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基于微观TDHF-QRx方法研究势垒之上反应耗散动力学

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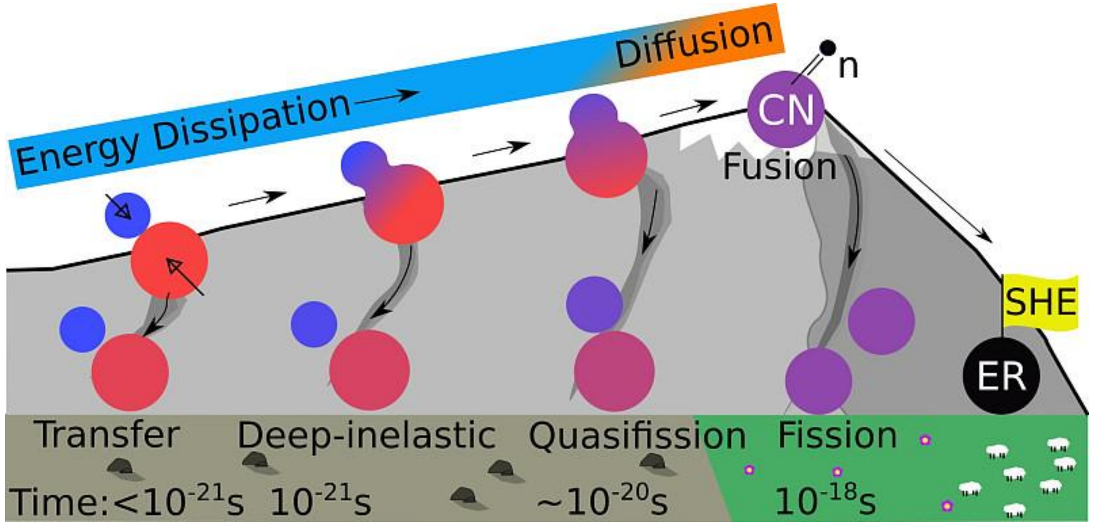
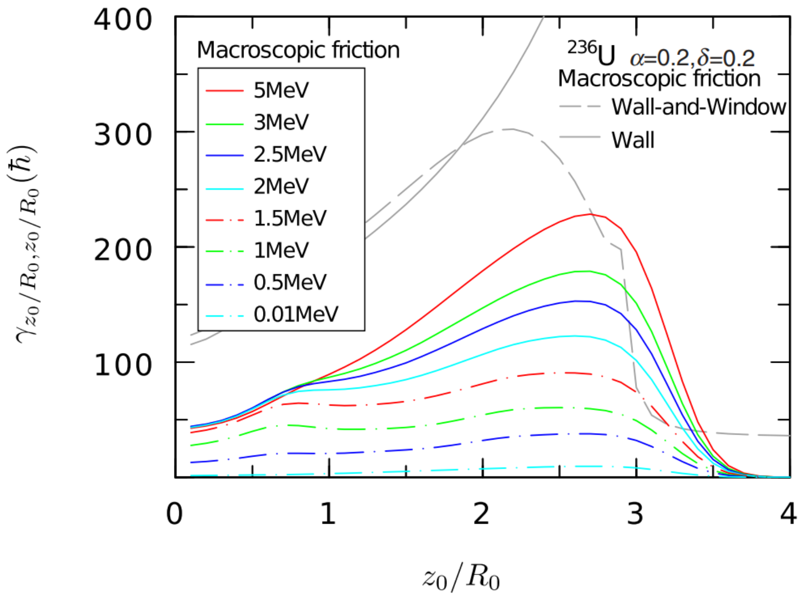
Energy dissipations in reactions





Energy dissipation:
energy transfer from collective to internal d.o.f

- time-scale
- excitation energies
- equilibrium
- fluctuation

Classical description:
Wall-and-window formula

K. Cook, ANU research project
PRC94, 044602 (2018)

Microscopic description

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- *N*-body dynamical problem: Liouville-von Neumann equation

$$i\hbar\frac{\partial\hat{\rho}_{1\ldots N}}{\partial t}=\left[\hat{H}_{1\ldots N},\hat{\rho}_{1\ldots N}\right]\qquad \hat{\rho}_{1\ldots N}=\sum_{i=1}^{M}|\Psi^{(i)}_{1\ldots N}\rangle\, p_i\,\langle\Psi^{(i)}_{1\ldots N}|$$

