Symmetry Energy: Mixed Messages from Nuclear Fragmentation

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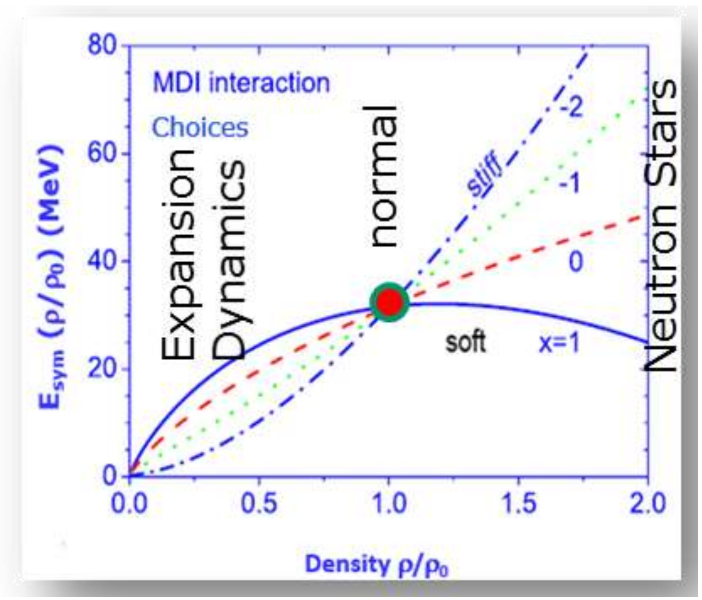
CECIL/CHIMERA Collaboration



Basic Questions:

- Nuclear Equation of State: <ε> of a nucleon in n/p symmetric and asymmetric nuclear matter *in equilibrium*, at different densities (profiles) & temperatures.
- Symmetry energy <ε_{sym} (ρ, T, I)>

Method:

→ For finite nuclei, study limits of nuclear (meta-) stability and disintegration modes, specifically "chemical" modes → isotopic regularities in fragmentation

cluster emission

Challenges: Limited scopes of experiments and models produce ambiguities.

Discussion of examples: (^{40,48}Ca+^{112,124}Sn@35,45 A MeV)

Progress in phenomenological understanding: expansion dynamics & surface properties of excited nuclei.

Deducing a Nuclear Equation of State

Goal: Find fundamental nuclear instabilities.
Application: (iso)EOS

……..

Potentially achieved in model dependent fashion, mechanistic info required

Capture/ Fusion → g.s. Nuclei ← Inelastic Collision

g.s. Nuclei

↓

Interacting,Composite Nuclear System*

Non-equilibrium Breakup, ….

Pre-equilibrium Emission

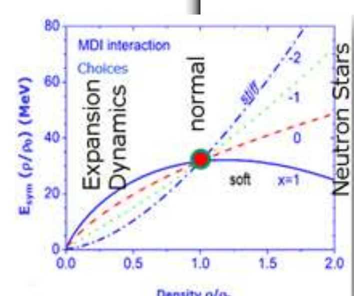
Composite Nucleus*

↓

Equilibrated Compound Nucleus*

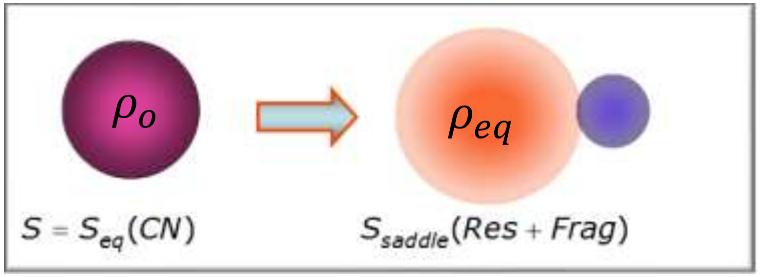
↓

Exptl. Decay Characterization → Model Interpretation → EOS



Generic Model

Regularities in Statistical Cluster Emission



Emission probability $\propto$ formation

$$\Gamma \propto e^{\Delta S} \simeq e^{Q/T} \qquad (if \quad T \approx const)$$

$$\Delta S = S_{saddle} - S_{eq} \approx \Delta E^{*th} / T := Q/T$$

$$E^{*th}_{saddle} \approx E^{*}_{tot} - E_B(1 - \frac{\rho_{eq}}{\rho_o})^2 - V_{saddle}$$

$$E_B = binding \;, V_{saddle} = coll, config$$

Same cluster (N,Z) emitted from either CN_1 or CN_2, same E^*_{tot}

$$\frac{\Gamma_{CN_2}(N,Z)}{\Gamma_{CN_1}(N,Z)} \propto \exp\left[\left(\Delta E_B(1 - \frac{\rho_{eq}}{\rho_o})^2 + \Delta V_{saddle}\right) \Big/ T\right] = \exp\left[\frac{\Delta Q}{T}\right]$$

Decay widths $\leftrightarrow \Sigma$ interaction energies + EOS (isoEOS)

$$First - order\ expansion\ of\ E_B\ and\ V_{saddle}:\ reference\ cluster\ (N_0, Z_0)$$

$$V_{saddle}(CN,N,Z) \approx V_{CN0} + \left(\frac{\partial V_{saddle}}{\partial N}\right)_Z [N - N_0] + \left(\frac{\partial V_{saddle}}{\partial Z}\right)_N [Z - Z_0] \ and\ E_B(CN,N,Z) = \ldots$$

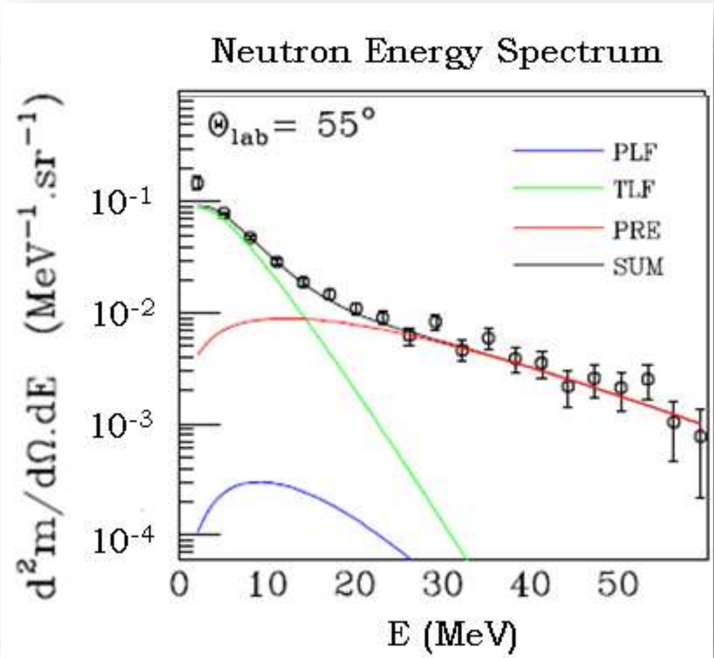
$$R_{12} := \frac{\Gamma_{CN_2}(N,Z)}{\Gamma_{CN_1}(N,Z)} \propto \exp\left[\left(\frac{\Delta a_{CN}}{T}\right) \cdot N + \left(\frac{\Delta b_{CN}}{T}\right) \cdot Z\right] = e^{\alpha \cdot N + \beta \cdot Z}$$

"Isoscaling" with cluster N,Z Parameters α, β

Complications 1,2

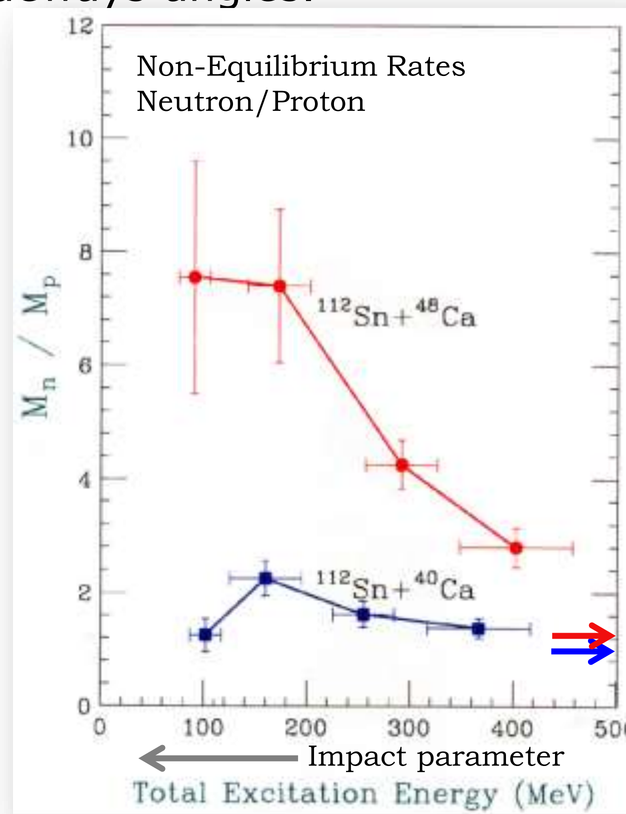
1. Isospin Dependent Preeq. Dynamics $^{40,48}Ca+^{112}Sn$@35A MeV

Specific experimental setup to measure exclusive n & p with PLFs.



(Agnihotri et al., 1998; Schröder et al., 2001)

Significant rates of fast, non-equilibrium emission of neutrons and protons.
Obvious at sideways angles.

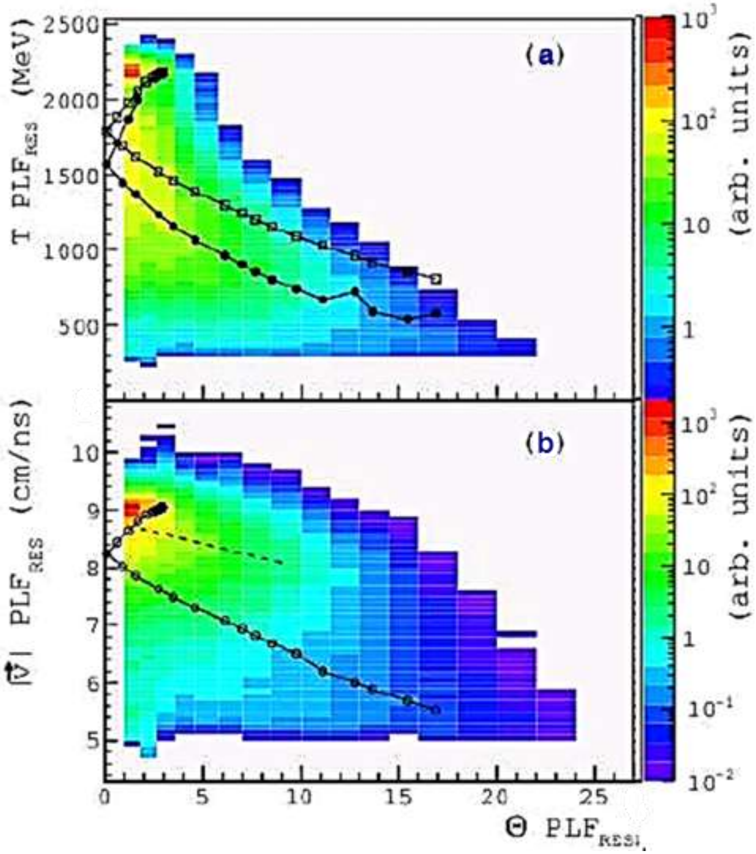


Fast and asymmetric depletion of system by neutrons compared to protons.
Global iso-equilibrium for remnant system approached but not reached. PLFs remember initial A/Z.

