原子核密度汎関数法に基づく超重核の生成、核分裂の記述

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Superheavy element (SHE)

Relation between SHE and r-process

Fission of heavy, superheavy nuclei, ambiguity

Nuclear density functional theory (DFT)

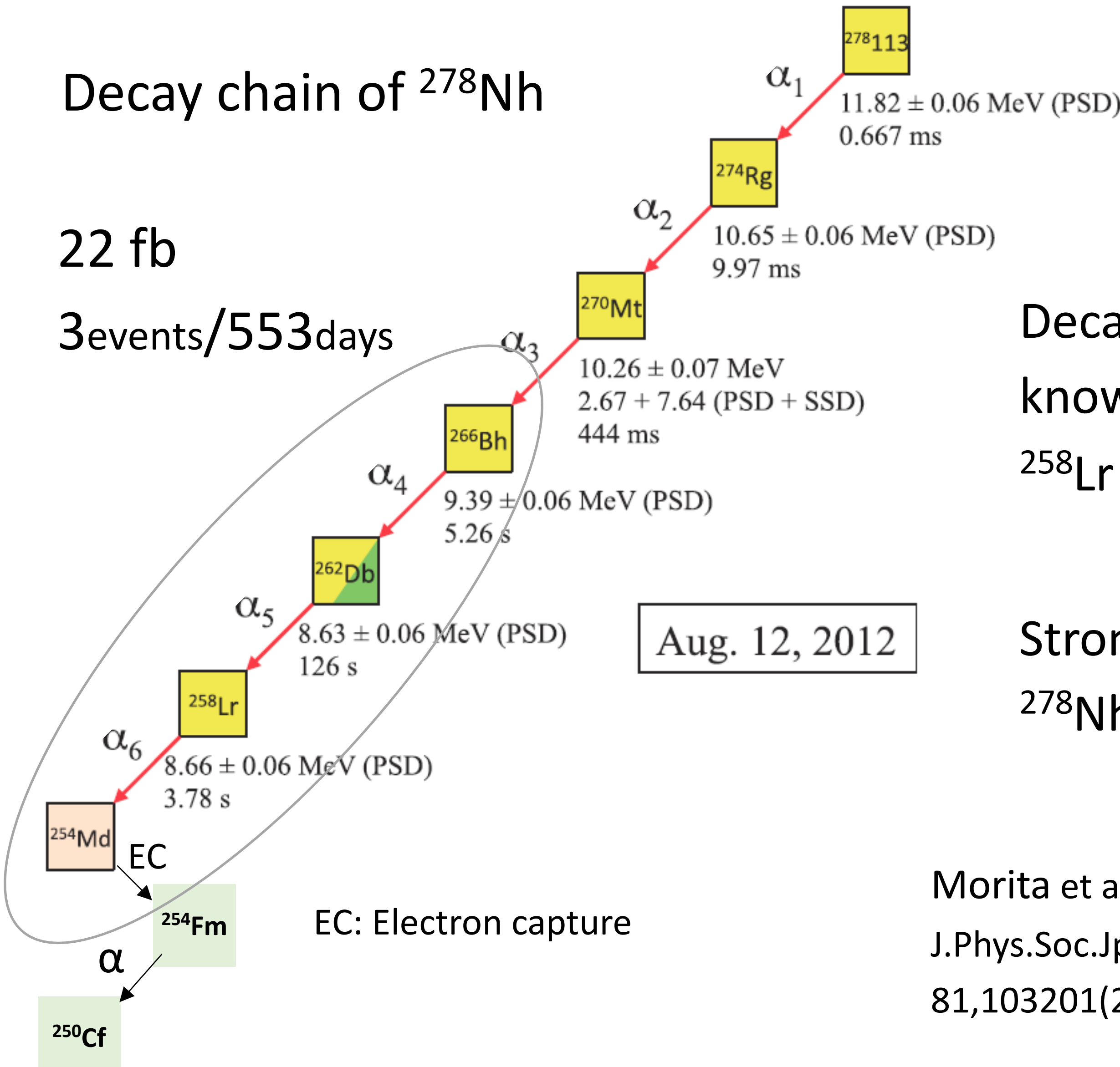
Study of fission and fusion

Introduction: Superheavy element (SHE)

