Nuclear thermodynamics and isospin degree of freedom

Marie-France Rivet

Institut de Physique Nucléaire, Orsay

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Nuclear thermodynamics

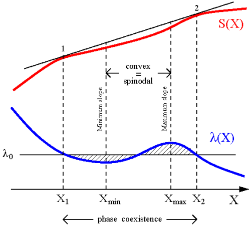
- Nuclear thermodynamics widely studied during the last two decades : what happens when a nucleus (nuclear system) is heated, compressed, diluted . . .
- Nuclear interaction similar to Van der Waals forces for fluids : expected phase transition for nuclear systems. Nuclei (finite systems) show some specific behaviour in the transition region. Multifragmentation is seen as the manifestation of this phase transition.
- More recently experimental and theoretical works focus on the role of isospin, to probe the symmetry energy term of the EOS. Around the Fermi energy, densities $\rho \leq \rho_0$ are explored, which are important for studying structure of exotic nuclei, neutron star crust, supernova explosions . . .

Content

Phase Transition of finite systems

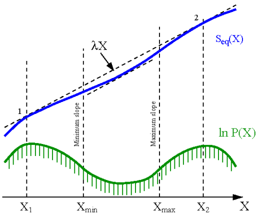
Predicted specific signals

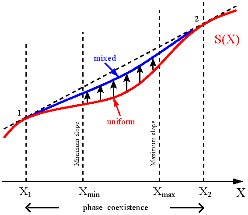
Chomaz, Colonna, Randrup Phys. Rep. 389 (2004)



Backbending caloric curve and negative heat capacity in the spinodal zone

Bimodal distribution of extensive variables (Energy, Z_{max})



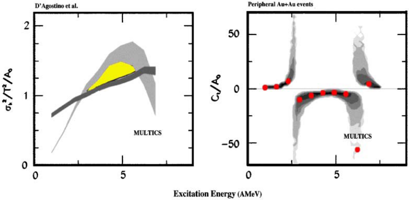


Phase coexistence - spinodal instabilities

Phase transition of finite systems

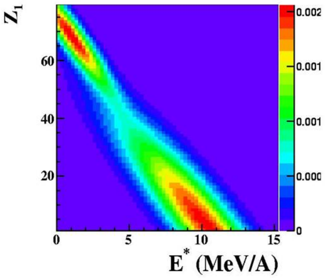
Experimental observations

35 AMeV Au (+Au)



D'Agostino et al. NPA 699 (2002)

60-100 AMeV Au (+Au)



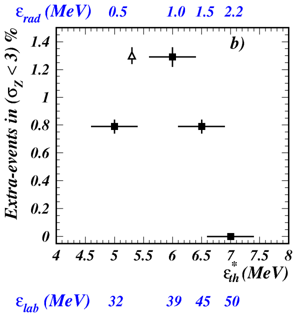
Bonnet & INDRA, PRL 103 (2009)

Latent heat

$8.1(\pm 0.4)_{stat}(+1.2-0.9)_{syst}$ MeV

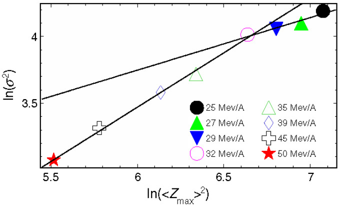
Phase transition : dynamics (spinodal instabilities)

^{129}Xe+^{nat}Sn 32-50 AMeV - Central collisions.



Z_{max} Δ-scaling

Multifragmentation is an aggregation phenomenon



Gruyer & INDRA, PRL 110 (2013)

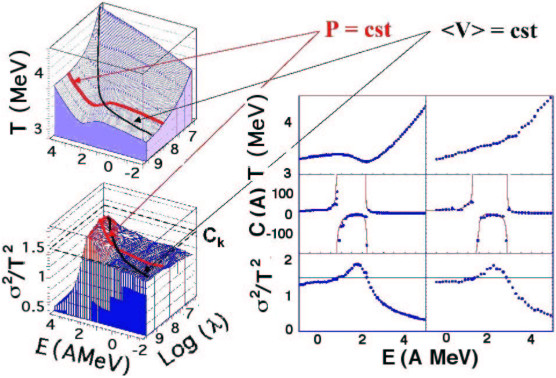
Spinodal instabilities

Extra-production of equal-sized fragments

Tabacaru & INDRA, EPJA 18 (2003)

Phase transition : caloric curves I

The shape of the caloric curve depends on the path in the potential landscape.



