Dynamics of Low-Energy Heavy-Ion Collisions and the Synthesis of Exotic Nuclei

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Special thanks to:
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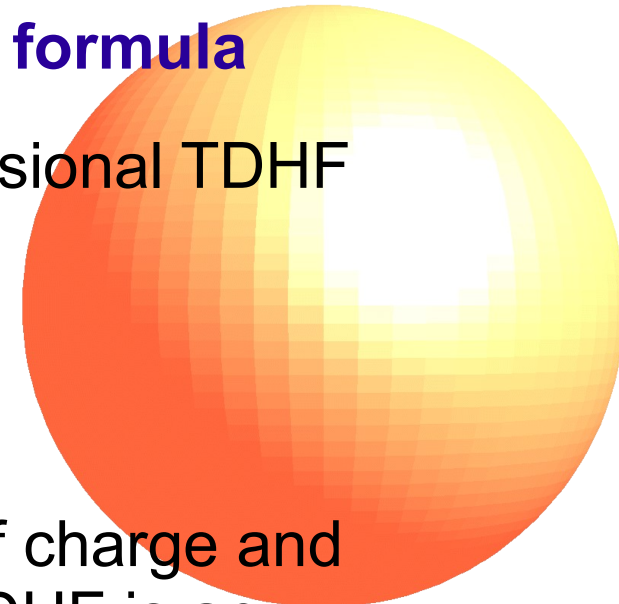
Contents

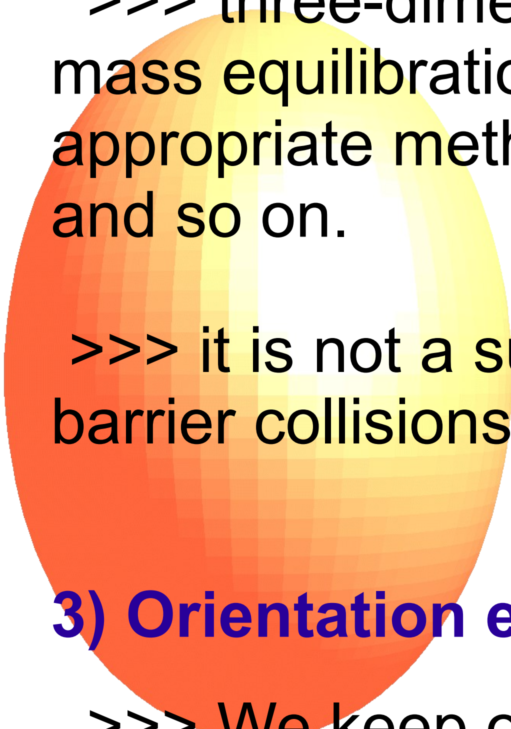
1) Charge equilibration upper energy-limit formula



>>> the validity is confirmed by three-dimensional TDHF calculations with a full Skyrme interaction

2) Charge and mass equilibration

>>> three-dimensional TDHF calculations of charge and mass equilibration is discussed, where the TDHF is an appropriate method naturally including the shell structure and so on.



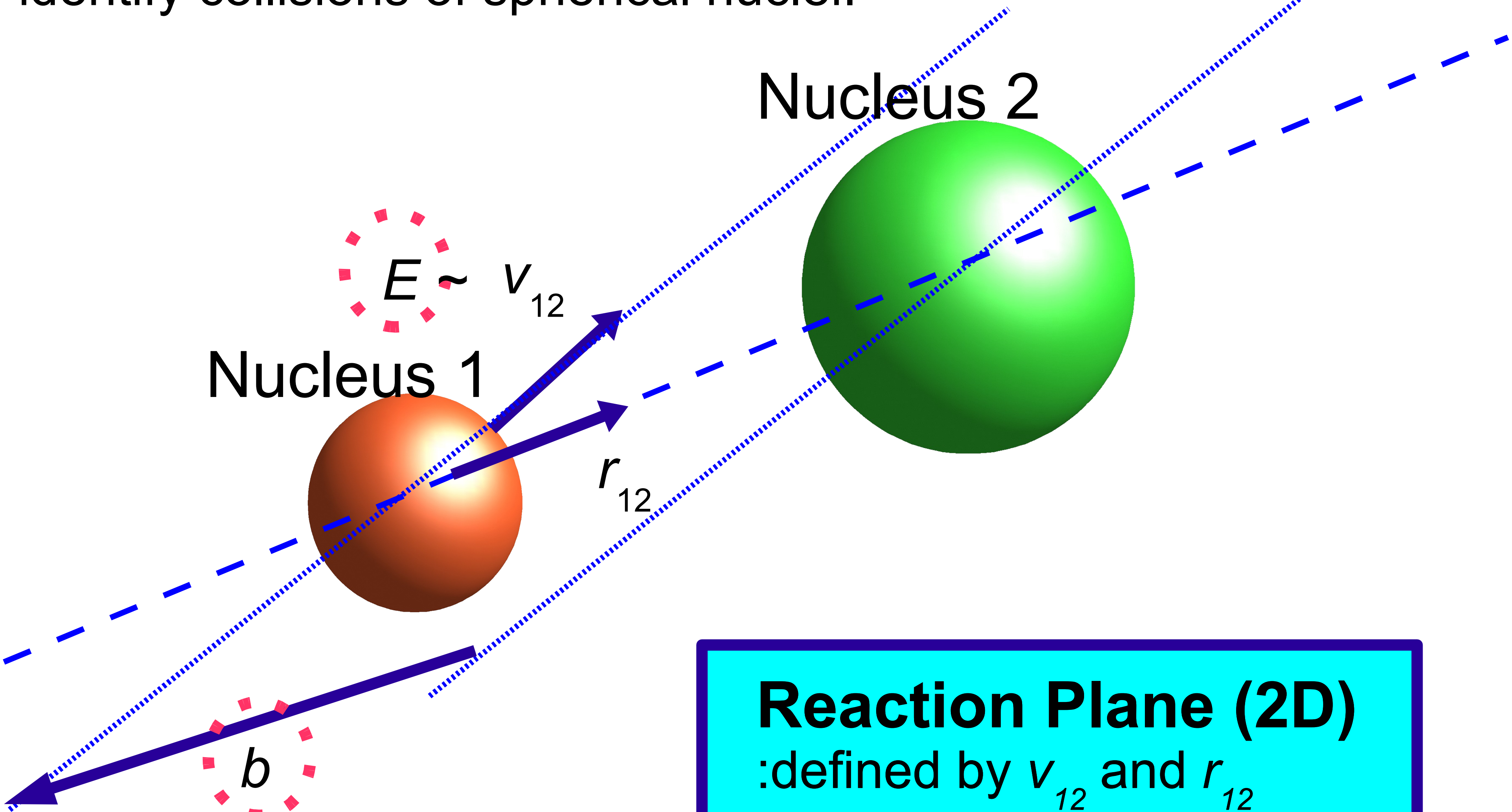
>>> it is not a sufficient method to investigate the sub-barrier collisions (tunneling process is hard to be treated).

3) Orientation effect (latest results, now studying...)

>>> We keep our eyes on the relation between C.E. and Orientation effect.

Heavy-ion collisions of spherical nuclei

Only v_{12} and r_{12} are two degrees of freedom to identify collisions of spherical nuclei.



Reaction Plane (2D)
:defined by v_{12} and r_{12}

3-dimensional TDHF calculations

Systematic 3-dimensional TDHF calculations with respect to **"bombarding energy"** and **"impact parameter"** is performed for the following reactions:

Each 1MeV/A

Each 2.5fm

TDHF calculations with SLy4 interaction

$^{208}Pb + ^{238}U$

$^{208}Pb + ^{132}Xe$

$^{208}Pb + ^{132}Sn$

$^{208}Pb + ^{24}Mg$

$^{208}Pb + ^{24}O$

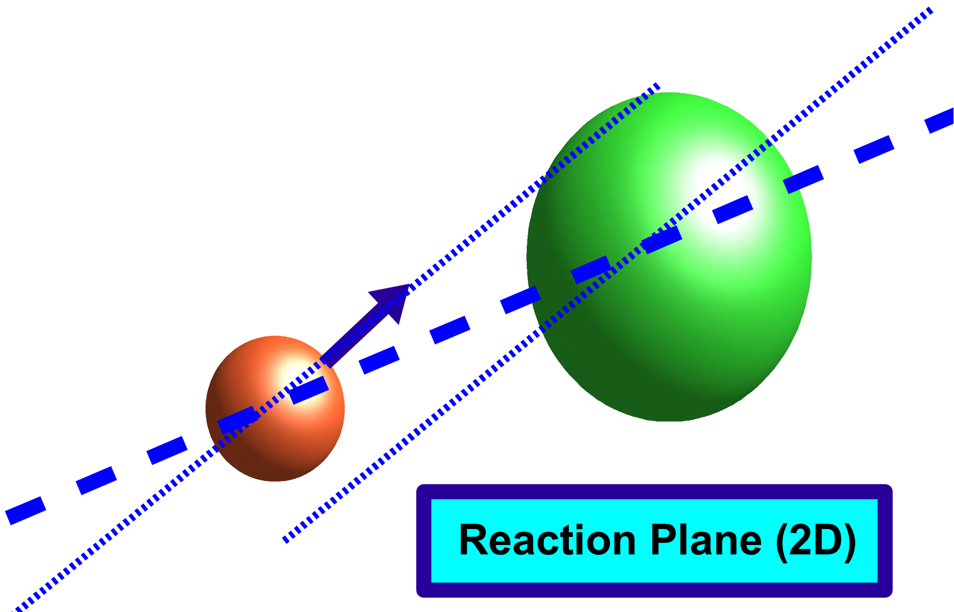
$^{208}Pb + ^{4}He$

$^{24}Mg + ^{24}O$

$^{208}Pb + ^{238}U$

This is a large-scale calculation using ~ 30 CPU with 50GB memory (Cluster-Machine+others)

As a result, we have been calculated during 1 ~ 3 months for each collision.



The concept: Charge equilibration

Charge equilibration is the homogenization of N/Z ratio during heavy-ion collisions.

Let us consider heavy-ion collisions of two different nuclei (more precisely, two nuclei with different N/Z ratio).

