Exploring the neutron-rich nuclei - reaction aspects

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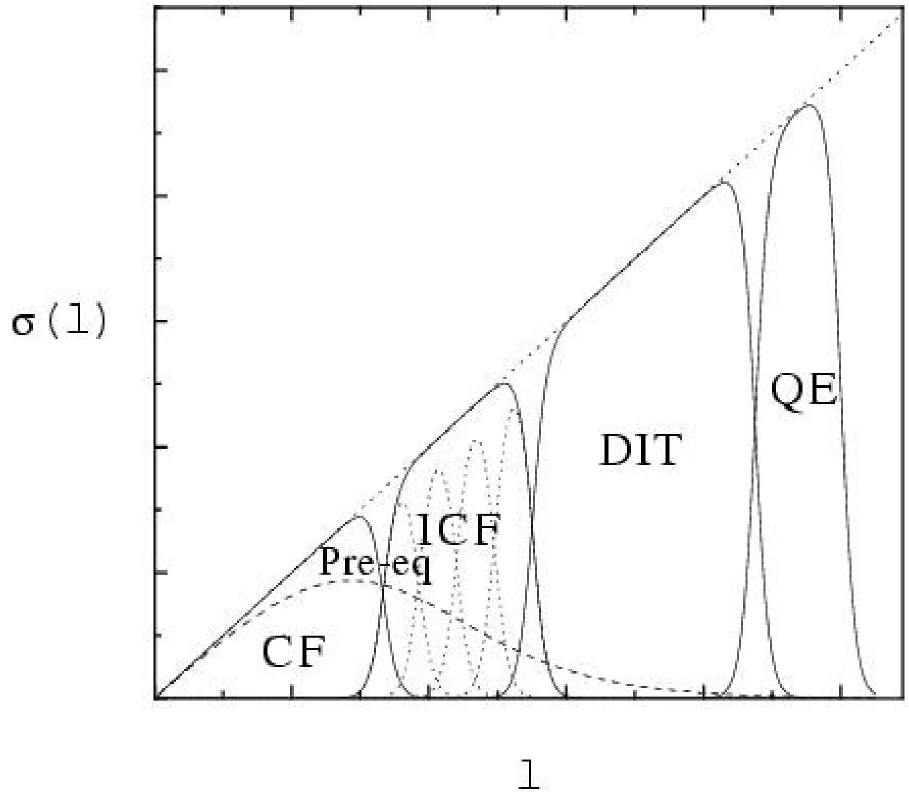
Nucleus-nucleus collisions at beam energies below 100 AMeV:



- peripheral elastic and quasi-elastic (QE) collisions
- semi-peripheral deep-inelastic collisions (DIT) collisions
- incomplete (ICF) and complete (CF) fusion in central collisions
- pre-equilibrium emision typically preceding ICF/CF and DIT

(code framework described in M. Veselský, Nuclear Physics A 705 (2002) 193)

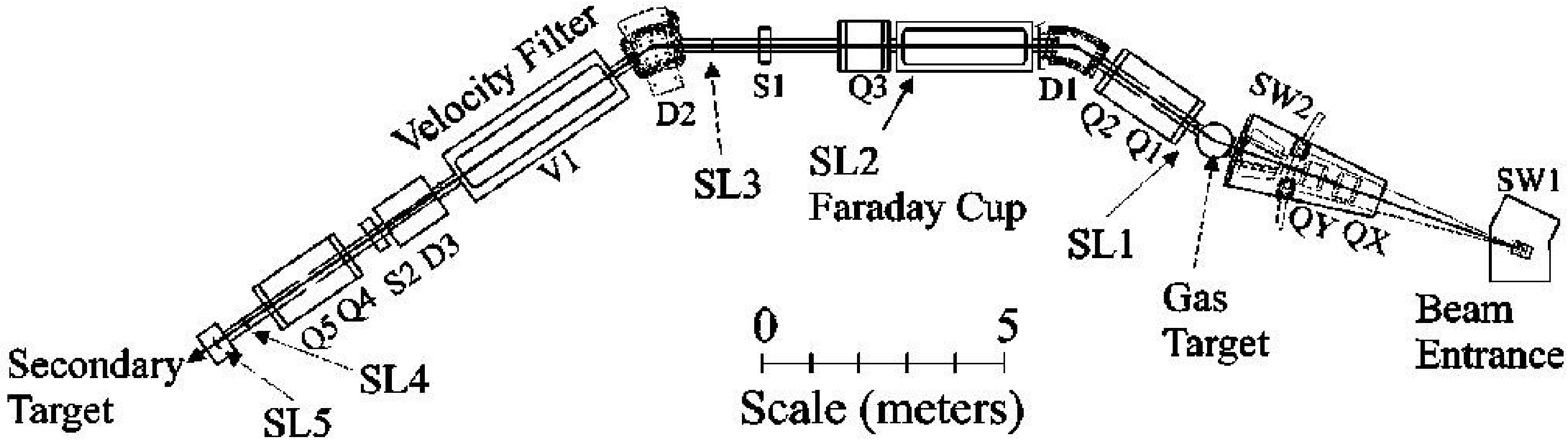
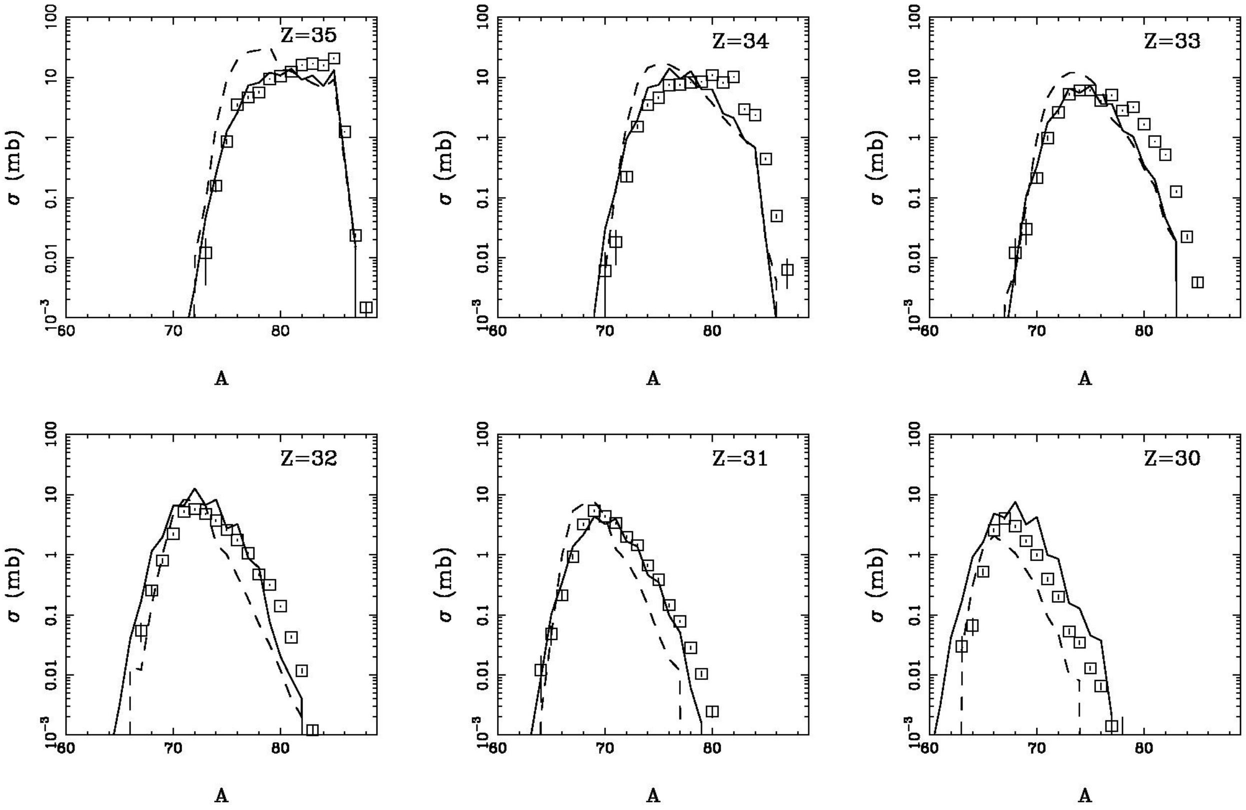


FIG. 1. Schematic diagram of the Momentum Achromat Recoil Spectrometer (MARS).

Experiments at fragment separator MARS (Cyclotron Lab, Texas A&M University).
Observation of the heavy residues, isotopic resolution up to mass A=100.

^{86}Kr + ^{64}Ni at 25 AMeV – peripheral collisions



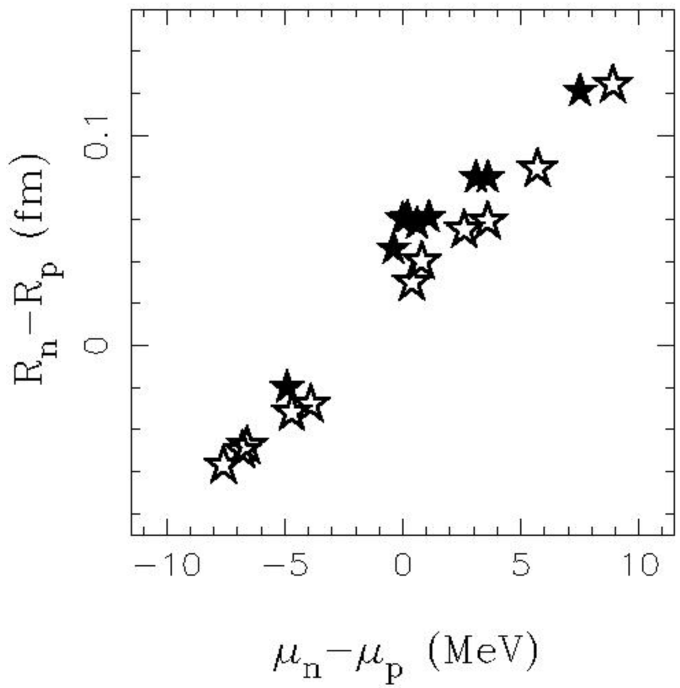
Comparison of experimental yield to simulation successful in multifragmentation

Reaction stage: DIT (Tassan-Got and Stefan, NPA 524 (1991) 121)

De-excitation: solid line - GEMINI, dashed line -SMM

Correlation of skin thickness to isovector chemical potential
(V. Kolomietz et al, PRC 64(2001)024315, extended Thomas-Fermi calculation)

– R_n-R_p determines the difference of N/Z at $(R_n+R_p)/2$ (surface) from the bulk N/Z, correlates to isovector chemical potential



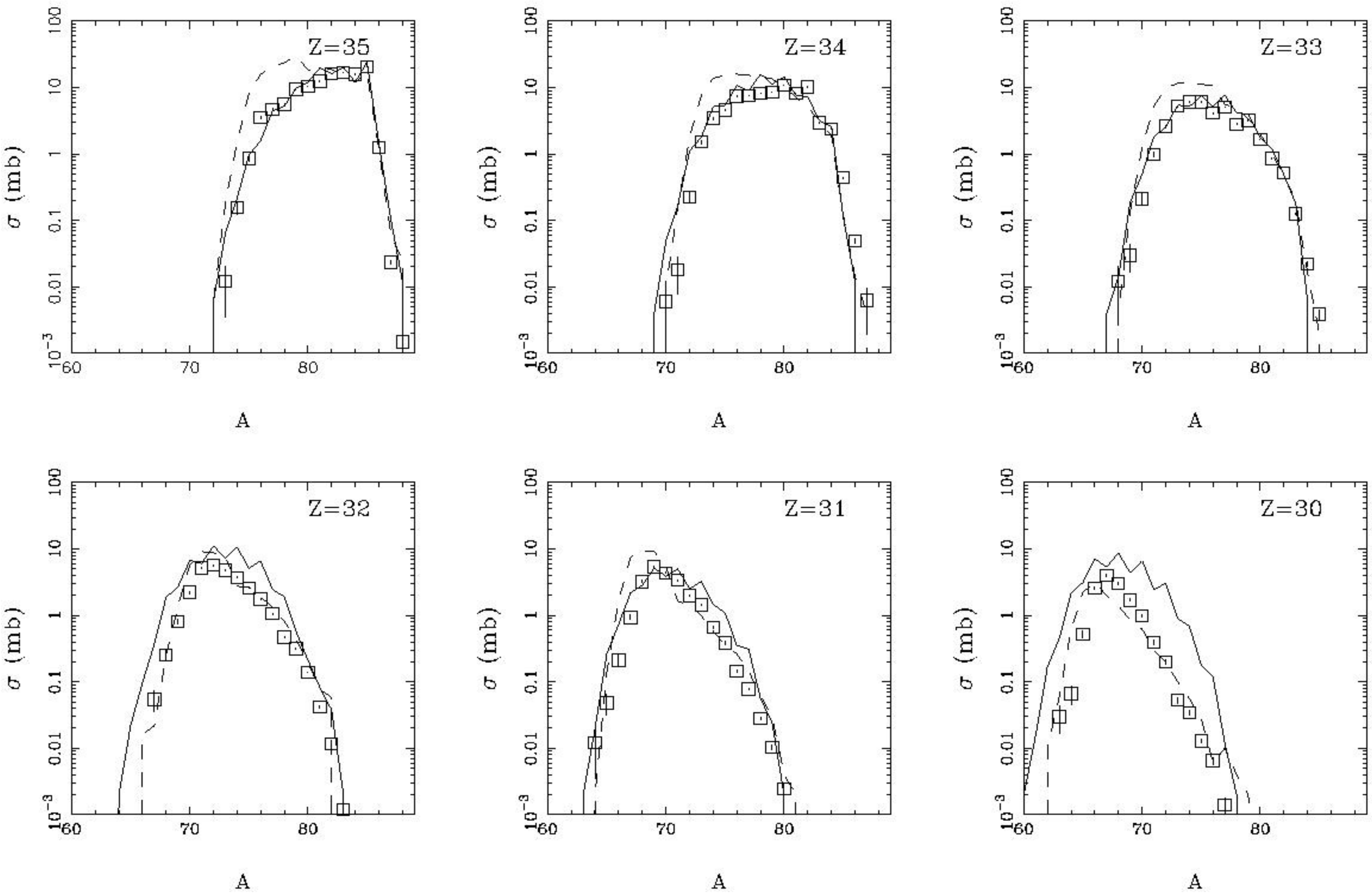
– DIT (T-G) : macroscopic formula for R_n-R_p used, values unrealistically large but bulk N/Z dynamics described well

