Equilibration Dynamics in Nuclear Reactions

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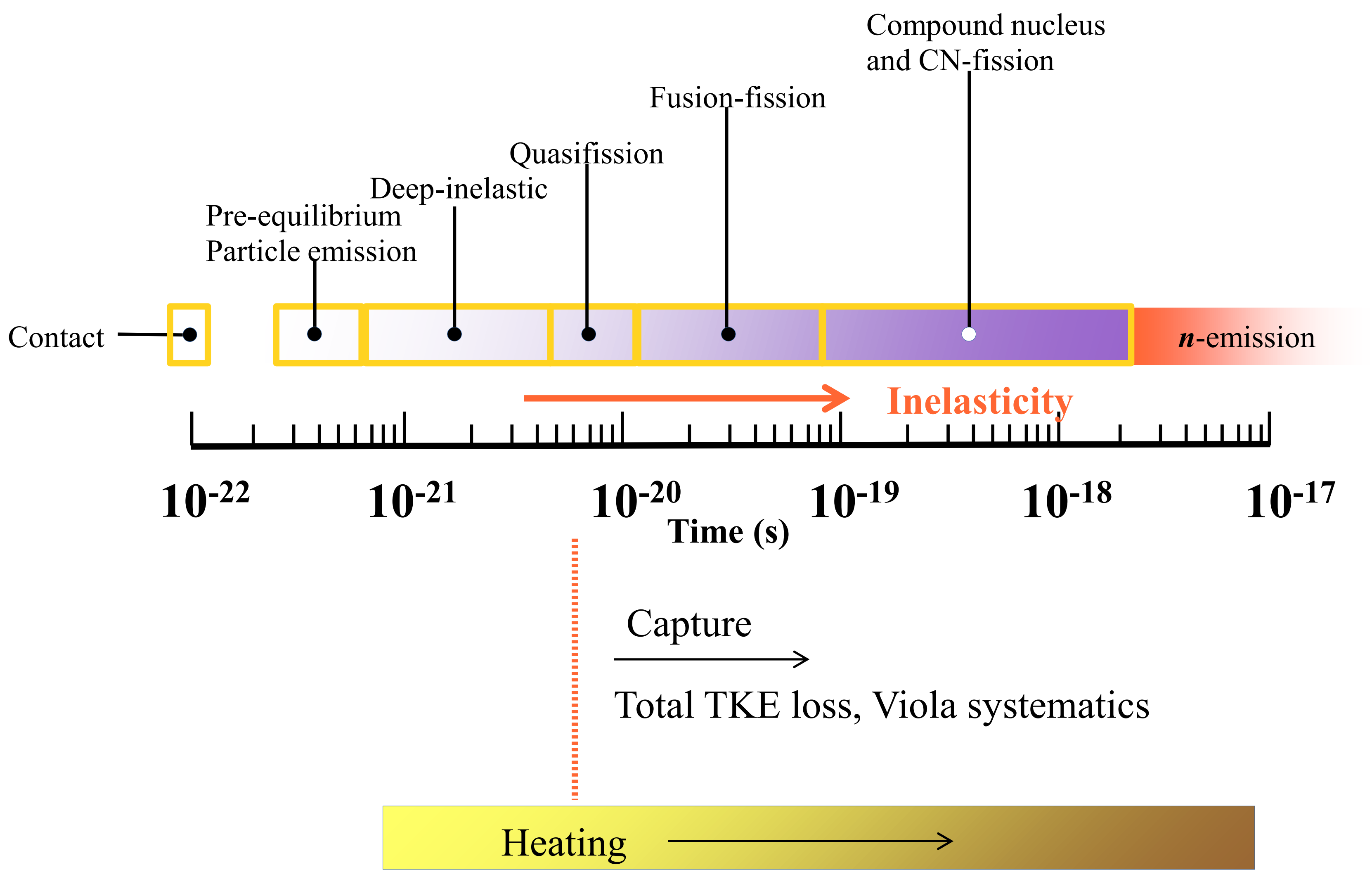
Topics:

I. Time-scales for low-energy heavy-ion reactions
II. Equilibration dynamics of mass, isospin, energy
III. Isospin dynamics and fusion barriers

Research supported by: U.S. Department of Energy, Division of Nuclear Physics

I. Time scales and inelasticity for nuclear reactions



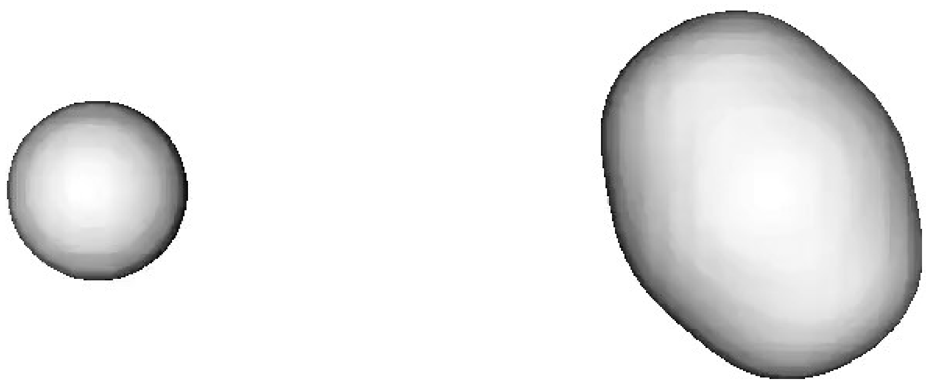
Courtesy of Yu. Ts. Oganessian

II. Equilibration dynamics – mass in quasifission

Equilibration:
Mass
Isospin
Energy dissipation

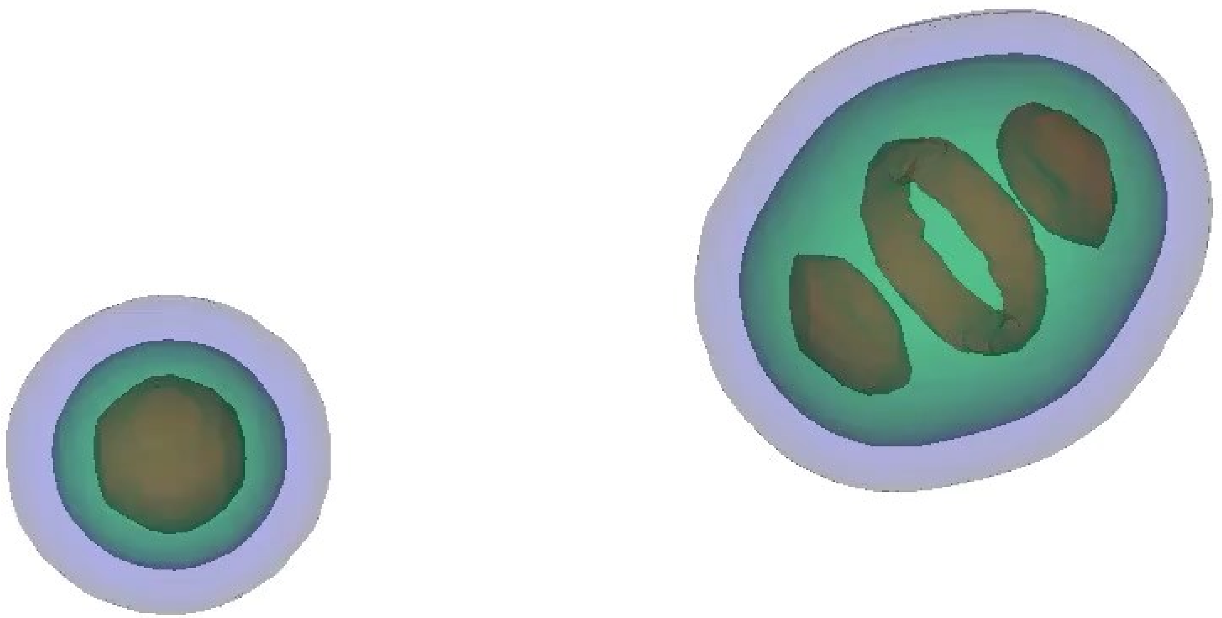
Dynamics:
Time scales
Equilibration interrupting
mechanisms

Quantum:
Shell effects



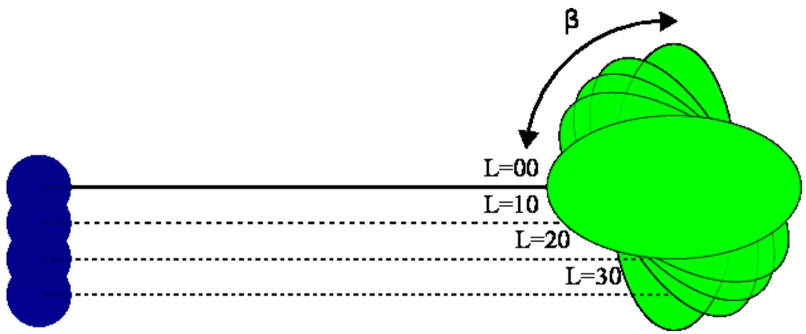
Theory:
TDHF is proven to be an excellent diagnostic tool for QF reproducing exp features
Fluctuations can be studied with SMF and TDRPA.