In some cases, N/Z ratio reaches the equilibrium during the collision, while it does not necessarily occurs. It depends on some conditions e.g. the bombarding energy, the impact parameter, and the sort of initial nuclei.

The equilibrium of N/Z ratio is called "**charge equilibrium**", and the process of reaching it during the collision is called "**charge equilibration**".

1) Charge equilibration upper energy-limit

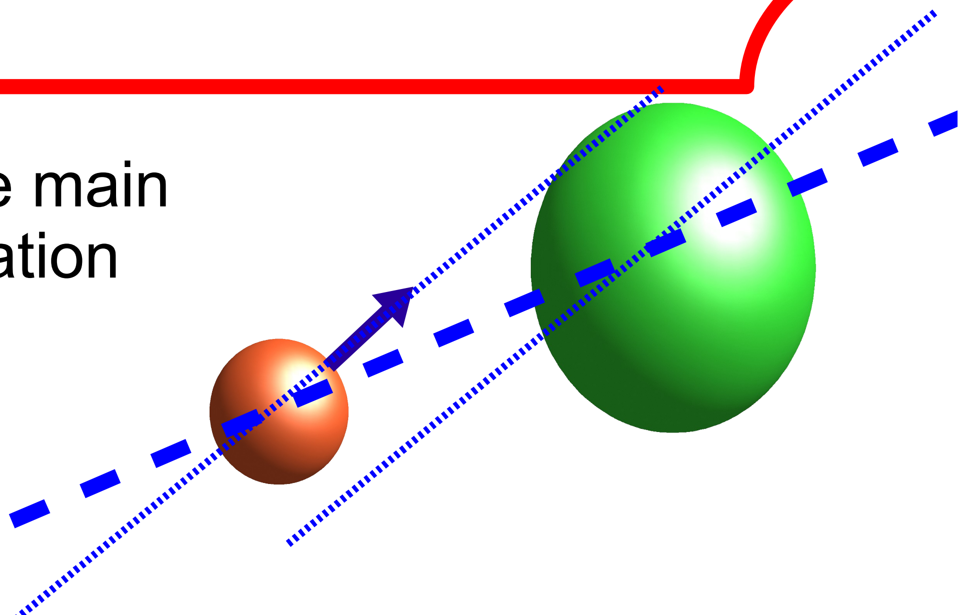
Question 1

Charge equilibration is considered to be empowered by

_ Isovector GDR
_ Symmetry energy
_ Diffusion process

But it has still been open what is the main driving force of charge equilibration.

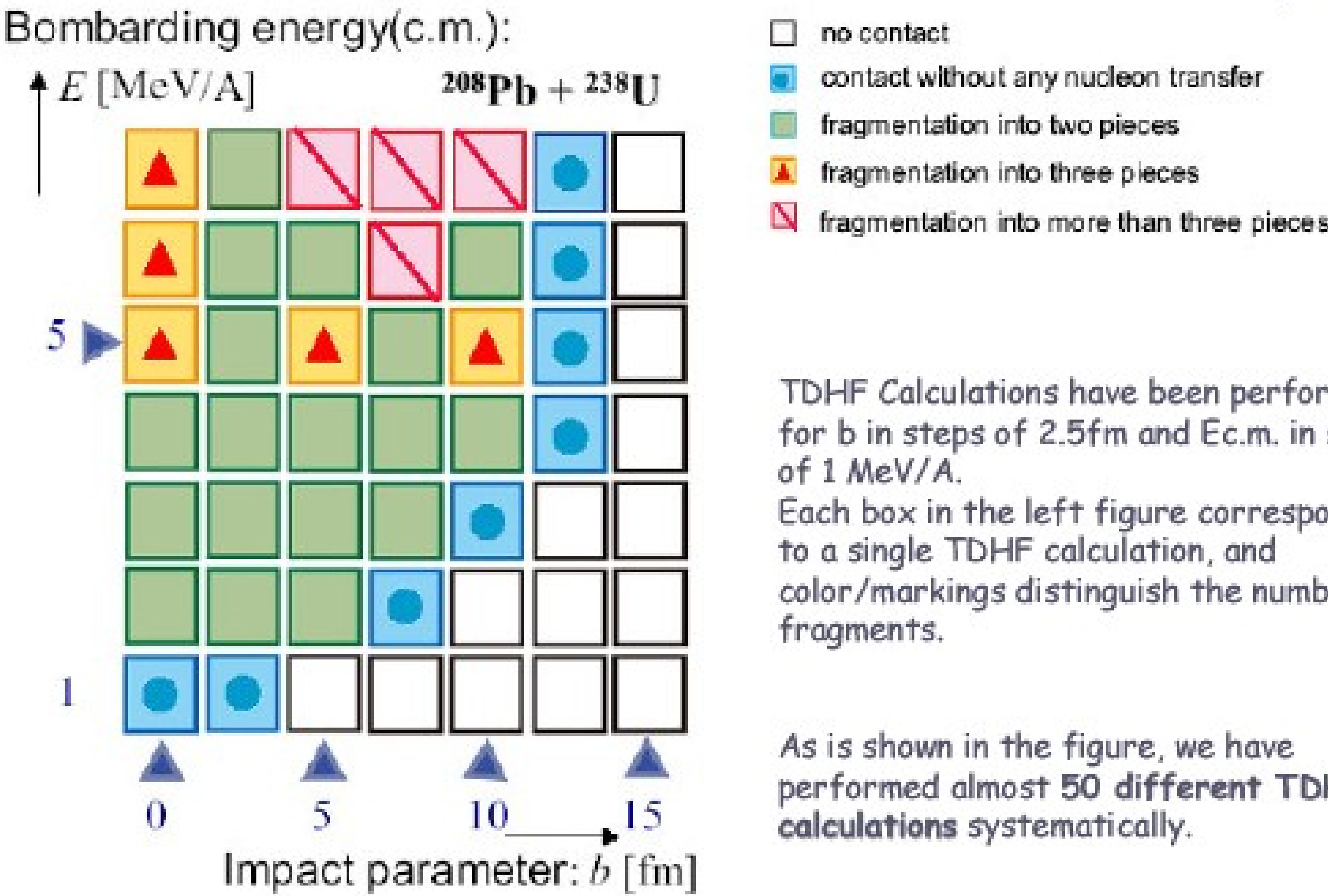
In this presentation, we discuss the main driving force of the charge equilibration based on the 3-dimensional TDHF calculations.



Example of $^{208}Pb + ^{238}U$

Systematic TDHF calculations

Sly4

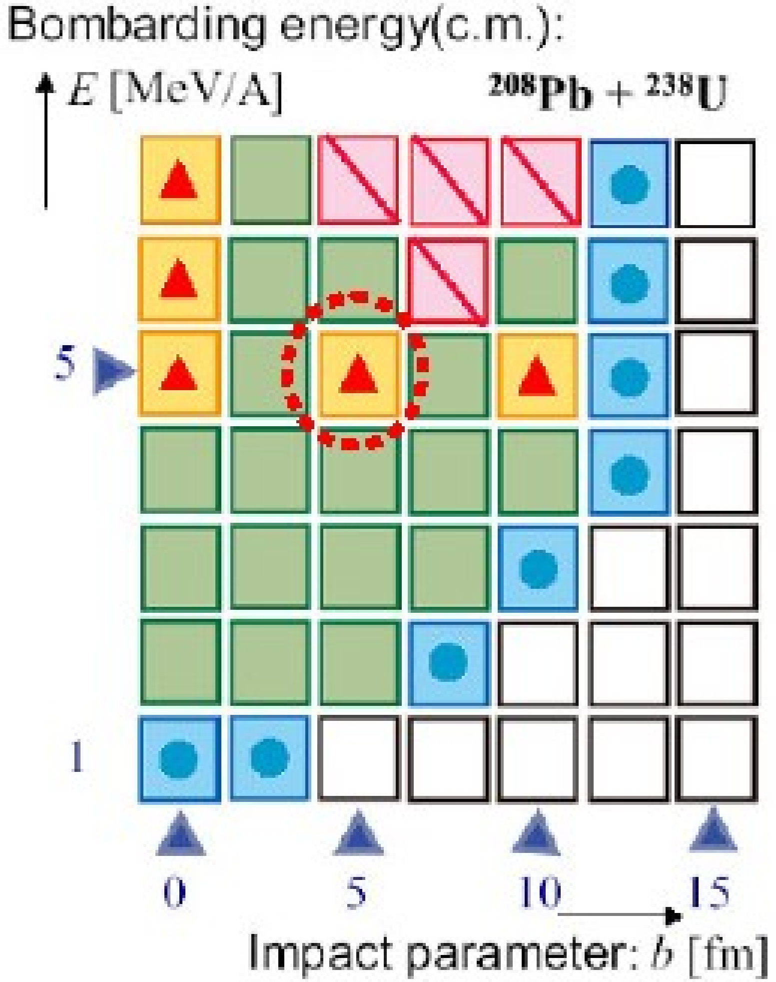


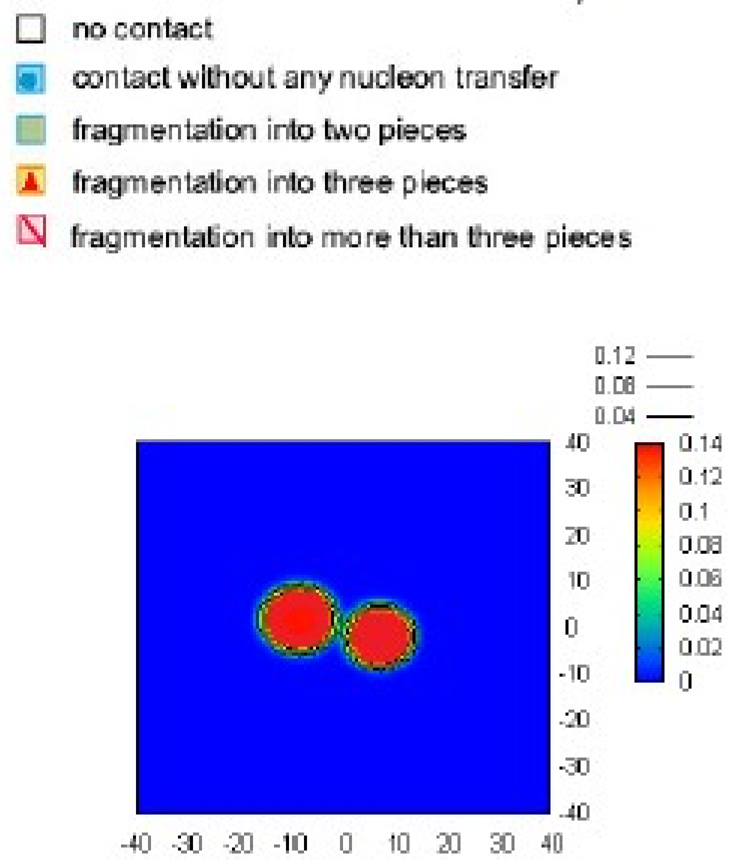
TDHF Calculations have been performed for b in steps of 2.5fm and Ec.m. in steps of 1 MeV/A.
Each box in the left figure corresponds to a single TDHF calculation, and color/markings distinguish the number of fragments.