- modified DIT (Nucl.Phys. A765, 252 (2006)), phenomenological correction, effect of shell structure on nuclear periphery (assuming validity of the R_n-R_p vs μ_n-μ_p correlation) and thus on transfer probability estimated as:

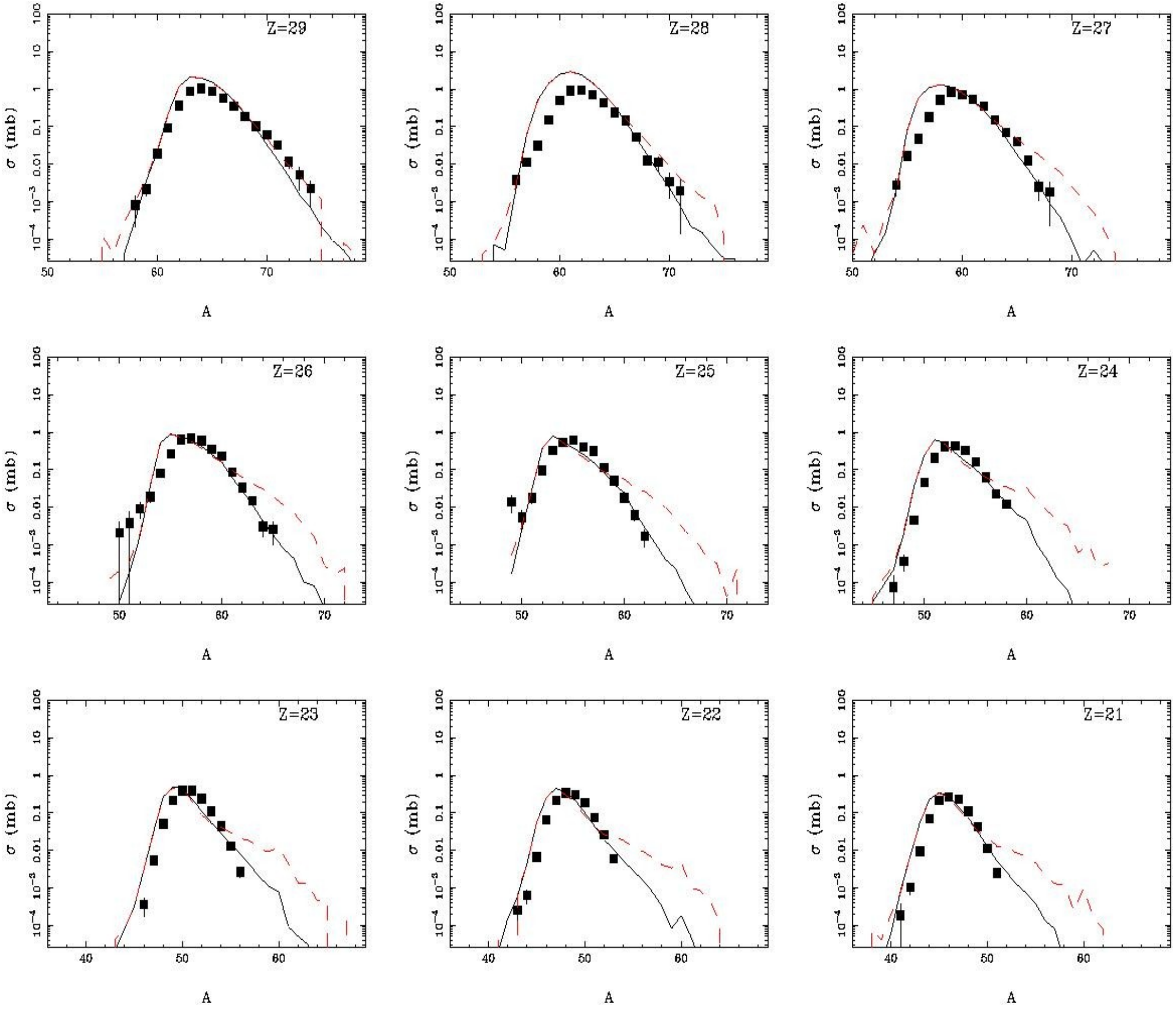
$$P_n(P \to T) \longrightarrow e^{-0.5\kappa(\delta S_{nP} - \delta S_{pP} - \delta S_{nT} + \delta S_{pT})} P_n(P \to T)$$
$$P_p(P \to T) \longrightarrow e^{0.5\kappa(\delta S_{nP} - \delta S_{pP} - \delta S_{nT} + \delta S_{pT})} P_p(P \to T)$$

where $\delta S_{...} = S_{...}^{exp} - S_{...}^{mac}$, κ is a free parameter (κ = 0.53 determined as optimal value), s > 0 fm (only non-overlapping configurations considered)

^{86}Kr + ^{64}Ni at 25 AMeV   DIT + shell structure at n-skin (NPA765(2006)252)



De-excitation : solid line - GEMINI, dashed line -SMM
n-rich products close to projectile – low excitation energy, both codes similar
for lighter elements SMM consistent, GEMINI overestimates width
SMM overestimates yields of stable products – missing fragment emission from CN
Consistent results also for reactions ^{86}Kr + ^{112,124}Sn at 25 AMeV
Isospin flow away from equilibrium !!!



For $\Delta Z > 7$ - 8 cold fragments from ICF increasingly dominate

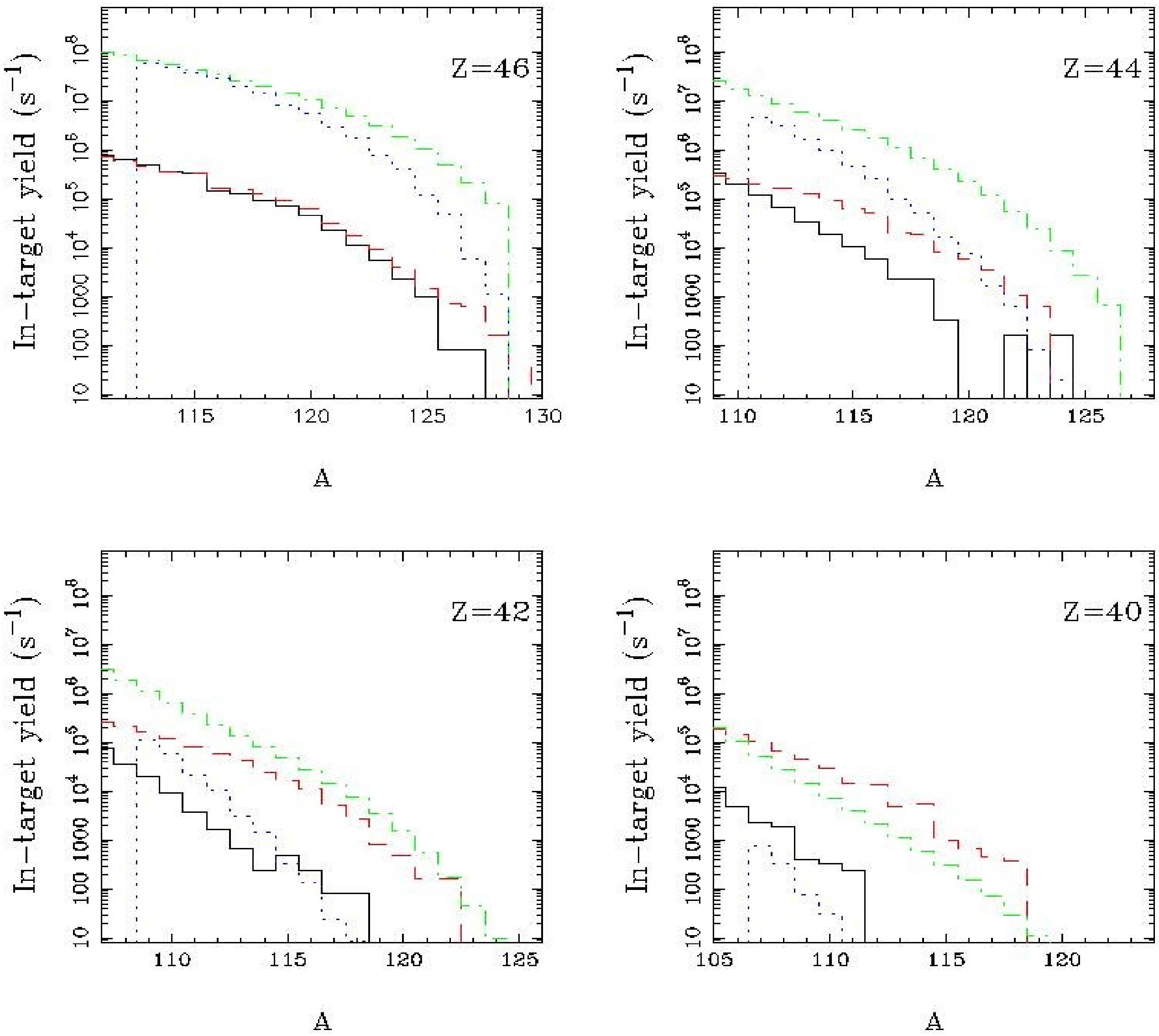
Model of incomplete fusion modified for cold fragments (Nucl.Phys. A781, 521 (2007)):

$$E^{*}(A,Z) \sim w\ (\ A - A(N/Z_{proj})\ )\ m_{nuc}\ {v^{rel}_{ICF}}^{2} / 2$$

Component of excitation energy for pick-up of excess neutrons. Better description, behavior consistent with fast transfer of multiple neutrons –
from neutron-rich neck ?

^{86}Kr(25AMeV)+^{124}Sn - 1-7 deg, semi-peripheral collisions

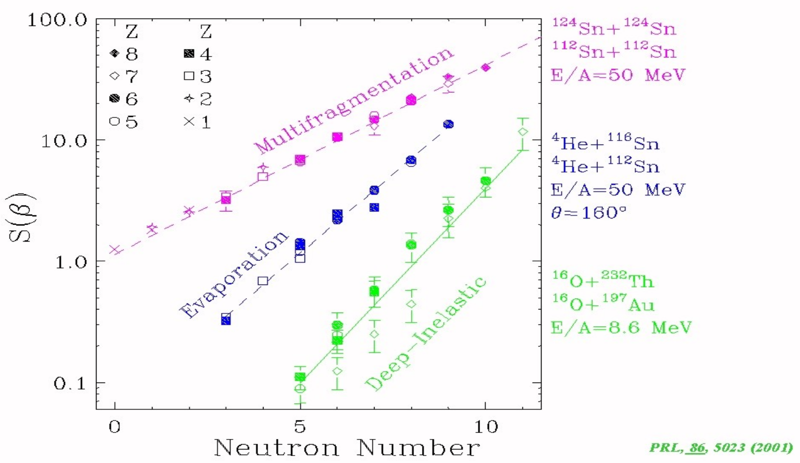
Solid lines – modified ICF, dashed line – original ICF (NPA 705(2002)193)

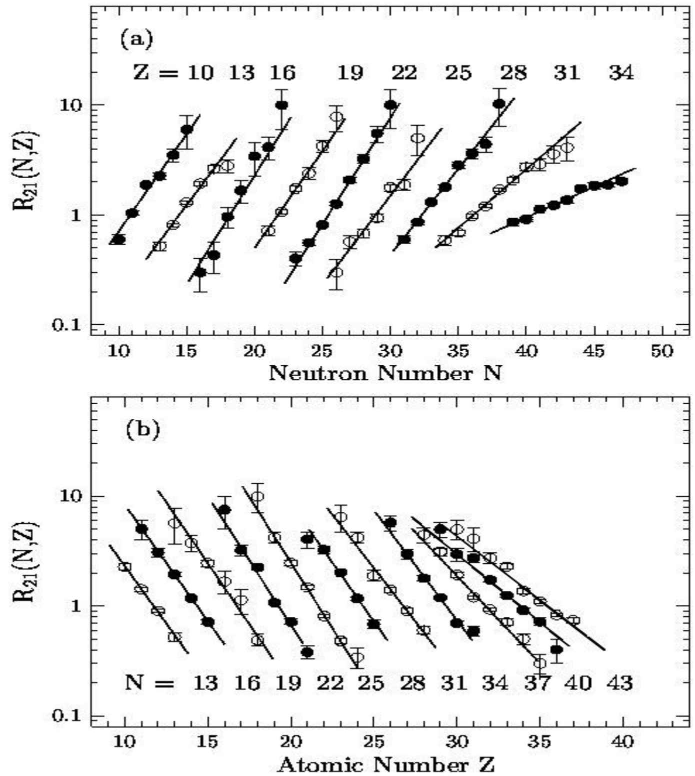


^{132}Sn beam - in-target production rates for fragmentation and Fermi energy domain (^{132}Sn(28AMeV)+^{238}U) for expected Eurisol beam rate 10^{12} s^{-1} and optimal target thickness. Black lines - modified DIT/ICF (N/Z-dependent excitation energy), red lines - standard DIT/ICF, green and blue lines – fragmentation codes EPAX and COFRA, respectively.

