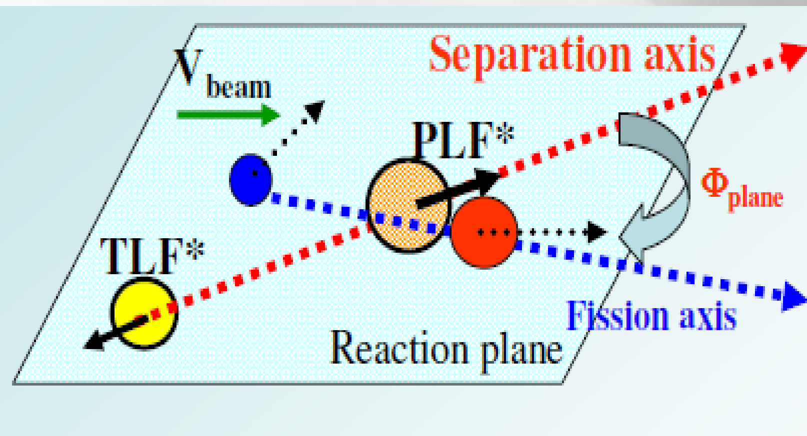
Comparison among 3 systems: compatibility with asystiff parametrization: **E_{sym}^{pot} linearly increasing with density**.



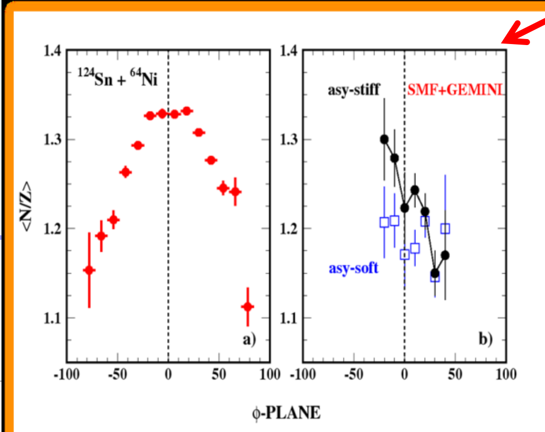
Incomplete fusion cross section at 25 MeV/A with ^{40}Ca projectile (CHIMERA - LNS data)
The more n-rich entrance channel **^{40}Ca+ ^{48}Ca** push the CN towards the stability valley
The two N≈Z systems **^{40}Ca+ ^{40}Ca, ^{40}Ca+ ^{48}Ti** push CN towards the proton drip line

NEOS, symmetry energy and neck fragmentation

Neck fragmentation observed at 10-50 AMeV incident energies in **semi-peripheral heavy ion collisions**: Emission of **light products (Z<10)** emitted in the interaction zone with a velocity intermediate between those of the 2 main partners (PLF/TLF) -

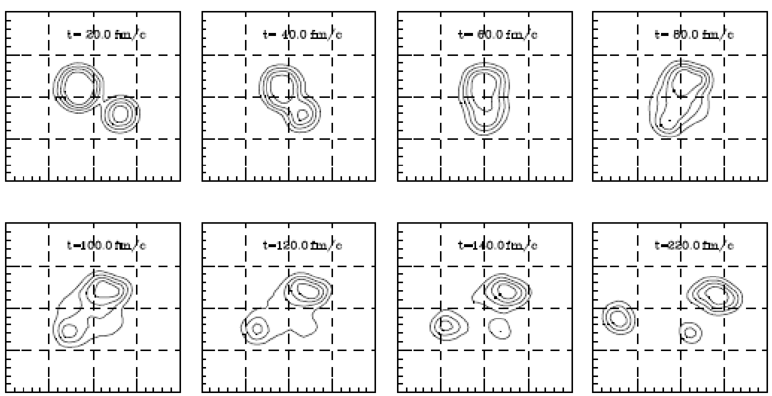


Characterization: alignement of PLF, TLF and neck fragments. Max of in-plane angular distribution at $\Phi_{plane}=0°$



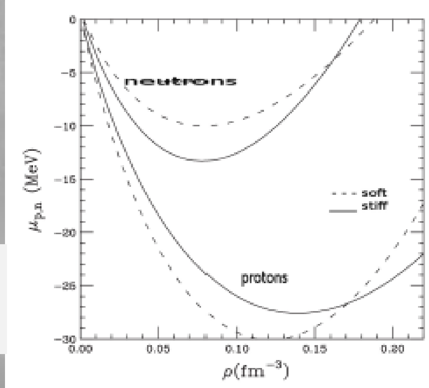
E. De Filippo - Chimera data

Asy-stiff: more isospin migration to the "neck" fragments. ***SMF calculations: more statistic needed to reach clear conclusions***



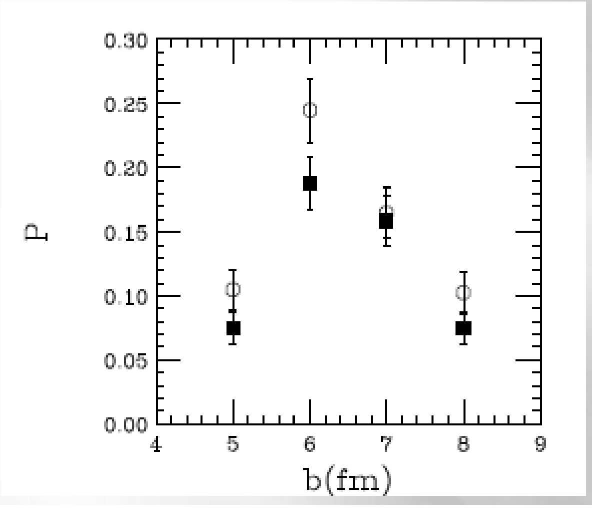
Typical densty plot for ^{124}Sn+^{64}Ni reaction at 35 MeV/n at b=6fm (semi-peripheral)

Isospin transport effects: neck fragments produced in a slightly dilute region, $\rho_0/2 < \rho < \rho_0$, in contact with normal density PLF/TLF : effects of drift coefficient.



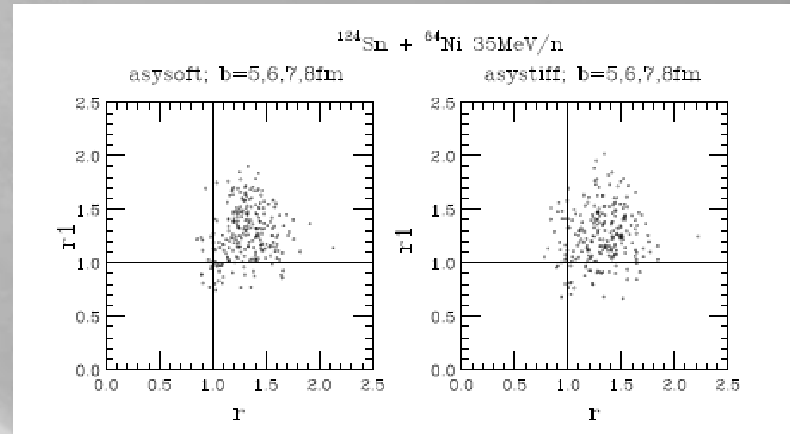
p and n move now in opposite directions:
p from neck to PLF/TLF
Larger n flow with asy-stiff EOS
neck-IMF more n-rich than MF-IMF

NEOS, symmetry energy and neck fragmentation



Impact parameter dependence of the neck emission for n-rich **(empty circles)** and n-poor **(black square)** systems

