Analysis of kinetic energy dissipation by collision angle in Multi-nucleon Transfer Reactions

Toward understanding the mechanism of Multi-nucleon transfer reactions!

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Outline

1. Introduction
   - – Background and significance of multinucleon transfer reactions
   - – Motivation for theoretical study
2. Theoretical Framework
   - – Model and methods used

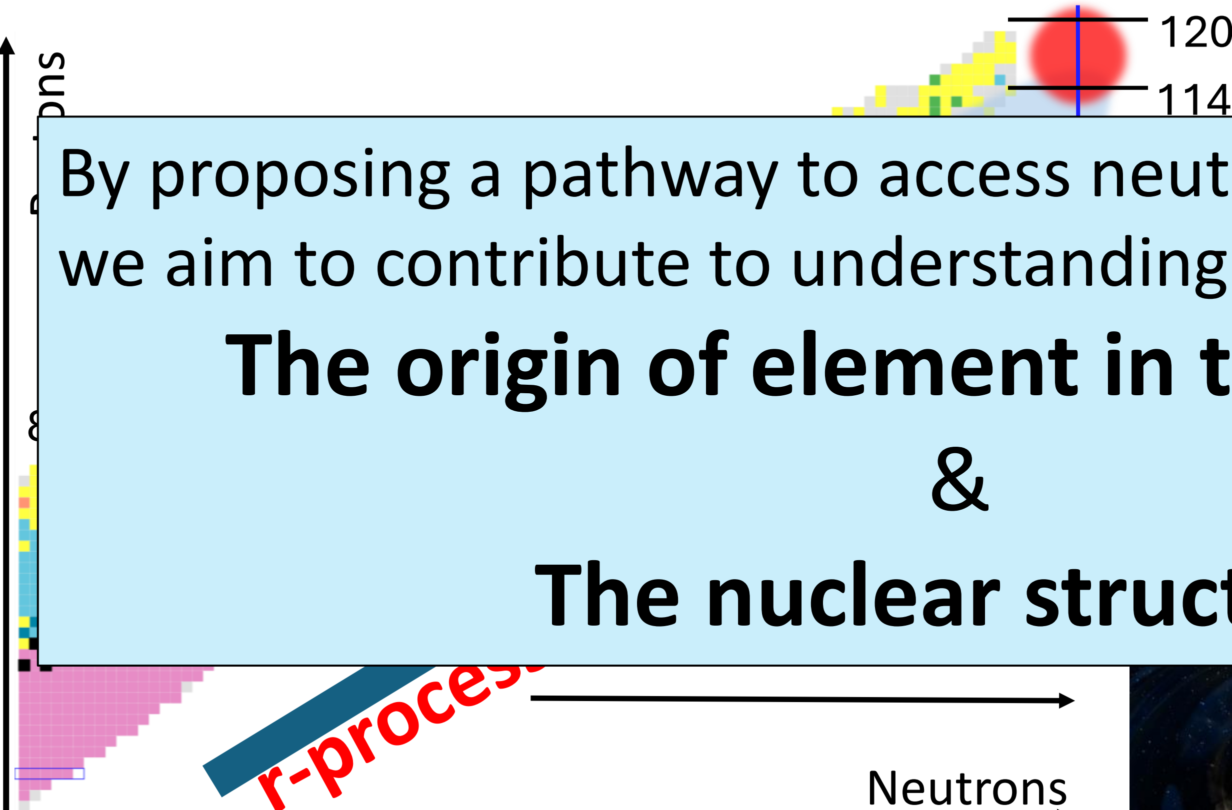
Skip Some

In the morning section
K. Okada (JAEA)
Y. Aritomo (Kindai Univ.)

3. Results and Discussion
   - – Key predictions from the calculations
   - – Discussion of their results
4. Conclusion
   - – Summary

Production of neutron-rich nuclei in **heavy/superheavy** region

Primary objective :
To clarify the mechanism of producing neutron-rich nuclei in the heavy/superheavy region



Island of Stability

NNDC

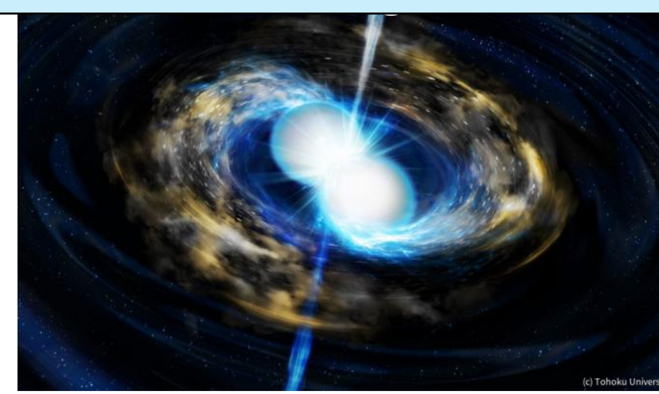
Nuclear chart

By proposing a pathway to access neutron-rich nuclei,
we aim to contribute to understanding