Next Example

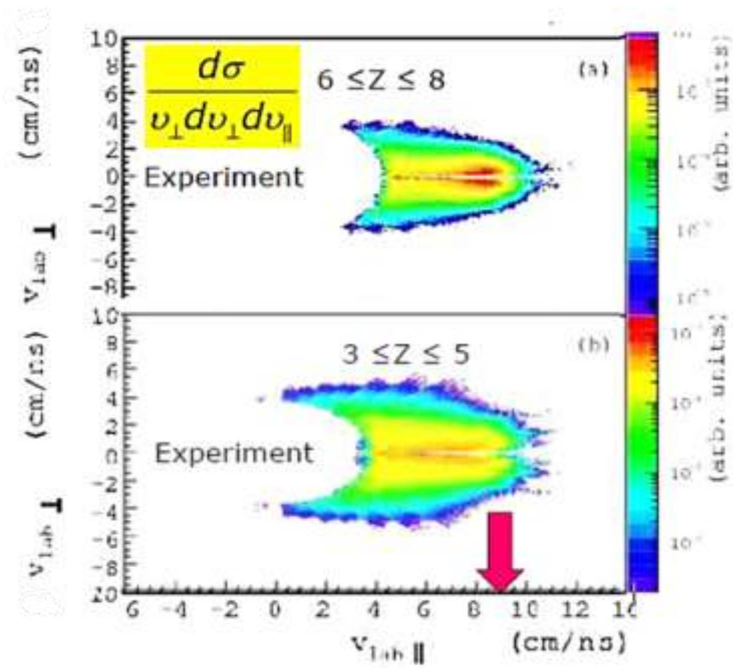
2. Dynamic Splitting of PLF* after Dissipative Rxns

$^{48}Ca+^{112,124}Sn$, E/A = 45 MeV, CECIL Expt. @ LNS Catania



Experimental Wilczyński contour diagrams for $^{48}Ca+^{112}Sn$ @E/A=45 MeV.
Top: PLF energy vs. angle,
Bottom: PLF velocity vs. angle.

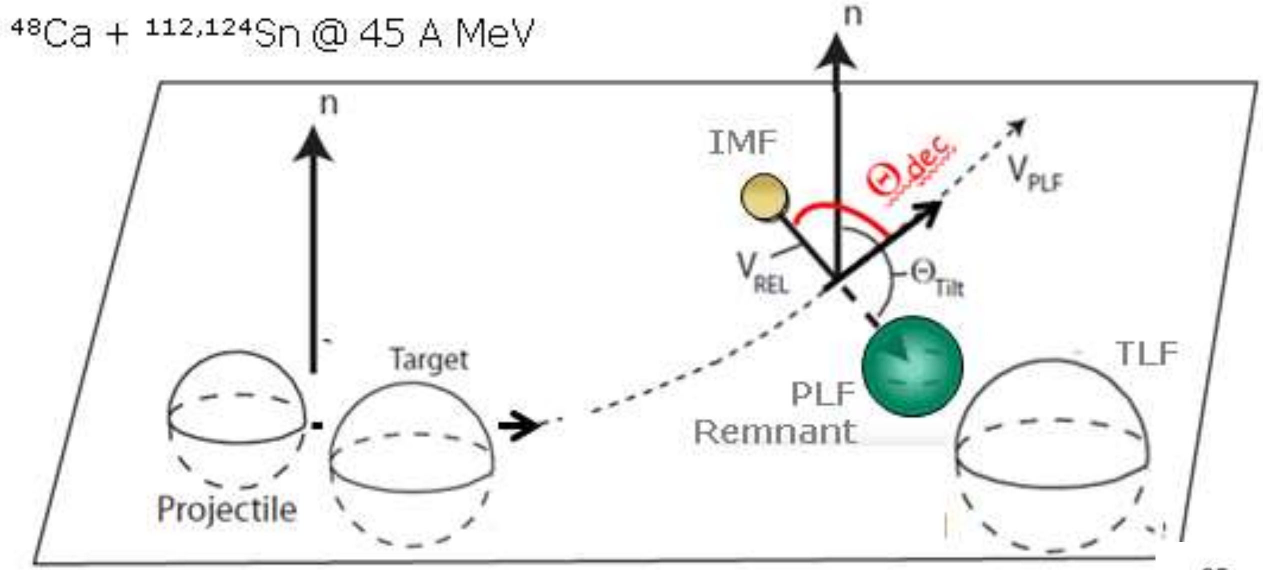
Nucleon exchange model (CLAT). Sequential evaporation: GEMINI.

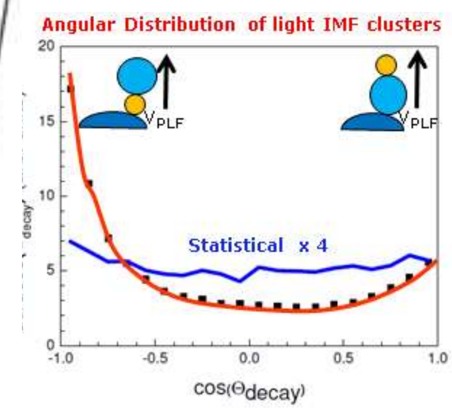


Galilei invariant cross sections
a) for heavier PLF remnants
b) for lighter remnants (IMFs).

2. Dynamic Splitting of PLF* after Dissipative Rxns

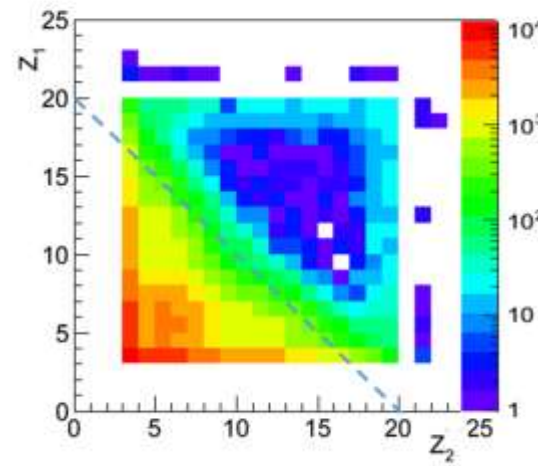
Prompt projectile splitting in proximity (under the influence) of target.
Nuclear surface interactions → **aligned asymmetric breakup**





Evidence for dynamics: $^{48}Ca+^{112,124}Sn$

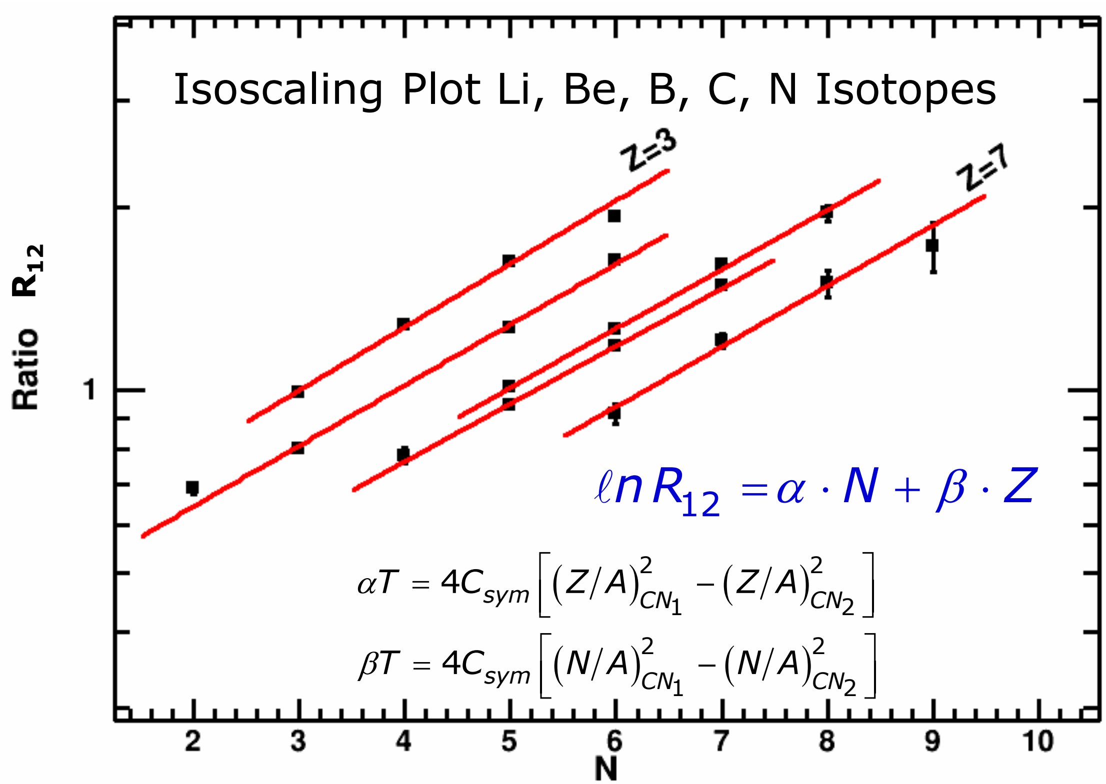
1. Alignment of breakup axis in plane, in direction of flight
2. F/B of heavy/light.
3. Relative velocity =2x equil. systematics
4. Symmetric component (not fission)



Perform Isoscaling Analysis

Isoscaling in Dynamic PLF* Splitting ($^{48}Ca+^{112,124}Sn$)

PLFs from 2 dissipative reactions split dynamically.
Compare cluster yields → ratios.



$$PLF^* \rightarrow PLF' + (N,Z)$$

$$R_{12} := \frac{Y_{N,Z}\left(^{48}Ca + ^{124}Sn\right)}{Y_{N,Z}\left(^{48}Ca + ^{112}Sn\right)}$$

$$\left.\begin{array}{l} PLF_1^* = (Z_1 = 20, A_1 = 49) \\ PLF_2^* = (Z_2 = 18, A_2 = 43) \\ T = (2.6 \pm 0.3) MeV \end{array}\right\rangle \rightarrow C_{sym} = 17-19 MeV$$

$$\left.\begin{array}{l} PLF_1^* = (Z_1 = 25, A_1 = 48) \\ PLF_2^* = (Z_2 = 26, A_2 = 49) \\ T = (5.5 \pm 0.3)\ MeV \end{array}\right\rangle \rightarrow C_{sym} = 31 MeV$$

Ambiguity due to uncertain reconstruction → Identify cluster origin/mechanism.

Ambiguity Range for Model Parameter C_{sym}

Z_1	A_1	Z_2	A_2	T(MeV) (±)	C_{app}
23	54	22	51	1.7 (0.1)	22.2
24	55	23	52	2.1 (0.1)	23.8
23	52	22	49	2.4 (0.1)	24.8
20	49	18	43	2.8 (0.1)	19.1
21	51	19	45	2.9 (0.1)	20.0
24	56	23	51	4.5 (0.1)	24.5
28	46	27	45	5.6 (0.1)	31.7

PLF*s {[Z_1, A_1], [Z_2, A_2]} split, effective temperature *T* apparent symmetry energy coefficients C_{app}. (Fit range 3 isotopes per Z)

Z1	A1	Z2	A2	T(MeV) (±)	C_{app} (MeV)
23	55	22	52	1.47 (0.01)	21.5
24	56	23	53	1.81 (0.02)	23.3
24	55	23	52	2.14 (0.02)	24.6
24	54	23	51	2.52 (0.03)	25.8
24	52	23	49	3.41 (0.04)	27.9
24	56	22	50	3.95 (0.05)	23.9
23	49	22	46	4.09 (0.05)	29.2
24	55	22	49	4.69 (0.05)	25.2
24	57	21	48	5.44 (0.06)	23.1

PLF* s {[Z_1, A_1], [Z_2, A_2]} split, effective temperature *T* apparent symmetry energy coefficients C_{app}. (Fit range 4 isotopes per Z)

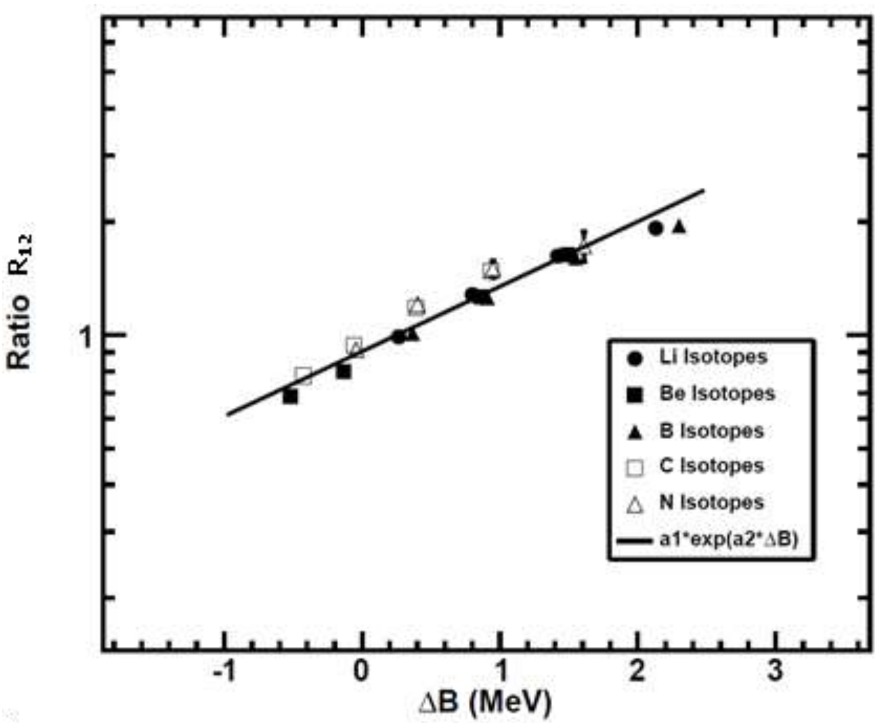
α(±)	β(±)	Fit Range Isotopes
0.230 (0.002)	0.122 (0.008)	3
0.222 (0.002)	0.113 (0.008)	4

Parameters factors 2-3 smaller than in other reactions.