Decay chain of ^{278}Nh

22 fb

3events/553days



Energy of α particle

Life time

Decay chain is connected to known nuclides ^{266}Bh, ^{262}Db, ^{258}Lr

Strong proof to synthesize ^{278}Nh

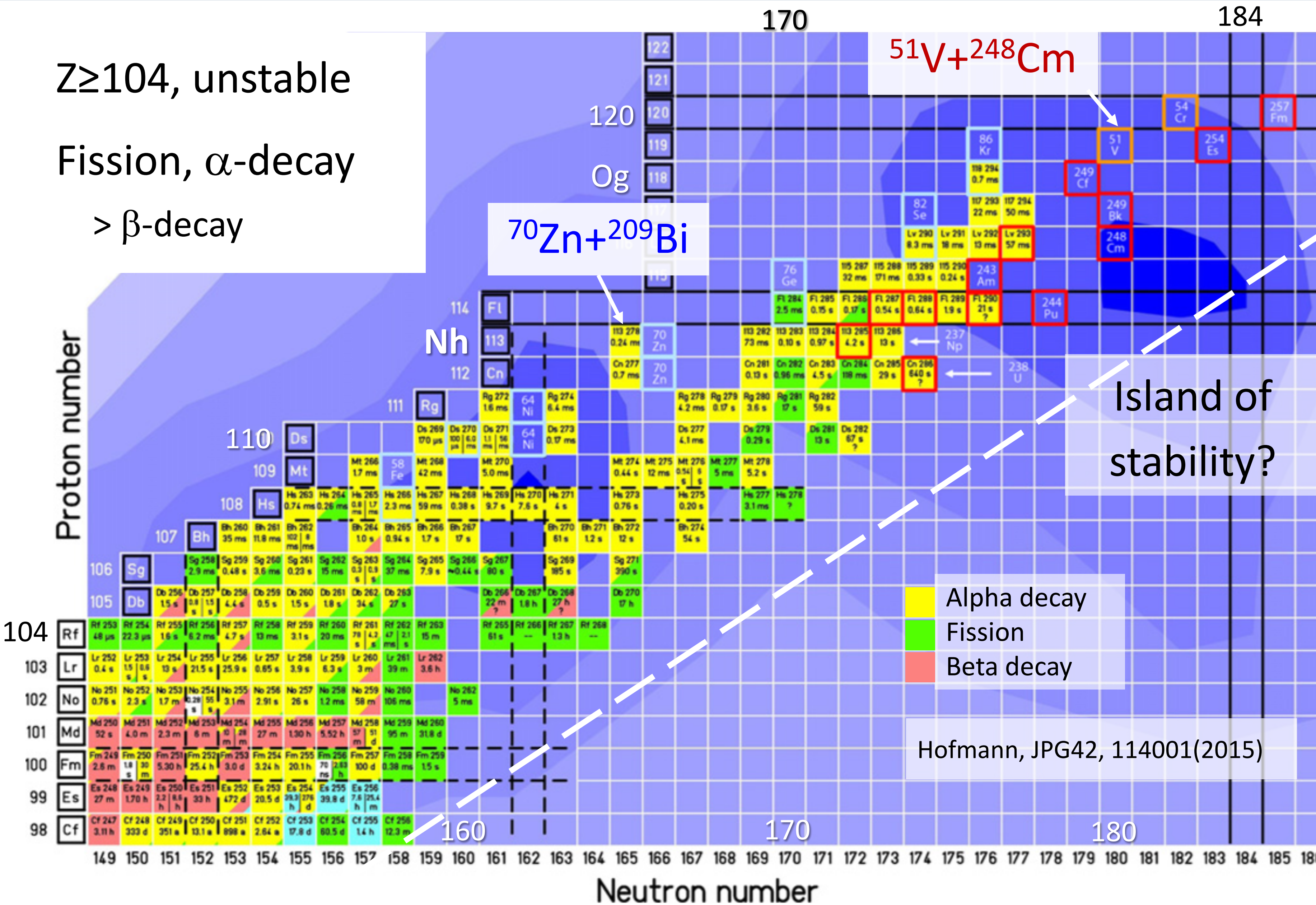
Morita et al.,
J.Phys.Soc.Jpn.
81,103201(2012)

