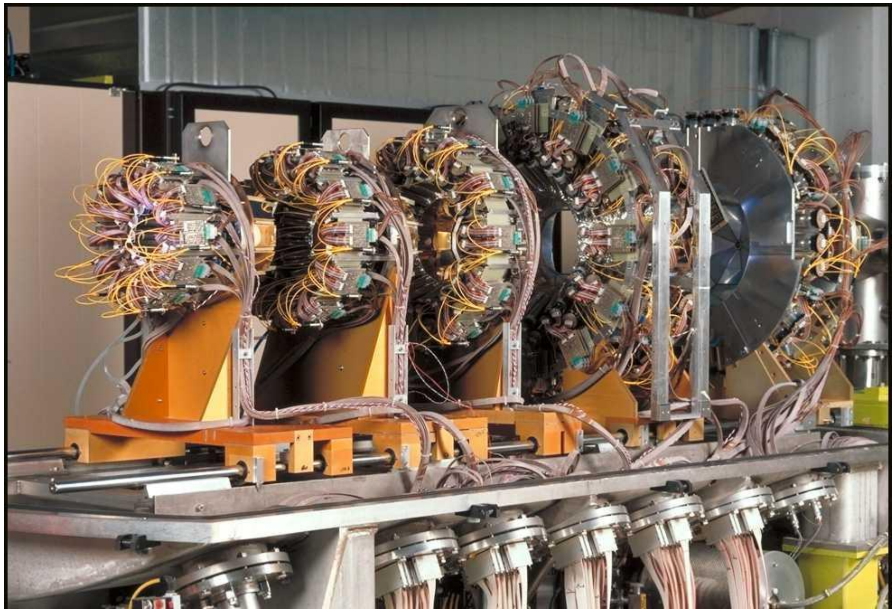
Phase transition dynamics in hot nuclei and N/Z influence

INDRA Coll.



$^{124}Xe + ^{112}Sn$, $^{136}Xe + ^{124}Sn$ at 32,45 AMeV
Quasifusion events from central collisions

Bernard Borderie

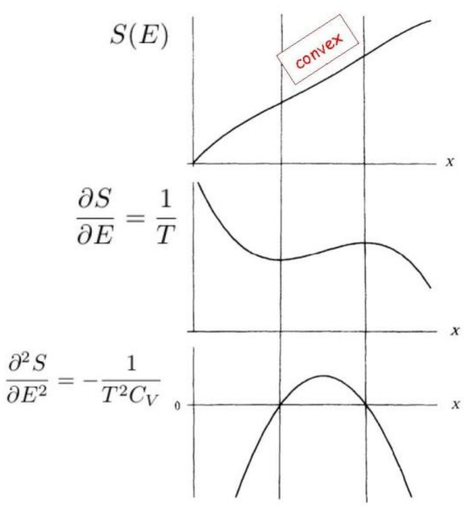
NSD2019 May 13-17

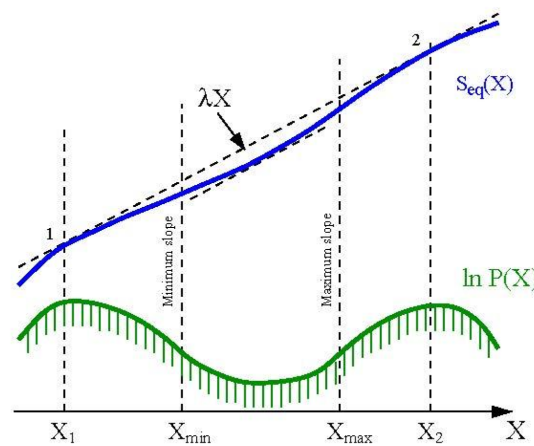
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Liquid-gas phase transition in hot nuclei:
the situation before the present study

Predicted specific signals of phase transition which are a direct consequence of the local convexity of entropy expected for finite systems have been observed.

⇒Negative heat capacity with a microcanonical sampling and related
⇒Backbending for pressure-constrained caloric curves
⇒Bimodal distribution of an order parameter (charge of the heaviest fragment) with a canonical sampling





P(X) ~ exp(S(X)-λX)

Liquid-Gas phase transition in nuclei, BB and J.D. Frankland, Prog. Part. Nucl. Phys. 105 (2019) 82

Bernard Borderie

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

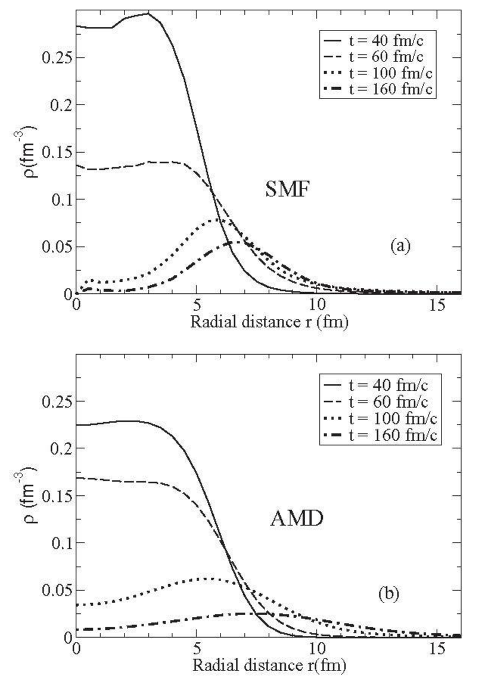
Liquid-gas phase transition in hot nuclei:
the situation before the present study

The answer to a key point was still pending - what is the nature of the dynamics of the transition, i.e. the fragment formation

Two mechanisms proposed which both reproduced fragment size dist.