The origin of element in the universe

&

The nuclear structure



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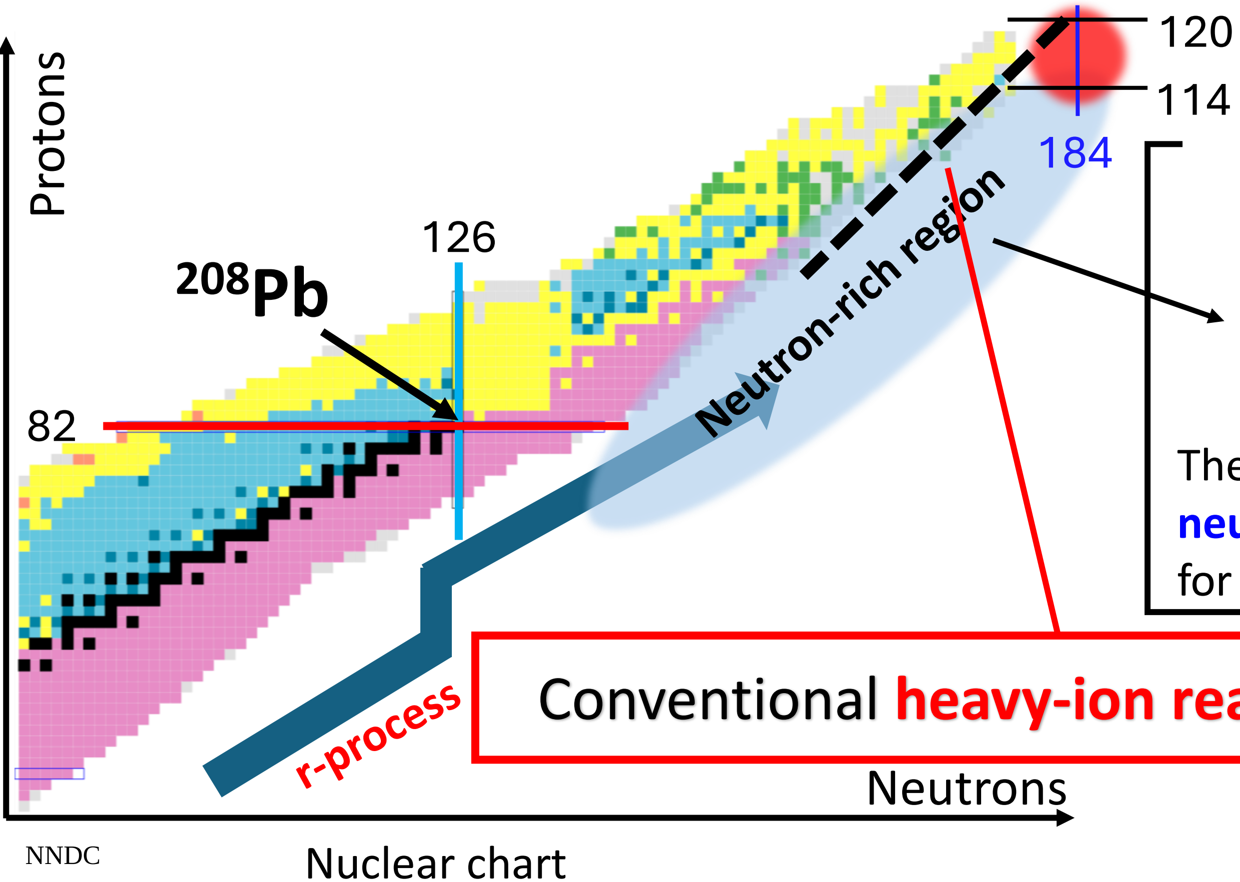
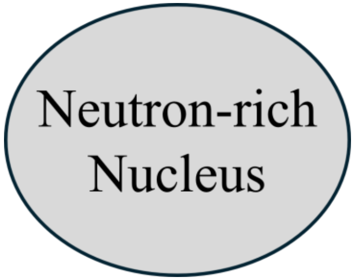


Nuclear chart

Aimed neutron-rich nuclei

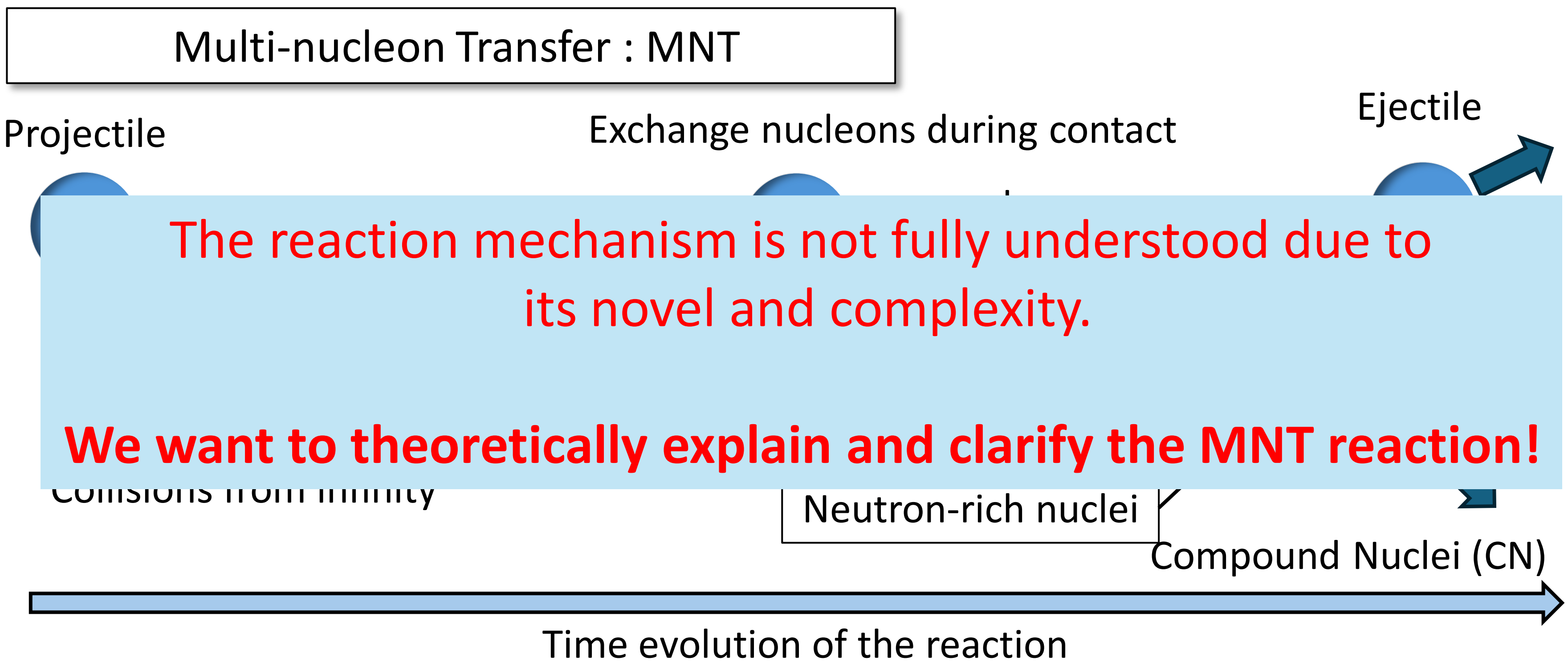


The production of **unknown neutron-rich nuclei** is necessary for **"two topics"**.

