Nuclear Thermometry

First Question:

Do the different methods yield consistent results?
(when appropriately understood and/or corrected)

Second Question:

What is the motivation to measure temperatures?
What are the current results and the conclusions?

First Question:

Do the different methods yield consistent results? (when appropriately understood and/or corrected)

Most experimental methods rely on the application of thermodynamic relations to characterize the conditions at freeze-out.

Expected problems:

- **The nucleus is a microscopic system.**
  (External probe is not applicable.)
- **The nucleus is an isolated system.**
  (E^* = const., particle number = const., ...)
- **The nucleus is a Fermionic system.**
  (Fermi statistics, Fermi motion.)
- **The nucleus is an electrically charged system.**
  (Coulomb trajectories.)
- **The nucleus heats up and cools down in a dynamical process.**
  (Different signatures may correspond to different freeze-out conditions, production during evaporation, expansion contributes to kinetic energy of fragments.)
- **The thermodynamical parameters** (e.g. pressure, volume, chemical potential) **are not under control.**
- **Experimental signatures are modified by secondary decay.**
  (Search for robust signatures, light IMFs are least affected,)

Methods:

- **Population approach** → Boltzmann distribution
  Thermodynamical principle: Exponential population curve.

  $Y_i \sim \exp(-E_i/T)$

  - Population of excited states (bound or unbound)
  - Double ratios of isotopic yields (Albergo et al. 1985)
  - Isotopic yields from given source (Veselsky et al. 2000)

- **Kinetic approach** → Maxwell distribution → Slope thermometer
  Thermodynamical principle: Gaussian distribution in 3-dimensional velocity space.

  $dY/dE_{kin} = E_{kin} \exp(-E_{kin}/T)$

- **Statistical emission** from an equilibrated source→ Slope thermometer

  gammas (R. Ortega et al., NPA 734 (2004) 541)

  nucleons

- **Thermal-energy approach** → Isospin thermometer
  Principle: Measure of evaporation cascade from thermalized source by **variation of *N*/*Z*.**

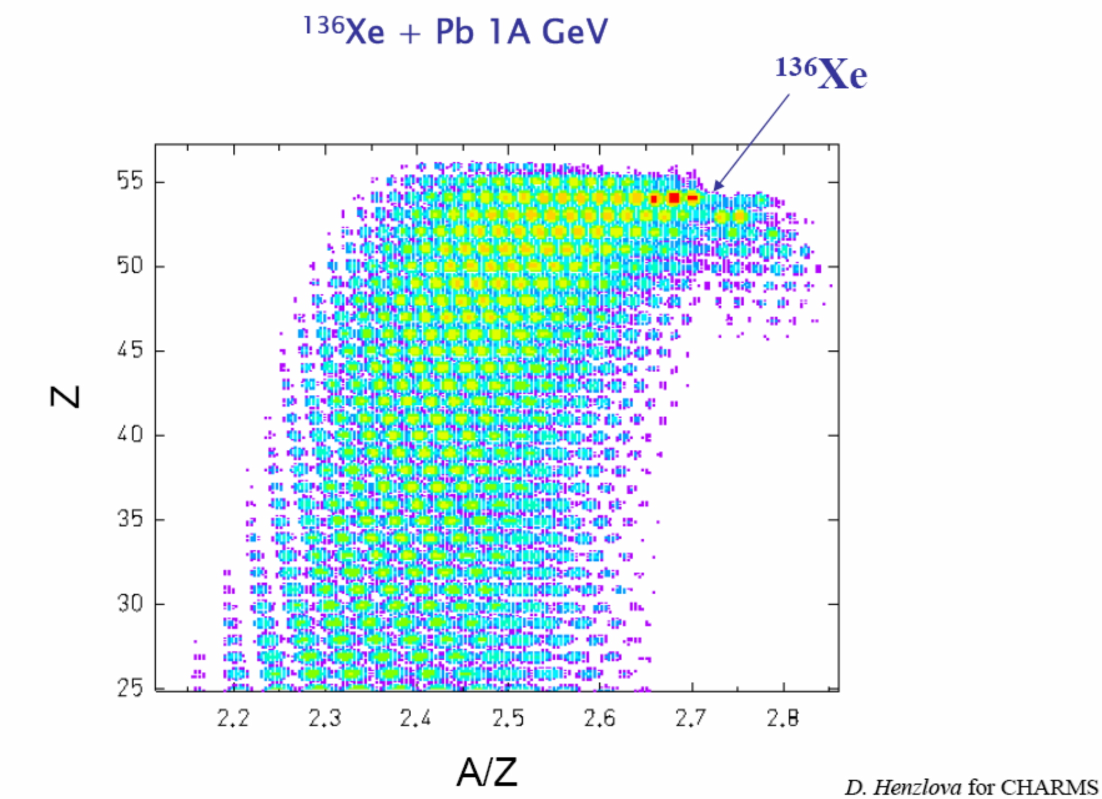
  (K.-H. Schmidt et al., PLB 300 (1993) 313)

Thermal-Energy Approach
(Isospin Thermometer[1,2])

Basic Idea:

