# Suppression of charge equilibration leading to the synthesis of exotic nuclei

## Mechanism of charge equilibration and beyond

Yoritaka Iwata
**EMMI, GSI Helmholtz Center**

Collaborations:
Takaharu Otsuka (Tokyo)
Joachim A. Maruhn (Frankfurt)
Naoyuki Itagaki (Kyoto)
Hans Feldmeier (GSI, Darmstadt)

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C Simenel (Saclay), K Nishio (JAEA, Tokai)

# Introduction

- Why “charge equilibration” ?
- Proposed mechanism of charge equilibration
- Upper Limit Formula
- TDHF for the Upper Limit
- Experiment for the Upper Limit
- Prediction of exotic/super-heavy nuclear synthesis
- Summary

**Original papers:**
**Iw.-Otsuka-Maruhn-Itagaki, Phys.Rev. Lett., accepted.**
**Nucl. Phys. A 836 (2010) 108.**
**Eur. Phys. J. A 42 (2009) 613.**

Proceedings:
Eur. Phys. J. W. 2 (2010) 13002.
AIP conference proceedings 1175 (2009) 363.
AIP conference proceedings 1098 (2009) 308.

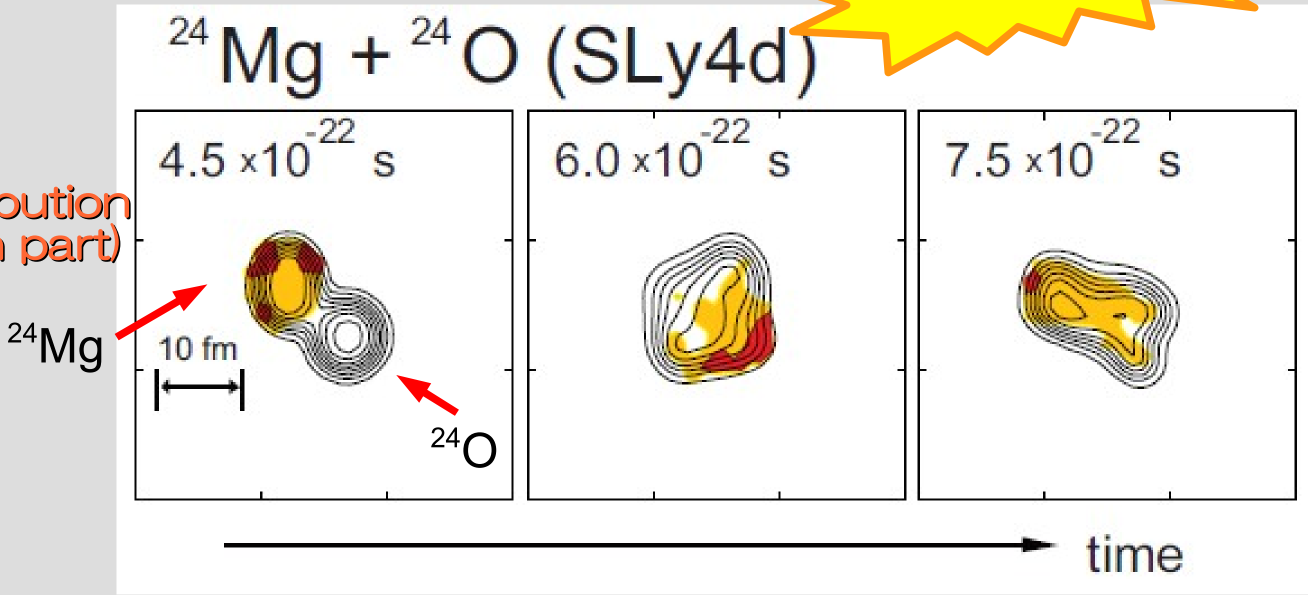
# Why charge equilibration ?

Dynamics of charge equilibration (3-dimensional TDHF):

typical

$E_{lab}/A$ = 18MeV
$b$ = 5 fm

Colored regions show the distribution of charge (relatively proton-rich part)



Eur. Phys. J. W. 2 (2010) 13002.

Charge equilibration takes place acompanying with the dipole oscillation !

Charge equilibration hinders the exotic nuclear synthesis.

Charge equilibration is a necessary condition for fusion.

# Why charge equilibration ?

- Charge equilibration governs the sysnthesis of exotic nuclei:

  Disappearance of charge equilibration is necesary to
  **the sysnthesis of exotic nuclei**

How to switch-off charge equilibration ?

- Charge equilibration is crucial to the fusion process,
  as well as fusion-fission, quasi-fission ...
  Indeed, fusion must not be achieved without having charge equilibrium.

  Appearance of charge equilibration is ideal to
  **the synthesis of super-heavy nuclei**

Can we control the fusion/fragmentation (moreover fusion-fission) ?

# *Why charge equilibration ?*

## *A standing problem for 30 years*

What is the mechanism of charge equilibration ?

- Both appearance and disappearance of charge equilibration are important issues to go further into the existence-limit of nulei. However, it has been a well-known open problem for 30 years.
- As far as collective motions are concerned, its relation to the dipole oscillation has been pointed out (Simenel et. al. PRL86(2001), PRC76(2007)).

Here we propose a solution to this problem.

**- Many articles in 70's and 80's deal with this problem -**

**References (as far as I have reached and studied … ):**

P. Bonche and N. Ngo, Phys. Lett. B (1981)
E. Suraud M. Pi, and P. Schuck, Nucl. Phys. (1989)
C. Simenel Ph. Chomaz and G. de France, Phys. Rev. Lett. (2001)
C. Simenel Ph. Chomaz and G. de France, Phys. Rev. C (2007)

*(TD)HF*

V. Baran et. al., Phys. Rev. Lett. (2001)
V. Baran et. al., Phys. Rep. (2005)
V. Baran et. al., Phys. Rev. C (2009)

*VUU type transport*

# *We propose*
# *“the mechanism of fast charge equilibration”*

The regime of individual singleparticle motion **spreads out** following the lowering of the potential barrier between the two nuclei after the touching.

_ Because this spreading occurs as a consequence of unblocked single-particle motion, the process can be very fast; a particle travels into the other side within $10^{-22}$ s, which roughly corresponds to the Fermi energy of normal nuclear matter.Therefore, protons and neutrons from both nuclei, particularly **those near the Fermi levels**, are mixed within a short time after the touching.

_ Because this spreading needs **a certain time**, it does not lead to charge equilibration in the initial stage if **the relative velocity** of the colliding nuclei is too high.