Meaning of apparent "C_{sym}" ?

17-19 MeV $\leqslant C_{sym} \leqslant$ 32 MeV

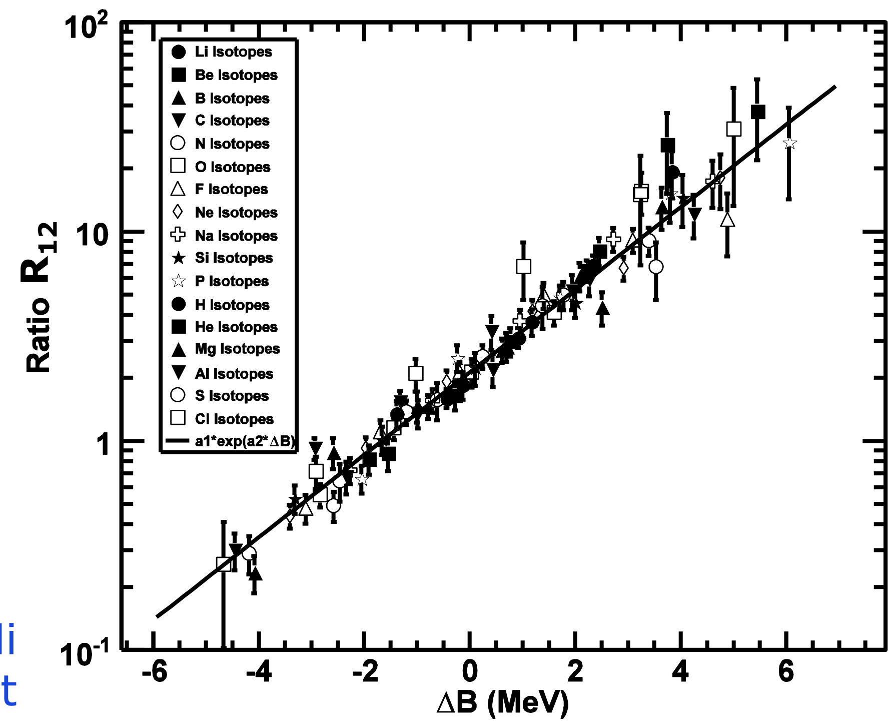
Scaling With Ground State Energies (Q_{gg})



Inspect yield dependence on binding energies of IMFs in PLFs for ^{48}Ca + $^{124,112}Sn$ reactions ($Q \propto \Delta B$). Phase space (***S***) scales with Q.

$$\ell n R_{12} = c - \left(B_2 - B_1\right)/E_0 = c + \Delta B/E_0$$

$$E_0 \approx \left(2.7 \pm 0.5\right) MeV$$

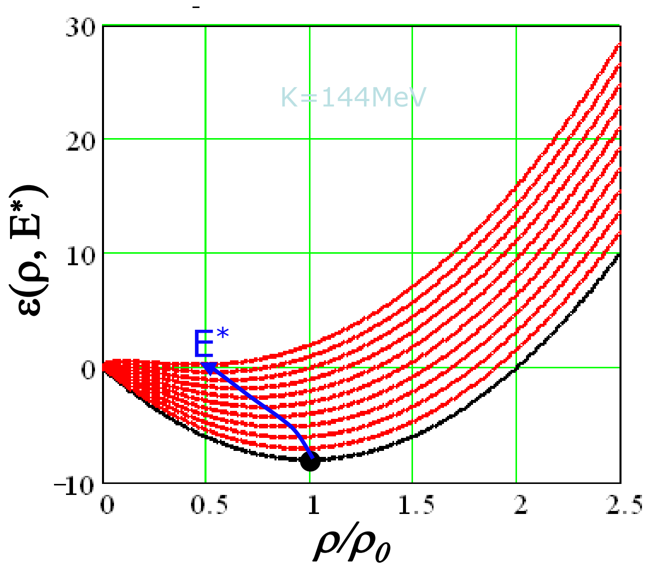


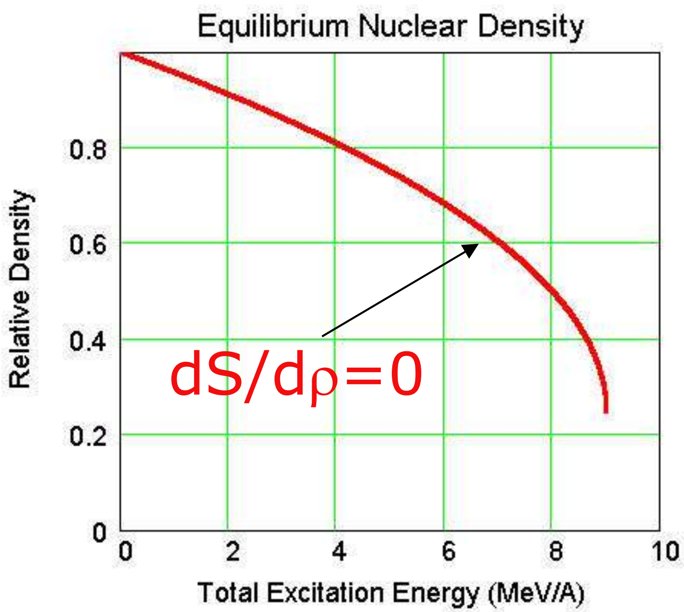
Binding energy difference scaling of experimental yield ratios for ^{48}Ca+$^{112,124}Sn$ PLF splitting reactions. Why?

Different mechanism: $^{86,78}Kr$ + $^{64,58}Ni$ reactions at 35 A MeV (TAMU data) but same scaling.

Need realistic CN model

Expansion in Interacting-Fermi Gas Model for CN





Simplest version: harmonic approximation of $\varepsilon(\rho)$ → analytical formulation

$$\varepsilon(\rho) = -\varepsilon_0 + (K/18)\left[1 - \left(\frac{\rho}{\rho_0}\right)^2\right] + \ldots \qquad \text{EOS}$$

$$S = 2\sqrt{a \cdot E^*_{th}} \quad \rightarrow \quad E^*_{th} = E^*_{tot} - E^*_{conf}$$

Entropy

"little-a" = level density parameter

$$a = a_{Volume} + a_{Surface} = \left(A\alpha_V + A^{\frac{2}{3}}\alpha_S\right)\left(\frac{\rho}{\rho_0}\right)^{-\frac{2}{3}}$$

$$\left(\frac{\partial S}{\partial \rho}\right)_{E^*_{tot}} = 0 \quad \rightarrow \quad \begin{cases} \rho_{eq} \\ T \end{cases} \quad \left(\textit{microcan. model}\right)$$

Experimental ***a*** systematics → model relates E* ←→ Density ←→ T

More sophisticated CN model

Isoscaling with an Interacting Fermi Gas Model

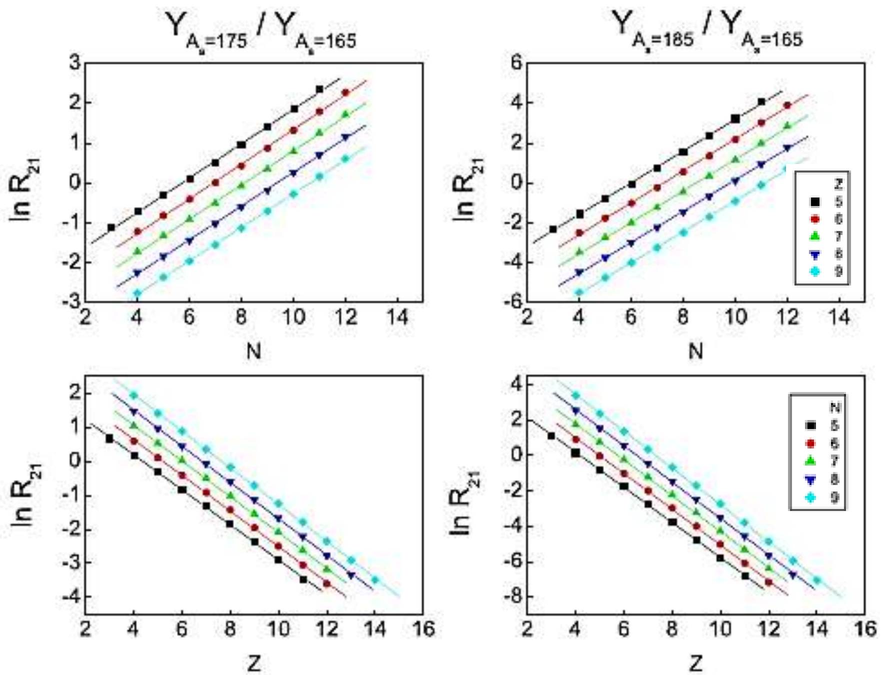
Studied schematic model isoscaling dependence on T for $\rho=\rho_0$. and for g.s. I dependence.
Ad hoc ansatz for surface symmetry energy (ρ,T) → Essentially similar isoscaling plots.

$$E_v(\rho) = \left[B_0 + \frac{K}{18}\left(1-\rho/\rho_0\right)^2\right]\cdot\left(1-\kappa_v I^2\right)A$$

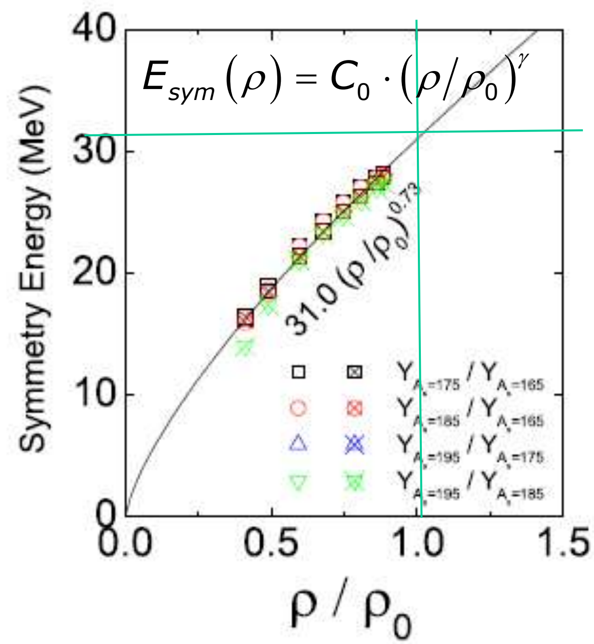
$$E_s(T) = \left[\alpha_s(T) - T\,\frac{d\alpha_s(T)}{dT}\right]\cdot\left(1-\kappa_s I^2\right)A^{2/3}$$??

$$B_0 = -16MeV,\ K = 260MeV,\ \kappa_v = 1.927$$

$$\alpha_s(T) = 18\cdot\left(\frac{T_c^2 - T^2}{T_c^2 + T^2}\right)^{5/4},\ T_c = 18MeV,\ \kappa_s = 2.3$$