As is shown in the figure, we have performed almost **50 different TDHF calculations** systematically.

Example (deep inelastic collision)

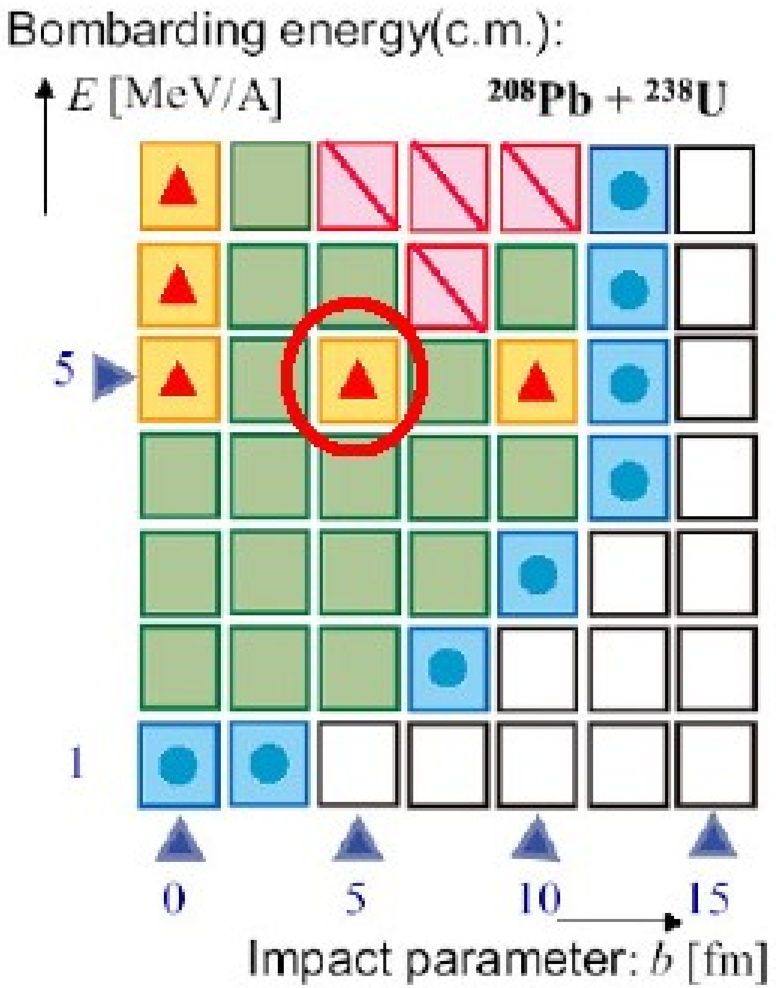
Sly4

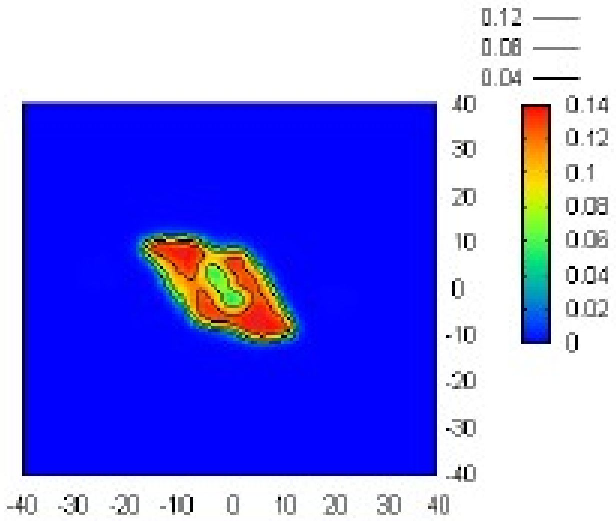




Example (deep inelastic collision)

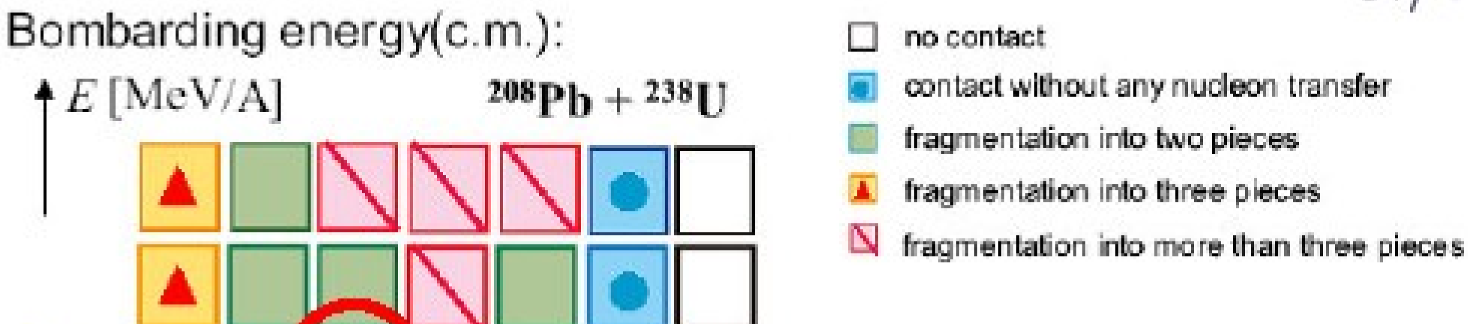
Sly4

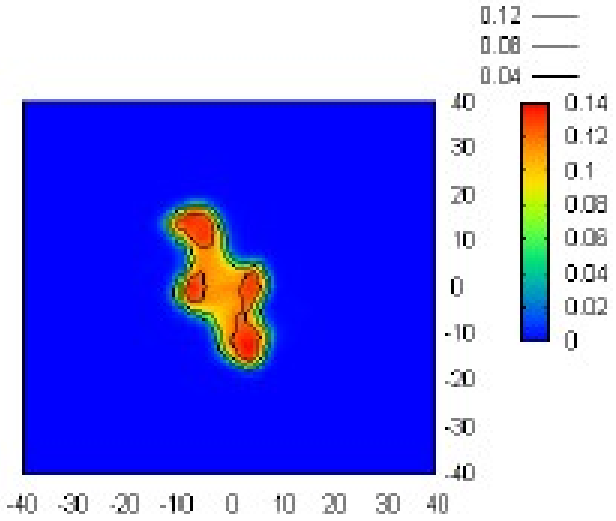




Example (deep inelastic collision)

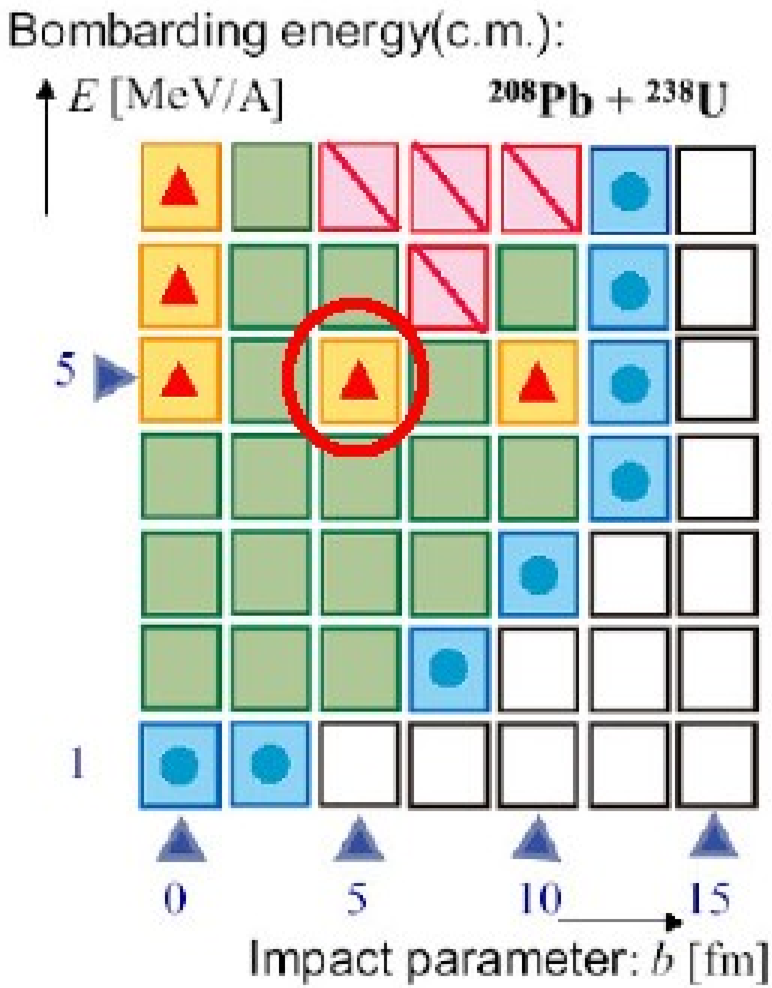
Sly4



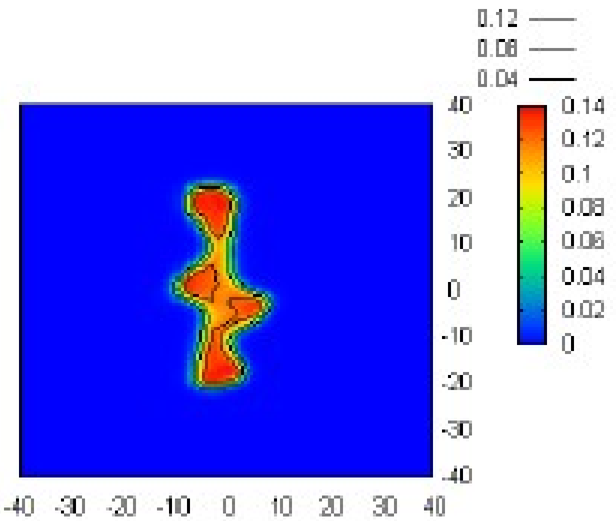


Example (deep inelastic collision)