# Fast charge equilbration conjecture

Consequently,
this equilibration mechanism is formulated as

*the upper energy limit formula for charge equlilbration:*

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

$$\rho_{\min} = \min_i \left( \frac{N_i \left(\frac{4\pi r_0}{3} A_i^{1/3}\right)^{-1}}{(1-3\bar{\epsilon})(1+\bar{\delta})}, \frac{Z_i \left(\frac{4\pi r_0}{3} A_i^{1/3}\right)^{-1}}{(1-3\bar{\epsilon})(1-\bar{\delta})} \right),$$

Charge equilibration appears, if energy is lower

# SystematicTDHF calculations for the Upper Limit

- Nuclear matter

Mean free path of the nuclear matter

zero-temperature

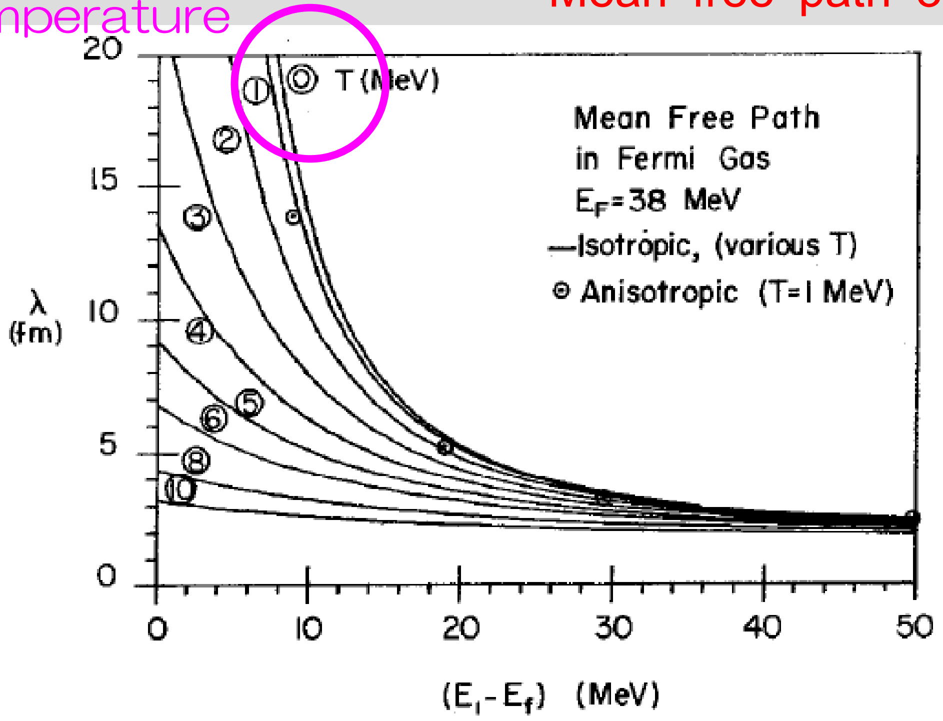


Fig. 2. The calculated nucleon mean free path, $\lambda$, in a nuclear Fermi gas of temperature $T$ and Fermi energy, $E_F = 38$ MeV. The nucleon mean free path is given as a function of its energy above the Fermi energy, $(E_1 - E_F)$, for various values of $T$. The curves are obtained by calculating the expression (9), which assumes isotropic differential cross sections. The four circled points are computed from (8) using more realistic anisotropic cross sections and a temperature of $T = 1$. They show that the error involved in the isotropic assumption is not important in the present discussion.

ex) radius of $^{238}$U
$1.2 * 238^{1/3} = 7{,}4$ fm

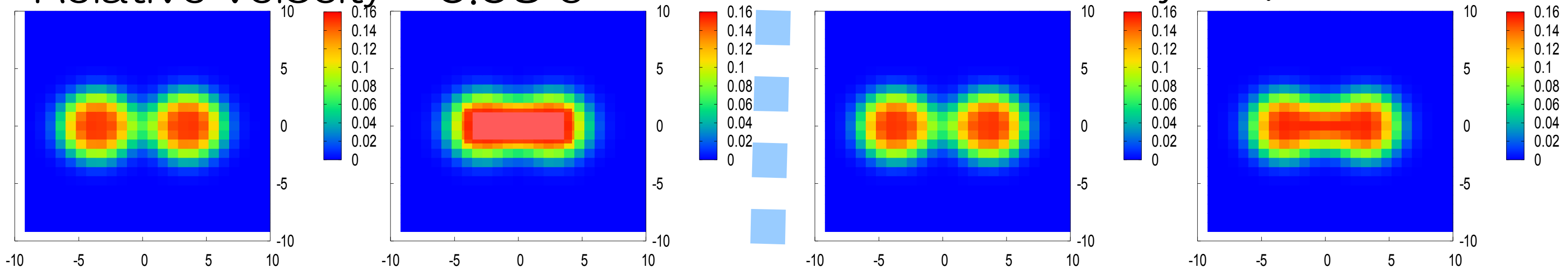
Collins and Griffin, Nucl. Phys A (1980)

# *Intuitive evidence from TDHF*

$^{16}O + {}^{16}O$

Relative velocity = 0.05 c

Relative velocity = 0.025 c



Contact time

$0.75*10^{-22s}$ later

Contact time

$0.75*10^{-22s}$ later

Two collisions with different bombarding energies, where the time evolutions of the total densities are shown..

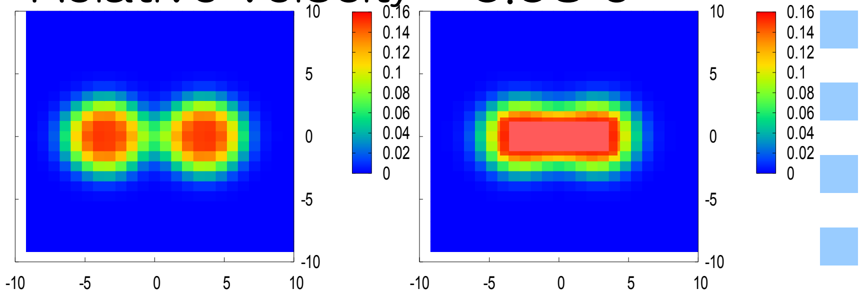
For both cases the states finally evolve into Fusion.

Next, in order to see the role of neutron with the Fermi velocity let us pick out the neutron-density of one side.