⇒Fragmentation process generated by spinodal instabilities amplified at low density (Stochastic Mean Field approaches)

=>Many-body correlations which are sufficient to produce fragments at early times (molecular dynamics models: AMD etc…)



^{112}Sn + ^{112}Sn b=0.5 fm 50 AMeV
Density profiles at several times

M. Colonna, A. Ono and J. Rizzo PRC 82 (2010) 054613

What about spinodal instabilities?

Bernard Borderie

NSD2019 May 13-17

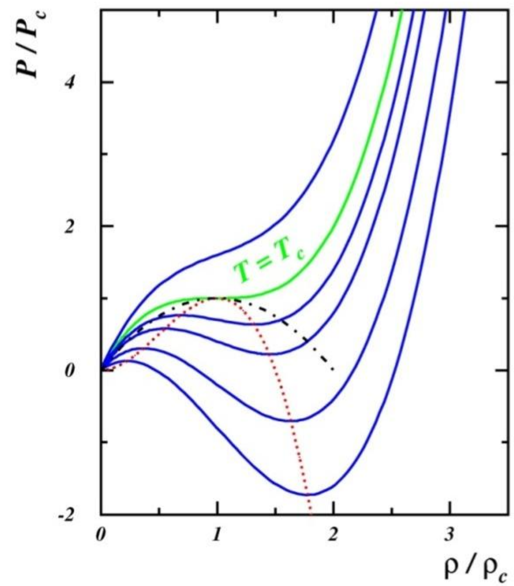
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

spinodale zone mechanically unstable

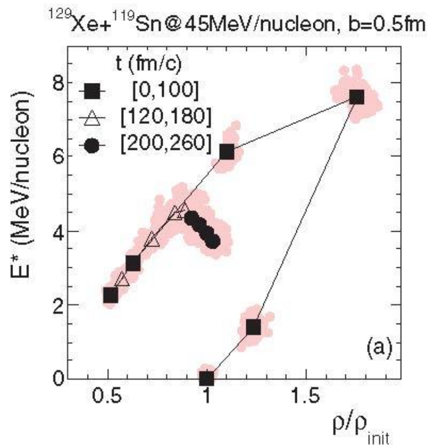
negative compressibility

$\delta P/\delta\rho<0$ $\rho_c \approx 0.3\text{-}0.4\ \rho_0$

unstable medium
density fluctuations exponentially amplified
=> Fragment formation



This unstable region is reached with central heavy ion collisions at Fermi energies

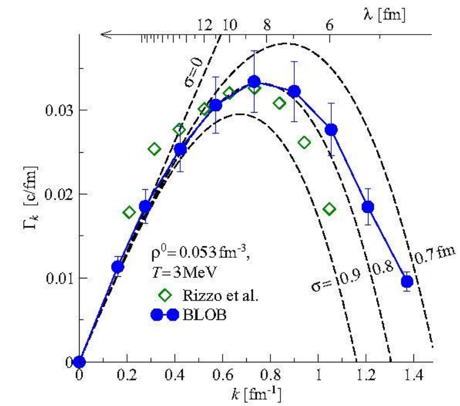


compression expansion phase
=> trajectory

E. Bonnet et al., PRC 89 (2014) 034608

spinodal instabilities
density fluctuations are exponentially amplified

BLOB: fluct. introduced in
full phase space from induced
NN collisions



matter dispersion relation
P. Napolitani, M. Colonna PRC 97 2017 054609

Infinite nuclear matter: most unstable modes correspond to wavelengths lying around $\lambda = 2\pi/k \approx 8\text{-}10$ fm

primitive fragments with nearly equal size around Ne ($A \approx \rho\lambda^3$)

and associated characteristic times around $1/\Gamma_k \approx 30\text{-}50$ fm/c

Variational approach
to study small fluct. -> multipole expansion
of the velocity potential

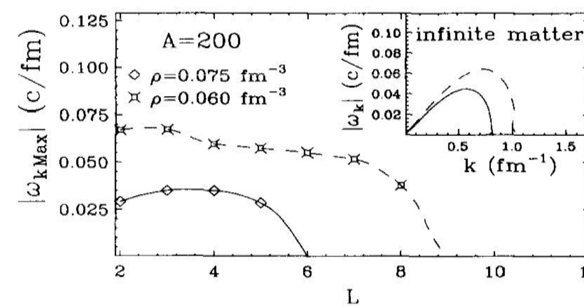


Fig. 3. Growth rates of the most unstable modes for a source with $A = 200$ nucleons with a Fermi shape profile as a function of the multipolarity L at central densities $\rho_0 = 0.060$ fm^{-3} (dashed line) and $\rho_0 = 0.075$ fm^{-3} (solid line). The insert shows the fluid dynamical dispersion relation for infinite matter as a function of the wave number k.

finite systems (A=200) – quasifusion nuclei :
breaking of the translational symmetry
due to surface =>growth rates of the most unstable modes are nearly the same for different multipolarities L up to a maximum multipolarity L_{max}
=>partitions with nearly equal-sized primitive fragments depending on L (multiplicity)