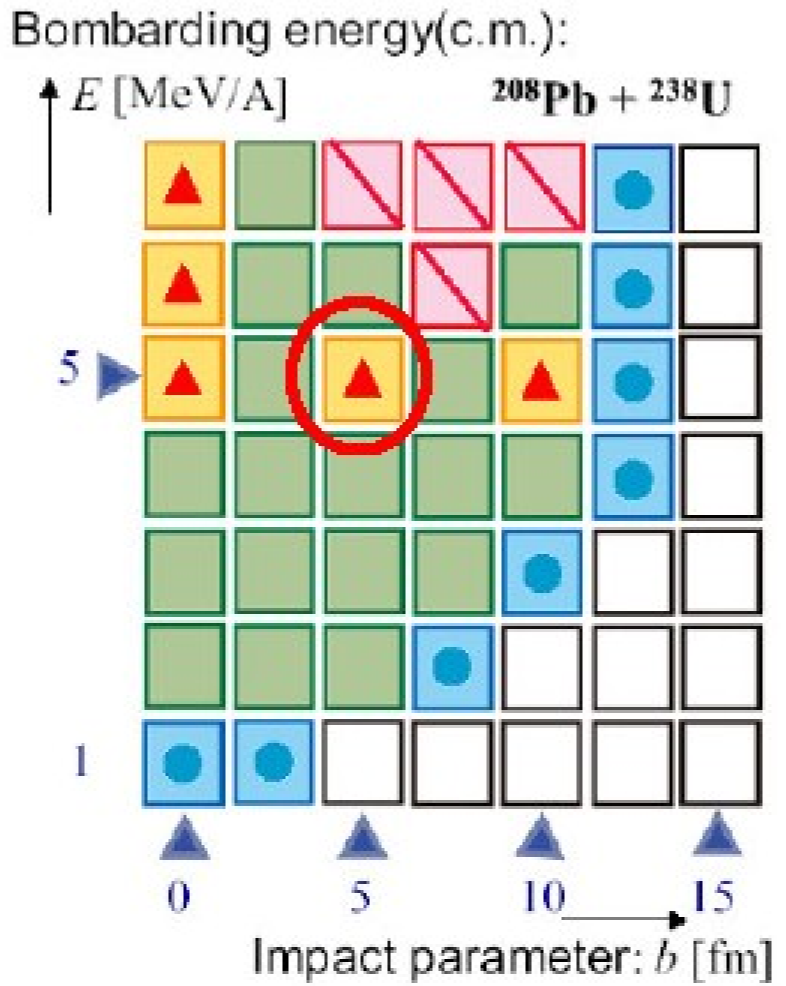
Sly4

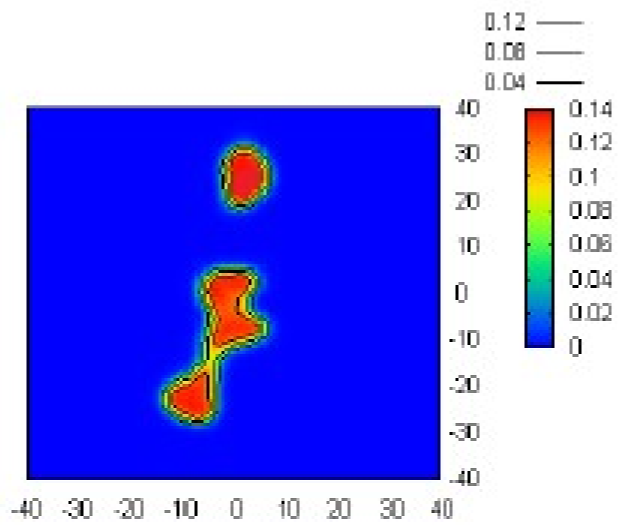


no contact
contact without any nucleon transfer
fragmentation into two pieces
fragmentation into three pieces
fragmentation into more than three pieces



Example (deep inelastic collision)





Example of $^{208}Pb + ^{238}U$

TDHF calculation

Energy dependence of the collision (Fixed impact parameter b = 9.2 fm)

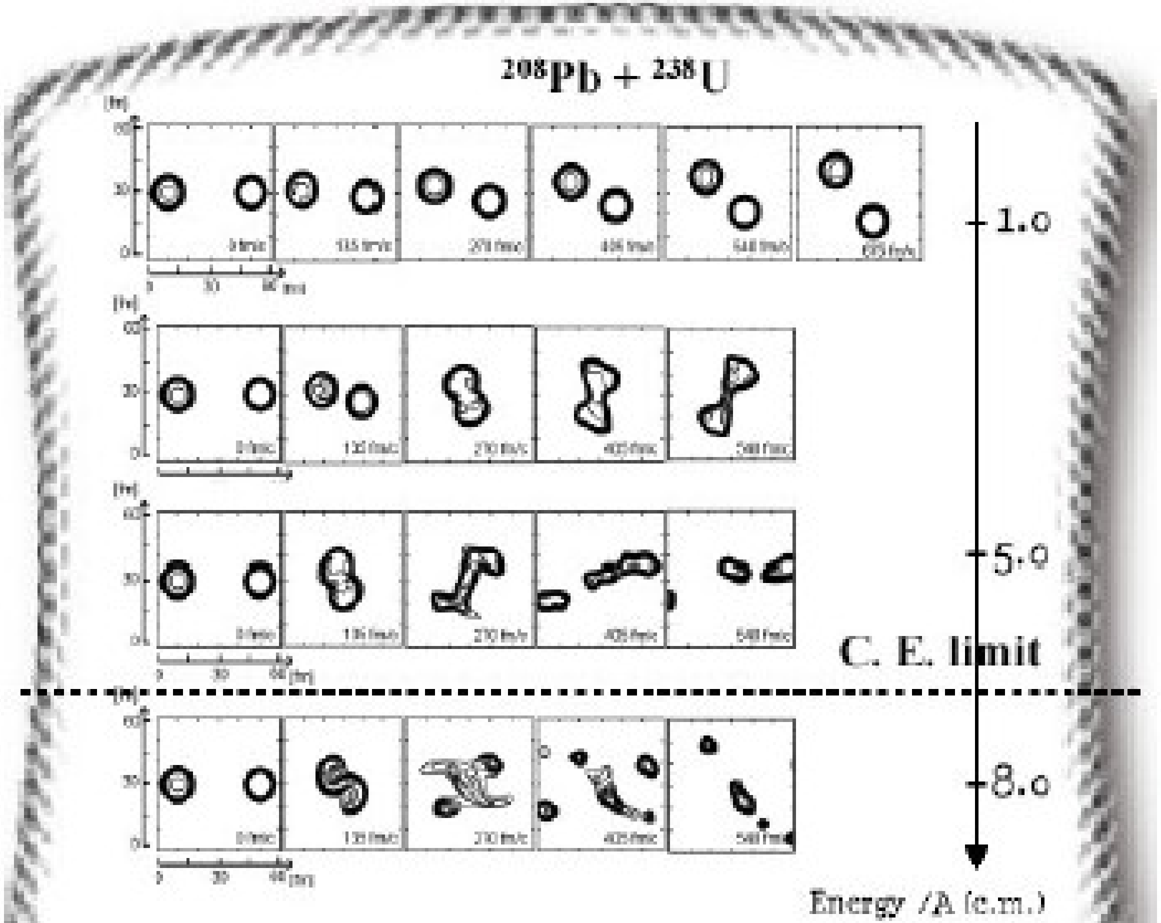


Fig.4 Time evolution of total density

- In a low energy case of $E_{c.m.}$ = 1.0 MeV/A, the two nuclei donot get into a contact. It is somewhat similar to pure Coulomb scattering.
- In a intermediate energy case of $E_{c.m.}$ = 5.0 MeV/A, the two nuclei get into a contact, and then break up into three pieces. The fragments have almost the same N/Z ratio, which agrees with the charge-equilibrated one.
- In a higher energy case of $E_{c.m.}$ = 8.0 MeV/A, two nuclei get into a contact, and then break up into many pieces. The fragments do not have the same N/Z ratio. There is no charge equilibration.

The upper energy limit of the charge equilibration is located between $E_{c.m.}$ = 5.0 MeV/A and $E_{c.m.}$ = 8.0 MeV/A. More details are discussed in the next 5).