Basic properties of Superheavy elements

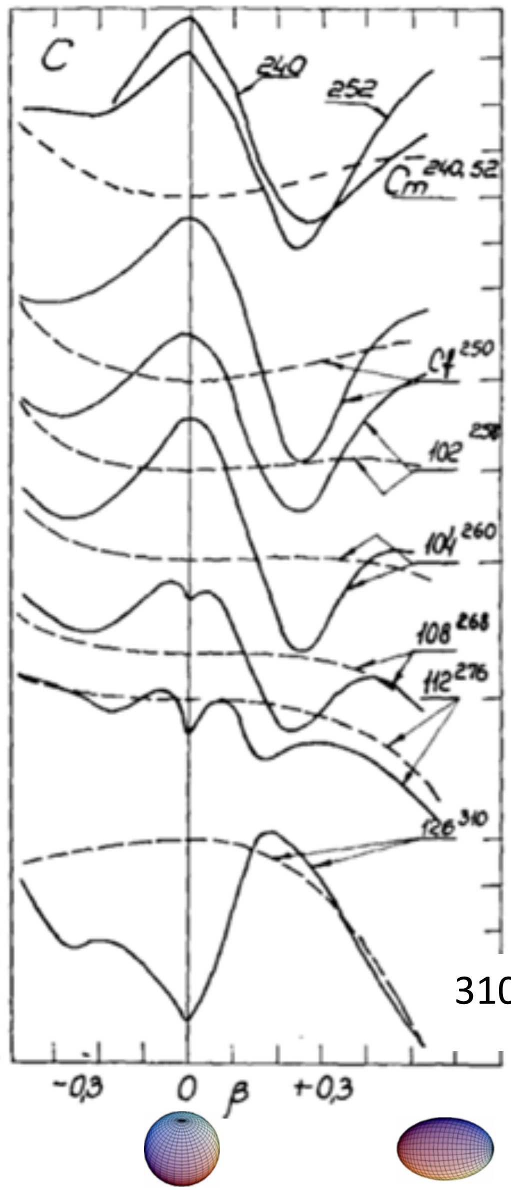
Z≥104, unstable

Fission, α-decay

> β-decay



Basic properties of Superheavy elements 2



Strutinsky, Nucl.Phys.A95, 420(1967)

– – - LDM

—— Micro.

↕ 2 MeV

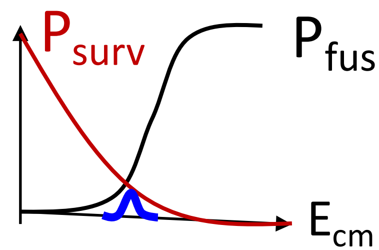
$^{310}126$

- Fission barrier by macroscopic liquid-drop model is lost in SHE
- Only microscopic models give a finite barrier -> Shell effect
- Next magic numbers