Conventional **heavy-ion reactions** have limitations

Multi-nucleon transfer (MNT) reaction approach

Therefore, MNT reaction approach has recently attracted attention as a method of producing neutron-rich nuclei.



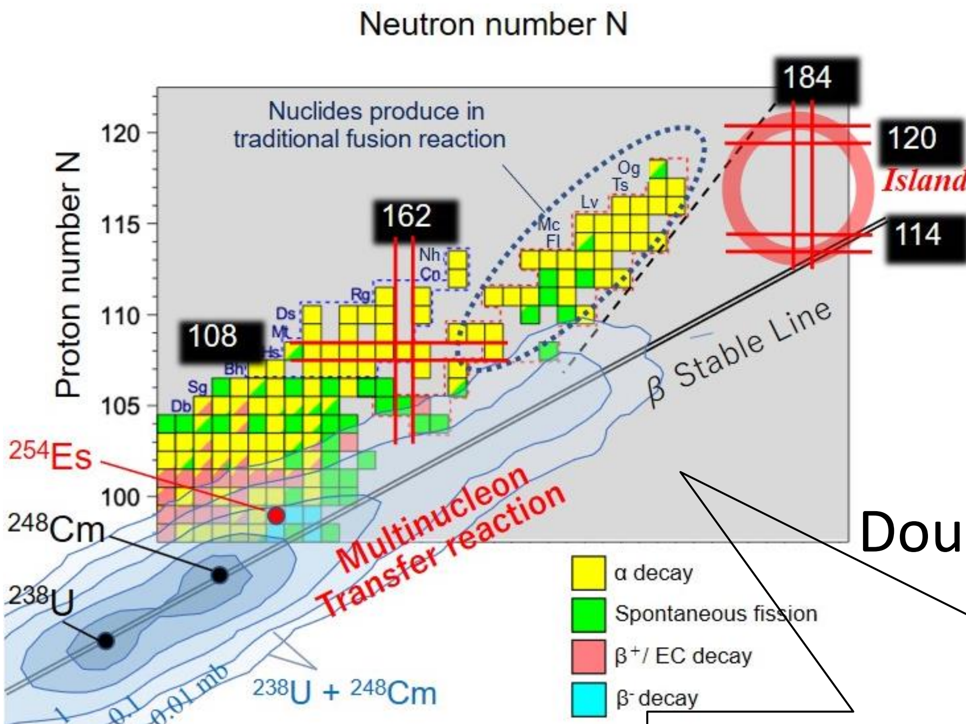
The reaction mechanism is not fully understood due to its novel and complexity.

We want to theoretically explain and clarify the MNT reaction!

This reaction overcomes the limitations of conventional method

MNT reaction for future works

MNT reaction for synthesis of Island of stability and SHE

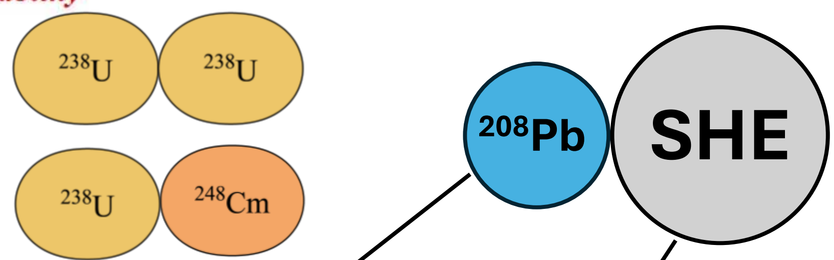


Calculation from reference (JAEA Nishio)

Such as $^{238}U+^{238}U$, $^{238}U+^{248}Cm$

at collision

post-collision



Double magic effects

Counterpart of **^{208}Pb**

Reaching the "**Island of Stability**" is suggested

of macroscopic calculation

Our dynamical model has advantages

Zagrebeav *et al.*, Phys. Rev. C **73,** 031602 (2006).

Summary of Background and Motivation

- **Our primary objective** is to clarify the mechanism of producing neutron-rich nuclei in the heavy/superheavy regions
- **Limitations of conventional methods** in accessing unknown neutron-rich nuclei in these regions
- **Attention to MNT reaction** as a promising alternative approach

Background

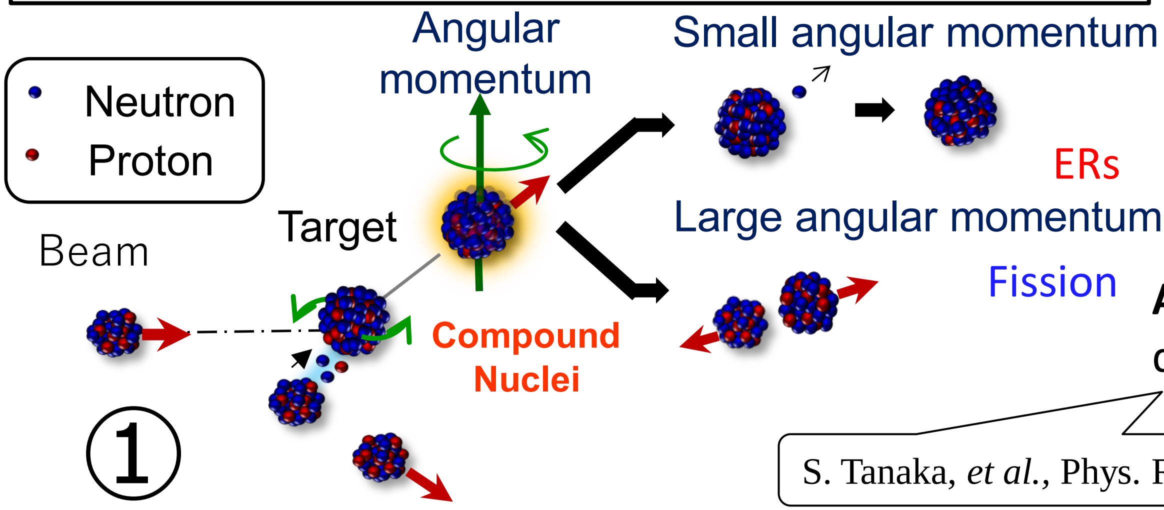
- This study aims to investigate the mechanism of MNT reactions
- In this presentation, we focus on:
  - Angular momentum of Compound Nuclei (CN)
  - Energy dissipation of $E_{c.m.}$