3) Statistics of Final Products

Histograms of final products (impact parameters are summed up)

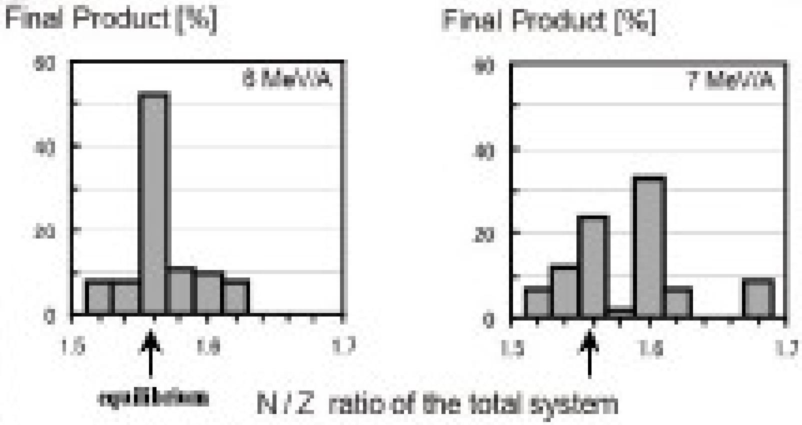


Fig.5-1 Distribution of N/Z ratio

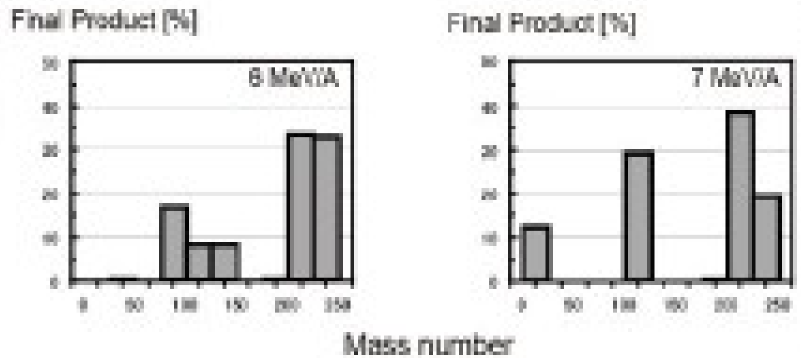


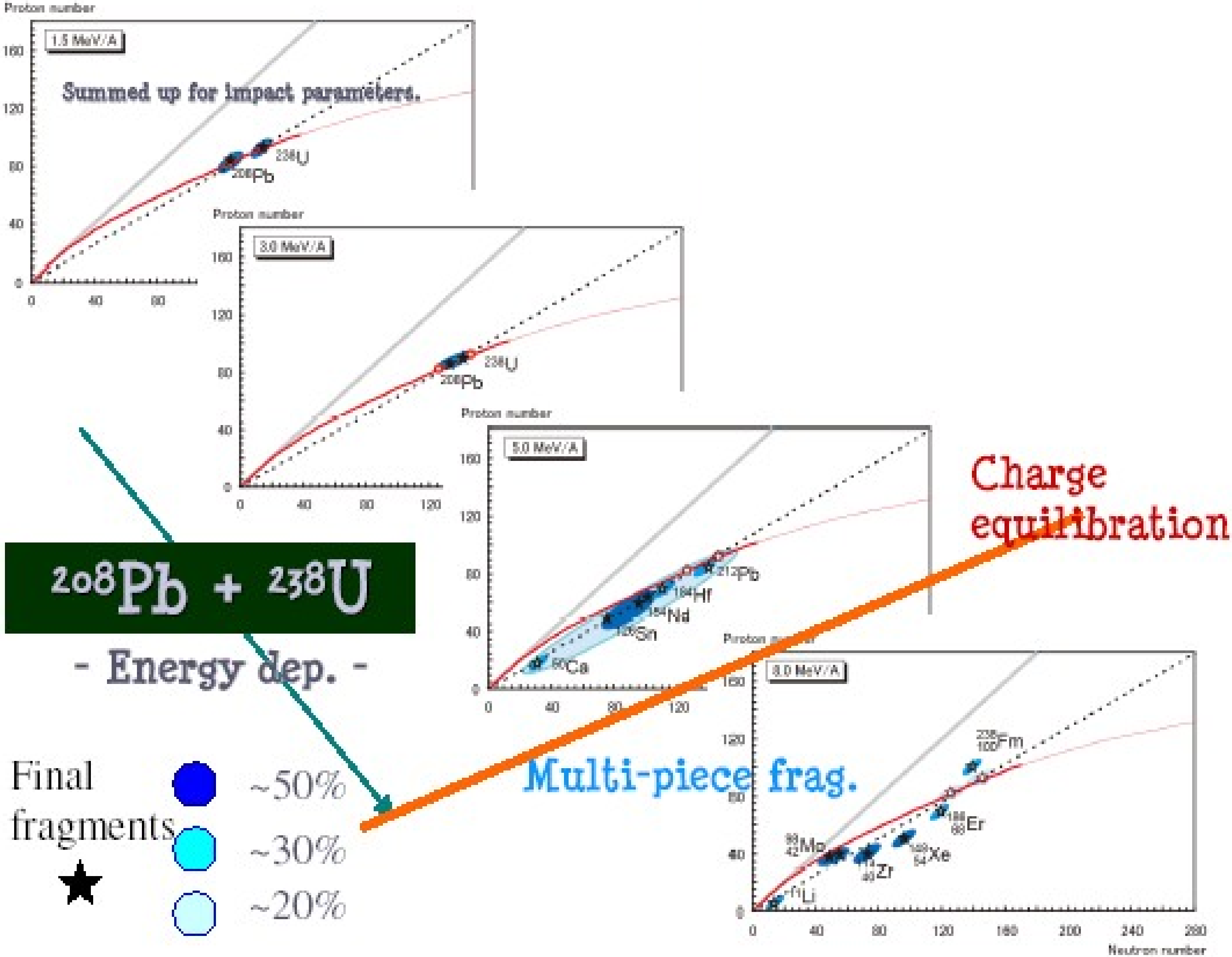
Fig.5-2 Distribution of Mass

The TDHF results shown in figures 5-1 and 5-2 are the summed up in terms of the impact parameters.

From Fig.5-1, TDHF calculations show that 52% of the final products are equilibrated at 6MeV/A, but 23% at 7MeV/A. The shape of the N/Z distribution changes drastically.

From Fig.5-2, TDHF calculations show that the masses of final fragments are located around 110 and 230 for 6MeV/A, but 25, 100 and 230 for 7MeV/A. In the former case, the reaction is dominated by fragmentation into two or three pieces. In the latter case, fragmentation into four pieces appears, which produces lighter-mass fragments.

Pb:1.54 U:1.59



Proton number
1.5 MeV/A
Summed up for impact parameters.
208Pb
238U
3.0 MeV/A
5.0 MeV/A
212Pb
184Hf
154Nd
126Sn
60Ca
8.0 MeV/A
238 100 Fm
168 68 Er
98 42 Mo
140 54 Xe
114 40 Zr
Li
Neutron number
Charge equilibration
Multi-piece frag.
208Pb + 238U
- Energy dep. -
Final fragments
~50%
~30%
~20%

Table 1. Summary of TDHF calculations

Reactions	Upper energy-limit [Mev/A]
$^{208}Pb + {}^{238}U$	$6.0 < E_{CE} < 7.0$
$^{208}Pb + {}^{132}Xe$	$6.0 < E_{CE} < 7.0$
$^{208}Pb + {}^{132}Sn$	$6.0 < E_{CE} < 7.0$
$^{208}Pb + {}^{24}Mg$	$2.0 < E_{CE} < 3.0$
$^{208}Pb + {}^{24}O$	$2.0 < E_{CE} < 3.0$
$^{208}Pb + {}^{16}O$	$1.0 < E_{CE} < 2.0$
$^{208}Pb + {}^{4}He$	$E_{CE} < 1.0$

Mass-dependence can be found in this table.
How can we understand it ?

“Charge Equilibration” upper energy-limit Formula

By comparing the Fermi velocity with the relative velocity ...

If the touching time is large enough for a single nucleon with Fermi velocity to propagate throughout the two colliding nuclei, the charge equilibration can take place.

Based on the Fermi-gas with the droplet model, we propose

$$E_{CE} = \frac{\hbar^2 \left(3\pi^2 \rho_{min}\right)^{2/3}}{2m} \frac{A_1 A_2}{A_1 + A_2} + \frac{e^2}{4\pi\epsilon_0 r_0} \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} \quad (1)$$

The derivation and the meaning of this formula should be referred to AIP conference proceedings “Fusion 08”

This formula agrees quite well with TDHF3d calculations

	Eq. (1)	TDHF
$^{208}Pb + ^{238}U$	6.91	6.5±0.5
$^{208}Pb + ^{132}Sn$	6.36	6.5±0.5
$^{208}Pb + ^{24}O$	2.18	2.5±0.5
$^{208}Pb + ^{16}O$	1.75	1.5±0.5
$^{208}Pb + ^{4}He$	0.48	< 1.0

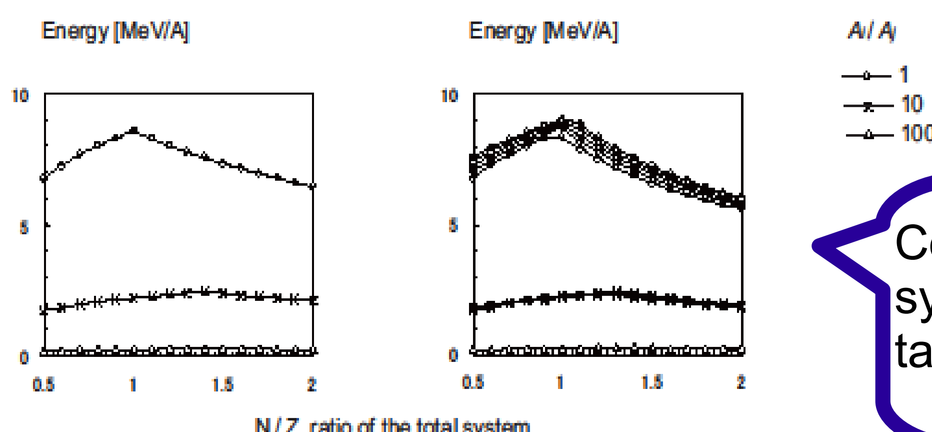
“Charge Equilibration” upper energy-limit Formula

We proposed ...

Based on the Fermi-gas with the droplet model, we propose

$$E_{\mathrm{CE}} = \frac{\hbar^2 \left(3\pi^2 \rho_{min}\right)^{2/3}}{2m} \frac{A_1 A_2}{A_1 + A_2} + \frac{e^2}{4\pi\epsilon_0 r_0} \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} \qquad (1)$$

Graphical representation



Coulomb and symmetry energy is taken into account

FIG. 1: N/Z dependence of the charge equilibration upper energy limit in the center-of-mass frame based on Eq. (1), assuming that $N_1/Z_1 = N_2/Z_2$ (compare [Iwata-FUSION08]). The total N and Z values are used without any modification for the left, and the modified values by the droplet model are taken for the right in which the lines with different total masses 100, 200, 300, 400, and 500 are plotted (from lower to upper). A_i/A_j denotes the maximum of A_1/A_2 and A_2/A_1.