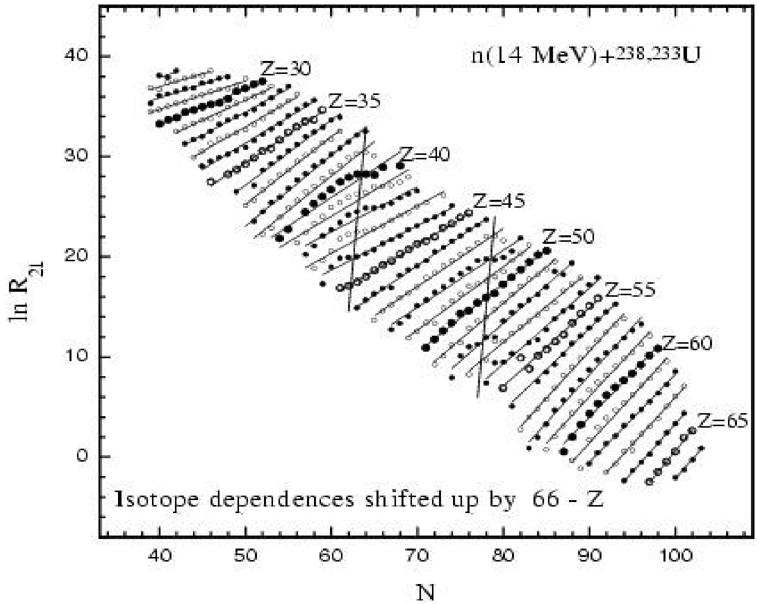
M.B. Tsang et al., PRL 86(2001)5023

$$Y_2/\,Y_1 \propto e^{(N\Delta\mu_n + Z\Delta\mu_p)/T}$$





G. Souliotis et al., PRC 68(2003)24605



M. Veselský et al., PRC 69(2004)44607

<u>Isoscaling in nuclear processes</u>

- symmetry energy (hot systems)
- isospin equilibration (binary reactions)
- fluctuation-dissipation (fission)
- shell structure in scission configuration
- signal of isospin-asymmetric liquid-gas ph. tr.
- universal tool to estimate production of exotic nuclei in reactions of stable and exotic beams !!!

Rare Isotope production at 15 MeV/nucleon:

Reactions recently measured with MARS at 4° and 7°
(support from Eurisol DS)

^{86}Kr (15 MeV/u, 10 pnA) + ^{64,58}Ni (2.2 mg/cm^2) (θ_{gr}~ 6.0°)
+ ^{124,112}Sn (2.0 mg/cm^2) (θ_{gr}~ 8.0 °)

^{40}Ar (15 MeV/u, 10 pnA) + ^{64,58}Ni (2.2 mg/cm^2) (θ_{gr}~ 7.0°)
+ ^{124,112}Sn (2.0 mg/cm^2) (θ_{gr}~ 9.0 °)

Measured quantities:

x-position at First Image (Bρ info.), ΔE_1, E_r, time of flight (START-STOP)

Extracted physical quantities:

Velocity, Energy loss, Total Energy
Mass-to-charge ratio: A/Q — $B\rho \sim A/Q \times \upsilon$
Atomic Number Z — $Z \sim \upsilon\, \Delta E^{1/2}$
Ionic charge Q — $Q \sim f(E, \upsilon, B\rho)$
Mass number A — $A = Q_{int} \times A/Q$

Reconstructed: PLF Yield distribution (Z,A,υ)
at each of the two beam-angle settings

Cyclotron Institute
Texas A&M University

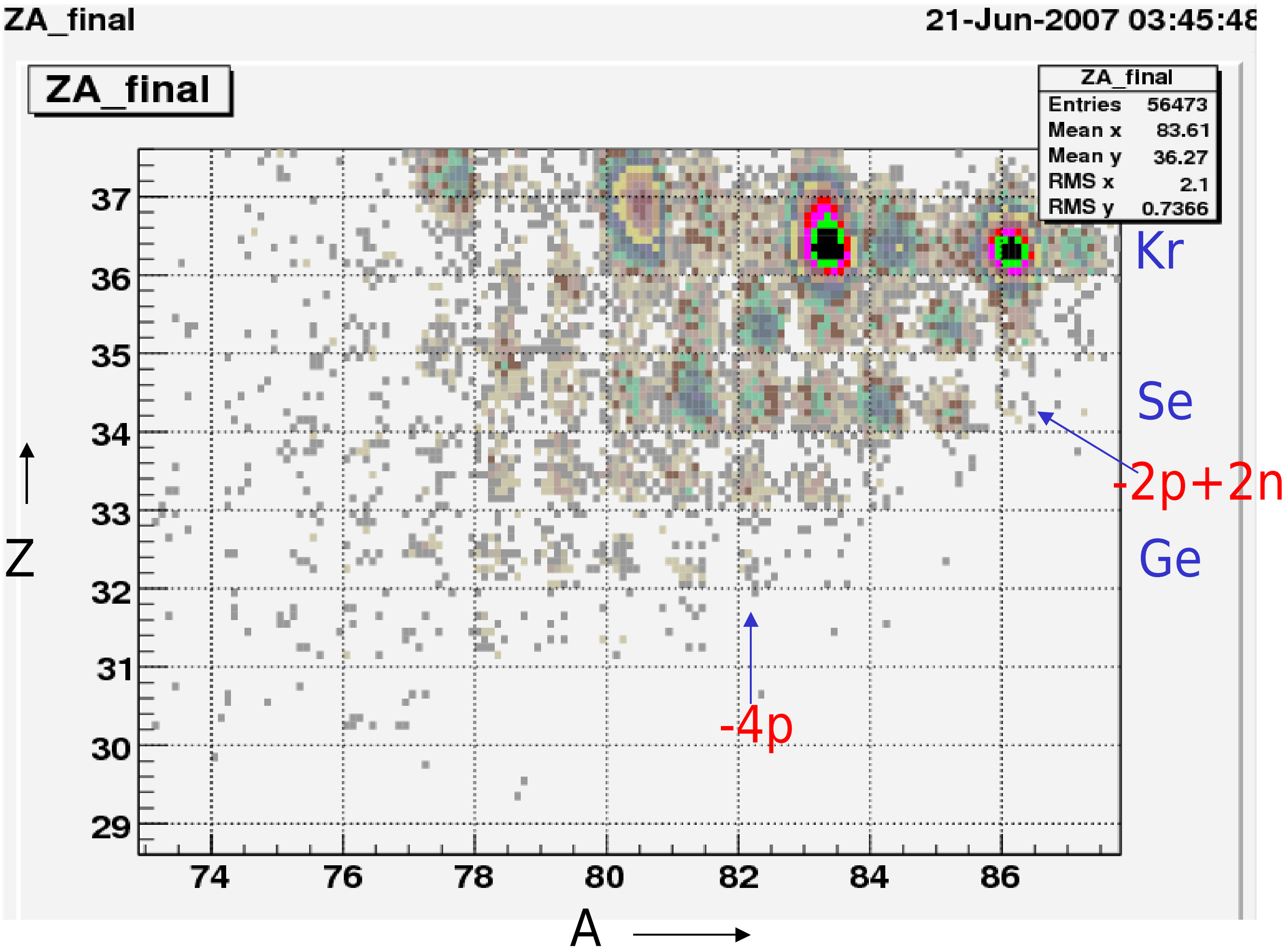
Rare Isotope production at 15 MeV/nucleon:

Example of on-line Z-A:

^{86}Kr(15MeV/u) + ^{124}Sn

Bρ=1.5 Tm

Reaction Angle: 7.0 deg.



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Conclusions I.

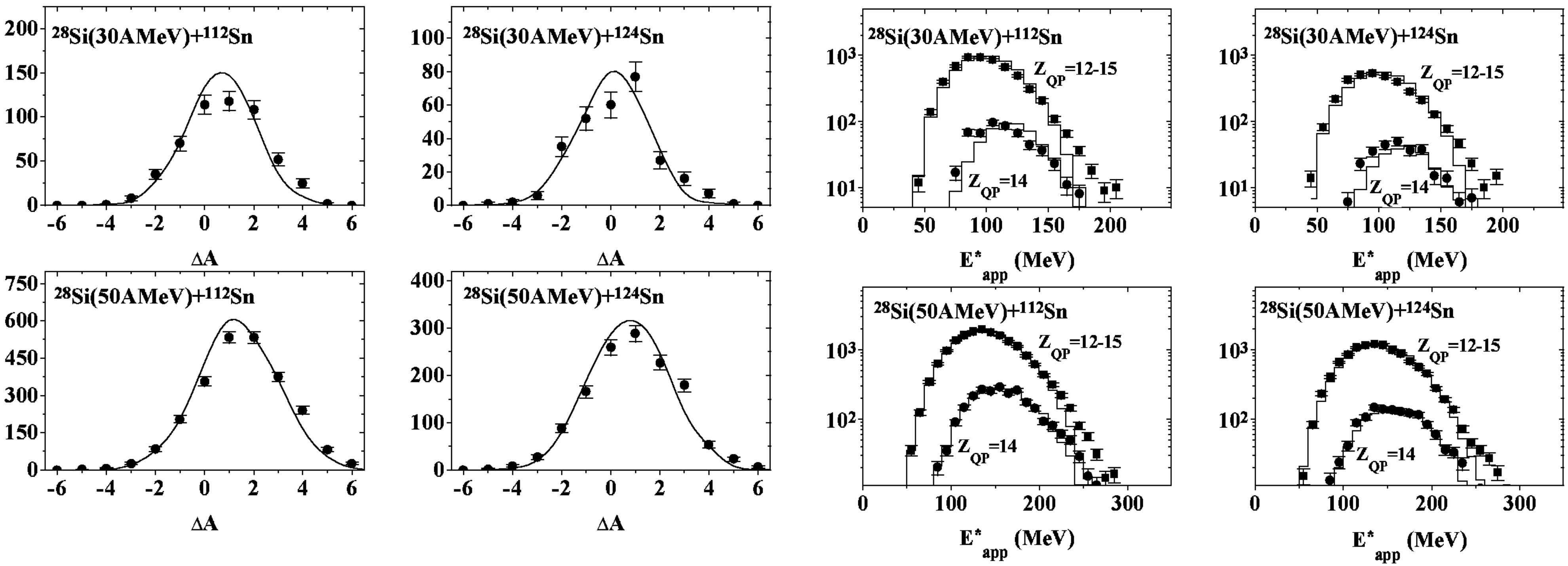
- way to extremely neutron-rich nuclei via nucleus-nucleus collisions around the Fermi energy

- interesting effects (structure of nuclear periphery, transparency ?, neutron-rich neck structure ?) can be observed when comparing high resolution experimental data to precise simulations