- Born-Bogoliubov-Green-Kirkwood-Yvon hierarchy equations

$$i\hbar\frac{\partial\hat{\rho}_{1\ldots k}}{\partial t}-\left[\hat{H}_{1\ldots k},\hat{\rho}_{1\ldots k}\right]=\sum_{i=1}^{k}\mathrm{T}_{k+1}\left(\left[\hat{V}_{i(k+1)},\hat{\rho}_{1\ldots k+1}\right]\right)$$

$$i\hbar\frac{\partial\hat{\rho}_{1}}{\partial t}=\left[\hat{T}_{1},\hat{\rho}_{1}\right]+\mathrm{Tr}_2\left(\left[\hat{V}_{12},\hat{\rho}_{12}\right]\right)$$

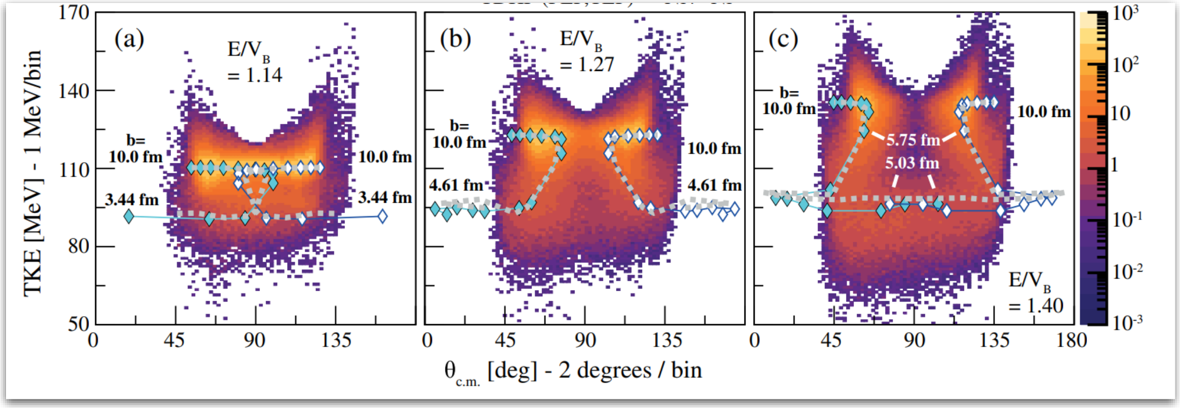
⬇ *independent particle approximation*

- Time-dependent Hatree-Fock (TDHF) equation

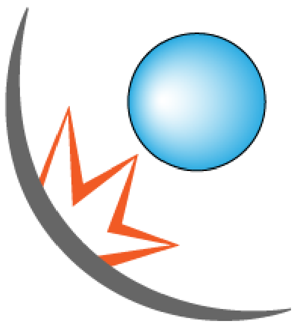
$$i\hbar\frac{\partial\hat{\rho}_{1}}{\partial t}=\left[\hat{h}_{1},\hat{\rho}_{1}\right]$$

"the **strong quantitative agreement** between experiment and a quantum many-body approach including **only one-body dissipation** mechanism for **low-energy heavy ion collisions**… "

--Phys. Rev. Lett. 120, 022501 (2018)

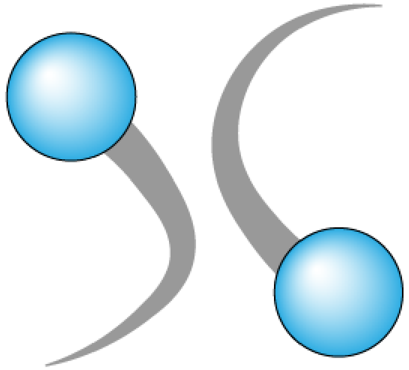


Dissipation mechanisms



One-body dissipation

- from mean-field changes



Two-body dissipation

- from nucleon-nucleon collisions
- blocked due to Pauli principle at low energies
- dynamical correlation

Add two-body dissipation into the TDHF

Including two-body dissipation

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First BBGKY equations

$$i\hbar\frac{\partial\hat{\rho}_1}{\partial t}=\left[\hat{T}_1,\hat{\rho}_1\right]+\mathrm{Tr}_2\left(\left[\hat{V}_{12},\hat{\rho}_{12}\right]\right)$$