Quasifission in $^{48}Ca + ^{249}Bk$

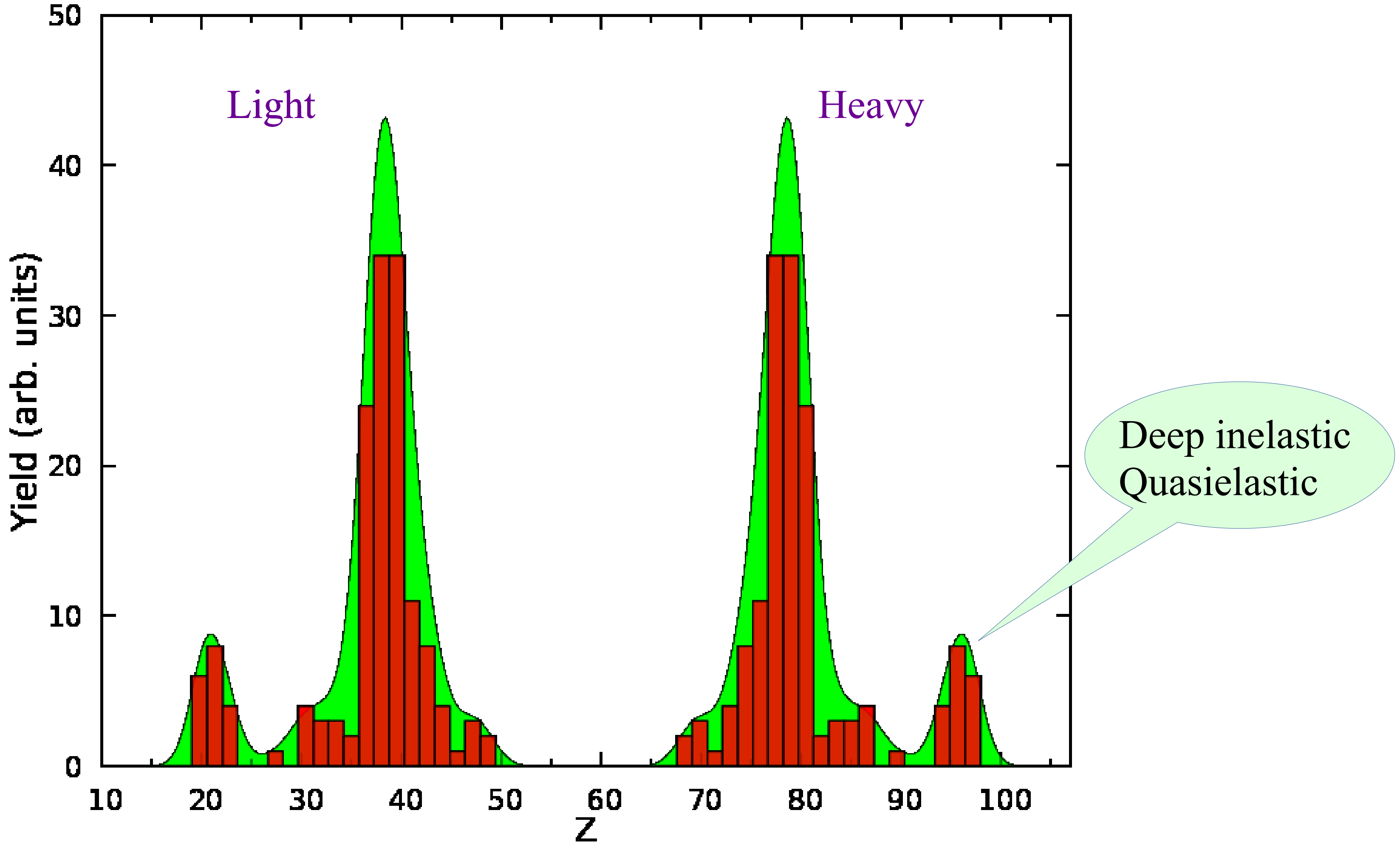


$E_{c.m.}$= 234 MeV, L=90 $\hbar$ β=150^o
Final fragments: ^{99}Zr, ^{198}Ir
contact time 8 zs

Quasifission – ^{48}Ca + ^{249}Bk – orientation and shell effects

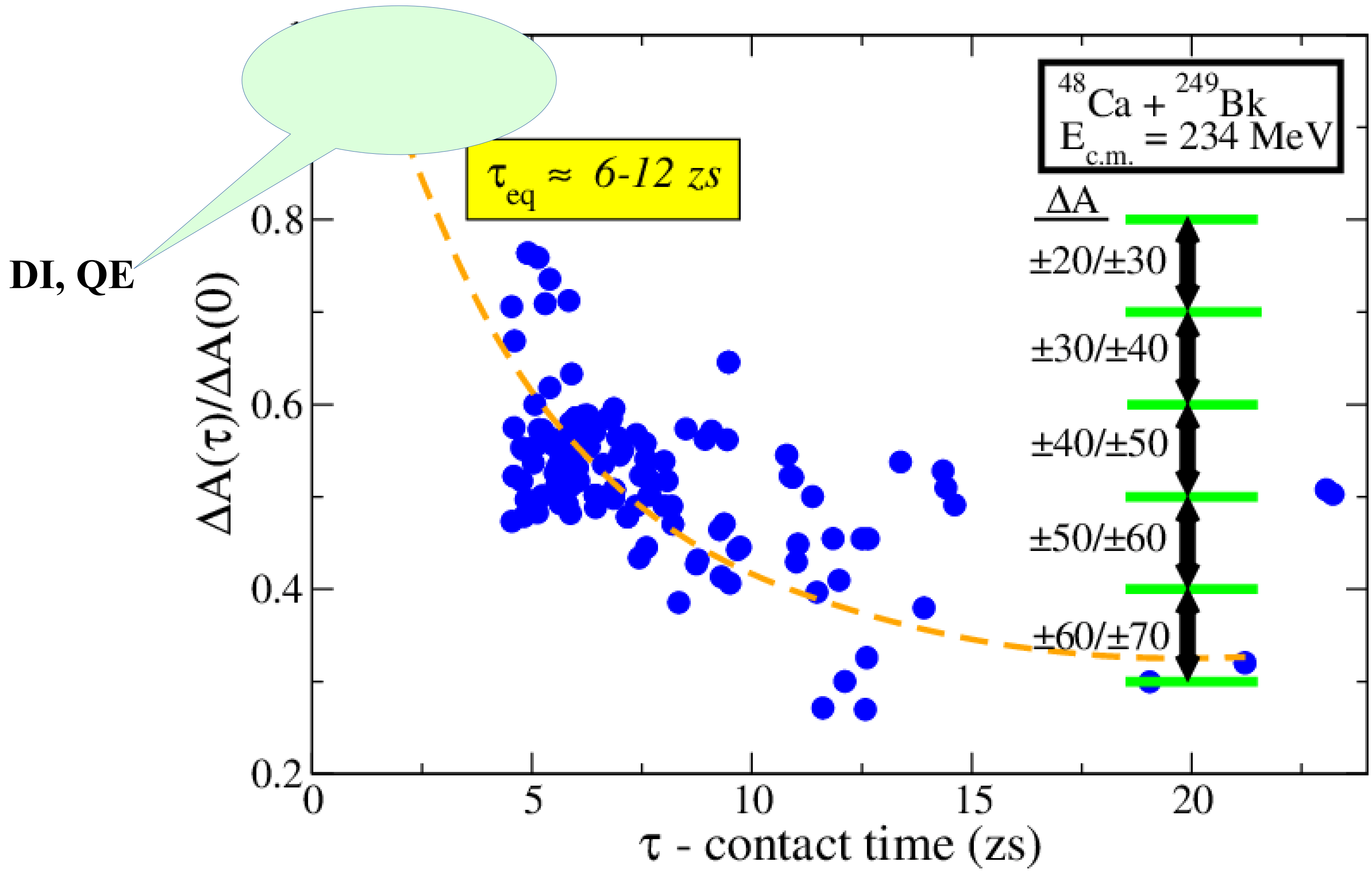


- Most comprehensive QF calculation
- All β in range (0°,180°) Δβ=15°
- Entire L range for each β
- Each (β,L) run takes 1-3 days on 20 core CPU



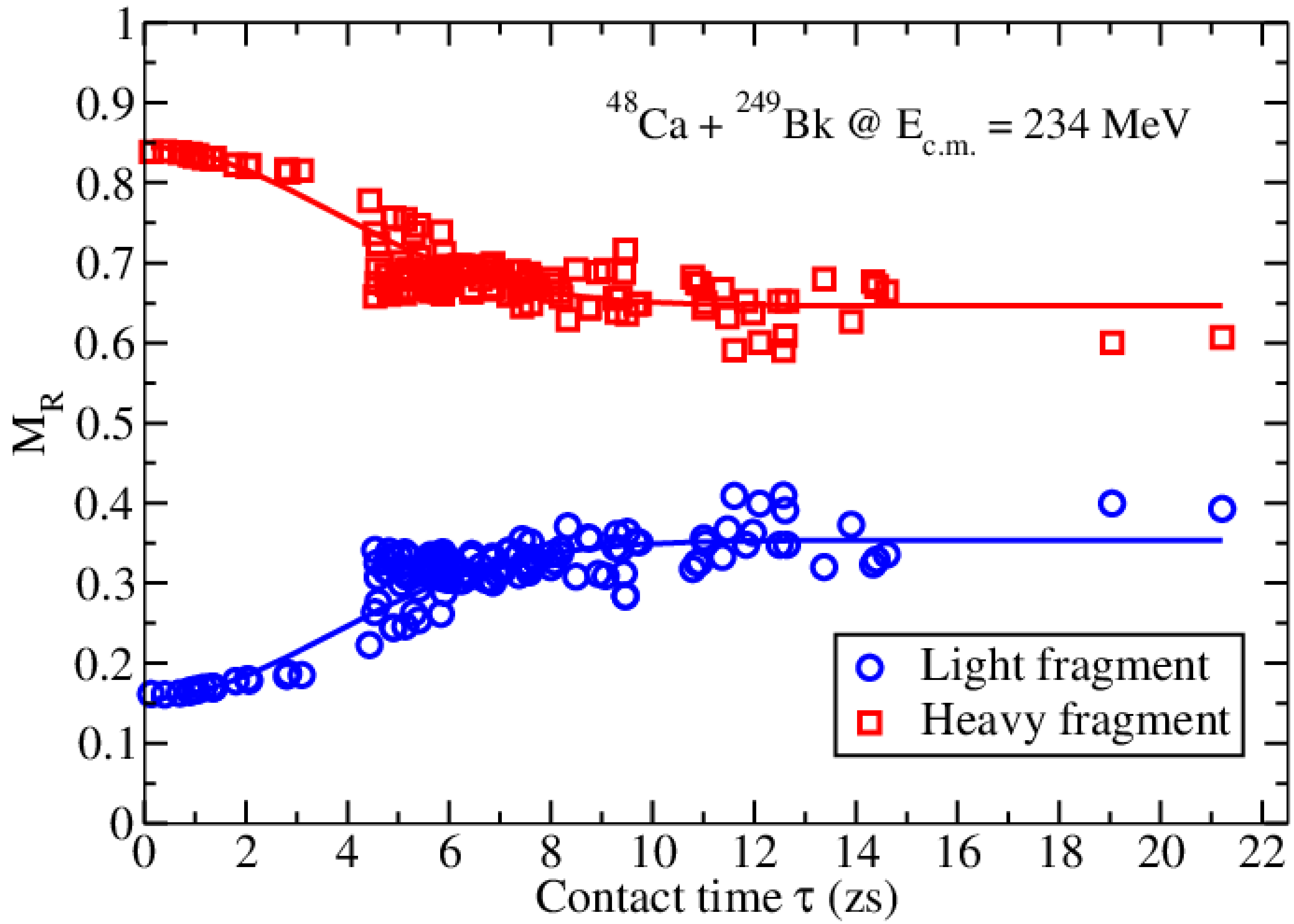
Quasifission in $^{48}Ca + ^{249}Bk$ – equilibration time