# *Intuitive evidence from TDHF*

$^{16}O + ^{16}O$

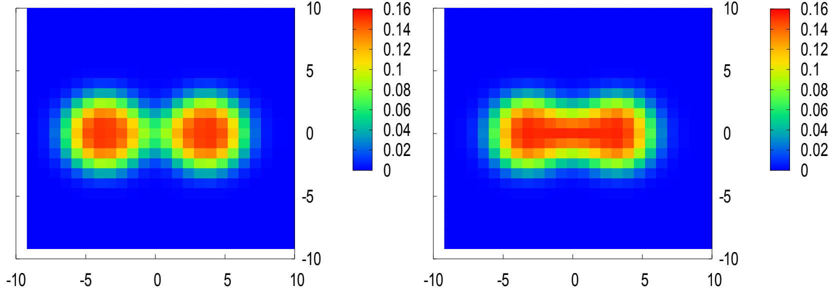
Relative velocity = 0.05 c



Contact time

$0.75*10^{-22s}$ later

Relative velocity = 0.025 c

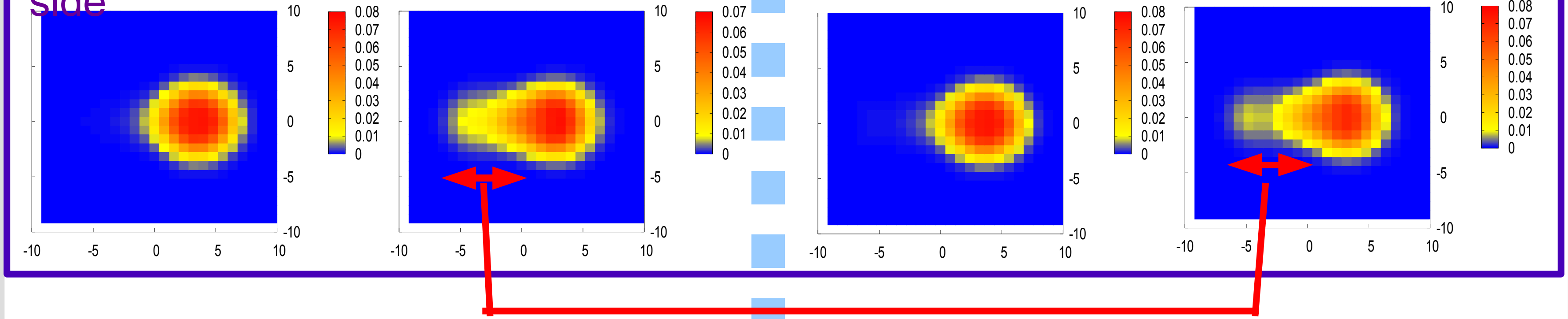


Contact time

$0.75*10^{-22s}$ later

Neutrons originally belongs to the right hand side

Incrementation is taken to be smaller for the better sight



$6\ \mathrm{fm} / 0.75*10^{-22}\mathrm{s} = 0.27\ c$

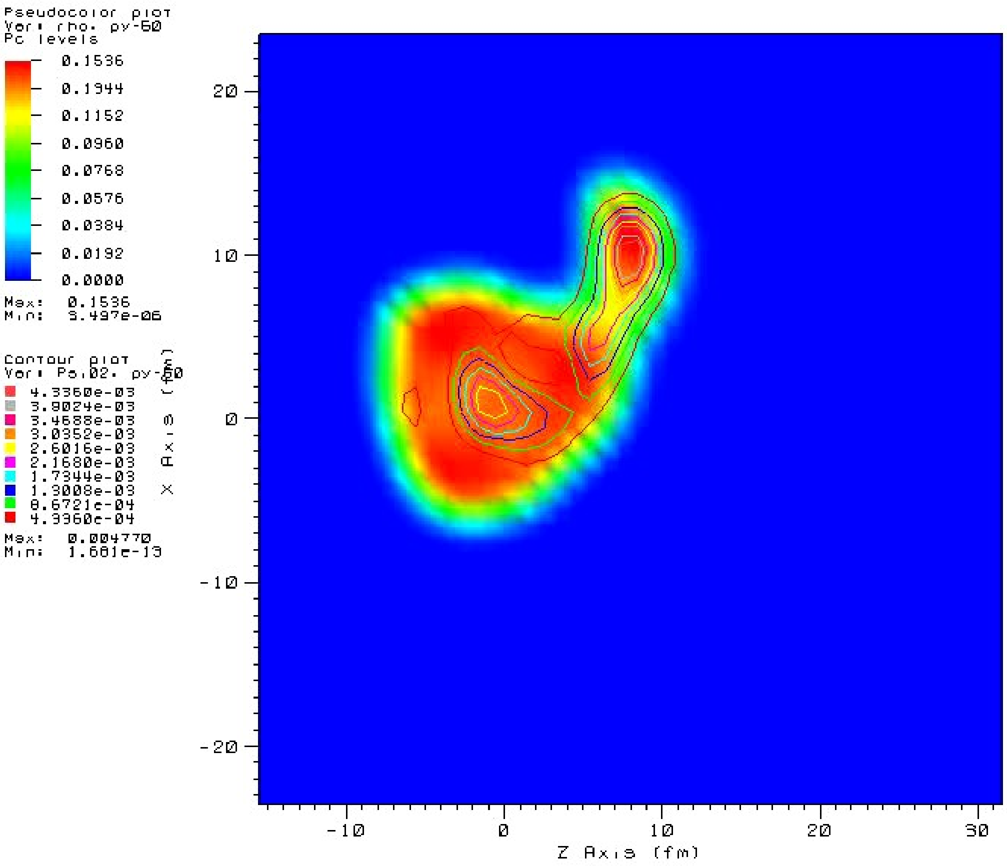
Rather independet of
the relative velocity

Contribution of the nucleons with the fermi velocity is implied
It is reasonable, because the fastest propergation speed in nuclei might be fermi velocity