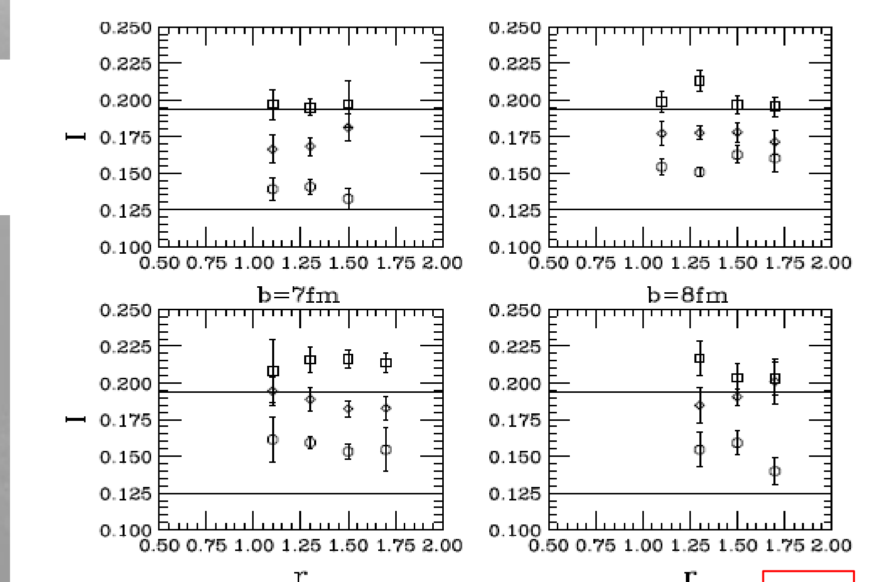
No **evident dependence** on symmetry term stiffness in fragment angular or relative velocities distributions, but asymmetry is still small in the considered cases.



New observables: **Wilczynski-2 plot**, that is

$r = v_{rel}(NIMF\text{-}PLF)/v_{Viola}(PLF)$

$r1 = v_{rel}(NIMF\text{-}TLF)/v_{Viola}(TLF)$



More clear: Stiffness of the symmetry term dependence on the **I** content of the Neck IMFs (NIMF):

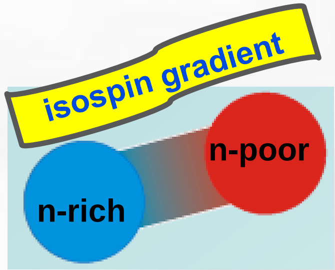
Squares: **superasystiff**

Rombs : **asystiff**

Circles: **asysoft**

NIMF are more **n-rich** than IMF from semicentral collisions. PLF and TLF **lower asymmetry** than NIMF

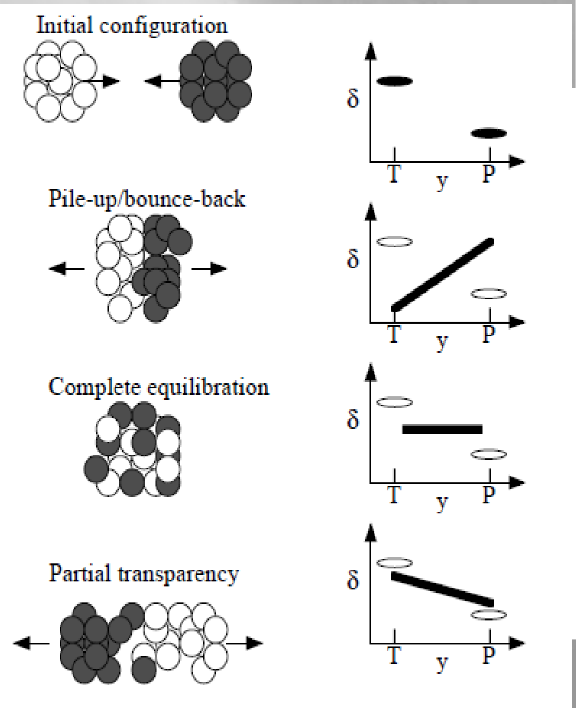
Isospin diffusion

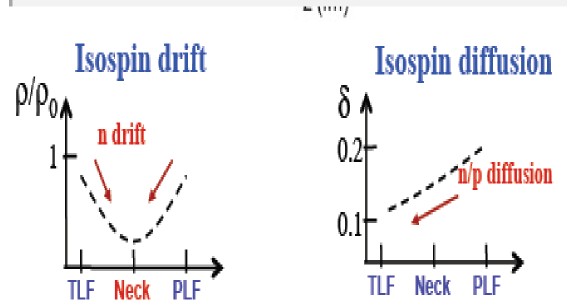


The question of whether or not **an excited nuclear system reaches** equilibrium **before decaying** is of importance when trying to determine **the events** that occur in hot nuclear matter just **prior to fragment emission**.
Isospin equilibrium is one **type of equilibrium** that **excited nuclear matter** can **achieve**.

N/Z equilibration depends on the **INTERACTION TIME** thus the **reaction impact parameter & beam energy** play a fundamental role**.** At **low energy (<20 AMeV)** is a **fast process (10^{-22}s)**
In the **Fermi energy domain**, the **time scale** for fragmentation decay becomes **comparable** to or **shorter** than the **time scales** characterizing the attainment of **isospin equilibration**

When two nuclei with **different N/Z asymmetries** come into contact, **diffusion of neutrons and protons** is initiated and continues until the system disintegrates or until the chemical potentials for neutrons and protons in both nuclei become equal.
The **rate of diffusion** is influenced by the **initial densities of neutrons and protons** in the emitting nuclei, the neutron and proton **mean free paths**, and the **mean field potentials**.
At **low energy** deep inelastic → diffusion influenced by **gradient of concentration** (no big density fluctuations)
At intermediate and high energy → diffusion is driven by the gradient of concentration and of density (through the **neck**)





$$\delta = \frac{N-Z}{N+Z}$$

The isospin diffusion proceeds along the neck region driven by the symmetry energy term strenght and it is favoured by a soft term of the ASY-EOS → enhance degree of equilibration

Isospin diffusion

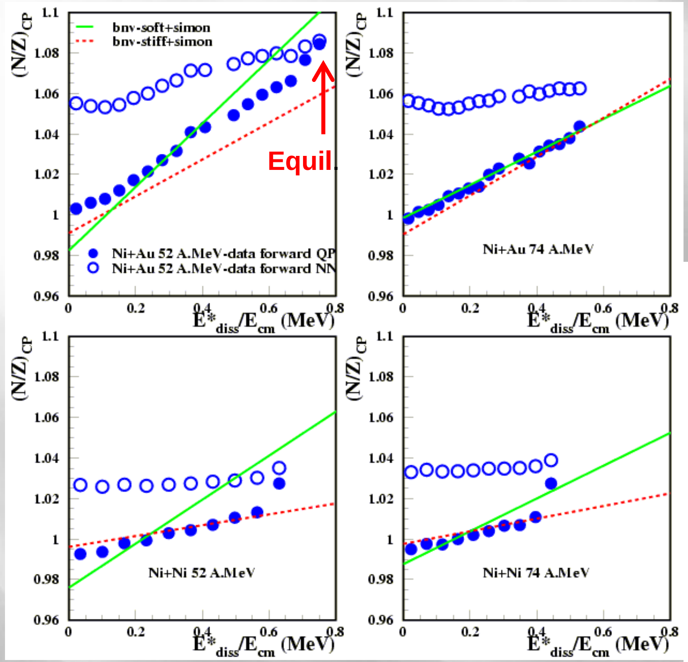
PHYSICAL REVIEW C 79, 064614 (2009)

Isospin diffusion in ^{58}Ni-induced reactions at intermediate energies. I. Experimental results