- **Thermal energy after freeze-out feeds an evaporation cascade.**
- **Evaporation residues tend to approach the attractor line.**
- **Loss of neutron excess is a measure of the thermal energy.**
- **Calibration by evaporation calculations.**

Experimental raw data:



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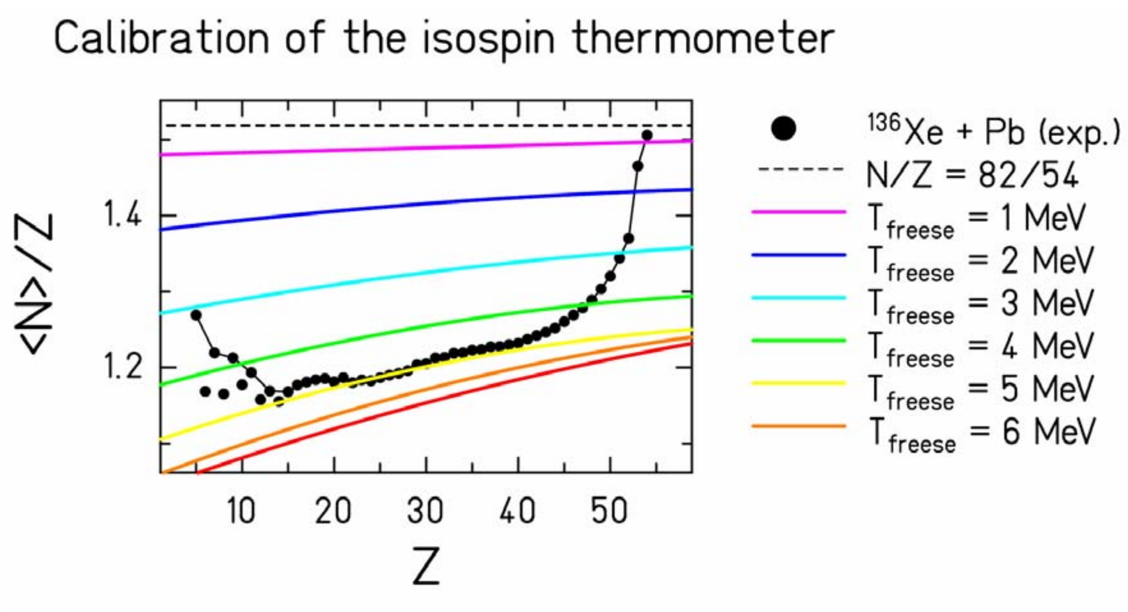
[1] K.-H. Schmidt et al., Phys. Lett. B 300 (1993) 313
[2] K.-H. Schmidt, M. V. Ricciardi, A. S. Botvina, T. Enqvist, Nucl. Phys. A 710 (2002) 157

Thermal-Energy Approach
(Isospin Thermometer)

An Example:



Experiment: ^{136}Xe (1A GeV)+ Pb (D. Henzlova PhD)
Model includes evaporation of n, p, α.
N/*Z* assumed to be unchanged until freeze-out.

High *Z*: Thermal energy increases with abraded mass.

Intermediate *Z*: Constant value $T_{\mathrm{freeze}} \approx 5$ MeV.

Low *Z*: Lowering of symmetry energy at freeze-out?
(D. Henzlova, A. S. Botvina, in preparation)

The approach determines the thermal energy at freeze-out.

The approach is applicable to heavy residues.

Direct experimental results:

- Population approach → Boltzmann distribution
  - Population of excited states
    - Gives relatively **low** values
  - Double ratios of isotopic yields
  - Isotopic yields from given source
    - Give **intermediate** values
- Statistical photon emission

  Consistent with isotopic-yield results
- Kinetic approach → Maxwell distribution → Slope thermometer
    - Gives relatively **high** values
- Thermal-energy approach → Isospin thermometer
    - Consistent with isotopic-yield results

Corrections and particularities:

General: Finite-size effects[3], emission-time differences[4], chemical/thermal equilibration?, multi-source emission[5]

- **Population approach** → Boltzmann distribution
  - Population of excited states
    - Secondary decay, γ decay[8], freeze-out rather late?
  - Double ratios of isotopic yields (Albergo et al.)/
  - Isotopic yields from given source (Veselsky)
    - Secondary decay[8,6], recombination[7], Coulomb[8]
- **Kinetic approach** → Maxwell distribution → Slope thermometer
    - Expansion, Fermi motion[9,10], Coulomb
- **Thermal-energy approach** → Isospin thermometer
    - Isospin diffusion, Neutron distillation, Details of evaporation model especially at high E*