# *Intuitive evidence from TDHF*

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

Calculated by J. A. Maruhn



350 MeV
8.8 fm

# *Systematic TDHF calculations for the Upper Limit*

- Charge equilbration calculated by TDHF

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

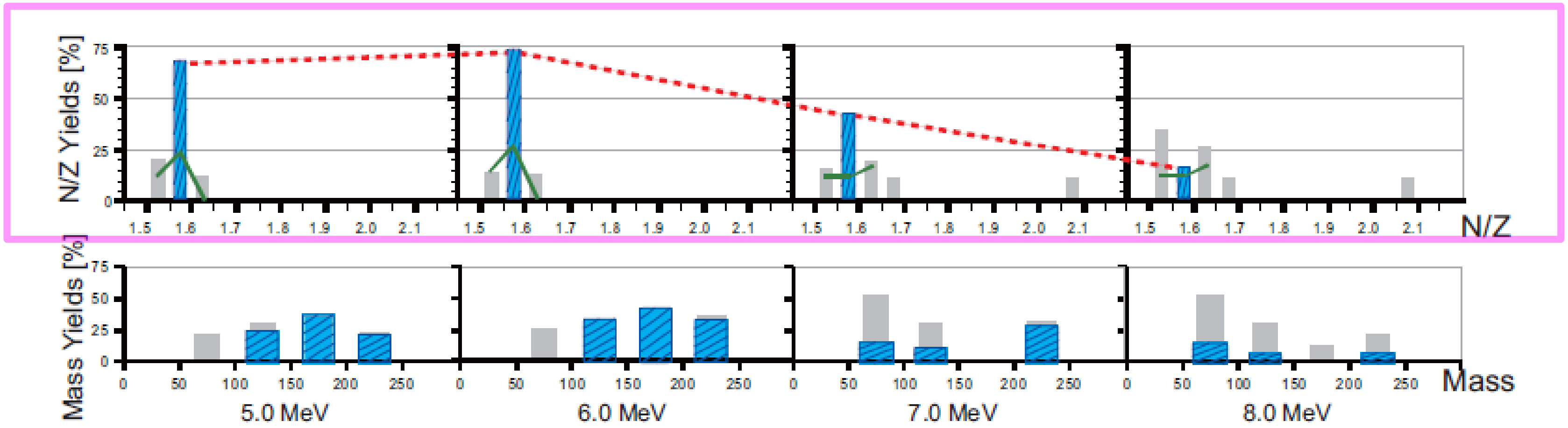


FIG. 1: Four cases with different $E_{cm}/A$ values are presented for the collisions of $^{208}$Pb + $^{132}$Sn. The upper and the lower panels show the yield distributions of fragments obtained by TDHF calculations (SLy4d) as a function of their $N/Z$ ratios and masses, respectively (the $N/Z$ ratio is discretized by 0.05, and the mass by 50), where the $N/Z$ ratios for $^{208}$Pb and $^{132}$Sn are 1.54 and 1.64, respectively. The effective freeze-out time turns out to be $11.5\times10^{-22}$ s. Columns showing the charge equilibrium to the final value $N/Z$=1.58 are hatched, and they are connected by dashed lines for the upper panel. The line graphs shown in the upper panel pick out the peripheral cases with the impact parameter of 7.5 fm ($b_r$ = 0.57).

Iw. *et. al.*, Phys.Rev. Lett., accepted.

In order to compare to experiments,
TDHF calculations are summed-up weighted by **the geometric cross section**

# SystematicTDHF calculations for the Upper Limit

- Comparison between the formula and TDHF calclations

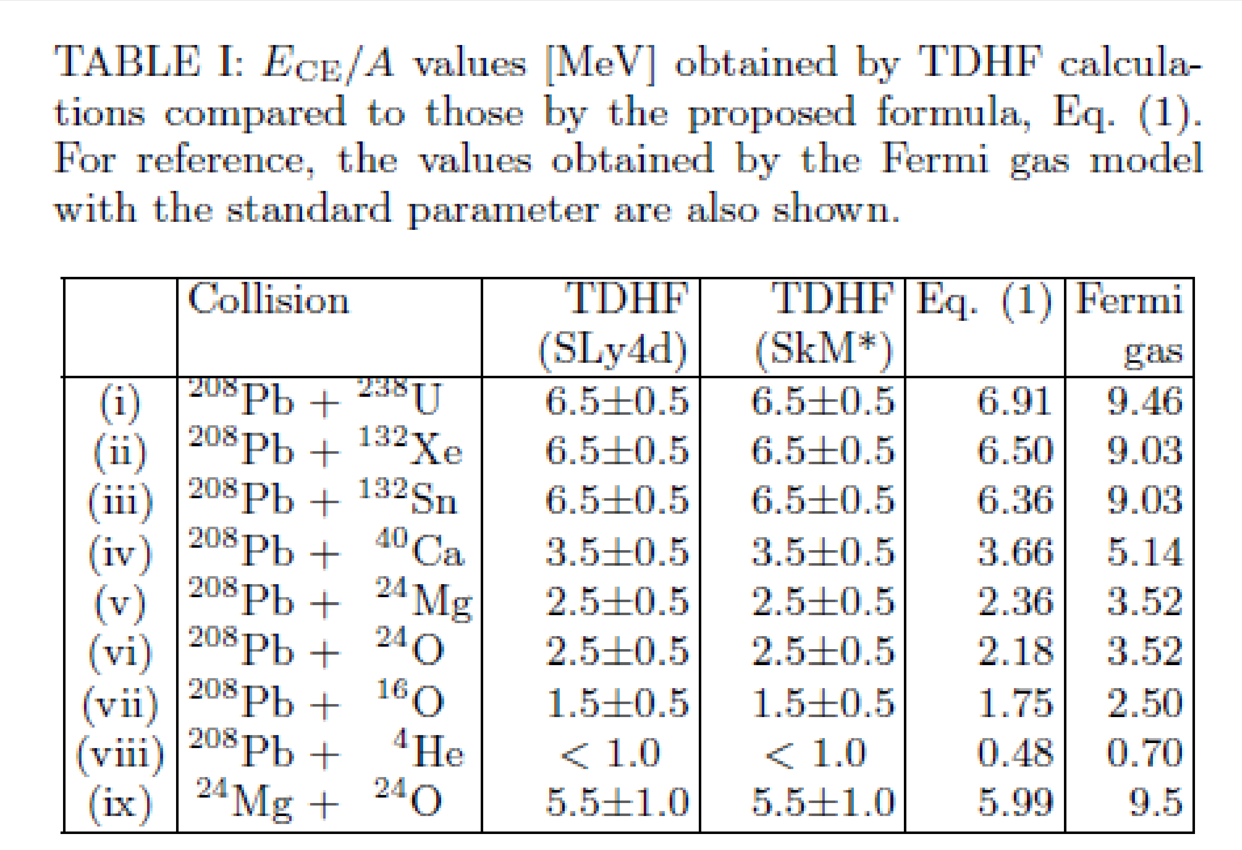


TABLE I: $E_{\mathrm{CE}}/A$ values [MeV] obtained by TDHF calculations compared to those by the proposed formula, Eq. (1). For reference, the values obtained by the Fermi gas model with the standard parameter are also shown.

