Constraining the density dependence of the symmetry energy with experimental results from heavy-ion collisions

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Outline

Introduction

The knowledge of the density dependence of the nuclear symmetry energy is critical in nuclear physics and astrophysics for understanding:

At low density

neutron skin, pigmy resonance - nuclear structure at the drip line
competition between mechanisms - neutron distillation in fragmentation
neutron star formation and crust

At high density

neutron star mass-radius relation
transition to a deconfined phase
formation of black holes

Experimental constraints ?

First determination, at T=0 and $\rho = \rho_0$, from fits of binding energies with LD mass formula, with a symmetry term:

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

Bulk term only (Bethe-Weizsacker)

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

New Experimental constraints

How to explore densities different from ρ_0? Heavy-ion collisions provide the only means to compress/expand nuclear matter in a terrestrial laboratory. (N.B. $T \nearrow$)

Comparison of some isospin dependent variables measured in Heavy Ion collisions with the results of

- transport codes: follow dynamics of a nucleus-nucleus collision with time.
- statistical frameworks: No dynamics. Start at a “freeze-out” equilibrated stage, when nuclear interaction becomes negligible.

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

Some observables sensitive to E_{sym}.

- Subsaturation densities
  - Competition of reaction mechanisms : fusion vs deep inelastic
  - isospin diffusion
  - N/Z of fast nucleon emission
  - isospin distillation : isospin content of light fragments
  - Neck fragmentation at Fermi energies
  - neutron skin
- Suprasaturation densities
  - n, p collective flows
  - Meson production

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The statistical ensembles

Statistical ensembles:

- microcanonical: fixed total energy and particle number. Appropriate for isolated systems like nuclei. ex. MMM (Raduta), SMM(s) (Bondorf, Botvina and other variants)
- canonical: Fixed number of nucleons and T, can exchange E with a reservoir. Reasonable approximation for $A \geq 200$ and $T \geq 6$ MeV.
- grandcanonical: the system can exchange energy and particles with a reservoir. Only average values are fixed. Governed by T. Meaningful for nuclei at large E* when only mean values are considered.

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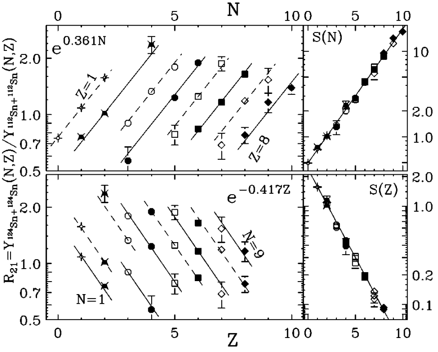
Iso(tope)scaling
Isotopic distributions

Consider two systems (1) and (2), with different masses ($A(2) > A(1)$). Look at the yield $Y(N, Z)$ of nuclei produced in both systems.



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

isoscaling formulae

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

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

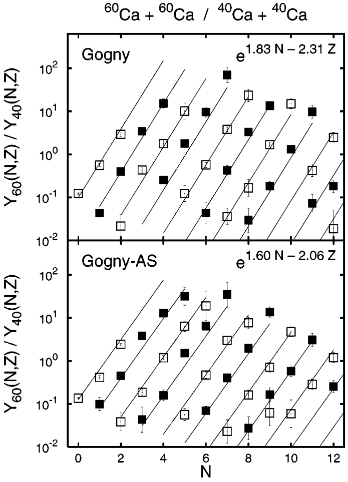
$$S(Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \exp -\alpha N$$

Isoscaling

if statistical reaction mechanisms and close T in both systems.

Isoscaling in (dynamical) transport codes ?

AMD: A. Ono et al., PRC 68 (2003) 051601



E/A=35 MeV; t=300 fm/c (10^{-21}s)

Isoscaling is observed as soon as the isotopic distributions are Gaussians around mean values. The coefficients are determined by the difference between mean values divided by the width (*V. Baran et al. Phys. Rep. 410 (2005)*)

Isoscaling and symmetry energy

In a grandcanonical framework, one has
$Y^{(i)}(A,Z) = \exp\left(\frac{1}{T^{(i)}}(-G(N,Z) + \mu_N^{(i)} N + \mu_Z^{(i)} Z)\right)$
Considering two systems at same T and P, isoscaling is satisfied for this relation with: $\alpha = (\mu_N^{(2)} - \mu_N^{(1)})/T$

The free energy $G(N,Z)$ can be approximated by:

$$G(N,Z) = a(Z) + c_0(Z)N + c_{sym}(Z)(N-Z)^2/A$$

which gives for the most probable value for each system $\langle N\rangle(Z)$:

$$c_{sym}(Z)\left\{1 - 4[Z/\langle A\rangle(Z)]^2\right\} = \mu_N^{(i)} - a(Z)$$

Finally, subtracting (1) from (2): $4\frac{c_{sym}(Z)}{T} = \frac{\alpha}{\Delta\left(\frac{Z^2}{\langle A\rangle^2}\right)}$

In the formalism, the symmetry energy is that of hot fragments:

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

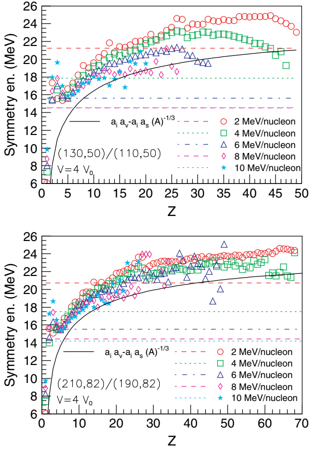
If C_{sym} did not depend on Z, and $(N/Z)_{frag} = (N/Z)_{sys}$, we could get the symmetry energy of the fragmenting system

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

This was done by several groups, who found very low values of c_{sym}. But these values are in contradiction with the inputs of the model used.

Isoscaling and symmetry energy

But ...MMM calculations *A. Raduta and F. Gulminelli, PRC 75 (2006) 024605.*



Solid line: input C_{sym} of the model.

Symbols:

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

Better for very excited large source and small fragments (grandcanonical).

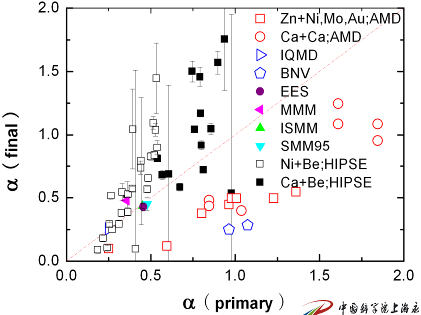
hor. lines :

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

Good only for very heavy fragments at low E*.

Isoscaling and symmetry energy

effect of secondary decays *Yao Fu et al. Chin. Phys. Lett. 26 (2009) 082503*



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SINAP
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

Generally

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

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

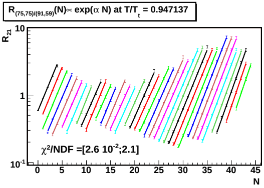
Widths of excited isotopic dist. smaller in Dynamical, while final widths are more similar in both cases.

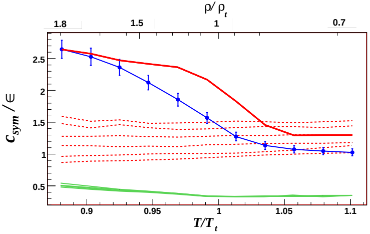
Isoscaling and symmetry energy

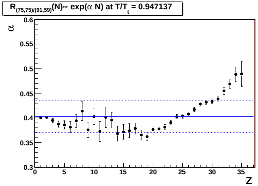
Finally the isoscaling α parameter extracted for light isotopes does not appear very reliable for a direct determination of the symmetry energy.
But as α was shown to linearly vary with the *I* value of the systems It appears as a useful isospin dependent variable.

Isoscaling in the Lattice gas model

Z_{max} is promising (*G. Lehaut et al. PRL102 (2009) 142503)*







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

$\alpha(Z_{max})$ qualitatively better agrees with the input symmetry energy

Needs to detect and fully identify Z_{max} :NEW EXP. DEVICES TO GET A FOR Z>10 on large Ω, e.g. FAZIA.

the EOS of asymmetric nuclear matter

To a good approximation, at T=0, the EOS of nuclear matter is:

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

symmetric matter

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

The second term is smaller than the symmetric part $\Rightarrow$ isospin effects should be rather small.
Better constrained if I can vary on a larger range (RIBs). Present results from stable beams.

The symmetry term of the mean field, E_{sym}

E_{sym} gets a kinetic contribution from Pauli correlations and a potential contribution from the isovector part of the effective nuclear interactions.

$$\frac{E_{sym}}{A}(\rho) = \frac{\varepsilon_F(\rho)}{3} + \frac{C}{2} F(\rho/\rho_0)$$

with $F(1)$=1 and $C \approx$32 MeV (a_4 term of the mass formula)

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

or with a second order expansion around normal density :

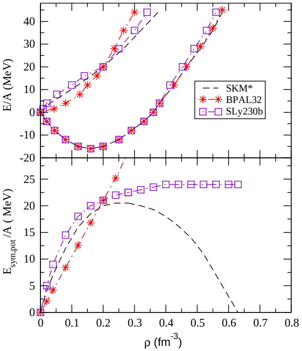
$$\frac{E_{sym}}{A}(\rho) = a_4 + \frac{L}{3}(\frac{\rho-\rho_0}{\rho_0}) + \frac{K_{sym}}{18}(\frac{\rho-\rho_0}{\rho_0})^2$$

γ, L define the asy-stiffness of the EOS and allow comparison between different formulations.

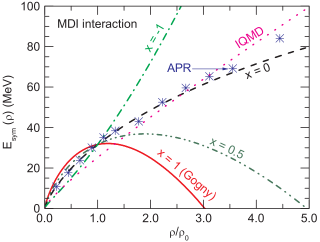
Some symmetry terms in mean field

The form of the (potential) symmetry term is still highly controversial.