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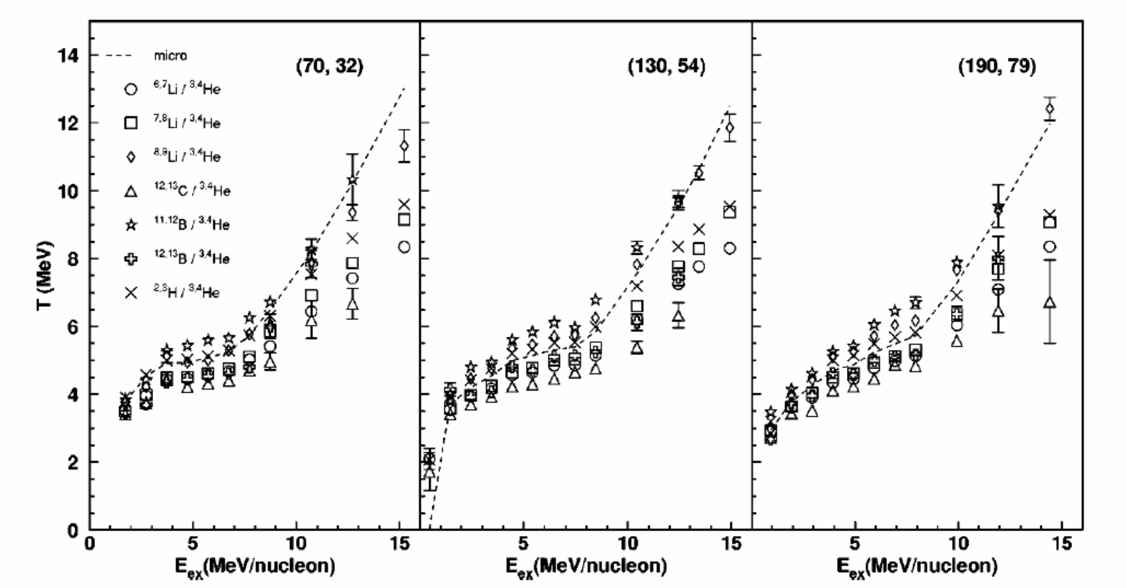
[3] Al. H. Raduta *et al.*, Phys. Rev. C 59 (1999) R1855
[4] V. E. Viola et al., Phys. Rev. C 59 (1999) 2660
[5] S. Hudan et al., nucl-ex/0501022
[6] Al. H. Raduta *et al.*, Nucl. Phys. A 671 (2000) 609
[7] S. K. Samaddara *et al.*, Phys. Rev. C71 (2005) 011601
[8] S. Shlomo *et al.*, Rep. Prog. Phys. 68 (2005) 1
[9] G. D. Westfall et al., Phys. Rev. C 17 (1978) 1368
[10] T. Odeh *et al.*, Phys. Rev. Lett. 84 (2000) 4457

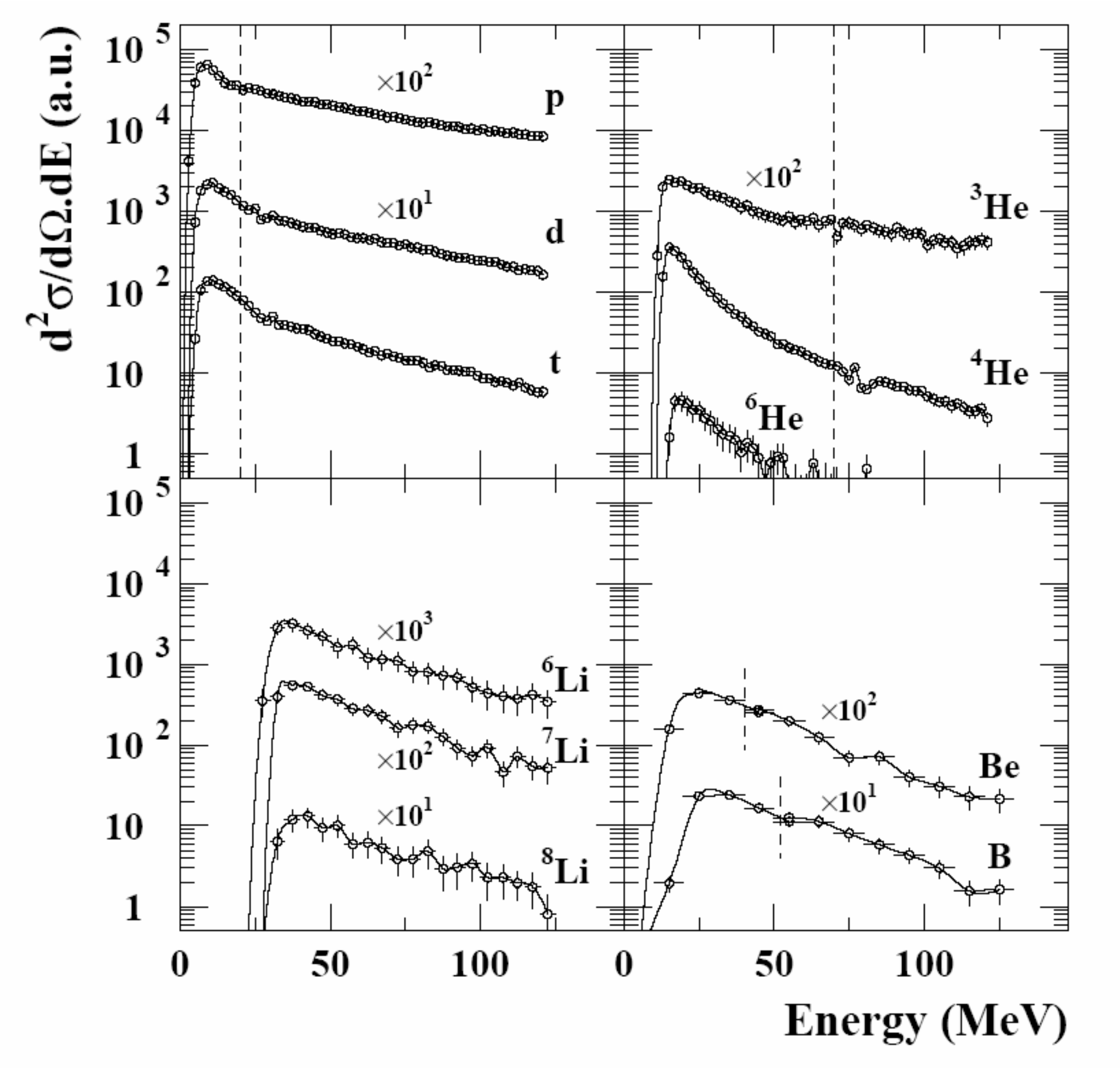
Finite-size effects (Theory)