$$\Delta A(t) = A_{TLF}(t) - A_{PLF}(t)$$



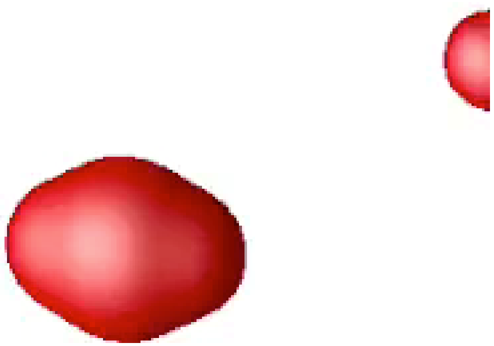
1 zs = 10^{-21} sec

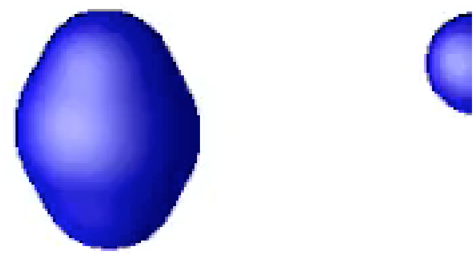
Quasifission in $^{48}Ca + ^{249}Bk$ – equilibration time



$$M_R = \frac{M_{frag}}{M_1 + M_2}$$

Quasifission – ^{40}Ca + ^{238}U

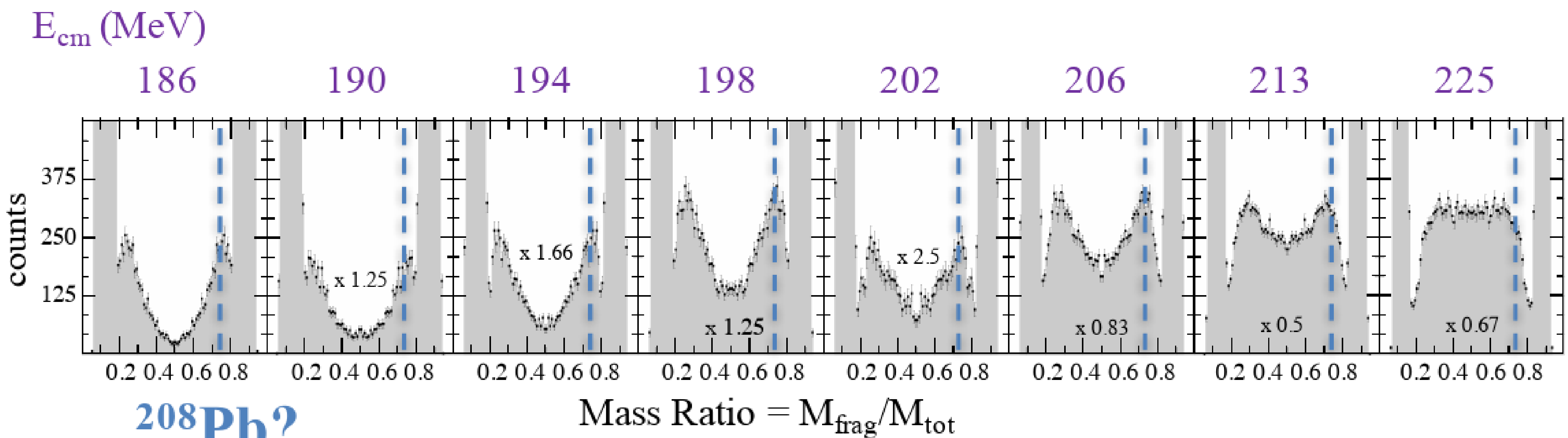




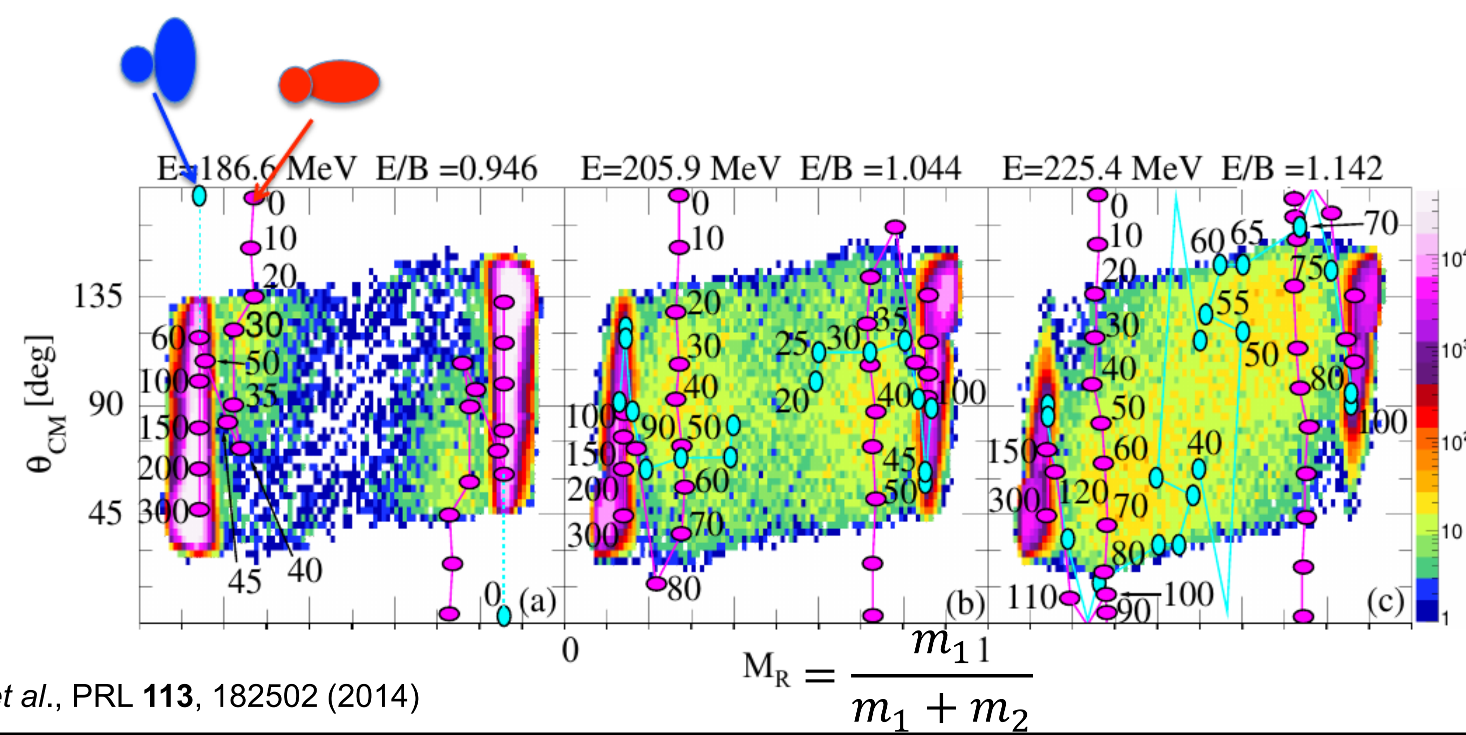
$E_{c.m.}$= 225 MeV, L=100 $\hbar$ip)
Final fragments: ^{78}Ge, ^{200}Hg
contact time < 20 zs

$E_{c.m.}$ = 225 MeV, L=40 $\hbar$ide)
Final framents: ^{140}Ba,^{138}Ba
contact time > 20zs