Constant $\langle V \rangle$

monotonous increase

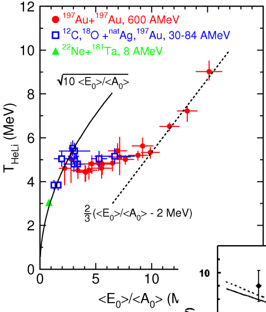
Constant pressure

backbending

Chomaz et al., NPA 749 (2005)

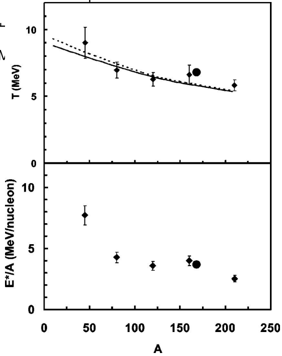
During a nuclear reaction, the transition is probably neither isochoric nor isobaric

Phase transition : experimental caloric curves



Pochodzalla et al.,

PRL 75 (1995)



Natowitz et al., PRC 65 (2002)

E^* from calorimetry ;
T from spectral slopes, or double isotope ratios

Compilation of many exp. data

- $\sim$ Same shape of CC for A=30-240
- The temperature at the plateau, T_{lim}, decreases and is reached at lower energy when A increases.
- T_{lim} depends on Coulomb, surface and isospin.

Bonche et al. NPA 437 (1885) ; De et al. PRC 73 (2006)

Phase transition : caloric curves

New : T_Q from protons $p_\perp$ fluctuations

$\sigma^2 = < Q_{xy}^2 > - < Q_{xy} >^2 = 4m^2 \; T_Q^2 \; F_{QC}$

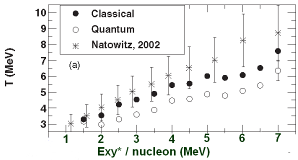
$Q_{xy} = p_x^2 - p_y^2$; $F_{QC} = 0.2(T/\epsilon_f)^{-1.71} + 1$

$\epsilon_f = 36 \; (\rho/\rho_0)^{2/3}$

Zheng et al., PLB 696 (2011)

$T_Q < T_{c\ell}$

45 AMeV ^{32}S+^{112}Sn A_{QP}=32

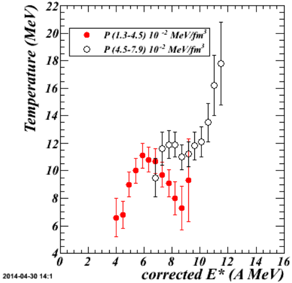


Central Xe+Sn collisions (32-50 AMeV)

Borderie & INDRA, PLB 723 (2013)

- Simulated FO $\Rightarrow V^{FO}, M_p^{FO}$
- T_Q from FO protons .
- Microcanonical pressure
  $P = T \frac{<M_C>}{V} \approx \frac{2}{3} \frac{<K>}{V}$
- caloric curves at “constant pressure”

Stein et al., JPhG 41 (2014)



The asymmetric nuclear matter EOS

Take into account that nuclear matter is a two-component fluid.

Isospin influences nuclear dynamics and thermodynamics because of the symmetry energy term of the asymmetric nuclear matter EOS.

$$\varepsilon(\rho, I) = \varepsilon(\rho, I = 0) + \varepsilon_{sym}(\rho) \times I^2 + \mathcal{O}(4)$$

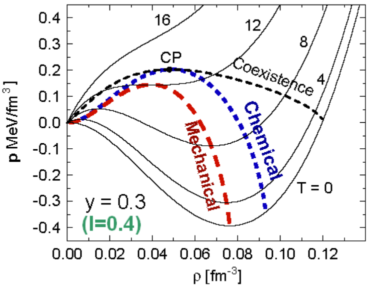
$$I = \frac{\rho_n - \rho_p}{\rho} = \frac{N-Z}{A} \; ; \; \varepsilon = \frac{E}{A}$$