Isotopic caloric curves calculated for seven isotope pairs by the Formula of Albergo et al. in the case of three representative source nuclei. The microcanonical caloric curve is represented by a dashed line.

Al. H. Raduta, Ad. R. Raduta, Phys. Rev. C 59 (1999) R1855

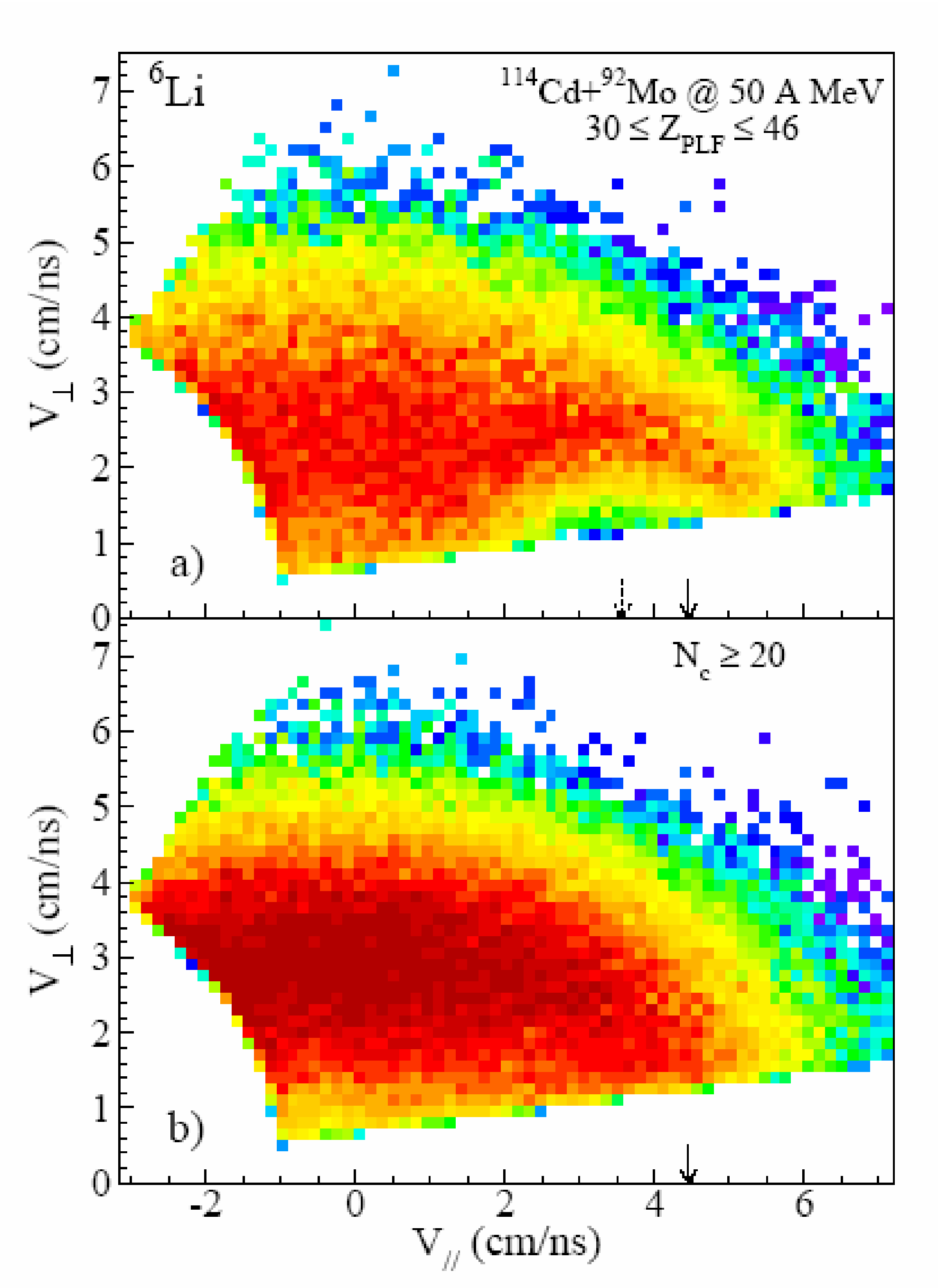
Influences on kinetic properties



Energy spectra of different isotopes for ^{12}C + ^{124}Sn at 300 A MeV. (Le Fèvre et al., nucl-ex/0409026)