Question 1

Charge equilibration is considered to be governed by

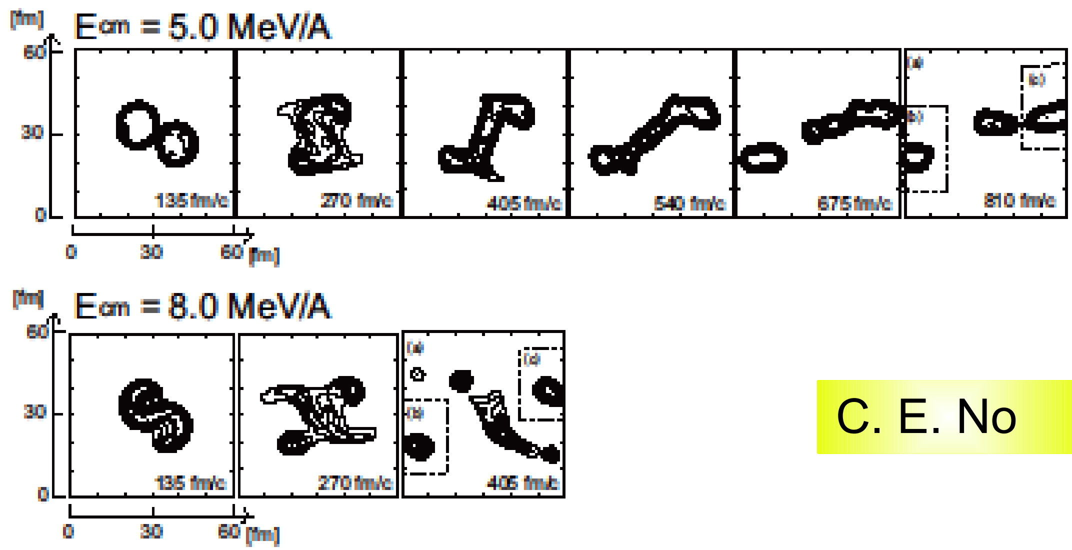
_ Isovector GDR
_ Symmetry energy
_ Diffusion process

But it has still been open what is the main driving force of charge equilibration.

The Fermi energy is essential for determining **the upper-energy limit(presence or absence)**, while the symmetry and the Coulomb energies are secondary factor for this limit.

- The charge equilibration is a rapid process ~ 10^{-22} sec propagating with Fermi velocity (quantum waves in the fermionic system)
- The charge equilibration similarly occurs in the collisions involving very heavy nuclei, although there exists a large Coulomb repulsion leading to the localization of charges.

Application of C. E. formula (exotic production)



C. E. Yes

C. E. No

Fig. 8. Time evolution of the total density. The impact parameter is fixed to be 9.2 fm. We have separated into three parts as is shown in 810 fm/c for the case of $E_{cm} = 5.0$ MeV/A, and in 405 fm/c for the case of $E_{cm} = 8.0$ MeV/A.

Table 2. N/Z ratios of parts (a), (b) and (c) in Fig. 8 are shown, where we take the averaged N/Z value for the part (a) of $E_{cm} = 8.0$ MeV/A.

	(a)	(b)	(c)
$E_{cm} = 5.0$ MeV/A	1.54	1.56	1.58
$E_{cm} = 8.0$ MeV/A	1.64	1.42	1.47

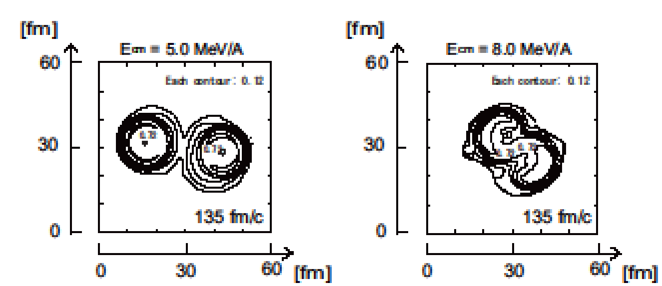


Fig. 9. Snapshots of TDHF calculations at 135 fm/c, where the proton-to-neutron density ratio is shown. Each contour is set to be 0.12, while thick contours to 0.24. These two figures precisely correspond to the cases shown in Fig. 8.

2) Charge and mass distribution

Question 2

How can we understand the mass equilibration in the early stage of heavy-ion collision ?

In particular, can we find the relation with charge equilibration ?

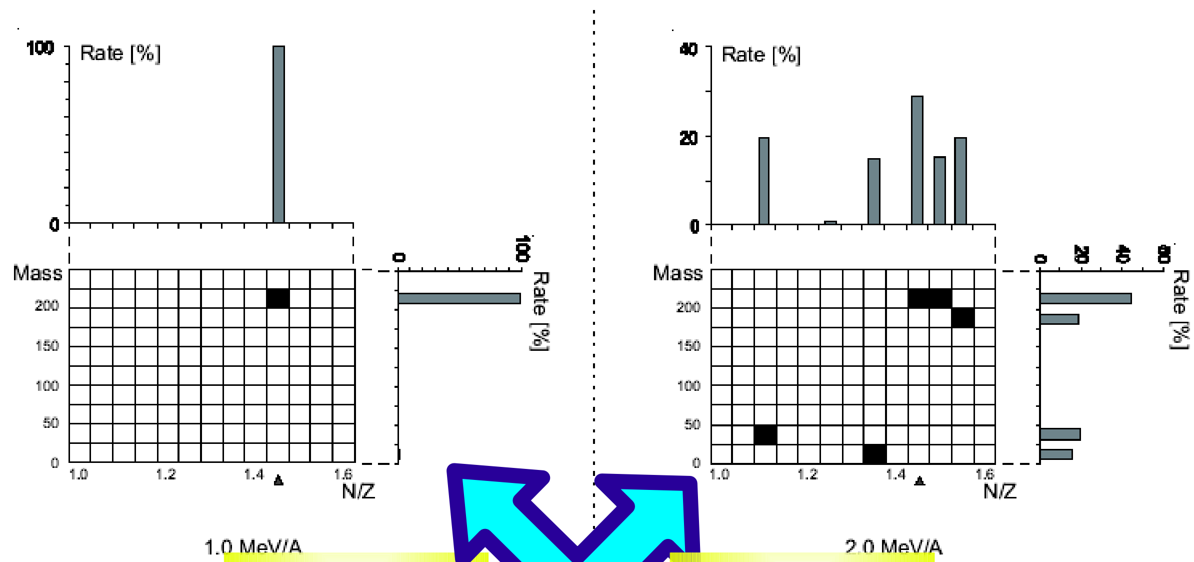
Motivation:
To understand the equilibration of both charge and mass is the essential for obtaining the aimed final fragment nucleus.

To clarify the difference between two things

Difference in Charge and Mass Equilibration

Lighter case

$^{208}Pb + ^{16}O$

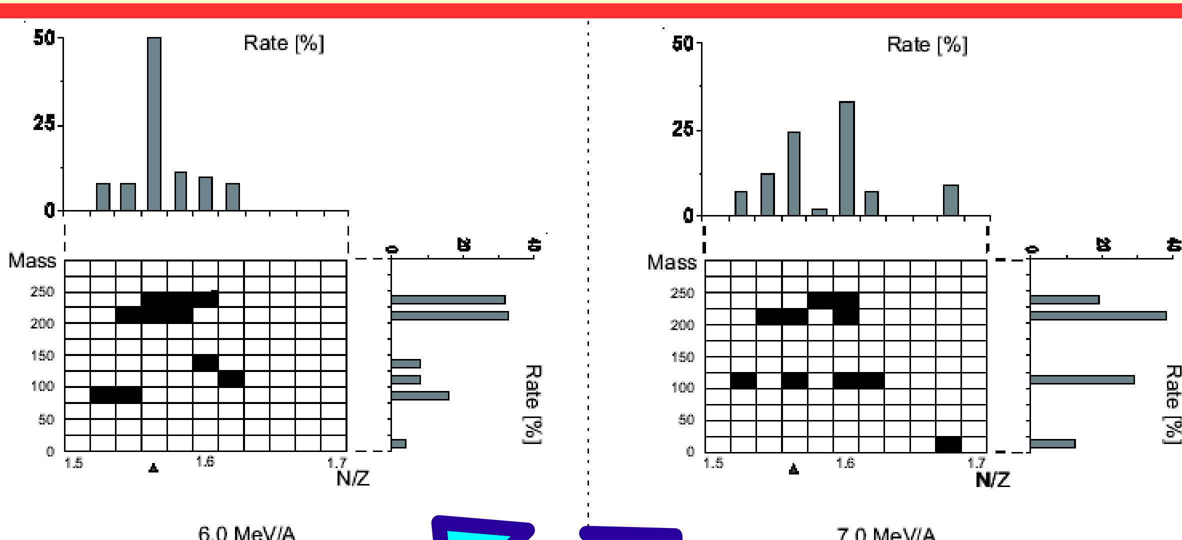


C. E. Yes

C. E. No

Fig. 5. Histogram of final fragments (weighted by impact parameter) in the central collisions between ^{208}Pb and ^{16}O, where the horizontal and vertical axes mean N/Z ratio and the mass number, respectively. N/Z ratio is incremented by 0.05 and the mass number by 25. Black or White square shows the existence or non-existence of final products (larger than 5 % of the total products are produced or not). Triangles designate the charge equilibrium. Cases of E_{cm} = 1.0 and 2.0 MeV/A are shown.

Explicit difference exist between lighter and heavier reactions



C. E. Yes

C. E. No

Fig. 6. Histogram of final fragments (weighted by impact parameter) in the central collisions between ^{208}Pb and ^{238}U, where the horizontal and vertical axes mean N/Z ratio and the mass number, respectively. N/Z ratio is incremented by 0.05 and the mass number by 25. Black or White square shows the existence or non-existence of final products (larger than 5 % of the total products are produced or not). Triangles designate the charge equilibrium. Cases of E_{cm} = 4.0 and 8.0 MeV/A are shown.

Heavier case

$^{208}Pb + ^{238}U$

Based on our TDHF calculations (including all other sample reactions), the difference between charge and mass equilibration might be arising from whether reaction includes the heavy nuclei or not.

What is the border to distinguish “heavy” and “light” reactions ?

Abstract idea (submitted to ENAM proceedings)

We focus on the formation of **rigid merged system** as an intermediate state.