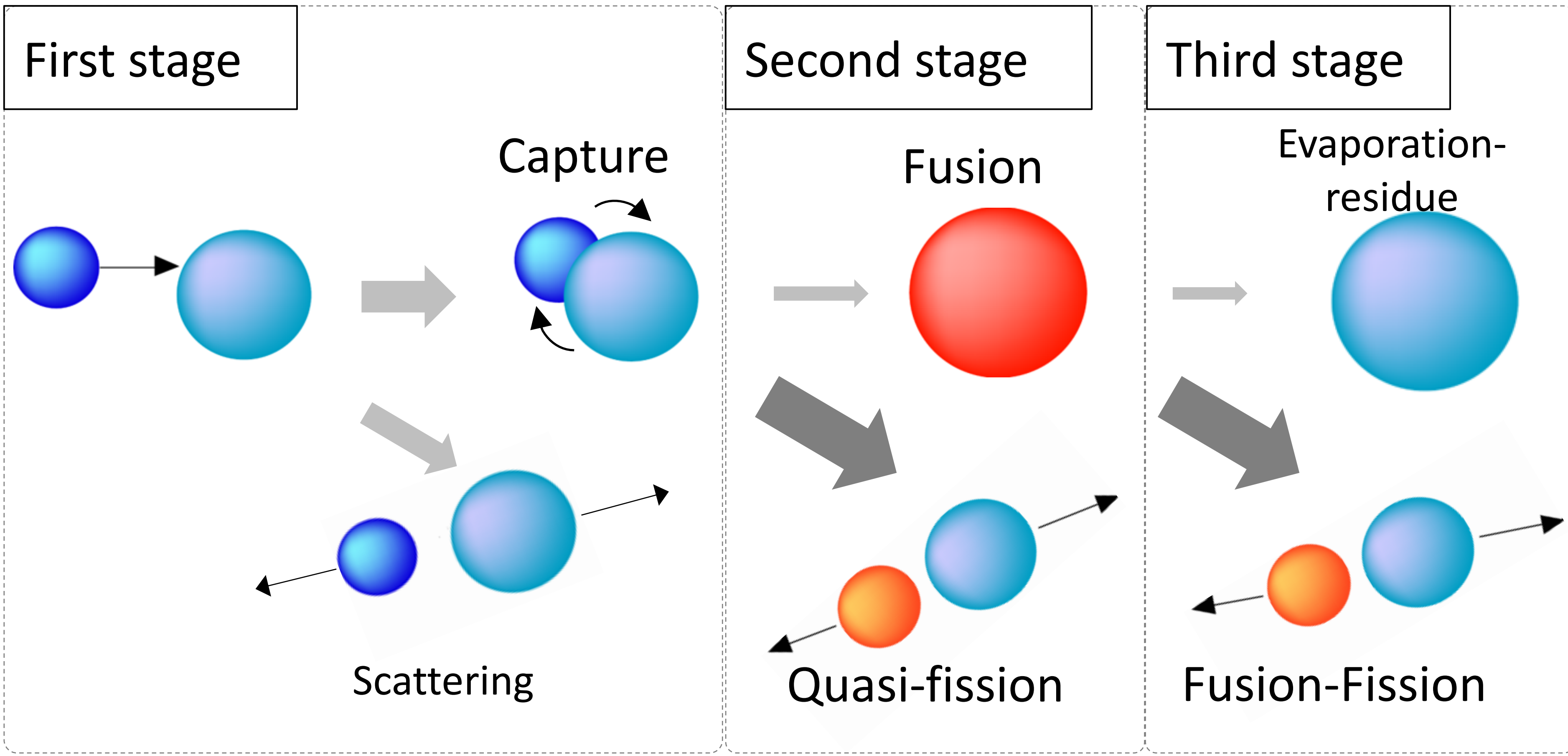
  Z=114, 120, 126? N=184?

