Quantum Fluctuation Effects on Nuclear Fragment and Atomic Cluster Formation

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2. Basic Idea
   — How to Include Quantum Fluctuation
3. Canonical Ensemble
   — Statistics and Fragmentation
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   — Ξ^- Absorption at Rest
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BASIC IDEA

- *Microcanonical Phase Volume*

$$\Omega(E) = \mathrm{Tr}\left(\delta(E-\hat{H})\right) = \int d\Gamma\, \rho_E(Z)$$

$$\rho_E(Z) = \langle Z|\delta(E-\hat{H})|Z\rangle \equiv \exp(-\mathcal{F}_E(Z))$$

$$\neq \delta(E-\mathcal{H})$$

→ Wave Packet ≠ Energy Eigenstate

- *Fokker-Planck Equation*

$$\frac{D\phi(Z;t)}{Dt} = \left[-\sum_i \frac{\partial}{\partial q_i}\left(V_i - \sum_j M_{ij}\frac{\partial}{\partial q_j}\right)\right]\phi$$

$$V_i = -\sum_j M_{ij}\frac{\partial \mathcal{F}_E(Z)}{\partial q_j}$$

→ Quantum Canonical Ensemble = Statis Solution

- *Equivalent Langevin Equation*

$$\frac{Dq_i}{Dt} = V_i + \sum_j g_{ij}\zeta_j$$

$$g\cdot g = M \qquad \prec \zeta_i(t)\,\zeta_j(t') \succ = 2\delta_{ij}\,\delta(t-t')$$

→ Quantal Langevin Model

CANONICAL ENSEMBLE

- *Partition Function*

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

$$\mathcal{W}_\beta(Z) = \langle Z|\exp(-\beta\hat{H})|Z\rangle \equiv \exp(-\mathcal{F}_\beta(Z))$$

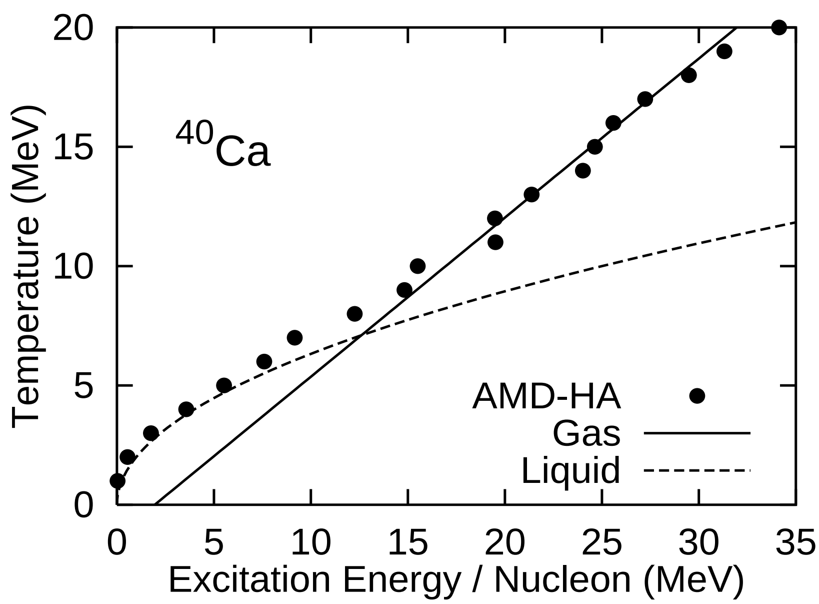
$$\neq \exp(-\beta\mathcal{H})$$

- *Harmonic Approximation*

$$\mathcal{W}_\beta(Z) \approx \exp\left[-\frac{\mathcal{H}}{D}\left(1-e^{-\beta D}\right)\right]$$

$$D(Z) \equiv \sigma_E^2/\mathcal{H}$$

$\rightarrow$ Improved β Expansion



Gas(Classical): $T = \dfrac{2E}{3A} - 1.3$ MeV

Liquid(Quantum): $T = 2\sqrt{E}$ MeV

QL Model at Fixed Temperture

• *Modified Einstein Relation*

By using Harmonic App.,

$$V_i \equiv -\sum_j M_{ij} \frac{\partial \mathcal{F}_E(Z)}{\partial q_j} = -\alpha\beta \sum_j M_{ij} \frac{\partial \mathcal{H}}{\partial q_j}$$