B. Jacquot et al., PLB 383 (1996) 247

Bernard Borderie

NSD2019 May 13-17

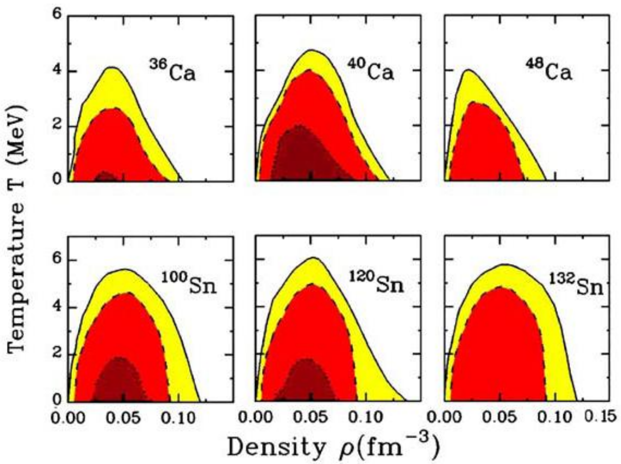
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

Spinodal region/instabilities with N/Z variation

Self consistent quantum approaches (TDHF+RPA modes)
=>more asymmetric systems are less unstable

Sn isotopes: shorter inst. growth times
disappear when N/Z changes from 1.4 to 1.64

Inst. regions with L=3



instability growth time dashed lines 100 fm/c
dotted lines 50 fm/c

M. Colonna et al., PRL 88 (2002) 122701

Spinodal instabilities – a fossil signature is expected for finite nuclei

For infinite nuclear matter, the most unstable modes present in the spinodale region favor partitions of nearly equal-sized fragments (Z = 8-10)
But this simple picture is blurred by several effects

-the beating of different modes
-the coalescence of nascent fragments

For multifragmenting nuclei even more

- surface effects -breaking of the translational symmetry
  (equal-sized fragments for different multipolarities/ multiplicities)
- the decay of excited fragments (minor effect)
- hot nuclei produced by collisions have to stay long enough
  in the spinodal region (≈ 3 characteristic time: 100-150 fm/c for N/Z 1-1.4 and 200-300fm/c for larger N/Z)

=>Stochastic mean field simulations of collisions predict less than 1% of extra events with nearly equal-sized fragments (G. Tabacaru et al., EPJA 18 (2003) 103)
which means A FOSSIL SIGNATURE OF SPINODAL INST.

Experimentally we indeed observe a Z distribution without any bumps revealing nearly equal-sized fragments.

how to search for a possible very weak « fossil » signature?
And if yes can we observe a reduction of the signal with the increase of N/Z as theoretically predicted ?

Spinodal instabilities – quasifusion events

^{124,136}Xe + ^{112,124}Sn 32,45 AMeV - experimental signature

Very high statistics experiment (6-8 10^7 events with $M \geq 4$)
Quasi complete events ≥ 80% Z_{syst}
Central collisions – quasifusion
-shape event sorting
(kinetic energy flow tensor for Z>4)
-32 AMeV 40mb (250mb)
- 45 AMeV 25mb (180mb)
(det.efficiency + selec.)

Intra-event charge correlations

very high sensitivity method down to levels of 0.002-0.003% events

CHARGE CORRELATION METHOD

•A VERY SENSITIVE METHOD

FOR EACH EVENT n_Z BEING THE NUMBER OF FRAGMENTS WITH CHARGE Z

$$\langle Z \rangle = \frac{1}{M} \sum_Z n_Z Z \qquad (1)$$

$$\sigma_Z^2 = \frac{1}{M} \sum_Z n_Z (Z - \langle Z \rangle)^2 \qquad (2)$$

CORRELATION FUNCTION

$$\left. \frac{Y(\sigma_Z, \langle Z \rangle)}{Y'(\sigma_Z, \langle Z \rangle)} \right|_M \qquad (3)$$

⇑
UNCORRELATED YIELD
(EXACT MULTINOMIAL FORMULA
TOTAL CHARGE CONSERVATION)

Bernard Borderie

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Intra-event charge correlations – uncorrelated yield

Exact multinomial formula (P. Désesquelles PRC 65 (2002) 034604)

⇒ independent emission model with total charge conservation constraint mandatory to not distort CF values for weak signals

Partition constrained conditional probabilities $P_{cc}(N)$ N : partition

${}^{intr}P_z(z)$: intrinsic probability of charge z

$$P_{cc}(N) = \alpha\,(\Sigma\, n_z)!\ \Pi\ {}^{intr}P_z(z)^{nz}\ \delta_{ztot}\ \Sigma\ zn_z$$

n_z : number of fragments with charge z

α : normalisation factor $\Sigma\, P_{cc}(N) = 1$

${}^{intr}P_z(z)$ evaluated by inversion of the equ.
by means of a recursive procedure of
minimisation which stops when
10^{-12} between 2 steps is reached