V. Baran et al., Phys. Rep. 410 (2005) 335.



B.A. Li PRL102(2009)



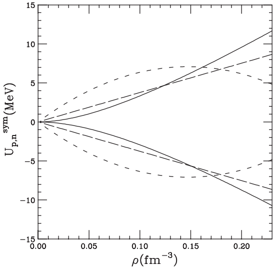
The symmetry energy is termed

"asy-soft" if E^{pot}_{sym} presents a maximum (between ρ_0 and $2\rho_0$), followed by a decrease and vanishing ($\gamma < 1$)

"asy-stiff" if it continuously increases with ρ ($\gamma > 1$)

The potential symmetry term of the mean field

n and p potentials have opposite signs.



I=0.2 (ex ^{124}Sn)
$U > 0$ neutrons
$U < 0$ protons

Attractive potential for p (opposite to Coulomb !).
asy-soft more attractive than asy-stiff below ρ_0, less above ρ_0

The ingredients of transport codes

- Mean field : all results of the last two decades agree for a "soft" isoscalar term, K_∞=200-230 MeV.
  Isoscalar (+ isovector) momentum dependence or not.
- Residual interaction :
  free $\sigma_{NN}(E, I, \theta)$ or in-medium correction.

In the following comparisons, each code keeps same properties of symmetric matter and same residual interaction, only E_{sym} is varied.

Transport codes : Glossary

- BUU, VUU (Boltzmann/Vlasov-Uehling-Uhlenbeck), IBUU, RBUU (Bertsch, Danielewicz, Bao-An Li)
- Landau-Vlasov (Sébille)
  BNV (Boltzmann-Nordheim-Vlasov)
  (di Toro, Colonna)
- Molecular Dynamics
  - the QMD (Quantum Molecular Dynamics) family
    QMD (Aichelin), IQMD (Hartnack), ImQMD (Z. Li), UrQMD (Bass) ...
  - CoMD (Constrained MD - Bonasera & Papa, Catania)

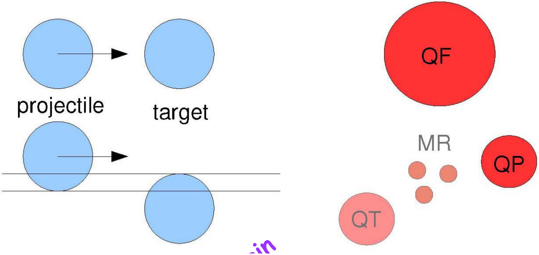
Identification of fragments in transport codes

Fragments are identified either

- with a clusterization algorithm, in r space or in r, p space.
- following local densities : low densities correspond to free nucleons, higher ones to clusters of nucleons (fragments).

Nuclear collisions at Fermi energies

Central ($\sim$ head-on) collisions: some nucleons/light nuclei escape rapidly (preequilibrium). The big remnant either de-excite to an evaporation residue, or multifragments.

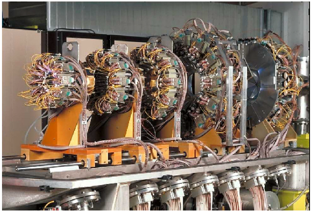


(semi)Peripheral collisions: two remnants of projectile (QP) and target(QT). In between nucleons and light nuclei (mid-rapidity, neck). QP/QT de-excite by evaporation or multifragment.

Glossary: the 4π arrays used

Detect and identify charged products, neutrons need additional devices.

- Fermi energies
  Miniball (+LASSA) - MSU (USA)
  INDRA - GANIL (France)
  CHIMERA - LNS Catania (Italy)
- relativistic energies
  - FOPI - GSI Darmstadt (Germany)



Competition of dissipative mechanisms
Fusion vs deep inelastic in central collisions

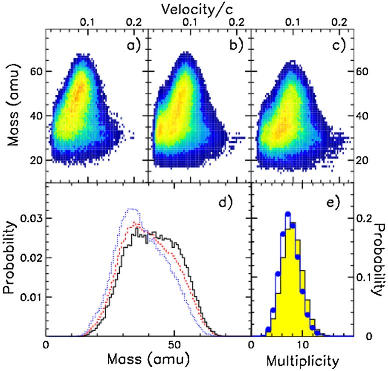
Effect of isospin understood in terms of the amount of repulsion existing during the interaction of two surfaces (i.e. below ρ_0).

- For n-rich systems, fusion is favoured with asy-soft : the proton symmetry field is more attractive and thus the interaction between the incoming nuclei is stronger, the dissipation larger.
- For n-poor conversely fusion is easier for asy-stiff : because of a repulsive field for p (“proton skin”), p are promptly emitted, which decreases Coulomb and makes fusion more likely.