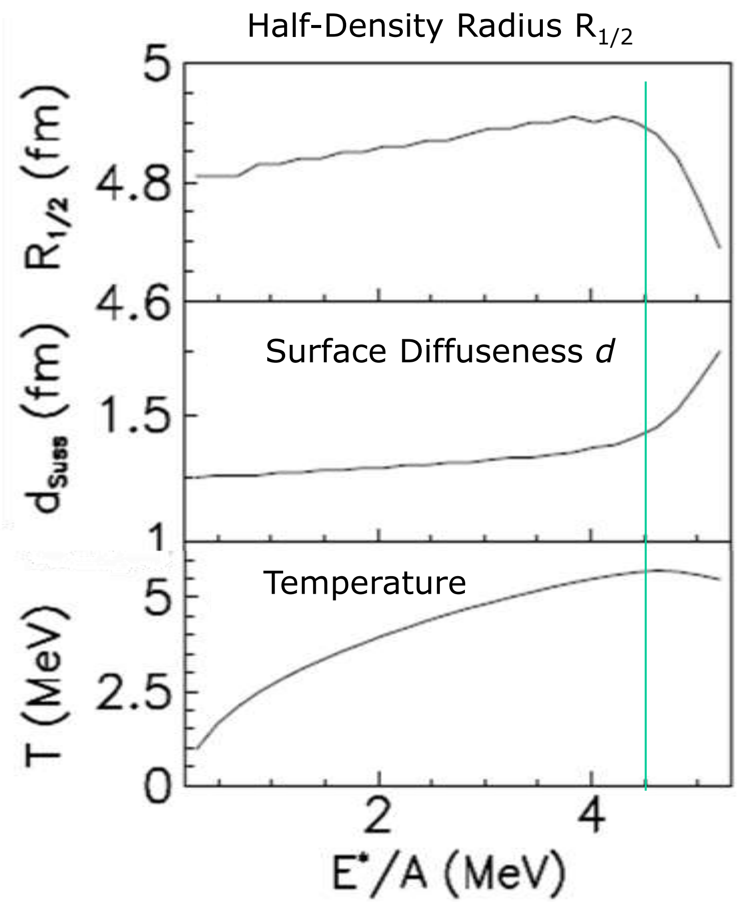


Source CNs: E^*_{tot}/A = 5 MeV
Left {*As* = 175, *As* = 165}
Right: {*As*= 185, *As* = 165}
Top: Ratios of *Z* = 5*i*9 isotope yields.
Bottom: Ratios of *N* = 5*i*9 isotone yields



Need better model surface

Surface Vaporization



Tõke & Schröder, PRC subm. (2011), PLB subm. (2013)

$$S_{conf}\left(E_{conf}, I\right) := 2\cdot\sqrt{a_{conf}\cdot\left(E_{tot}-E_{conf}\right)}$$ *Configuration entropy*

$$a_{conf} := \alpha_0 \cdot \rho_0^{2/3}\cdot R(I)\int \rho^{1/3}(\vec{r})d^3r$$ *Level density parameter*

$\rho(r)$: *Matter density*, $R(I)$: *iso – asymmetry factor*

$$E_{conf}(\rho, I) := c_V\cdot\left(1-\frac{\rho}{\rho_0}\right)^2 + c_I\cdot\left(\frac{\rho}{\rho_0}\right)\cdot I^2$$ *Harmonic approximation*

$$\delta^2 S \geq 0 \rightarrow \ instability \rightarrow \text{"sudden" decay}$$

* New nuclear modes *

Up to E*/A ≈ 4.5 MeV expansion, surface diff

- *T* levels off *T ≈ 5.6 MeV* (like experiment),
- C negative → instability
- n-rich surface parts vaporize first, ejected.
- Residues n-poorer but hotter →
- With I^2 "Distillative Boiling"

Finite – range calculations:

More general Skyrme interactions (K = 220 MeV)

$$\varepsilon_{int}^{EOS}(\rho) := \rho\cdot\left[a\cdot\left(\frac{\rho}{\rho_0}\right)+\frac{b}{\sigma+1}\cdot\left(\frac{\rho}{\rho_0}\right)^{\sigma}\right]$$

$a = -62.43 MeV$
$b = 70.75 MeV$
$\sigma = 2.0$

$$E_{conf}^{EOS} = R_{norm}\int \varepsilon_{int}^{EOS}\left(\rho(\vec{r})\right)\cdot\exp\{-\frac{(\vec{r}-\vec{r}')^2}{2\lambda^2}\}d^3r d^3r'$$ *Folding*

Summary & Conclusions

- Generic character of isotopic regularities (isoscaling), sensitivity to sum of EOS and interaction terms. Ratios obscure some physics.
- Significant ambiguity due to poor identification of parent isotopes ("resolution effects").
- Isoscaling observed also for competing mechanisms (dynamic splitting).
- Ground state masses explain (several) isoscaling phenomena.
- Progress in thermodynamics of finite nuclei (expansion, surface, caloric).
- Development of phenomenological method to interpret nuclear decay modes (boiling, distillative vaporization, cluster emission barriers).

Experimental/theoretical challenges:

- Characterize reaction mechanism.
- Determine pre-equilibrium modes (mean field vs. scattering).
- Determine equilibrium conditions of CN emitting clusters.

➢ Need more specific (exclusive) experiments with high statistics.

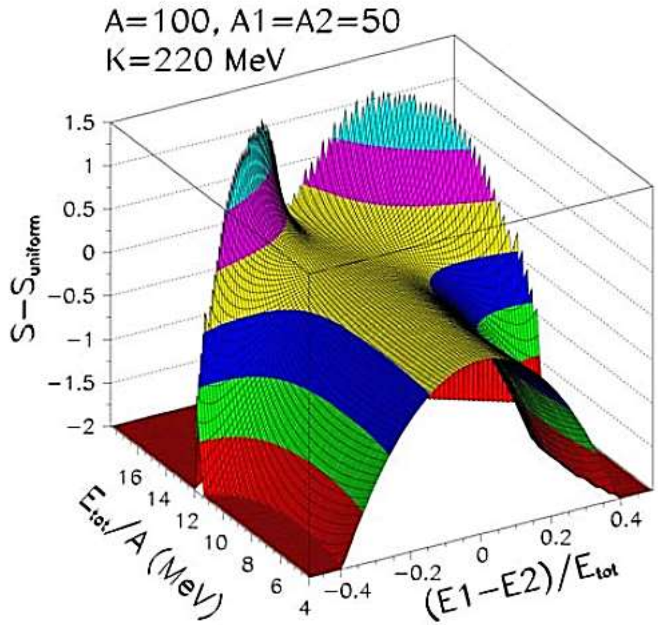
➢ More direct measurements of isospin sensitive observables (incl. n's).

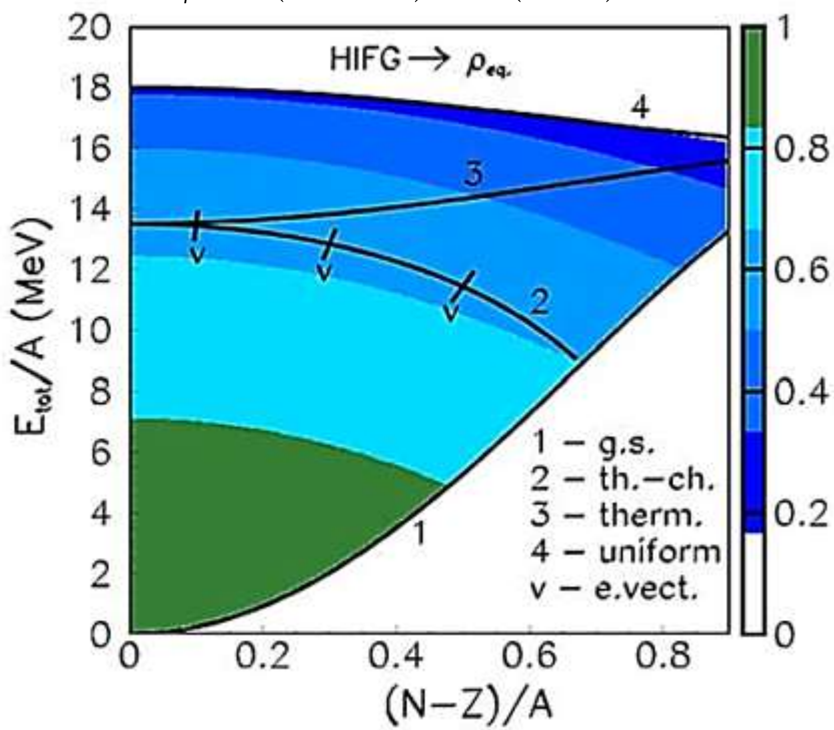
➢ Realistic modeling of many primary reaction and secondary decay features simultaneously.

THANK YOU !

Instability Modes of Finite Nuclei

$$E_{conf} = c_V \left(1 - \rho/\rho_0\right)^2 + c_I \left(\rho/\rho_0\right) I^2$$

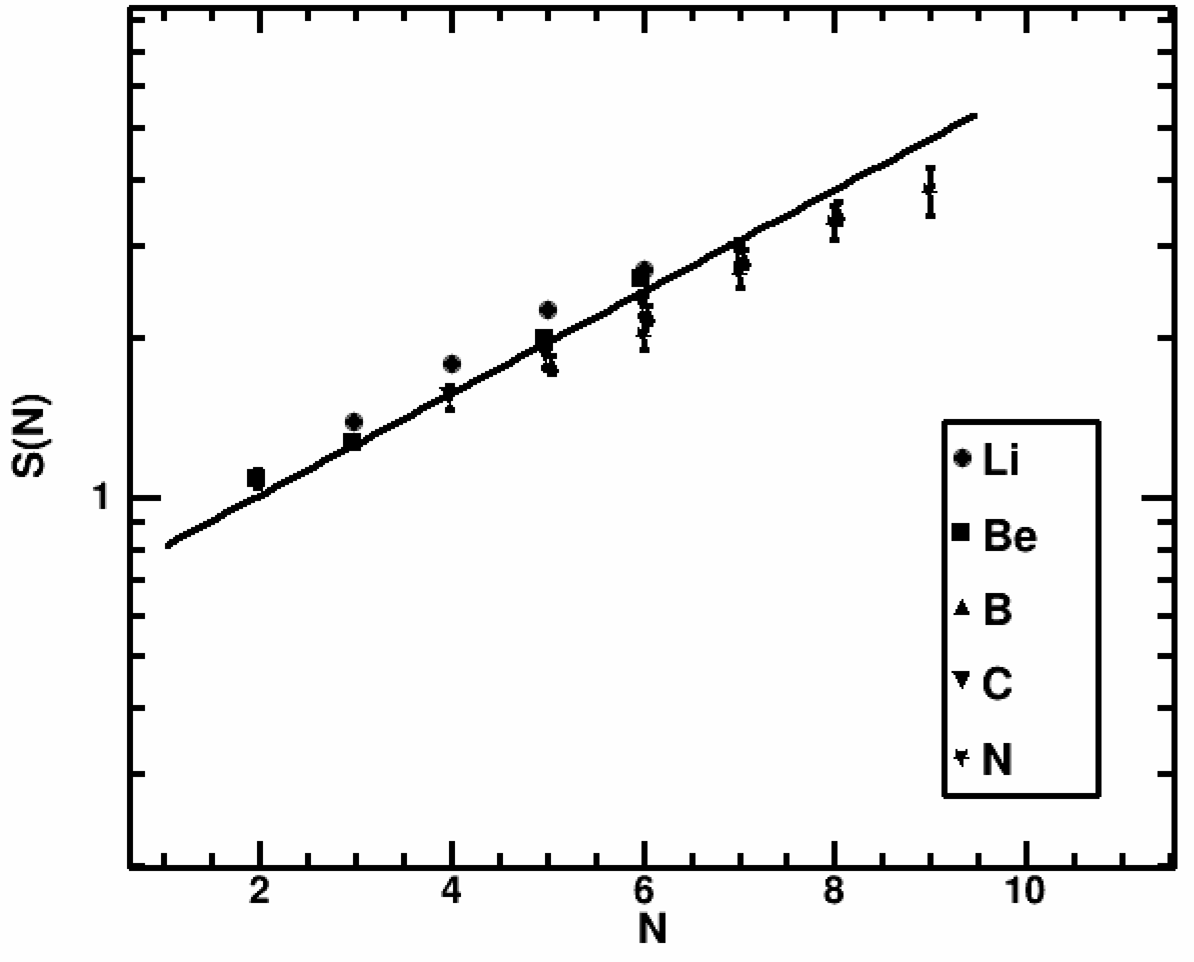




Entropy *S* of a two-phase system (1,2) vs. total energy, E_{tot}/A, and energy asymmetry, $(E_1-E_2)/E_{tot.}$.
S is given relative to entropy, $S_{uniform}$, of the uniform system (1+2).