→ **Time-dependent Density Matrix**
TDDM^P
Extend TDHF

No correlation → **TDHF**

$$i\hbar\frac{\partial\hat{\rho}_1}{\partial t}=\left[\hat{h}_1,\hat{\rho}_1\right]$$

Molecular chaos → **quantum Boltzmann equation**

$$i\hbar\frac{\partial\hat{\rho}}{\partial t}=\left[\hat{h}\left[\hat{\rho}\right],\hat{\rho}\right]+\hat{I}_{\mathrm{coll}}\left[\hat{\rho}\right]$$

Relaxation-time approx.

P.-G Reinhard and E. Suraud,
AOP 354, 183–202 (2015) for atom

TDHF-QRx

$$i\frac{\partial\hat{\rho}}{\partial t}=\left[\hat{h},\hat{\rho}\right]+\frac{1}{\tau_{\mathrm{relax}}}\left(\hat{\rho}-\hat{\rho}_{\mathrm{eq}}\left[\rho,\boldsymbol{j},E_{\mathrm{tot}}\right]\right)$$

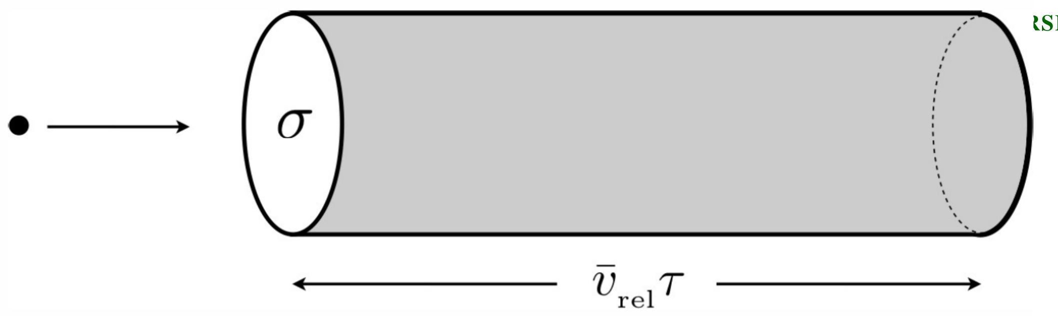
semi-classical limit → **BUU model**

$$\frac{\partial f_1}{\partial t}+\{f_1,\ h\}=I_{\mathrm{coll}}^{\mathrm{UU}}$$

Relaxation-time approximation

- **classical case**

$$\left(\frac{\partial f}{\partial t}\right)_{\mathrm{coll}} = -\frac{f - f^0}{\tau} = -\frac{\delta f}{\tau}$$



$$f^0 = f^0(\boldsymbol{r}, \boldsymbol{p})$$

a distribution function describing a *local equilibrium*

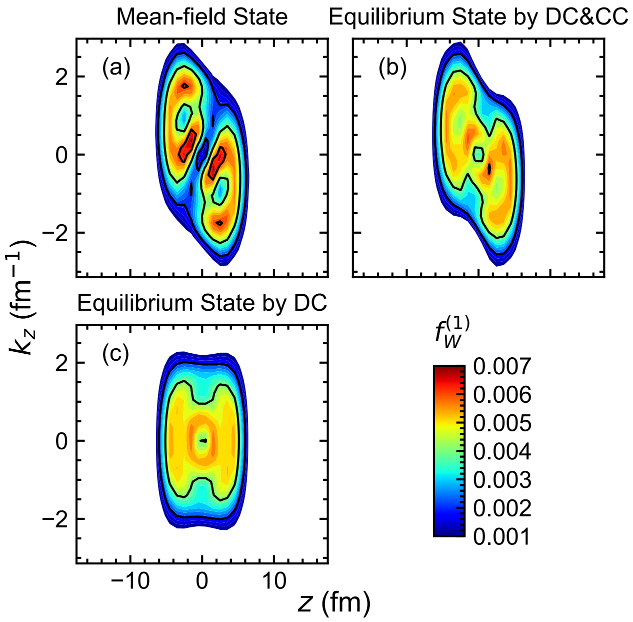
average free time

$$1/\tau = n\bar{v}_{\mathrm{rel}}\sigma$$

D. Arovas, Thermodynamics and Statistical Mechanics

- **nuclear case**

quantum equilibrium state calculated by density & current constraint Hatree-Fock



PRC 32.172 (1985)