- isoscaling – a tool to predict production of n-rich nuclei

Dominant reaction mechanism – DIT+SMM simulation

M. Veselský et al., PRC 62(2000)64613

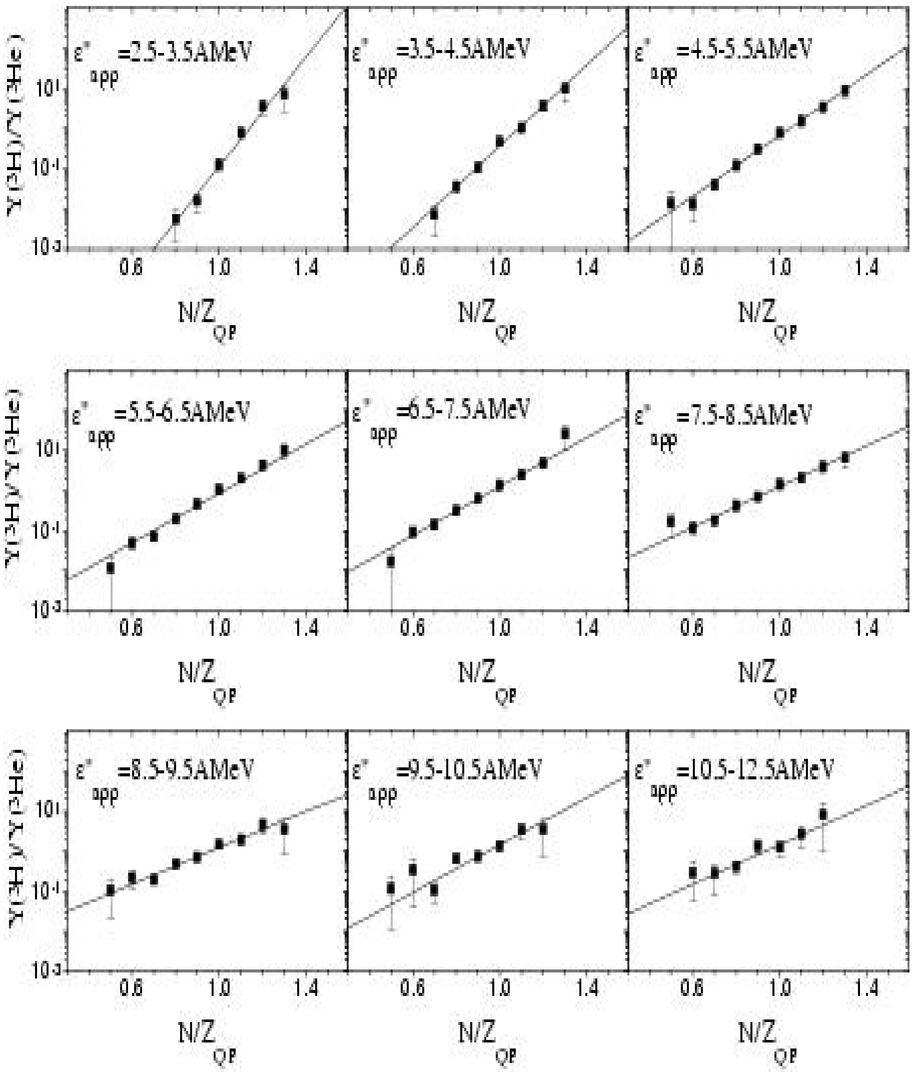


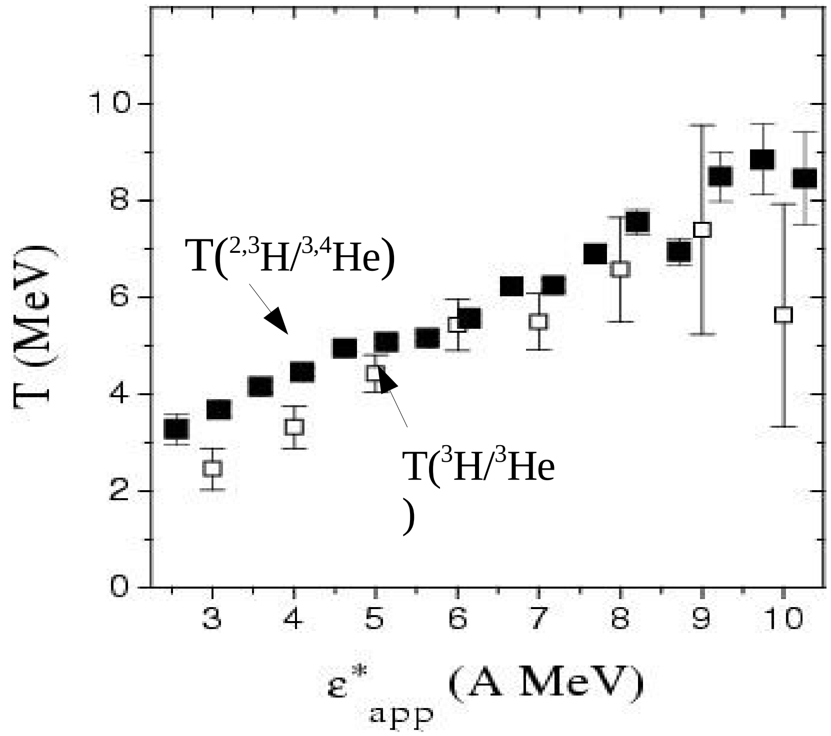
Left - Experimental (solid circles) and simulated (solid lines) mass change distributions for the fully isotopically resolved quasiprojectiles with Z_{QP}=14.

Right - Distributions of excitation energies of the quasiprojectiles. Symbols mean experimental distributions of the set of isotopically resolved quasiprojectiles with Z_{QP}=14 (solid circles) and Z_{QP}=12-15 (solid squares). Solid histograms mean simulated distributions using DIT+SMM.

DIT - L. Tassan-Got, C. Stefan, Nucl. Phys. A 524 (1991) 121.
SMM - J.P. Bondorf et al., Phys. Rep. 257 (1995) 133.

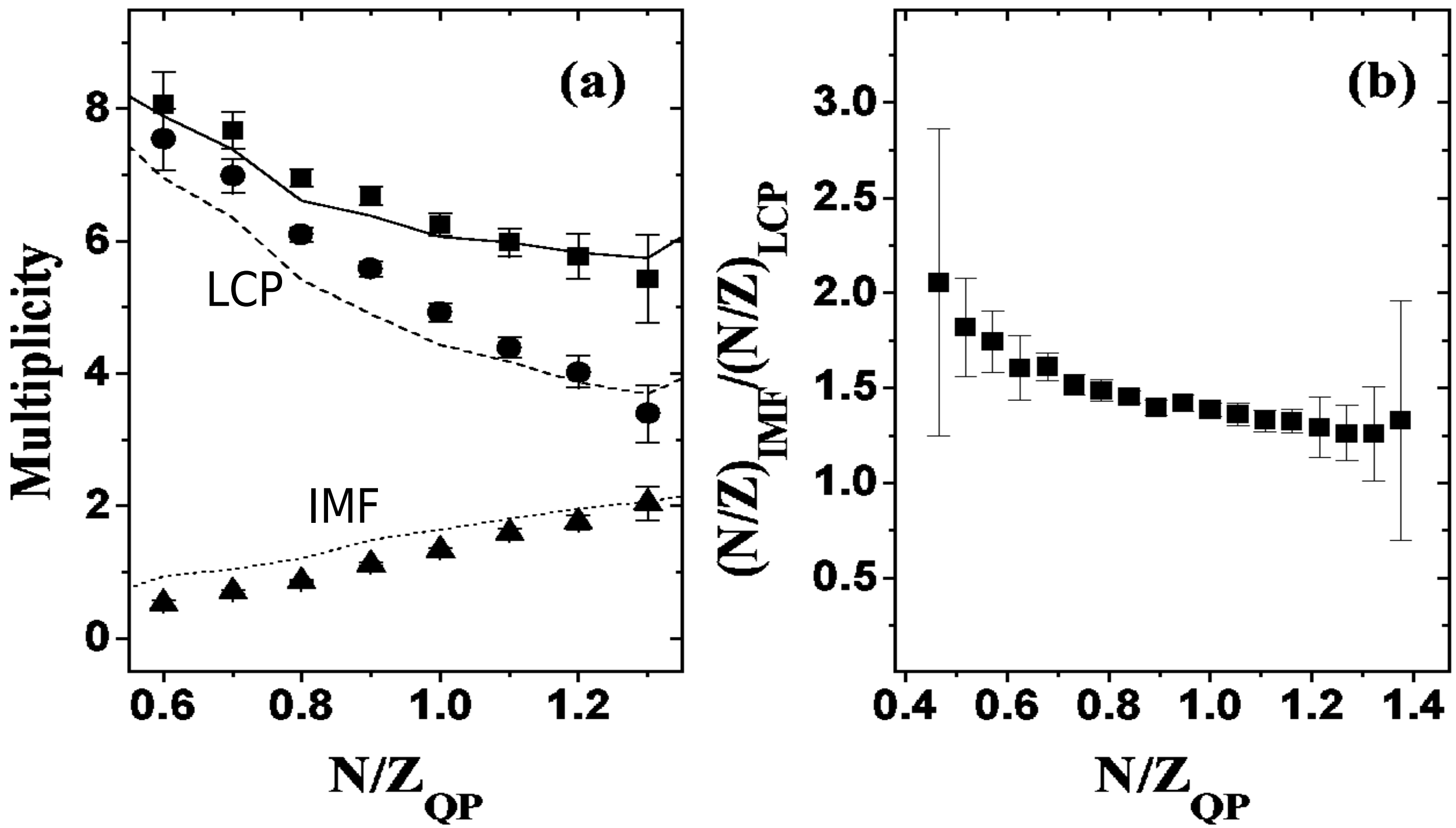
M. Veselsky et al., PLB 497 (2001) 1.





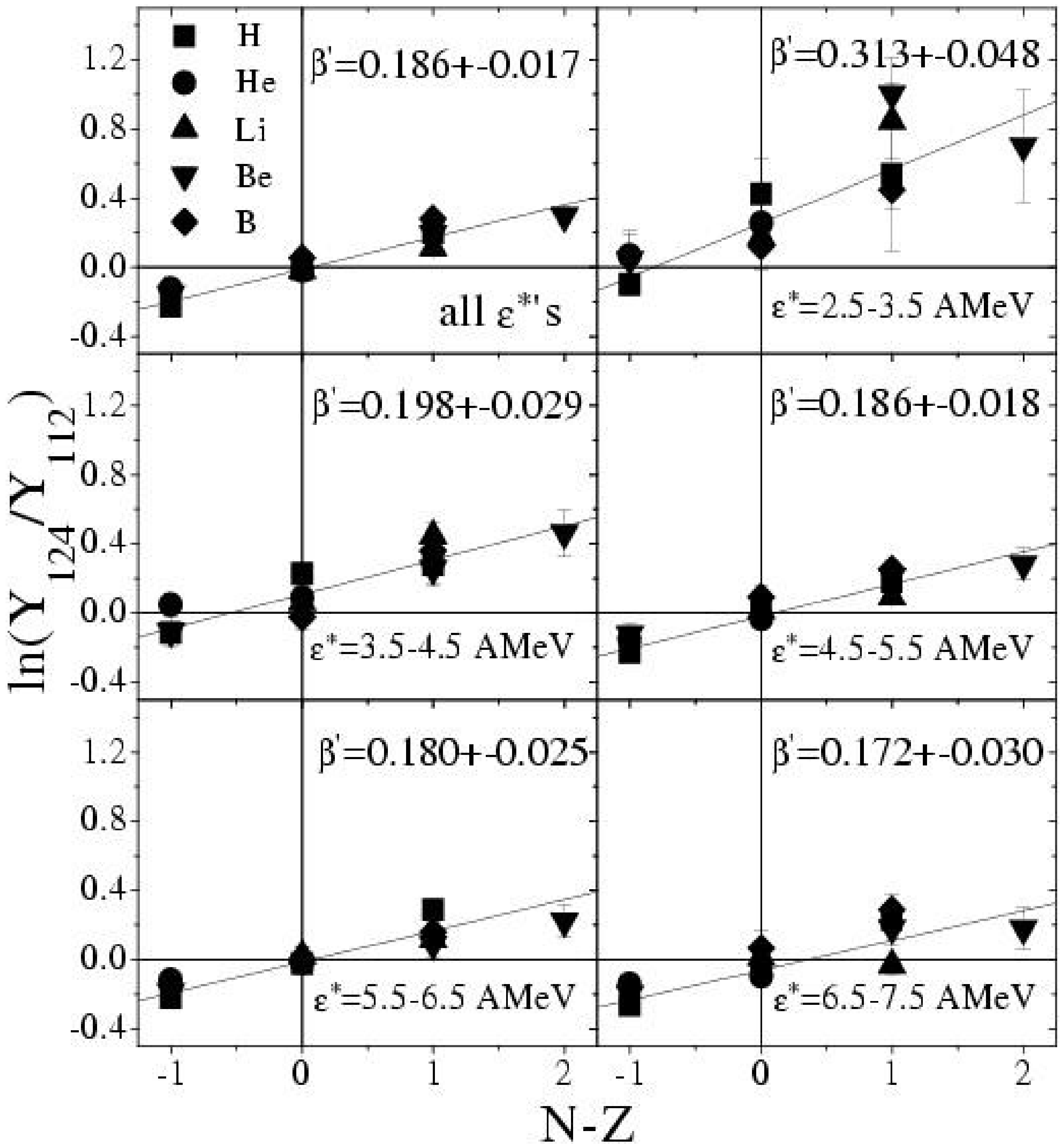
$$\ln(Y(^3\mathrm{H})/Y(^3\mathrm{He})) = \ln(K(T)) + (\mu_n - \mu_p)/T$$