E. Galichet,[1,2,*] M. F. Rivet,[1] B. Borderie,[1] M. Colonna,[3] R. Bougault,[4] A. Chbihi,[5] R. Dayras,[6] D. Durand,[4] J. D. Frankland,[5] D. C. R. Guinet,[7] P. Lautesse,[7] N. Le Neindre,[1,4] O. Lopez,[4] L. Manduci,[4] M. Pârlog,[8] E. Rosato,[9] B. Tamain,[4] E. Vient,[4] C. Volant,[6] and J. P. Wieleczko[5]
(INDRA Collaboration)

$$R_i(X) = \frac{2X_{AB} - (X_{AA} + X_{BB})/2}{X_{AA} - X_{BB}}$$

Isospin Imbalance Ratio
from mixed and symmetric systems



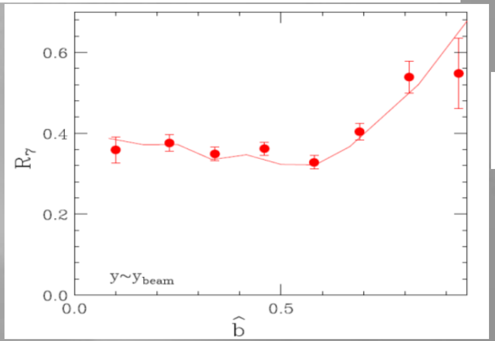
Evident diffusion in Ni+Au (N/Z =1.38) as compared to Ni+Ni (N/Z=1.07) as reference Asystiff better overall agreement

BNV used as a clock

- **For Ni+Au at 52 A MeV maximum measured dissipation corresponds to b=5 fm in BNV calculations that is t_{int}=130fm/c±10 fm/c → equilibration**

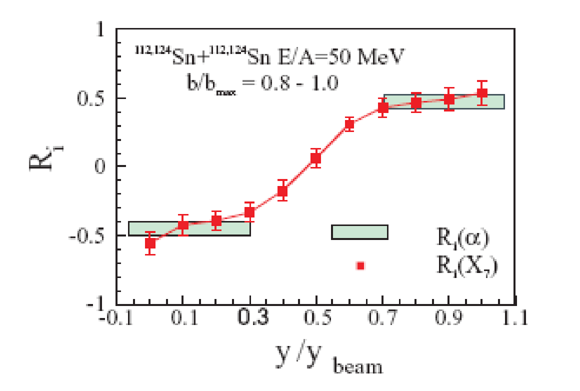
Forward NN ($V_{particle} > V_{lab}^{proj}/2$
forward QP frame ($V_{particle} > V_{rec}$QP)

Semiperipheral Collision measurements performed with **INDRA.** ***N/Z* ratio** for complex particles is plotted **as a function of the normalized dissipated energy** for the four reactions.



x_7=ln(Y(^{7}Li)/Y(^{7}Be))

linear function of the asymmetry
($\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$)
of the emitting source



R_i=+/-1 no diffusion
R_i=0 equilibrium

No equilibrium even for central collision at 35 MeV/A in the Sn case.

Upper limit energy for charge equilibration: & influence on exotic nuclei formation

Yoritaka Iwata et al. :arXiv:1001.0850v1 [nucl-th]

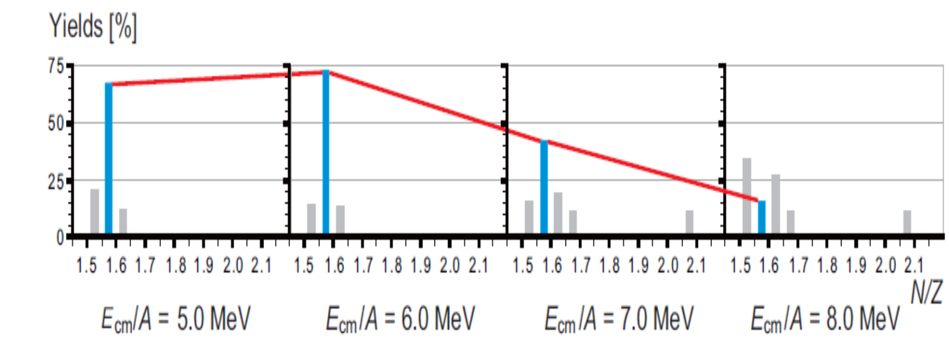


FIG. 1: Yield distribution of final fragments as a function of their N/Z ratios for the collisions of ^{208}Pb + ^{132}Sn (N/Z ratio is discretized by 0.05) based on TDHF calculation (SLy4d). Four cases with different E_{cm}/A values are presented. Columns corresponding to the equilibrium value of N/Z=1.58 are colored in blue, and connected by red lines. For reference, the N/Z ratios for ^{208}Pb and ^{132}Sn are 1.54 and 1.64, respectively.

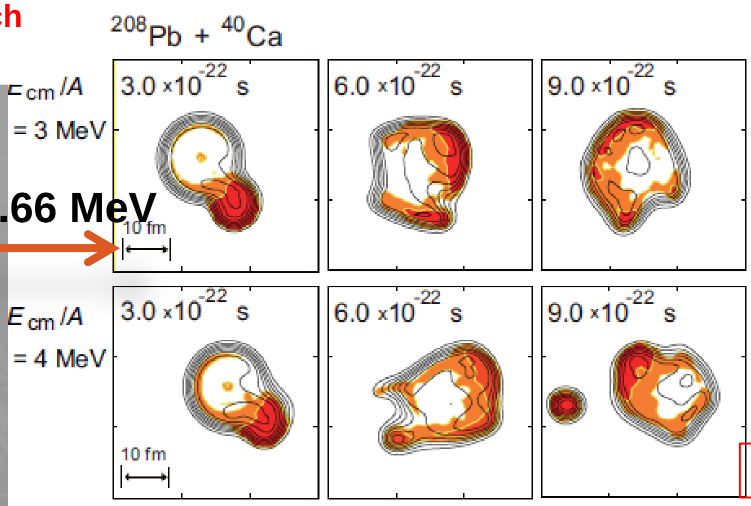
The **upper limit of the energy** in the laboratory frame **for charge equilibration** is expressed as the sum of the kinetic energy for velocity $v^F{}_{min}$ and the Coulomb energy at touching

The peak energy of the yield distribution as a function of N/Z is almost constant at the beginning, and **is shifted later** with the lowering of peak height. A **clear decrease of the yield of charge-equilibrated fragments** for **Ecm/A 7.0 MeV** is noticed. On the other hand, **very neutron-rich nuclei with N/Z 2.0** simultaneously start to be produced.

Real-time dynamics of charge distribution for ^{208}Pb + ^{40}Ca (SLy4d) is shown for a fixed impact parameter 7.5 fm. The upper and the lower panels show cases with E_{cm}/A= 3.0 MeV and 4.0 MeV, respectively.

The upper energy limit is 3.66 MeV, fusion appears at Ecm/A = 3.0 MeV (upper panels), and break-up is seen at 4.0 MeV(lower panels).
-**unstable fragments** are emitted only for the bombarding energy higher than the upper-limit; for instance, a small fragment in the lower-right panel is **^{62}Mn,** for which the stable isotope is ^{55}Mn.