Motivation

To understand the mechanism of MNT reaction

The case if CN is a heavy or superheavy nucleus

by JAEA (Dr. Nishio)



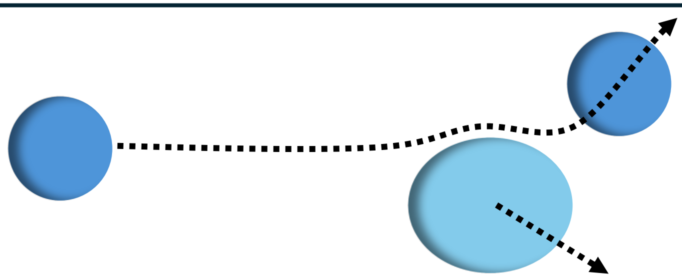
Important physical quantity

Angular momentum of the CN determines the fission or survival.

S. Tanaka, *et al.*, Phys. Rev. C**105**, L021602 (2022).

Need the highly accurate prediction of **angular momentum** by theoretical models.

②



Projectile’s kinetic energy → Internal energy

Dissipation

It is a key quantity in determining the excitation energy.

Details of this study

1. The consideration of deformed target nuclei (stable actinide nuclei) to access the heavy and superheavy regions
2. The inclusion of the collision angle, which becomes important when using deformed targets

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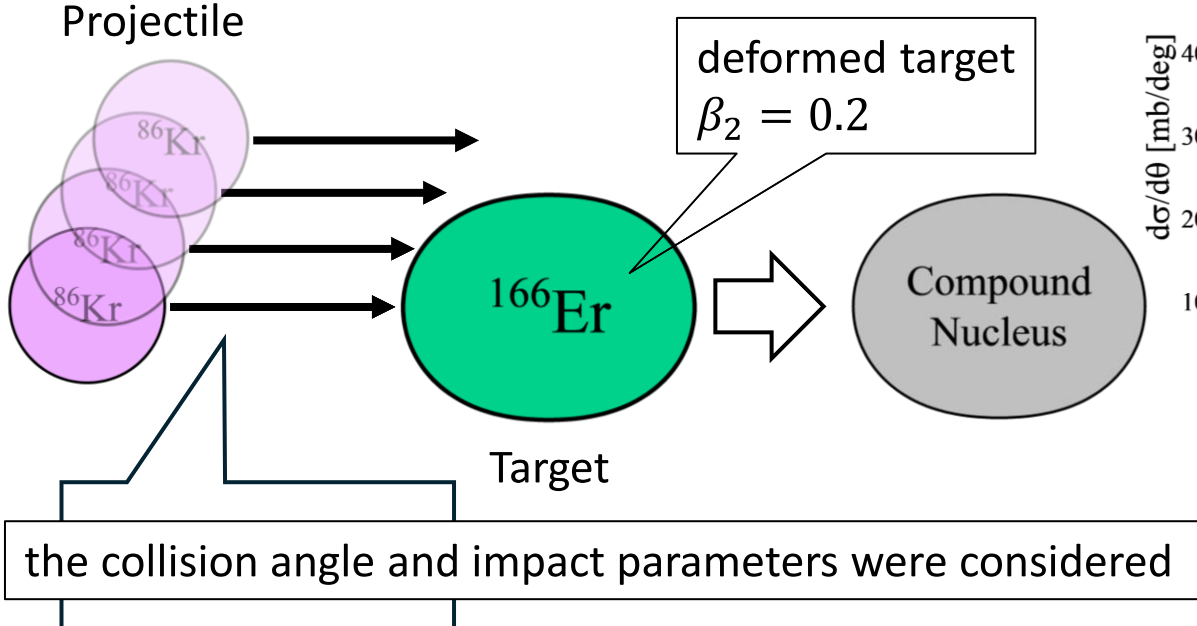
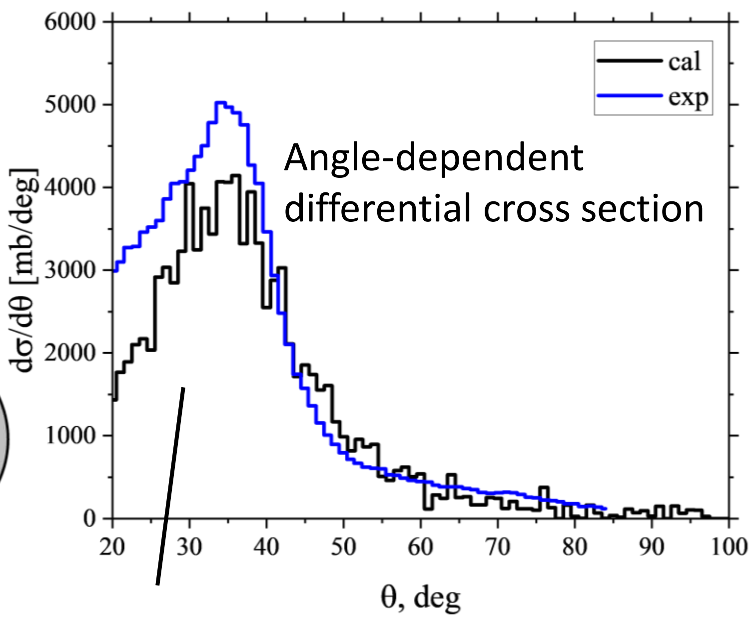
Conditions of this calculation





Each parameter was determined by fitting to experimental data.