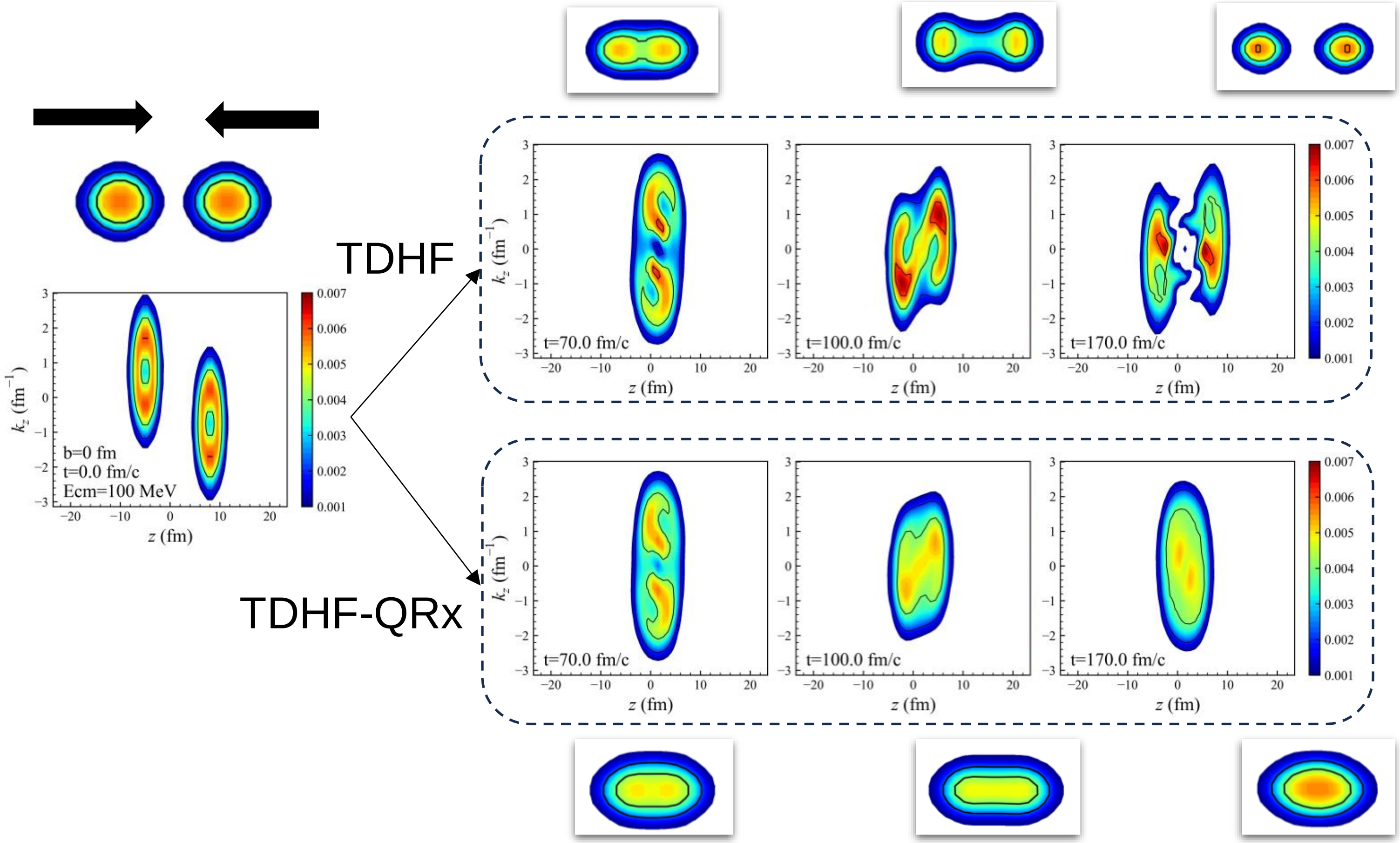
The relaxation time for nuclear matter

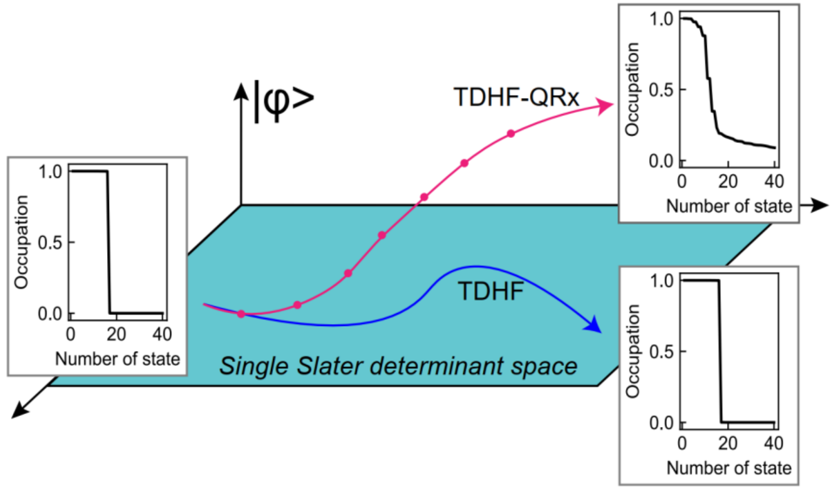
$$\hbar\tau_{\mathrm{relax}}^{-1} = 7.9\hbar^2\sigma_{nn}v_{\mathrm{F}}\rho_0 T^2/\varepsilon_{\mathrm{F}}^2$$