- **Pre-equilibrium emission**
- **Coulomb repulsion**
- **Expansion (flow)**
- **Fermi motion**
- **Secondary decay**

Multi-source emission (Experiment)

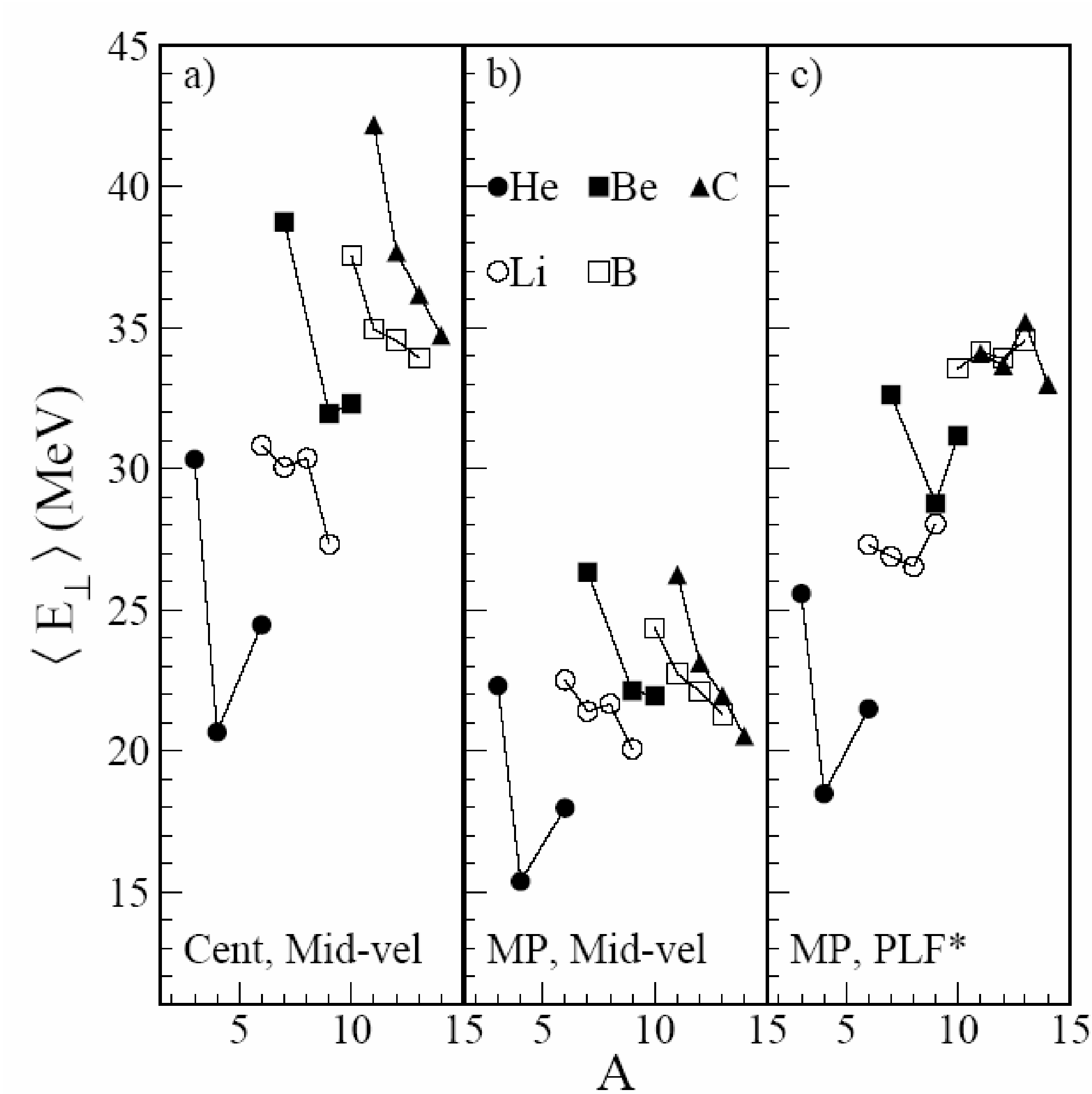


Invariant cross sections of ^{6}Li fragments in the c.m. frame.
a) Peripheral collisions, b) Central collisions.

S. Hudan et al., nucl-ex/0501022

Higher E_{kin} for neutron-deficient nuclei (Exp.)