$$\alpha = \frac{1-\exp(-\beta D)}{\beta D} < 1$$

→ Smaller Friction = Relatively Larger Fluctuation

• *Quantal Langevin Equation*

$$\dot{p} = f - \alpha\beta M^p \cdot (v-u) - \beta M^p \cdot u + g^p \cdot \zeta^p$$

$$\dot{r} = v + \alpha\beta M^r \cdot f + g^r \cdot \xi^r$$

$$f \equiv -\frac{\partial \mathcal{H}}{\partial r}, \quad v \equiv \frac{\partial \mathcal{H}}{\partial p}$$

• *Thermal Distortion*

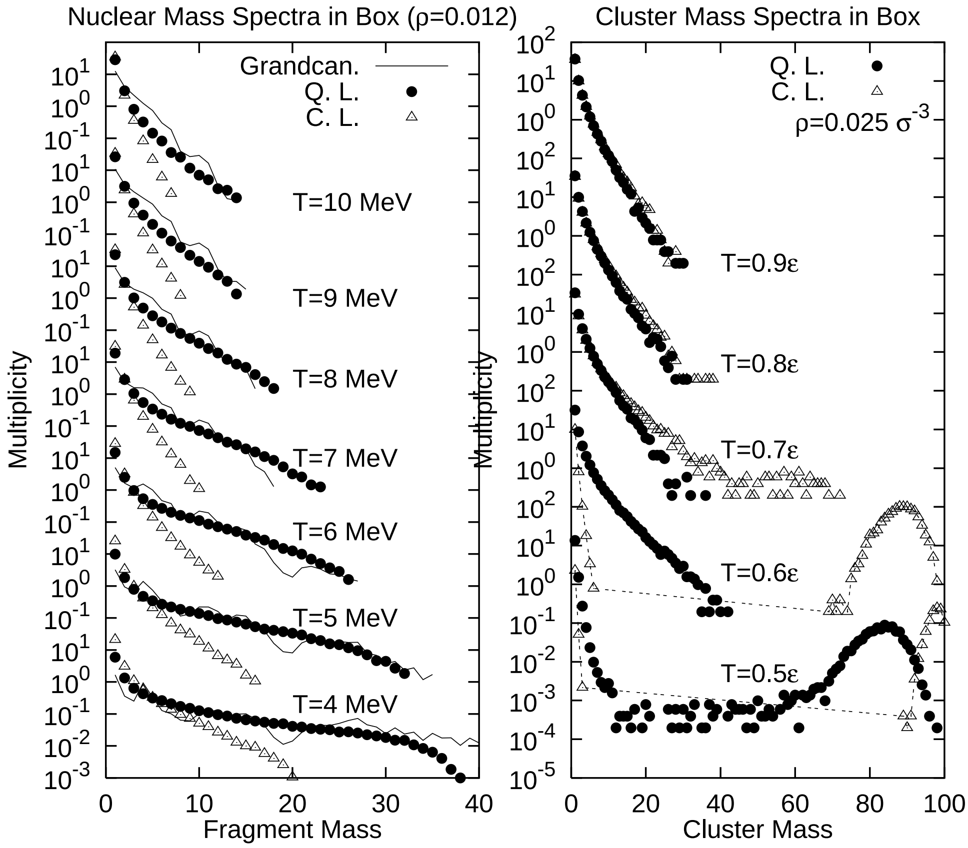
$$\prec \hat{O} \succ_\beta \equiv \frac{1}{\mathcal{Z}_\beta} \mathrm{Tr}\left(\hat{O} \exp(-\beta \hat{H})\right) = \frac{1}{\mathcal{Z}_\beta} \int d\Gamma \, \mathcal{W}_\beta(Z) \, \mathcal{O}_\beta(Z)$$

$$\mathcal{O}_\beta(Z) = \frac{\langle Z_{\beta/2} | \hat{O} | Z_{\beta/2} \rangle}{\langle Z_{\beta/2} | Z_{\beta/2} \rangle}, \quad |Z_{\beta/2}\rangle \equiv \exp(-\beta \hat{H}/2)|Z\rangle$$

→ Low E Eigen Component is Enhanced.