Contours of the equilibrium matter density vs. iso-asymmetry, $(N - Z)/A$ and E_{tot}/A.
Slid lines: 1) ground-state energy
2) boundary of meta-stability domain
3) boundary of domain of positive heat capacity
4) boundary of domain stable against uniform expansion.

Further theoretical model extension:
Saddle and barrier energies → J.Tõke



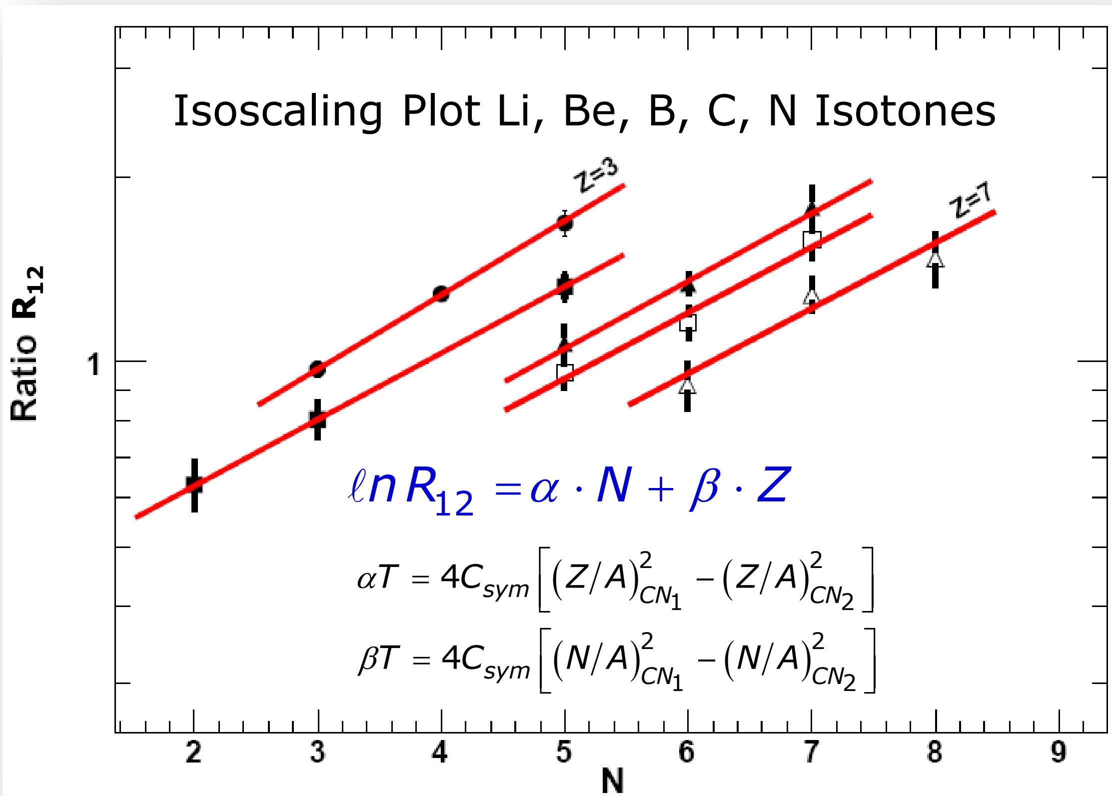
S(N)
1
2
4
6
8
10
N
Li
Be
B
C
N

Isoscaling in Dynamic PLF* Splitting (^{48}Ca+^{112,124}Sn)

Early (1970s) Russian work (cf. Schröder & Huizenga),
more recently: Tsang et al., PRC64, 054615(2001)

PLFs from 2 dissipative reactions split dynamically. Compare cluster yields.

CECIL II @LNS
(Rochester/CHIMERA, Conf.+tbp)



Cont'd → Sheth Nyibule → Ph.D.

$$PLF \rightarrow PLF' + (N,Z)$$

$$R_{12} := \frac{Y_{N,Z}\left({}^{48}Ca + {}^{124}Sn\right)}{Y_{N,Z}\left({}^{48}Ca + {}^{112}Sn\right)}$$

$$\left.\begin{array}{l} PLF_1^* = (Z_1 = 20, A_1 = 49) \\ PLF_2^* = (Z_2 = 18, A_2 = 43) \\ T = (2.6 \pm 0.3) MeV \end{array}\right\rangle \rightarrow C_{sym} = 17 MeV$$

$$\left.\begin{array}{l} PLF_1^* = (Z_1 = 25, A_1 = 48) \\ PLF_2^* = (Z_2 = 26, A_2 = 49) \\ T = (5.5 \pm 0.3)\ MeV \end{array}\right\rangle \rightarrow C_{sym} = 31 MeV$$

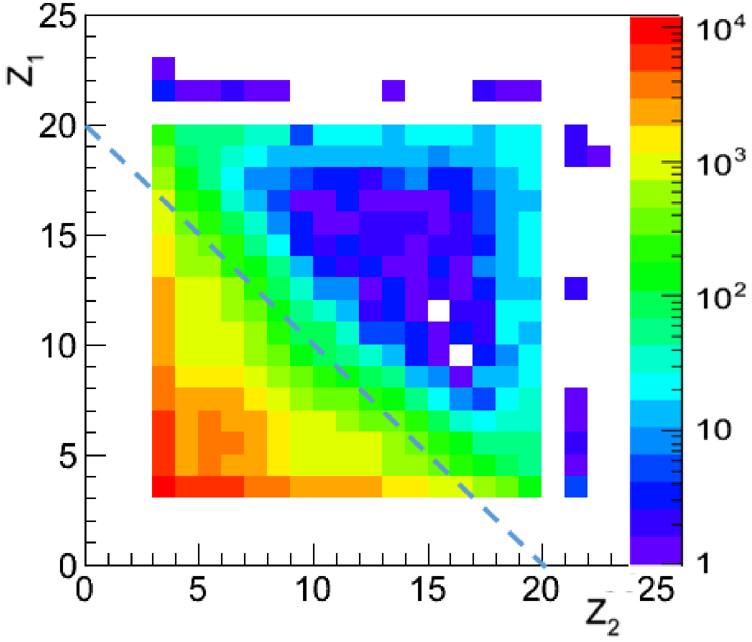
Ambiguity due to uncertain reconstruction → Identify cluster origin/mechanism.

- ❑ Need reaction model to simulate simultaneous observables.
- ❑ Need realistic model to relate $\{\alpha, \beta\}$ ←→ $C_{sym}(\rho)$

Extend statistical CN model

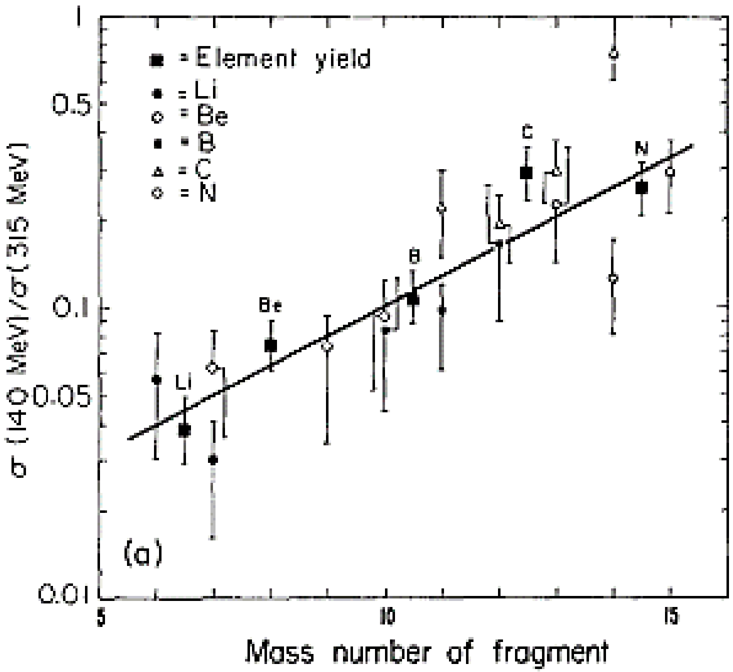
Hurdles for Studies of the Symmetry Energy

- Competing reaction mechanisms produce similar isotopic phenomena
- Lack of equilibration in most reaction systems
- Non-uniform symmetry energy (bulk vs. surface)
- Poor definition/reconstruction of equilibrated system
- Indirect determination of isospin dependencies (ratios)
- Unsystematic “spot” studies, variation of reaction parameters (E_{cm}, L,..)
- Secondary evaporation effects/”side feeding”



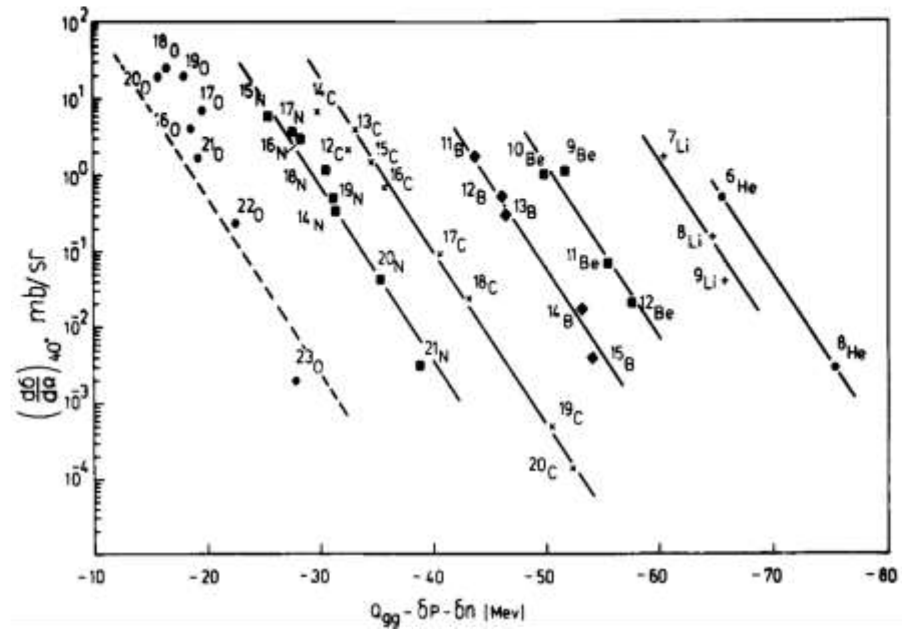
Related observations
v.Harrach/Specht,
Fuchs et al.,
Wilczyński et al.,
de Filippo et al.

Early Studies



C. K. Gelbke et a., Phys. Lett 65, 227 (1976)

^{16}0 (140, 315 MeV) + ^{94}Zr, ^{197}Au, ^{208}Pb, ^{232}Th.
→ Isotopic yields, variation with target and bombarding energy (E/A=8-20 MeV).