Quasifission – ^{40}Ca + ^{238}U – shell effects

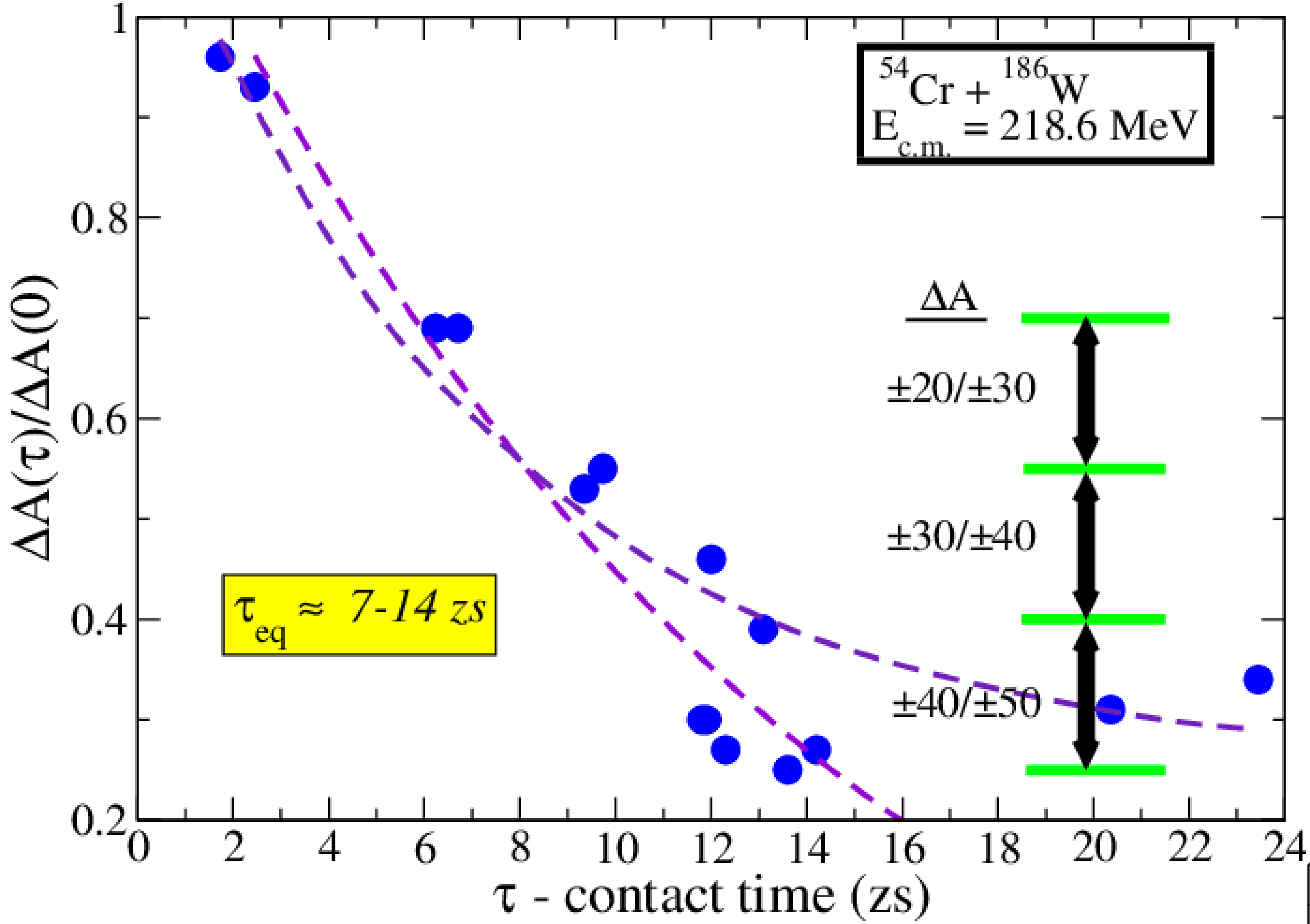


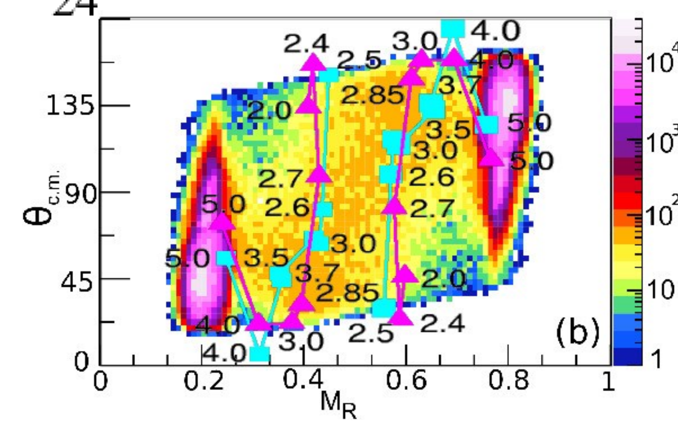
^{208}Pb?



Wakhle *et al.*, PRL **113**, 182502 (2014)

Quasifission in ^{54}Cr + ^{186}W – equilibration time





K. Hammerton, *et al.* PRC **91**, 041601(R) (2015)

Summary for mass equilibration

- ~ **10 zs** to reach mass equilibrium
  (Toke *et al.* PRC 1985, du Rietz *et al.*, PRC 2013)

- Orientation dependence effects time-scales
  - slow QF versus fast QF

First exp. evidence

- Shell effects influence/hinder equilibration (Z=82)
  - 40Ca + 238U (Wakhle *et al.* + TDHF)
  - 48Ti + 238U (M. Morjean *et al.* PRL 119, 222502 (2017))

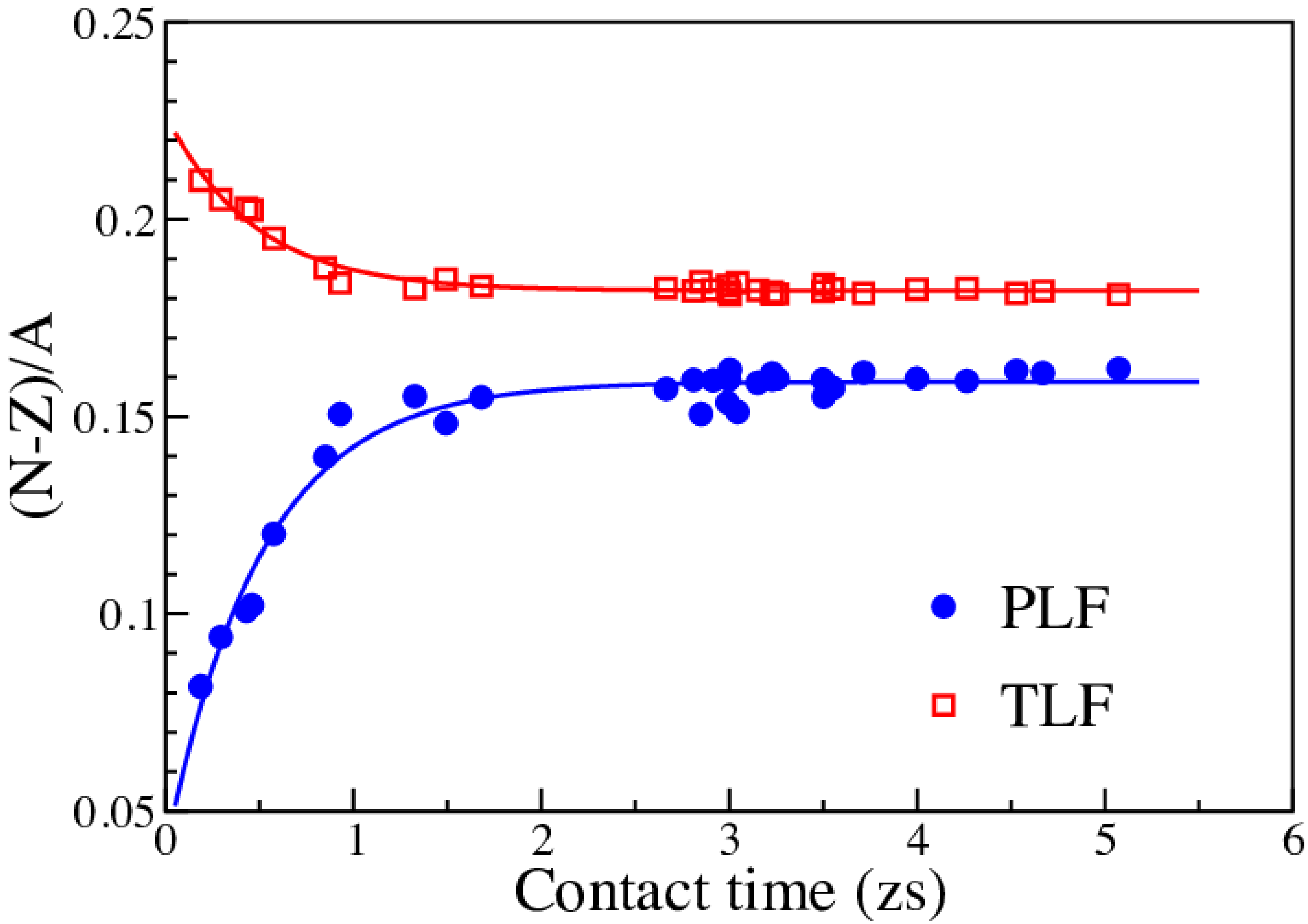
- Other shell effects observed in TDHF
  - preference for neutron rich Zr isotopes for light fragment
  - optimal pair that minimizes energy

Isospin equilibration

- Connection with symmetry energy, isospin dependence of EoS
- Much faster than mass equilibration: Equilibration ~ exp(-t/**0.3zs**) from experiments at Fermi energy (Jedele *et al.*, PRL 118, 2017)
- Needs faster reaction mechanisms than quasifission
- Deep-inelastic collisions
(Planeta *et al.*; deSouza *et al.*, PRC 1988, K. Stiefel *et al*, PRC 2014)

Isospin equilibration – $^{78}Kr+^{208}Pb$ – 8.5 MeV/A

Umar, Simenel, Ye PRC **96**, 024625 (2017)