| | Collision | TDHF (SLy4d) | TDHF (SkM*) | Eq. (1) | Fermi gas |
|---|---|---|---|---|---|
| (i) | $^{208}$Pb + $^{238}$U | 6.5±0.5 | 6.5±0.5 | 6.91 | 9.46 |
| (ii) | $^{208}$Pb + $^{132}$Xe | 6.5±0.5 | 6.5±0.5 | 6.50 | 9.03 |
| (iii) | $^{208}$Pb + $^{132}$Sn | 6.5±0.5 | 6.5±0.5 | 6.36 | 9.03 |
| (iv) | $^{208}$Pb + $^{40}$Ca | 3.5±0.5 | 3.5±0.5 | 3.66 | 5.14 |
| (v) | $^{208}$Pb + $^{24}$Mg | 2.5±0.5 | 2.5±0.5 | 2.36 | 3.52 |
| (vi) | $^{208}$Pb + $^{24}$O | 2.5±0.5 | 2.5±0.5 | 2.18 | 3.52 |
| (vii) | $^{208}$Pb + $^{16}$O | 1.5±0.5 | 1.5±0.5 | 1.75 | 2.50 |
| (viii) | $^{208}$Pb + $^{4}$He | $< 1.0$ | $< 1.0$ | 0.48 | 0.70 |
| (ix) | $^{24}$Mg + $^{24}$O | 5.5±1.0 | 5.5±1.0 | 5.99 | 9.5 |

Iw. *et. al.*, Phys.Rev. Lett., accepted.

# Experiments for thr Upper Limit

Agree with Experiments, for example,
Appearance of charge equilibration:

_ $^{40}$Ar + $^{58}$Ni at $E_{\mathrm{lab}}/A$=7.0 MeV,

_ $^{56}$Fe + $^{165}$Ho ($^{209}$Bi) at $E_{\mathrm{lab}}/A$= 8.3 MeV.

B. Tsang, private communication

(Recently) at MSU
_ $^{124,112}$Sn + $^{124,112}$Sn at $E_{\mathrm{lab}}/A$= 35 and 50 MeV

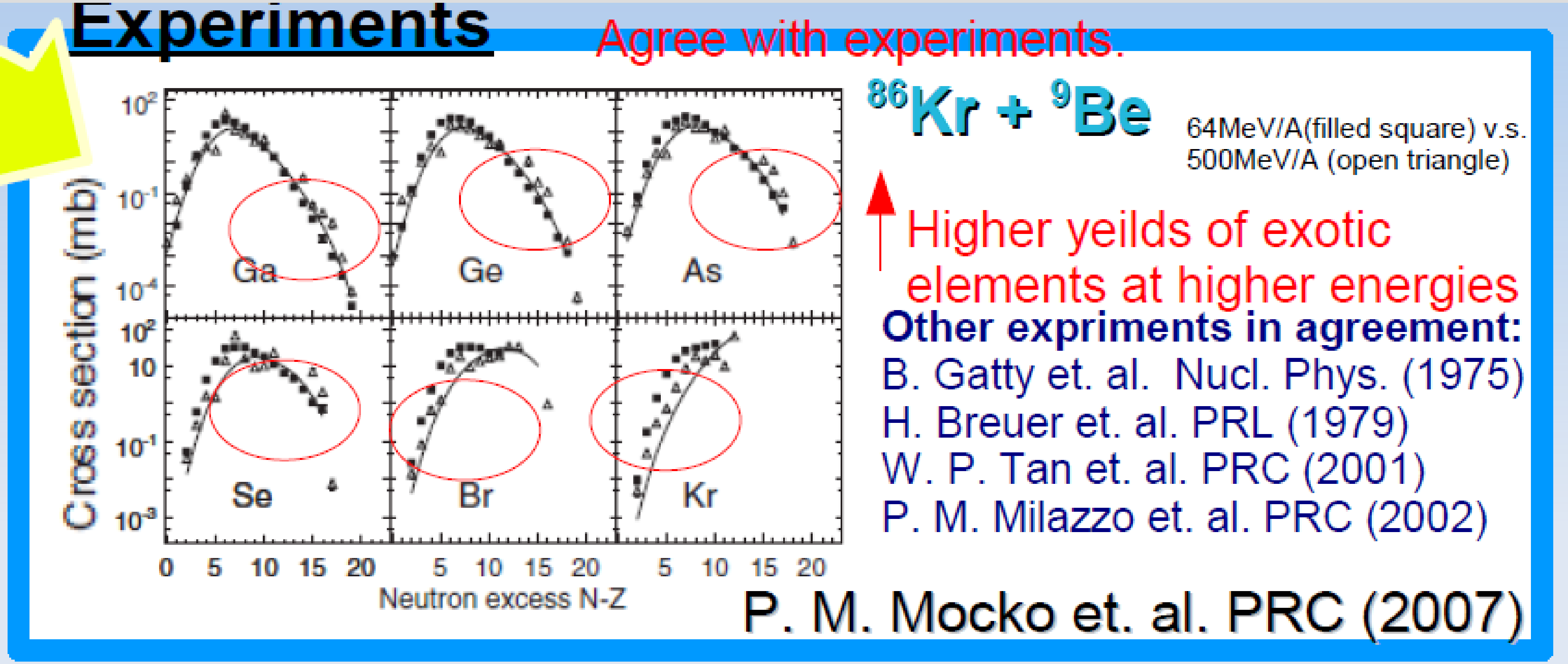
Disappearance of charge equilibration:
_ $^{112}$Sn + $^{124}$Sn at $E_{\mathrm{lab}}/A$=50 MeV .

It is remarkable that the final fragments are not so close to charge equilibrium even when the energy is set to $E_{\mathrm{lab}}/A$=35 MeV. This experimental result is understood now, because the upper limit of charge equilibration is calculated to be $E_{\mathrm{lab}}/A$=27.6 MeV from Eq. (1).

# Experiments for thr Upper Limit

## Experimental results

Indeed, the yield of exotic fragments was increased simply by putting the beam energy higher than the present upper-limit.



**Experiments**

Agree with experiments.