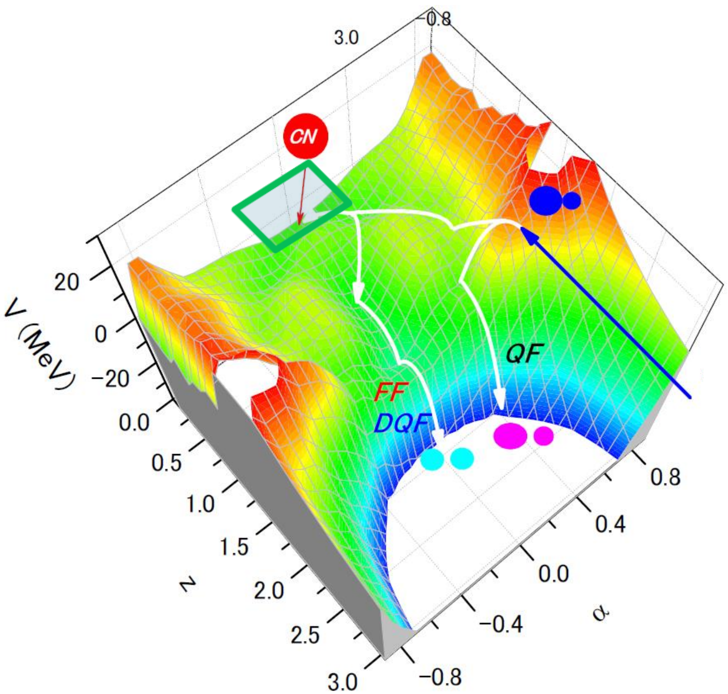
Gobbi A, Lynen U, Olmi A, Rudolf G and Sann H 1981 Proc. Int. School of Phys. 'Enrico Fermi', Course LXXVII (Varenna, 1979) (Amsterdam: North-Holland) p 1

Dynamical Model

Dynamical Model

➞ Possible to follow the time evolution of the shape of the nucleus

Two-center Shell Model (TCSM) + Langevin equation



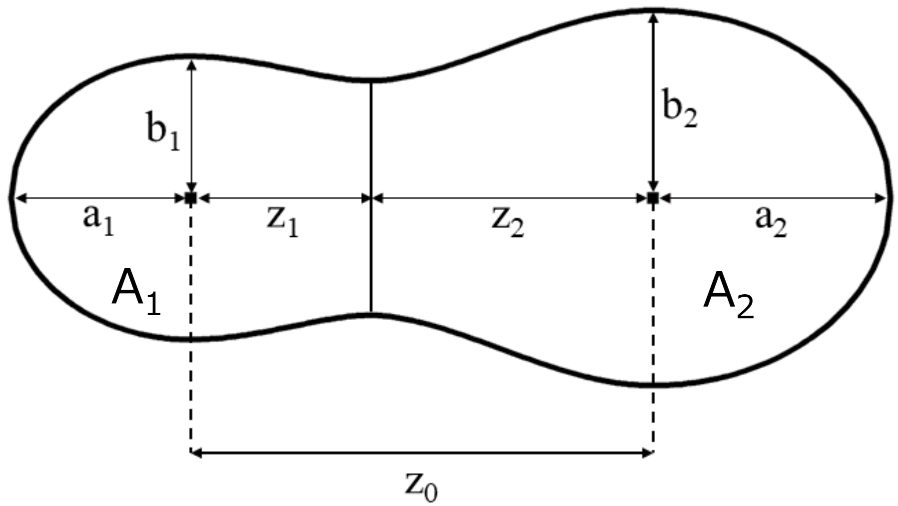
Required for dynamical model

- Potential for the shape of the nucleus represented by **Two-center Shell Model**
- Equation of motion (**Langevin equation**) to calculate trajectory using potential

Two-center shell model

Collective coordinates $q(z,\delta,\alpha)$

- ✓ Two center of distance : $z = \dfrac{z_0}{R_{CN} B}$
- ✓ Deformation : $(\delta_1 = \delta_2)$ $\delta = \dfrac{3(a-b)}{2a+b}$
- ✓ mass asymmetry : $\alpha = \dfrac{A_1 - A_2}{A_1 + A_2}$