$E_{cm}{}^{lim}/A$= 3.66 MeV



The level density parameter : Isospin and Temperature effects

The **Level density parameter** is closely connected to the **nuclear EOS** ⇒ it is important both for **nuclear structure** and for the **dynamics** and **thermodynamics of hot nuclei**

Many parameters influence the **level density parameter:**

- **pairing and shell effects**
- **surface effects**
- **deformation and angular momentum**
- **temperature**
- **isospin**

The level density parameter vanish at high E*, limitingT ? (rupture of the balance between surface, coulomb and bulk energies) and with **extreme isospin composition?**

→ **direct link** to **EOS**

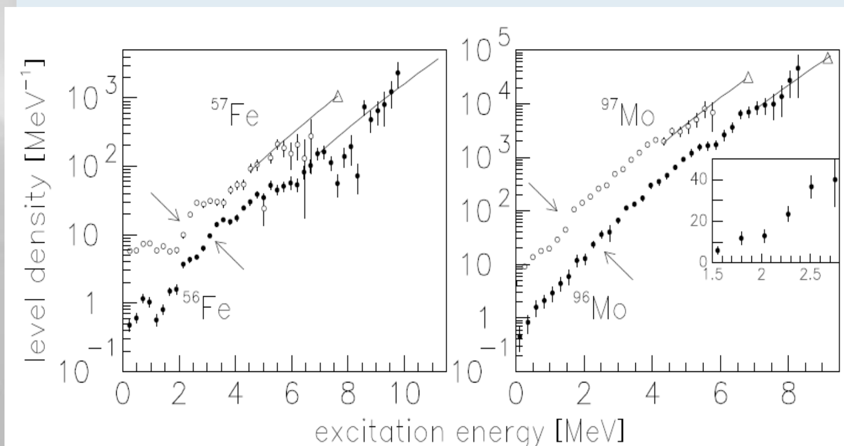
$$\rho(E^*) = \frac{\sqrt{\pi}}{12}\frac{\exp(2\sqrt{aE^*})}{a^{1/4}(E^*)^{5/4}}$$

$$\rho(E^*,J) = (2J+1)\left(\frac{\hbar^2}{2I}\right)^{3/2}\frac{\sqrt{a}}{12}\frac{\exp(2\sqrt{aU})}{U^2},$$

$$U = E^* - E_{rot}(J) \qquad E_{rot}(J) = \frac{J(J+1)\hbar^2}{2I}$$

$$a = \alpha A$$

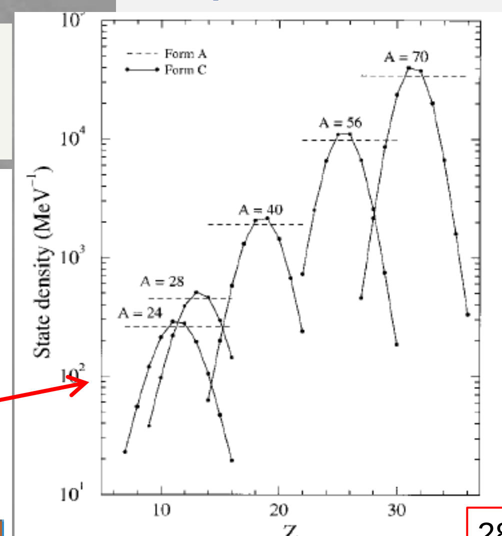
Does the level density parameter depend on isospin?



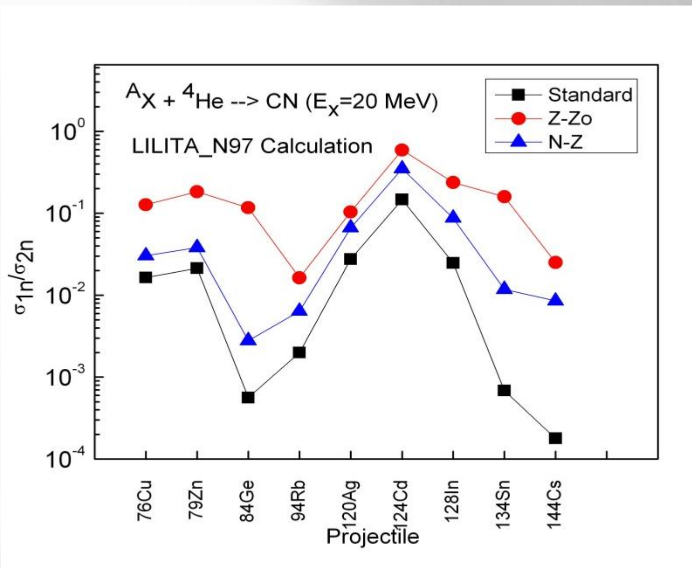
A. Schiller et al. – arxiV:nucl-ex/0302028v1(2003) Evolution of level density step structure

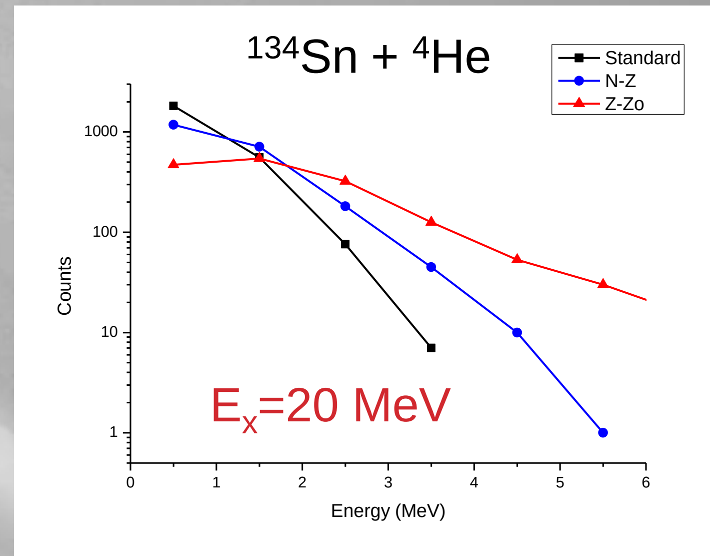
S.I. Al-Quraishi et al.- Phys. Rev. C63 (2001) 065803 & Phys. RevC67, 015803(2003)

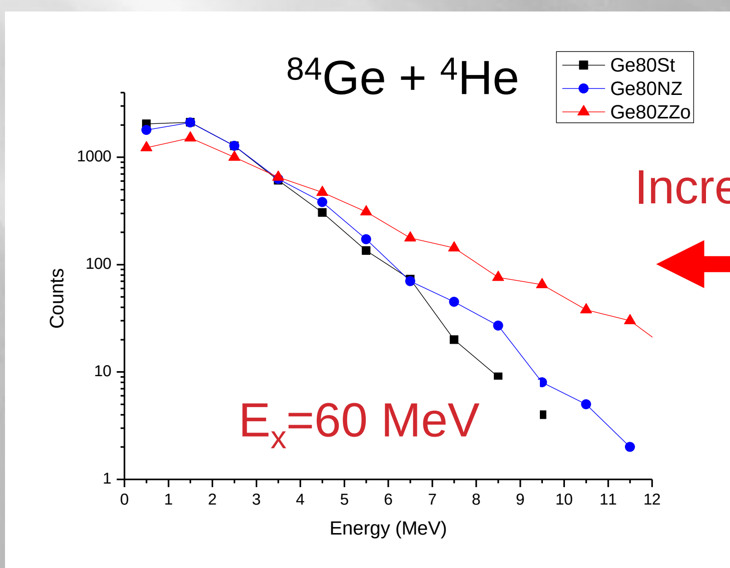
$$\alpha A$$
$$\alpha A + \beta A^{2/3}$$
$$\alpha A / \exp[\beta(N-Z)^2]$$
$$\alpha A / \exp[\gamma(Z-Z_0)^2]$$
$$\alpha A / \exp[\beta(N-Z)^2 + \gamma(Z-Z_0)^2]$$
$$\alpha A / \exp[(\beta(N-Z)^2+1)\gamma(Z-Z_0)^2]$$