Competition of reaction mechanisms

Amorini et al. PRL 102 (2009) 112701

target: ^{48}Ca ^{46}Ti ^{40}Ca



a) to d): largest fragment

- ^{40}Ca @ 25A MeV at LNS Catania
  Detection with CHIMERA 4π array (1192 modules)
- Selection of events with:
  - $32 < \sum_i Z_i < 40(42)$
  - $\sum_i P_i > 0.7 \times P_{beam}$
  - $M \geq 5$ (^{48}Ca) or 6 (other targets)
  - d): $0.04 < v_1/c < 0.15$

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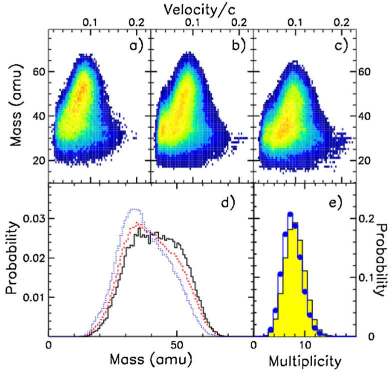

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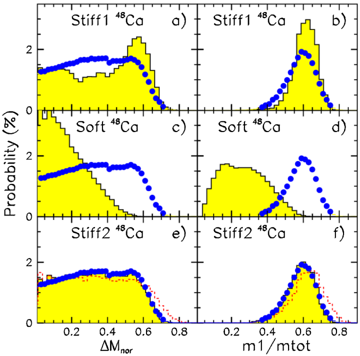


CoMD-II + GEMINI (shaded histos)

3 symmetry energy terms:

Soft = γ = 0.5

Stiff2 = γ = 1

Stiff1 = $\gamma \approx$ 1.5

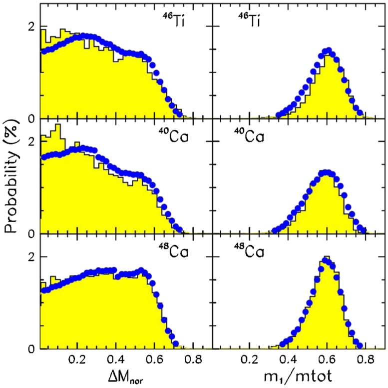
Comparison with data for the n-rich system

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

• data

Competition of mechanisms

Fusion vs deep inelastic in central collisions



For the 3 systems, good agreement between results (dots) and CoMD-II + GEMINI (shaded histos) using the asy-stiff parametrization, E_{sym}^{pot} linearly dependent on the density.

"Exchange of isospin" between QP and QT during the collision, until N/Z equilibration (=that of the total system). Depending on t(b,E) at which QP/QT re-separate, equilibration might or not be reached

Interplay between

1. Isospin transport due to density gradients (migration) depends on the slope of the symmetry energy :

$$D_{\mathrm{n}}^{\rho} - D_{\mathrm{p}}^{\rho} \propto 4I\frac{\partial E_{sym}}{\partial \rho}$$

2. Transport due to isospin concentration gradients (diffusion) depends on the absolute value of the symmetry energy

$$D_{\mathrm{n}}^{I} - D_{\mathrm{p}}^{I} \propto 4\rho E_{sym}$$

Use of imbalance (or isospin transport) ratio

Study of isospin transport/equilibration for an isospin sensitive quantity x:

$$R^x_{P,T} = \frac{2(x^M - x^{eq})}{(x^H - x^L)} \text{ with } x^{eq} = (x^H + x^L)/2$$

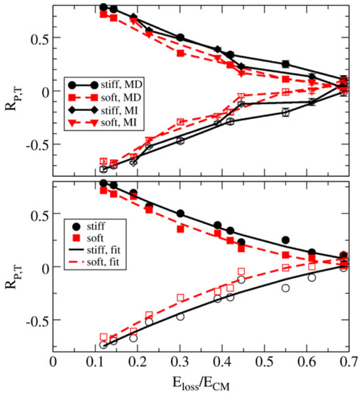
H and L refer to two symmetric reactions between n-rich and n-poor nuclei, M to the mixed reaction.
$R = \pm 1$ in projectile(P)/target(T) regions, R=0 when isospin equilibrium is reached.

Different observables x will provide the same result if they are linearly related.

The use of ratios is expected to minimize effects such as pre-equilibrium, Coulomb, secondary de-excitation ... and emphasize the influence of the asymmetry term.

Study of isospin diffusion vs dissipation

Di Toro et al. Prog. Part. Nucl. Phys. 62 (2009) 389



$x = (N - Z)/(N + Z)$

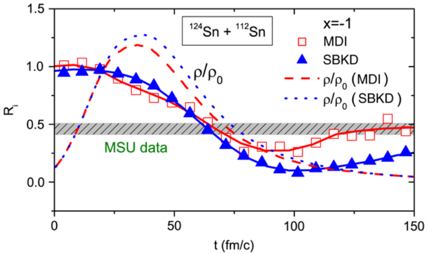
Results of the BNV transport code

Reactions Sn+Sn @35A and 50A MeV.
H=124; L=112
"universal" curve when sorting with $E_{loss}/E_{c.m.}$
isospin equilibrium reached faster, with less dissipation, for asy-soft EOS.