Z. Physik A 289, 103 - 105 (1978)
AOP 354, 183–202 (2015)

Two-body dissipation effects

- $^{16}O+^{16}O$ central collisions



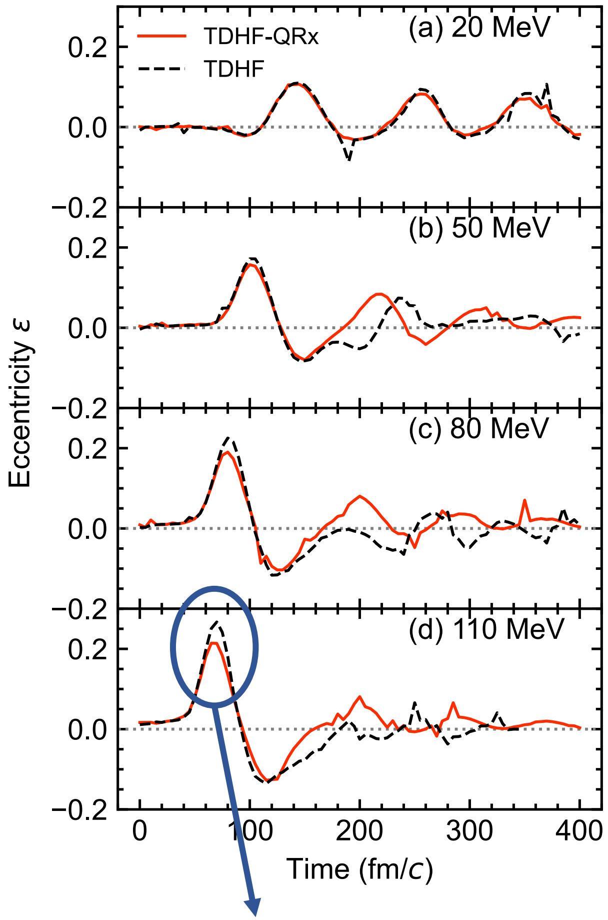


- beyond mean-field description of reactions for TDHF-QRx

Two-body dissipation effects

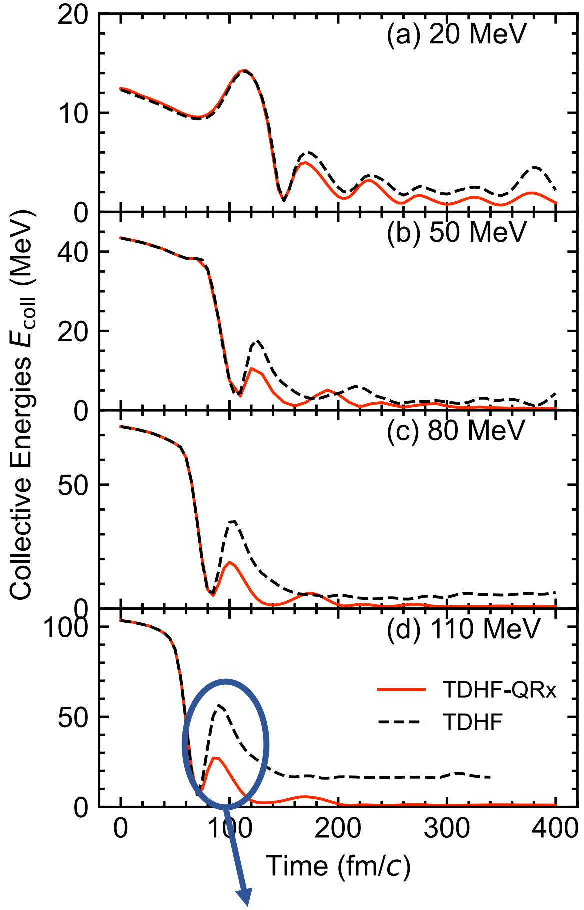
- $^{16}O+^{16}O$ central collisions

Phase-space eccentricity



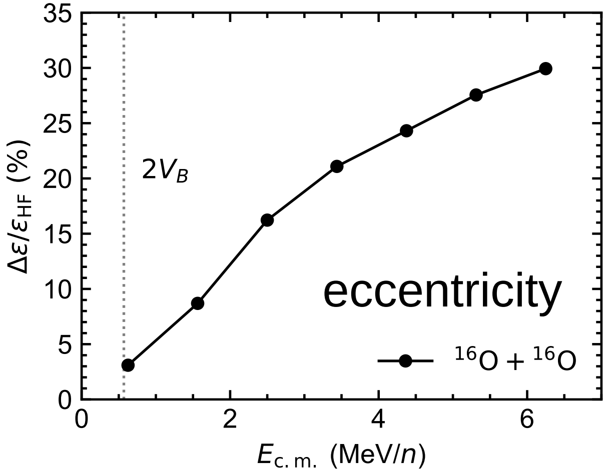
higher phase-space equilibrium

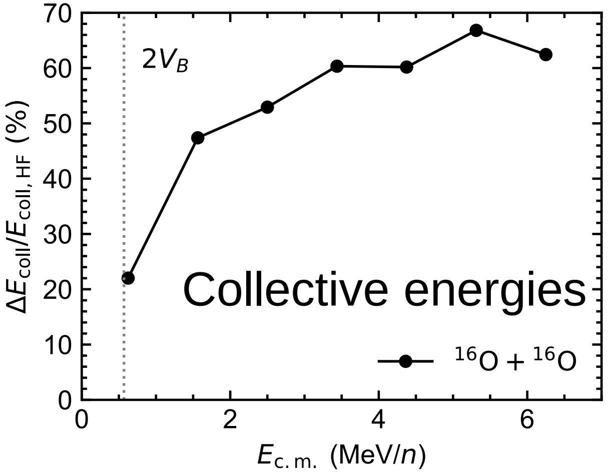
Collective energies



higher dissipation

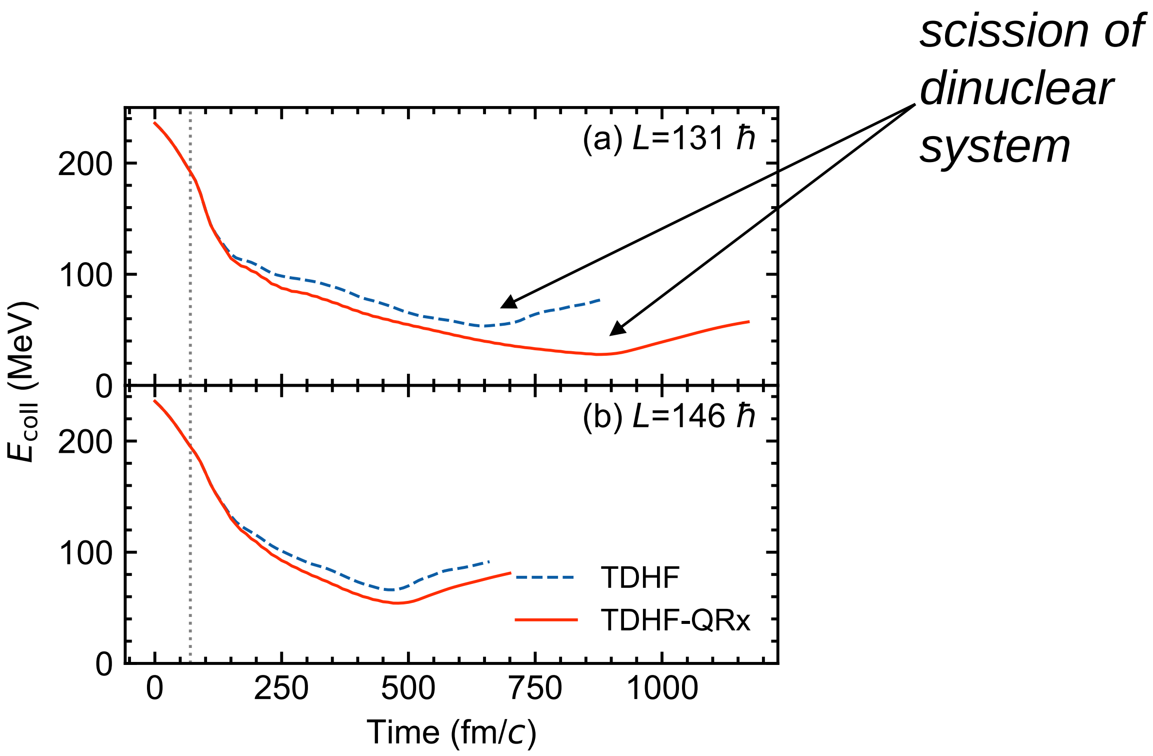
Relative deviation:

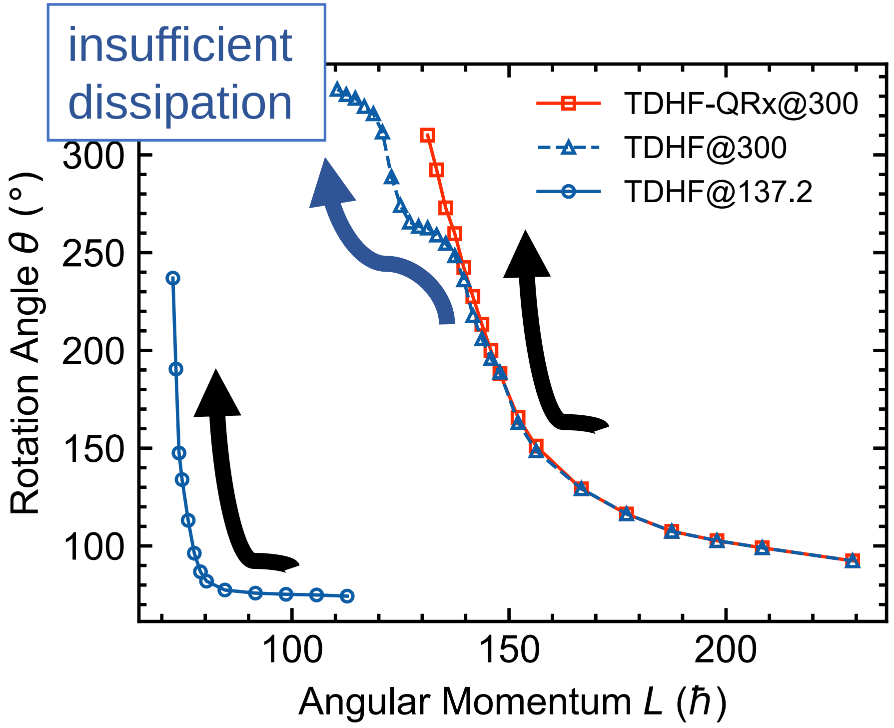




Two-body dissipation effects

- $^{60}Ni+^{60}Ni$ non-central collisions





- longer contact time → deeper equilibrium process
- better description of dissipation-L correlation

Summary

- The dissipation describes the energy transformations from collective to internal d.o.f, widely existing in nuclear reactions.
- Based on the TDHF, we apply the quantum relaxation-time approximation (QRTA) to address the two-body collisions, developing the new version of TDHF-QRx approach.
- We show the effects of two-body dissipation on the process and fragments of heavy-ion collisions, showing capability in studying the dissipation dynamics well above fusion barrier within quantal framework.

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Thanks for your attention !