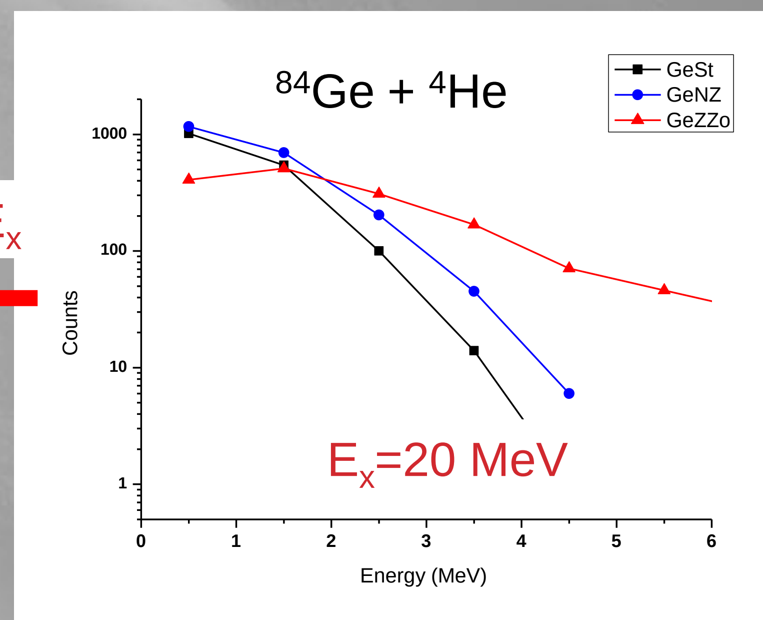
The level density parameter : Isospin and Temperature effects







Increasing E_x

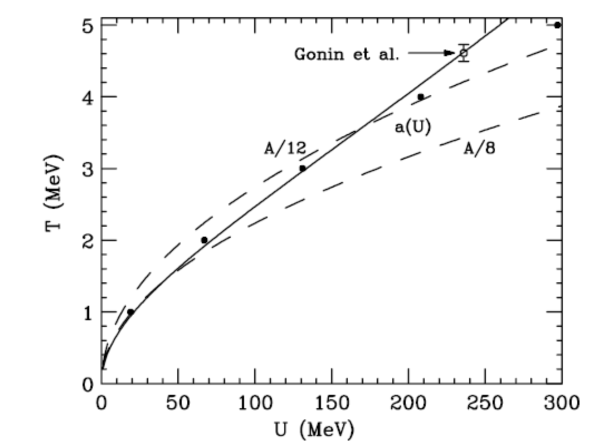


The level density parameter : Isospin and Temperature effects

$^{58}Ni + ^{92,100}Mo$ from 5 to 9 MeV/n (1 MeV/n step)

EAL: **evaporation attraction line** where **residues** are **«attracted»** due **to equal decay width for n & p**

As one move to **n-rich** side **n-decay width dominates**, to **p-rich p-decay dominates**

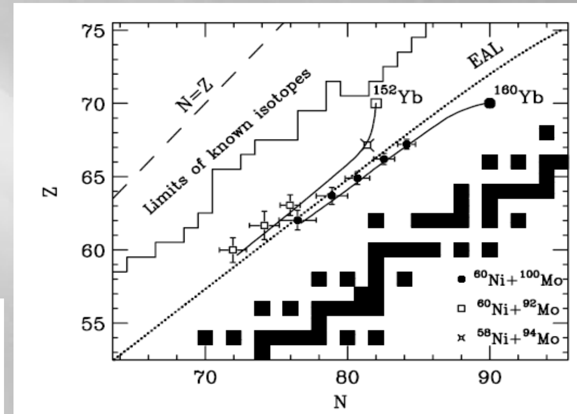


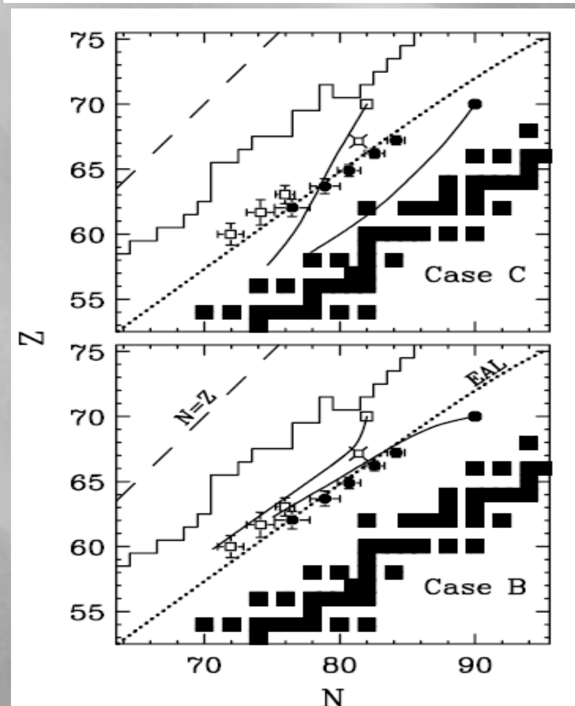
Temperature as a function of thermal excitation energy: solid curve from fitted excitation energy dependent level density parameter

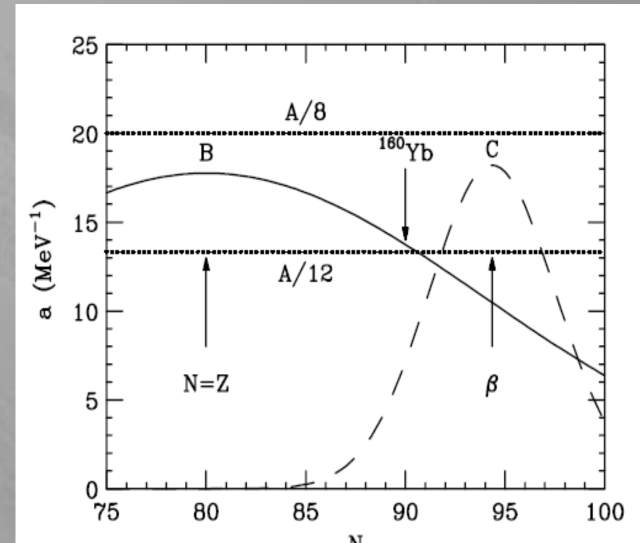
$$a(U) = A/(K + \kappa * U/A)$$

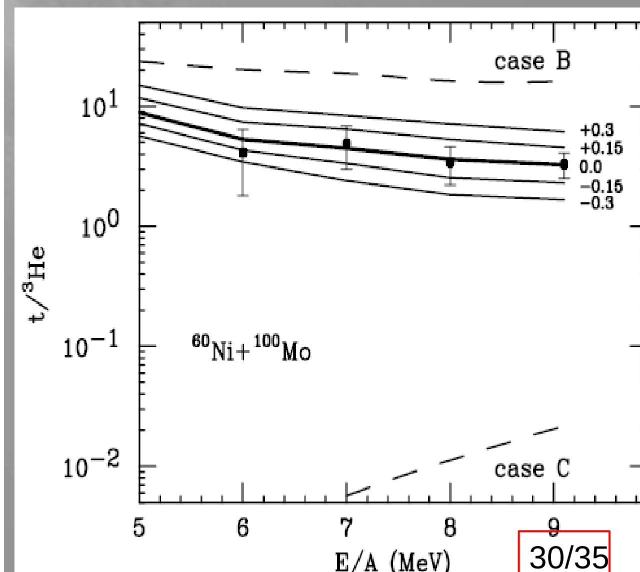
Is the dependence on isospin really strong as Al Quraishi predict?