Fragmentation at Fixed Temperture

- *Nuclear and Atomic Fragment Mass Distribution*



Why is the Quantum Fluctuation Effect Opposite ?

- *Effective Temperature* $= \dfrac{(Diff.\ \ Coeff.)^2}{Drift.Coeff.}$

For Atomic Cluster: (Distortion is Small)

$$T_{\text{eff}} = \frac{g^2}{\alpha\beta M} = \frac{T}{\alpha} = \frac{D}{(1 - e^{-D/T})} > T$$

For Nuclear Fragment: (Distortion is Large)

$$T'_{\text{eff}} = \frac{g^2 e^{-D/T}}{\alpha\beta M} = \frac{D}{e^{D/T} - 1} < T$$

Fragmentation in Nucleus-Nucleus Collision

- *QL Equation at Given E*

$$\rho_E(Z) \equiv \langle Z|\delta(E-\hat{H})|Z\rangle \propto \frac{(\mathcal{H}/D)^{E/D}}{\Gamma(E/D+1)}\exp(-\mathcal{H}/D)$$

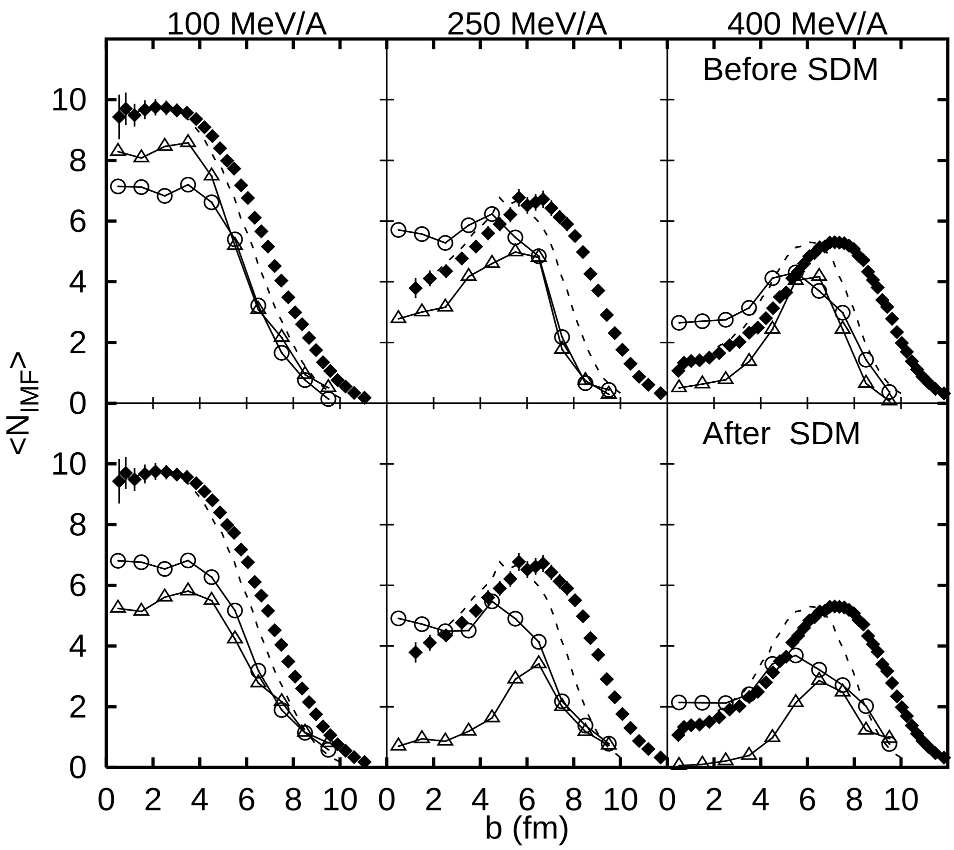
(Continuous Poisson)

$$V_i \simeq -\beta_{\mathcal{H}}\sum_j M_{ij}\frac{\partial\mathcal{H}}{\partial q_j} = -\frac{\mathcal{H}-E}{\sigma_E^2}\sum_j M_{ij}\frac{\partial\mathcal{H}}{\partial q_j}$$