Intra-event charge correlations – quasifusion nuclei

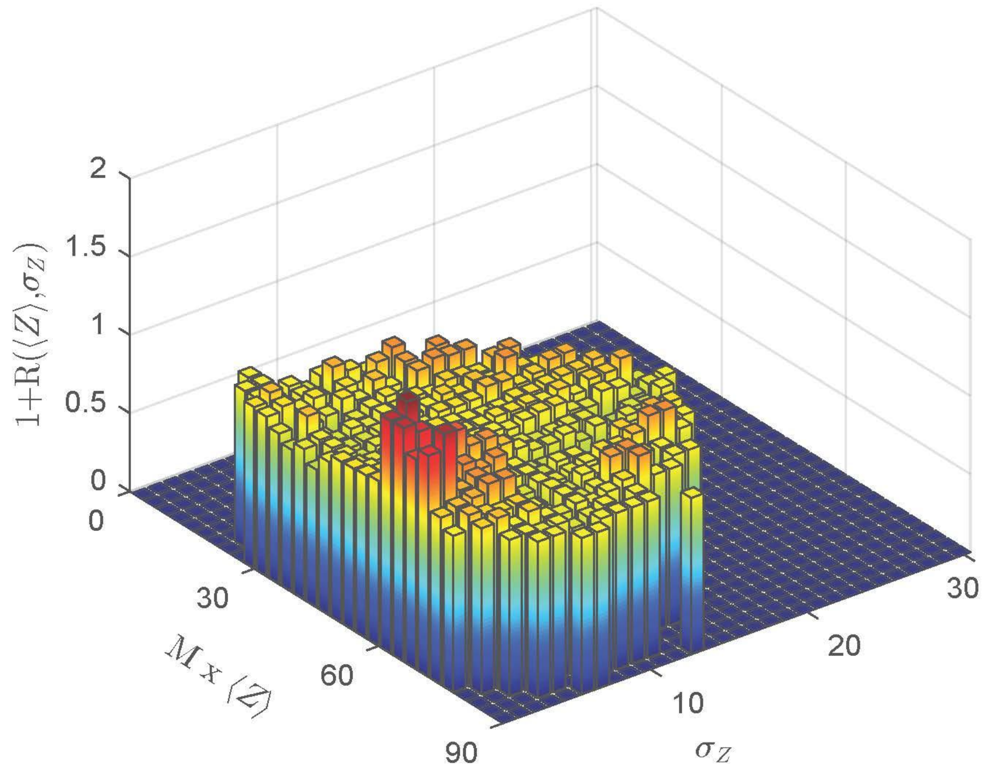
partitions with nearly equal-sized frag. depending on M observed
=> we can built CFs for all events whatever their multiplicity
by replacing <Z> by M x <Z>
uncorrelated yields constructed and weighted in proportion to events of each M

^{124}Xe + ^{112}Sn 32 AMeV – M= 3-6 => CF signals ≈ 1.6 – 1.3

M x <Z> (bin = 3): peaks 60-63, 63-66, 66-69 and 69-72
σ_Z < 1

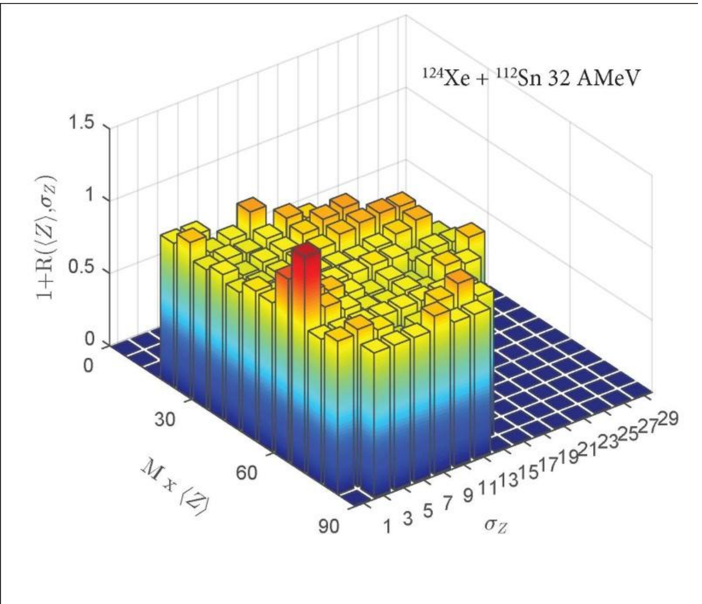
significant peaks for
2 < σ_Z < 1

broadening comes from deexcitation of primary fragments with around 3 AMeV excitation energy which generates an extra σ_Z value of around one Z unit