$^{86}$Kr + $^{9}$Be

64MeV/A(filled square) v.s. 500MeV/A (open triangle)

Higher yeilds of exotic elements at higher energies

**Other expriments in agreement:**

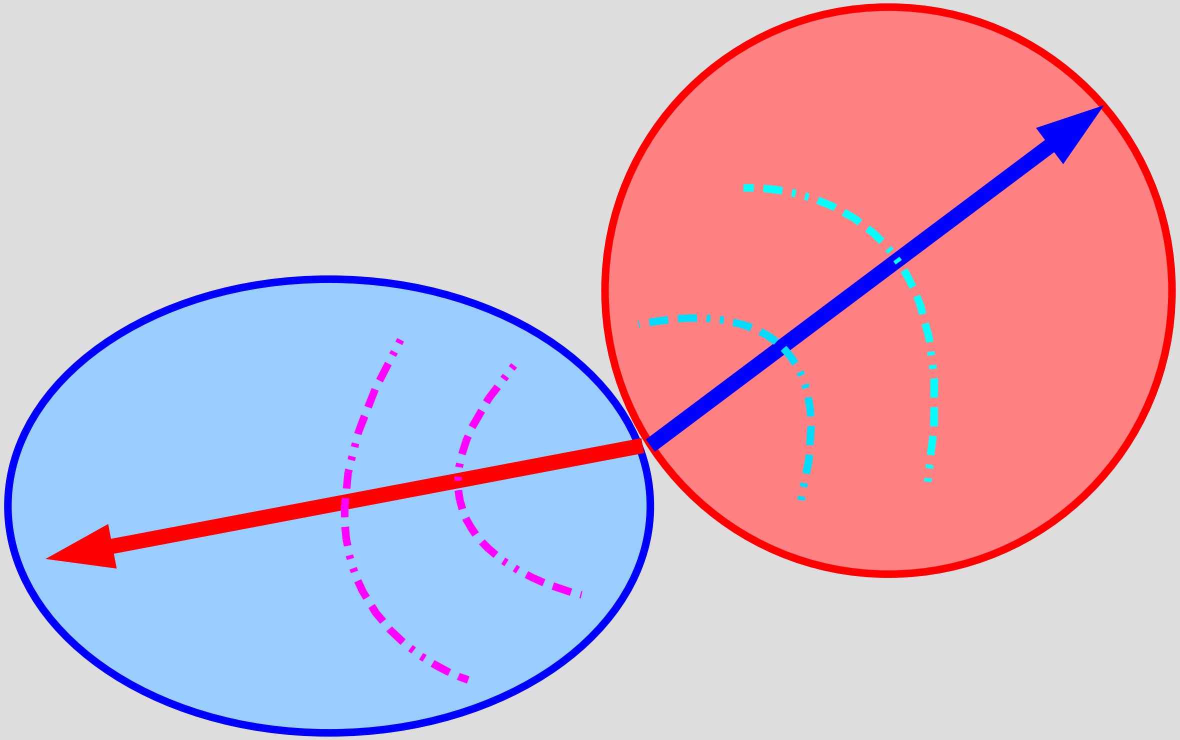
B. Gatty et. al. Nucl. Phys. (1975)
H. Breuer et. al. PRL (1979)
W. P. Tan et. al. PRC (2001)
P. M. Milazzo et. al. PRC (2002)

P. M. Mocko et. al. PRC (2007)

# *Fast charge equilibration conjecture*

- **The conjecture of the fast charge equilibration** has been confirmed.

Independent of the direction of the collision (impact parameter),
the equilibating wave propergates around the Fermi velocity



**Mechanism:**
**The regime of individual single particle motion spreads out following the lowering of the potential barrier between the two nuclei after the touching.**

In the charge equilibration, protons and neutrons from both nuclei, particularly **<u>those near the Fermi levels</u>**, are mixed within a short time after the touching.

# *Impact on super heavy synthesis*

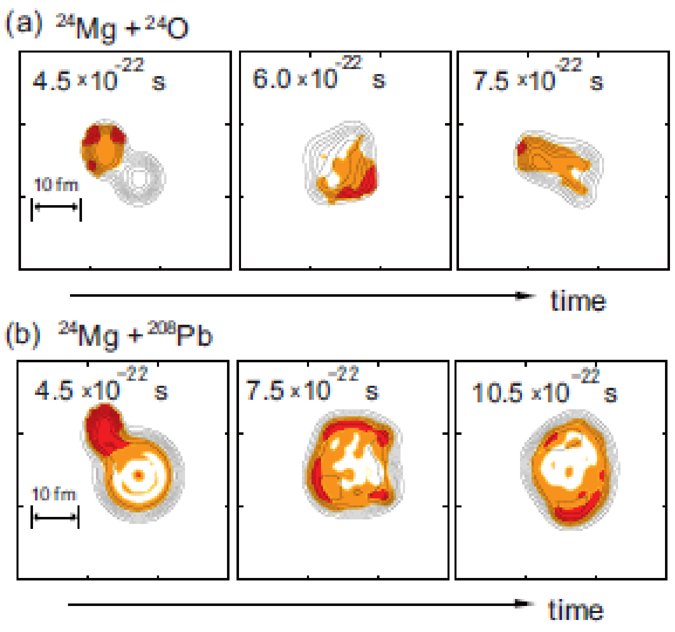
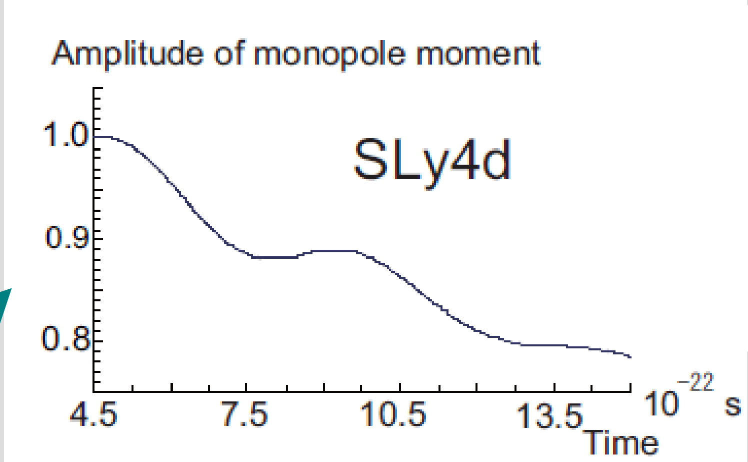


FIG. 4: Charge equilibration for $^{24}$Mg + $^{24}$O and $^{24}$Mg + $^{208}$Pb (SLy4d) are shown for $E_{cm}/A = 4.5$ MeV and 2.0 MeV with the impact parameters of 5.0 and 7.5 fm ($b_r = 0.72$ and 0.71), respectively. For both cases, $^{24}$Mg is incoming from the left and the states evolve into fusion. The description manner is the same as Fig. 3, where parts with the proton-neutron density ratio larger than 1.00 (0.75) and 0.80 (0.70) are colored in red and yellow, respectively.