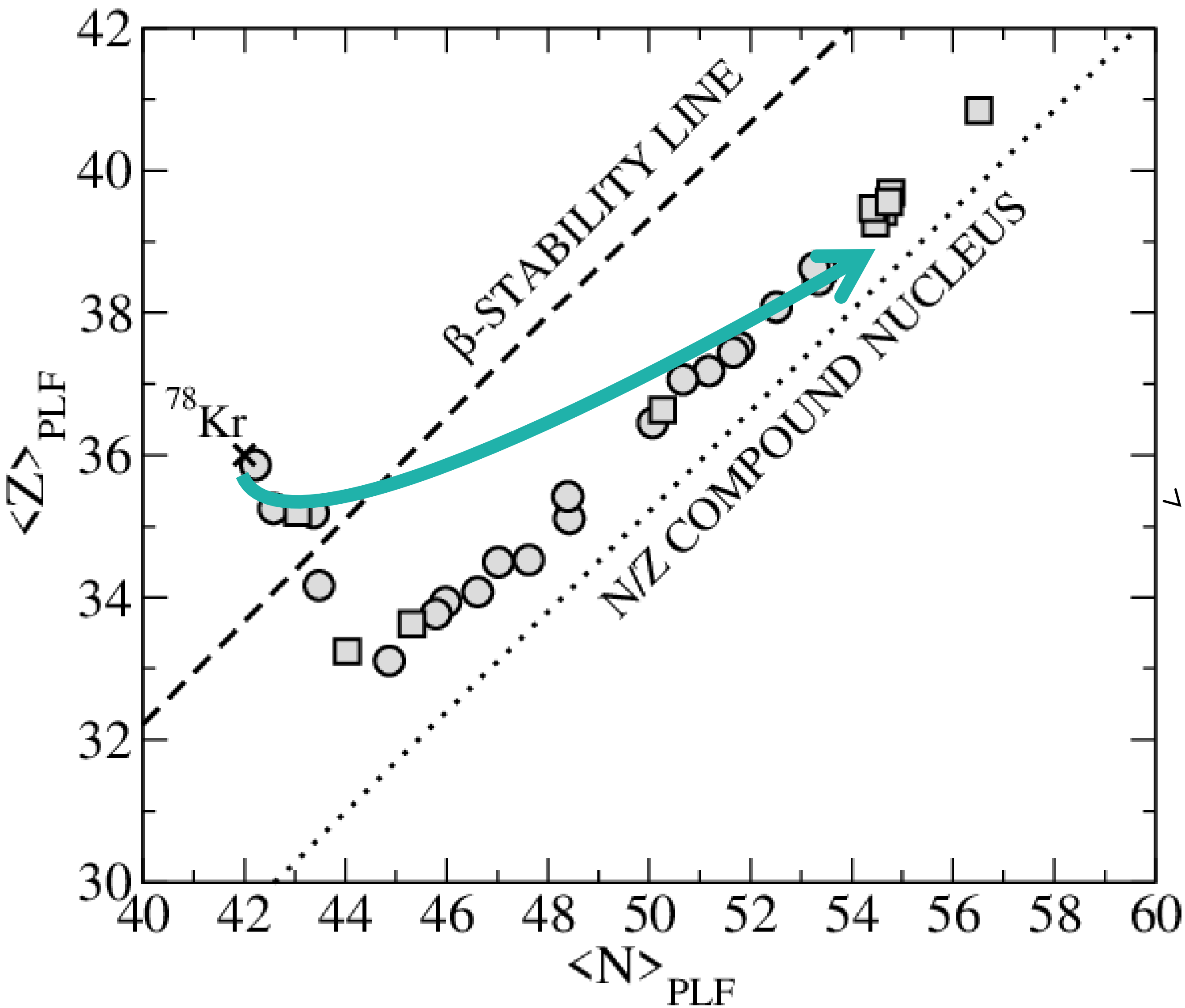


Broad range of fast contact times

~ **1 zs** to reach isospin equilibrium

Isospin equilibration – ^{78}Kr+^{208}Pb – 8.5 MeV/A

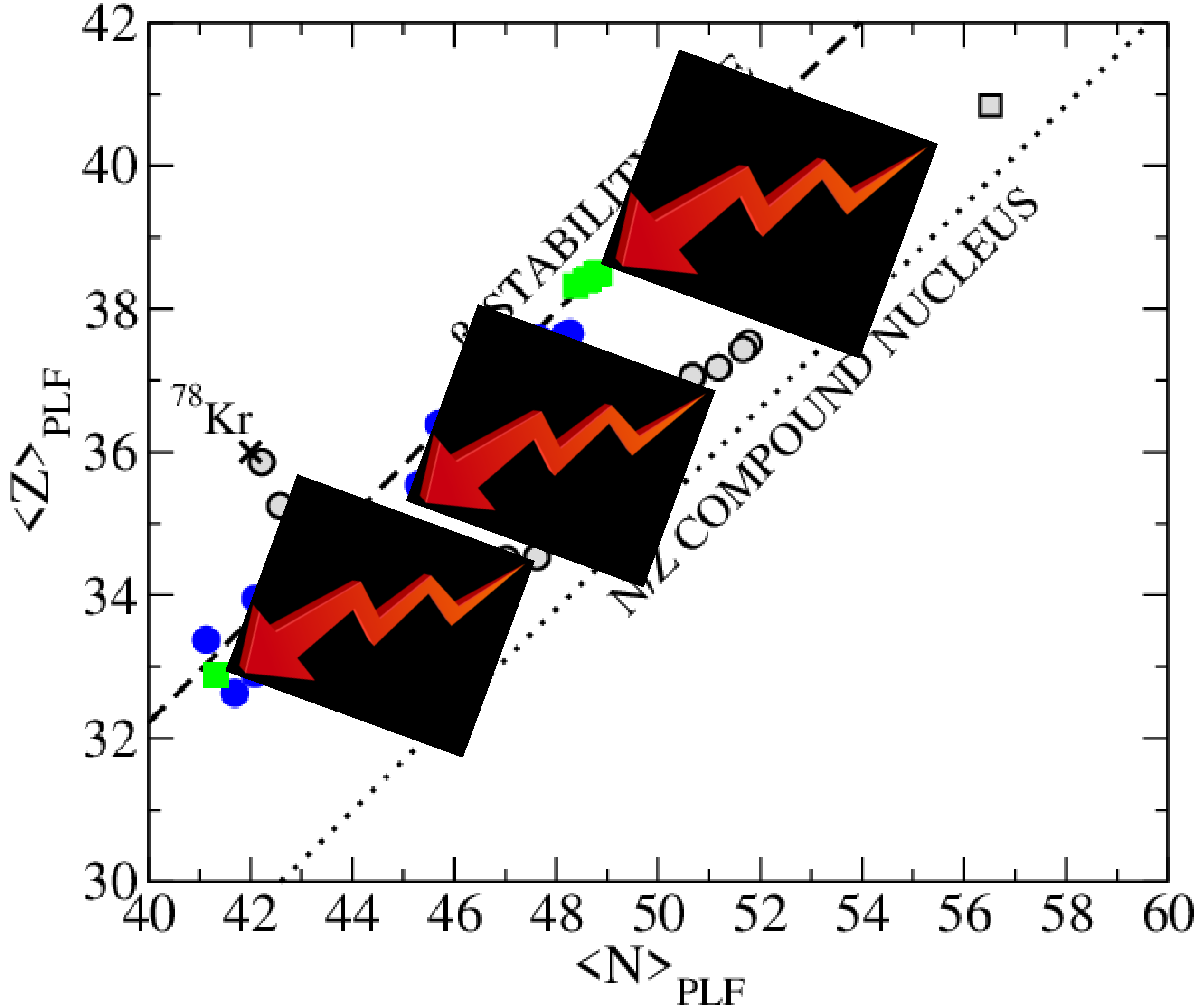
Umar, Simenel, Ye PRC **96**, 024625 (2017)



Isospin and mass equilibration (TDHF)

Need reconstruction of the primary fragments (statistical codes)

Isospin equilibration – ^{78}Kr+^{208}Pb – 8.5 MeV/A

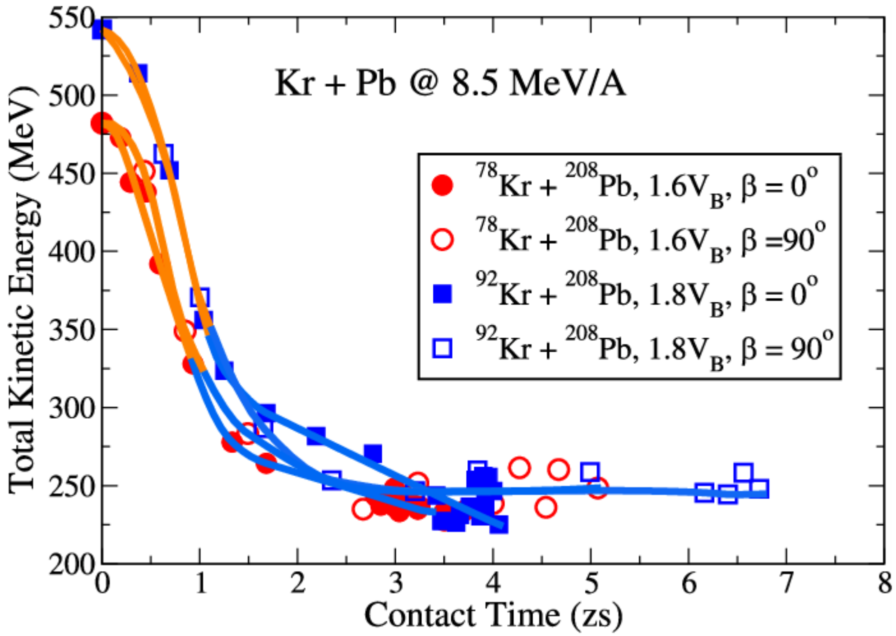


Isospin and mass equilibration (TDHF)

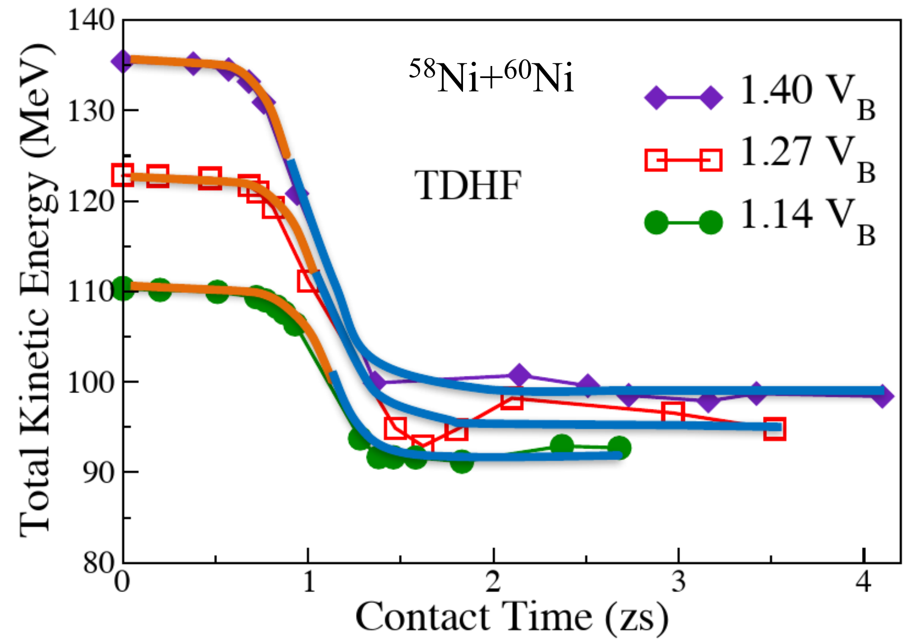
Statistical deexcitation (GEMINI)