Note:

1. Fluctuations even in Isolated system.
2. Drift term = Energy Recovering Force
   → Small Excitation Energy of Fragments

- *IMF Multiplicity in Au+Au Collision*



Application to Small System

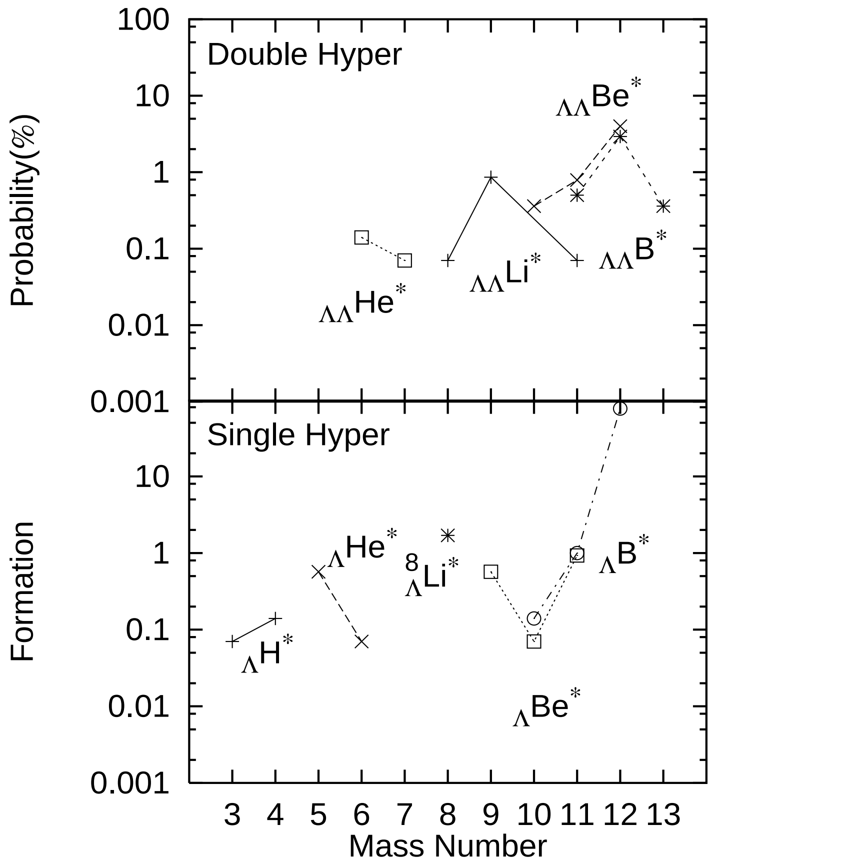
- Ξ^- *Particle Absorption at Rest on* ^{12}C

1. Elementary Process $\cdots$ $\Xi^- + p \rightarrow \Lambda + \Lambda + 28.3\mathrm{MeV}$
2. Double Hyper Nuclei $\cdots \Xi^- + {}^{A}\mathrm{Z} \rightarrow {}_{\Lambda\Lambda}\mathrm{Z} + X \sim 1\%^{a}$ *a.* S. Aoki et al. Prog.Theor.Phys. 85 (1991) 1287
3. Theoretical Approach

	Dynamical	Dyn. + Stat. Decay	Species
AMD	$\sim$ 70 %	$\sim$ 30 %	$^{13}_{\Lambda\Lambda}\mathrm{B}$
AMD-QL	$\sim$ 10 %	$\sim$ 5 %	Various

$\rightarrow$ Larger Fluctuation Enhances Λ Evaporation!