Yield ratios and temperature

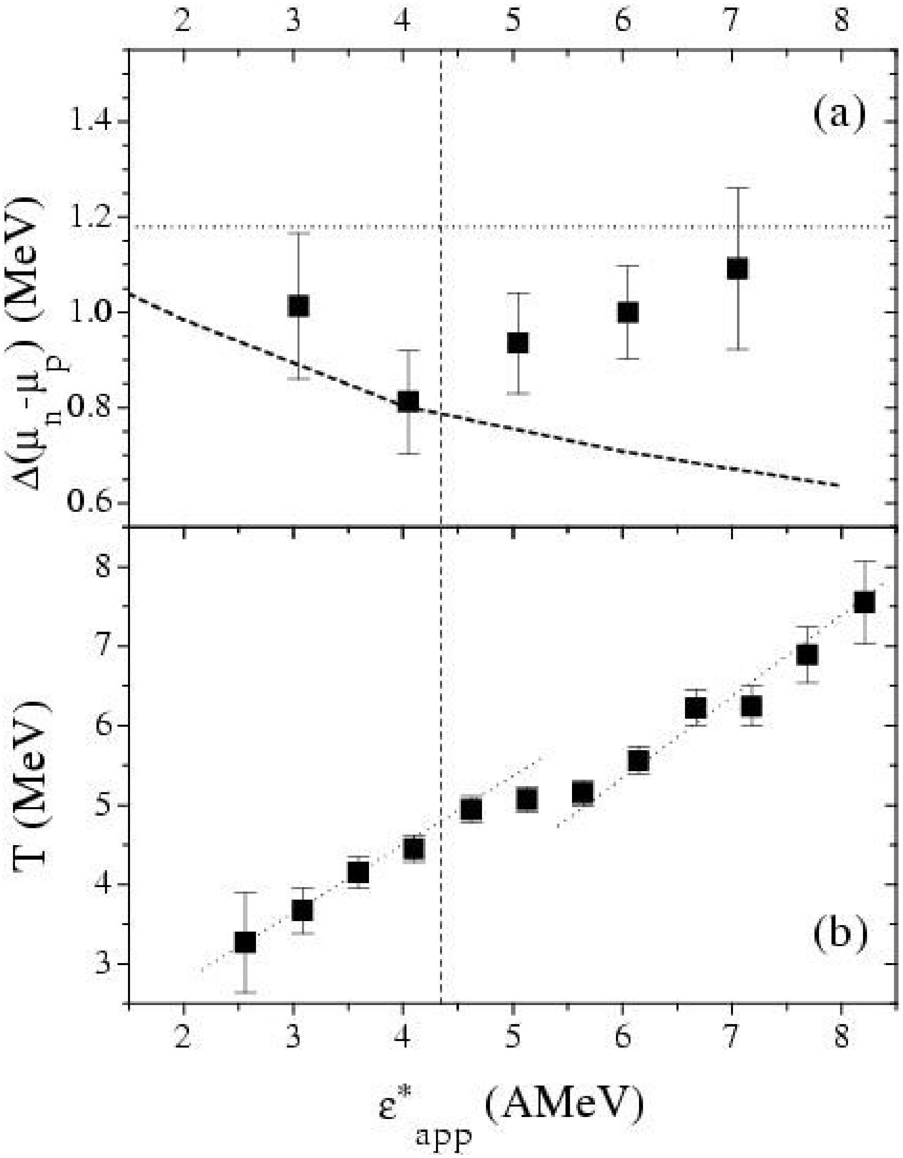


Distribution of isospin between “phases“ (M. Veselský et al., PRC 62(2000)41605)

Isoscaling

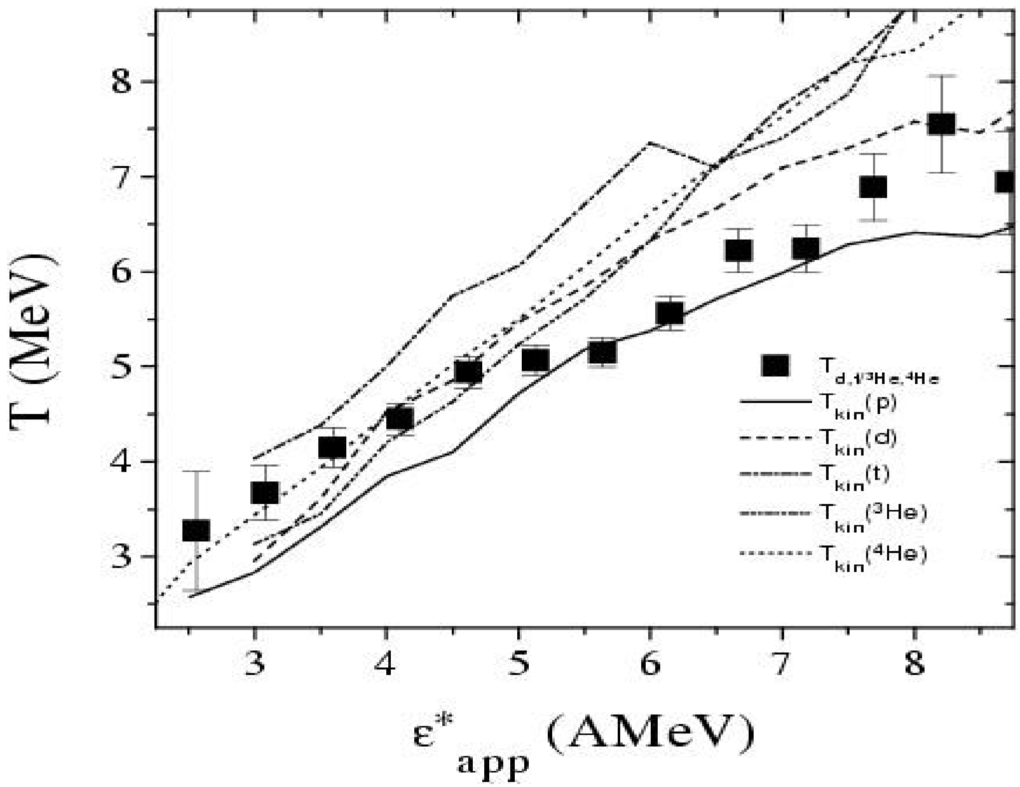


H
He
Li
Be
B
β'=0.186+-0.017
all ε*'s
β'=0.313+-0.048
ε*=2.5-3.5 AMeV
β'=0.198+-0.029
ε*=3.5-4.5 AMeV
β'=0.186+-0.018
ε*=4.5-5.5 AMeV
β'=0.180+-0.025
ε*=5.5-6.5 AMeV
β'=0.172+-0.030
ε*=6.5-7.5 AMeV
ln(Y124/Y112)
N-Z

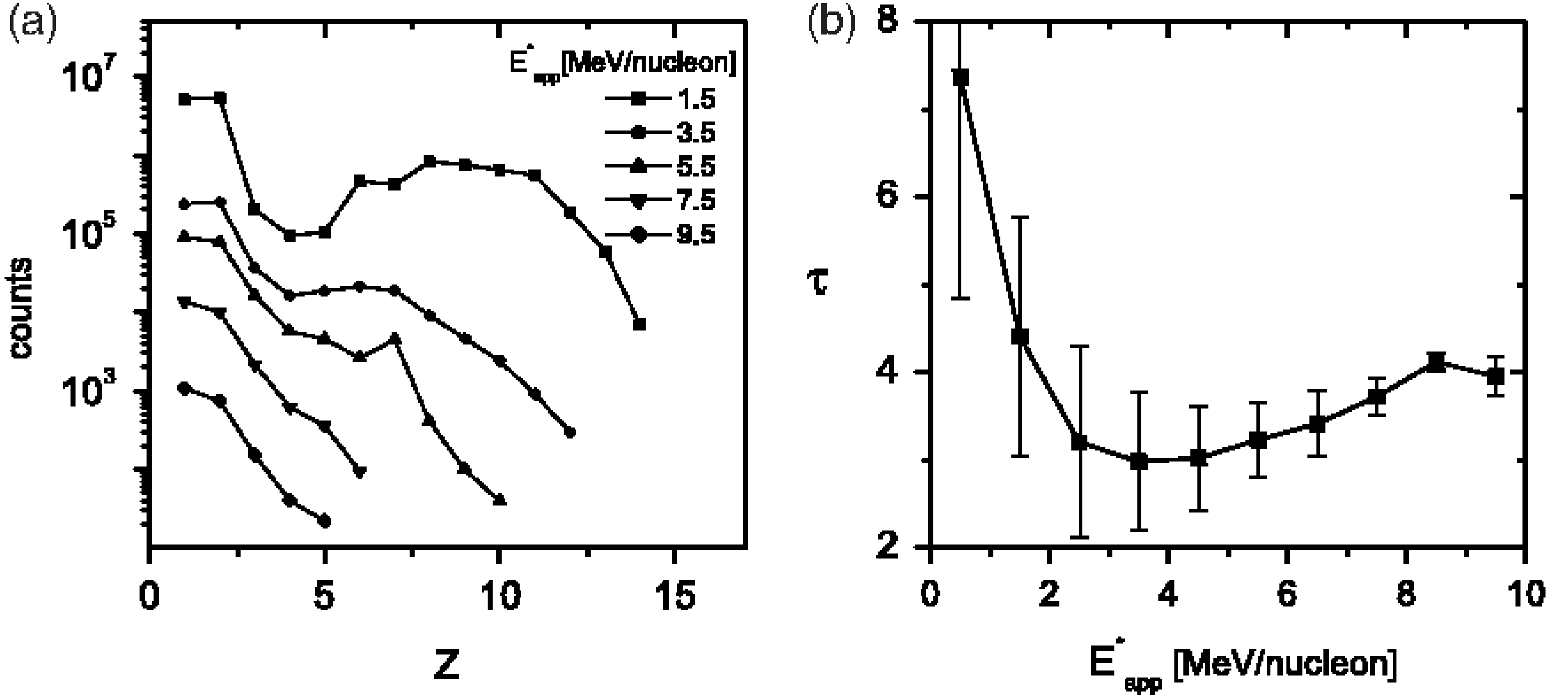


Correlated signals of phase transition -

M. Veselsky et al., NPA 749 (2005) 114c.

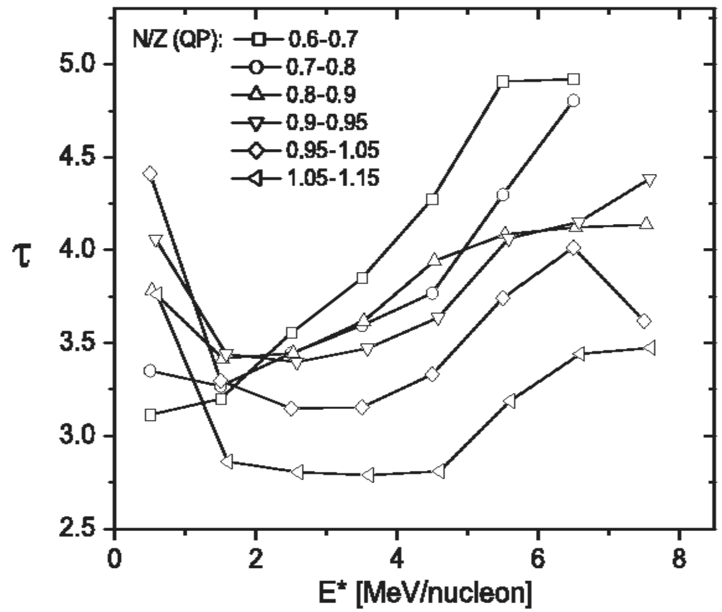


Kinematic temperatures - signal of equilibration with nucleon gas



Signals of criticality ?

M. Jandel et al., PRC 74(2006)54608.



Quasiprojectile calorimetry - corelated signals of the first order phase transition

Other multifragmentation data – signals of criticality, thus implying second order phase transition

Confusing situation !!!

Can both types of phase transition coexist ?