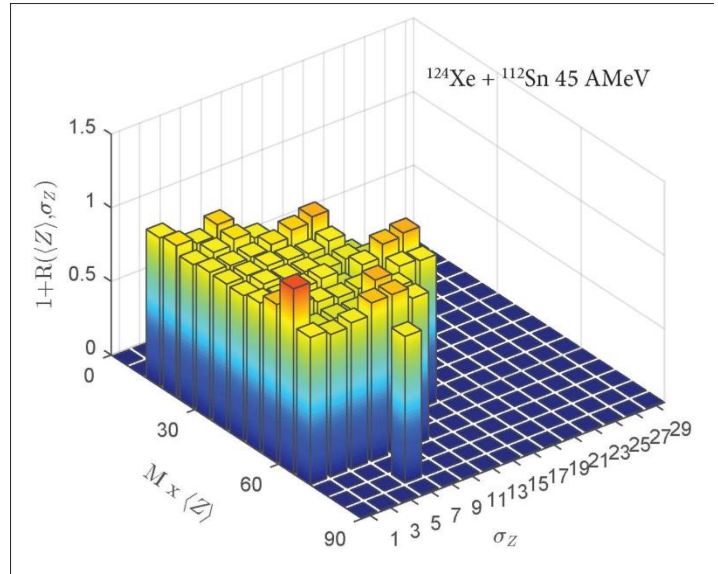


BB et al. (INDRA Coll.), PLB 782 (2018) 291

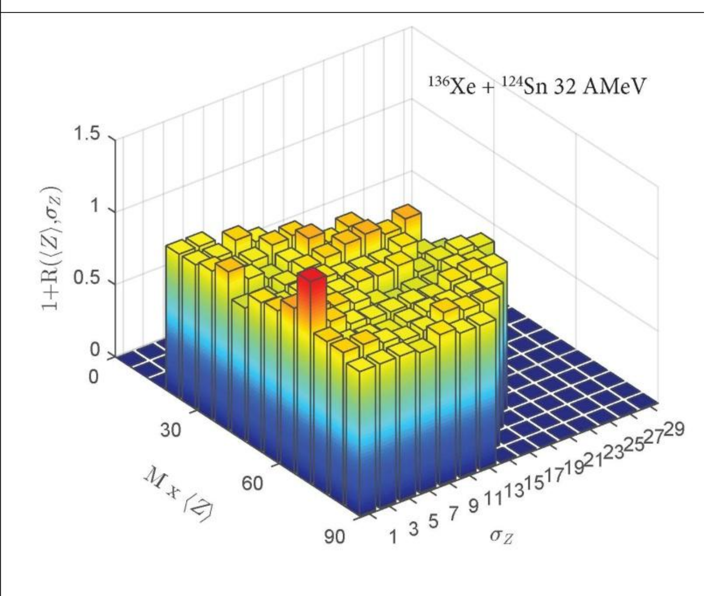
Summary - figures with M x $\langle Z \rangle$ - bin 6 and σ_Z – bin 2
CF values 1.5 to 1.08 - conf. level CFs 2.08 to 7.29 σ



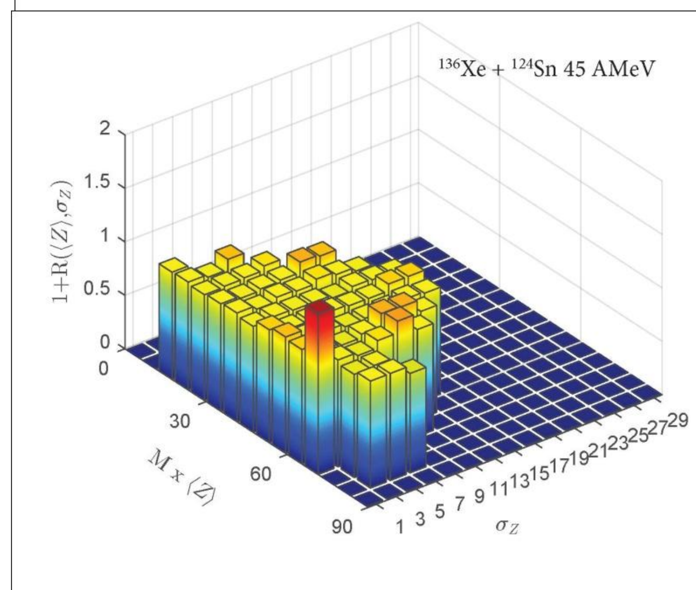
6.1σ
7.3σ



0.8σ
2.3σ



3.0σ
6.5σ



2.1σ

Phase transition dynamics in hot nuclei and N/Z influence
Conclusions

To search for a possible very weak « fossil » signature?

With a confidence level of 6-7σ one can say that phase transition dynamics of hot nuclei is produced by spinodal instabilities (32 AMeV).

The signature is a fossil signature and concerns only 0.068 – 0.064% of events at most

The finite size effects concerning the extra production of partitions with nearly equal-sized frag. and corresponding to different multipolarities are carefully observed on the four systems studied

Can we observe a reduction of the signal with the increase of N/Z?

Inc. Energy (AMeV)	32	45
M x <Z>	60-72	54-66
N/Z = 1.27	0.068(0.004)% – 336 evts	0.025(0.003)% - 77 evts
total number of events	494445	307161
N/Z= 1.50	0.064(0.004)% - 217 evts	0.0065(0.0017)% - 15 evts
total number of events	335709	229835

At 45 AMeV a large reduction with the increase of N/Z is observed consistent qualitatively with the increase of the instability growth time and the reduction of the reaction time

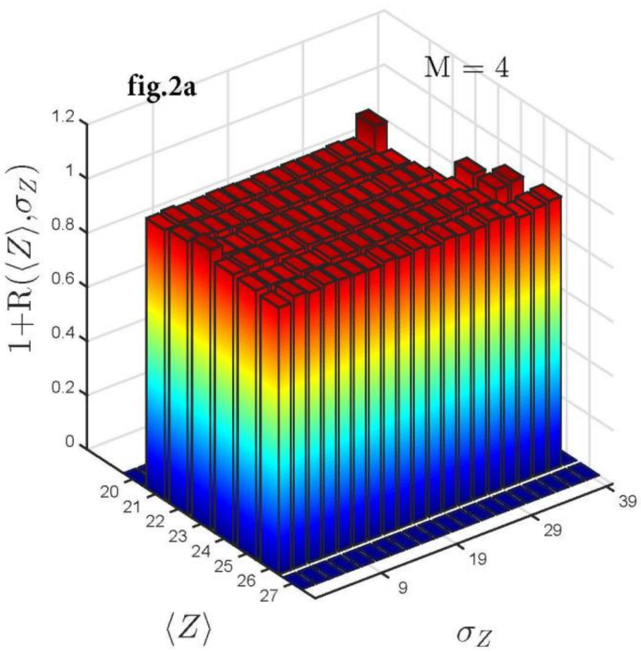
Bernard Borderie

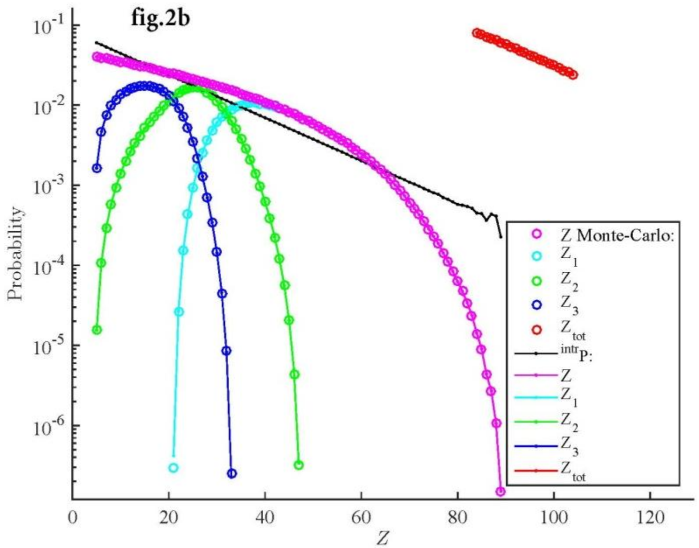
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

sensitivity of the intrinsic probability method

Monte Carlo simulation – events >= 80% of Zsystem=104 – fragments Z>4
charged reaction products produced according to P(Z) prop.to exp(-0.1Z)