Information on $\varepsilon_{sym}(\rho)$

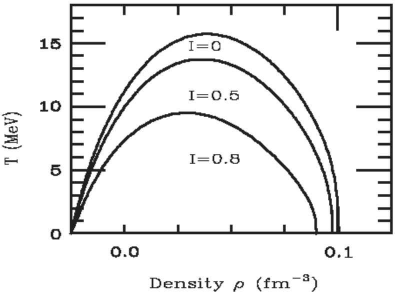
But : $I < 1$: isospin effects are small.
For stable nuclei the range is $0 < I < 0.2$.

Evolution of the EOS with isospin - Nuclear matter

Spinodal instabilities arise from fluctuations in both I and ρ. Mechanical $(\frac{\partial P}{\partial \rho})_{T,y} < 0$ and chemical $(\frac{\partial \mu_p}{\partial y})_{T,P} < 0$ instabilities are strongly connected.



Müller & Serot PRC 52 (1995)

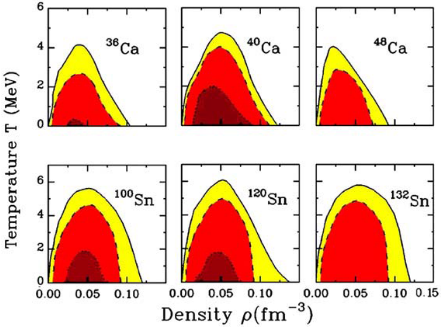


Baran et al. NPA 632 (1998)

Isospin asymmetry leads to shrinking of the spinodal region, reducing both T_c and ρ_c.

Evolution of the EOS with isospin - Nuclei

Phase diagram for octupole instabilities.

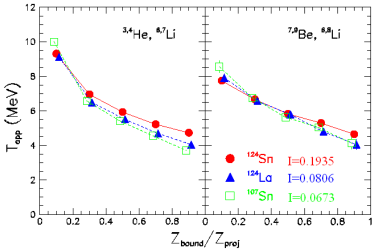


More asymmetric systems are spinodally more stable.

Colonna, Chomaz, Ayik PRL 88 (2002)

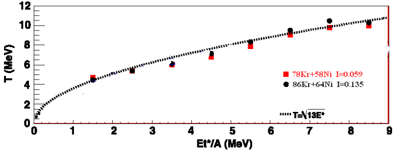
Caloric curve and isospin : experiments I

600 AMeV ^{124}Sn,^{124}La,^{107}Sn (+Sn)



E^*

35 AMeV ^{78}Kr+^{58}Ni,^{86}Kr+^{64}Ni



E^* from calorimetry (measured n) .
T_Q from protons

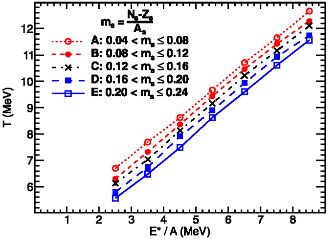
Wuenschel et al. NPA 843 (2010)

Sfienti et al. PRL 102 (2009)

Small isospin effect, slightly higher temperatures for n-rich systems

Caloric curve and isospin : experiments II

35 AMeV ^{70}Zn+^{70}Zn,^{64}Zn+^{64}Zn,^{64}Ni+^{64}Ni



$48 \leq A \leq 52$

McIntosh et al. PLB719 (2013)

NIMROD+ISiS 4π array inside n-Ball

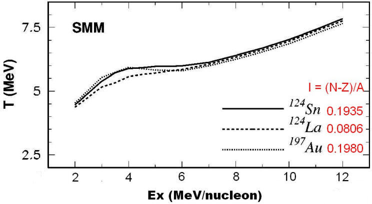
- Reconstructed hot QP, including neutrons
  $\Rightarrow$ known isospin of the emitter
- T_Q from protons
- E^* from calorimetry

Monotonic caloric curves, no plateau (NB T_{lim} found $\sim$ 9-10 MeV for light nuclei)

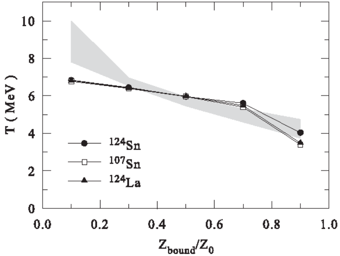
Strong isospin effect, lower temperatures for n-rich sources.