Evolution toward the phase transition in nuclear systems:

- heated by the energy dissipated in the initial (dynamical) stage
- isolated in the latter stages, no heat transfer in/out of the system
- adiabatic expansion (constant entropy) until spinodal region is entered
- during phase change enthalpy must be conserved

Asymmetric nuclear matter – EoS with most essential terms

$$\Delta E_{asym} = Aa_s(\frac{\rho}{\rho_0})^{2/3}(\frac{I}{A})^2 = Aa_s(\frac{V_0}{V})^{2/3}(\frac{I}{A})^2 \qquad (115)$$

Equation of state

$$\Delta p_{asym} = -(\frac{\Delta E_{asym}}{dV})_T = \frac{2a_s\rho_0}{3}(\frac{\rho}{\rho_0})^{5/3}(\frac{I}{A})^2 \qquad (116)$$

$$p = \frac{NT}{V} + a\rho^2 + b\rho^3 + \boxed{\frac{2a_s\rho_0}{3}(\frac{\rho}{\rho_0})^{5/3}(\frac{I}{A})^2} \qquad (117)$$

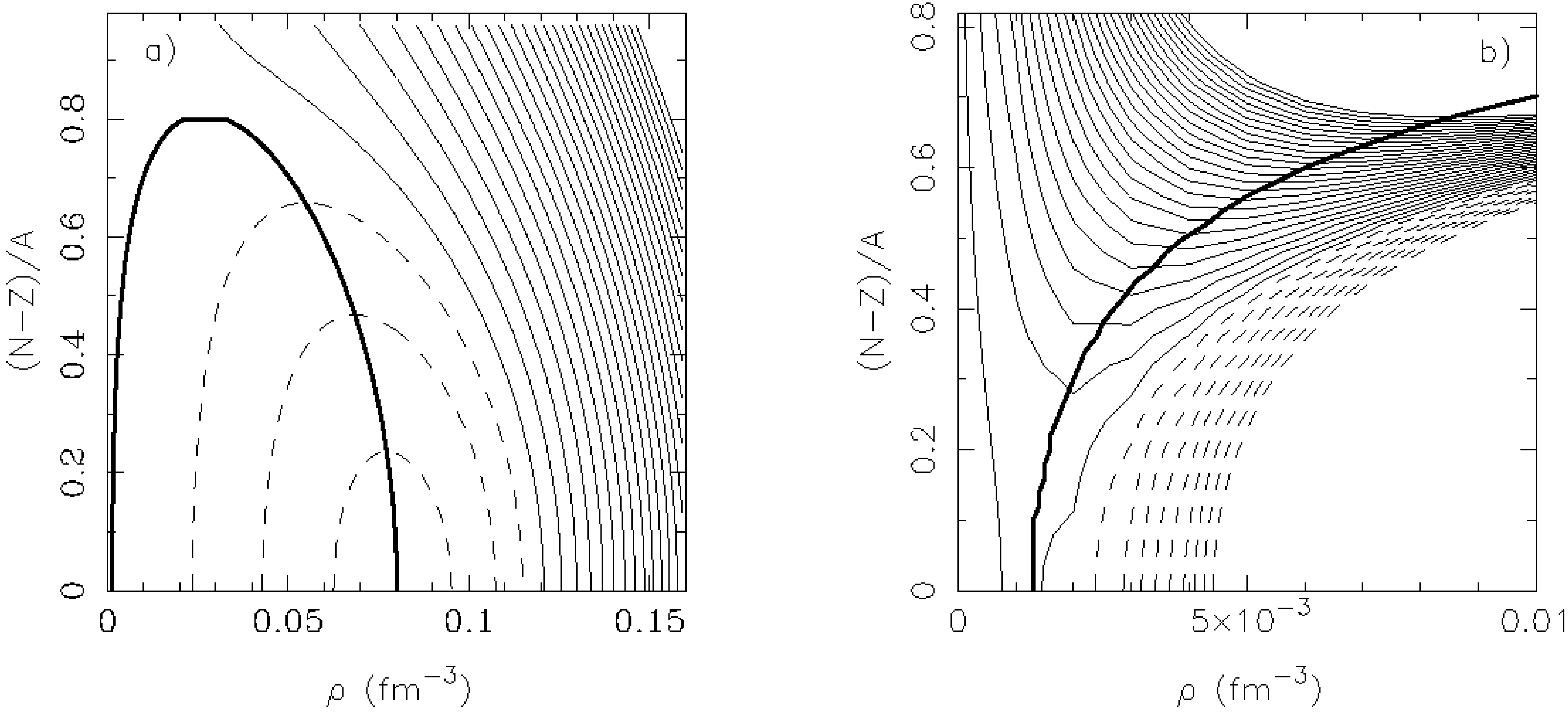
Entropy

$$dS = C_V\frac{dT}{T} + (\frac{dp}{dT})_V dV \qquad (118)$$

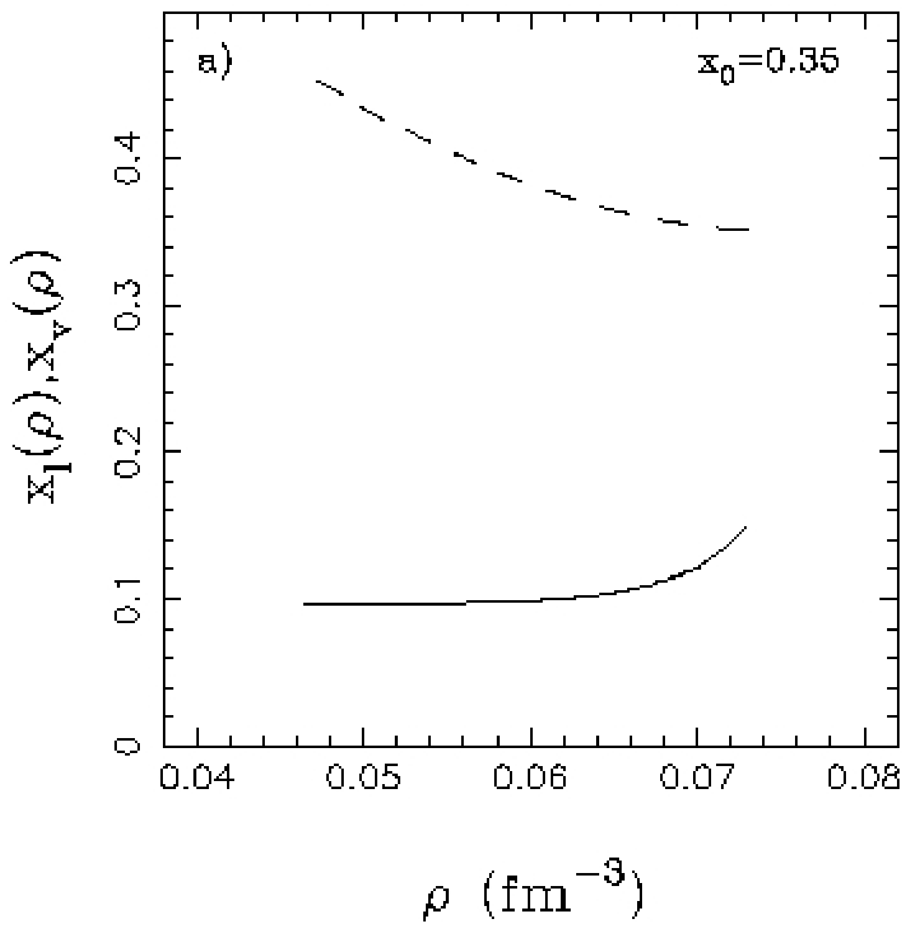
$$dS = Nc_V\frac{dT}{T} + N\frac{dV}{V} \qquad (119)$$

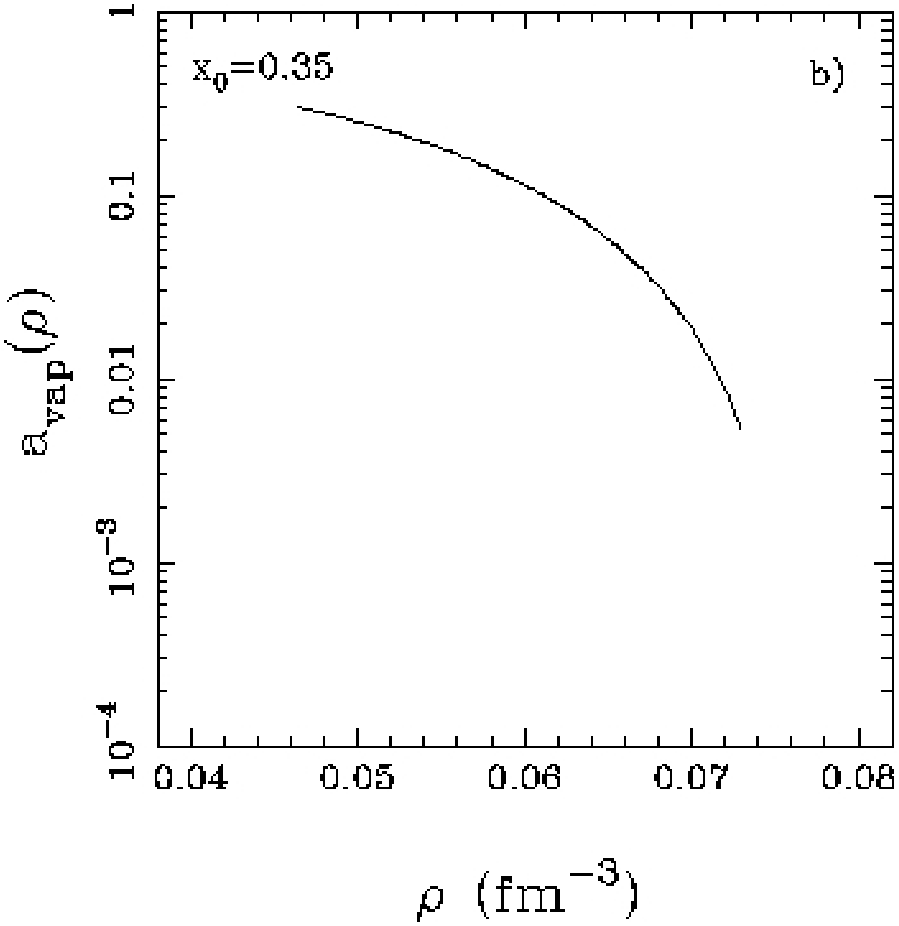
again entropy and isoentropic process like ideal gas !!!