Isospin diffusion
MSU data

4 systems studied: ^{124}Sn+^{124}Sn, ^{112}Sn+^{112}Sn, ^{124}Sn+^{112}Sn and ^{112}Sn+^{124}Sn @ 50 *A*MeV.
For x use of the isoscaling parameter α
and the ratio of yields of mirror nuclei $\ln\left[Y(^7Li)/Y(^7Be)\right]$.
Both are linearly connected with I
An experimental impact parameter is obtained from M_{cp} distributions.
Experimental cut b/b_{max}>0.8.
Comparisons are made with transport codes with b=6 fm, in which $x = I$.

$X = \alpha$

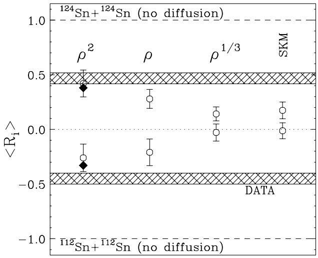


Comparison to IBUU04, b=6 fm (B.A. Li)
Best agreement for asy-stiff: x=-1 $\equiv \gamma$=1.6-2

Isospin diffusion

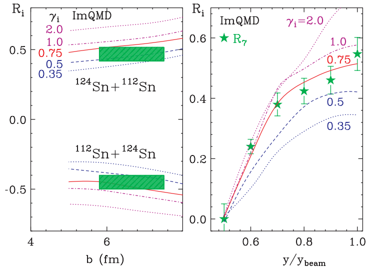
MSU data

$x = \alpha$ (*Tsang PRL 92 (2004) 062701*)



Comparison to BUU97 (B. A. Li):
asy-stiff $\gamma \sim$*2*

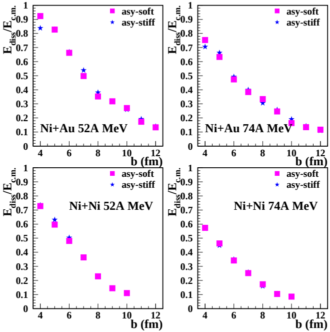
$x = \alpha$ (left) and R_7 (right $*$) both agree in QP region $y/y_{beam} > 0.7$ (*Tsang PRL 102 (2004) 122701*)



Comparison ImQMD (Z. Li):
asy-soft $\gamma \sim$*0.7*

Isospin diffusion vs impact parameter
INDRA data

One projectile, two targets : ^{58}Ni + ^{58}Ni and ^{58}Ni + ^{197}Au at 52*A* and 74*A* MeV.



sorting variable

$E_{diss} = E_{c.m.} - \frac{1}{2}\mu V_{rel}^2$ with
$V_{rel} = V_{QP}^{rec} \times \frac{A_{tot}}{A_{target}}$
BNV shows that this variable gives a good measure of the impact parameter

Isospin diffusion vs impact parameter

INDRA data *E. Galichet et al. PRC 79 (2009) 064614/15*

The isospin variable

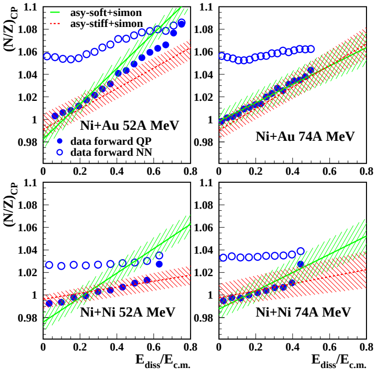
$(< N > / < Z >)_{CP} = \sum_{N_{evts}} \sum_{\nu} N_{\nu} / \sum_{N_{evts}} \sum_{\nu} P_{\nu}$

ν=H, He, Li, Be isotopes.

free protons are excluded, as neutrons are not measured.

Variable measured with particles (1) forward in the NN frame and (2) forward in the QP frame.

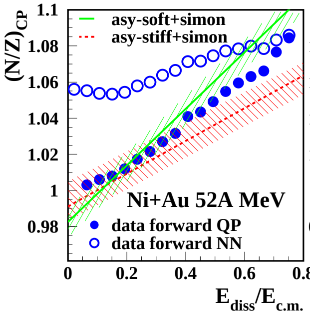
The latter value is compared with the results of a BNV calculation, after de-excitation of the QP* using the SIMON code of D. Durand.



When considering the 4 systems

A better overall agreement is obtained with the asy-stiff EOS,

in which the potential term of the symmetry energy varies linearly with the density.



The values of $< N >/< Z >)_{CP}$ forward of the NN velocity (dominated by MR particles) and forward in the QP frame (QP evaporation) become equal at high dissipation ($E_{diss}/E_{c.m.}$ ~0.75); this is a good indication that we did observe the N/Z equilibration of the system, and should sign an asy-stiff EOS.