(Different emission times)



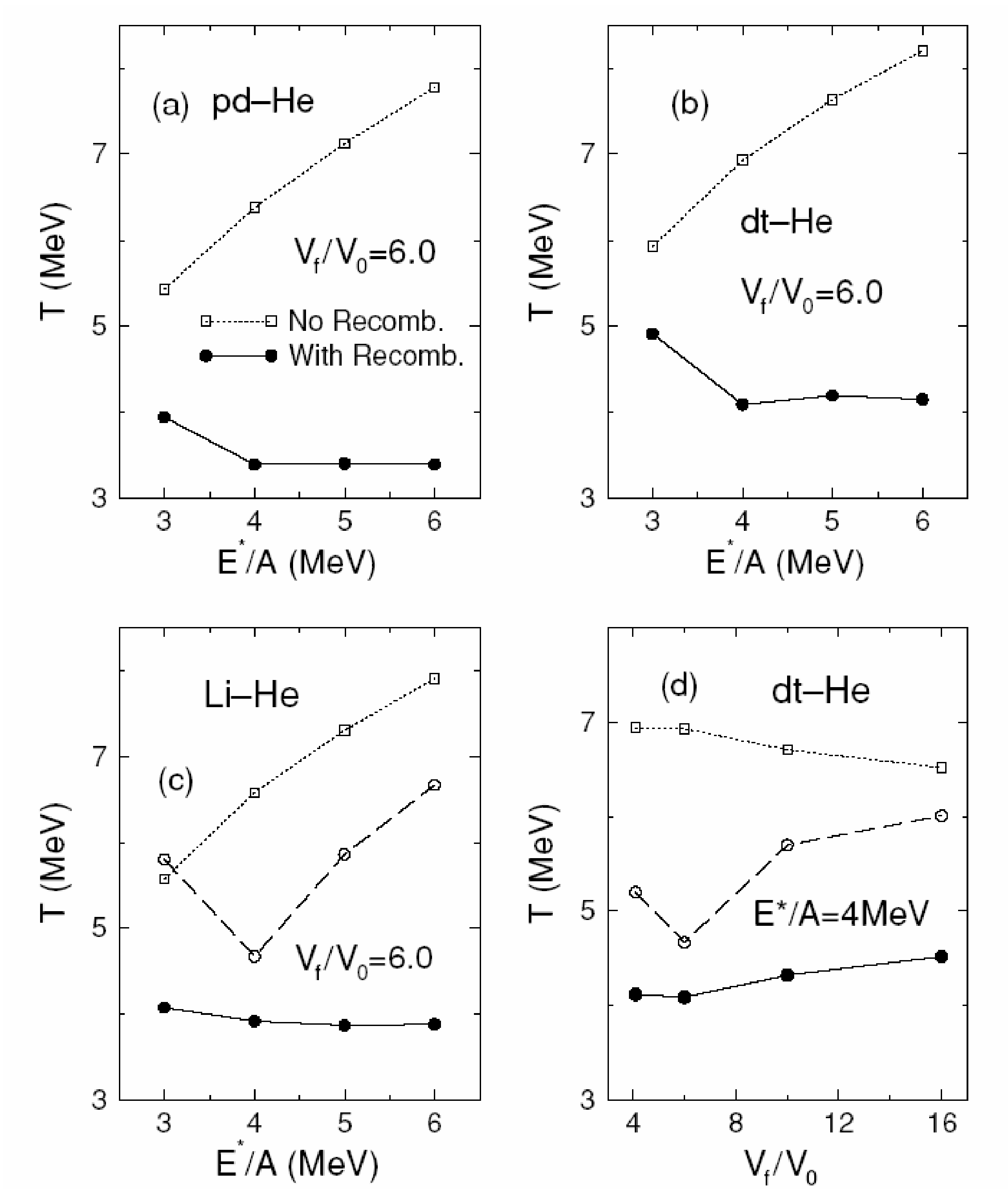
Average transverse energies for central and mid-peripheral (MP) collisions.