Caloric curve and isospin

Predictions I



Ogul & Botvina PRC 66 (2002)



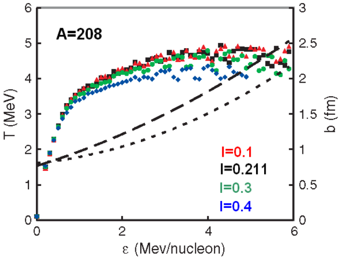
Ogul et al. PRC 83 (2011)

- In the SMM model, the limiting (microcanonical) temperature, in the transition region, increases with increasing asymmetry I.
- Correct agreement with Sfienti's data.
- Same evolution with I predicted when considering a nucleus in equilibrium with its vapor *(Besprovany & Levit PLB 217 (1989))*

Caloric curve and isospin

Predictions II

A = 208 nuclei

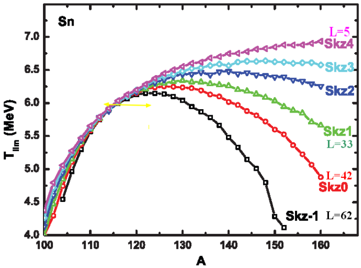


Hoel et al. PRC 75 (2007)

- Isolated mononucleus (no vapor)
- The caloric curve depends very little on asymmetry between for I = 0-0.3.
- The trend is to decrease the temperature for more asymmetric system.

Caloric curve and isospin

isotopic distribution of T_{lim}



Li Ou et al. PRC 89 (2014)

- Nucleus in equilibrium with vapor
- Isotopic distribution of T_{lim} calculated for Skyrme forces with different asy-stiffness (SkzN *Margueron et al. PRC 66 (2002)*
- Strong effect of asy-EOS on n-rich side, small on p-rich side
- The limiting temperature increases from p-rich to stable nuclei, and decreases for very n-rich nuclei (Coulomb and symmetry energy effects).

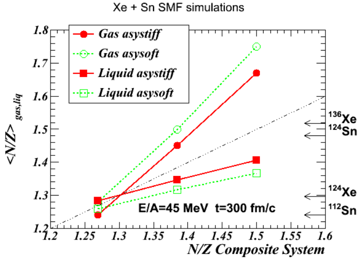
Importance to estimate the isospin of the considered systems

Isospin distillation

Stochastic Mean Field calculations

In the transition region, gas & liquid have different N/Z.

45 AMeV Xe+Sn - central collisions



Asy-stiff ($\propto \rho$) (Solid lines)

Asy-soft (dashed lines) EOS

Opposite effect of asysoft/stiff-EOS on gas and liquid N/Z

more n-rich systems

gas more n-rich than liquid
stronger effect with asy-soft EOS.

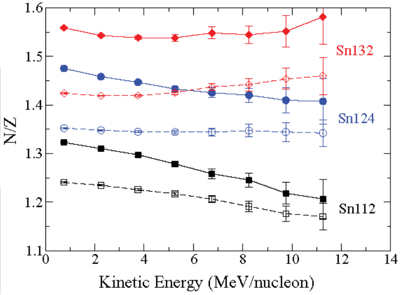
$^{124}Xe+^{112}Sn$

gas and liquid $\sim$ the same N/Z as the composite system, little dependence on EOS.