V. V. Volkov, Phys. Rep. 44, 93 (1978), summary of early Russian work

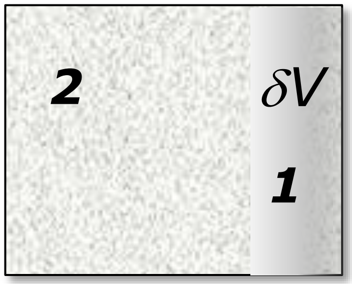
^{22}Ne (172 MeV) + ^{232}Th, $\theta=40^0$
Common T_{eff} → equilibrated system

End

Nuclear Stability Criteria (Gibbs)

Meta-Stability: $(\mathbf{S} \rightarrow \mathbf{S_{max}}) \rightarrow (S - S_{max}) \approx \delta^2 S < 0 \rightarrow$ driving force

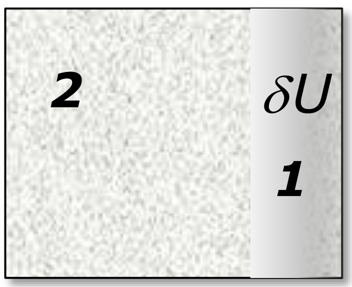
Normal Modes



Mechanical Stability $\delta^2 S = -\frac{1}{\kappa_T}\frac{(\delta T)^2}{T \cdot V} < 0$

Isothermal compressibility $\kappa_T = -(1/V)(\partial V/\partial p) > 0$

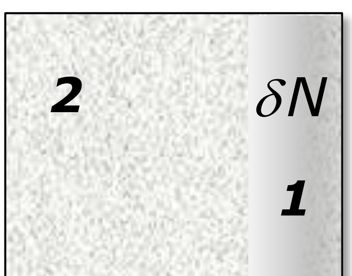
Density fluctuations $\sigma_\rho^2 \approx \bar{\rho}^2 (T/V)\kappa_T$



Thermal Stability $\delta^2 S = -C_V \left(\frac{\delta T}{T}\right)^2 < 0$

Isochoric heat capacity $C_V = (\partial U/\partial T)_V > 0$

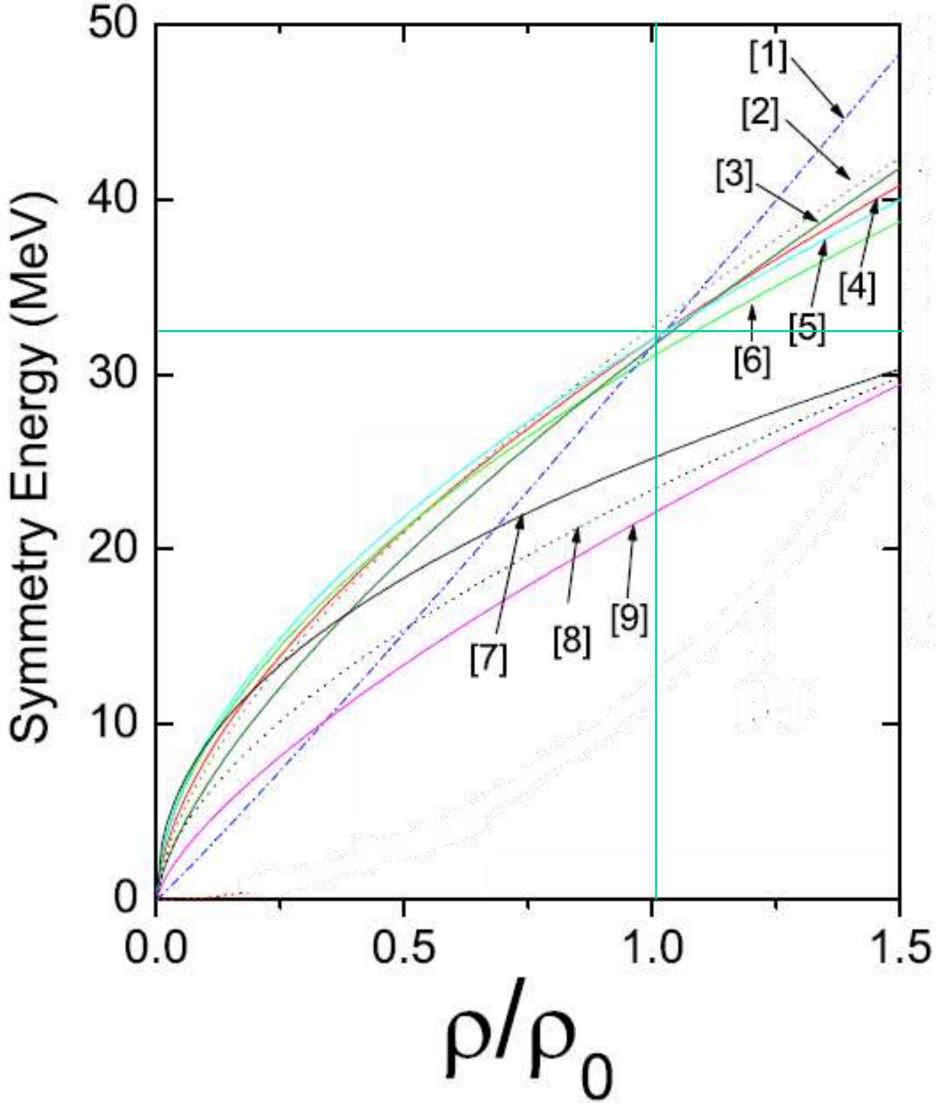
Energy fluctuations $\sigma_E^2 \approx T^2 C_V$



Chemical Stability $\delta^2 S = -\sum_{i,j}\left(\frac{\partial}{\partial N_j}\frac{\mu_i}{T}\right)\delta N_i \delta N_j < 0$

Chemical potential $\mu_i = (\partial U/\partial N_i)_{S,V,N_j} > 0$

Chemical fluctuations $\sigma_N^2 \approx T\,(\partial \mu/\partial N)_{V,T}^{-1}$



Symmetry Energy (MeV)
50
40
30
20
10
0
0.0
0.5
1.0
1.5
ρ/ρ0
[1]
[2]
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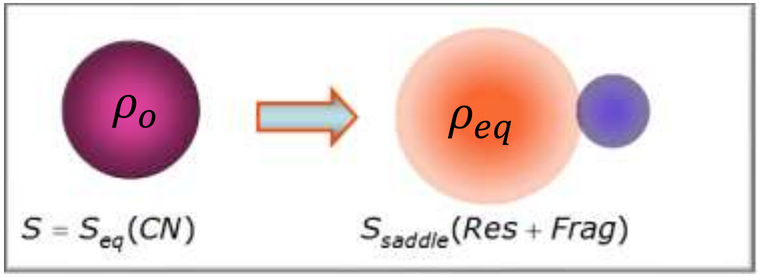
N & Z Dependence of Statistical Cluster Emission



Emission probability $\propto$ formation

$$\Gamma \propto e^{\Delta S} \simeq e^{Q/T} \qquad (if \quad T \approx const)$$

$$\Delta S = S_{saddle} - S_{eq} \approx \Delta E^{*th} / T := Q/T$$

$$E^{*th}_{saddle} = E^{*}_{tot} - E_{Bind}(1 - \frac{\rho_{eq}}{\rho_o})^2 - V_{saddle}$$

Fixed cluster (N,Z) emitted from either $CN_1(I_1)$ or $CN_2(I_2)$, same $E*$

$$\frac{\Gamma_{CN_2}(N,Z)}{\Gamma_{CN_1}(N,Z)} \propto \exp\left[\left(V_{saddle_1} - V_{saddle_2}\right)/T\right] = \exp\left[\Delta Q/T\right] \qquad \textit{Decay Widths}$$

$$\Delta Q = \Delta V_{saddle}\left[\rho, E^{*}_{tot}, I\right] \qquad \textit{same cluster, different } CN_1, CN_2$$

$$V_{saddle}(CN,N,Z) \approx V_{CN0} + \left(\frac{\partial V_{saddle}}{\partial N}\right)_Z [N - N_0] + \left(\frac{\partial V_{saddle}}{\partial Z}\right)_N [Z - Z_0]$$

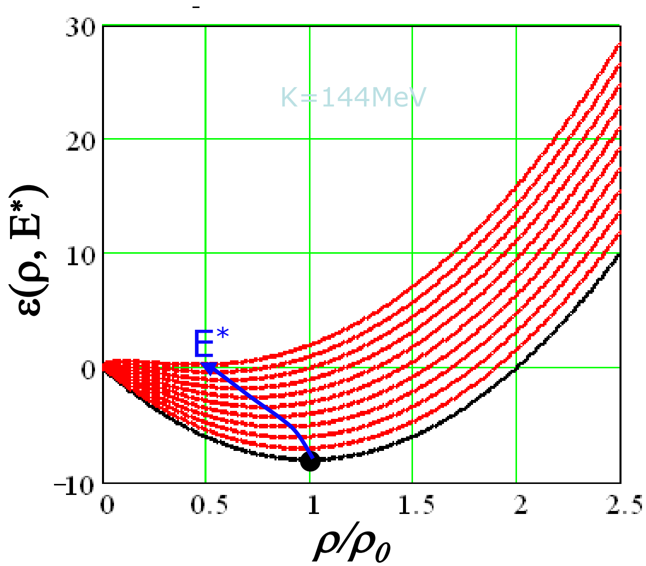
Reference cluster (N_0, Z_0)

$$V_{saddle}(CN,N,Z) \approx Q_{CN} + a_{CN}N + b_{CN}Z, \quad \textit{factors depend on } \rho$$

$$R_{12} := \frac{\Gamma_{CN_2}(N,Z)}{\Gamma_{CN_1}(N,Z)} \propto \exp\left[\left(\frac{\Delta a_{CN}}{T}\right)\cdot N + \left(\frac{\Delta b_{CN}}{T}\right)\cdot Z\right] = e^{\alpha \cdot N + \beta \cdot Z}$$

"Isoscaling" with cluster N,Z

Interacting Fermi Gas Model for CN

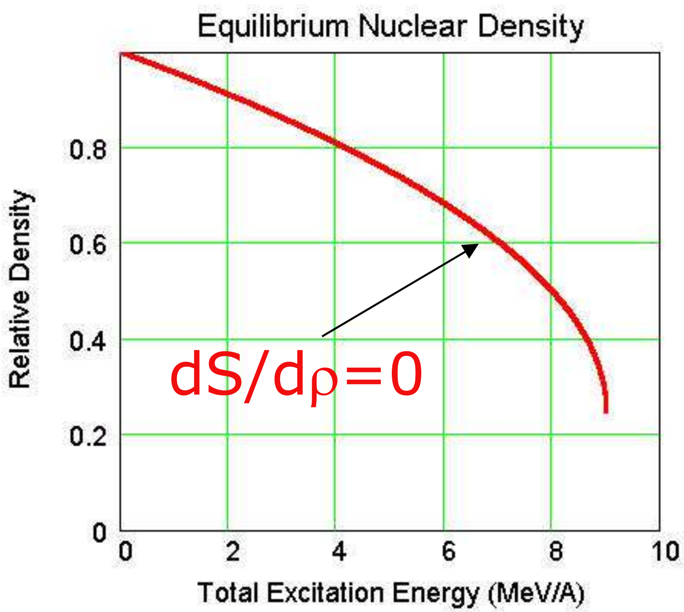


Simplest version: harmonic approximation of ε(ρ) → analytical formulation

$$\varepsilon(\rho) = -\varepsilon_0 + (K/18)\left[1-(\rho/\rho_0)^2\right] \qquad \text{EOS}$$

$$S = 2\sqrt{a \cdot E^*_{th}} \rightarrow E^*_{th} = E^*_{tot} - E^*_{conf} \qquad \text{Entropy}$$

$$\left(\frac{\partial S}{\partial \rho}\right)_{E^*_{tot}} = 0 \rightarrow \begin{cases} \rho_{eq} \\ T \end{cases}$$



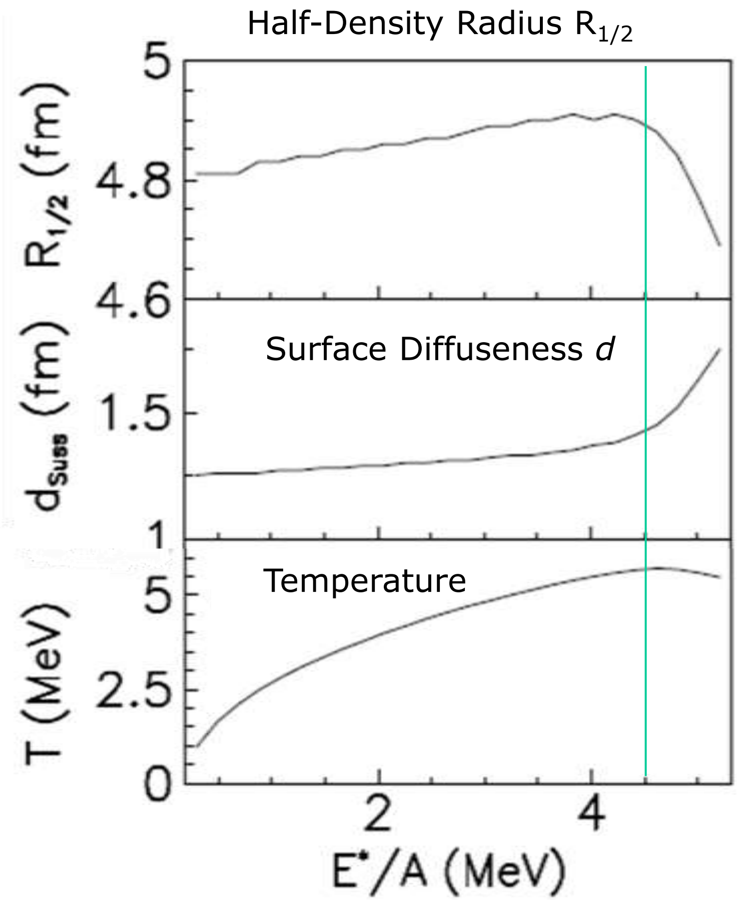
Experimental ***a*** systematics → model relates
E* ⟵⟶ Density ⟵⟶ T

$$Coulomb\ Radius\ r_C = 1.16 \cdot (\rho/\rho_o)^{-1/3}\ fm$$

Level Density Parameter

$$a = a_{Volume} + a_{Surface} = (A\alpha_V + A^{\frac{2}{3}}\alpha_S)(\rho/\rho_o)^{-\frac{2}{3}}$$