n/p ratio at Fermi energies

- This variable is directly sensitive to the symmetry energy, due to the opposite signs of the neutron and proton symmetry potentials. The most important information comes from high energy (early emitted) nucleons.
- Experimentally studied by the MSU group: they look at c.m. p and n energy spectra for $70° < \theta_{cm} < 110°$, in central collisions. They take into account the n and p contained in light clusters.
- To minimize uncertainties due to the different apparatuses, calibrations, efficiencies for n and p measurements, they use double ratios of spectra:

$$DR(n/p) = R_{n/p}(H)/R_{n/p}(L)$$

n/p ratio at Fermi energies

- This variable is directly sensitive to the symmetry energy, due to the opposite signs of the neutron and proton symmetry potentials. The most important information comes from high energy (early emitted) nucleons.
- Experimentally studied by the MSU group: they look at c.m. p and n energy spectra for $70^\circ < \theta_{cm} < 110^\circ$, in central collisions. They take into account the n and p contained in light clusters.
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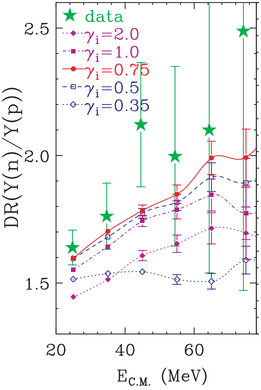
n/p ratio: comparison with transport codes

Tsang al. PRL102 (2009) 122701

50 AMeV ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn



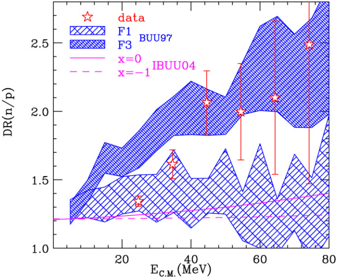
Compare with the ImQMD code, varying the symmetry energy term
Within a 2σ uncertainty, the result is $0.5 \leq \gamma \leq 1.05$, with best value 0.7.
Same value as that obtained from isospin diffusion

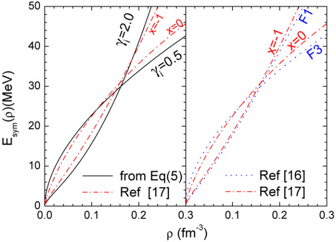
n/p ratio: comparison with transport codes

Zhang al. PLB 664 (2008) 145

Introduction
Statistical framework
the EOS of asymmetric nuclear matter - transport codes
Competition of reaction mechanisms
Isospin diffusion
n/p ratios
Isospin distillation
Neck fragmentation at Fermi energies
Neutron skin
Constraint on the EOS at supra-saturation density
Summary

50 AMeV ^{124}Sn+^{124}Sn and ^{112}Sn+^{112}Sn
Comparison with other codes (Bao-An Li 1997 and 2004):
IBUU04 fails, BUU97 indicates a soft asy-EOS γ=0.5.
BUUs results disagree with those from isospin diffusion



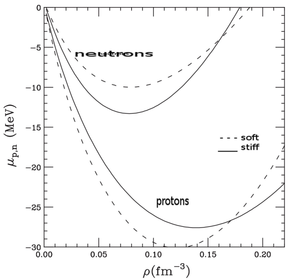


Isospin distillation (or fractionation)

Central collision Multifragmentation data

Test of symmetry energy in dilute matter. Signs a phase transition.

I=0.2



$$\mu_n - \mu_p = 4E_{sym}(\rho)I/A$$

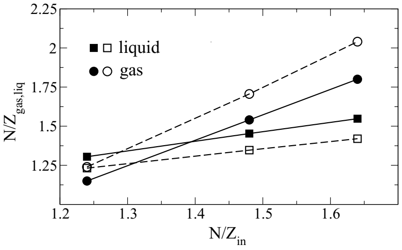
$\rho < \rho_0/2$

n and p move in phase to higher ρ
different slope $\Rightarrow$ clusters from bulk instability more symmetric.
n-enrichment of the gas phase
Effect stronger for soft asy-EOS.

Isospin distillation

BNV calculation
Central symmetric Sn+Sn collisions @50 *A*MeV

dashed line+open points = soft
full line and points = stiff



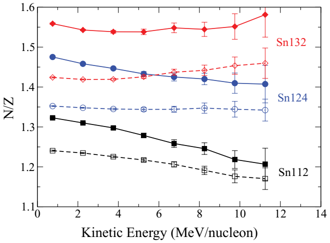
- Larger difference for asy-soft (E_{sym} larger at low ρ)
- Difference increases with N/Z
- $I_{frag} < I_{syst}$ for n-rich systems
  $I_{frag} > I_{syst}$ for “n-poor” systems
- Inversion liquid/gas at smaller N/Z for asy-stiff, because Coulomb effects dominate a smaller E_{sym} and more protons are emitted.

Isospin distillation

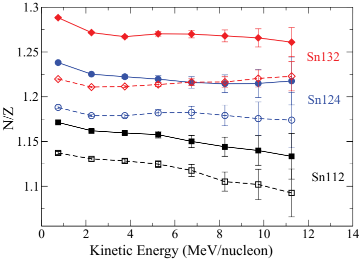
with radial flow

Central symmetric Sn+Sn collisions @50 *A*MeV- Hot fragments
Exp. we cannot distinguish “liquid” and “gas”, but we may follow N/Z vs kinetic energy of fragments.

dashed = soft
full = stiff



Slope characteristic of N/Z_{sys} and asy-stiffness
p-rich: Coulomb accelerate the more p-rich fragments $\Rightarrow$ negative slope
n-rich: E_{sym} more repulsive for n-rich fragments $\Rightarrow$ positive slope, larger for asy-soft.