M. Veselsky, nucl-th/0703077

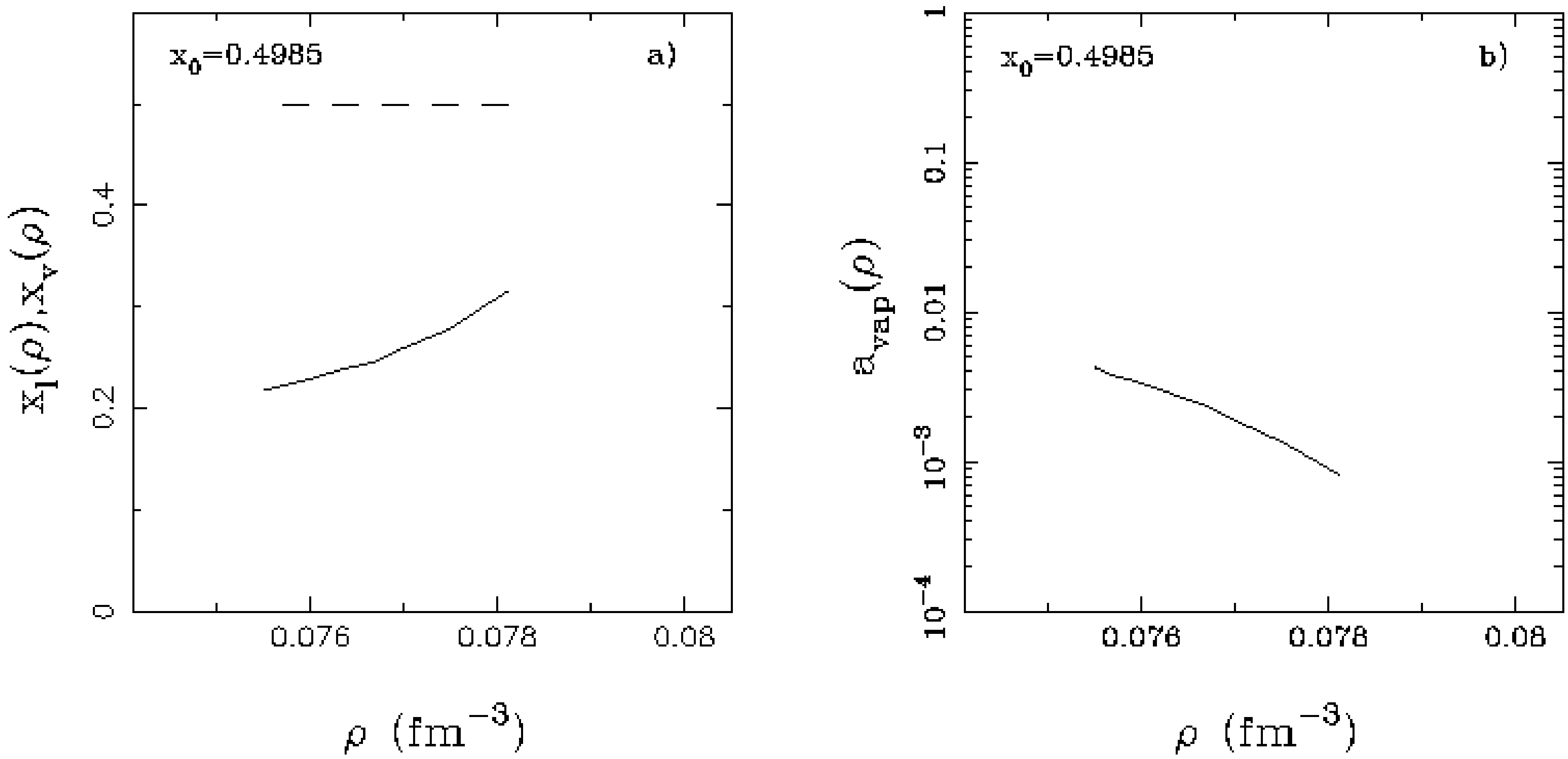


Spinodal region for isolated asymmetric nuclear matter



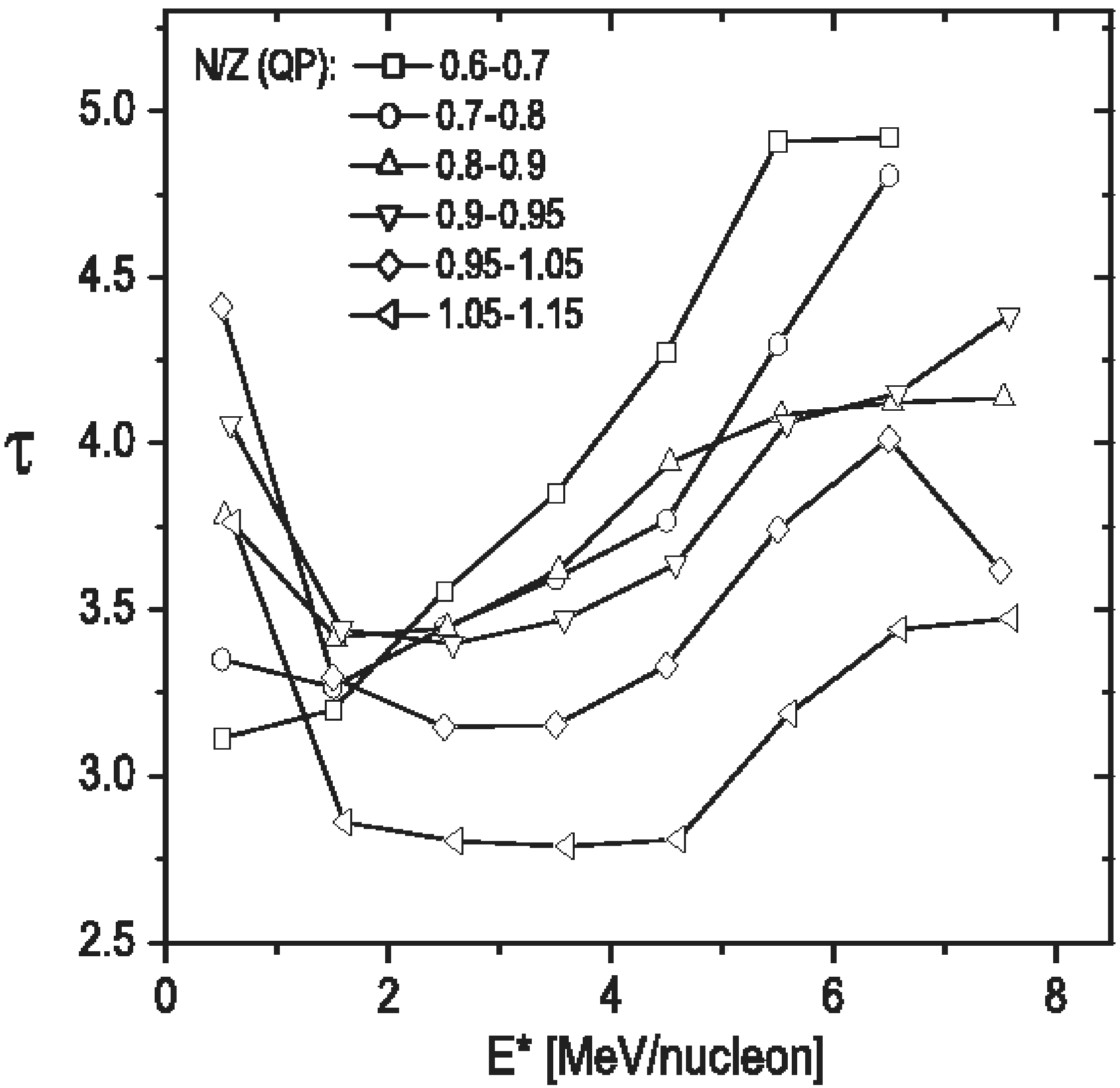


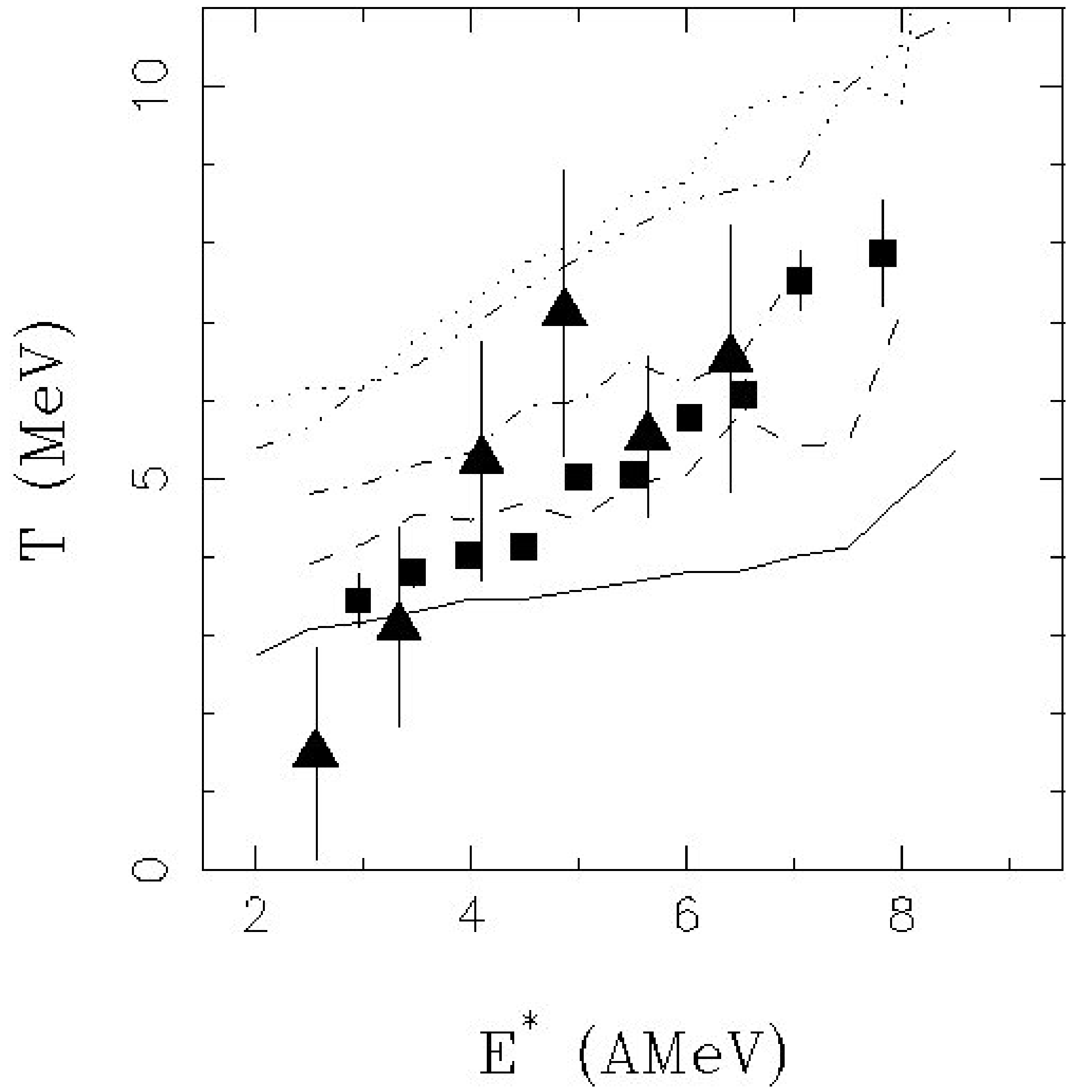
Asymmetric system – sizable part of the system can transform into very asymmetric gas phase => 1. order phase transition, the remnants of liquid phase will undergo percolation-like decay, since the system passed the fragmentation barrier



Symmetric system – only small part of the system transforms into asymmetric gas phase, the system will decay via percolation-like decay => dominant second order transition

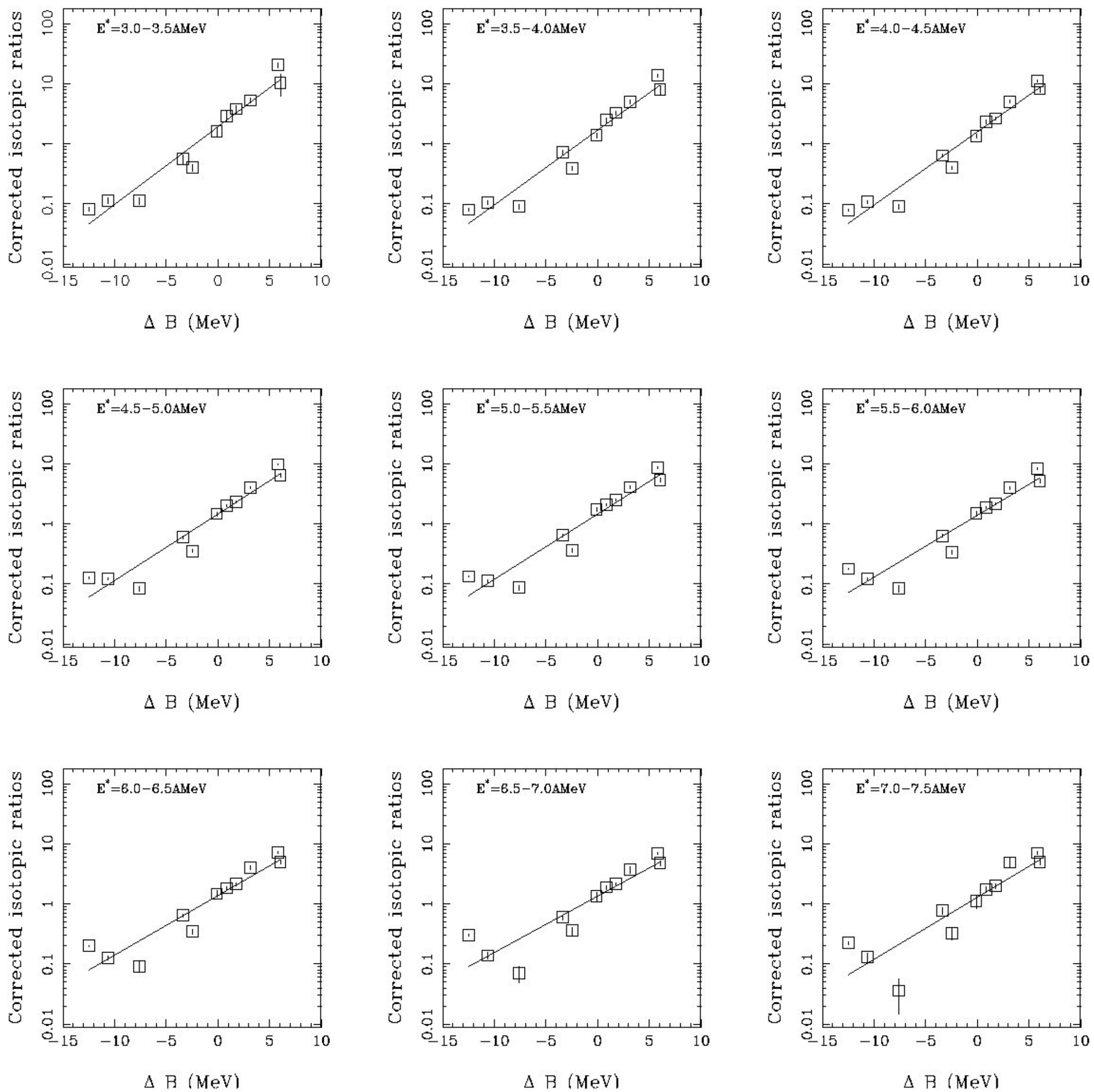
Signal of Transition from
second to first order
phase transition
with increasing asymmetry ?