Yes --- The charge equilibration almost becomes equivalent to the fusion.

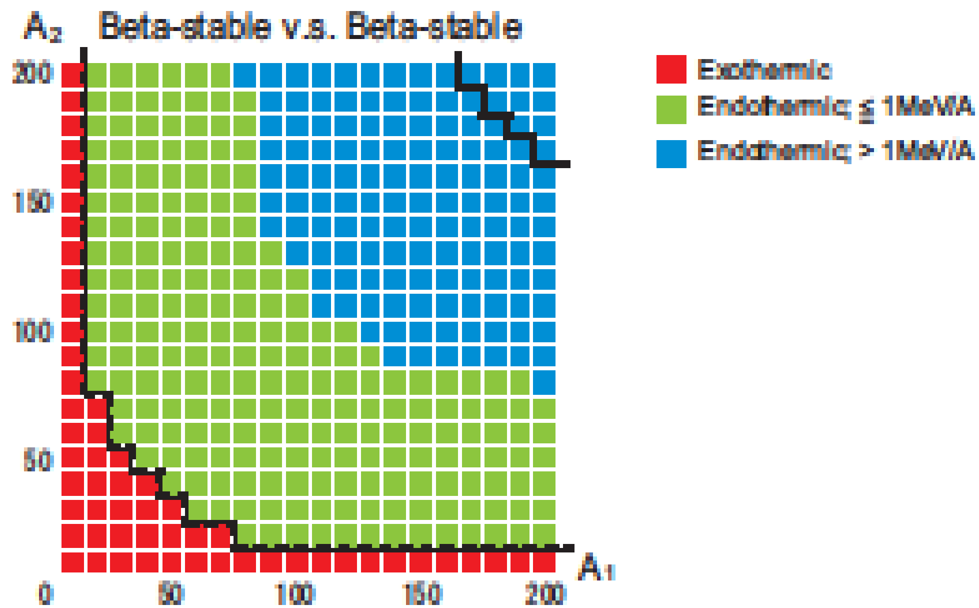
No --- The mass equilibration is sheerly different from “fusion”.

The proposed condition for distinguishing **"the formation of merged system"**

(a) $E_{cm} < \max(E_{CL}, E_Q + E_{CL})$,

(b) $\underline{E_{MS} < E_{LMS}}$,

(c) $E_{CR} < E_Q$,



Based on the liquid drop model
We restrict ourselves to the beta-stable nuclei

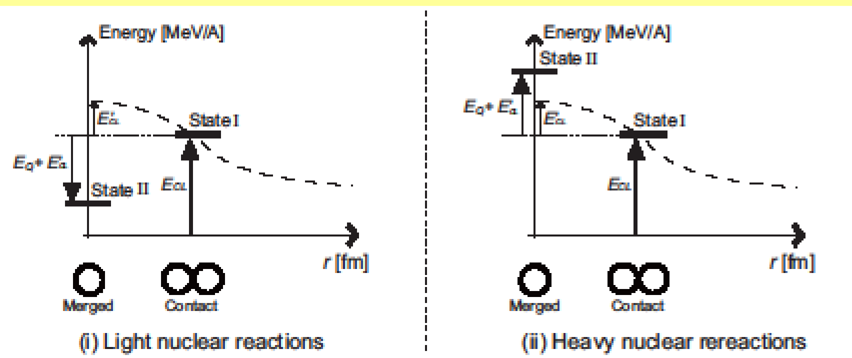


Fig. 2. The meaning of condition (2). The relative configuration of energy levels are deduced from Fig. 1. The energy levels are plotted on the Coulomb potential, where the Coulomb potential structures are shown by dotted lines. The states I and II denote the state at the contact time and the approximated merged system (we restrict ourselves to the spherical states), respectively. The horizontal axis r denotes the distance between centers of colliding nuclei, and E'_{CL}, which means the Coulomb energy at $r = 0$, is introduced to take into account the distance of collision correctly for the studies based only on the binding energy.

TDHF calculation shows the validity of this condition (the details are omitted here)

Question 2

How can we understand the mass equilibration in the early stage of heavy-ion collision ?

In particular, can we find the relation with charge equilibration ?

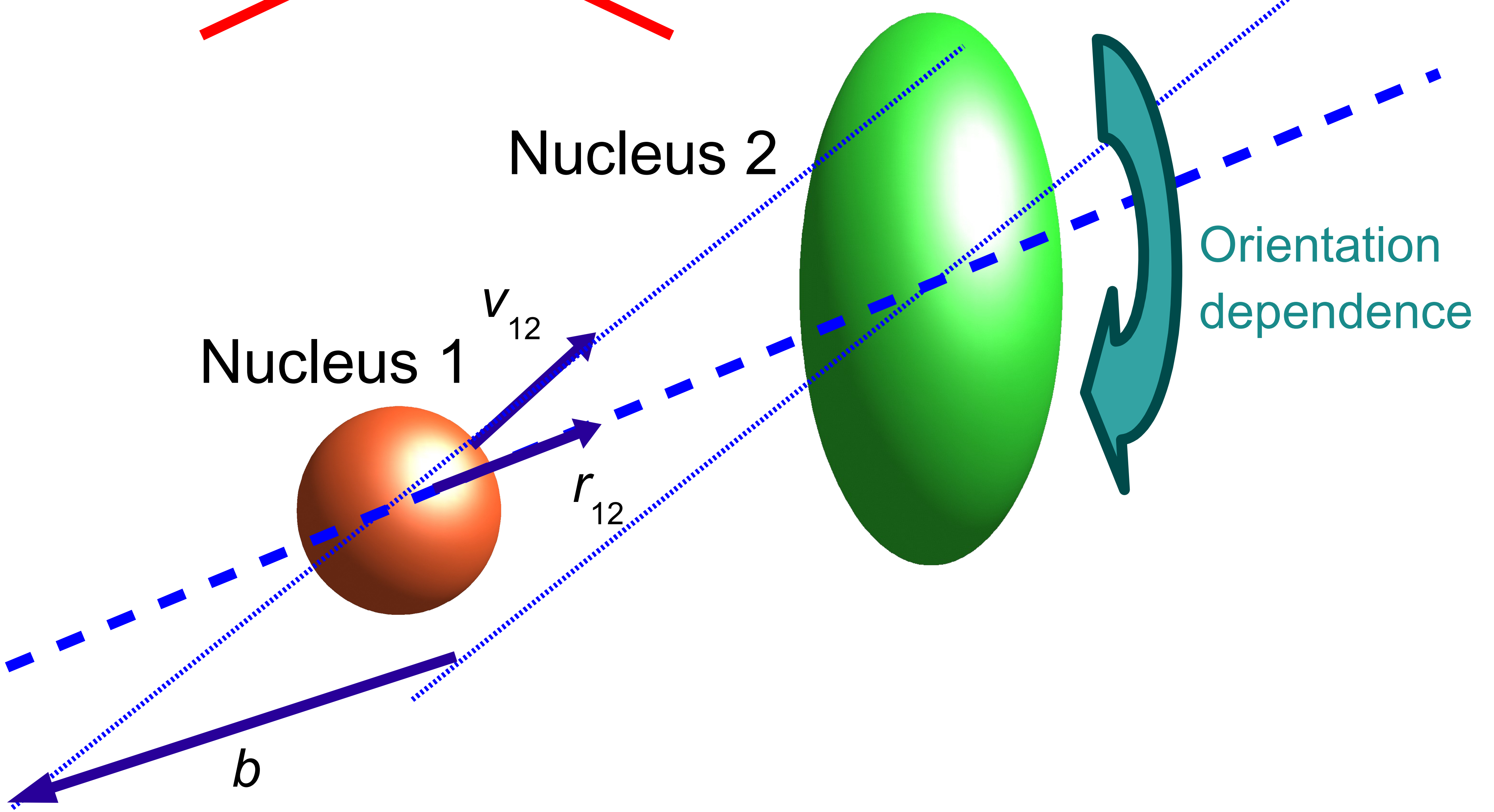
Results at Present:

The mass equilibration is similarly occurs to the charge equilibration in the **lighter nuclear reactions,** while it is not in the **heavier nuclear reactions.**

We point out the importance of the formation of merged system to understand the charge- mass equilibration (whether heavy or light reaction).

3) Orientation effect (preliminary)

Only v_{12} and r_{12} are two degrees of freedom to identify collisions of spherical nuclei.



The purpose of studying orientation effect ?

The importance of orientation effect has been already discussed.

PHYSICAL REVIEW C 77, 064607 (2008)

Effects of nuclear orientation on the mass distribution of fission fragments in the reaction of $^{36}S+^{238}U$

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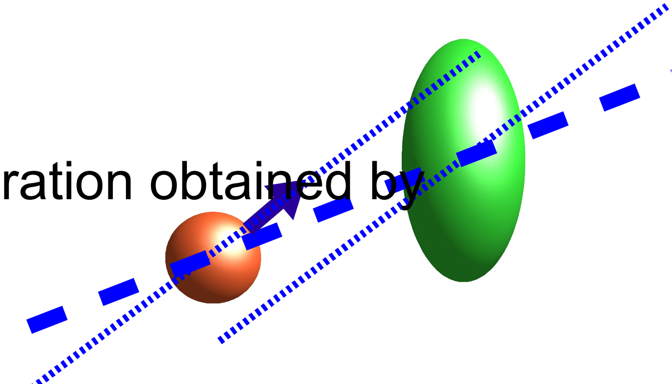
(Received 5 December 2007; published 18 June 2008)

There exists another degree of freedom (orientation) to fix the initial condition compared to the spherical cases.

The relation between charge equilibration and the orientation effect should be interesting.

(Private reason) First time comparison of charge equilibration obtained by TDHF3d to experimental results.