R.J. Charity et al. Phys.Rev.C67,044611(2003)









Limiting Temperature and Coulomb Instabilities

Evolution with mass & chemical composition

PHYSICAL REVIEW C 69, 034321 (2004)

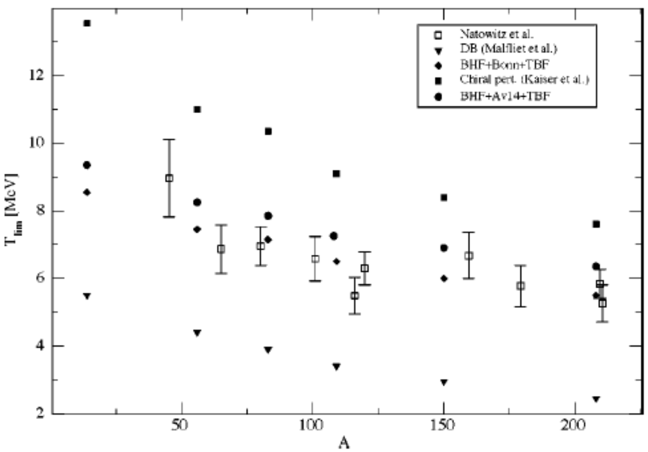


FIG. 3. Limiting temperatures as a function of mass numbers for different equations of state in comparison with the phenomenological values (open squares with error bars).

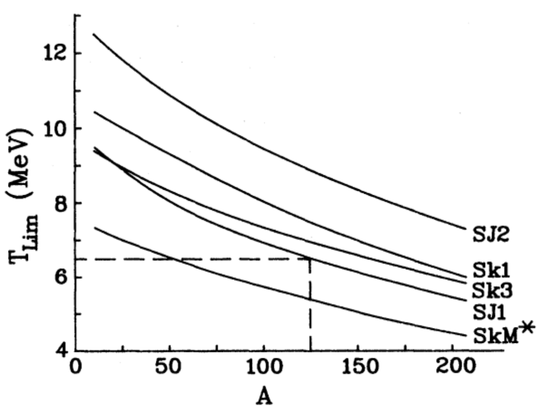
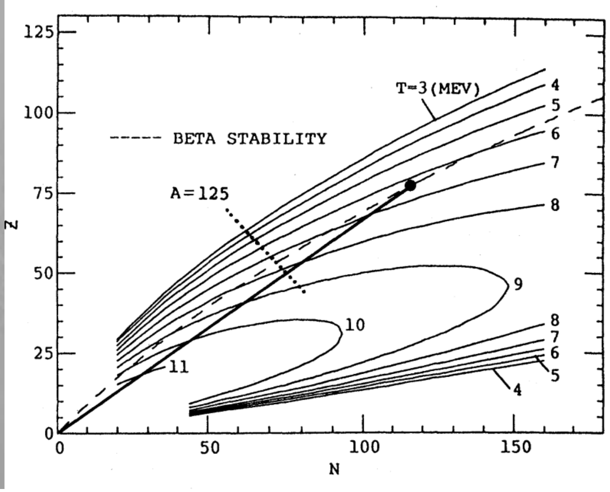


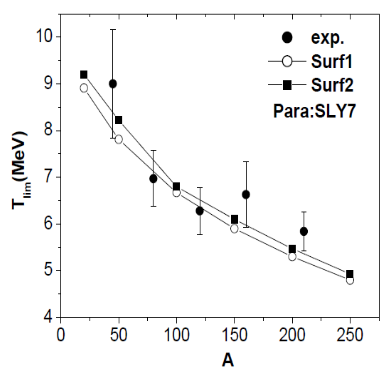
FIG. 3. Limiting temperatures calculated using various Skyrme interactions (Ref. [7]). The experimental result for $A \approx 125$ (Ref. [11]) is indicated by the dashed line.

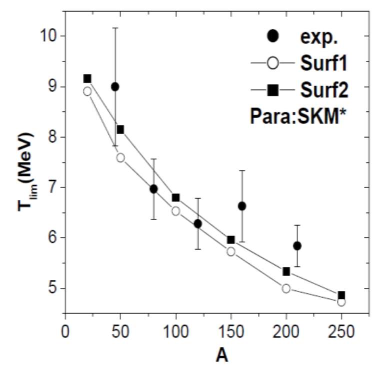
Study of T_{lim} along the β-stability line showed the sensitivness of T_{lim} from effective nucleon - nucleon interactions

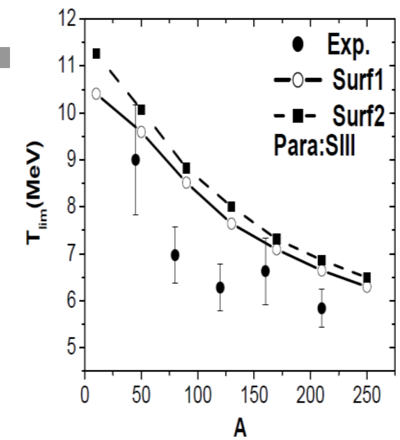
Zhuxia Li, Min Liu -arXiv:nucl-th/ 0402067v1(2004)



- **New Skyrme forces (e.g. SLy)→ to study properties away from β-stability line**
- **Surface tension (with and without isospin dependence)→ influence on T_{lim}**

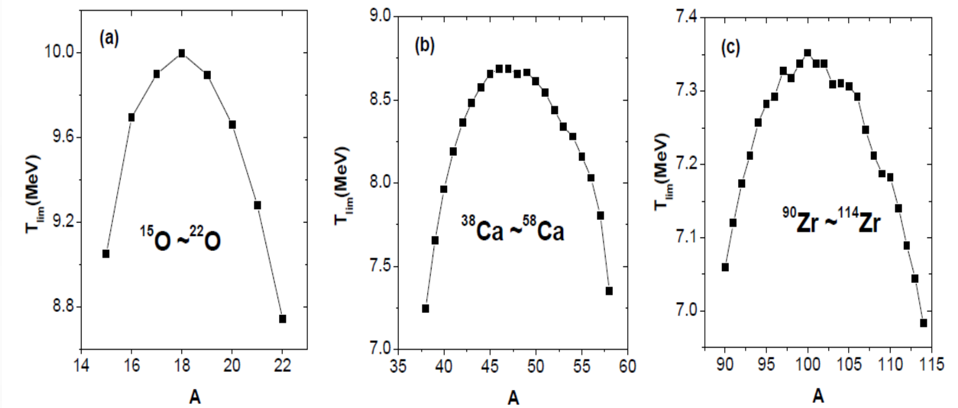






- **T_{lim} decrease with the system size, independently on the used force**
- **SLY7 & SKM* → soft EOS, while SIII stiff EOS (much higher T_{lim})**
- **Slight better description with surface tension surf2**