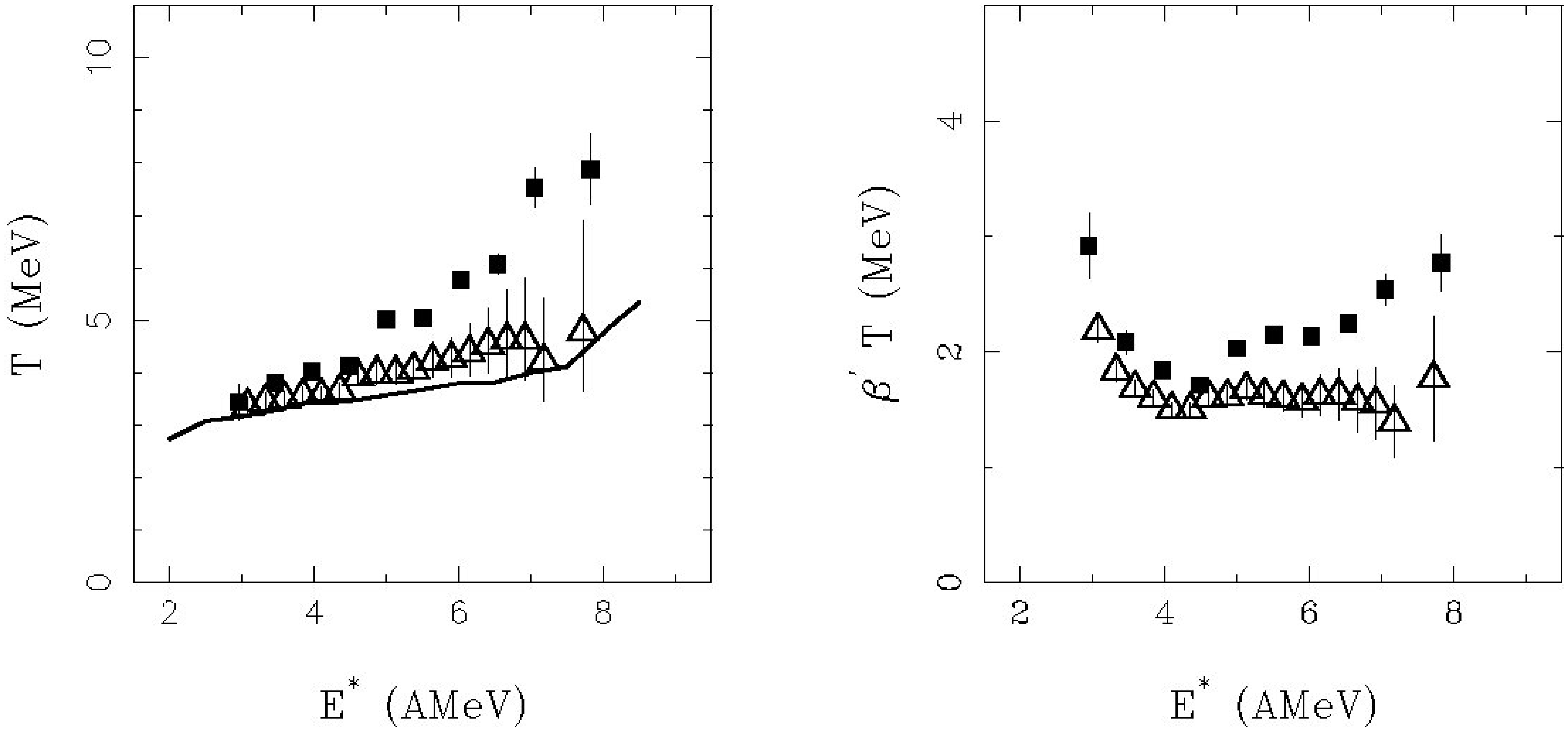




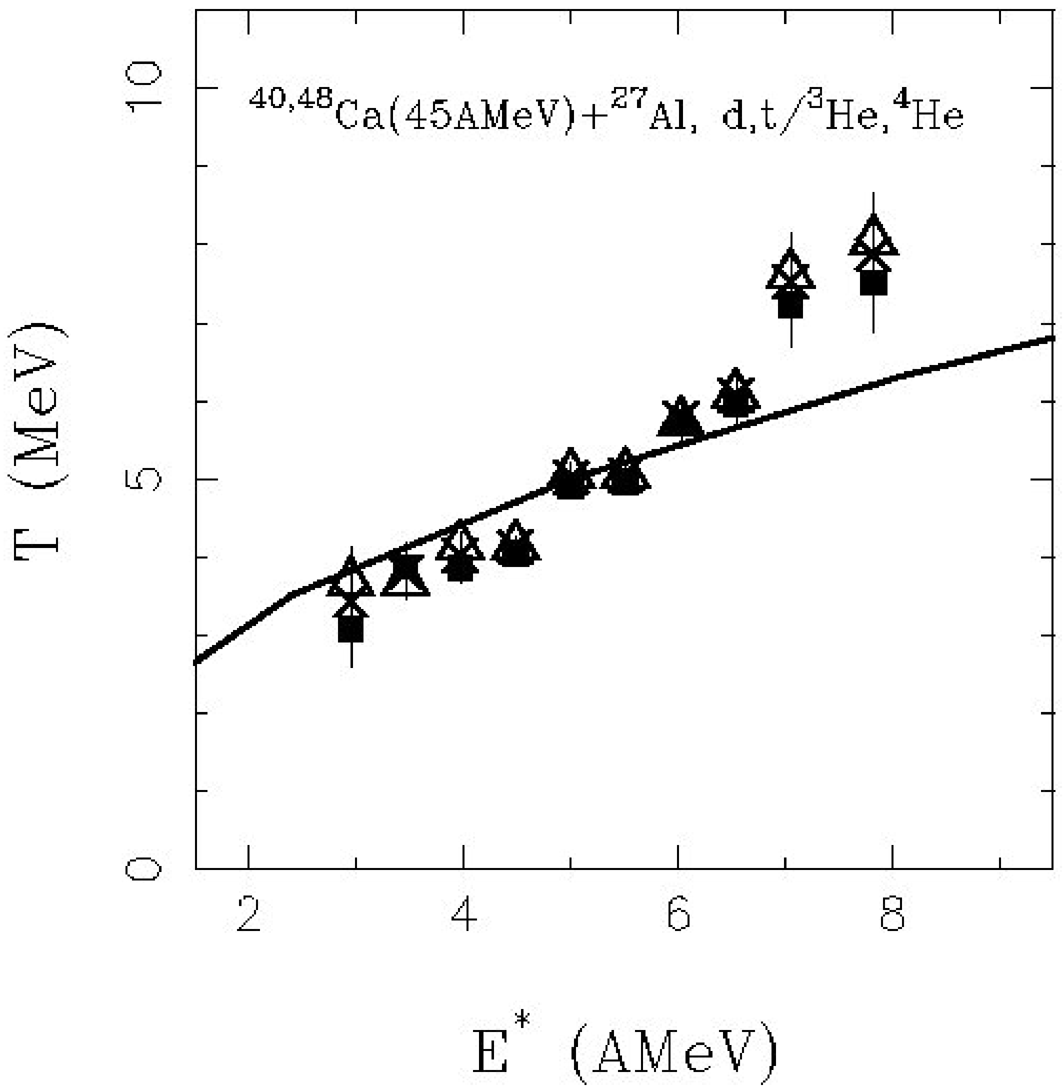
Caloric curves observed for the reactions 40,48Ca+27Al at 45 AMeV. Isotopically resolved quasi-projectiles with Z>20 are selected. Double isotope ratio temperatures d,t/3,4He (squares) and d,t/6,7Li (triangles) and kinematic temperatures of p,d,t,3,4He (solid, dashed, dash-dotted etc lines) are shown as function of excitation energy, reconstructed using observed charged particles.

Extraction of global temperatures
for the fragment partitions
(generalization of the method of
double isotope ratio thermometers)



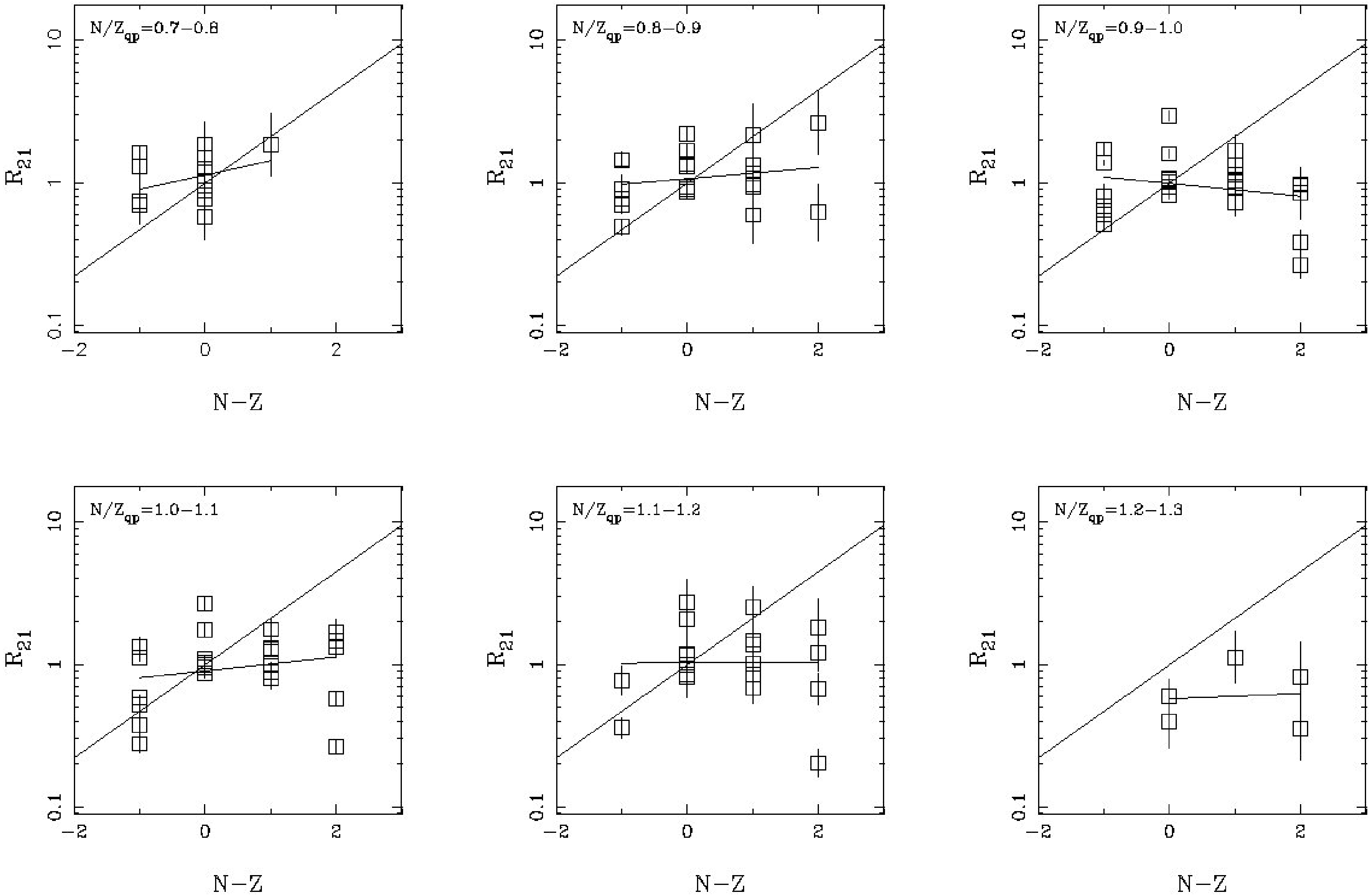


Caloric curves and isovector chemical potentials (from isoscaling) observed for the reactions 40,48Ca+27Al at 45 AMeV. Isotopicaly resolved quasiprojectiles with *Z*>20 are selected. Double isotope ratio temperature d,t/3,4He (squares) and global temperature (triangles) are used. Excitation energy is reconstructed using observed charged particles.



Double isotope ratio temperature d,t/3,4He observed for the reactions 40Ca+27Al (squares) and 48Ca+27Al (triangles) at 45 AMeV. Isotopicaly resolved quasiprojectiles with Z>20 are selected. Excitation energy is reconstructed using observed charged particles. Line shows theoretical dependence, obtained using simple EoS for isolated system entering spinodal region.

Independence on neutron excess provides signal of dynamical emission of neutrons (prior to thermal equilibrium !!!).



Zero-th order isoscaling – identical N/Z-bins compared
test of independence of chemical potential on neutron excess

Conclusions II.

1. nuclear multifragmentation – isospin asymmetric liquid-gas phase transition for asymmetric systems, percolation-like phase transition for symmetric systems

2. system size dependence – consistent results, strong effect of secondary decay for heavier systems

3. dynamical emission of neutrons – neck region ?

Recommendations for Eurisol Instrumentation :

1. consider use of gas catcher (or comparable device) to collect the n-rich products away from zero angle

2. charged particle array for nuclear dynamics should be equipped by suitable neutron detectors, with improved capabilities

Collaborators :

G.A. Souliotis, S.J. Yennello, A.L. Keksis et al. (Cyclotron Institute, Texas A&M University)

K. Wang, Y.G. Ma (SINAP Shanghai)

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China: MoST 2007CB815004