Discovery: Spinodal Surface Vaporization



* New nuclear modes *

n-rich surface parts vaporize first,
Residues n-poorer but hotter.
With I^2 "Distillative Boiling"

Tõke & Schröder, PRC subm. (2011), PLB subm. (2013)

$$S_{conf}\left(E_{conf}, I\right) := 2\cdot\sqrt{a_{conf}\cdot\left(E_{tot}-E_{conf}\right)}$$ *Configuration entropy*

$$a_{conf} := \alpha_0\cdot\rho_0^{2/3}\cdot R(I)\int\rho^{1/3}(\vec{r})d^3r$$ *Level density parameter*

$$\rho(r) := C\left(R_{1/2}, d\right)\cdot\rho_0\cdot\left[1-erf\left(\frac{r-R_{1/2}}{\sqrt{2}d}\right)\right]$$ *Matter density*

$$R(I) :\approx \left[1-\frac{1}{9}I^2\right] = \left[1-\frac{1}{9}\left(\frac{N-Z}{A}\right)^2\right]$$ *Asymmetry factor*

$$E_{conf}\left(\rho, I\right) := c_V\cdot\left(1-\frac{\rho}{\rho_0}\right)^2 + c_I\cdot\left(\frac{\rho}{\rho_0}\right)\cdot I^2$$ *Harmonic approximation*

$\delta^2 S \geq 0 \rightarrow$ *instability* $\rightarrow$ *"sudden" decay*

Finite – range calculations:

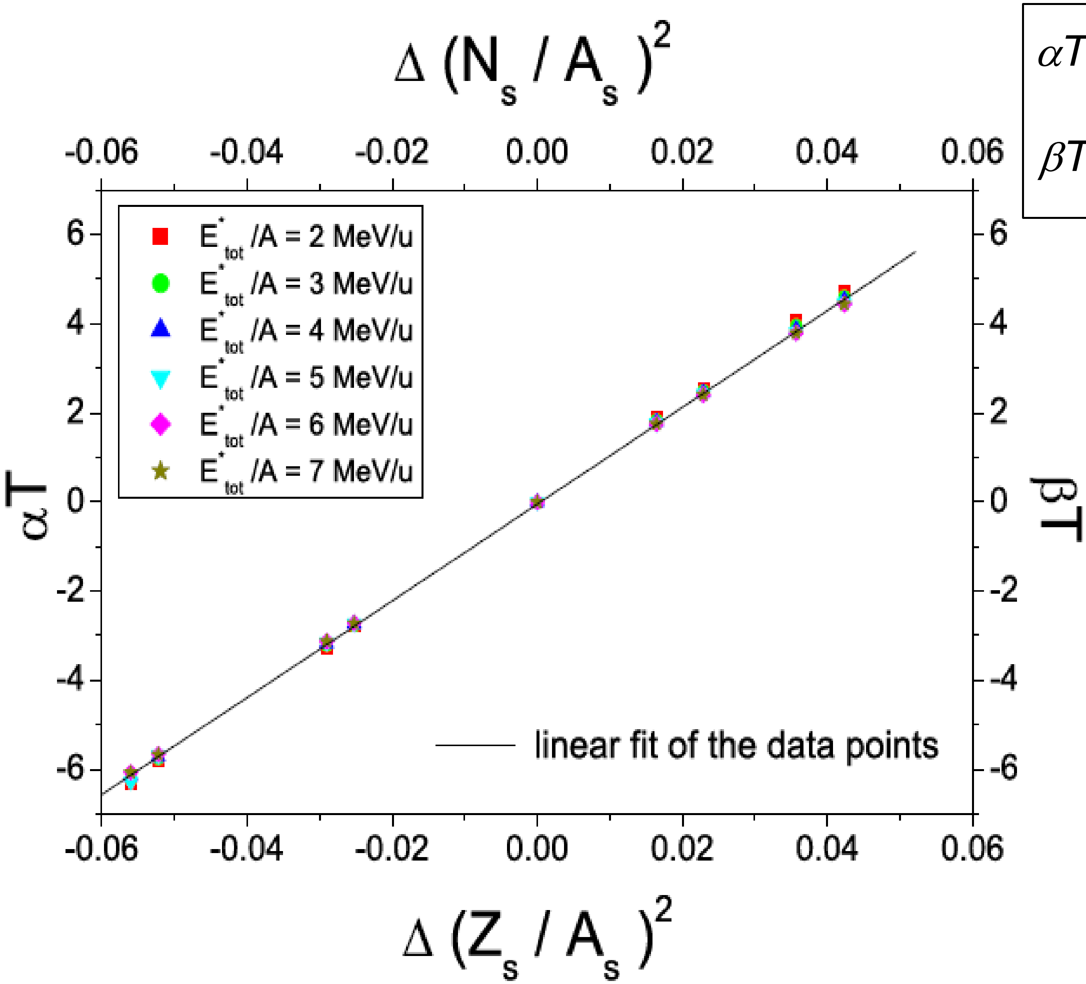
More general Skyrme interactions (K = 220 MeV)

$$\varepsilon_{int}^{EOS}(\rho) := \rho\cdot\left[a\cdot\left(\frac{\rho}{\rho_0}\right)+\frac{b}{\sigma+1}\cdot\left(\frac{\rho}{\rho_0}\right)^{\sigma}\right]$$

$a = -62.43 MeV$
$b = 70.75 MeV$
$\sigma = 2.0$

$$E_{conf}^{EOS} = R_{norm}\int\varepsilon_{int}^{EOS}\left(\rho\left(\vec{r}-\vec{r}'\right)\right)\cdot\exp\{-\frac{\left(\vec{r}-\vec{r}'\right)^2}{2\lambda^2}\}d^3rd^3r'$$ *Folding*

Combined C_{sym} Fit (all CN, all E^*_{tot}/A_{CN})



$$\alpha T = 4C_{sym}\left[(Z/A)^2_{CN_1} - (Z/A)^2_{CN_2}\right]$$

$$\beta T = 4C_{sym}\left[(N/A)^2_{CN_1} - (N/A)^2_{CN_2}\right]$$

Without $a_{surf} \rightarrow$

$C_{sym} = (27.3 \pm 0.1)\,MeV$

With $a_{surf} \rightarrow$

$C_{sym} = (27.6 \pm 0.1)\,MeV$

Surface entropy increases α and $|\beta|$ (More matter in surface)
But decreases T → cancellation of effects.

Equation of State of Nuclei/Nuclear Matter

EOS of asymmetric nuclear matter

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

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

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

Slope $$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0}$$ theoretical values -50 to 200 MeV

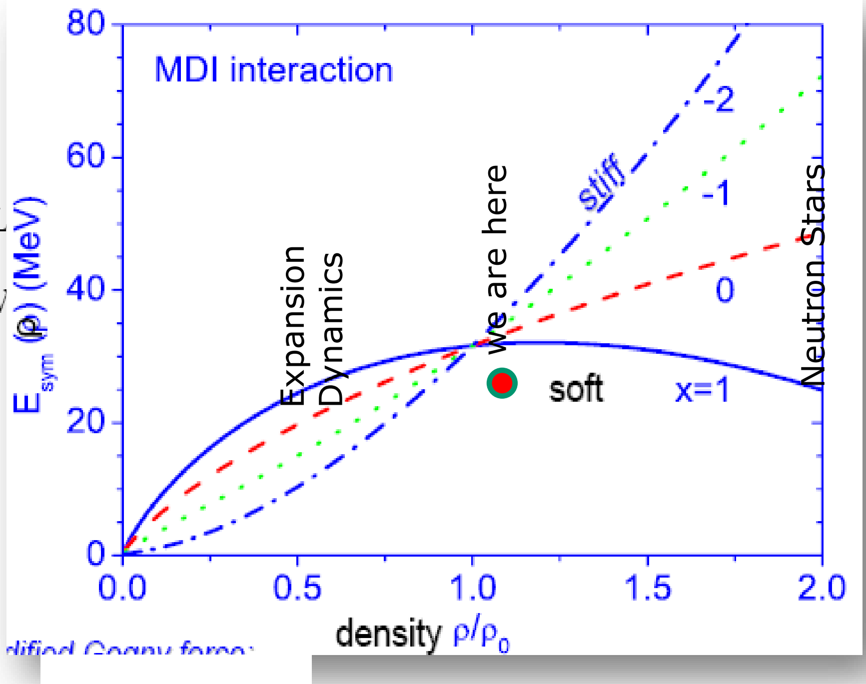
Curvature $$K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial^2 \rho}\right|_{\rho=\rho_0}$$ theoretical values -700 to 466 MeV

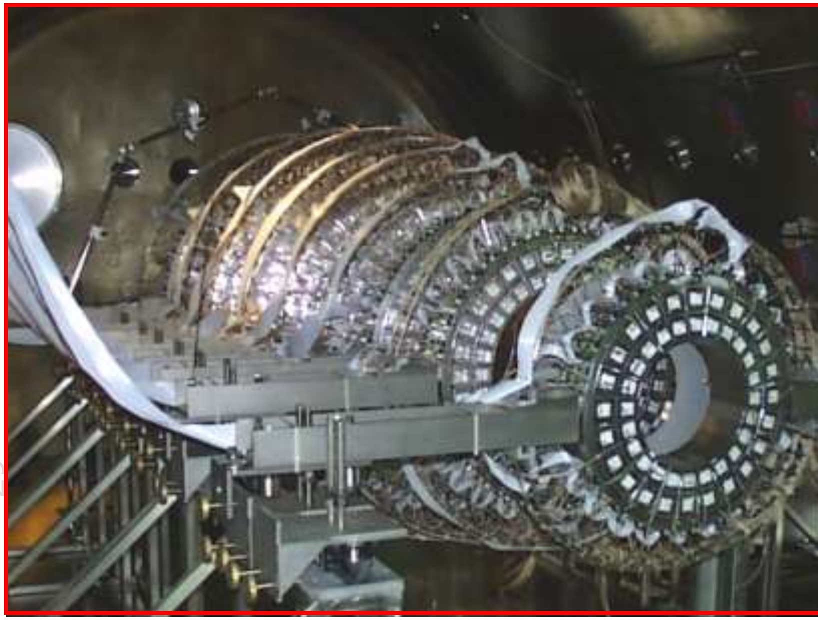
Nuclear matter Incompressibility $$K(\delta) = K_0 + K_{asy}\delta^2, \quad K_{asy} \approx K_{sym} - 6L$$

experimental values K_0~ 230-240 MeV, K_{sym}~566 ±1350-139 ±1617 MeV

EOS: Total energy of a nucleon in nuclear matter is density dependent (ρ_0 = 0.17 n/fm³)