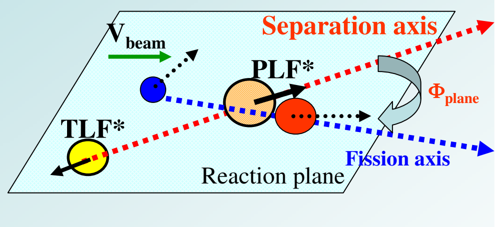


Final fragments : Some differences is expected to persist after fragment de-excitation.

Analyses in progress at MSU and Orsay/Laval (PhD of F. Gagnon-Moisan)

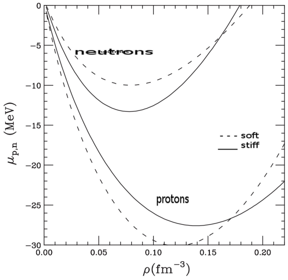
Neck fragmentation at Fermi energies

Neck dynamics observed at energies 15-50 AMeV in semi-peripheral collisions: large cross sections.
It concerns light products (Z$<$10) emitted in the interaction zone, with a velocity intermediate between those of the 2 main partners (PLF/TLF)
Characterized by alignment of PLF, TLF and neck fragments: max. of in-plane angular distribution at $\Phi_{plane} = 0$



Neck fragmentation at Fermi energies

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.

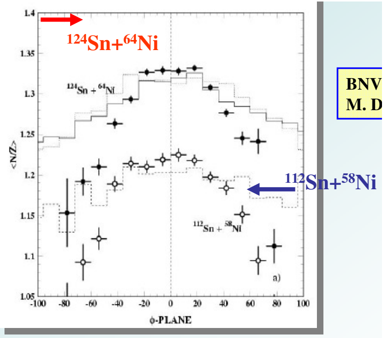


p and n move now in opposite directions:
p from neck to PLF/TLF
Larger n flow with asy-stiff EOS
neck-IMF more n-rich than MF-IMF

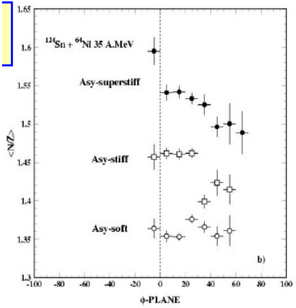
Neck fragmentation at Fermi energies

CHIMERA data

NeckIMF N/Z vs alignment



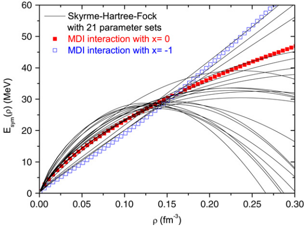
Stochastic BNV results



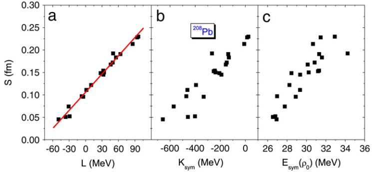
Better agreement with an asy-stiff EOS around ρ_0 ($\gamma \approx 1.6$)

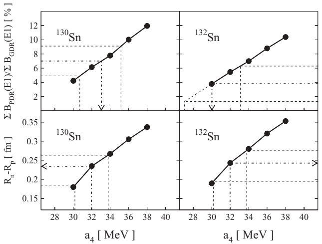
Pigmy resonance and neutron skin of heavy nuclei

Klimkiewicz et al. PRC76 (2007) 051603



21 Skyrme forces (*LW Chen et al PRC72 (2005) 064309*)





In MF calculations the n-skin thickness depends linearly on the slope of the symmetry energy at normal density. PDR strength linearly depends on S.

Pigmy resonance of heavy nuclei

measurements *Klimkiewicz et al. PRC76 (2007) 051603*

By comparing the strength ratio PDR/GDR for ^{132}Sn and ^{130}Sn constraints are put on a_4 and L :

$$a_4 = 32.0 \pm 1.8 \text{ MeV}$$
$$L = 43 \pm 15 \text{ MeV}$$

This corresponds to a soft asy-EOS, with $\gamma \in [0.4; 0.6]$

n, p collective flows

Flow observables expressed as the 1^{st} and 2^{nd} coefficients of the Fourier expansion of the azimuthal distribution of particles:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi}(y, p_t) = 1 + v_1 \cos(\phi) + 2 v_2 \cos(2\phi)$$

v_1 transverse flow $\Rightarrow$ azimuthal anisotropy of the transverse nucleon emission.

v_2 elliptic flow $\Rightarrow$ competition between in-plane and out-of-plane emissions.

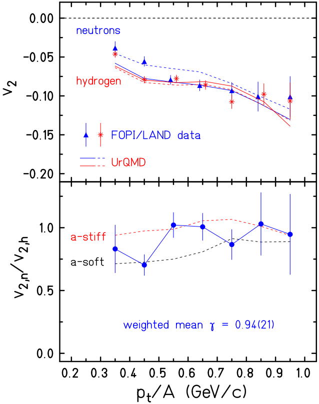
$v_2 > 0$ in-plane emission favoured

$v_2 < 0$ out-of-plane emission (squeeze-out)

n, p collective flows

FOPI/LAND Data *W. Trautmann et al. nucl-ex0907.2822*

Au+Au@400 *A*MeV. Combined data for central and mid-peripheral collisions.