300000 events => CF values in the range 0.95-1.05 for low σ_Z (<2)



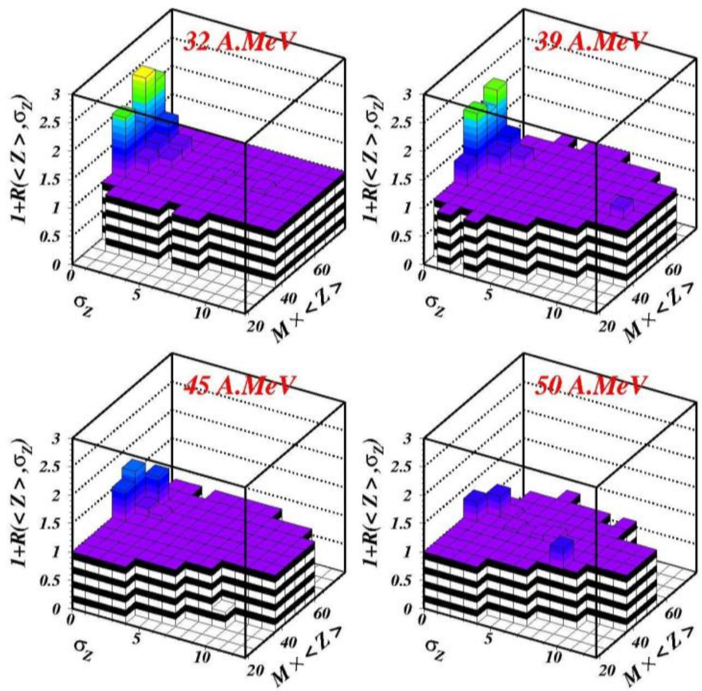


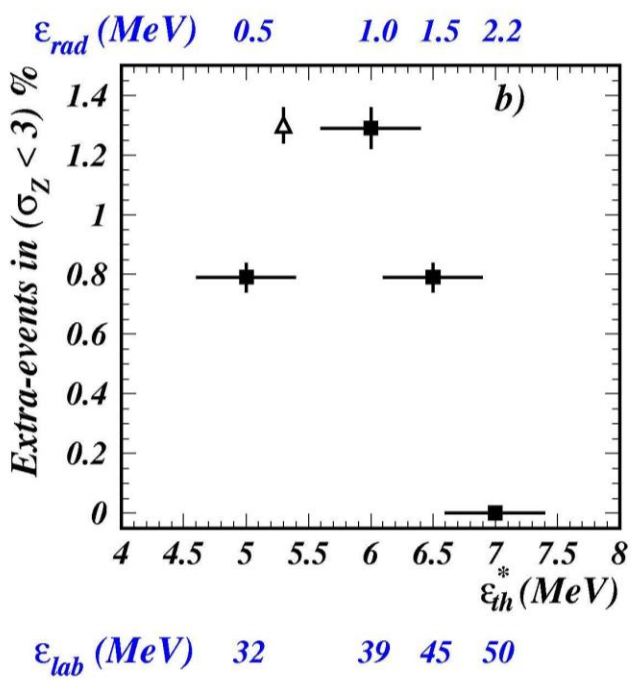
fossil signature with confidence level of 2-3 σ (previous experiments)

(QF $^{129}Xe+^{nat}Sn$ 32-50 AMeV)

spurious peaks at low σ_Z are present (low statistics)

Variation of the incident energy from 32 to 50 AMeV and quantitative comparison with predictions of BOB (open point).





G. Tăbăcaru et al. EPJA 18 (2003) 103

B.B. et al. PRL 86 (2001) 3252

Bernard Borderie

NSD2019 May 13-17

Intra-event charge correlation – uncorrelated yield

Exact multinomial formula (P. Désesquelles PRC 65 (2002) 034604)

=> independent emission model with total charge conservation constraint

Partition constrained conditional probabilities $P_{cc}(N)$ N : partition

${}^{intr}P_z(z)$: intrinsic probability of charge z

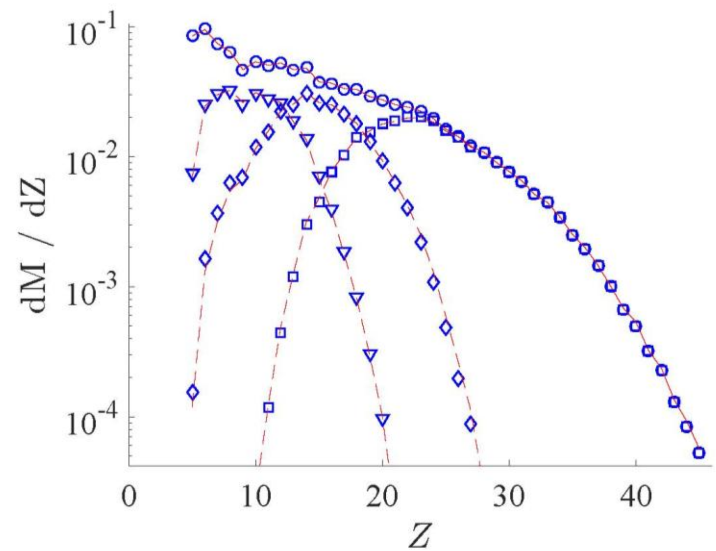
$$P_{cc}(N) = \alpha\, (\Sigma\, n_z)!\ \Pi\ {}^{intr}P_z(z)^{nz}\ \delta_{ztot}\ \Sigma\, z n_z$$