n-p asymmetry energy is uncertain

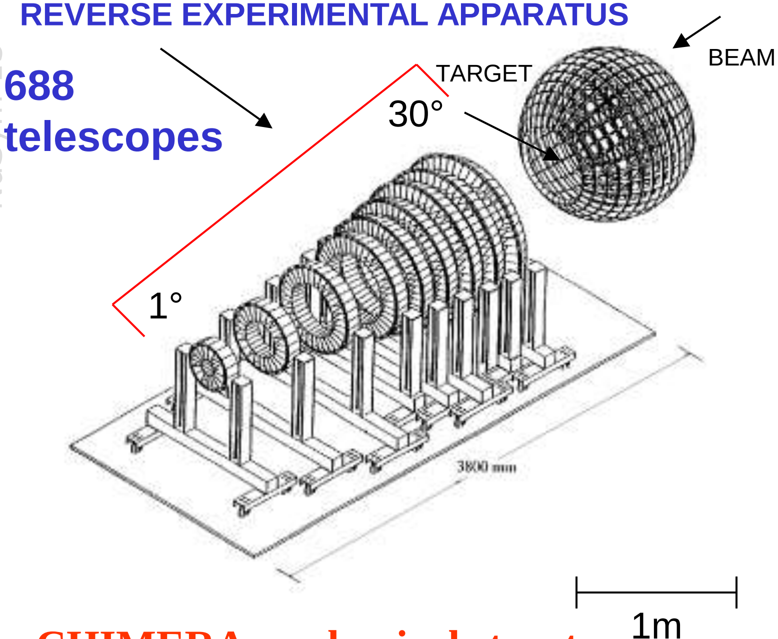




THE CHIMERA DETECTOR

Laboratori del Sud, Catania/Italy

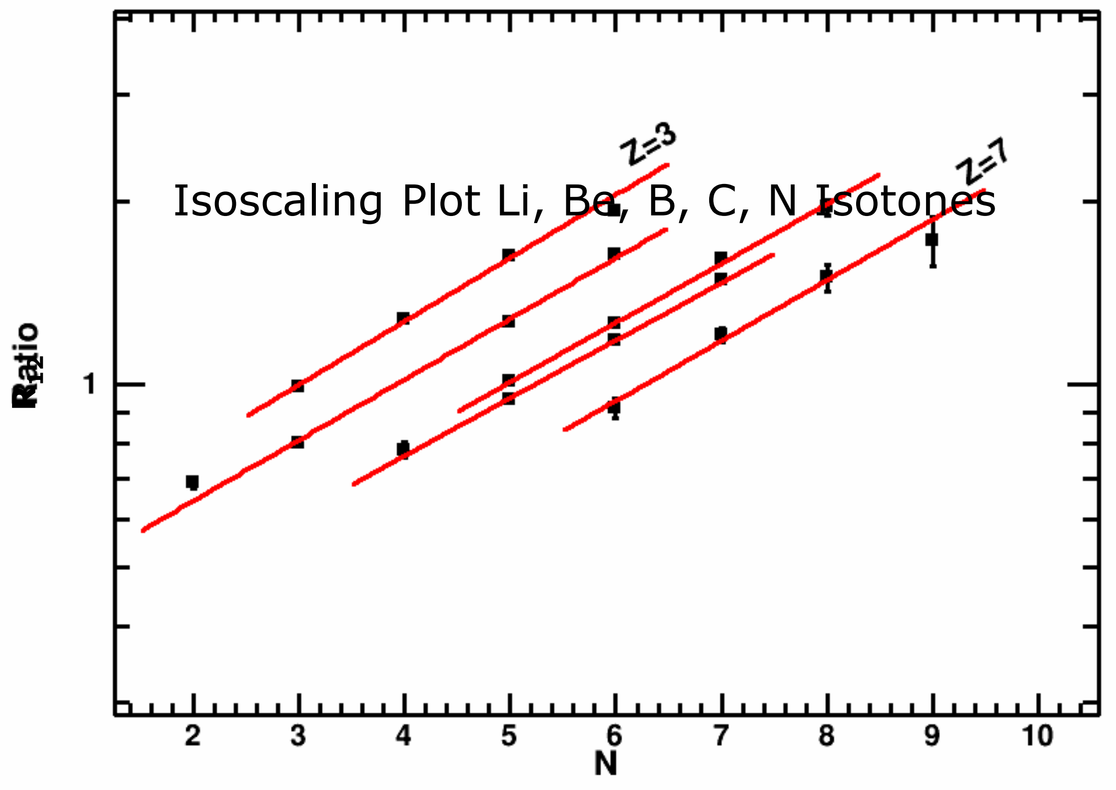
REVERSE EXPERIMENTAL APPARATUS



CHIMERA mechanical structure

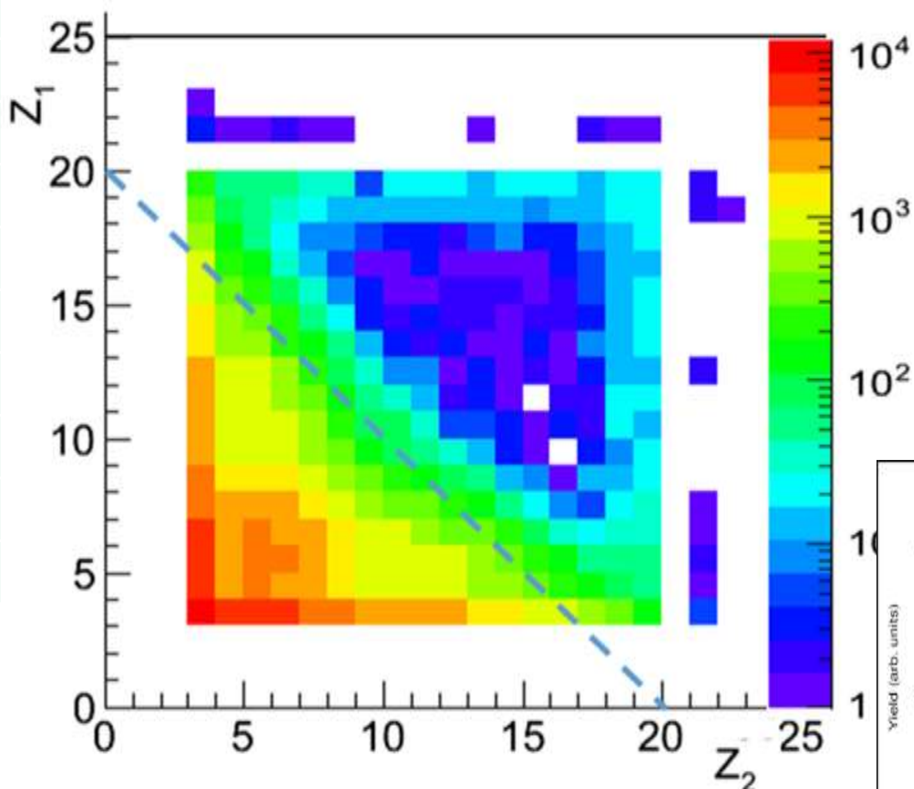
CHIMERA characteristic features

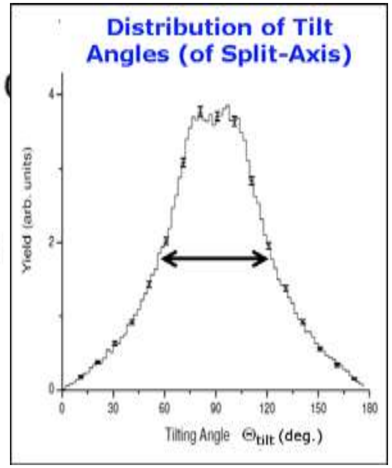
Experimental Method	**ΔE-E → Charge** **ΔE-E E-TOF → Velocity, Mass** **Pulse shape Method → LCP**
Basic element	**Si (300μm) + CsI(Tl) telescope**
Primary experimental observables	**TOF δt ≤ 1 ns** **Kinetic energy, velocity** δE/E Light charged particles ≈2% Heavy ions ≤ 1%
Total solid angle ΔΩ/4π	**94%**
Granularity	**1192 modules**
Angular range	**1°< θ < 176°**
Detection threshold	**<0.5 MeV/A for H.I.** **≈ 1 MeV/A for LCP**



Isoscaling Plot Li, Be, B, C, N Isotones
Z=3
Z=7
Ratio
R_{12}
1
N
2
3
4
5
6
7
8
9
10

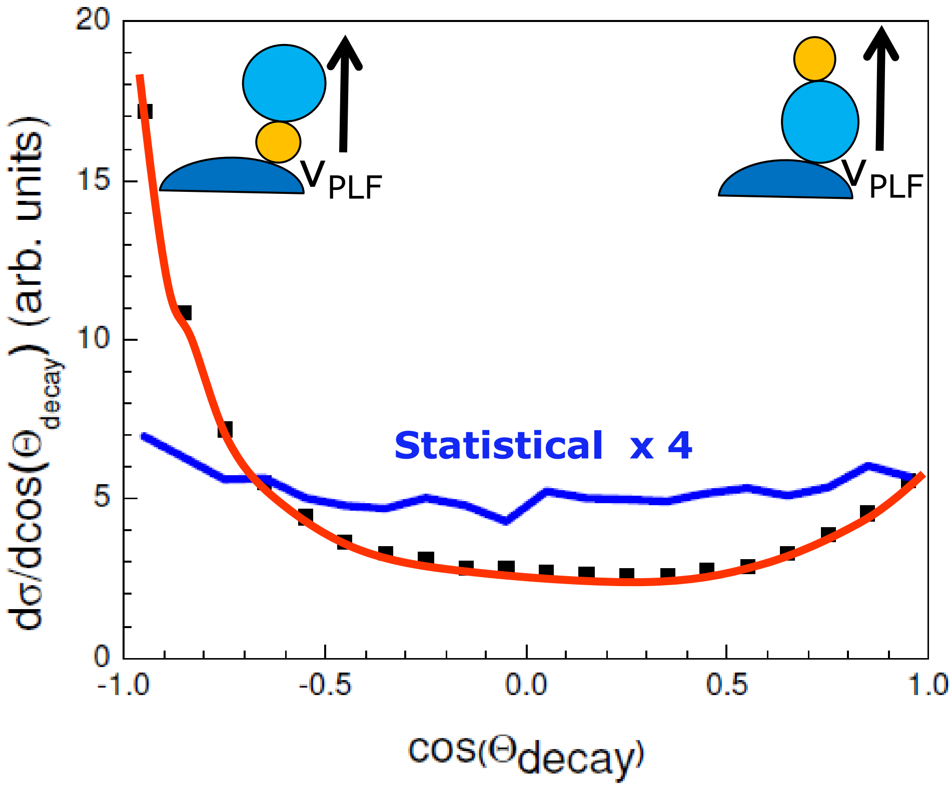
Z1	A1
23	55
24	56
24	55
24	54
24	52
24	56
23	49
24	55
24	57

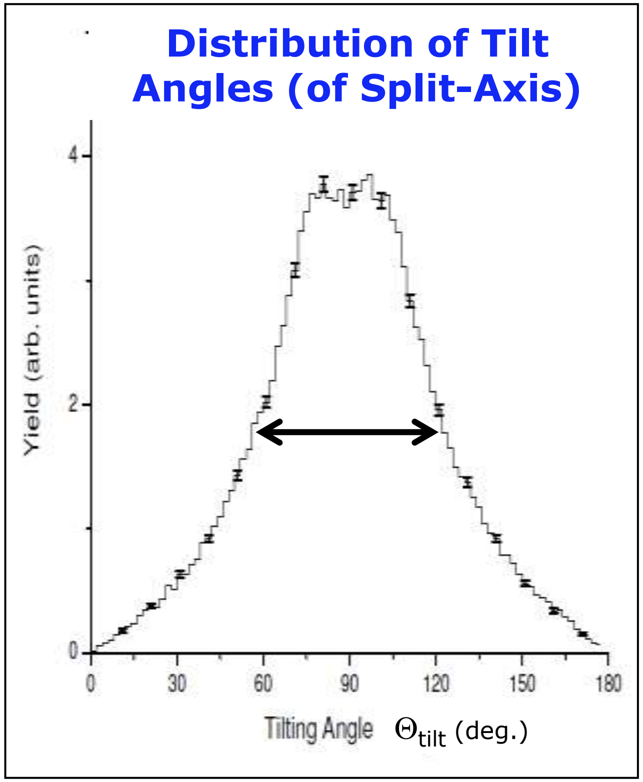




Angular Alignment and Coplanarity

Angular Distribution of light IMF clusters





Preferred orientation of deformed pre-scission PLF: lighter IMF backwards (towards TLF) → **Minimizing energy**

Orientation of the PLF scission axis $\Theta_{Tilt} \approx 90^0 \pm 25^0$.
→ **Coplanarity**