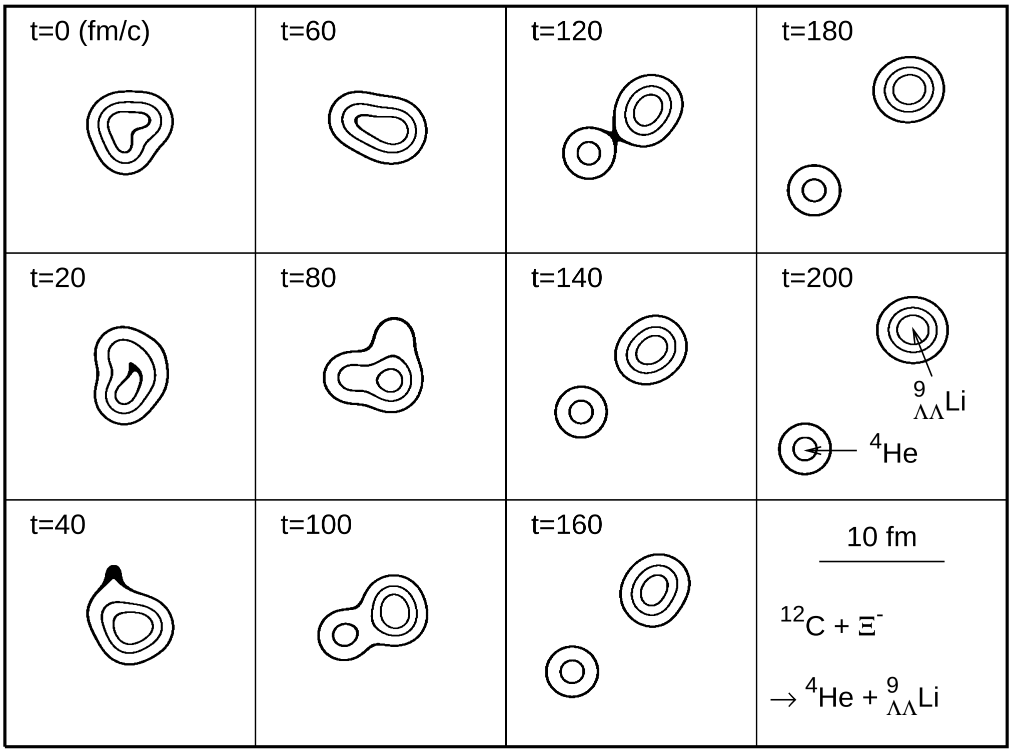
Fragment Distribution before statistical decay(AMD-QL)



- *Twin-Single Hyper Production*

1. Definition $\cdots$ $\Xi^- + {}^{A}\mathrm{Z} \rightarrow {}_{\Lambda}\mathrm{Z} + {}_{\Lambda}\mathrm{Z}'$
2. Observed $\cdots$ $\Xi^- + {}^{12}\mathrm{C} \rightarrow {}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be}$ $(2 events/80)^b$
   b. S. Aoki et al. Phys.Lett. B355 (1995) 45
3. Dynamical Fragmentation ?
   (This channel does not have the largest Q−value.[c])
   c. Yamada & Ikeda, PTP Suppl. 117 (1994) 445
4. Theoretical Approach

	Dynamical	Channel
AMD	~ 0 %	
AMD-QL	~ 0.5 %	${}^{4}_{\Lambda}\mathrm{H}+{}^{9}_{\Lambda}\mathrm{Be}$, ${}^{5}_{\Lambda}\mathrm{He}+{}^{8}_{\Lambda}\mathrm{Li}$, etc.
	~ 5 %	Other Fragmentation



SUMMARY & OUTLOOK

- *Quantal Langevin Model*

1. Larger Fluctuations (Quantum & Statistical)
2. Thermal Distortion (Smaller Excitation Energy)

$\rightarrow$ Enhancement of Stable Dynamical Fragments

- *Achievements*

a. Caloric Curve

b. Nuclear Fragmentation (Fixed T, Au+Au, Ξ^- Abs.)

c. Shift of T_c of Atomic Cluster Formation

- *Possible Next Challenge*

$\rightarrow$ Big Bang Nucleosynthesis through Liquid-Gas Phase Transition