Formation of superheavy elements

Z≤118 have been synthesized by heavy-ion fusion reactions

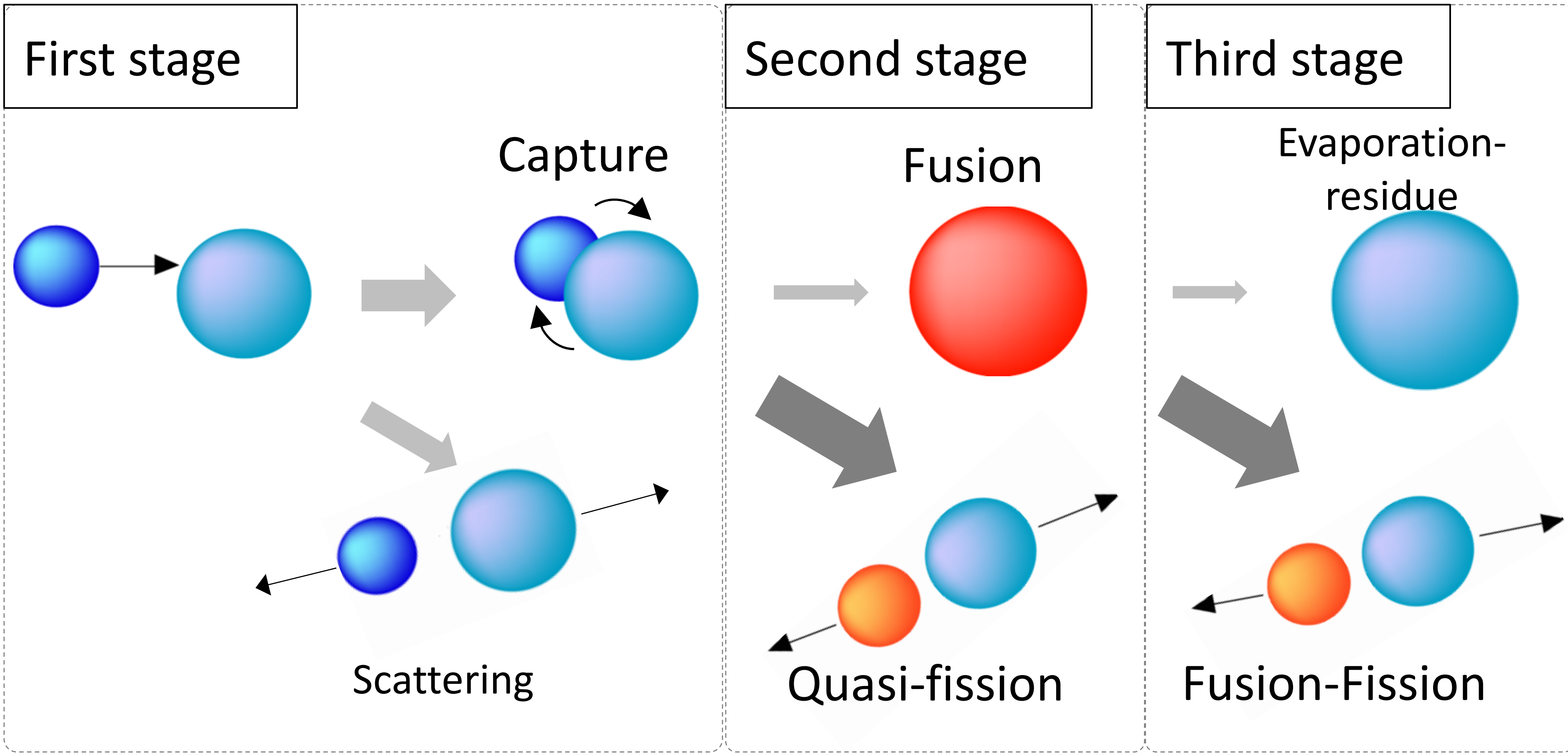


$P_{ER} = P_{fus} \times P_{surv}$



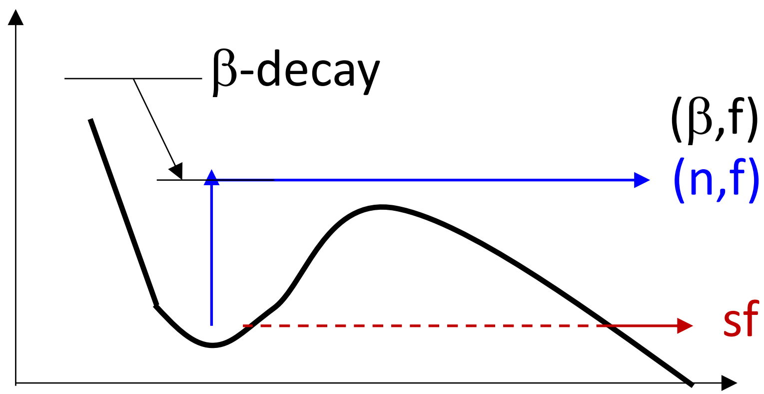
Nuclear fission