Energy dissipation

Umar, Simenel, Ye PRC **96**, 024625 (2017)

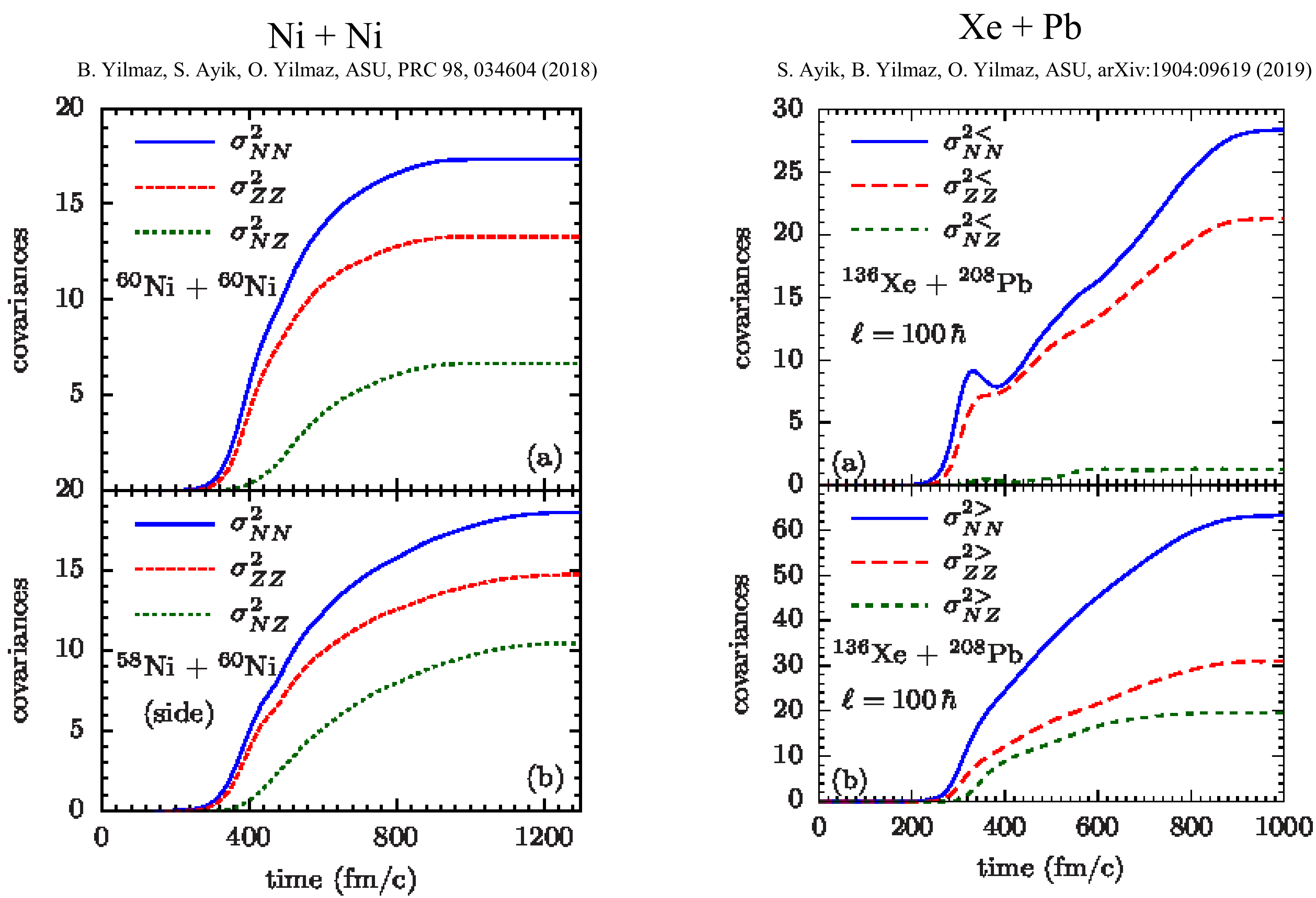


Williams et al., PRL **120**, 022501 (2018)



≈ 1.5zs to reach equilibrium (full energy dissipation)

Time-scale for fluctuations in stochastic mean-field (SMF)



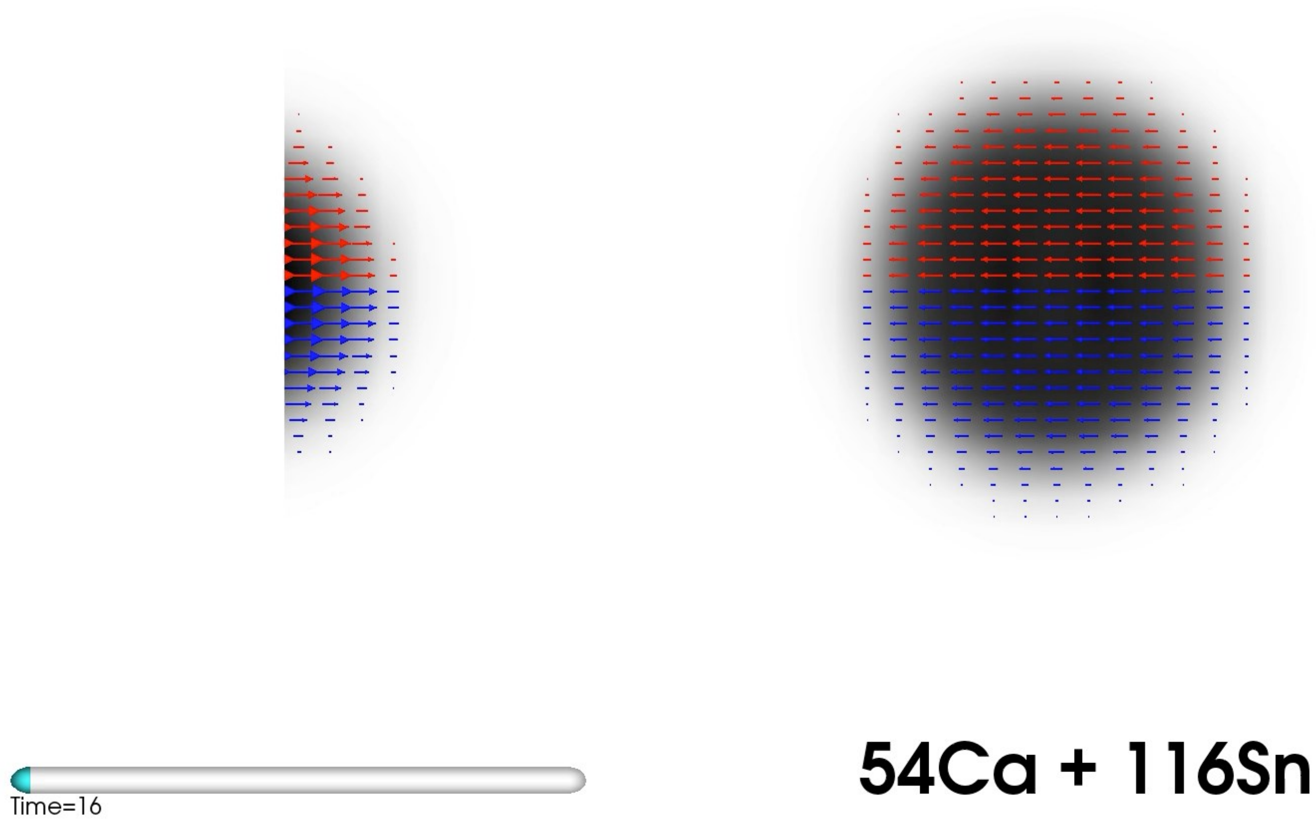
Time-scale ~ 2.5-3 zs

Quantum equilibration dynamics

	Time to equilibrium	
Mass $^{40,48}Ca+^{238}U,^{249}Bk$ Cr+W and many others Slowed by shell effects	~ 10 zs	QF
Isospin $^{78}Kr+^{208}Pb$	~ 1 zs	DIC
Energy $^{78}Kr+^{208}Pb$ $^{58}Ni+^{60}Ni$	~ 1.5 zs	DIC
Mass Fluctuations $^{58}Ni+^{60}Ni$, Xe+Pb SMF, TDRPA S. Ayik, et al. arXiv:1904:09619 (2019) Williams et al., PRL **120**, 022501 (2018)	~ 3 zs	DIC

Need more systematics……..