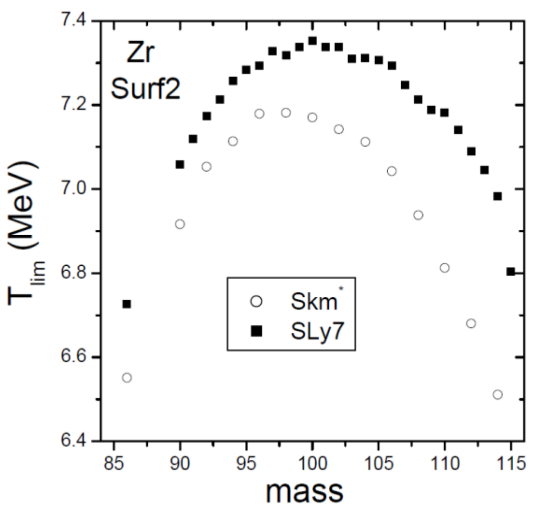
MASS AND ISOTOPE DEPENDENCE OF LIMITING TEMPERATURE FOR HOT NUCLEI



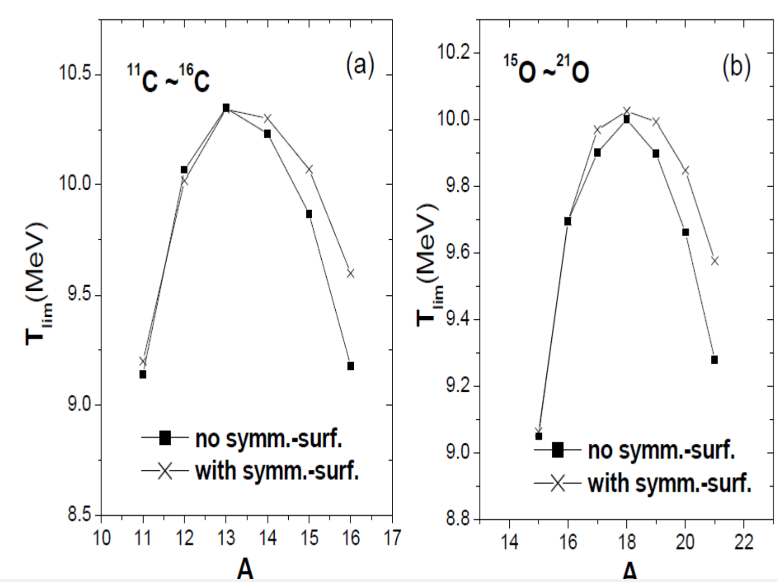
Zhuxia Li, Min Liu -arXiv:nucl-th/0402067v1(2004)

Calculations with Skyrme SLy7 and surf2:

- **parabolic shape of isotope distribution of T_{lim}**
- **Centroid not at β-stability value but on n-rich side.**



Difference in the dependence on the isospin part of interaction for **Zr** using Skyrme **SKM* or SLy7** (the last designed to describe **asymmetric matter properties**)
SLy7→ larger T_{lim} →larger difference at growing **isospin asymmetry I**



Symmetry term contribute also **to the surface tension (surface part of the symmetry term):**
if this is taken into account the result **is larger (visible)** on the **n-rich side** only.

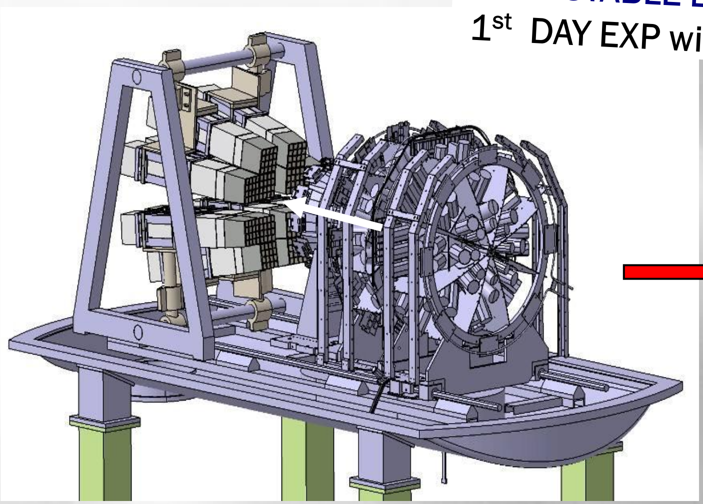
FAZIA: Phase II Bis

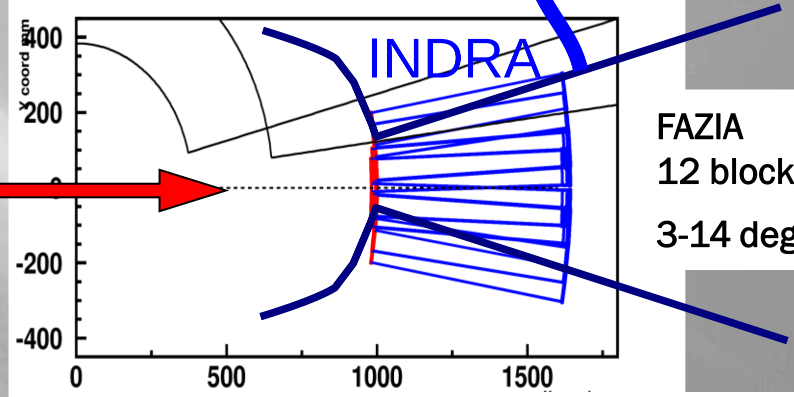
Medium-range plan 2012-2015

Several proposal under discussion to perform measurements on neck emissions, fragmentation and dissipation

The 192 telescopes of FAZIA demonstrator will be ready at the end of 2013.
Initially they will be coupled with : INDRA
Then with: GARFIELD@LNL, RIPEN@LNL and CHIMERA@LNS)

WITH STABLE BEAMS &
1st DAY EXP with SPIRAL2





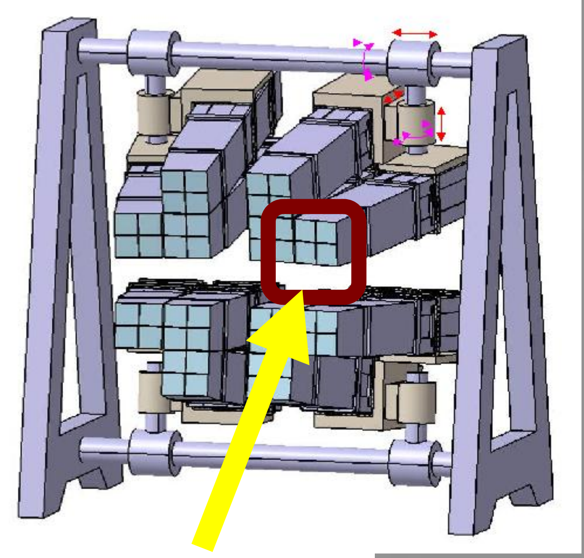
FAZIA
12 blocks:
3-14 deg

Coupling FAZIA + INDRA

Transport properties of isospin asymmetric nuclear matter:
neck emission and isospin drift

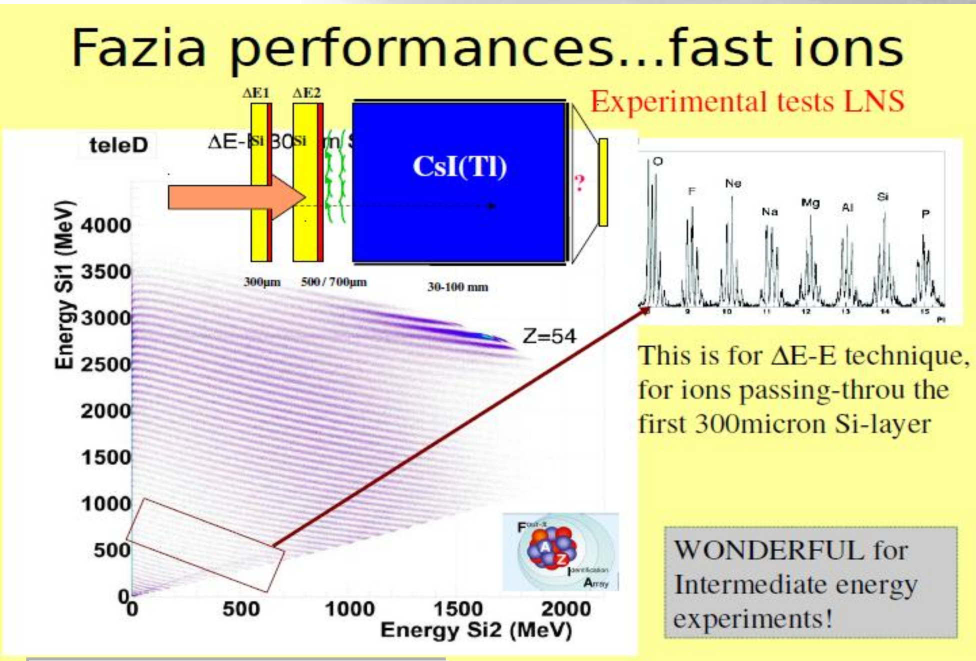
^{40,48}Ca+^{40,48}Ca at 15, 25, 35AMeV, ^{58}Ni+^{58}Ni at 30-45AMeV
Related to deep-inelastic processes, isospin equilibration and drift; isoscaling for massive ejectiles