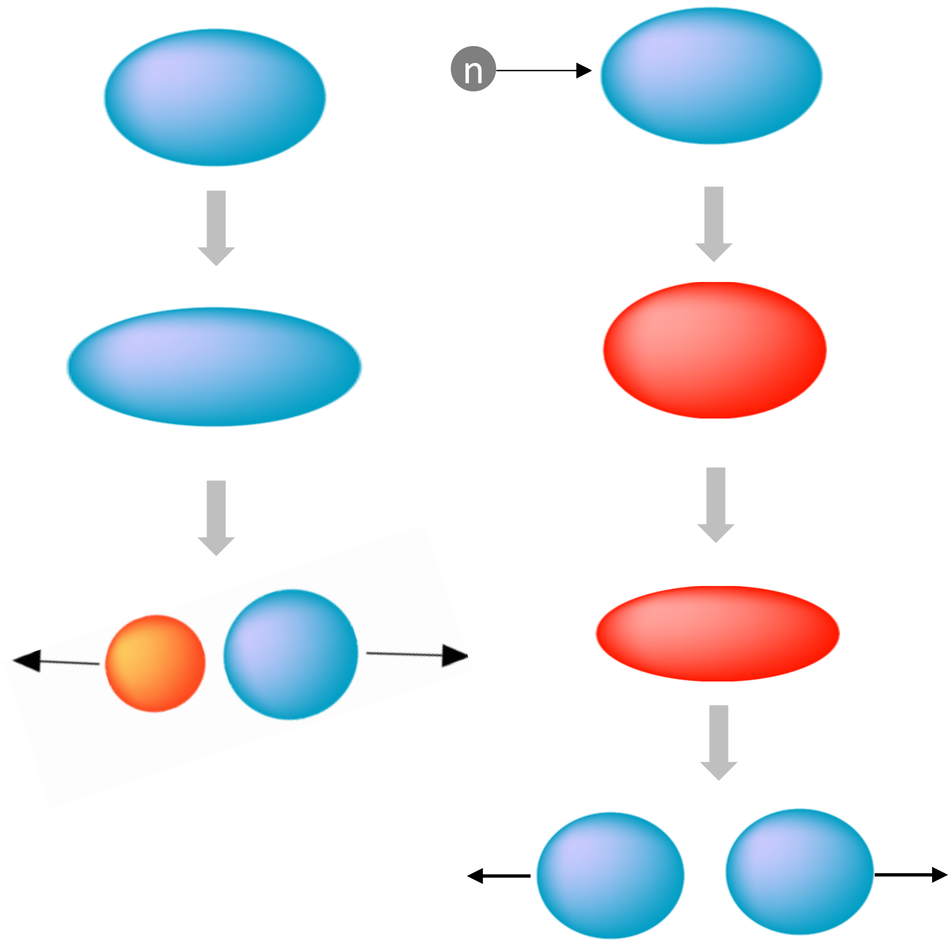
Fission is dominant process over SHE synthesis



Different types of fission relevant to r-process

- Spontaneous fission (sf)
- Neutron-induced fission (n,f)
- β-delayed fission (β,f)
- Other





Density functional theory (DFT)