Isospin distillation and flow

SMF simulations 50 AMeV Sn + Sn (central collisions)
Primary hot fragments

Asy-stiff ($\propto \rho^2$) (Solid lines)
and Asy-soft (dashed lines) EOS



Colonna et al. PRC 78 (2008)

Two competing trends govern N/Z magnitude & slope :

Coulomb accelerates more

p-rich fragments (slope< 0)

E_{sym} more repulsive

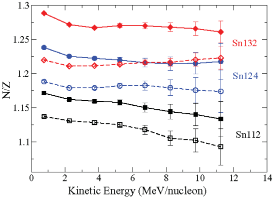
for n-rich fragments (slope> 0, more for asy-soft EOS)

Isospin distillation and flow

Central Sn+Sn (Xe+Sn) collisions

SMF calculations

$E/A = 50$ AMeV

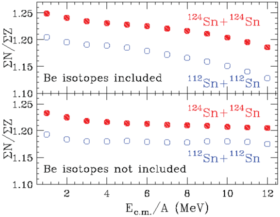


Some effect still visible after evaporation

Colonna et al. PRC 78 (2008)

Experiment

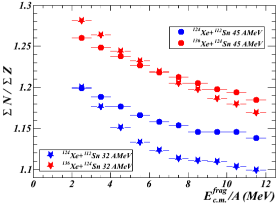
$E/A = 50$ AMeV



Liu et al. PRC 86 (2012)

Experiment

$E/A = 32, 45$ AMeV



F. Gagnon-Moisan et al. PhD (2010) & IWM2009

⚠ SMF underestimates measured $E_{c.m.}$.
To be done again with BLOB (P. Napolitani & M. Colonna).

Level density and isospin

Level density parameters are direct properties of nuclear EOS.
They are expected to depend on isospin (effective neutron/proton masses)
It would be important to have consistent EOS and *a* parameters when coupling transport codes and evaporation codes

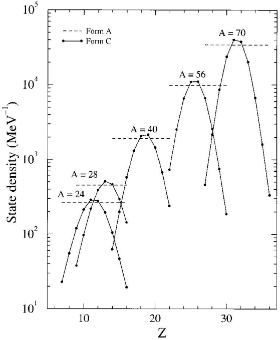
Level density parameter and isospin

Empirical formulae $a(I)$ from fits to a large number of measured level densities
Al-Quraishi et al. PRC63 (2001) & PRC 67 (2003)

(A) $a = \alpha A$

(B) $a = \alpha A / \exp \beta (N - Z)^2$
a maximum for N=Z

(C) $a = \alpha A / \exp \gamma (Z - Z_0)^2$
a maximum for $Z = Z_0$
Z_0 = valley of stability



$\alpha \approx 0.1$ in the 3 cases.
Best fit with form (C) : a becomes very small when approaching the drip lines.

Level density parameter and isospin

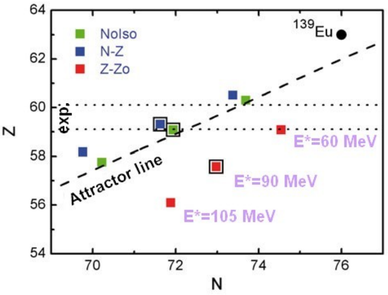
Experimental data

$^{32}S+^{107}Ag \rightarrow {}^{139}Eu$ (I=0.0935) - E^{*}=90 MeV *Moro et al. EPJA (2012)*

- LILITA_N97 code
- $a(I)$: form (A) (B) and (C)
- only n, p, α evap ; no fission

Partial multiplicity

	Protons	Alphas
Exp	1.21 ± 0.18	0.40 ± 0.06
NoIso	1.47	0.46
$N - Z$	1.24	0.47
$Z - Z_0$	2.17	0.61



Results rule out the *a* dependence from the distance to the valley of stability (form C)

Summary

- Effects of isospin on nuclear thermodynamics at $\rho < \rho_0$ and E/A$<$100 MeV are theoretically predicted and experimentally visible.
- Experimentally, the hot nucleus asymmetry remains often uncertain, due to preequilibrium emission, and evaporation.
- Coulomb effects impede those of the symmetry energy. Effects of the asy-EOS more visible for n-rich systems (caloric curves, isospin distillation).
- It appears important to master the variation of the level density parameter with asymmetry. Experiments are needed. On the theoretical side, consistency between the EOS (transport codes) and the level density parameter (de-excitation codes).