Configuration of the nucleus

centre distance ：$z_0 = |z_1| + |z_2|$

scaling parameter ：$B = \frac{3+\delta}{3-2\delta}$

$R_{CN} = r_0 (A_{CN})^{1/3}, r_0 = 1.2\text{fm}$

A_1： mass of fragment1

A_2： mass of fragment2

A_{CN}： mass of CN

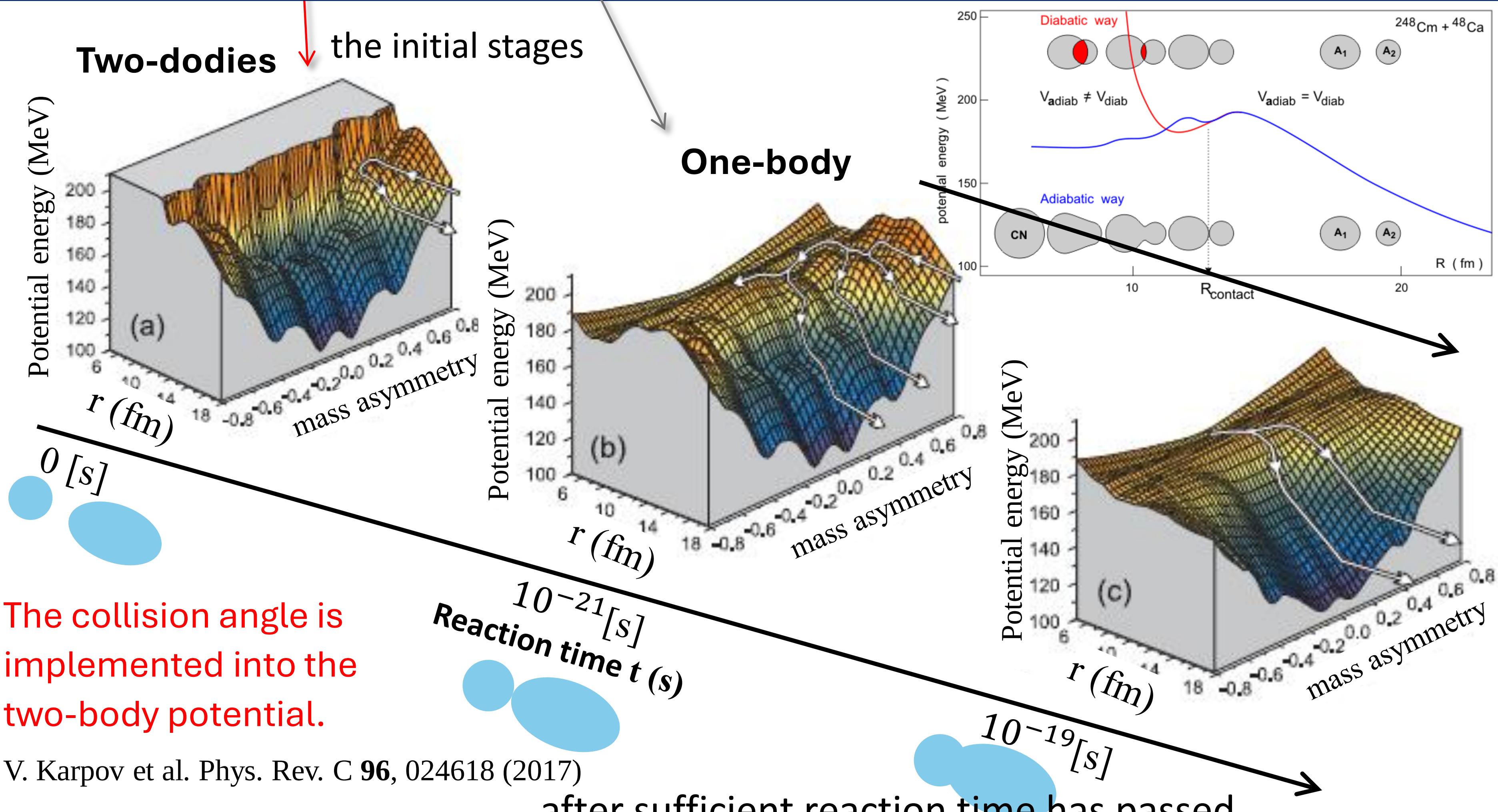
Maruhn and Greiner, Z. Phys. 251(1972) 431

Transition from two-body to one-body potential

$$V(q,\mathrm{t}) = V_{\mathrm{dia}} f_{\epsilon}(t) + V_{\mathrm{adi}}[1 - f_{\epsilon}(t)]$$

$$f_{\epsilon} = \frac{1}{1+\exp(-\frac{t}{\tau_{relax}})}$$

$$\tau_{\mathrm{relax}} = 1.0 \times 10^{-21}\ [\mathrm{s}]$$



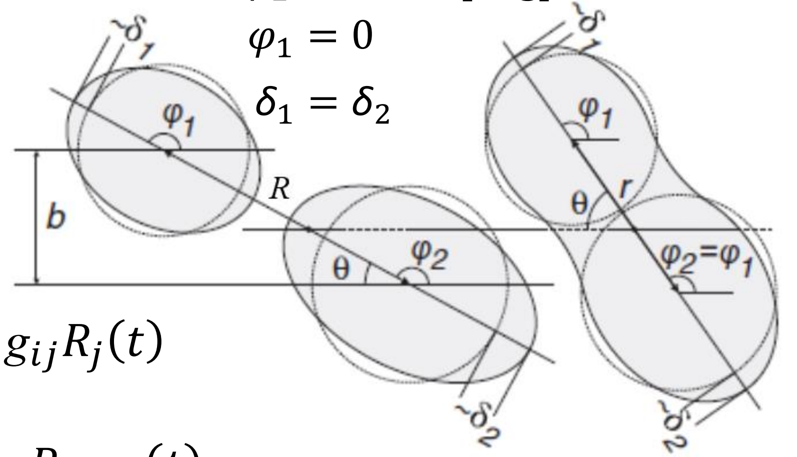
The collision angle is implemented into the two-body potential.

V. Karpov et al. Phys. Rev. C **96**, 024618 (2017)

after sufficient reaction time has passed

Multi-dimensional Langevin equation

$\varphi_2 = 0\sim 90$ [deg]
$\varphi_1 = 0$
$\delta_1 = \delta_2$



$$\frac{dq_i}{dt} = (m^{-1})_{ij}p_j, \qquad \frac{d\theta}{dt} = -\frac{l}{\mu_R R^2},$$

$$\frac{d\varphi_1}{dt} = \frac{L_1}{\xi_1}, \qquad \frac{d\varphi_2}{dt} = \frac{L_2}{\xi_2}, \qquad a_{1,2} = \frac{R}{2} \pm \frac{(R_1 - R_2)}{2}$$

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk}p_j p_k - \gamma_{ij}(m^{-1})_{jk}p_k + g_{ij}R_j(t)$$

$$\frac{dl}{dt} = -\frac{\partial V}{\partial \theta} - \gamma_{tang}\left(\frac{l}{\mu_R R} - \frac{L_1}{\xi_1}a_1 - \frac{L_2}{\xi_2}a_2\right)R + Rg_{tang}R_{tang}(t)$$

$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{tang}\left(\frac{l}{\mu_R R} - \frac{L_1}{\xi_1}a_1 - \frac{L_2}{\xi_2}a_2\right)a_1 - a_1 g_{tang}R_{tang}(t)$$

$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{tang}\left(\frac{l}{\mu_R R} - \frac{L_1}{\xi_1}a_1 - \frac{L_2}{\xi_2}a_2\right)a_2 - a_2 g_{tang}R_{tang}(t)$$