S. Hudan et al., nucl-ex/0501022

compare also

V. E. Viola et al., Phys. Rev. C 59 (1999) 2660

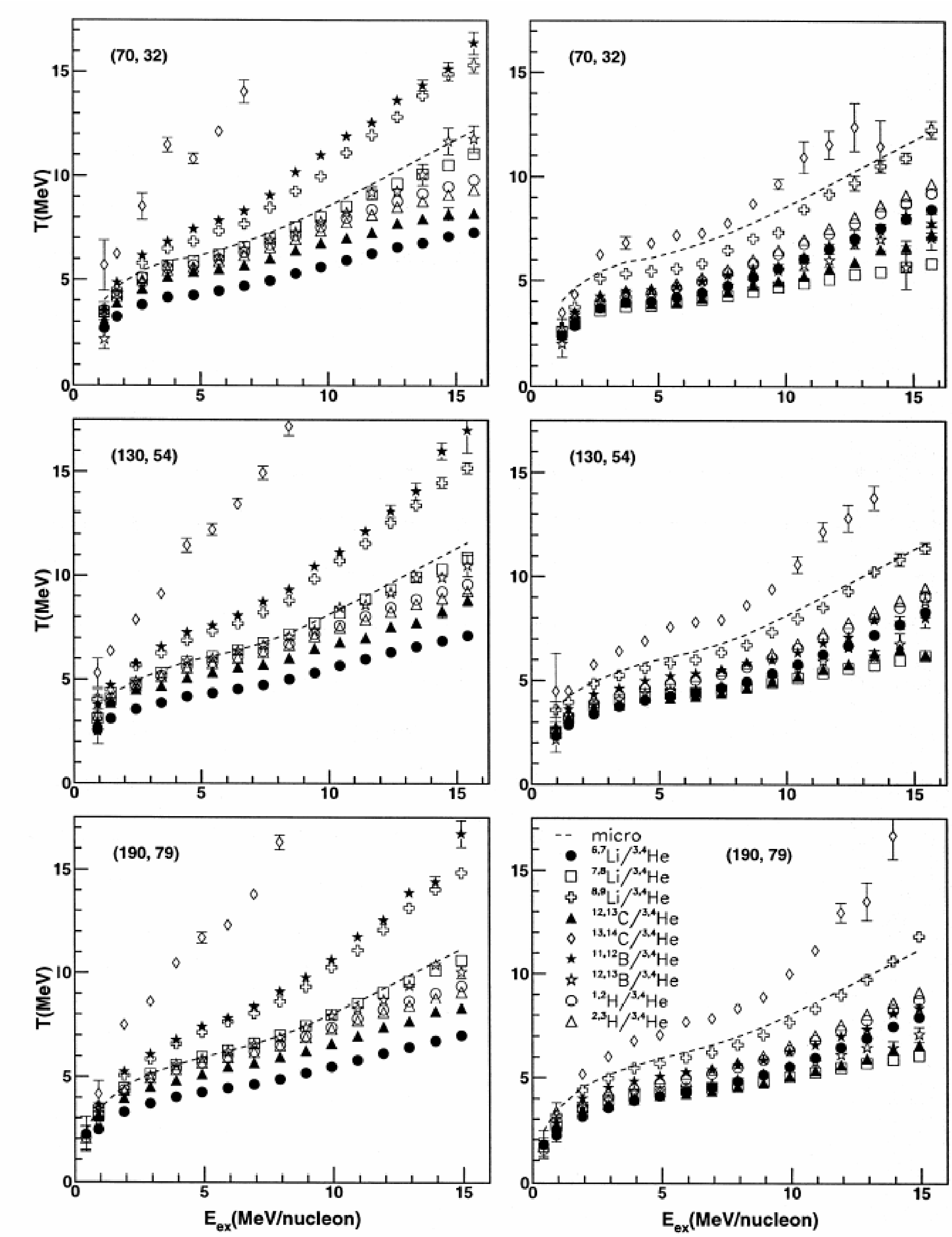
Recombination (Theory)



Isotopic double-ratio temperatures for fragmenting ^{197}Au with and without recombination. Dashed lines: microcanonical temperatures.

S. K. Samaddar et al., Phys. Rev. C 71 (2005) 011601

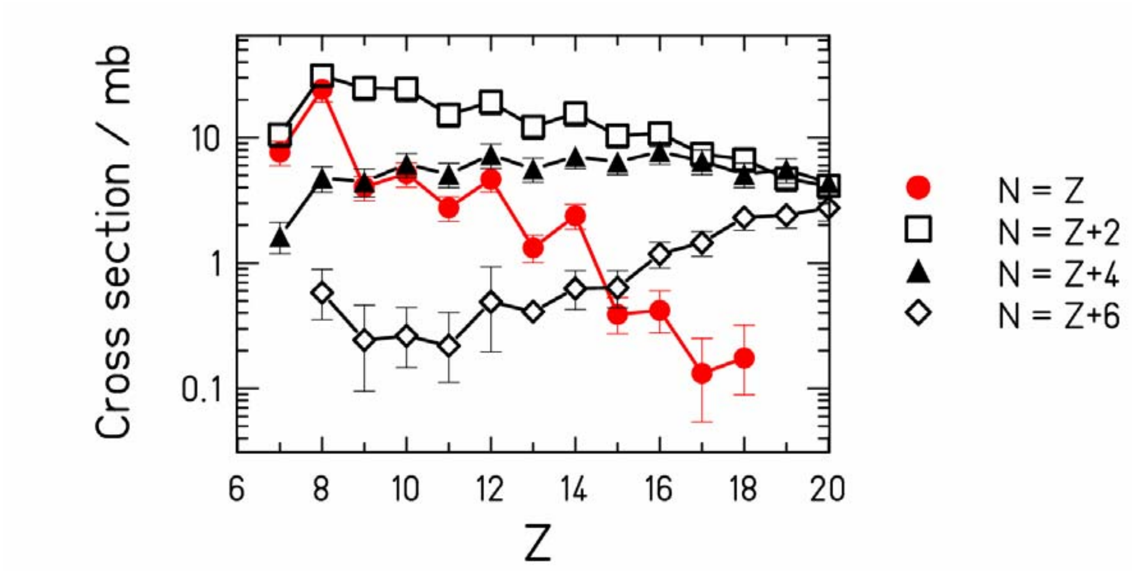
Secondary decay (Theory)



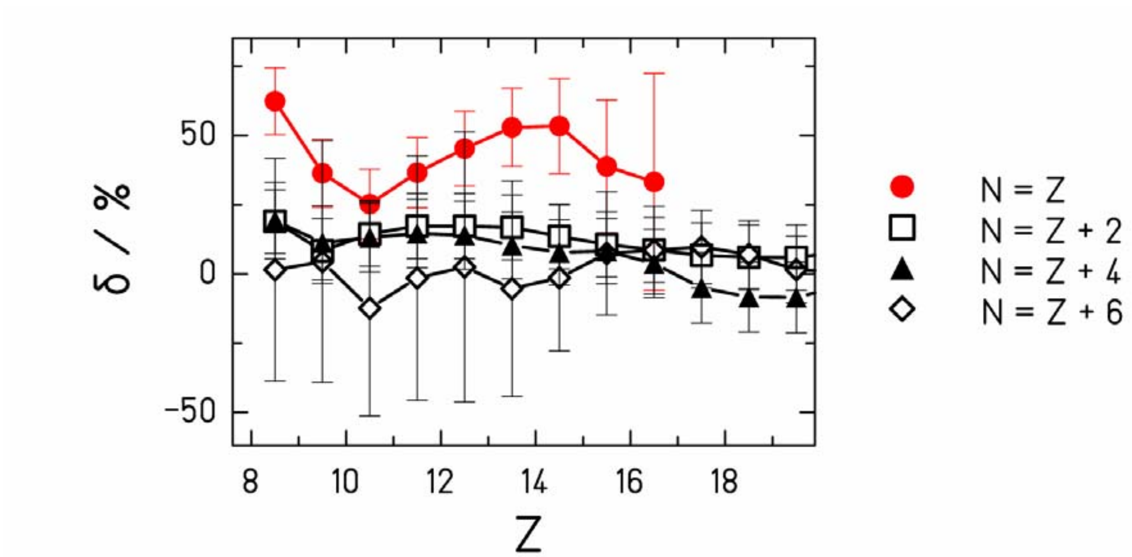
Caloric curves corresponding to nine **isotopic thermometers** for three nuclear sources in primary decay (left) and asymptotic (right) stages. Dashed line: microcanonical curve.

Al. H. Raduta, Ad. R. Raduta, Nucl. Phys. A 671 (2000) 609

Complex structure in secondary decay (Exp.)



Formation cross sections of projectile-like residues in ^{238}U (1AGeV) + Ti along cuts with N-Z = constant.



Relative even-odd effect determined from the figure above.

Complex structure, e.g. extremely strong (≈50%!) even-odd staggering in N=Z nuclei must be considered when correcting for secondary decay.

M. V. Ricciardi et al., Nucl. Phys. A 733 (2004) 299

Conclusions

It is not straightforward to determine the thermodynamical temperature T ($1/T = dS/dE$) of a nuclear system.

There has been important theoretical progress in understanding the conceptual differences in the apparent temperature values from the different experimental methods.

Recent experiments provided more information on the influence of the reaction dynamics on the apparent temperature values.

We are aware of the enormous complexity of effects involved in the interpretation of apparent-temperature measurements. Do we still have more complexity to expect?

A final optimistic statement:

Apparent temperatures, even if uncertain in absolute value, seem to be surprisingly robust in showing signatures of phase transitions.

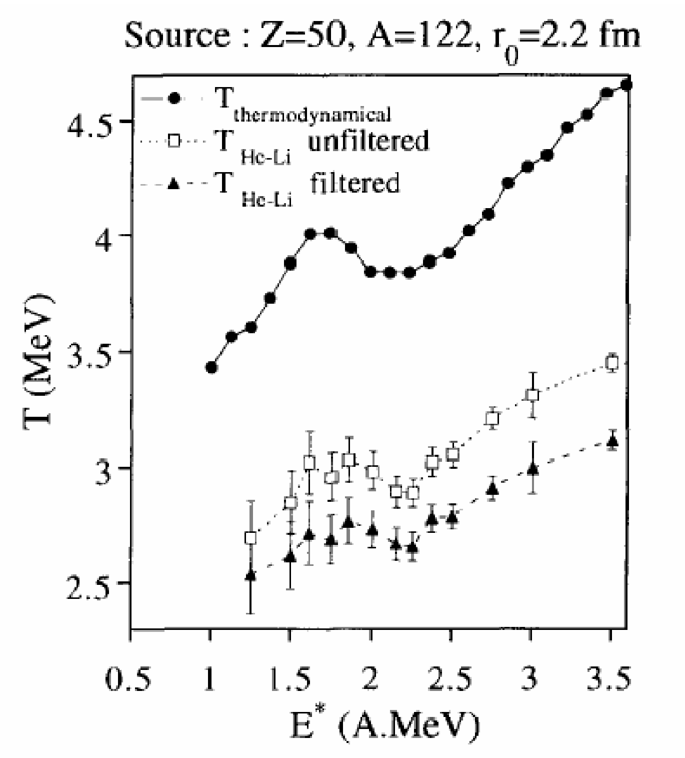


Figure: Caloric curves $T_{thd}(E^*)$ and $T_{He\text{-}Li}(E^*)$ from the MMMC calculation. $T_{He\text{-}Li}$ is shown unfiltered and filtered according to the INDRA setup. (From A. Le Fèvre et al., Nucl. Phys. A 657 (1999) 446.)