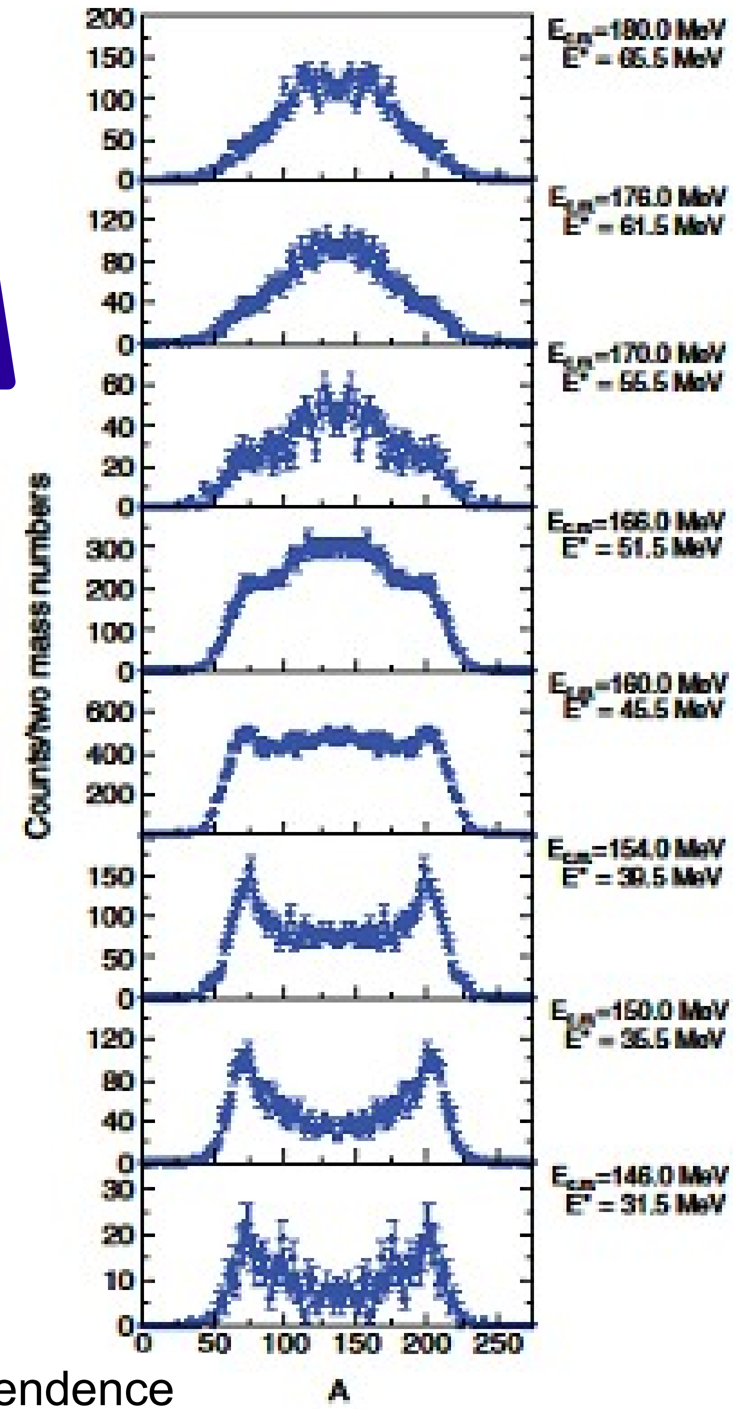
Single peak

Energy dependence is very interesting, but it is so low compared to the upper energy-limit of charge equilibration

Twin peak

C.E upper-limit

2.6 MeV/A + (238+30)
= 697 MeV



Energy dependence

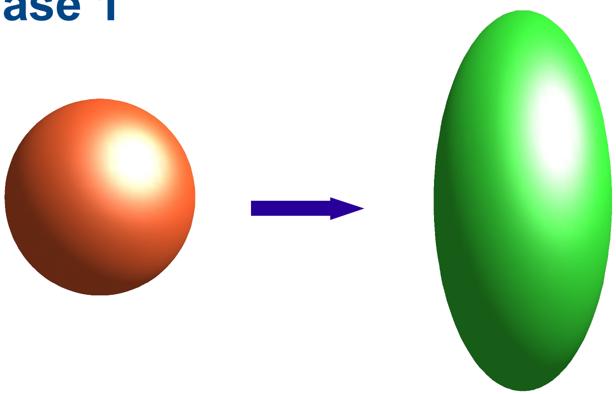
Nishio *et. al.* PRC (2008)

Orientation Effect

238 U + 30 Si

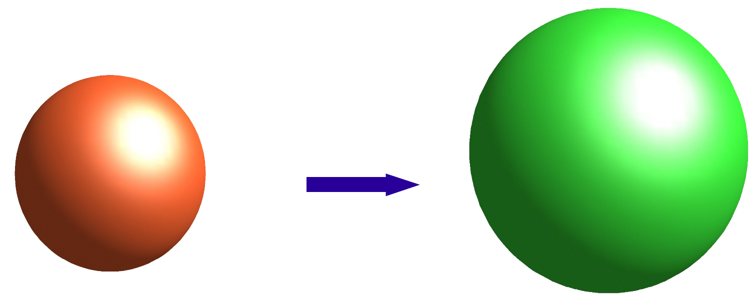
We have made a calculations of two types

Case 1



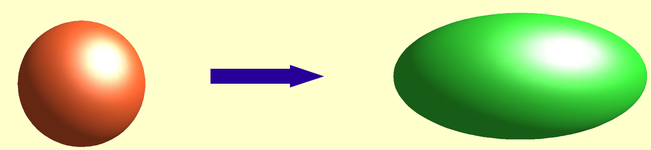
Deformed (perpendicular)

Case 2



Spherical

Now under calculation



Deformed (horizontal)

As the 1st stage of our research,

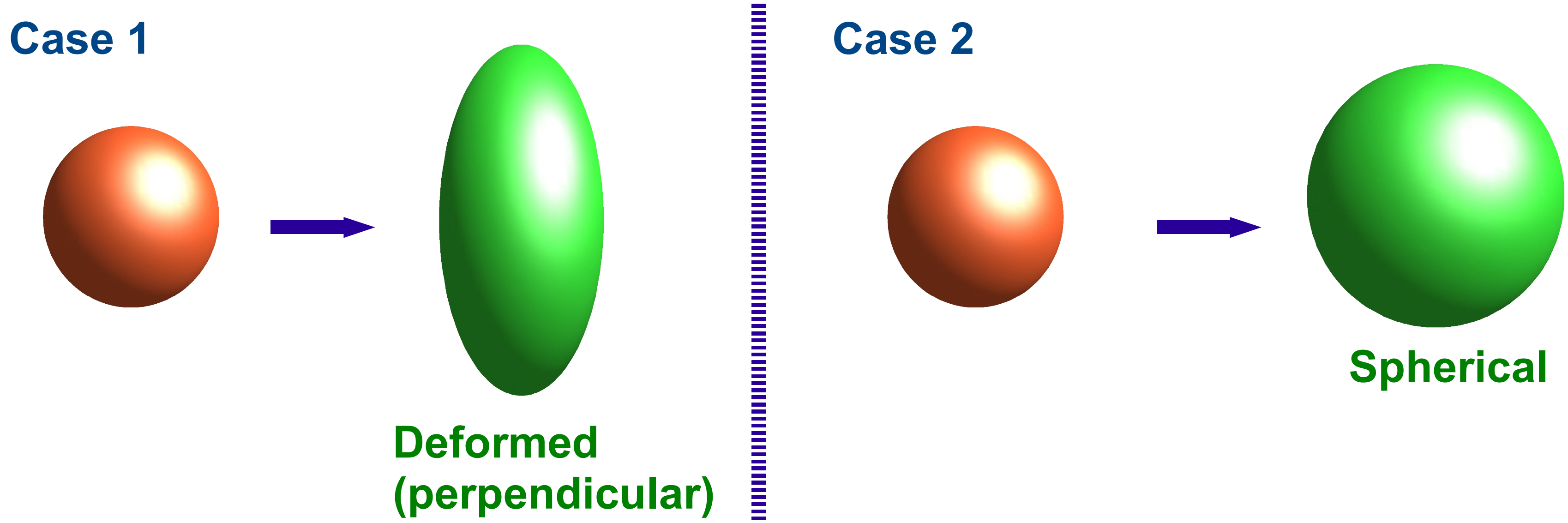
Although there should be many interesting Physics included in the orientation effect, we keep our eyes on **the charge equilibration upper energy-limit**.

How can it be different owing to **the orientation** ?

Orientation Effect

238 U + 30 Si

We have made a calculations of two types



The charge equilibration upper energy-limit.

TDHF3d: 2.0 – 3.0 MeV/A

TDHF3d: 2.0 – 3.0 MeV/A

There is no difference between them

2.61 MeV/A (c.m.) according to the upper-limt formula

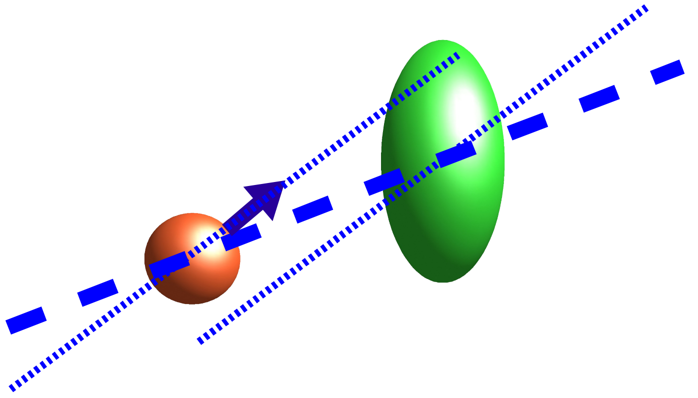
700MeV (c.m.)

The purpose of studying orientation effect ?

Our results:

•The upper energy-limit of charge equilibration is not so different owing t to the orientation.

→ Because it is so high energy compared with the experimental border energy for the single-twin mass-peak transition (most energetically orientation-affected energy).



Summary

1) Charge equilibration upper energy-limit formula

>>> **Fermi energy** is the first essential factor, **symmetry and Coulomb energies** are secondary factor.

2) Charge and mass equilibration

>>> Mass distribution (mass equilibration) is not so simply understood (we consider) such as the charge equilibration. Indeed, the wide mass distribution in the charge equilibrium exists, where we pointed out that the formation of merged system.

3) Orientation effect (still studying)

>>> We have a possibility that **the upper-limit of charge equilibration is not so affected by the orientation**.
It will be because the upper-limit energy is not so low as affected by the orientation.