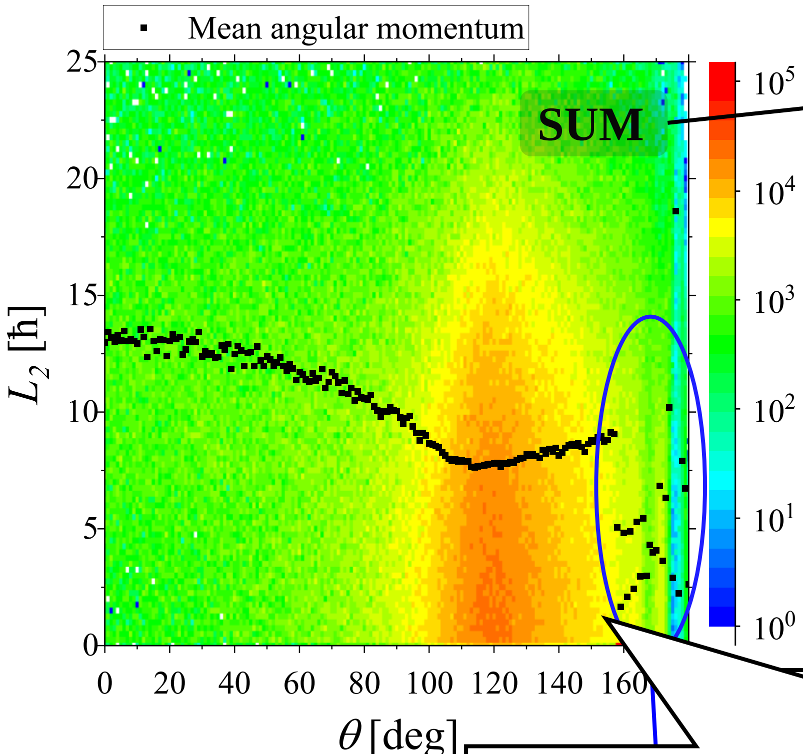
V. Zagrebaev and W. Greiner
J. Phys. G: Nucl. Part. Phys. **34** 1(2007);
J. Phys. G: Nucl. Part. Phys. **34** 2265(2007);
J. Phys. G: Nucl. Part. Phys. **31** 825(2005);
*A. V. Karpov and V. V. Saiko,PhysRevC.**96**.024618*

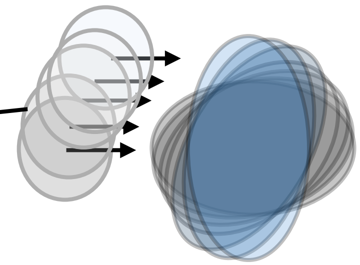
R : centre of distance
$R_{1,2}$: nuclear radius
θ :relative angle
l: relative angular momentum

$\varphi_{1,2}$: rotation angle
$\xi_{1,2}$: moment of inertia
$L_{1,2}$: angular momentum
γ_{tang} : tangential friction

γ_{ij}: Wall and Window dissipation (Friction)
m_{ij}: Hydrodynamical mass (Inertia)
$\langle R_i(t)\rangle = 0, \langle R_i(t_1)R_j(t_2)\rangle = 2\delta(t_1 - t_2)$: White noise (Markovian process)
g_{ij}: Random force(fluctuation) $\sum_k g_{ik}g_{jk} = T\gamma_{ij}$: Einstein relation

Analysis of calculation results 1

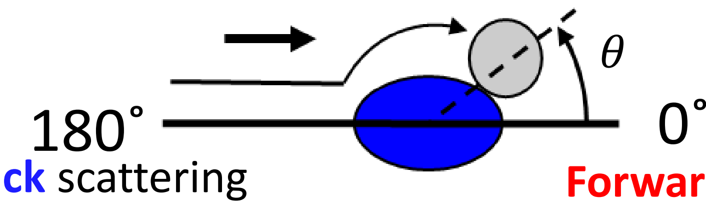




All impact parameters and collision angles are considered

θ : scattering angle of PLF

L_2 : angular momentum of TLF (CN)