**Iw. et. al., Phys.Rev. Lett., accepted.**



- Isovector **monopole** oscillation play a role in the charge equilibration, for heavy nuclear collision.
- Only isovector **dipole** oscillation has been known for the role of collective flow on the charge equilibration
- As a result, **the radial flow** contributes, where we should refer to the elliptic flow in high energy

# *Impact on super heavy synthesis*

## Ingredient of charge equilibration

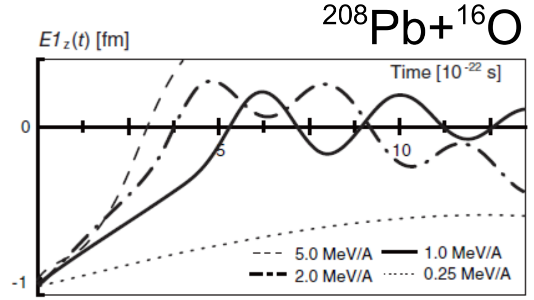


**Fig. 4.** Time evolution of the dipole moment in central collisions between $^{208}$Pb and $^{16}$O, where the cases of $E_{cm} = 0.25$, 1.0, 2.0, and 5.0 MeV/A are shown (from lower to upper curves). The values are normalized by the initial value $E1_z(0)$ (the same for figs. 5 and 6).

Light

Fusion

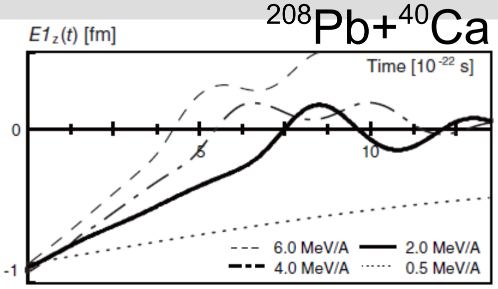


**Fig. 5.** Time evolution of the dipole moment in central collisions between $^{208}$Pb and $^{40}$Ca, where the cases of $E_{cm} = 0.5$, 2.0, 4.0, and 6.0 MeV/A are shown (from lower to upper curves).

Medium

+ Fusion-fission
with solid compound nucleus

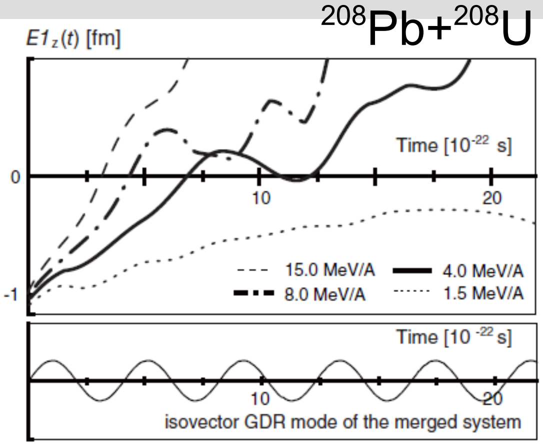


**Fig. 6.** Top: time evolution of the dipole moment in central collisions between $^{208}$Pb and $^{238}$U, where the cases of $E_{cm} =$ 1.5, 4.0, 8.0, and 15.0 MeV/A are shown. Bottom: for reference, the oscillation with the isovector-GDR mode of the merged system $^{446}$174 is shown in a simplified manner, where only the frequency of GDR is reproduced as the sine function.

Heavy

Mass of colliding nucleus

+ Quasi-fission

Iw. *et. al.*, Eur. Phys. J. A. (2009)

# *Impact on exotic nuclear synthesis*

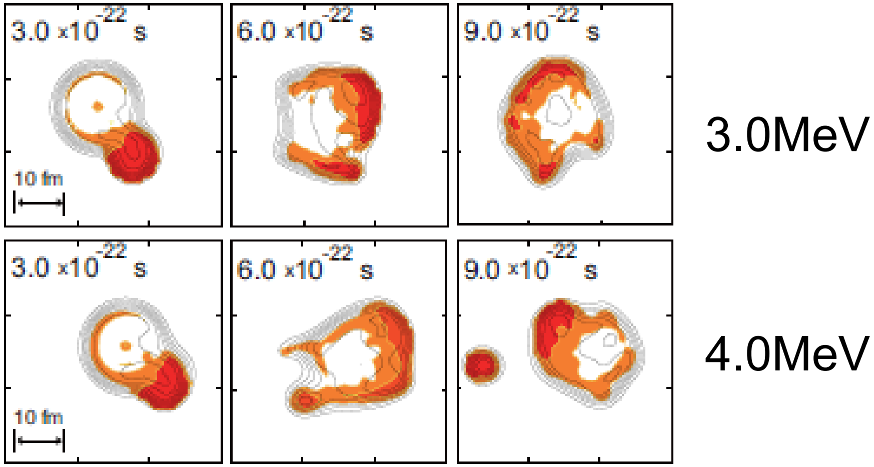


FIG. 3: Time evolution of charge distribution for $^{208}$Pb + $^{40}$Ca (SLy4d) is shown for the impact parameter of 7.5 fm ($b_r = 0.67$). The upper and the lower panels show cases with $E_{cm}/A = 3.0$ MeV and 4.0 MeV, respectively. $^{208}$Pb is coming from the left for both cases. The contours incremented by 0.02 fm$^{-3}$ show the density, where parts with the proton-neutron density ratio greater than 0.78 and 0.72 are colored in red and yellow, respectively.

**Iw. *et. al.*, Phys.Rev. Lett., accepted.**

$^{208}$Pb+$^{40}$Ca

- ➲Exotic nuclei are synthesized even in this reaction (beteen $\beta$-stable nuclei).

.