Isospin dynamics and fusion barriers



TDHF + density constraint (DC-TDHF)

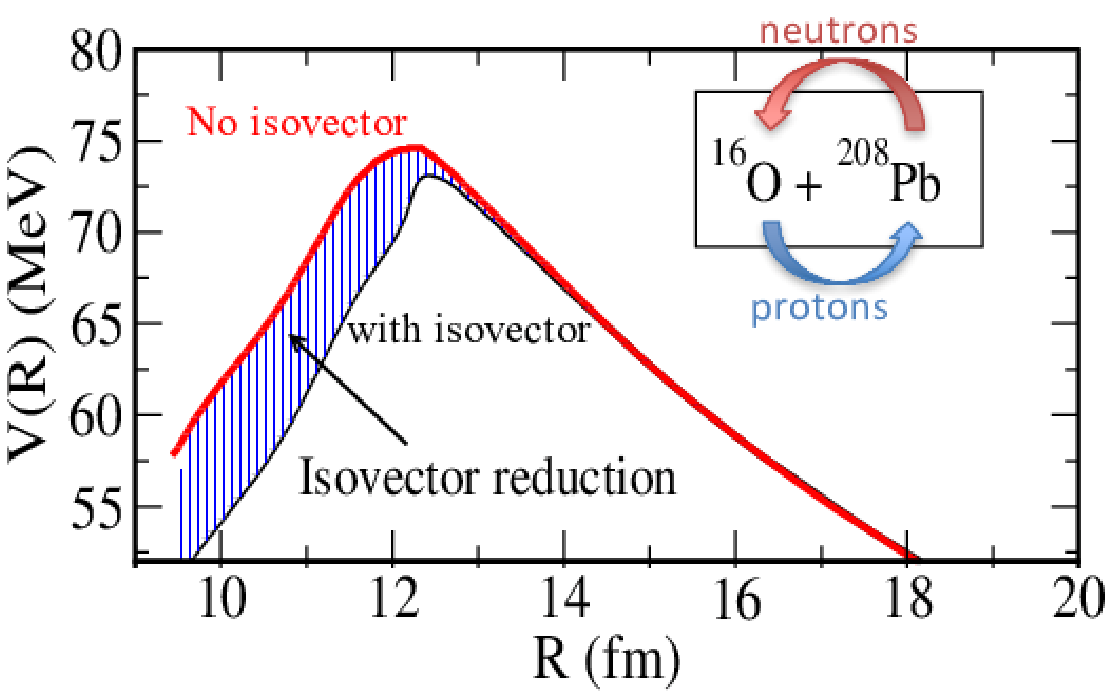
Skyrme EDF

$$\mathcal{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau_0 + \mathcal{H}_{I=0}(\mathbf{r}) + \mathcal{H}_{I=1}(\mathbf{r}) + \mathcal{H}_C(\mathbf{r})$$

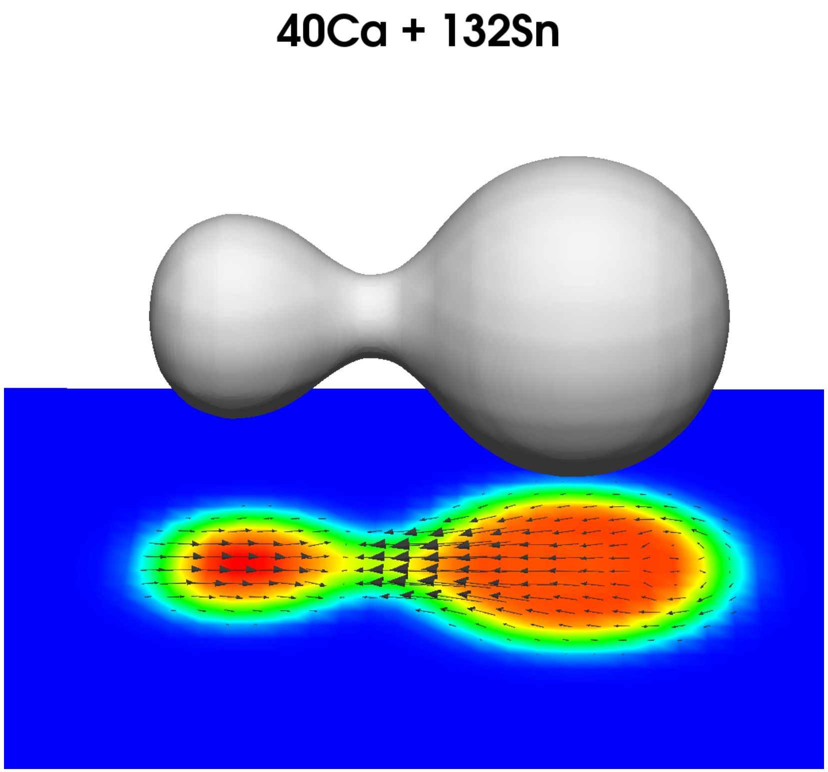
Allows for isospin decomposed ion-ion interaction barrier

$$\mathrm{V}(\mathrm{R}) = \mathrm{V}_{\mathrm{I}=0}(R) + V_{\mathrm{I}=1}(R) + V_C(R)$$

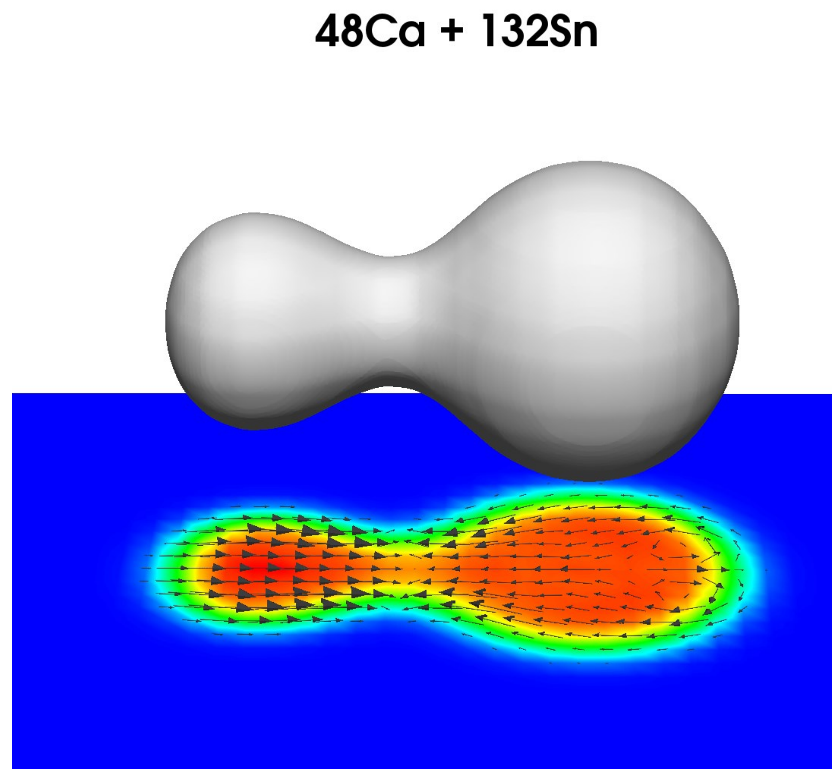
- Minimize energy with density constraint during unhindered TDHF
- Microscopic internuclear potential
- Parameter-free, only depends on chosen EDF
- Dynamical, energy-dependent
- Extensively applied to fusion barrier calculations



$^{40}Ca+^{132}Sn$ versus $^{48}Ca+^{132}Sn$

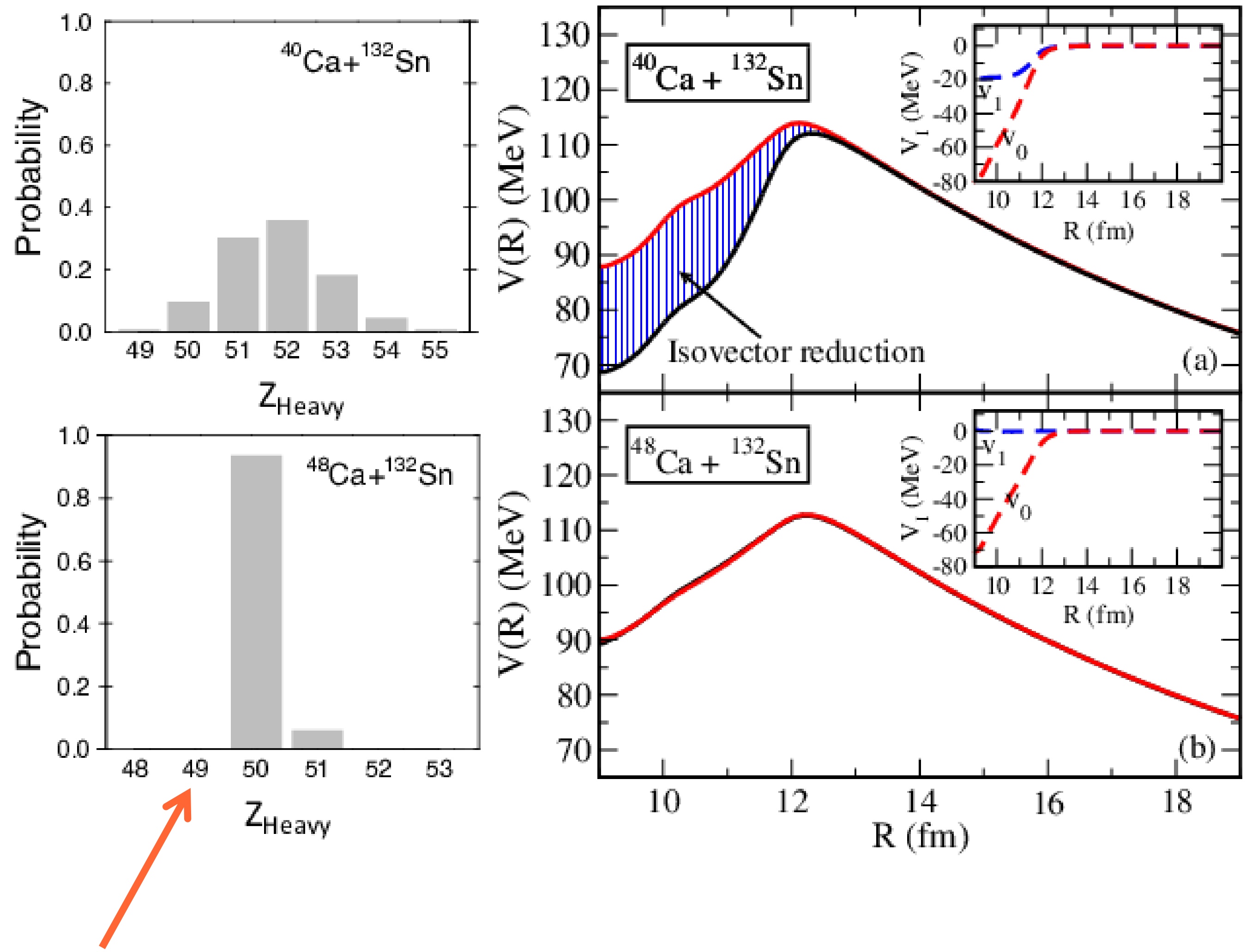


transfer



No net transfer

^{40}Ca+^{132}Sn versus ^{48}Ca+^{132}Sn – Q-value transfer channels



Particle number projection just below the barrier

Collaborators

Progress in Particle and Nuclear Physics 103 (2018) 19–66

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journal homepage: www.elsevier.com/locate/ppnp

