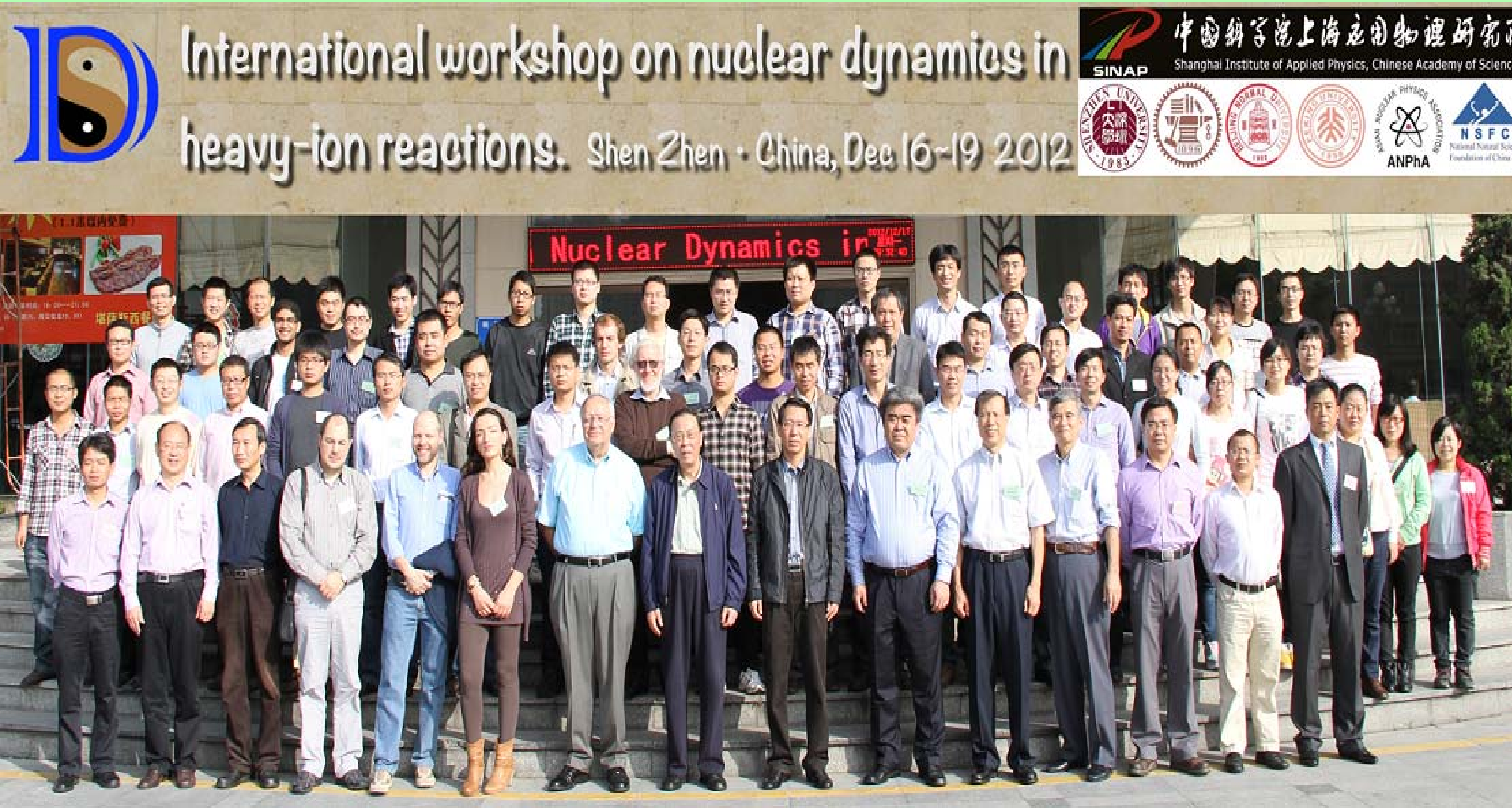
IWNDT, in Honor of Prof. Joe Natowitz, Aug. 19-22, 2013, Texas A&M, Texas

Determining nuclear temperature in heavy-ion collisions

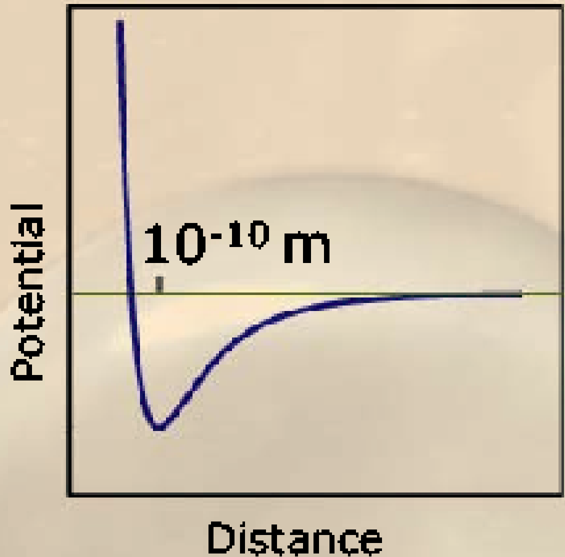
J. Su(苏军) and F.S. Zhang(张丰收)

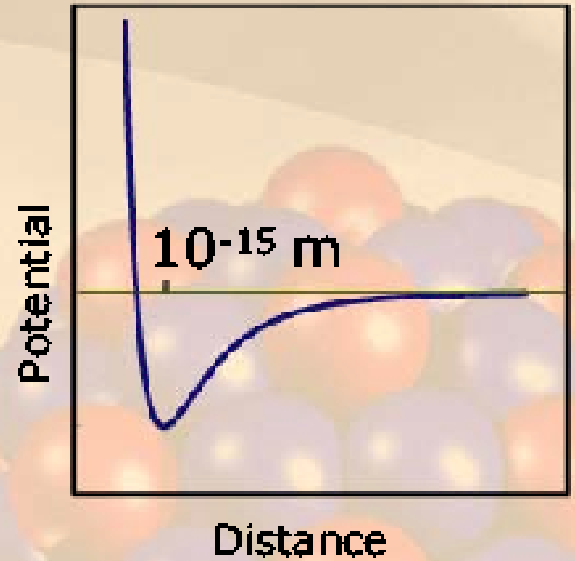
College of Nuclear Science and Technology
Beijing Normal University,
Beijing, China
Tel: 010-6220 5602，6220 8252-806
Fax: 010-6223 1765
E-mail: fszhang@bnu.edu.cn
http://lenp.bnu.edu.cn/hkxyweb/zhangfengshou.htm

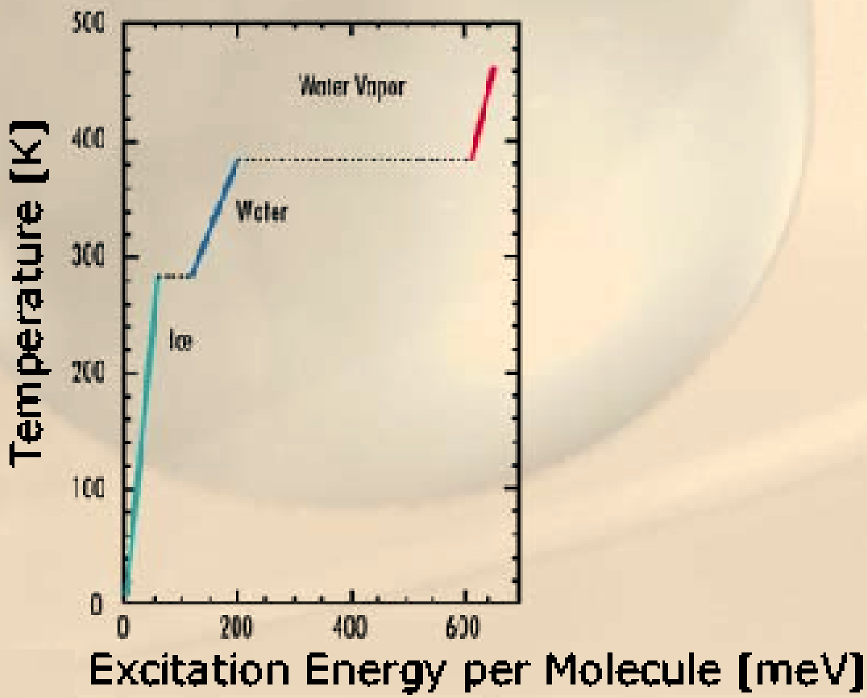
International workshop on nuclear dynamics in heavy-ion reactions, Shenzhen, China, Dec. 16-19, 2012

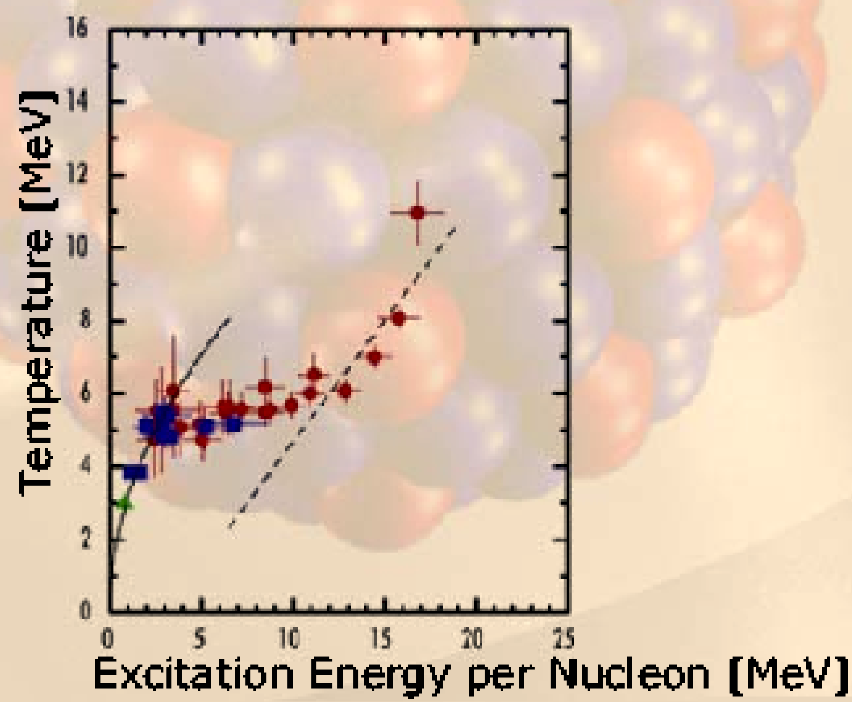


The Phases of Nuclear Matter







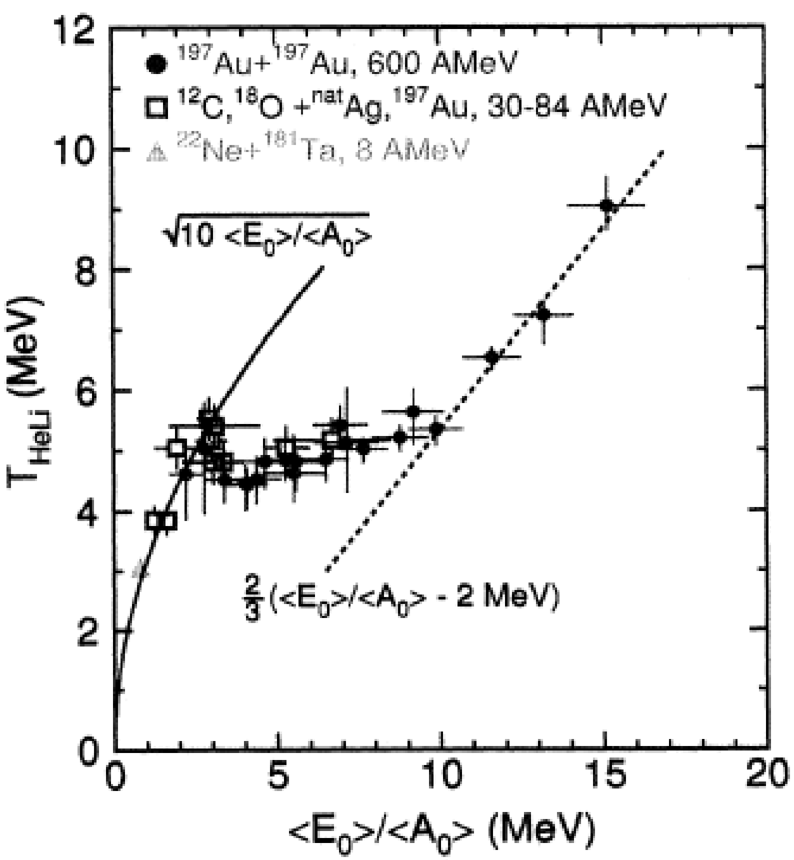


Probing the Nuclear Liquid-Gas Phase Transition

J. Pochodzalla,[1] T. Möhlenkamp,[2] T. Rubehn,[1] A. Schüttauf,[3] A. Wörner,[1] E. Zude,[1] M. Begemann-Blaich,[1] Th. Blaich,[4] H. Emling,[1] A. Ferrero,[5,*] C. Gross,[1] G. Immé,[6] I. Iori,[5] G. J. Kunde,[1,†] W. D. Kunze,[1] V. Lindenstruth,[1,‡] U. Lynen,[1] A. Moroni,[5] W. F. J. Müller,[1] B. Ocker,[3] G. Raciti,[6] H. Sann,[1] C. Schwarz,[1] W. Seidel,[2] V. Serfling,[3] J. Stroth,[1] W. Trautmann,[1] A. Trzcinski,[7] A. Tucholski,[7] G. Verde,[5] and B. Zwieglinski[7]

[1]*Gesellschaft für Schwerionenforschung, 64220 Darmstadt, Germany*
[2]*Forschungszentrum Rossendorf, 01314 Dresden, Germany*
[3]*Institut für Kernphysik, Universität Frankfurt, 60486 Frankfurt, Germany*
[4]*Institut für Kernchemie, Universität Mainz, 55099 Mainz, Germany*
[5]*Dipartimento di Fisica, Universitá di Milano and INFN, 20133 Milano, Italy*
ersitáand INFN, 95129 Catania, Italy
es, 00 681 Warsaw, Hoza 69, Poland

i January 1995)



Caloric Curve:

Au+Au, 600MeV/u

^{12}C,^{18}O+^{nat}Ag,^{197}Au, 30-84MeV/u

22Ne+181Ta, 8MeV/u

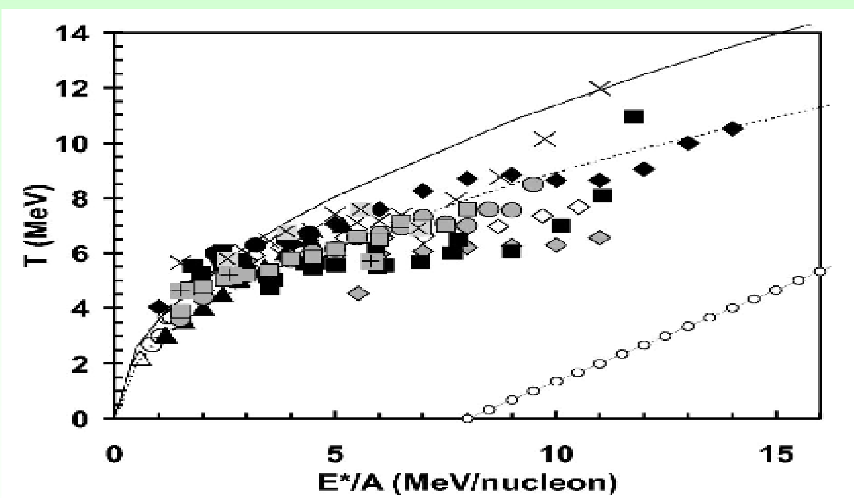
PHYSICAL REVIEW C, VOLUME 65, 034618

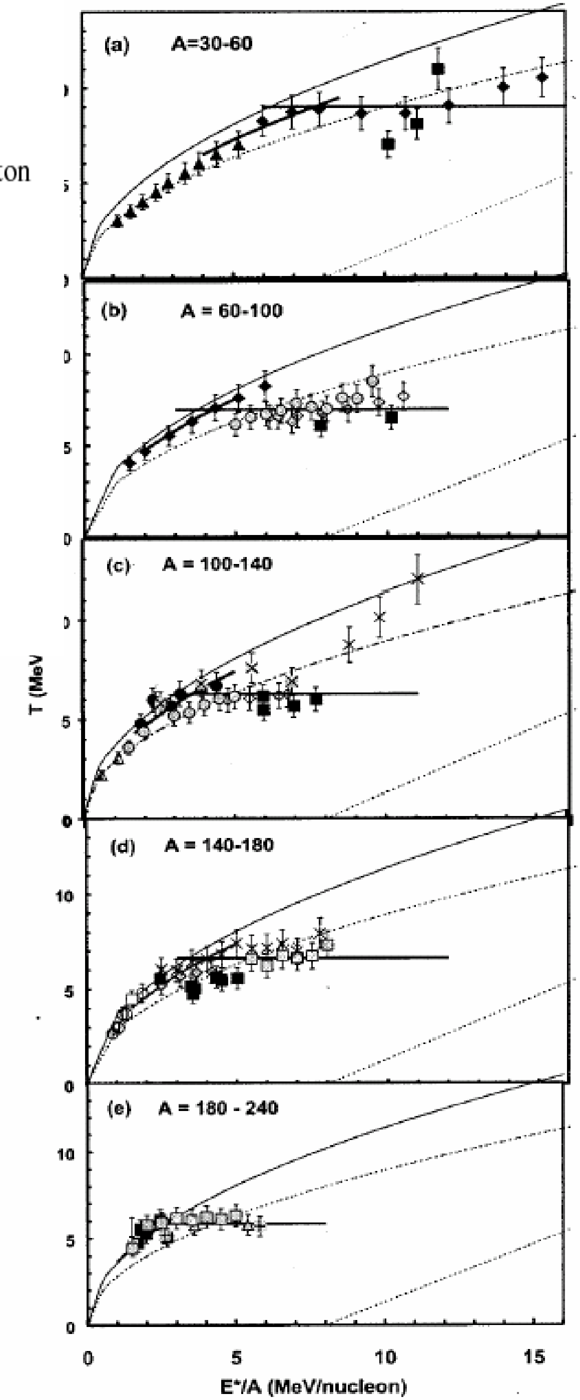
Caloric curves and critical behavior in nuclei

J. B. Natowitz, R. Wada, K. Hagel, T. Keutgen, M. Murray, A. Makeev, L. Qin, P. Smith, and C. Hamilton
Cyclotron Institute, Texas A&M University, College Station, Texas 77845
(Received 19 June 2001; published 4 March 2002)

Data from a number of different experimental measurements are used to construct caloric curves for five different regions of nuclear mass. These curves are qualitatively similar, and exhibit plateaus at the higher excitation energies. The limiting temperatures represented by the plateaus decrease with increasing nuclear mass, and are in very good agreement with results of recent calculations employing either a chiral symmetry model or the Gogny interaction. This agreement strongly favors a soft equation of state. Evidence is presented which suggests that critical excitation energies and critical temperatures might be determined from caloric curve measurements when the mass variations inherent in such measurements are taken into account.

DOI: 10.1103/PhysRevC.65.034618 PACS number(s): 24.10.−i, 25.70.Gh





There is a mass dependence clearly shown in the Caloric Curves

Outline

1. Introduction

2. Theoretical model

3. Results and discussion

4. Conclusions and outlooks

1. Introduction

Definition of Temperature

1.Statistical mechanics:

with fixed number of particles N at an energy E

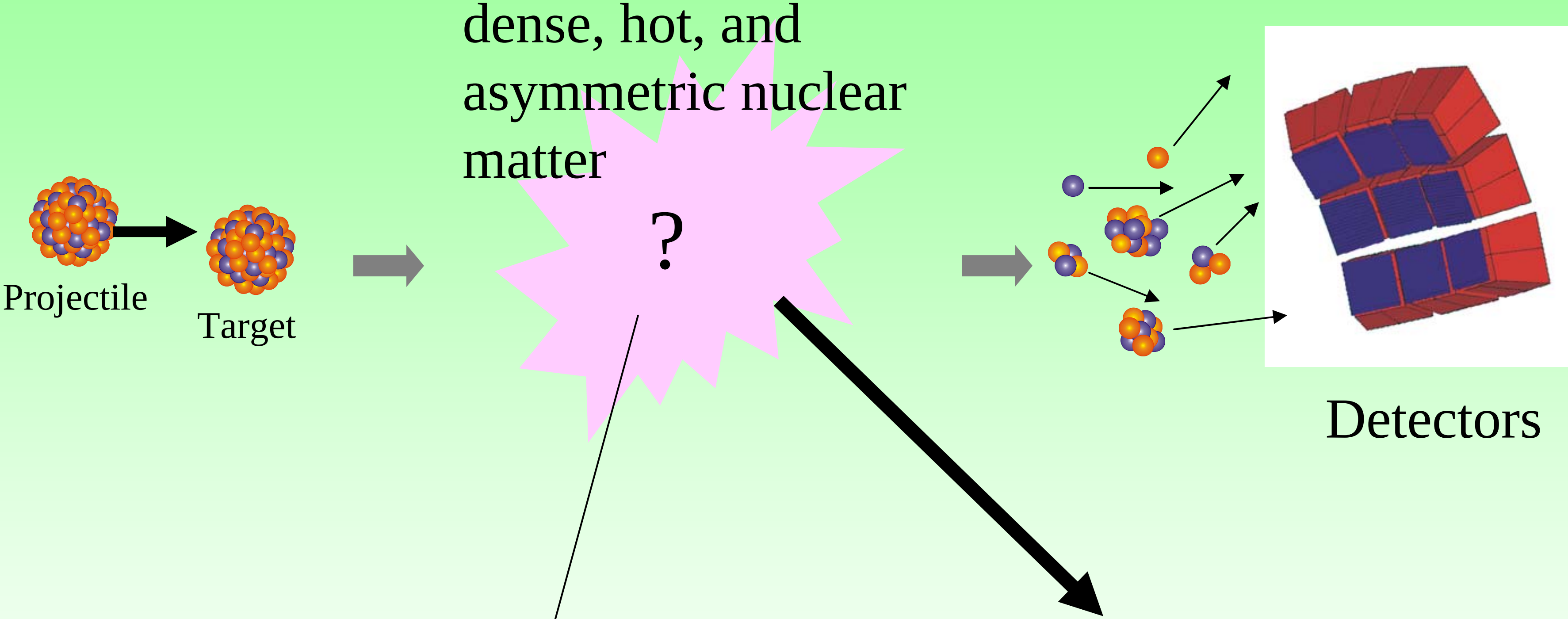
$$\frac{1}{T} = \frac{\partial S(E, N_{part})}{\partial E} = \frac{\partial \ln \rho(E, N_{part})}{\partial E}$$

2.The kinetic theory of gases :

In a classical ideal gas, the temperature is related to its average kinetic energy

$\langle E_k \rangle$=number of degree of freedom * $1/2k_BT$

Heavy ion collisions at intermediate and high energies



T=?

Equation of State
Of Nuclear Matter
$E(\rho, T, \delta) = ?$

The concept of temperature has been used in nuclear systems seventy years ago.

- From compound nuclei ($\rho \approx \rho_0$, T≈1-2 MeV,)

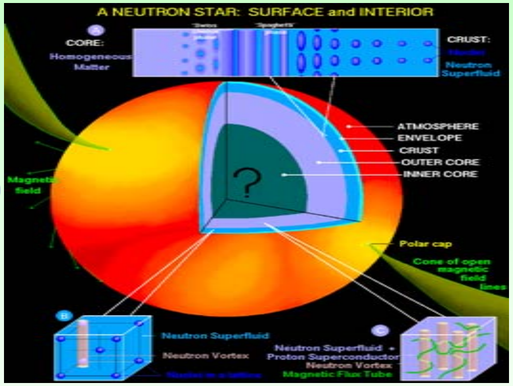
⇨ hot nuclei($\rho \approx \rho_0$,T>5 MeV),

⇨ highly excited nuclei ($\rho \approx 3\rho_0$,T>5 MeV)

⇨ asymmetrical highly excited nuclei

($\rho \approx 3\rho_0$,T>5 MeV, **δ>0**)

- Nuclear equation of state (EOS)

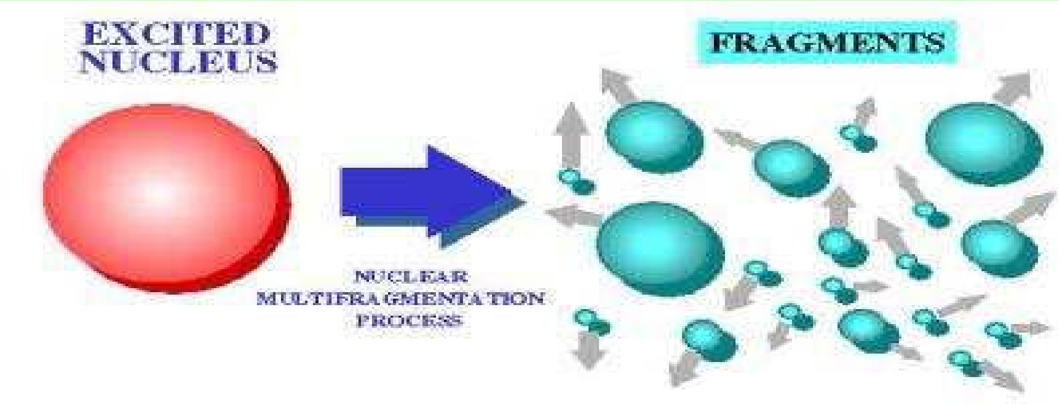


$$\rho \neq \rho_0, \quad T > 0, \ \underline{\delta > 0}$$

$$E(\rho, T, \underline{\delta}) = ?,$$

How to determine T in theory ?

Thermometer determination



- Kinetic approaches, Based on the canonical ensemble

  Slope thermometer — G. D. Westfall, Phys. Lett. B **116**, 118 (1982).

  Fluctuation temperature — S. Wuenschel et al., Nuclear Physics A **843**, 1 (2010).

- Population approaches, Based on the grand-canonical ensemble,

  Double ratios of isotopic yields — S. Albergo et al., Nuovo Cimento A **89**, 1 (1985).

  Population of excited states — D.J. Morrissey et al., Phys. Lett. B **148**, 423 (1984).

  Isobaric yields from a given soure — M. Veselsky et al., Phys. Lett. B **497**, 1 (2001).

• Kinetic energy approaches

Originally proposed in 1937 in case of n-induced reactions (Maxwell-Boltzmann distribution)

$$\frac{dY}{dE_{kin}} = f(E_{kin})\exp[-\frac{E_{kin}}{T}]$$

Slope thermometer

Westfall, PLB **116**, 118 (1982)

Jacak et al., PRL **51**, 1846 (1983)

Fluctuation thermometer

Wuenschel et al., NPA 843, 1 (2010)

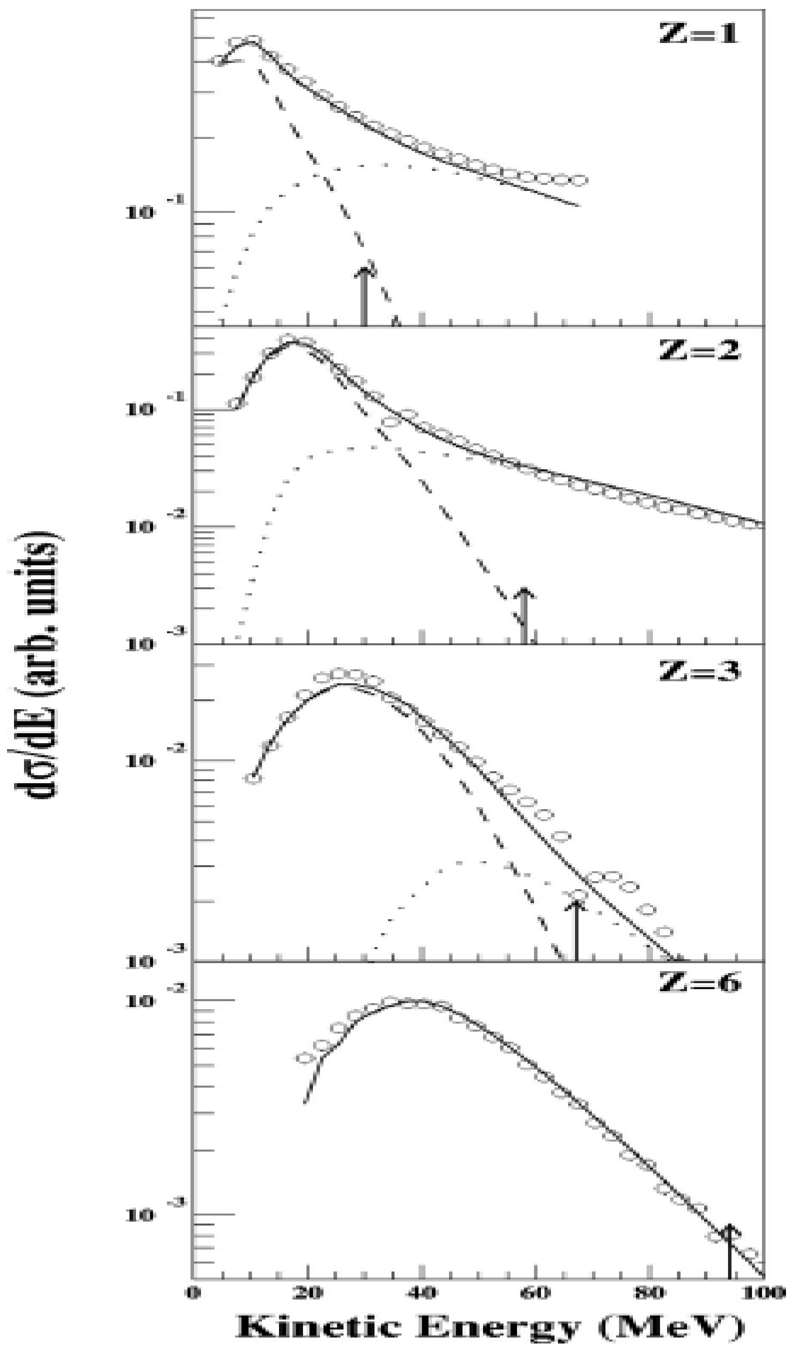
Slope thermometer

The slope temperature is extracted by fitting the slope of the particle spectra

The spectra shape can be Influenced by collective dynamical effects

Westfall et al, PLB **116**, 118 (1982)

Jacak et al., PRL **51**, 1846 (1983)



Fluctuation thermometer

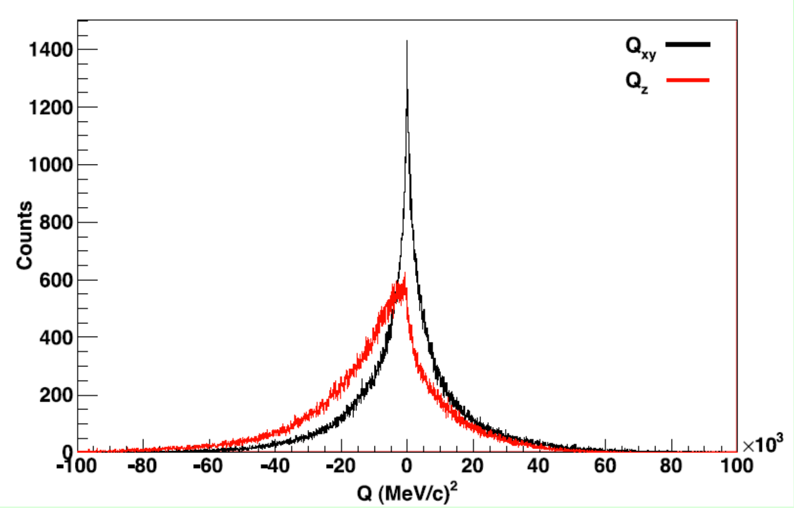
Using the momentum fluctuation, the nuclear temperature can also be derived.

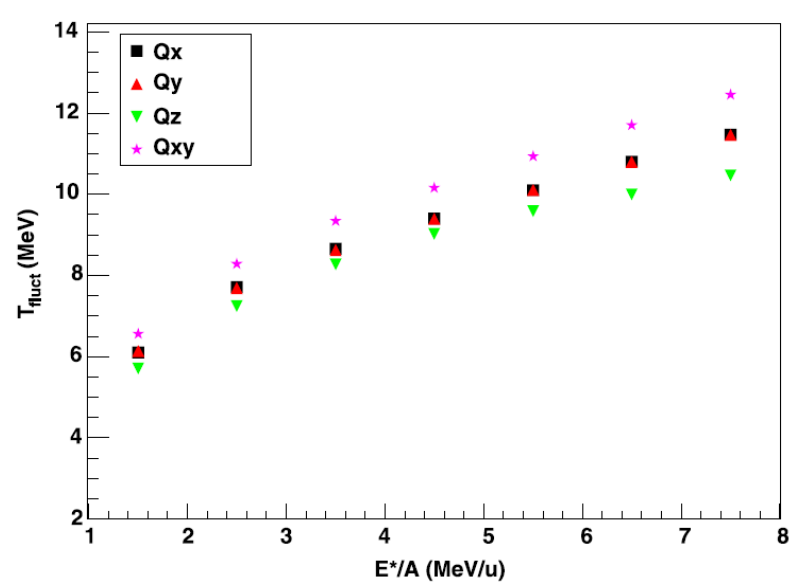
$$\sigma^2 = \langle Q_z^2 \rangle - \langle Q_z \rangle^2$$

$$\langle Q_z^2 \rangle = \int d^3p \left(2P_Z^2 - P_T^2\right)^2 f(p)$$

$$\sigma^2 = 12 m_0^2 T^2 \sum_i (\zeta_i A_i)^2$$

Wuenschel et al., NPA 843 (2010) 1





• Population of excited states

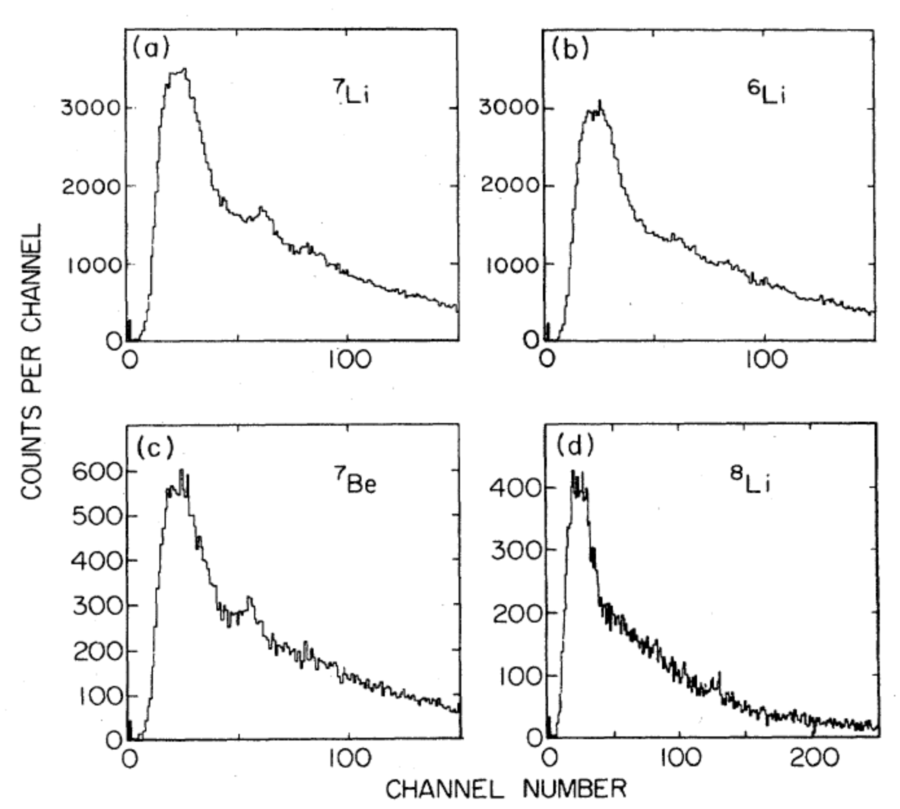
The ration of the populations of 2 states

$$R = \frac{2j_{\mu}+1}{2j_{l}+1}\exp[-\frac{\Delta E}{T}]$$

Correction: decay,

final-state interaction,…

Morrissey et al., PLB148, 423 (1984)



Double ratios of isotopic yields

density

$$\rho(A,Z) = \frac{N_{part}}{V} = \frac{A^{3/2}\cdot\omega(A,Z)}{\lambda^3}\cdot\exp\left(\frac{\mu(A,Z)}{T}\right)$$

Ratio between the 2 different emitted fragments

$$\frac{Y(A,Z)}{Y(A',Z')} = \frac{\rho(A,Z)}{\rho(A',Z')} = \left(\frac{A}{A'}\right)^{3/2}\cdot\left(\frac{\lambda^3}{2}\right)^{A-A'}$$
$$\cdot\frac{\omega(A,Z)}{\omega(A',Z')}\cdot\rho_{pF}^{Z-Z'}\rho_{nF}^{(A-Z)-(A'-Z')}$$
$$\cdot\exp\left(\frac{B(A,Z)-B(A',Z')}{T}\right)$$

Temperature

$$T = (\Delta B_1 - \Delta B_2)/\ln\left[\left(\frac{Y(A_1,Z_1)/Y(A_1+1,Z_1+1)}{Y(A_2,Z_2)/Y(A_2+1,Z_2+1)}\right)\right.$$
$$\cdot\left(\frac{(A_1+1)\cdot A_2}{A_1\cdot(A_2+1)}\right)^{3/2}$$
$$\left.\cdot\left(\frac{\omega(A_1+1,Z_1+1)\cdot\omega(A_2,Z_2)}{\omega(A_1,Z_1)\cdot\omega(A_2+1,Z_2+1)}\right)\right]$$

$$T_{\mathrm{HeLi}} = 13.3\ \mathrm{MeV}/\ln\left(2.2\frac{Y_{^6\mathrm{Li}}/Y_{^7\mathrm{Li}}}{Y_{^3\mathrm{He}}/Y_{^4\mathrm{He}}}\right)$$

$$T_{\mathrm{He}pd} = 18.4\ \mathrm{MeV}/\ln\left(5.5\frac{Y_p/Y_d}{Y_{^3\mathrm{He}}/Y_{^4\mathrm{He}}}\right)$$

$$T_{\mathrm{He}dt} = 14.3\ \mathrm{MeV}/\ln\left(1.6\frac{Y_d/Y_t}{Y_{^3\mathrm{He}}/Y_{^4\mathrm{He}}}\right)$$

$$T_{\mathrm{BeLi}} = 11.3\ \mathrm{MeV}/\ln\left(1.8\frac{Y_{^9\mathrm{Be}}/Y_{^8\mathrm{Li}}}{Y_{^7\mathrm{Be}}/Y_{^6\mathrm{Li}}}\right)$$

$$T_{t\mathrm{HeLiBe}} = 14.2\ \mathrm{MeV}/\ln\left(2.2\frac{Y_{^6\mathrm{Li}}/Y_{^7\mathrm{Be}}}{Y_t/Y_{^4\mathrm{He}}}\right)$$

$$T_{\mathrm{CLi}} = 11.5\ \mathrm{MeV}/\ln\left(5.9\frac{Y_{^6\mathrm{Li}}/Y_{^7\mathrm{Li}}}{Y_{^{11}\mathrm{C}}/Y_{^{12}\mathrm{C}}}\right)$$

$$T_{\mathrm{CC}} = 13.8\ \mathrm{MeV}/\ln\left(7.9\frac{Y_{^{12}\mathrm{C}}/Y_{^{13}\mathrm{C}}}{Y_{^{11}\mathrm{C}}/Y_{^{12}\mathrm{C}}}\right)$$

S. Albergo et al., Nuovo Cimento A 89, 1 (1985)

第 16 卷 第 7 期 高 能 物 理 与 核 物 理 Vol. 16, No. 7
1992 年 7 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS July, 1992

重离子碰撞中的激发能问题

张 丰 收 葛 凌 霄
(中国科学院近代物理研究所，兰州 730000)

摘 要

Excitation Energy in Heavy Ion Collisions

Zhang Fengshou Ge Lingxiao
(Institute of Modern Physics, Academia Sinica, Lanzhou, 730000)

Abstract

With Hartree–Fock approximation, the relation between excitation energy and temperature has been obtained and discussed for both infinite nuclear matter and finite nucleus Pb^{208}.

F.S.Zhang and L. X. Ge, HEPNP 16(1992)666

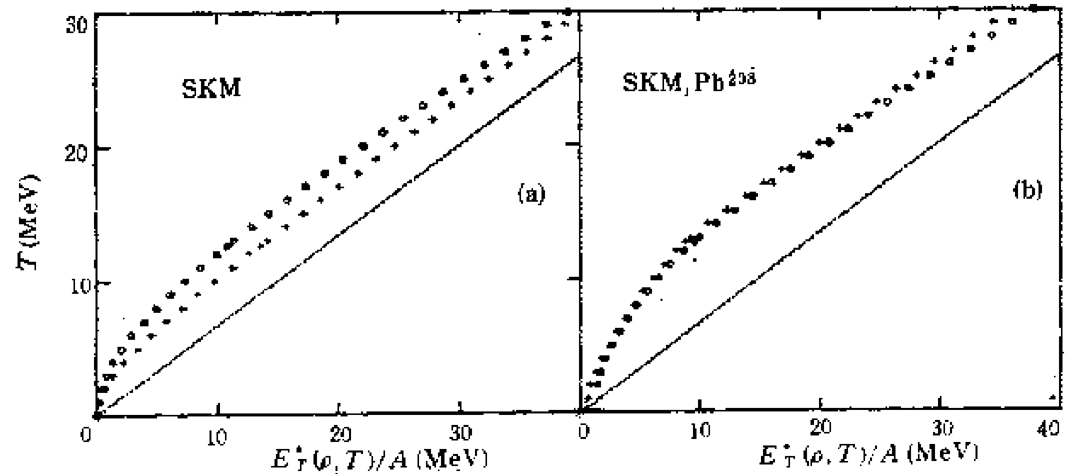


图1 不同密度下无穷大对称核物质和有限核 Pb^{208} 的单核子热激发能随温度的变化.
(a) $\rho(fm^{-3})$ 0.05++++ 0.16$^{\circ\circ\circ\circ}$ 自由核子— —
(b) $\rho(fm^{-3})$0.05$^{\circ\circ\circ\circ}$ 0.16 ++++ 自由核子——

第 25 卷 第 6 期　　高 能 物 理 与 核 物 理　　Vol.25, No.6
2001 年 6 月　　HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS　　June, 2001

A New Interpretation for ALADIN Caloric Curve*

LI Wen-Fei[1,2]　ZHANG Feng-Shou[1,2,3]　CHEN Lie-Wen[1,2]

1 (*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou* 730000, *China*)

2 (*Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou* 730000, *China*)

3 (CCAST (*World Laboratory*) *Beijing* 100080, *China*)

Abstract Within the framework of Hartree-Fock theory with extended Skyrme effective interaction, the excitation energy as a function of temperature and density was investigated and used to analyse the ALADIN calaric curve. Our work began on the assumption that the temperature plateau of ALADIN calaric curve was resulted from the compression excitation energy. The theoretical calculations with this assumption were in good agreement with the ALADIN caloric curve, which indicates that our assumption is reasonable, i.e., the temperature plateau of ALADIN calaric curve is resulted from the compression excitation energy, and liquid-gas phase transition isn't the only interpretation for the ALADIN caloric curve. Therefore, we provided a new interpretation for the ALADIN caloric curve.

Pochodzalla et al., ALADIN, PRL75(1995)1040

W.F.Li, F.S.Zhang, L.W.Chen HEPNP25(2001)538

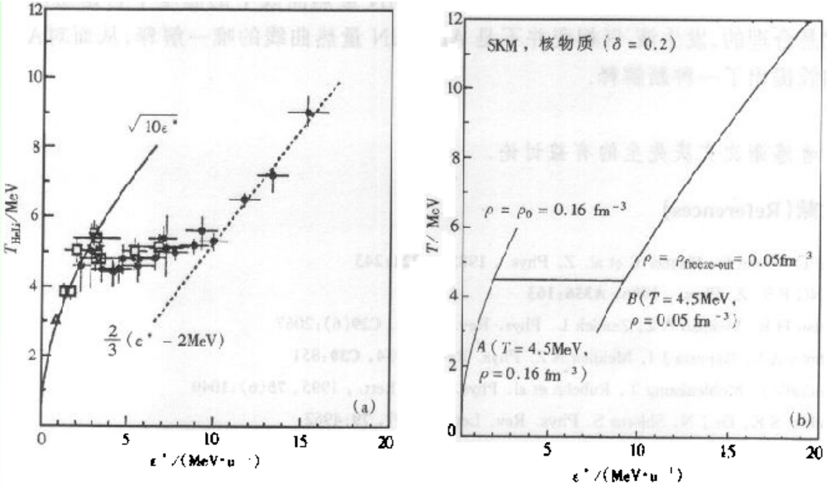


图 1　理论计算结果与实验结果的比较

(a) ALADIN 实验结果;(b) 本工作的理论计算结果.

● ^{197}Au + ^{197}Au, 600MeV/u; □ ^{12}C, ^{18}O + ^{nat}Ag, ^{197}Au, 30—84 MeV/u;

▲ ^{22}Ne + ^{181}Ta, 8 MeV/u.

Z. Phys. A 356, 163–170 (1996)

ZEITSCHRIFT
FÜR PHYSIK A

Phase transitions, correlations and fluctuations of nuclear multifragmentation

Feng-Shou Zhang[1,2]

[1] Institute of Modern Physics, Academia Sinica, P.O.Box 31, Lanzhou 730000, People's Republic of China
[2] GIP, CERFACS, 42 Avenue G. Coriolis, F–31057 Toulouse Cedex, France

Received: 5 May 1996 / Revised version: 10 May 1996
Communicated by X. Campi

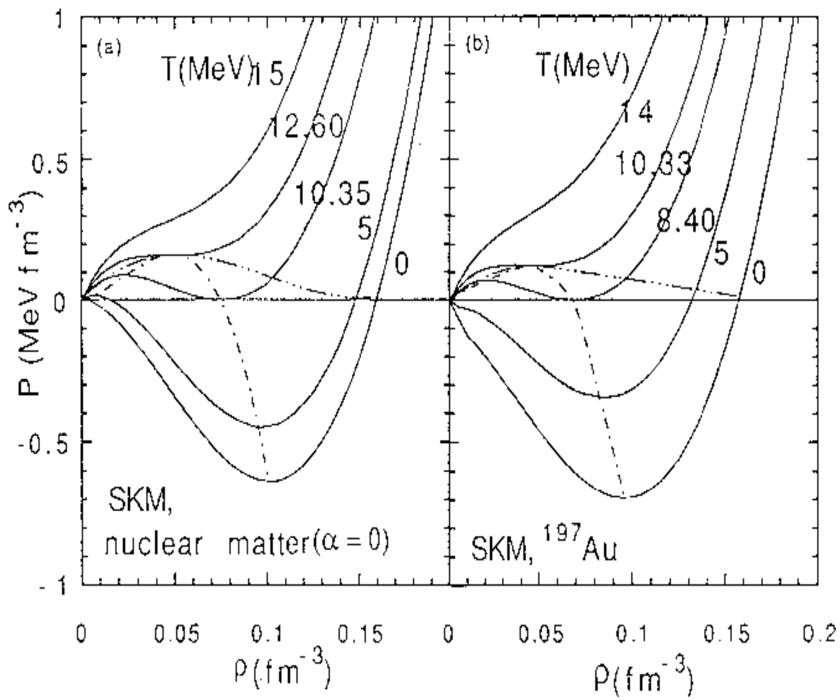


Fig. 1a,b. Pressure-density isotherms for nuclear matter (**a**) and ^{197}Au (**b**). In both figures, the coexistence line (*long dotted-dashed*) is defined as the boundary of two phase regions in thermodynamic equilibrium and the spinodal lines (*dotted-dashed*) are defined as the isothermal incompressibility vanish

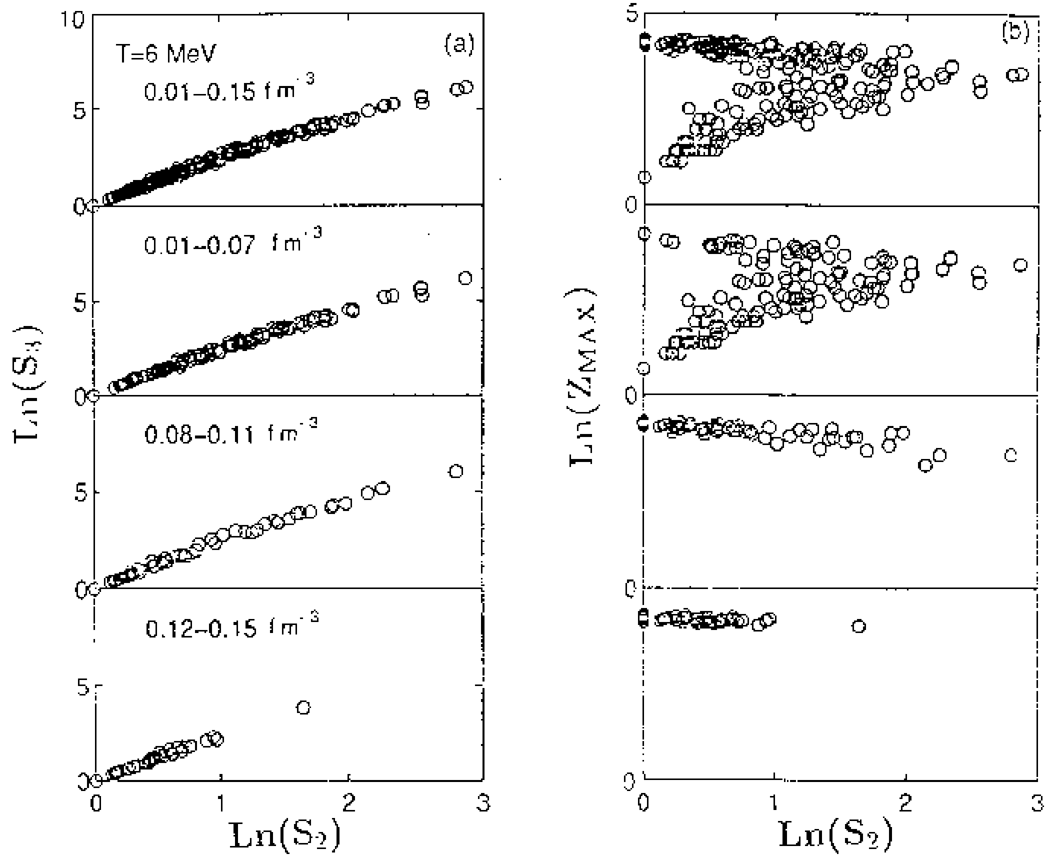


Fig. 5 a, b. The scatter plots of the correlation between Ln S_3 and Ln S_2 **a**, and the correlation between Ln (Z_{MAX}) and Ln S_2 **b**, for the spinodal, the super heated liquid, the hot liquid regions and their mixing for ^{197}Au at T=6 MeV

Review Paper
Kelic, Natowitz, Schmidt, EPJA30(2006)203

Eur. Phys. J. A **30**, 203–213 (2006)
DOI 10.1140/epja/i2006-10117-6

THE EUROPEAN PHYSICAL JOURNAL A

Nuclear thermometry

A. Kelić[1,a], J.B. Natowitz[2], and K.-H. Schmidt[1]

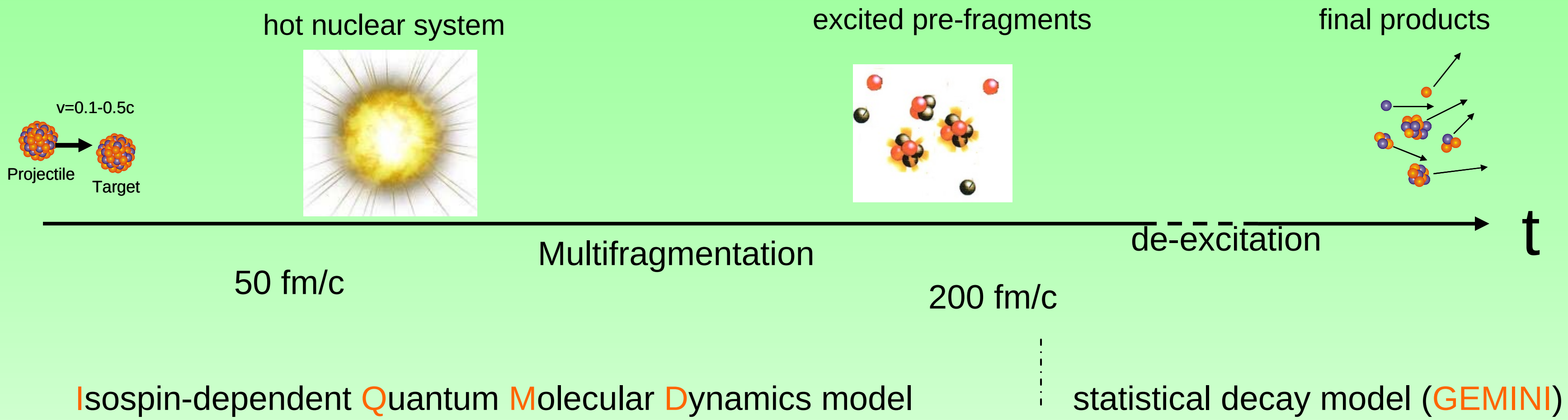
[1] GSI, Planckstr. 1, 64291 Darmstadt, Germany
[2] Department of Chemistry, Texas A&M University, College Station, TX 77842, USA

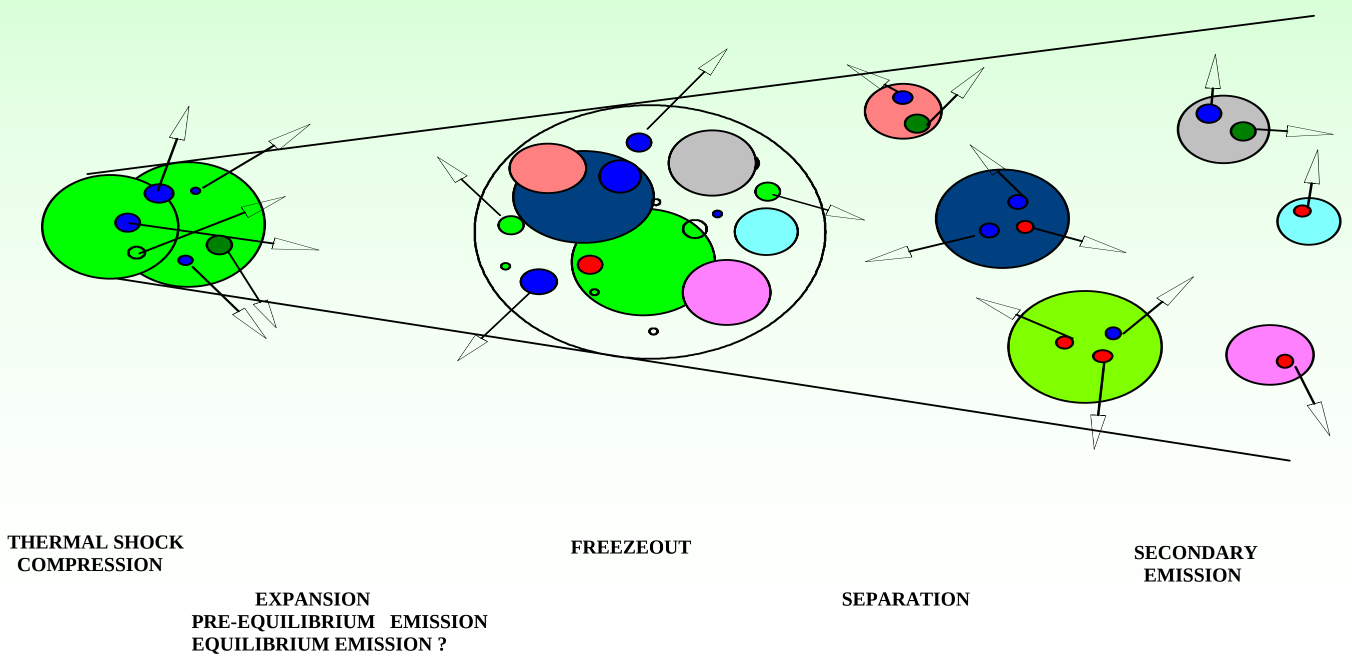
Received: 30 May 2006 /
Published online: 20 October 2006 –

Abstract. Different approaches for measuring nuclear temperatures are described. The quantitative results of different thermometer approaches are often not consistent. These differences are traced back to the different basic assumptions of the applied methods. Moreover, an overview of recent theoretical investigations is given, which study the quantitative influence of dynamical aspects of the nuclear-reaction process on the extracted apparent temperatures. The status of the present experimental and theoretical knowledge is reviewed. Guidelines for future investigations, especially concerning the properties of asymmetric nuclear matter, are given.

PACS. 24.60.-k Nuclear reaction: general: Statistical theory and fluctuations – 05.70.Fh Phase transitions: general studies – 25.70.-z Low and intermediate energy heavy-ion reactions – 21.10.Ma Level density

2. Theoretical Model





Isospin dependent quantum molecular dynamics model + Gemini

- mean field (corresponds to interactions)

$$U(\rho,\tau_z) = U^{loc} + U^{Yuk} + U^{Coul} + U^{Sym} + U^{MDI}$$

U^{loc}: density dependent potential

U^{Yuk}: Yukawa (surface) potential

U^{Coul}: Coulomb energy

U^{Sym}: symmetry energy

U^{MD}: momentum dependent interaction

- two-body collisions + pauli blocking
- initialization
- coalescence model
- Gemini

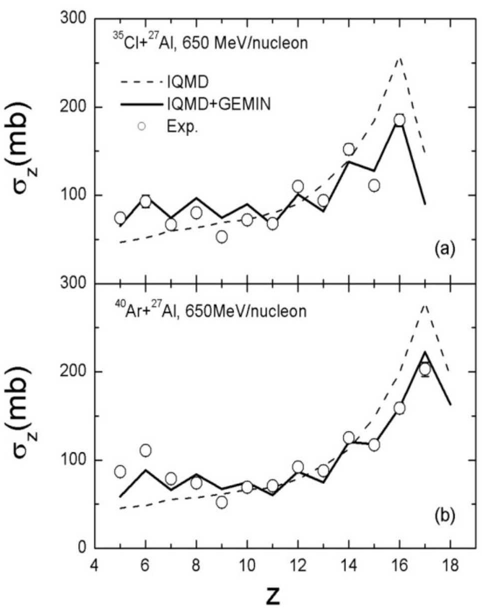
To check the model

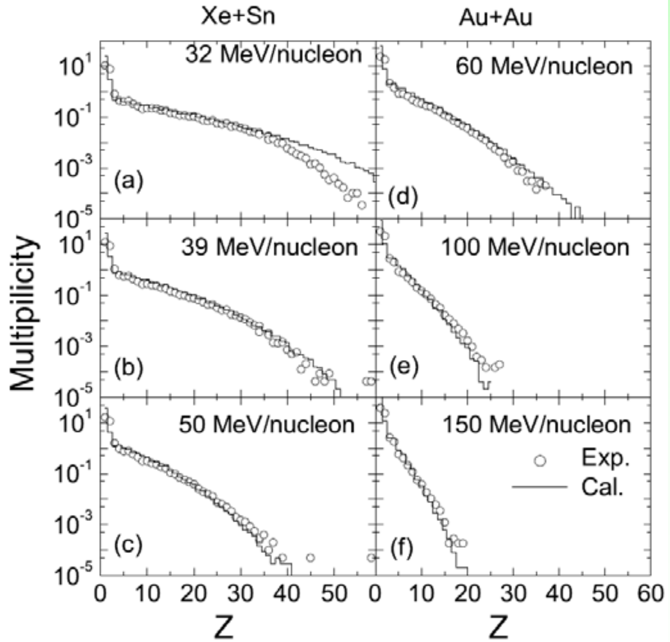
PHYSICAL REVIEW C 83, 014608 (2011)

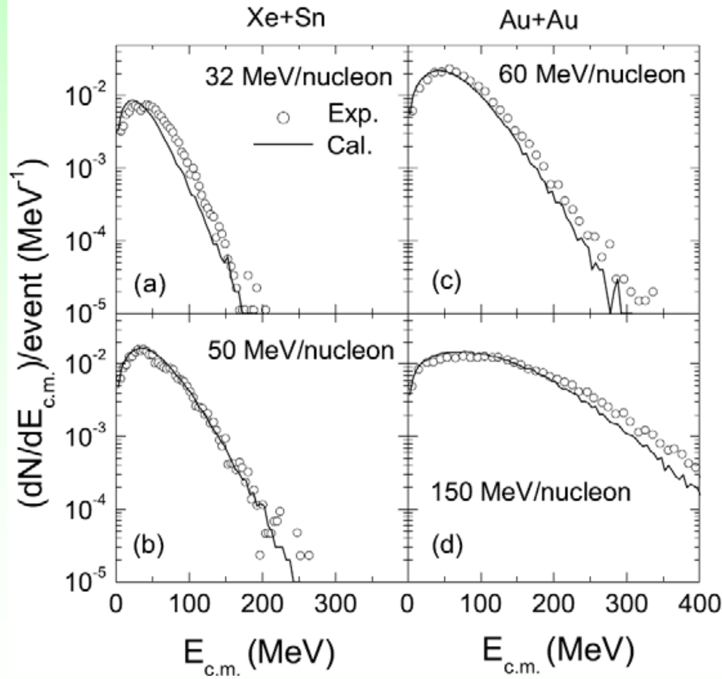
Odd-even effect in heavy-ion collisions at intermediate energies

Jun Su,[1,2] Feng-Shou Zhang,[1,2,3,*] and Bao-An Bian[4]
[1] *College of Nuclear Science and Technology, Beijing Normal University, 100875 Beijing, China*
[2] *Beijing Radiation Center, Beijing 100875, China*
[3] *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China*
[4] *School of Science, Jiangnan University, Wuxi, Jiangsu 214122, China*

(Received 7 December 2010; published 31 January 2011)



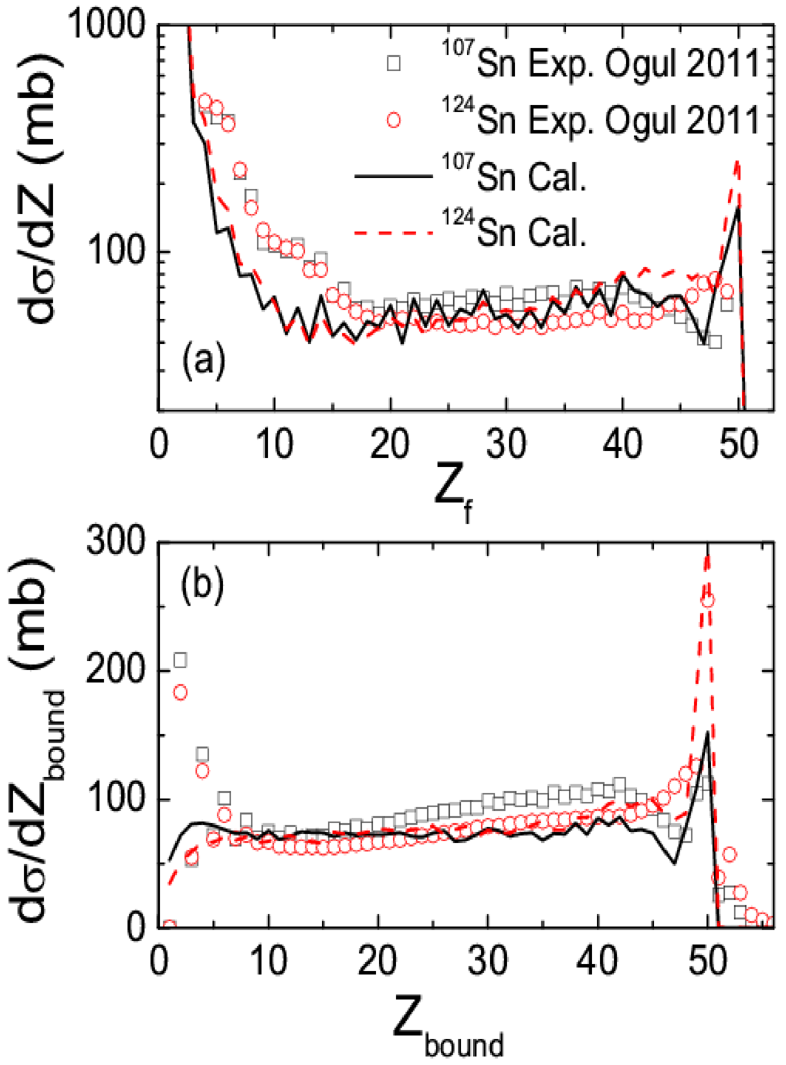




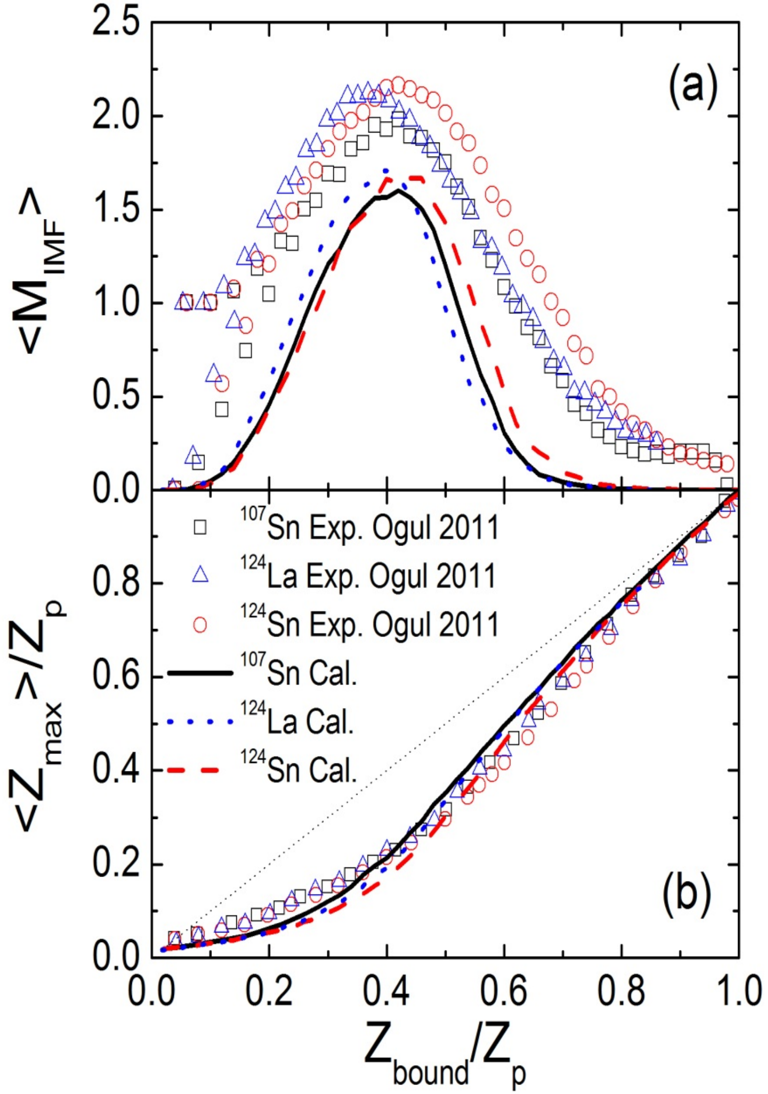
Charge distributions, multiplicities, and the energy spectra

3.Results and Discussion

Charge and Z_{bound} distributions



$\langle M_{IMF} \rangle$ and $Z_{max}/Z_p \sim Z_{bound}/Z_p$



J. Su and F. S. Zhang, PRC 84 037601 (2011)

PRL 102, 152701 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

Isotopic Dependence of the Nuclear Caloric Curve

C. Sfienti,[1] P. Adrich,[1] T. Aumann,[1] C. O. Bacri,[2] T. Barczyk,[3] R. Bassini,[4] S. Bianchin,[1] C. Boiano,[4] A. S. Botvina,[1,5] A. Boudard,[6] J. Brzychczyk,[3] A. Chbihi,[7] J. Cibor,[8] B. Czech,[8] M. De Napoli,[9] J.-É. Ducret,[6] H. Emling,[1] J. D. Frankland,[7] M. Hellström,[1] D. Henzlova,[1] G. Immè,[9] I. Iori,[4,*] H. Johansson,[1] K. Kezzar,[1] A. Lafriakh,[6] A. Le Fèvre,[1] E. Le Gentil,[6] Y. Leifels,[1] J. Lühning,[1] J. Łukasik,[1,8] W. G. Lynch,[10] U. Lynen,[1] Z. Majka,[3] M. Mocko,[10] W. F. J. Müller,[1] A. Mykulyak,[11] H. Orth,[1] A. N. Otte,[1] R. Palit,[1] P. Pawłowski,[8] A. Pullia,[4] G. Raciti,[9] E. Rapisarda,[9] H. Sann,[1,*] C. Schwarz,[1] H. Simon,[1] K. Sümmerer,[1] W. Trautmann,[1] M. B. Tsang,[10] G. Verde,[10] C. Volant,[6] M. Wallace,[10] H. Weick,[1] J. Wiechula,[1] A. Wieloch,[3] and B. Zwiegliński[11]

(ALADIN2000 Collaboration)

[1]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[2]*Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-91406 Orsay, France*
[3]*M. Smoluchowski Institute of Physics, Jagiellonian University, Pl-30059 Kraków, Poland*
[4]*Istituto di Scienze Fisiche, Università degli Studi and INFN, I-20133 Milano, Italy*
[5]*Institute for Nuclear Research, 117312 Moscow, Russia*
[6]*DAPNIA/SPhN, CEA/Saclay, F-91191 Gif-sur-Yvette, France*
[7]*GANIL, CEA et IN2P3-CNRS, F-14076 Caen, France*
[8]*IFJ-PAN, Pl-31342 Kraków, Poland*
[9]*Dipartimento di Fisica e Astronomia dell'Università and INFN-LNS, I-95123 Catania, Italy*
[10]*Department of Physics and Astronomy and NSCL, MSU, East Lansing, Michigan 48824, USA*
[11]*A. Sołtan Institute for Nuclear Studies, Pl-00681 Warsaw, Poland*

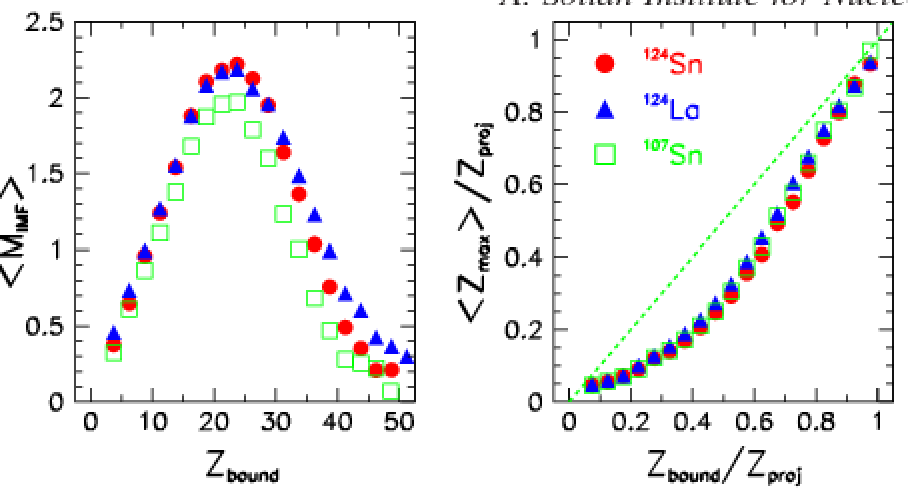


FIG. 1 (color online). Acceptance corrected mean multiplicity $\langle M_{IMF}\rangle$ of projectile fragments for ^{124}Sn (circles), ^{124}La (triangles), and ^{107}Sn (open squares) beams of 600 A MeV on ^{nat}Sn targets as a function of Z_{bound} (left panel) and correlations of $\langle Z_{max}\rangle$ with Z_{bound} (both normalized with respect to the atomic number Z_{proj} of the projectile, right panel).

PHYSICAL REVIEW C **83**, 024608 (2011)

Isospin-dependent multifragmentation of relativistic projectiles

R. Ogul,[1,2] A. S. Botvina,[1,3] U. Atav,[2] N. Buyukcizmeci,[2] I. N. Mishustin,[4,5] P. Adrich,[1] T. Aumann,[1] C. O. Bacri,[6] T. Barczyk,[7] R. Bassini,[8] S. Bianchin,[1] C. Boiano,[8] A. Boudard,[9] J. Brzychczyk,[7] A. Chbihi,[10] J. Cibor,[11] B. Czech,[11] M. De Napoli,[12] J.-É. Ducret,[9] H. Emling,[1] J. D. Frankland,[10] M. Hellström,[1] D. Henzlova,[1] G. Immè,[12] I. Iori,[8,*] H. Johansson,[1] K. Kezzar,[1] A. Lafriakh,[9] A. Le Fèvre,[1] E. Le Gentil,[9] Y. Leifels,[1] J. Lühning,[1] J. Łukasik,[1,11] W. G. Lynch,[13] U. Lynen,[1] Z. Majka,[7] M. Mocko,[13] W. F. J. Müller,[1] A. Mykulyak,[14] H. Orth,[1] A. N. Otte,[1] R. Palit,[1] P. Pawłowski,[11] A. Pullia,[8] G. Raciti,[12,*] E. Rapisarda,[12] H. Sann,[1,*] C. Schwarz,[1] C. Sfienti,[1] H. Simon,[1] K. Sümmerer,[1] W. Trautmann,[1] M. B. Tsang,[13] G. Verde,[13] C. Volant,[9] M. Wallace,[13] H. Weick,[1] J. Wiechula,[1] A. Wieloch,[7] and B. Zwiegliński[14]

[1]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*

[2]*Department of Physics, University of Selçuk, TR-42079 Konya, Turkey*

[3]*Institute for Nuclear Research, Russian Academy of Sciences, RU-117312 Moscow, Russia*

[4]*Frankfurt Institute for Advanced Studies, J.W. Goethe University, D-60438 Frankfurt am Main, Germany*

[5]*Kurchatov Institute, Russian Research Center, RU-123182 Moscow, Russia*

[6]*Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-91406 Orsay, France*

[7]*M. Smoluchowski Institute of Physics, Jagiellonian University, PL-30059 Kraków, Poland*

[8]*Istituto di Scienze Fisiche, Università degli Studi and INFN, I-20133 Milano, Italy*

[9]*DAPNIA/SPhN, CEA/Saclay, F-91191 Gif-sur-Yvette, France*

[10]*GANIL, CEA et IN2P3-CNRS, F-14076 Caen, France*

[11]*H. Niewodniczański Institute of Nuclear Physics, PL-31342 Kraków, Poland*

[12]*Dipartimento di Fisica e Astronomia-Università and INFN-Sezione CT and LNS, I-95123 Catania, Italy*

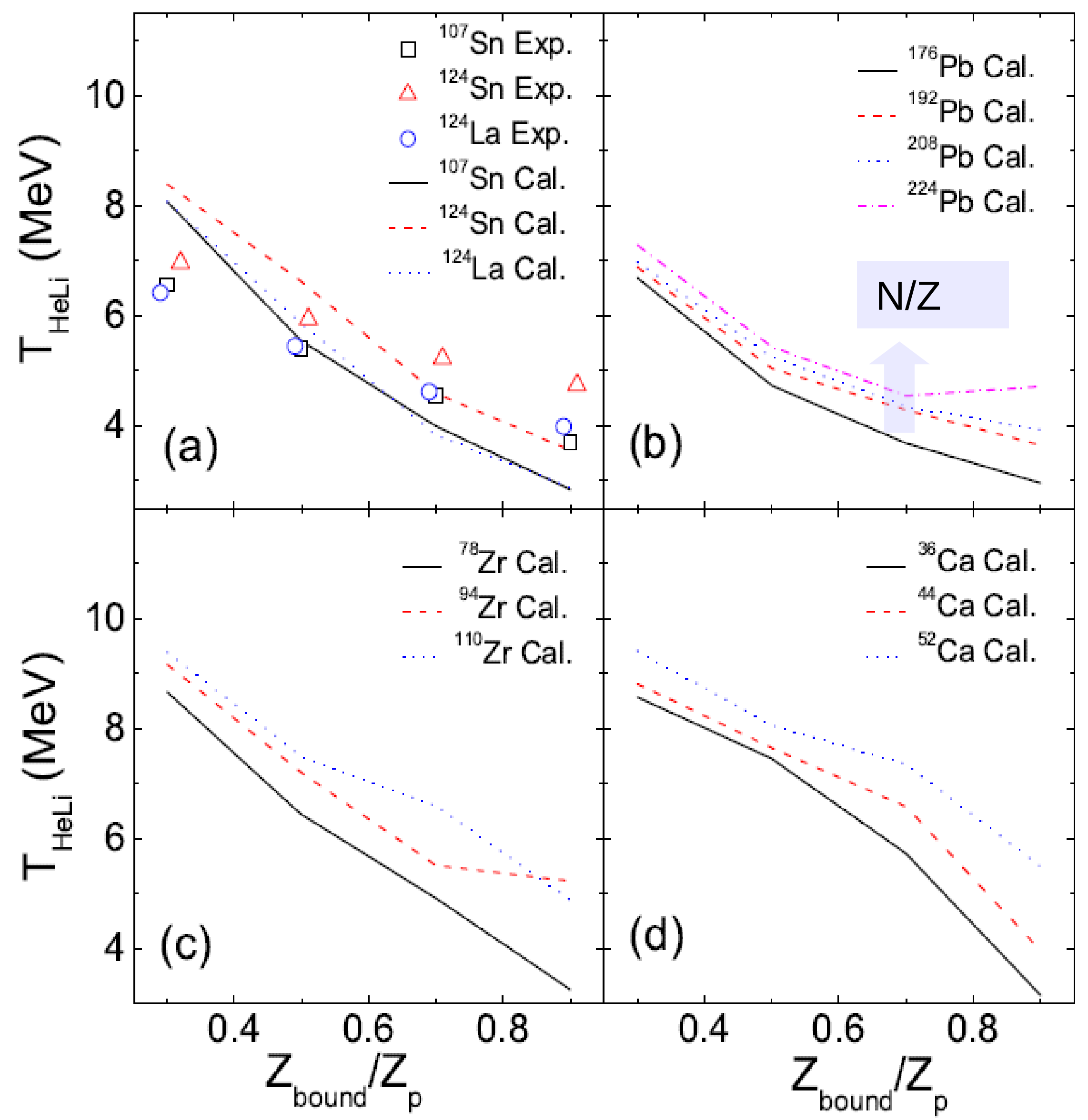
[13]*Department of Physics and Astronomy and NSCL, Michigan State University, East Lansing, Michigan 48824, USA*

[14]*A. Sołtan Institute for Nuclear Studies, PL-00681 Warsaw, Poland*

(Received 4 June 2010; published 24 February 2011)

J. Su and F. S. Zhang, PRC 84, 037601 (2011)

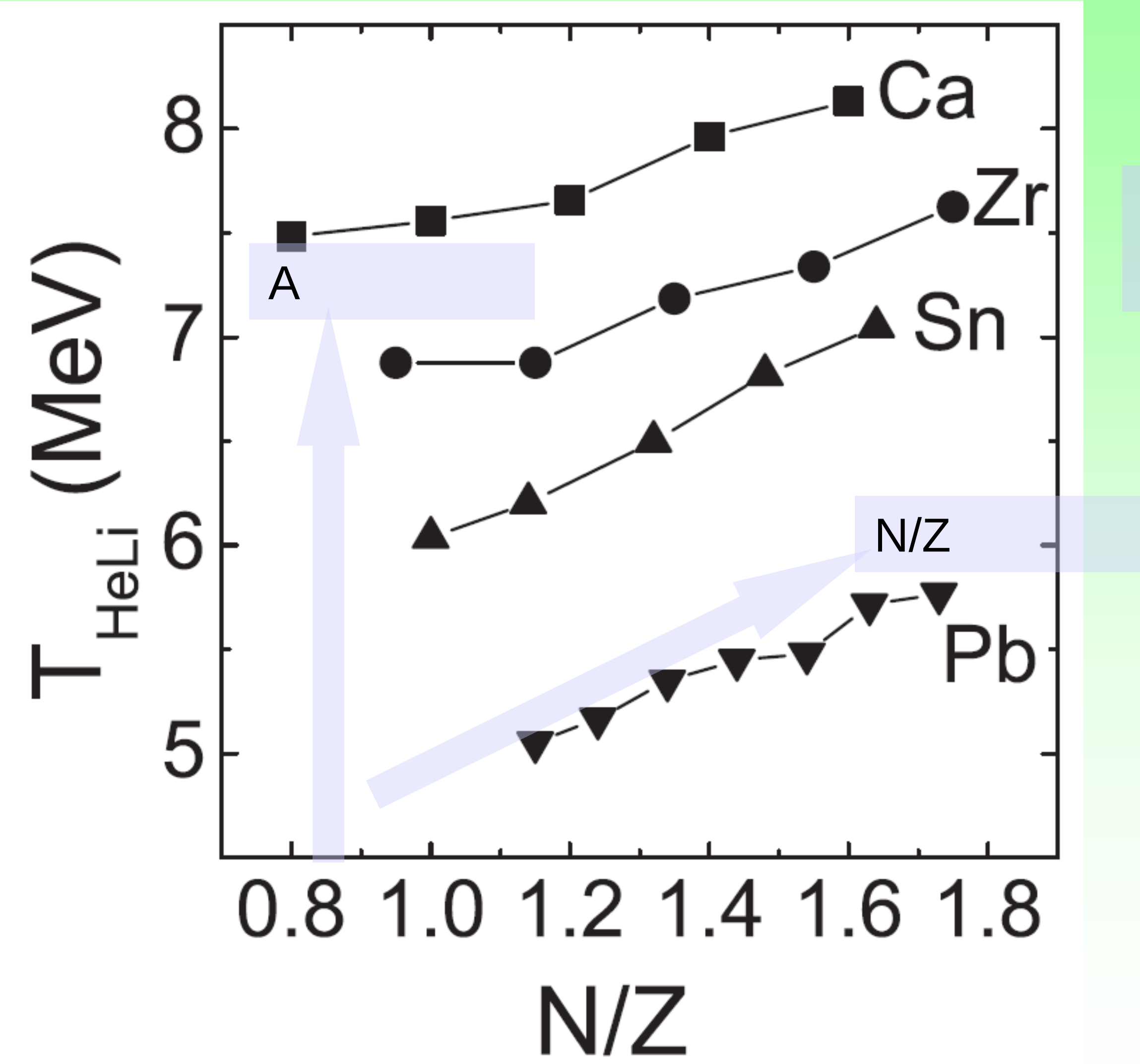
Istopic dependence of nuclear Temperature



The isotope temperatures show a smooth fall with increasing Zbound /Zp for the reactions

The T_{HeLi} for the neutron-rich projectiles are larger than those for the neutron-poor projectiles

N/Z and mass dependence of T_{HeLi}



With A decreasing，
T increasing;

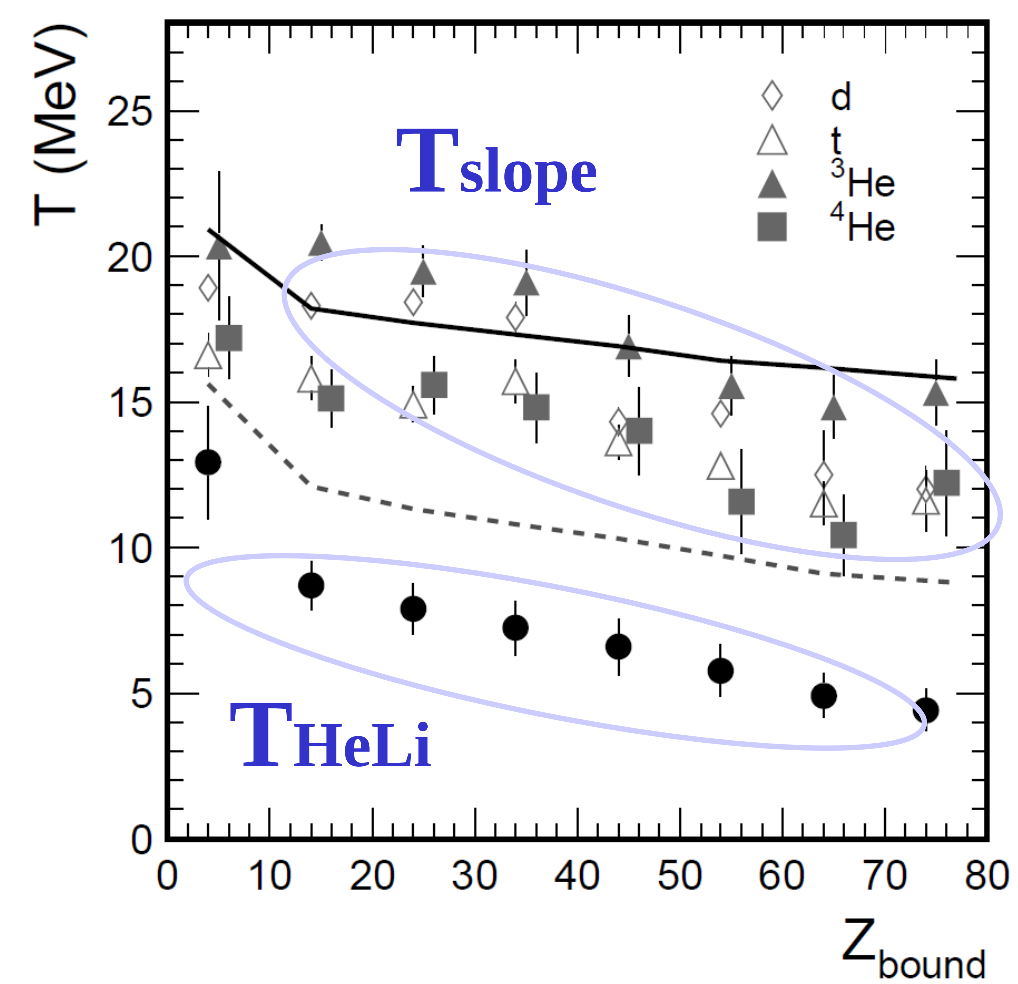
With N/Z increasing,
T increasing

J. Su and F. S. Zhang, PRC 84, 037601 (2011)

T_{slop} and T_{HeLi}

$$\frac{dY}{dE_{kin}} = f(E_{kin})\exp[-\frac{E_{kin}}{T_{slope}}]$$

$T_{slope} > T_{HeLi}$



Odeh et al. PRL, 84.4557 (2000)

How to distinguish the Fermi motion ?

Kinetci energy including： thermal, Fermi motion, Collective flow+ Coulomb

$E_{tot} = E_{thermal} + E_{Fermi} + E_{flow} + E_{Coulomb}$

Maxwell $f(p) \propto \exp(-\frac{p^2}{2mT})$

Fermi-Dirac $f(p) \propto \frac{1}{1+\exp((\frac{p^2}{2m}-\mu)/T)}$

Fermi 分布

T_{slop} and T'_{slop}

$$\langle E_k \rangle = \int \frac{p^2}{2m} f(p) \frac{dp}{d\varepsilon} d\varepsilon$$

$$T_{slope} = \frac{A-A_f}{A-1} \frac{2}{5} E_F (1+\frac{5\pi^2 T^2}{12E_F^2})$$

Su, Zhu, Xie, Zhang, PRC 85, 017604 (2012)

PHYSICAL REVIEW C VOLUME 51, NUMBER 2 FEBRUARY 1995

Temperatures of fragment kinetic energy spectra

Wolfgang Bauer
*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195
and National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,
Michigan State University, East Lansing, Michigan 48824*

(Received 6 October 1994)

Multifragmentation reactions without large compression in the initial state (proton-induced reactions, reverse kinematics, projectile fragmentation) are examined, and it is verified quantitatively that the high temperatures obtained from fragment kinetic energy spectra and lower temperatures obtained from observables such as level population or isotope ratios can be understood in a common framework.

PACS number(s): 25.70.Pq

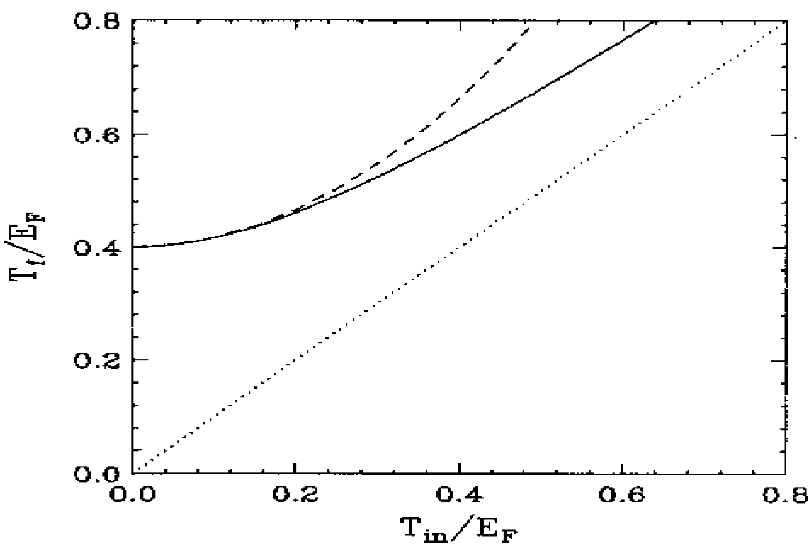


FIG. 2. Apparent temperature of fragment kinetic energy spectra (in units of the Fermi energy) as a function of the temperature, T_{in} of the Fermi gas. Solid line: numerical solution of Eq. (8) inserted into Eq. (7). Dashed line: analytic approximation, Eq. (11).

W. Bauer, PRC52(1995)803

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

NUCLEAR PHYSICS A

Nuclear Physics A 843 (2010) 1–13

www.elsevier.com/locate/nuclphysa

Measuring the temperature of hot nuclear fragments

S. Wuenschel [a,b], A. Bonasera [b,c,*], L.W. May [a,b], G.A. Souliotis [b,d], R. Tripathi [b], S. Galanopoulos [b,1], Z. Kohley [a,b], K. Hagel [b], D.V. Shetty [b,2], K. Huseman [b], S.N. Soisson [a,b], B.C. Stein [a,b], S.J. Yennello [a,b]

[a] *Chemistry Department, Texas A&M University, College Station, TX 77843, USA*

[b] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*

[c] *Laboratori Nazionali del Sud–INFN, v. S. Sofia 64, 95123 Catania, Italy*

[d] *Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, Greece*

Received 18 February 2010; received in revised form 22 April 2010; accepted 23 April 2010

Available online 21 May 2010

Physics Letters B 696 (2011) 178–181

ELSEVIER

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

PHYSICS LETTERS B

Density and temperature of fermions from quantum fluctuations

Hua Zheng [a,b], Aldo Bonasera [a,c,*]

[a] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*

[b] *Physics Department, Texas A&M University, College Station, TX 77843, USA*

[c] *Laboratori Nazionali del Sud, INFN, via Santa Sofia, 62, 95123 Catania, Italy*

PHYSICAL REVIEW C **85**, 017604 (2012)

Nuclear temperatures from kinetic characteristics

Jun Su,[1,2] Long Zhu,[1,2] Wen-Jie Xie,[1,2,4] and Feng-Shou Zhang[1,2,3,*]

[1]*The Key Laboratory of Beam Technology and Material Modification of Ministry of Education, College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China*

[2]*Beijing Radiation Center, Beijing 100875, China*

[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China*

[4]*Department of Physics, Yuncheng University, Yuncheng 044000, China*

(Received 10 January 2012; published 30 January 2012)

The kinematic characteristics of fragments are investigated using the isospin-dependent quantum molecular dynamics model accompanied by the statistical decay model GEMINI. The temperatures of single multifragmenting sources formed in those central heavy-ion collisions are extracted by two methods based on classical kinetic approaches. Differences between the slope temperature and the quadrupole temperature are discussed. Taking into account the Fermi-Dirac nature of finite nuclear systems, we derive the quantum temperatures. The quantum slope temperatures are lower than the isotope temperatures T_{HeLi}. The quantum quadrupole temperatures are higher than the isotope temperature.

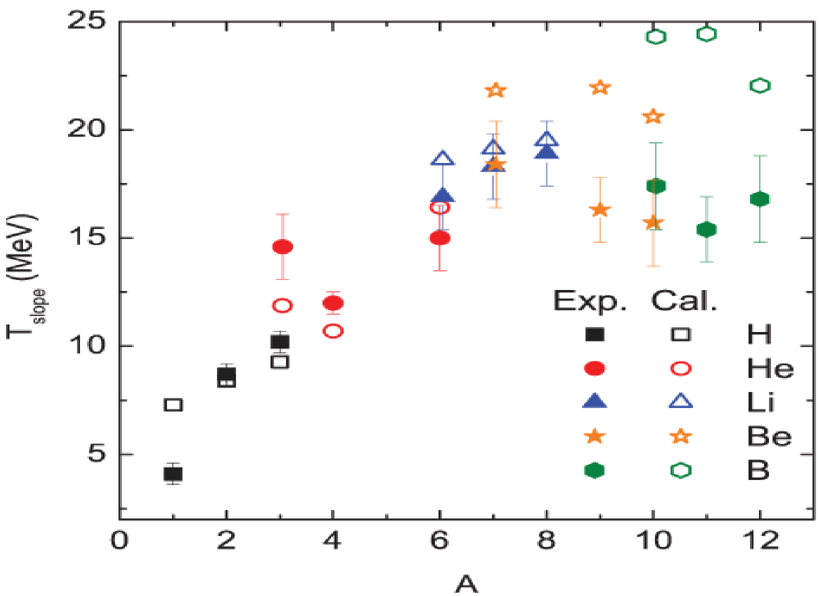


FIG. 3. (Color online) Comparisons of slope temperatures extracted from kinetic energy spectra of different fragments between the present simulations (cal.) and experimental data (exp.) [9] for Au + Au central collisions at 35 MeV/nucleon.

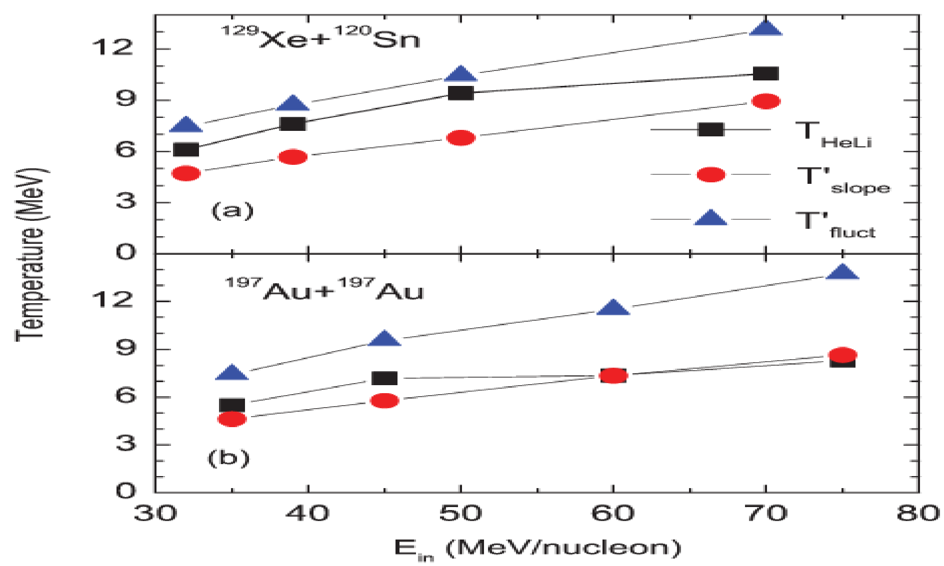
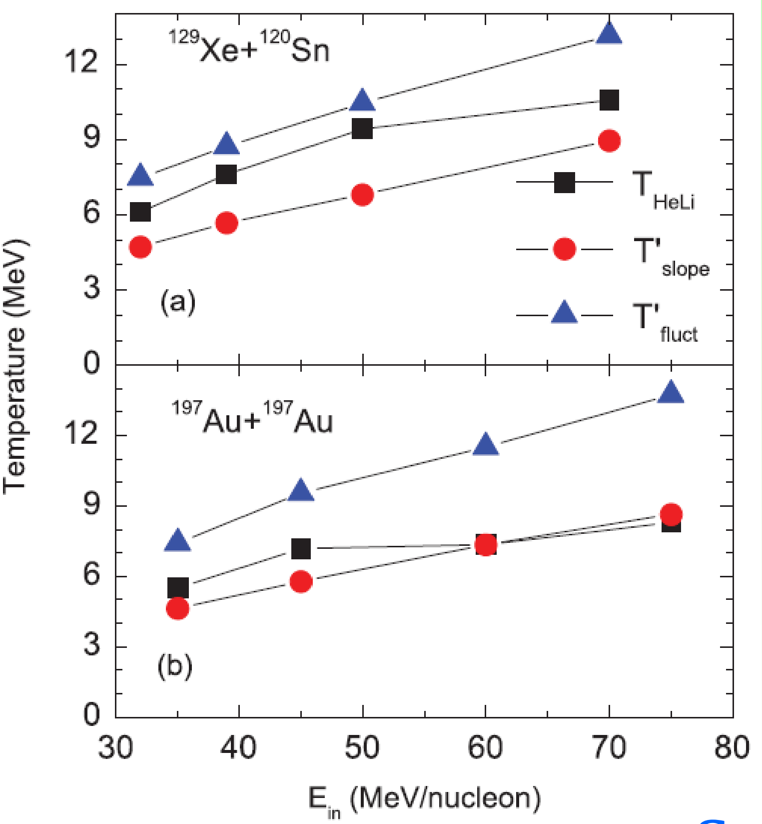


FIG. 4. (Color online) Temperatures derived by different methods as a function of incident energies for central collisions of ^{129}Xe + ^{120}Sn and ^{197}Au + ^{197}Au at an incident energy of from 30 to 80 MeV/nucleon. Squares, isotopic thermometer temperatures; circles, quantum slope temperatures; triangles, quantum quadrupole temperatures.

To compare the 3 nuclear thermometers

Assumption: the traditional definition of temperature is suitable.
Systems: central heavy-ion collisions (Xe+Sn, Au+Au)
Energy: 30 - 80 MeV/u
Observable: difference between T_{HeLi} and T_{slope} (T_{flu})



Maxwell distribution: $T>T_{HeLi}$
Fermi distribution: $T \sim T_{HeLi}$

Su, Zhu, Xie, Zhang, PRC 85, 017604 (2012)

$T_{Maxwell} > T_{Fermi} \sim T_{HeLi}$

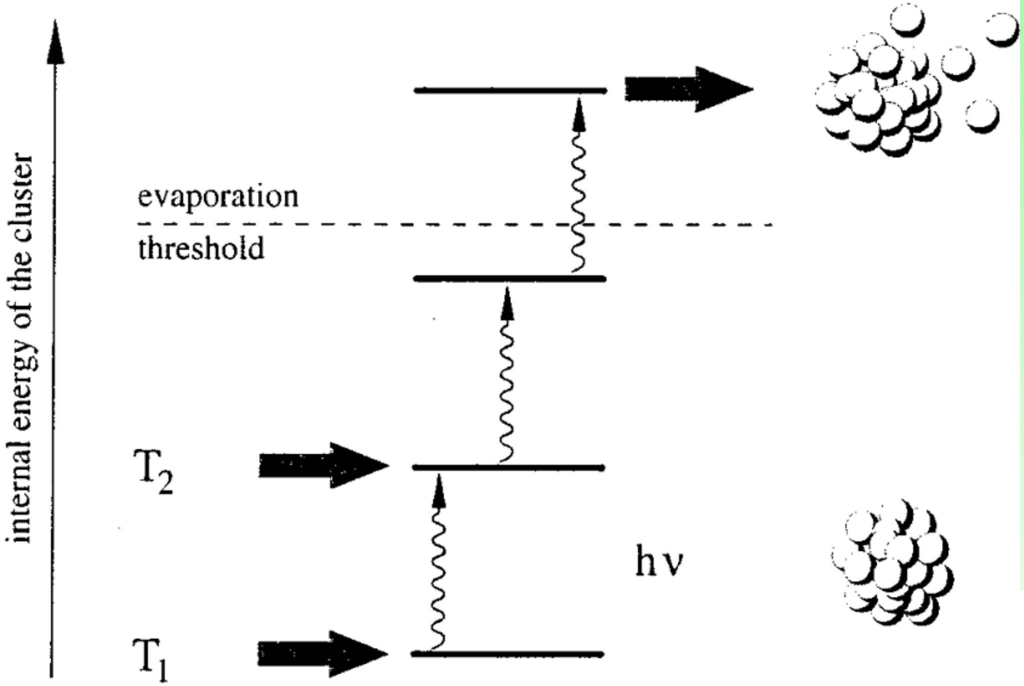
T_Maxwell > T_Fermi ~ T_HeLi

	(MeV/u)	T_{slope} (MeV)	T_{fluct} (MeV)	T'_{slope} (MeV)	T'_{fluct} (MeV)	T_{HeLi} (MeV)
$^{129}Xe+^{120}Sn$	32	8.2	8.6	4.7	7.8	6.1
	39	9.5	10.0	5.7	8.7	7.6
	50	11.4	12.0	6.8	10.4	9.4
	70	15.3	15.1	8.9	13.1	10.6
$^{197}Au+^{197}Au$	35	8.4	10.3	4.6	7.4	5.5
	45	10.0	11.0	5.8	9.6	7.2
	60	12.9	13.2	7.3	11.5	7.3
	75	15.3	15.8	8.6	13.7	8.3

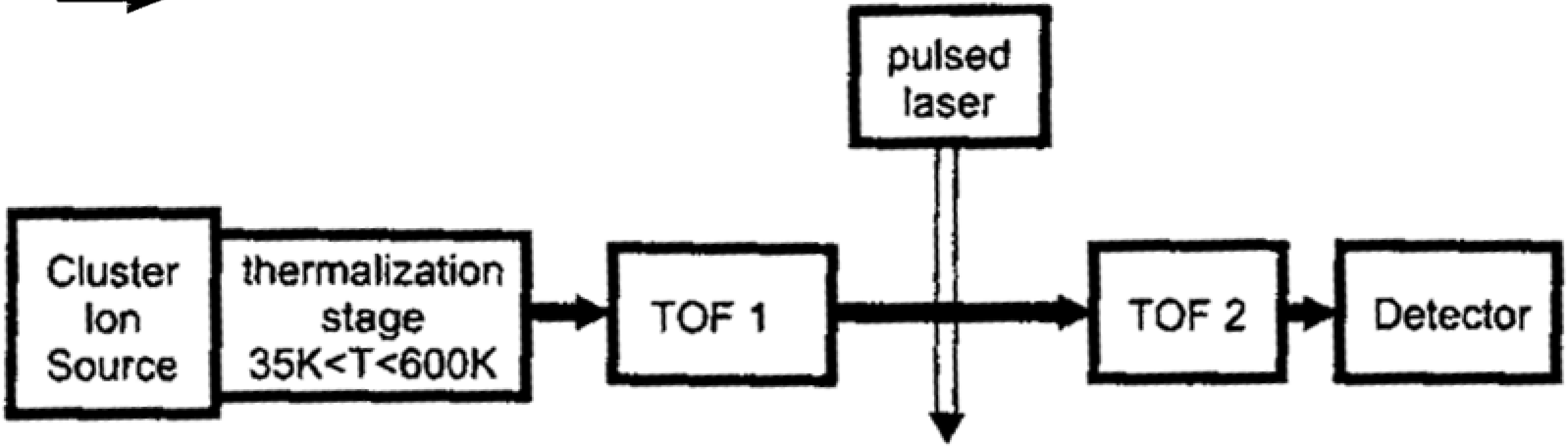
Su, Zhu, Xie, Zhang, Phys. Rev. C 85, 017604 (2012)

Haberland et al., Eur. Phys. J. D9, 1999, 1

Schmidt, Kusche, Issendorff, and Haberland, Nature, 393,238 ,1998



For sodium Clusters Na_n



$$Na_n^+(T_1) + jh\nu \Rightarrow Na_{n-x}^+(T_{evap.}) + xNa$$

$$U_n(T_1) + jh\nu = U_{n-x}(T_{evap.}) + \sum_{i=1}^{x} D_i + \sum_{i=1}^{x} \varepsilon_i$$

$$Na_n^+(T_2) + (j-1)h\nu \Rightarrow Na_{n-x}^+(T_{evap.}) + xNa$$

$$U_n(T_2) + (j-1)h\nu = U_{n-x}(T_{evap.}) + \sum_{i=1}^{x} D_i + \sum_{i=1}^{x} \varepsilon_i$$

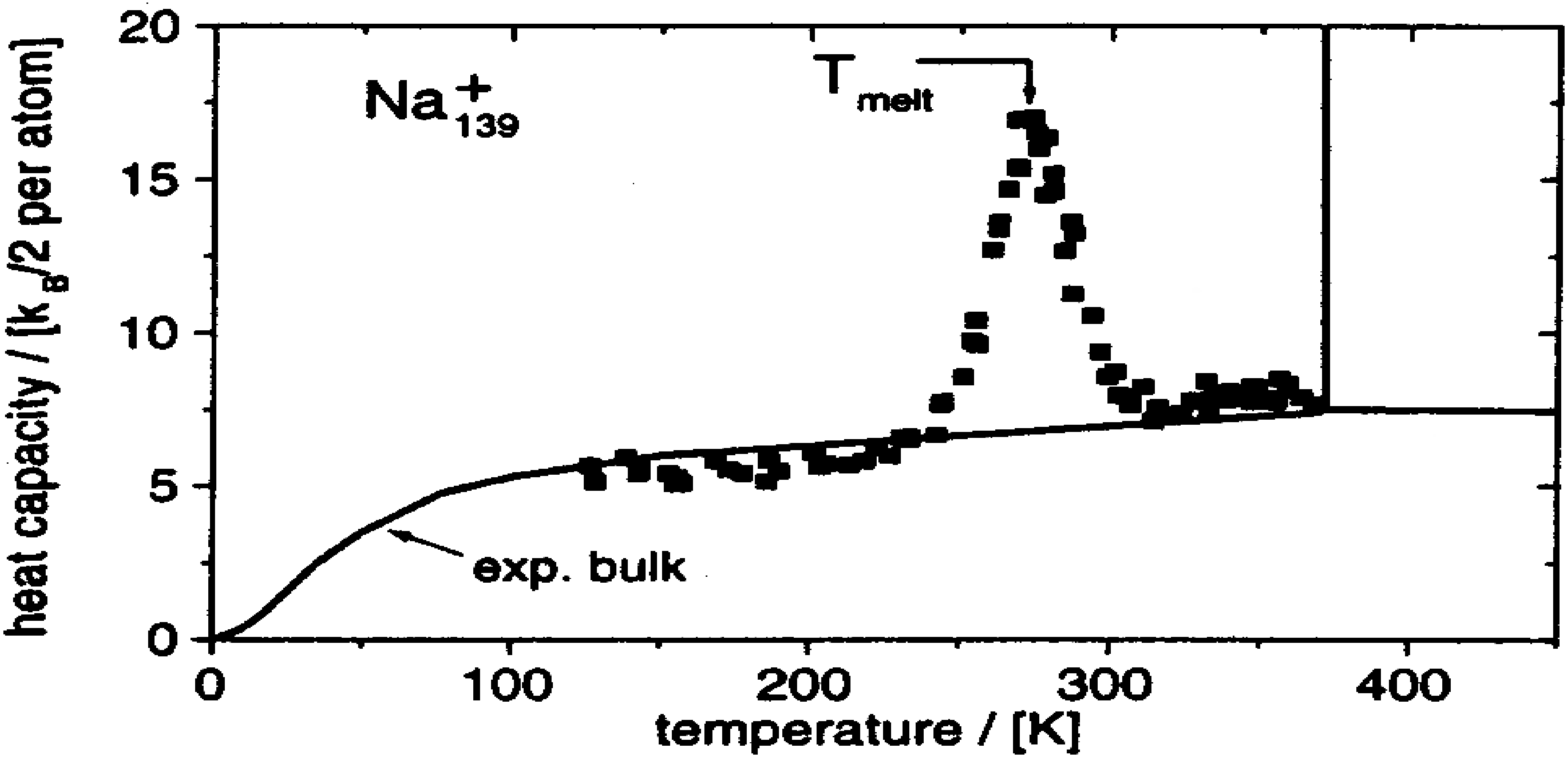
$$U(T_1) + h\nu = U(T_2)$$

$$U(T_1) + \delta U = U(T_2)$$

$$C(T) = \frac{\partial U}{\partial T} \approx \frac{\delta U}{\delta T} = \frac{h\nu}{T_2 - T_1}$$

Haberland et al., Eur. Phys. J. D9, 1999, 1
Schmidt, Kusche, Issendorff, and Haberland, Nature, 393,238 ,1998

Heat capacity of Na^{+}_{139} is plotted against the T



4. Conclusions and outlooks

1. To verify different methods for determination of T:
   kinetic energy method, population of excited states, double ratios of isotopic yields

2. In each method, to know the reliability for different conditions

3. New methods are welcome for determination of T and it is still very far to get a proper definition of liquid-gas phase transitions in nuclear system

Thank you for your attention !