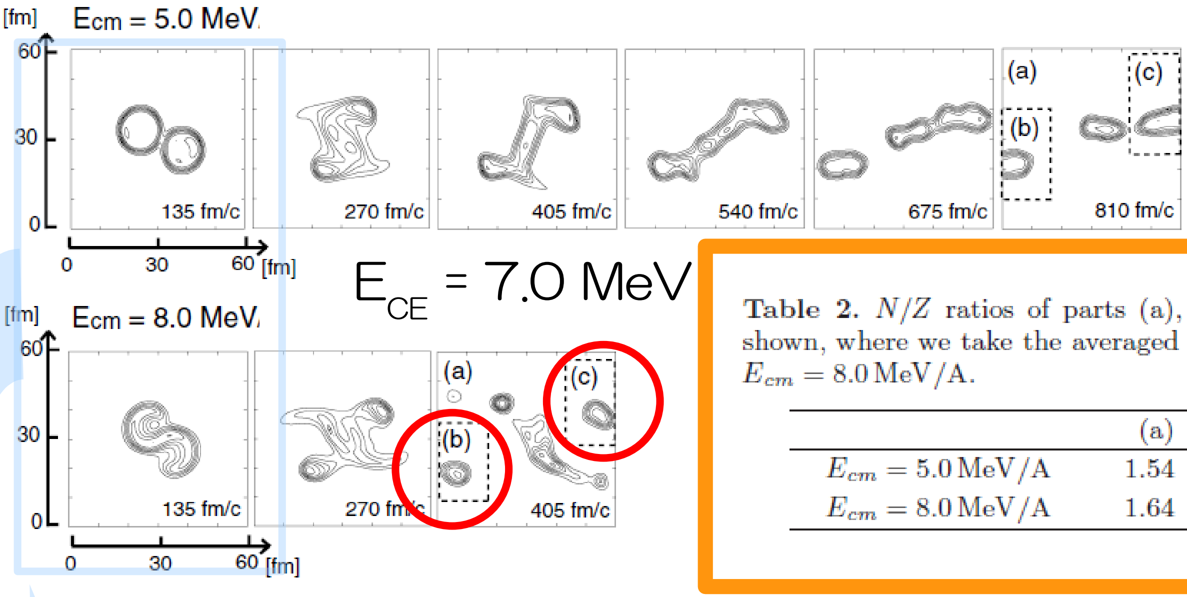
- ➲ This kind of nuclear synthesis is possible, merely by the putting the energy higher than the upper-limit.

Upper Energy = 3.7 MeV

Fusion
– lower energies

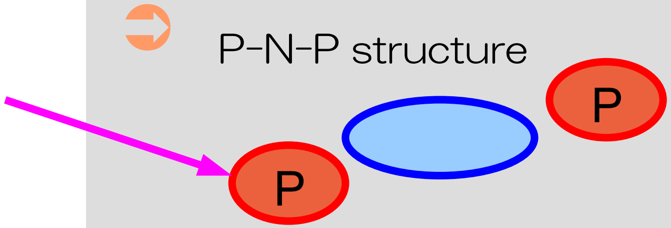
Exotic Fragmentation of Exotic Nuclei
– higher energies

# *Impact on exotic nuclear synthesis*



$E_{CE}$ = 7.0 MeV

Fig. 9. Time evolution of the total density for $^{208}$Pb + $^{238}$U. The impact parameter is fixed to be 9.2 fm. We have separated into three parts as 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.



P-N-P structure

**Table 2.** $N/Z$ ratios of parts (a), (b) and (c) in fig. 9 are shown, where we take the averaged $N/Z$ value for 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 |

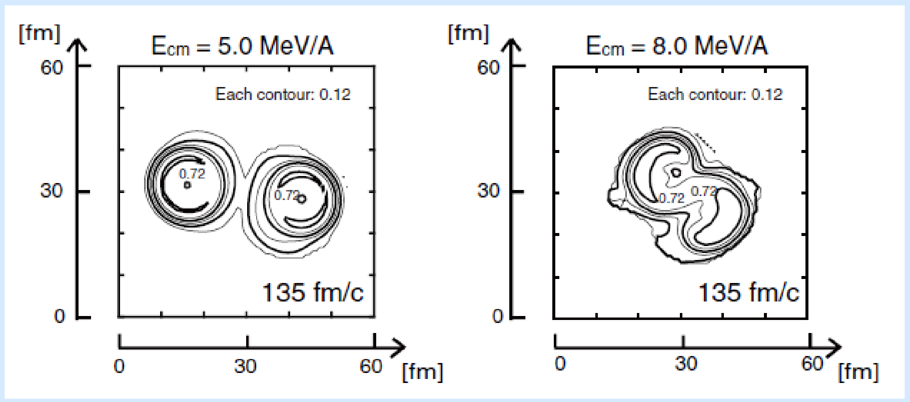


Fig. 10. Snapshots of TDHF calculations at 135 fm/$c$, where the proton to neutron density ratio is shown. Each contour is set to be 0.12, while thick contours are set to 0.24. The relatively proton-rich part with a ratio of 0.72 is localized around the edge of colliding nuclei. These two figures precisely correspond to the cases shown in fig. 9.

Although there exists a large **Coulomb excitation** and the resulting charge localization at the contact time, our research suggests that it does not have an essential influence on the final charge distribution.

**chage equilibration appears similarly to the heavy nuclear reactions**

**Iw. *et al.*, Eur. Phys. J. A (2009)**

# Present/future studies in Charge equlibration

## - equilibration and more -

Iwata *et. al,* Nucl. Phys. A (2010)

- The existence of the upper limit enegy in Charge Equilibration implies that charge equilibrated final fragments are favored in the lower enegies.
- There shoud be a strong restriction to dynamics (equilibration=number of transferred nucleons), if we have the lower enegies (where the charge equilibrium is achieved).

**The unified description of nucleon transfer in the lower energies:**

- Nucleon transfer at lower energies can be "completely" classified into 6 types in a geometric manner.
- It explains why the enhancement of neutron transfer is frequentlyobserved in the experiments including the neutron-rich nuclei.
- It explains why the proton-richness does not necessarily result in the enhancement of proton transfer.
- Neurton/proton richness does not play a role in the number of transferred nucleons.

# *Present/future studies in Charge equlibration*

# *- equilibration and more -*

Iwata-Feldmeier, in preparation

- We have established a method of obtaining Nuclear Potential from time-dependent calculation

_ we can obtain the nuclear potential momentum-dependently.

_ our method is less phenomenological; we do not need to change/add parameters one reaction to another.

_ our approach is diabatic, which might be rather interesting to compare to the preceding adiabatic-like potential obtained by TDHF (Umar-Oberacker)

_ our approach is somewhat mathematical all the potential is described by the 3rd order spline-interpolated functions, which will be advantageous in the future "further" research

_ potential reseach (parametrization business) will meet the collision dynamics before long.

# *Summary*

- **Appearance** of charge equilbration governs the fusion
  _ Super heavy Synthesis ... radial flow

- **Absence** of charge equilibration makes the N/Z ratio free
  _ Exotic nuclear synthesis ... even by beta-stable collisions

- Mechanism of charge equilibration is presented, where nucleons with the Fermi velocity play a crucial role.

*The upper energy-limit of charge equilibration has a crucial impact on the nuclear synthesis, giving a sound motivation for the production of further exotic isotopes by the latest and the future RI-beam facilities.*

- Charge equilbration will be studied in a sophisticated manner
  _ nuclear potential and collision dynamics
  _ going Beyond the Time-Dependent Mean-Field Theory

(Iwata-Feldmeir, in preparation)