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Review

Heavy-ion collisions and fission dynamics with the time-dependent Hartree–Fock theory and its extensions

C. Simenel[a,*], A.S. Umar[b]

PHYSICAL REVIEW C 95, 011601(R) (2017)

RAPID COMMUNICATIONS

Dependence of fusion on isospin dynamics

K. Godbey[1,*], A. S. Umar[1,†], and C. Simenel[2,‡]

PHYSICAL REVIEW C 96, 024625 (2017)

Transport properties of isospin asymmetric nuclear matter using the time-dependent Hartree-Fock method

A. S. Umar[1,*], C. Simenel[2,†], and W. Ye[3,‡]

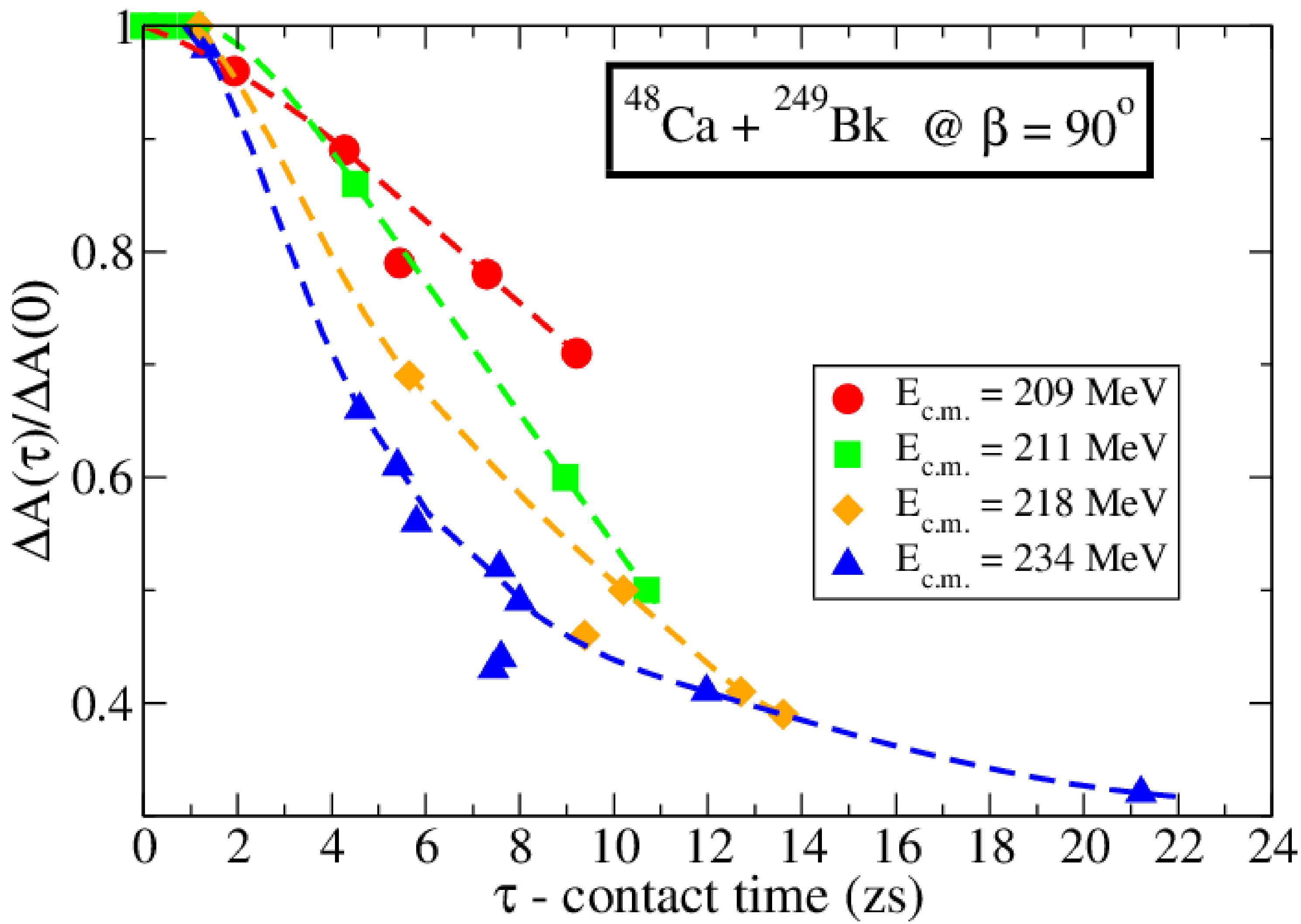
PHYSICAL REVIEW C **98**, 034604 (2018)

Multinucleon transfer in ^{58}Ni+^{60}Ni and ^{60}Ni+^{60}Ni in a stochastic mean-field approach

B. Yilmaz[1], S. Ayik[2], O. Yilmaz[3], and A. S. Umar[4]

Supplementary Slides

Equilibration time E-dependence



TDDFT + Density Constraint = Internuclear Potentials

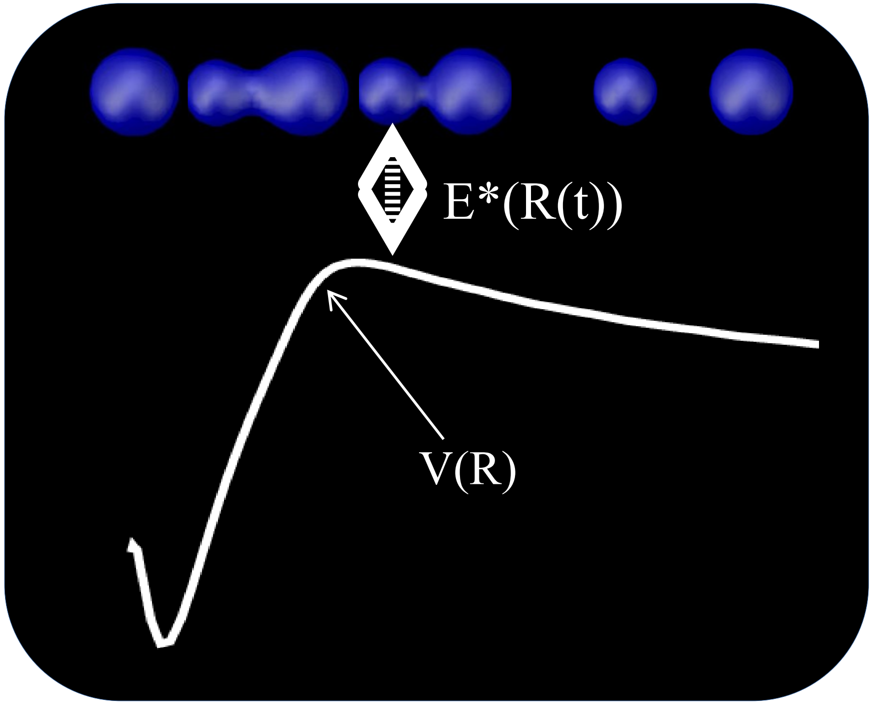
- Minimize energy with density constraint during unhindered TDDFT

$$E_{DC}(t) = min_{\rho}\left\{E[\rho_n,\rho_p] + \int d^3r\lambda_n(\mathbf{r})[\rho_n(\mathbf{r}) - \rho_n^{tdhf}(\mathbf{r},t)] + \int d^3r\lambda_p(\mathbf{r})[\rho_p(\mathbf{r}) - \rho_p^{tdhf}(\mathbf{r},t)]\right\}$$

- Microscopic dynamical internuclear potential – can calculate subbarrier fusion, capture

$$V(R) = E_{\mathrm{DC}}(R) - E_{A_1} - E_{A_2}$$

- Parameter-free, only depends on chosen EDF
- Dynamical, energy-dependent
- Calculate E*(t) and M(R)
- Extensively applied to fusion barrier calculations



TDHF + density constraint (DC-TDHF)

Energy written in terms of the Energy Density Functional (EDF)

$$\mathrm{E} = \int d^3\mathbf{r}\,\mathcal{H}(\mathbf{r})$$

Skyrme EDF

$$\mathcal{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau_0 + \mathcal{H}_{I=0}(\mathbf{r}) + \mathcal{H}_{I=1}(\mathbf{r}) + \mathcal{H}_C(\mathbf{r})$$

$$\mathrm{H_I}(\mathbf{r}) = C_\mathrm{I}^{\rho}\rho_\mathrm{I}^2 + C_\mathrm{I}^{s}\mathbf{s}_\mathrm{I}^2 + C_\mathrm{I}^{\Delta\rho}\rho_\mathrm{I}\Delta\rho_\mathrm{I} + C_\mathrm{I}^{\Delta s}\mathbf{s}_\mathrm{I}\cdot\Delta\mathbf{s}_\mathrm{I} +$$

$$\mathrm{C}_\mathrm{I}^{\tau}\left(\rho_\mathrm{I}\tau_\mathrm{I} - \mathbf{j}_\mathrm{I}^2\right) + C_\mathrm{I}^{T}\left(\mathbf{s}_\mathrm{I}\cdot\mathbf{T}_\mathrm{I} - \overleftrightarrow{J}_\mathrm{I}^{2}\right) +$$

$$\mathrm{C}_\mathrm{I}^{\nabla J}\left(\rho_\mathrm{I}\nabla\cdot\mathbf{J}_\mathrm{I} + \mathbf{s}_\mathrm{I}\cdot(\nabla\times\mathbf{j}_\mathrm{I})\right)$$

Allows for isospin decomposed ion-ion interaction barrier

$$\mathrm{V(R)} = \mathrm{E_{DC}}(R) - E_{\mathrm{A}_1} - E_{\mathrm{A}_2}$$

$$\mathrm{V(R)} = \mathrm{V_{I=0}}(R) + V_{\mathrm{I=1}}(R) + V_C(R)$$