n_z : number of fragments with charge z

α : normalisation factor $\Sigma\, P_{cc}(N) = 1$

${}^{intr}P_z(z)$ evaluated by inversion of the equ.
by means of a recursive procedure of
minimisation which stops when
10^{-12} between 2 steps is reached

${}^{124}Xe + {}^{112}Sn$ 32 AMeV M=4



Bernard Borderie

Intra-event charge correlations

^{124}Xe + ^{112}Sn 32 AMeV – M= 3-6

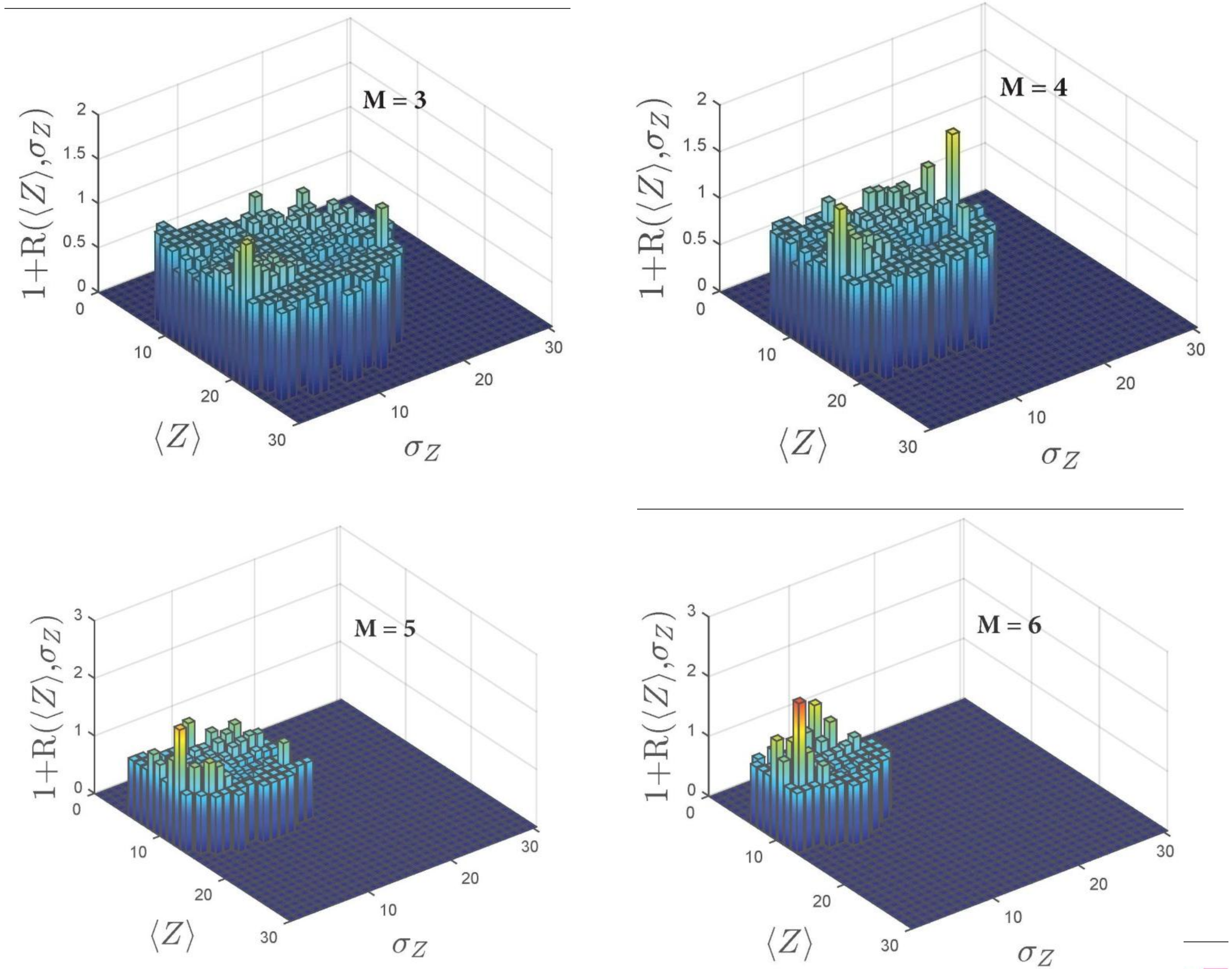
stat. error
on num.≥50%
CF => 1

$\langle Z \rangle$ bin 1
σ_Z bin 1

σ_Z < 1
Peaks observed for

M_f	$\langle Z \rangle$
3	20-22
4	15-18
5	12-14
6	10-12

$M_f \times \langle Z \rangle \approx$ cste
as expected for
finite systems



IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

Spinodal instabilities: introduction of isospin

A unique spinodal region in asymmetric nuclear matter
Only one type of instability (no chemical inst.)
Order parameter dominated by the isoscalar density => liquid-gas type transition