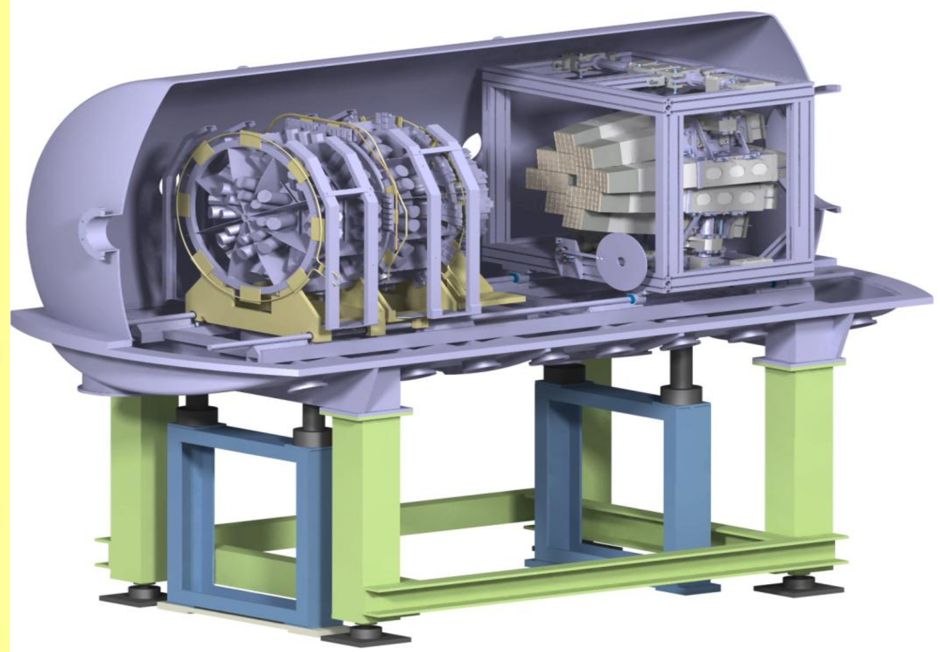
^{78,86}Kr+^{40,48}Ca ---> 20-60AMeV
Related to the surface or volume expansion in central collisions

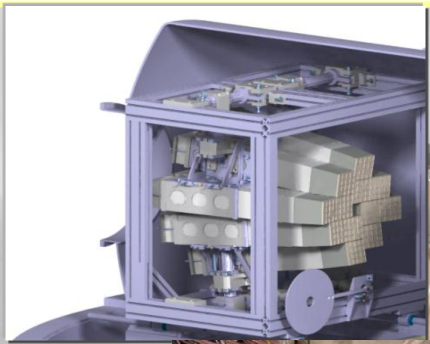


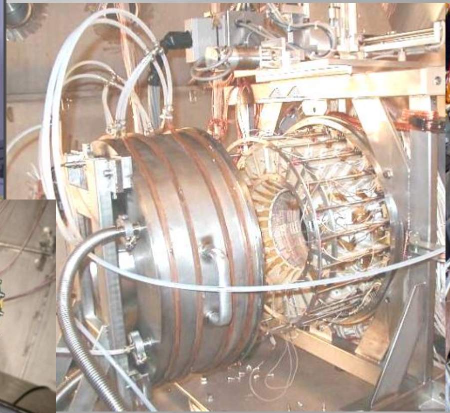
Basic BLOCK: 4x4 telescopes

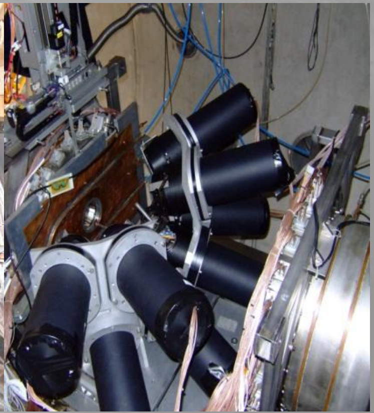
FAZIA: → coupling with INDRA & other detectors (GARFIELD etc.)



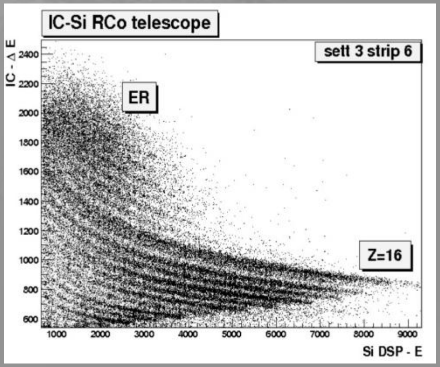








FAZIA+GARFIELD+
n (Ripen),
γ (Hector_like) detectors



CONCLUSIONS

A long term program concerning **thermodynamic** and **dynamics of hot nuclei** in relation with their chemical composition is forseen by several groups in different energy ranges to study **EOS** and **symmetry energy** dependence on density & temperature

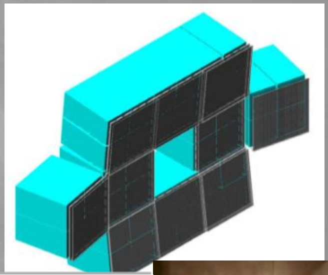
This program enters the study of phase transition and nuclear EOS for asymmetric matter.

Fundamental basic properties can be extracted like:

- Level Density
- Limiting Temperature
- Symmetry Energy Term Stiffness and its influence on different observables

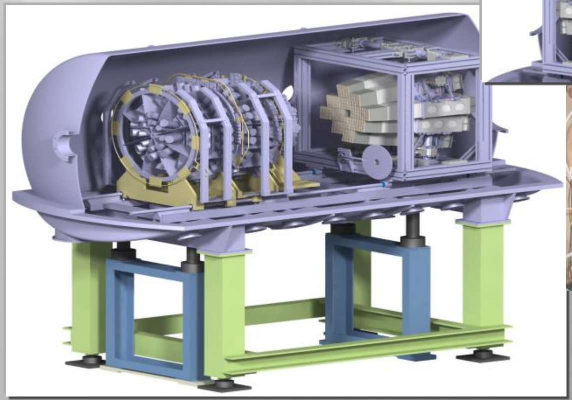
(**NIMF isospin contents, distillation of isospin, competition between reaction mechanisms etc.**)

- Equilibration of various degrees of freedom
- Decay modes and emission barriers…
- Pre-equilibrium n/p ratios, clustering…

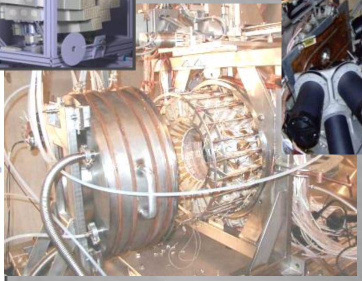


LNS: FRAG

Ganil: SPIRAL; SPIRAL2



LNL: SPES



THANK YOU