scattering

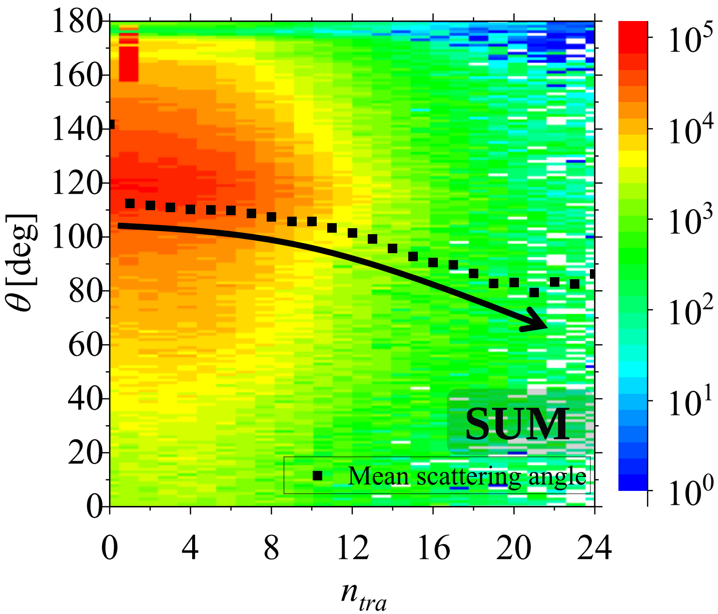
Mean L_2 is relatively small

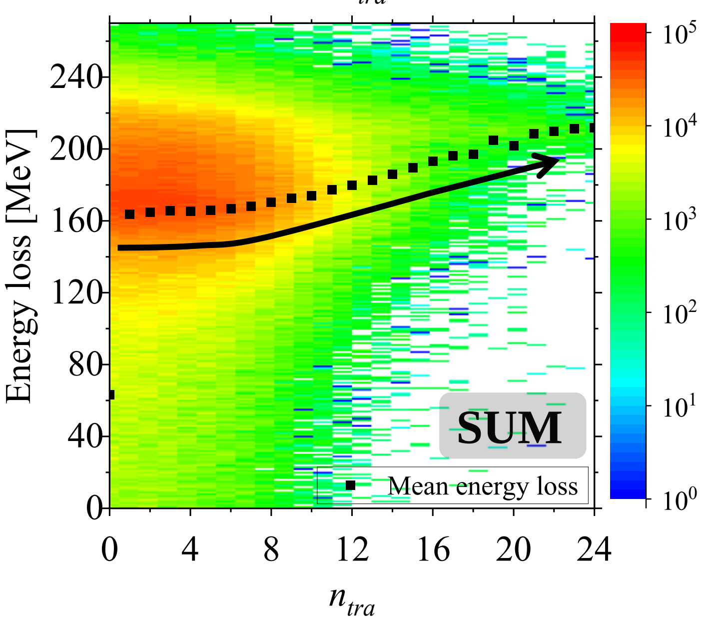
Fewer events

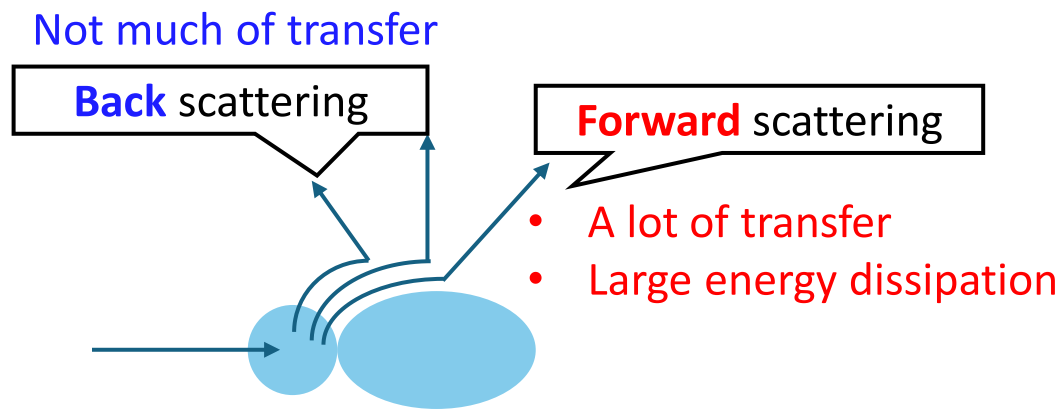
This figure is useful for predicting angular momentum from the scattering angles that can be measured experimentally.

Angular momentum brought into CN is dominated by contact time.

Analysis of calculation results 2







Forward scattering tendency is strongly suggested when the nucleon transfer increases.

➡Longer contact time increases nucleon transfer.

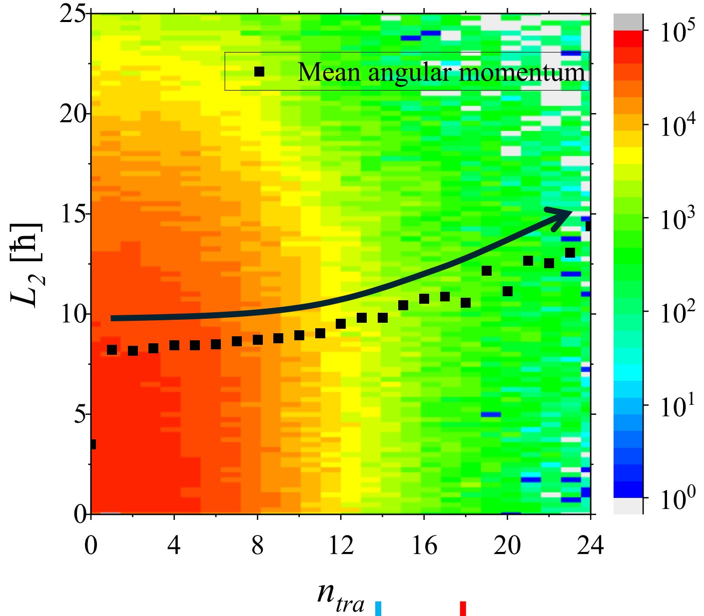
As the nucleon transfer increases, energy dissipation also increases.

➡Longer contact time increases energy dissipation.

n_{tra} : the number of nucleon transfer to the target

$Energy\ loss$: Energy dissipation of $\boldsymbol{E_{c.m.}}$

Analysis of calculation results 3



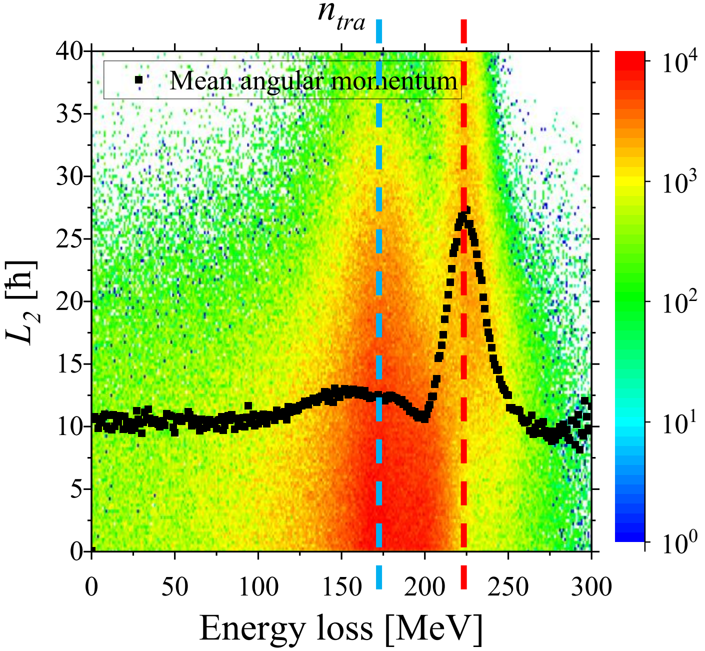
As the nucleon transfer increases,

the angular momentum also increases.

➡ It is clear from relationship between :

- Contact time and angular momentum
- Contact time and the nucleon transfer

From previous slides



The energy dissipation is particularly high with around 225 [MeV] and 117 [MeV]

➡ We analyzed two energy dissipation events based on trajectory of the nuclear shape obtained from the calculation.

- - - 225[MeV]

- - - 175[MeV]

Summary

1. Our primary objective is to clarify the mechanism of producing **neutron-rich nuclei in the heavy/superheavy regions**
2. Production of neutron-rich nuclei needs to understand of the **MNT reaction mechanism**
3. To clarify the mechanism, the relationship between E_{loss} and L_2, n_{tra}, and θ was investigated.
4. Toward future goals, considering collision angles by introducing deformed target
5. Analysis results :
    1. The L_2 brought into TLF is dominated by **contact time**
    2. **Longer contact time** increases n_{tra} and E_{loss}
    3. The E_{loss} are due to change in the number of masses

Thank you for your attention !