skyrme Gogny

Arrows indicate the directions of instability

first bisecting line
=> isoscalar density

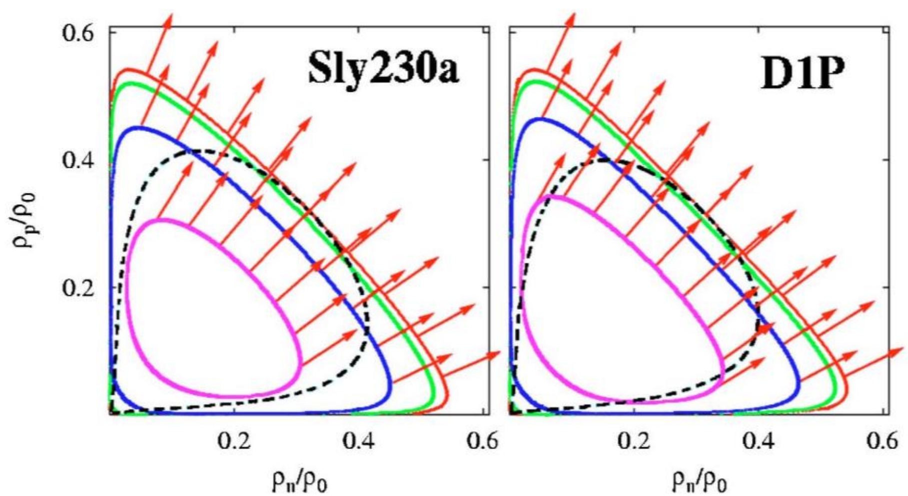


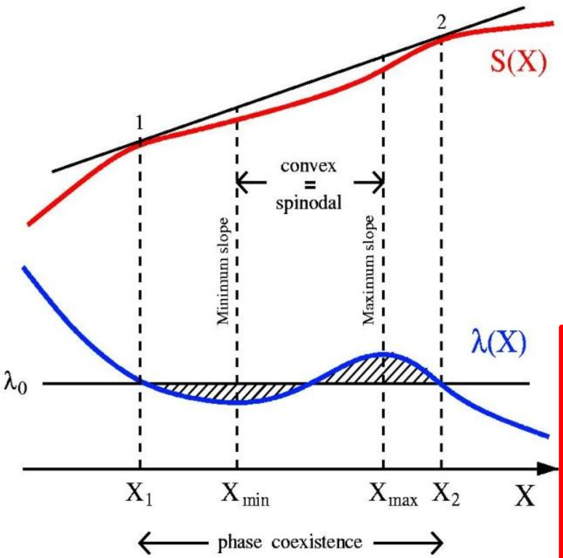
FIG. 4. This is the projection of the iso-eigenvalues on the density plane for Slya (left) and D1P (right). The arrows indicate the direction of instability. The mechanical instability is also indicated (dotted line).

contours of equal imaginary sound velocity i0.09c to i0.03c

J. Margueron et al., PRC 67 (2003) 041602(R)

Finite syst. and first order phase transition convexity of entropy

NEGATIVE HEAT CAPACITY



μ canonical sampling

(Fixed value of X)

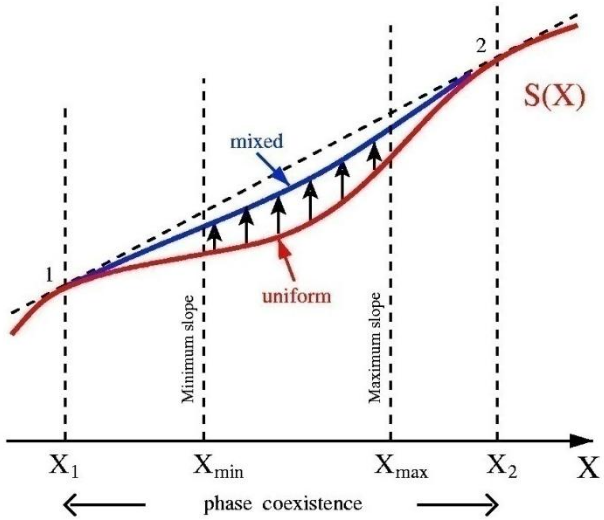
X extensive variable

(E, N, V)

Conjugate intensive variable

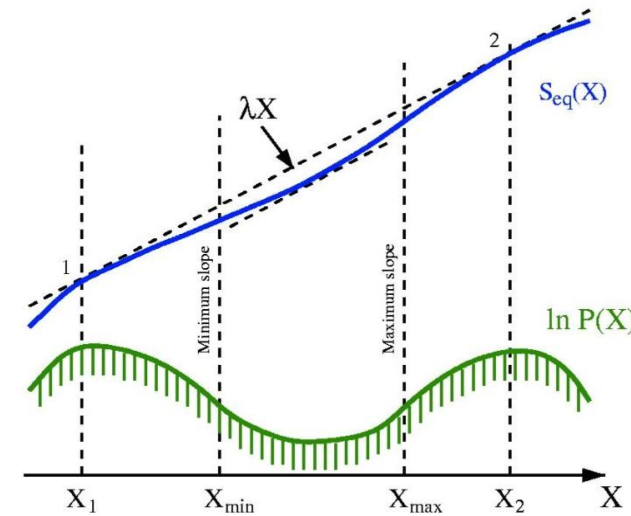
λ(**X**)=∂S / ∂ X

(1/T, - μ/T, P/T)



SPINODAL INSTABILITY

BIMODALITY



Canonical-Gaussian sampling

P(X) ~ exp(S(X)- λX)

Ph. Chomaz et al., Phys. Rep. 389

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY