INPC98, Aug. 24-28, 1998 @ Paris

Are Fragments Produced in Supercooled Nuclear Gas Phase ?

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J. Randrup LBL

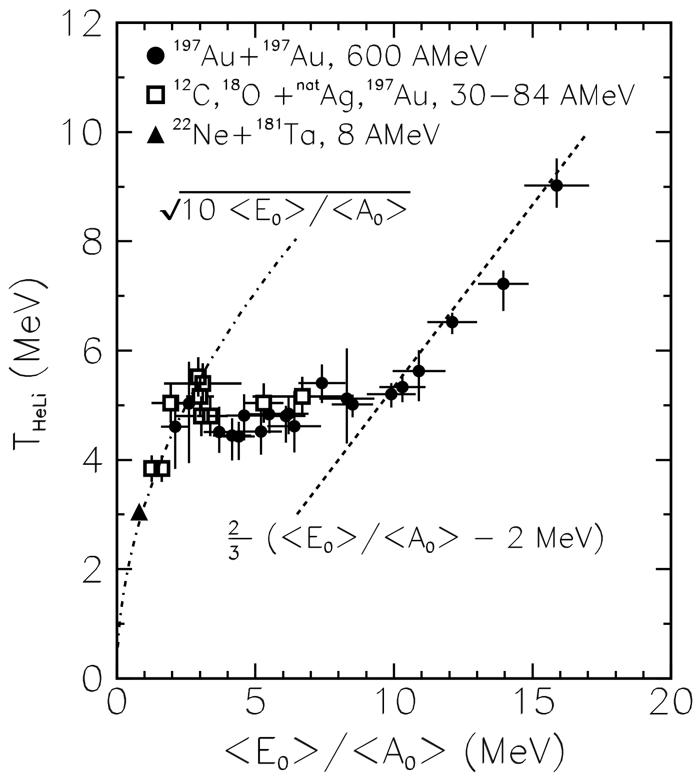
1. **Introduction**
2. **Basic idea to include Quantum Fluctuation**
   - ⋆ **Quantum Langevin Model**
3. **Nuclear Statistical Properties**
   - ⋆ **Caloric Curve and Fragment Distribution**
4. **Nuclear Reaction**
   - ⋆ **Proton-induced Reaction**
   - ⋆ **Hyperfragment Formation from Ξ^- Absorption at Rest**
   - ⋆ **IMF formation from Au+Au Collision**
5. **Densities and Temperatures at Fragment Formation**
6. **Summary and Outlook**

A.O. and J. Randrup,
PRL 75('95), 596; AP 253('97), 279; PL B394('97), 260; PRA 55('97), 3315R
A.O. et al., NP A630 ('98), 223c
A.O. and J. Randrup, Proc. INFN-RIKEN Symp., in press
Y.Hirata, Y.Nara, A.O., T.Harada, and J.Randrup, submitted to PTP

Nuclear Caloric Curve and L.-G. Phase Transition

- **Caloric Curve**

J.Pochadzalla et al.,PRL75('95),1040.



Low-T: $E^*/A = aT^2 \leftrightarrow$ **High-T:** $E^* = 1.5T + c$

Quantum Stat. $\leftrightarrow$ Classical Stat.

- **Expected Scenario**

First Order Phase Transition

$\rightarrow$ **SuperCooled Gas Phase** $\rightarrow$ **MultiFragmentation**

- **Problems...**

⋆ **Competition with Other Mechanism**

⋆ **Equilibrium is reached ?**

$\rightarrow$ **We need Microscopic Dynamics without any assumption on the Reaction Mechanism**

Quantal Langevin Model

$=$ 1. Wave packet statistics with Quantal Fluctuations
2. Wave packet dynamics with Quantal Fluctuations

on the same footing.

● Wave Packet Statistics

$$\mathcal{Z}_\beta \equiv \mathrm{Tr}\left(\exp(-\beta\hat{H})\right) \quad = \int d\Gamma\ \mathcal{W}_\beta(\mathbf{Z})$$

$$\mathcal{W}_\beta(\mathbf{Z}) \approx \exp\left[-\frac{\mathcal{H}}{D}\left(1-e^{-\beta D}\right)\right] = \exp(-\beta\mathcal{H} + \beta^2\sigma_E^2/2 + \cdots)$$

(Harmonic Approximation)

$$\prec \hat{O} \succ_\beta \equiv \frac{1}{\mathcal{Z}_\beta}\mathrm{Tr}\left(\hat{O}\exp(-\beta\hat{H})\right) = \frac{1}{\mathcal{Z}_\beta}\int d\Gamma\,\mathcal{W}_\beta(\mathbf{Z})\ \frac{\langle \mathbf{Z}_{\beta/2}|\hat{O}|\mathbf{Z}_{\beta/2}\rangle}{\langle \mathbf{Z}_{\beta/2}|\mathbf{Z}_{\beta/2}\rangle}$$

(Thermal Distortion)

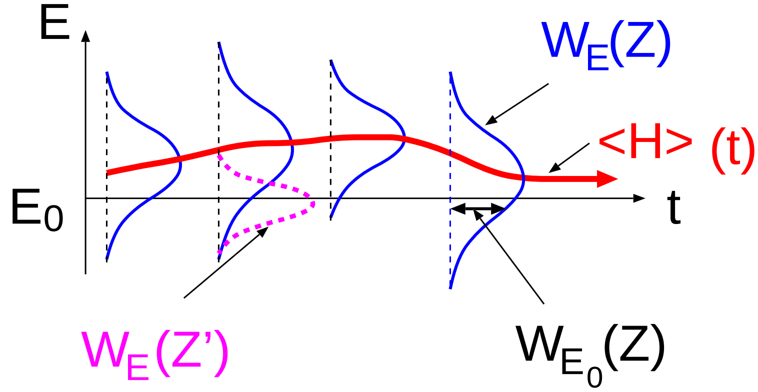
● Wave Packet Dynamics with Quantum Fluctuation

= Fluctuation-Dissipation Dynamics ($\rightarrow$ ensemble with $\mathcal{W}_\beta(\mathbf{Z})$)

$$\dot{\mathbf{p}} = \mathbf{f} - \beta_{\mathcal{H}}\mathbf{M}^p\cdot(\mathbf{v}-\mathbf{u}) + \mathbf{g}^p\cdot\boldsymbol{\zeta}^p\ ,$$

$$\dot{\mathbf{r}} = \mathbf{v} + \beta_{\mathcal{H}}\mathbf{M}^r\cdot\mathbf{f} + \mathbf{g}^r\cdot\boldsymbol{\zeta}^r\ ,$$

Drift **Diffusion**



+ Intrinsic Distortion ($\rightarrow$ Recover on-shell condition)

$$\frac{d\mathbf{p}}{d\tau} = -\frac{2\Delta p^2}{\hbar}(\mathbf{v}-\mathbf{u})\ , \qquad \frac{d\mathbf{r}}{d\tau} = \frac{2\Delta r^2}{\hbar}\mathbf{f}$$

until $\mathcal{H} = E$ before making an observation

Quantum Stat. Mech. of Wave Packets

Energy Fluctuation of Wave Packets

$$\sigma_E^2 = \langle \hat{H}^2 \rangle - \langle \hat{H} \rangle^2 \neq 0$$

modifies Statisitcal Weight !

- **Partition Function**

$$\begin{aligned} \mathcal{Z}_\beta &\equiv \mathrm{Tr}\left(\exp(-\beta \hat{H})\right) \quad = \int d\Gamma\ \mathcal{W}_\beta(\mathbf{Z}) \\ \mathcal{W}_\beta(\mathbf{Z}) &\equiv \langle \mathbf{Z} | \exp(-\beta \hat{H}) | \mathbf{Z} \rangle \ \neq \exp(-\beta \langle \hat{H} \rangle) \end{aligned}$$

- **Thermal Average**

$$\begin{aligned} \prec \hat{O} \succ_\beta &\equiv \frac{1}{\mathcal{Z}_\beta} \mathrm{Tr}\left(\hat{O} \exp(-\beta \hat{H})\right) = \frac{1}{\mathcal{Z}_\beta} \int d\Gamma\, \mathcal{W}_\beta(\mathbf{Z})\ \mathcal{O}_\beta(\mathbf{Z}) \\ \mathcal{O}_\beta(\mathbf{Z}) &\equiv \frac{\langle \mathbf{Z}_{\beta/2} | \hat{O} | \mathbf{Z}_{\beta/2} \rangle}{\langle \mathbf{Z}_{\beta/2} | \mathbf{Z}_{\beta/2} \rangle} \qquad \neq \langle \hat{O} \rangle \\ |\mathbf{Z}_{\beta/2}\rangle &\equiv \exp(-\beta \hat{H}/2) |\mathbf{Z}\rangle \qquad \neq |\mathbf{Z}\rangle \end{aligned}$$

- **Harmonic Approximation**

$$\begin{aligned} \mathcal{W}_\beta(\mathbf{Z}) &\approx \exp\left[-\frac{\mathcal{H}}{D}\left(1 - e^{-\beta D}\right)\right] = \exp(-\beta \mathcal{H} + \beta^2 \sigma_E^2/2 + \cdots) \\ D(\mathbf{Z}) &\equiv \sigma_E^2/\mathcal{H} \\ \mathcal{H}_\beta(\mathbf{Z}) &\equiv -\frac{\partial \log \mathcal{W}_\beta(\mathbf{Z})}{\partial \beta} \qquad \approx \mathcal{H}(\mathbf{Z})\ e^{-\beta D} \end{aligned}$$

$\rightarrow$ **Improved β Expansion**

From Quantum Statistics to Dynamics with Fluctuation

- **Equilibrium Distribution $\cdots$ Q. Microcan.**

$$\phi_{\rm eq}(\mathbf{Z}) \equiv \exp(-\mathcal{F}(\mathbf{Z})) \propto \langle \mathbf{Z}|\delta(E-\hat{H})|\mathbf{Z}\rangle$$

- **Fokker-Planck Equation: $\phi_{\rm eq}$ = Static Solution**

$$\frac{D\phi(\mathbf{Z};t)}{Dt} = \frac{\partial}{\partial \mathbf{q}} \cdot \left(\mathbf{M}\cdot\frac{\partial \mathcal{F}}{\partial \mathbf{q}} + \mathbf{M}\cdot\frac{\partial}{\partial \mathbf{q}}\right)\phi \ , \quad \{\mathbf{q}\} = \{\mathbf{r},\mathbf{p}\}$$

- **Equivalent Langevin Equation at Fixed E**

$$\begin{aligned} \dot{\mathbf{p}} &= \mathbf{f} - \beta_{\mathcal{H}}\mathbf{M}^p\cdot(\mathbf{v}-\mathbf{u}) &&+ \mathbf{g}^p\cdot\boldsymbol{\zeta}^p \ , \\ \dot{\mathbf{r}} &= \mathbf{v} + \beta_{\mathcal{H}}\mathbf{M}^r\cdot\mathbf{f} &&+ \mathbf{g}^r\cdot\boldsymbol{\zeta}^r \ , \end{aligned}$$

Drift **Diffusion**

$\mathbf{v} = \partial\mathcal{H}/\partial\mathbf{p}$, $\mathbf{f} = -\partial\mathcal{H}/\partial\mathbf{r}$
$\mathbf{u}$: Local Collective Velocity = Classical
$\mathbf{M} = \mathbf{g}\cdot\mathbf{g}$: Mobility Tensor

⋆ Effective Inverse Temperature:

$$\beta_{\mathcal{H}} \equiv \frac{\partial \mathcal{F}}{\partial \mathcal{H}} = \frac{\mathcal{H}-E}{\sigma_E^2}$$

$\cdots$ Drift Term Acts as a Energy Recovering Force

⋆ Classical Limit = Classical Canonical Eq.
$\cdots$ $\phi_{\rm eq} = \delta(\mathcal{H}-E)$ $\leftrightarrow$ $\dot{\mathbf{p}} = \mathbf{f},\ \dot{\mathbf{r}} = \mathbf{v}$

- **Intrinsic Distortion of Wave Packets**

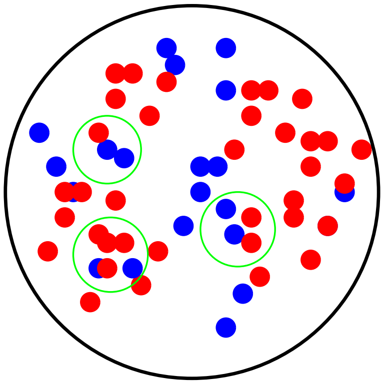
$$\frac{d\mathbf{p}}{d\tau} = -\frac{2\Delta p^2}{\hbar}(\mathbf{v}-\mathbf{u}) \ , \quad \frac{d\mathbf{r}}{d\tau} = \frac{2\Delta r^2}{\hbar}\mathbf{f}$$

until $\mathcal{H} = E$ before making an observation

Statistical Properties of Nuclei

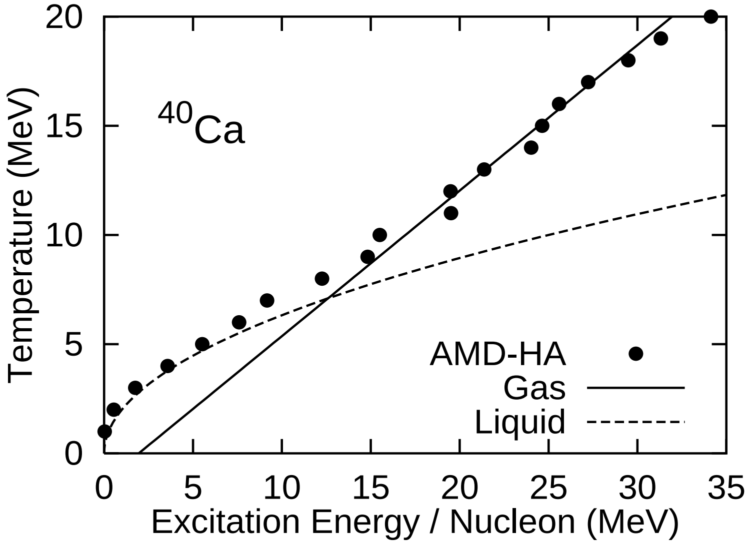
A.O. and J.Randrup, PRL 75('95),596;AOP 253('97),279;

A.O. et al., Proc. NN97, NPA, in press.



- ⋆ Equilibrium in a Sphere $R = r_0 A^{1/3}$ ($r_0 = 2.0$ fm)
- ⋆ AMD w.f. and $\mathcal{H}$ (Volkov)
- ⋆ Harmonic Approx.
- ⋆ Metropolis Sampling

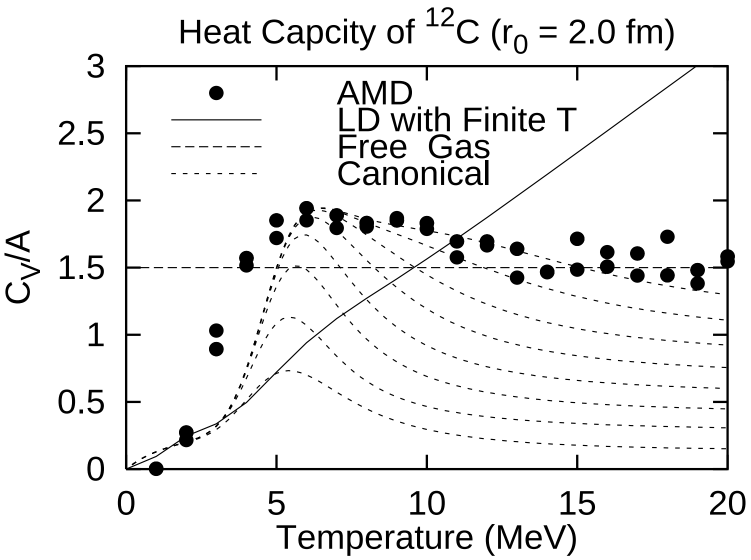
● Caloric Curve



G: $T = \frac{2}{3}(E/A - 2)$ MeV

L: $T = 2\sqrt{E/A}$ MeV

● Heat Capacity



Multifragmentation ?

Canonical

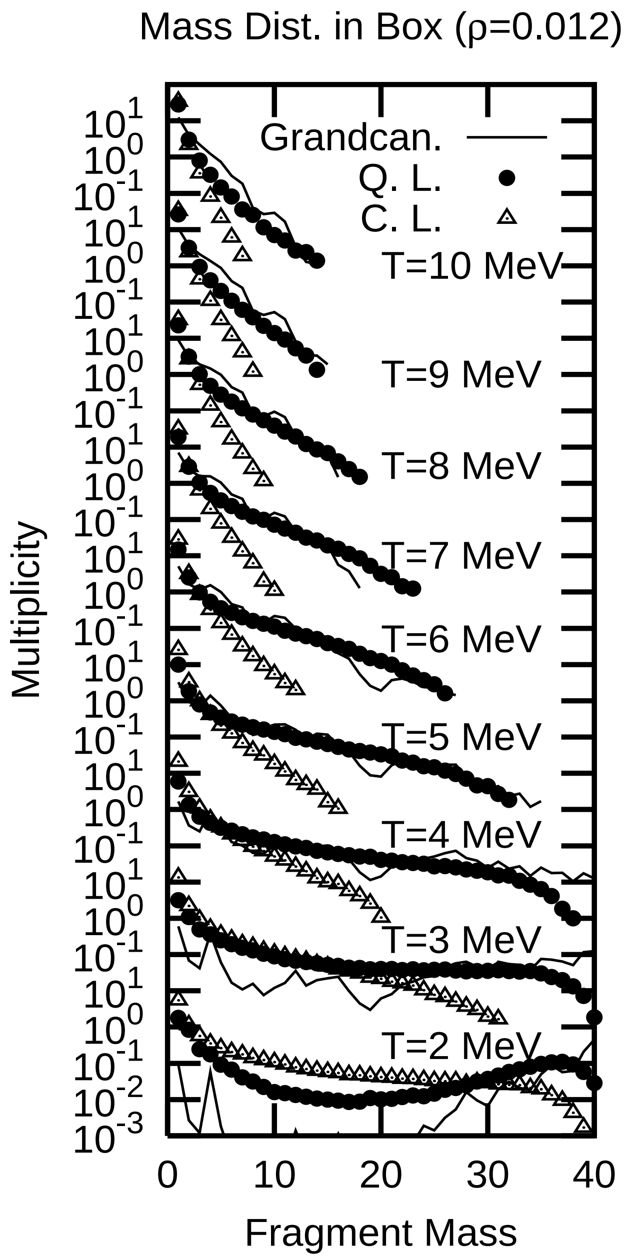
→ upto 9-body

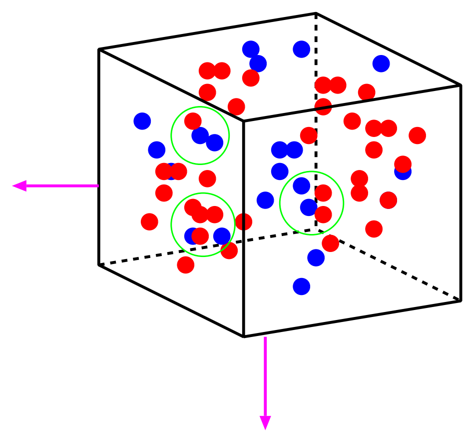
Thermal Fragmentation of Nuclei

A.O. and J. Randrup, PL B394('97), 260

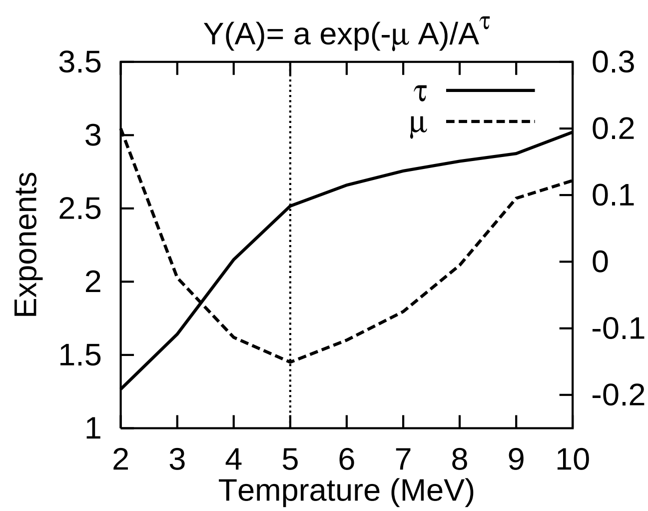
- ⋆ Equilibrium in a Box with Periodic B.C.
- ⋆ Time-Average by using QMD (Gogny) +Q.L.

● Mass Dist. at Fixed T





● Critical Properties



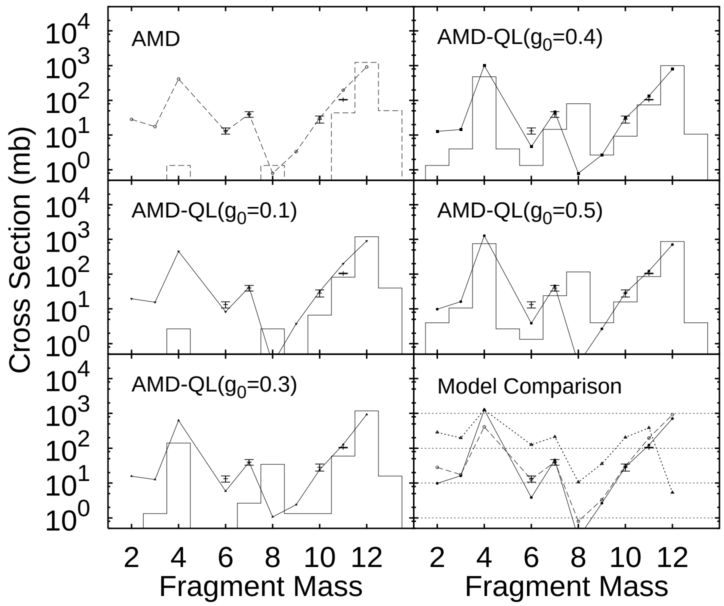
$$Y(A) \;\propto\; e^{-\mu A}/A^{\tau}(A \le 15)$$

$$\tau \;\simeq\; 2.5$$

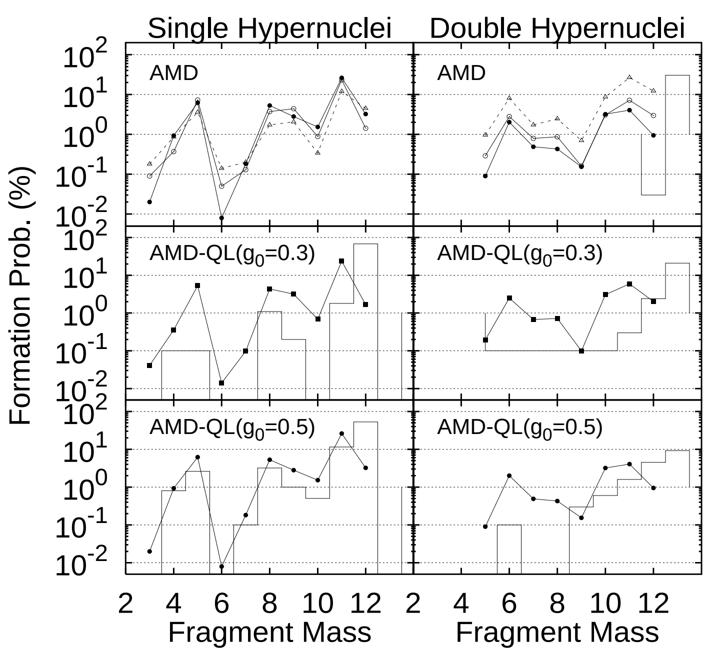
Light Ion Induced Reaction — AMD-QL

Hirata, Nara, Ohnishi, Harada, Randrup, submitted

- **Proton Induced Reaction at 45 MeV**



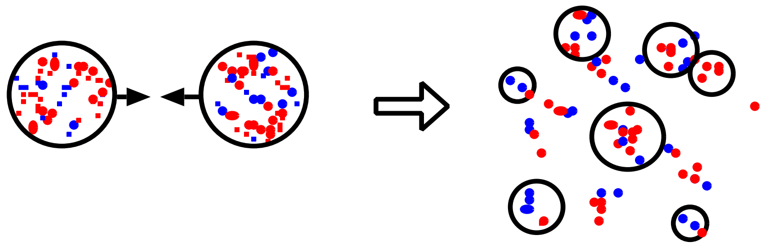
- **Ξ^- Absorption at Rest**



⋆ Sufficient Fluctuation Strength

→ Fragments are produced at low excitation DYNAMICALLY

Multifragmentation from Au+Au (I)
– IMF Multiplicity

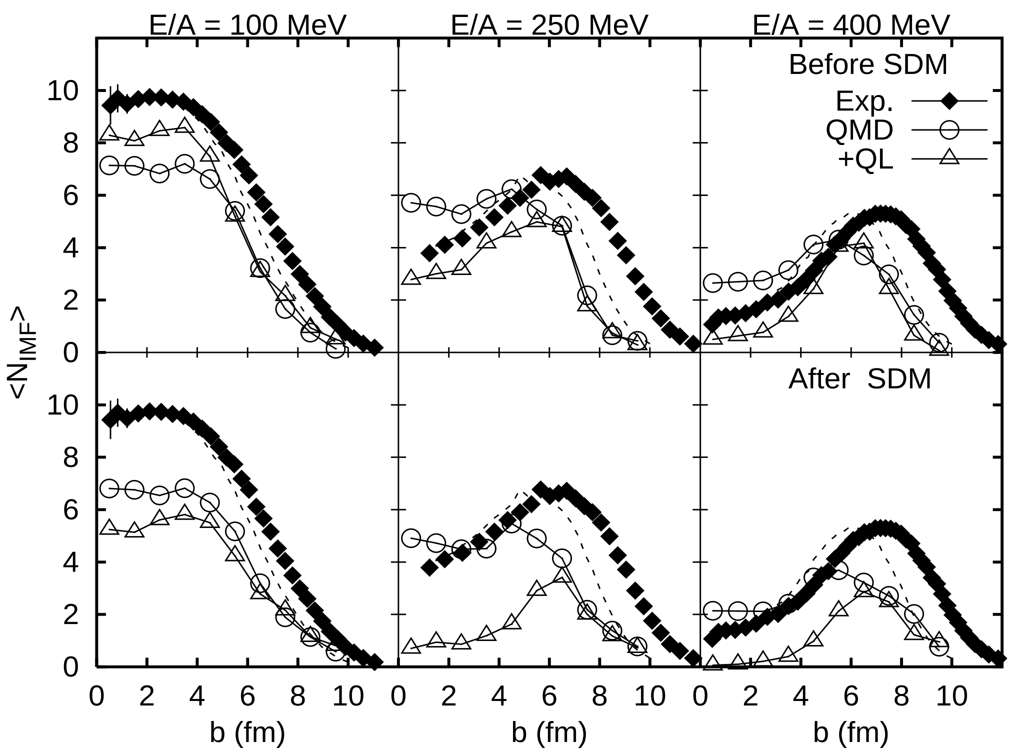


● MSU/ALADIN Data — E_{inc} and b-dependence

M.B.Tsang et al., PRL 71 ('93), 1502.

A.O. and J. Randrup, PL B394('97), 260.

c.f. Maruyama et al. PTP 98('97),87, Barz et al. PLB 359('96),261.



⋆ Exp.: b_{imp} sort = PM, $3 \leq Z_{imf} \leq 30$

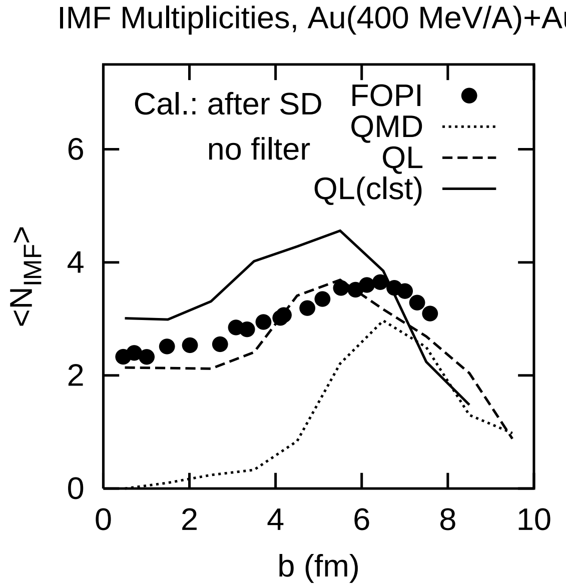
⋆ Calc.: QMD, Gogny+Pauli, No Det. Eff. is incl.

→ Dynamically Produced Fragments are cool enough to Survive Statistical Decay in QMD-QL !

Multifragmentation from Au+Au (II)
– Comparison with New Data

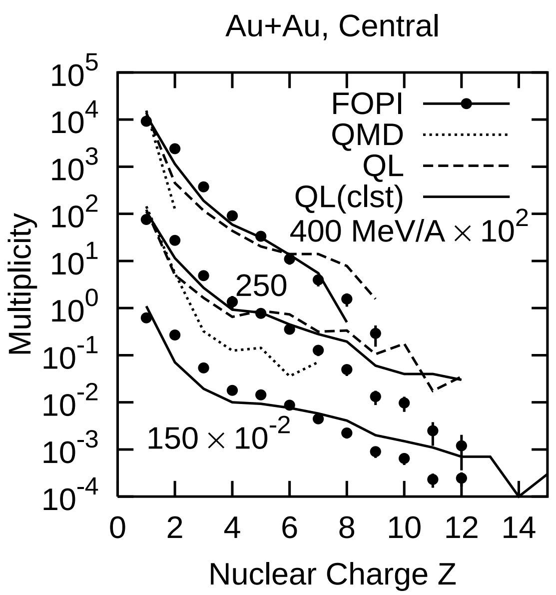
W. Reisdorf et al., NP A612 ('97), 493 $\cdots$ b_{imp} sort = PM, $3 \leq Z_{imf} \leq 15$

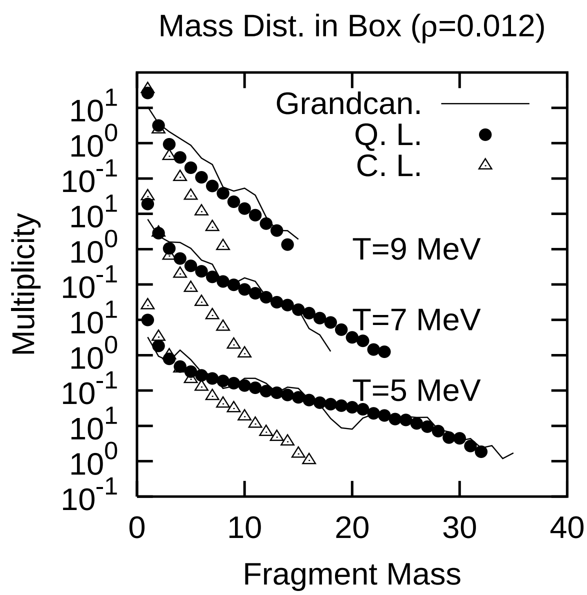
• IMF Multiplicity



• Charge and Mass Distribution

Heavy-Ion Collision:	Statistical Sampling:
Non-Equilibrium Formation	Formation at Equilibrium





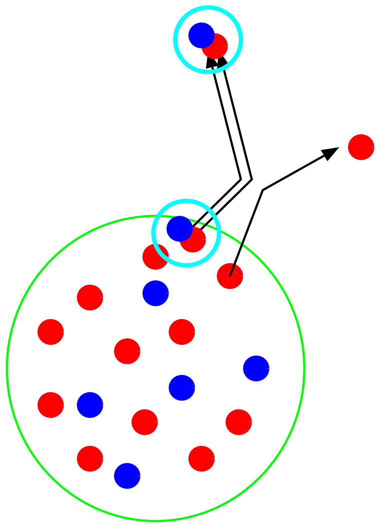
→ Are fragments produced after equilibrium is reached ?

● Cluster-Cluster Scattering

Danielewicz and Bertsch, NP A533 ('91), 712: (d, t, h)

Ono et al., PRC 47 ('91), 2652: (Nα)

Y. Nara et al. PL B346 ('95), 217: ($K^-\alpha \to \pi^4_\Lambda$H)

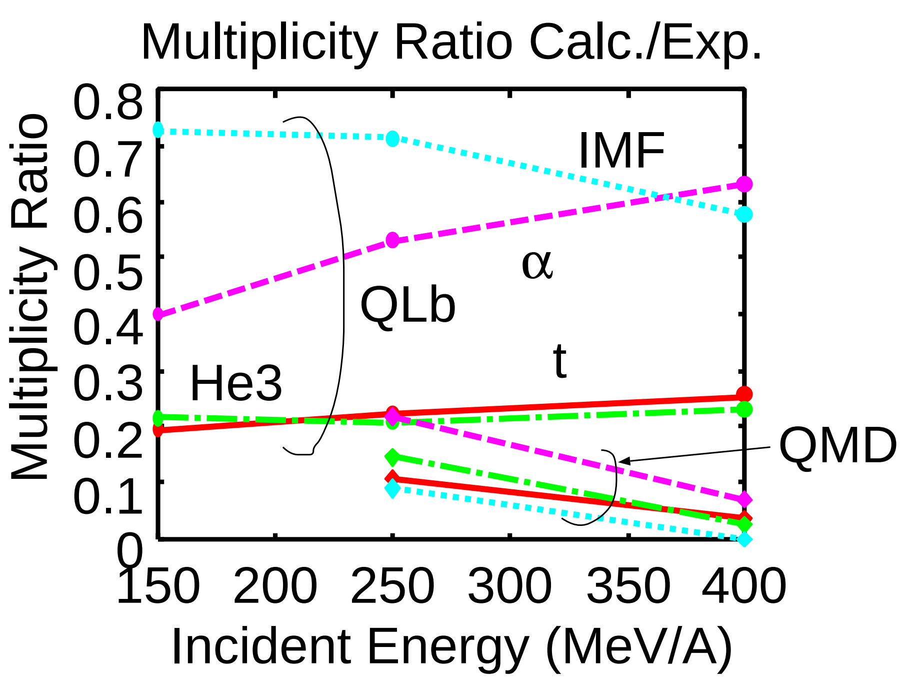


Cluster-Cluster (or N) Scattering

- **Black Disc Ang. Dist. & σ are assumed**
- **Seed of IMFs**
- **Only 0s clusters are considered**

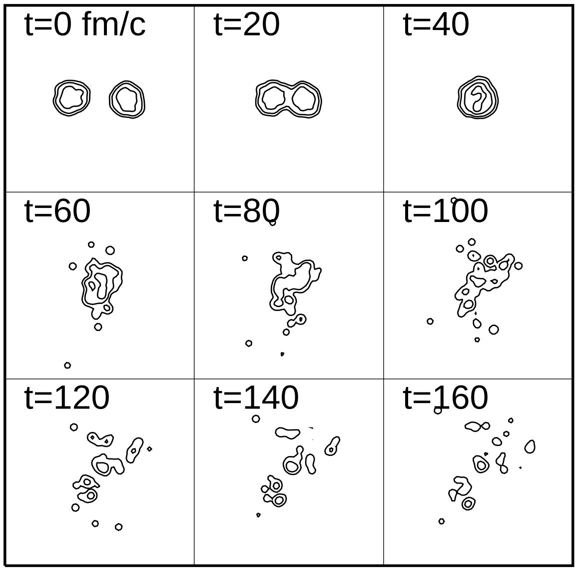
● Light Charged Particle Multiplicity

$\cdots$ Large underestimate for A=3

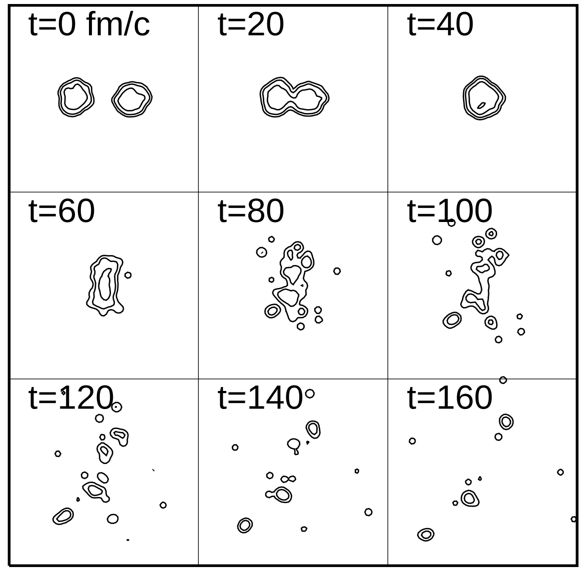


Density Evolution in Au+Au Collision

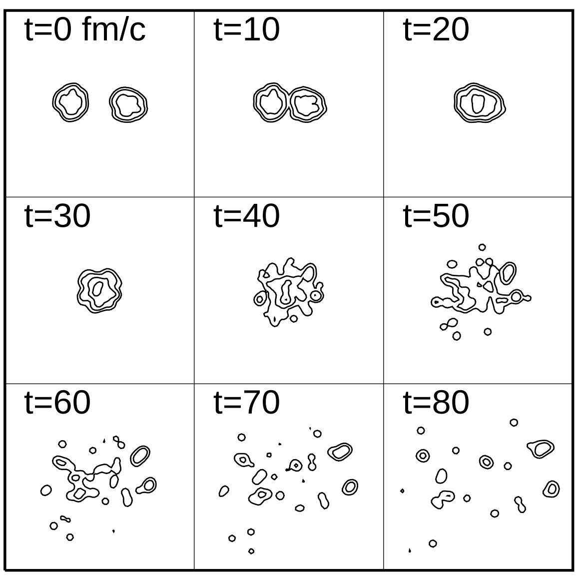
Au(150 MeV/A)+Au, QMD



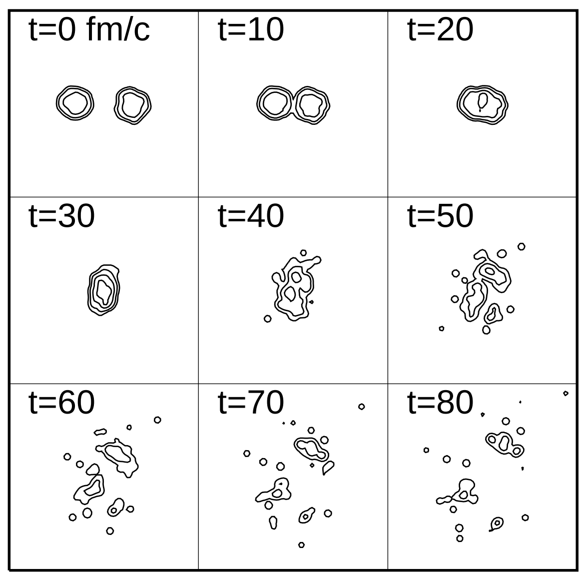
Au(150 MeV/A)+Au, QL



Au(400 MeV/A)+Au, QMD

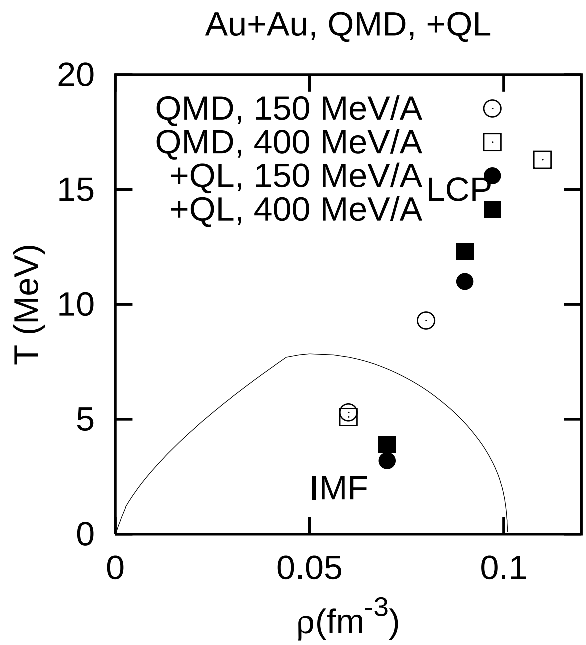


Au(400 MeV/A)+Au, QL



Densities and Temperatures at IMF formation

- **Average ρ-T at Fragment Formation**

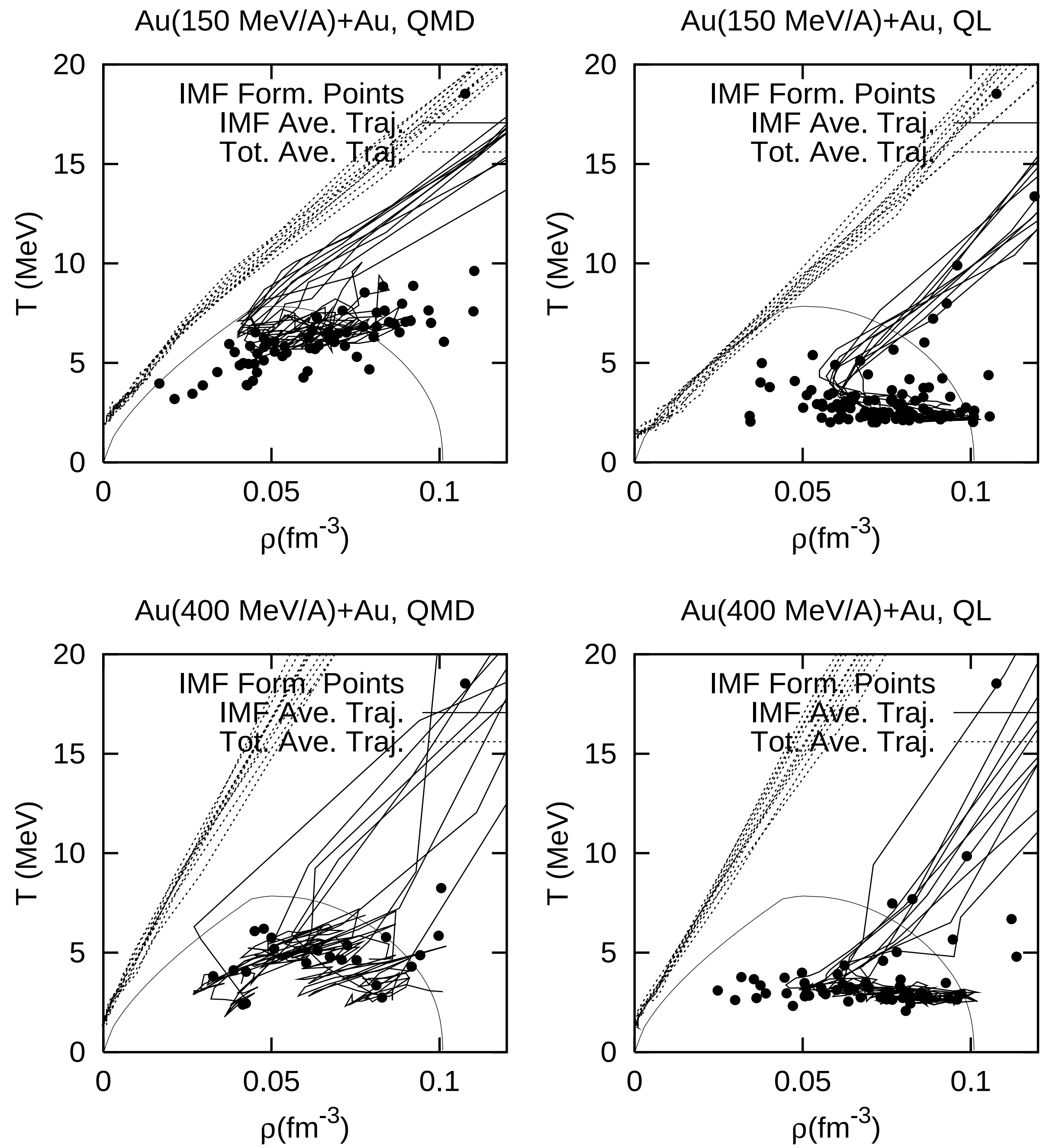


E_{inc}			$\prec \rho \succ$ (fm^{-3})	$\prec T \succ$ (MeV)	$\prec T' \succ$ (MeV)
150 MeV/A	QMD	LCP	0.08	9.3	5.8
		IMF	0.06	5.3	1.9
	QL	LCP	0.09	11.0	7.4
		IMF	0.07	3.2	0.6
400 MeV/A	QMD	LCP	0.11	16.3	12.4
		IMF	0.06	5.1	1.7
	QL	LCP	0.09	12.3	8.7
		IMF	0.07	3.9	1.0

In Average, IMF's are seems to be made
in the spinodal region...

ρ-T Evolution in Au+Au Collision

– Time-Dependence



⋆ IMF's are mainly formed
during re-compression stage
in Unstable Region of Nuclear Matter
if Quantum Fluctuation is incorporated.

SUMMARY & OUTLOOK

- **Quantal Langevin Model**

  ⋆ Based on the energy fluctuations of wave packets, which are not energy eigen states.

  ⋆ Dynamical Relaxation to Quantum Stat. Equil.

  ⋆ Larger Fluctuations (Quantum & Statistical)
  +Intrinsic Distortion (Smaller Excitation Energy)
  → Enhancement of Stable Dynamical Fragments

- **Achievements**

  a. Caloric Curve (Liquid → Gas)

  b. Thermal Fragmentation (Critical behavior)

  c. Dynamical Fragmentation in Light-Ion Induced Reactions (Proton-Induced, Ξ^- Absorption)

  d. Dynamical Fragmentation in Heavy-Ion Collisions (Au+Au, 150 ∼ 400 MeV/A)

- **ρ-T at Fragment Formation**

  ⋆ LCP ··· all the region of ρ-T

  ⋆ IMF ··· mainly formed during the re-compression stage
  in Unstable Region of Nuclear Matter
  Exception: 400 MeV/A w.o. Quantum Fluctuation