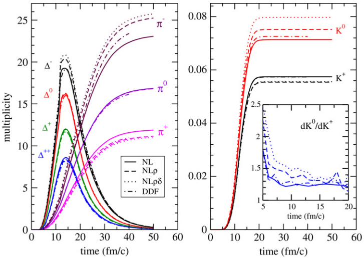


Comparison with UrQMD ($b < 7.5$ fm, filtered FOPI/LAND), with 2 γ values, 0.5 and 1.5. p_t dependence well described. n more sensitive to asy-stiffness.

From the ratio $v_{2,n}/v_{2,h}$ a linear interpolation between predictions gives $\gamma \approx 0.9 \pm 0.3$

New exp. CHIMERA/LAND to be performed in 2011 at GSI.

RMF calculations for 1AGeV Au+Au collisions (b=0)

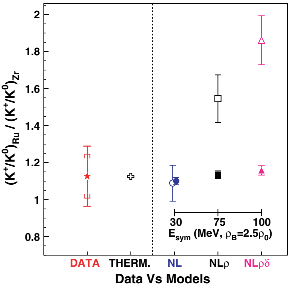


π^-/π^+, K^+/K^0 ratios should measure the N/Z of the dense participant zone. Kaons should be better probes, as pions are produced (and re-absorbed) all along the collision.
Larger expected effect of asy-EOS on K^+/K^0 than on π^-/π^+.

Supra-saturation density: K^+/K^0

FOPI data *X. Lopez et al. PRC75 (2007) 011901*

${}^{96}_{44}$Ru+${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr @ 1.5*A*GeV
Same mass, different isospins.

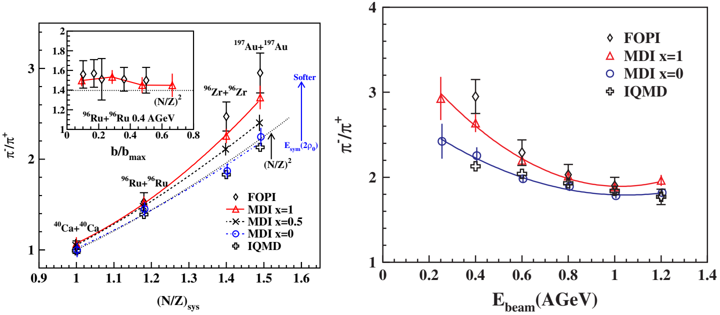


Calculations = RMF of the Catania group.
At that energy, and in view of the large experimental error bars, no information on E_{sym} can be obtained.

π^-/π^+ Soft asy-EOS at supra-saturation density ?

FOPI data *Reisdorf et al. NPA 781 (2007) 459*

Central collisions, estimated density $2\rho_0$



Result discriminant for heavier systems, near the π threshold: a very soft asy-EOS is favoured.

Problems and Drawbacks

- Impact parameter selection: it is better to calculate the same *b*-dependent variable in data and model. A *b* value just derived from data is more questionable.
- De-excitation. We measure cold fragments. Transport codes or statistical models consider hot fragments. In between we need a de-excitation code (reliability?).
- De-excitation weakens the expected effects.
- π, K in transport codes: in-medium effects ?

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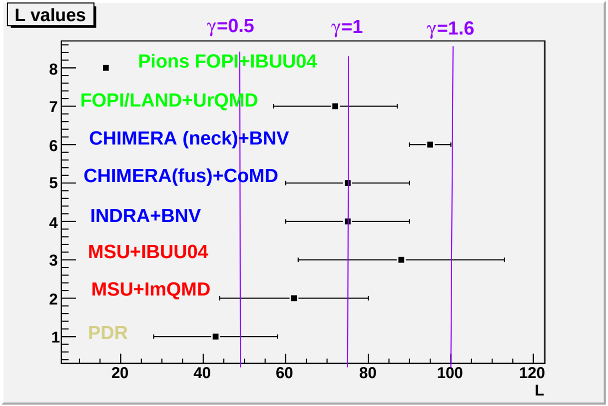

Difficult to give the asy-stiffness of the EOS in view of the presently existing data.

How to go further?

Some suggestions

1. Experimentally
   - Improve detection to get A and Z over a much larger Z range, and Ω
   - New experiments to better constrain evaporation codes
   - new RIBs
   - High statistics experiments
2. Theoretically
   - Implementation of predictive EOS (EDF)
   - Analyze the results of calculation in the same way as the data
   - Compare codes with all existing data

References

Two review papers for many more details

V. Baran, M. Colonna, V. Greco and M. Di Toro, Phys. Rep. 410 (2005) 335

Bao-An Li, Lie-Wen Chen and Che-Ming Ko, Phys. Rep. 464 (2008) 113