Hohenberg, Kohn, Phys. Rev. 136 (1964) B864 ~19000 citations
Kohn, Sham, Phys. Rev. 140 (1965) A1133 ~24000 citations

Many-body problem → One-body potential with non-interacting system

$E[\rho] \leftrightarrow \rho$ Energy is written by functional of density

$v(\boldsymbol{r}) \leftrightarrow |\Psi_0\rangle \leftrightarrow \rho_0(\boldsymbol{r})$ One to one correspondence between one-body potential, ground state, and density

$E_0 = \min_{\rho} E[\rho]$ The ground state energy is obtained by variational principle

Nuclear density functional exists, but its shape is unknown

Skyrme, Gogny, Covariant, etc.

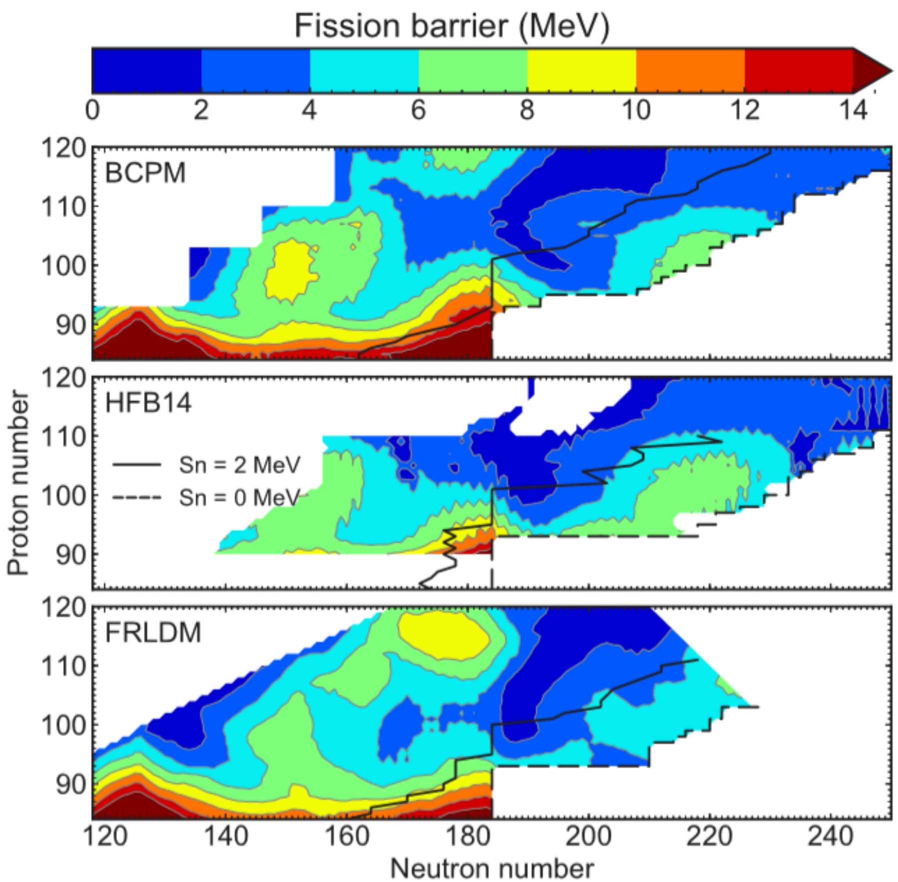
Bender, Heenen, Reinhard, Rev. Mod. Phys. 75 (2003) 121
Nakatsukasa, Matsuyanagi, Matsuo, Yabana, RMP88(2016) 045004

DFT-based r-process nucleosynthesis in NSM

Fission properties of superheavy nuclei for *r*-process calculations Phys.Rev.C97,034323 (2018)

Samuel A. Giuliani,[1,*] Gabriel Martínez-Pinedo,[1,2,†] and Luis M. Robledo[3,‡]
[1] *Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany*
[2] *GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*

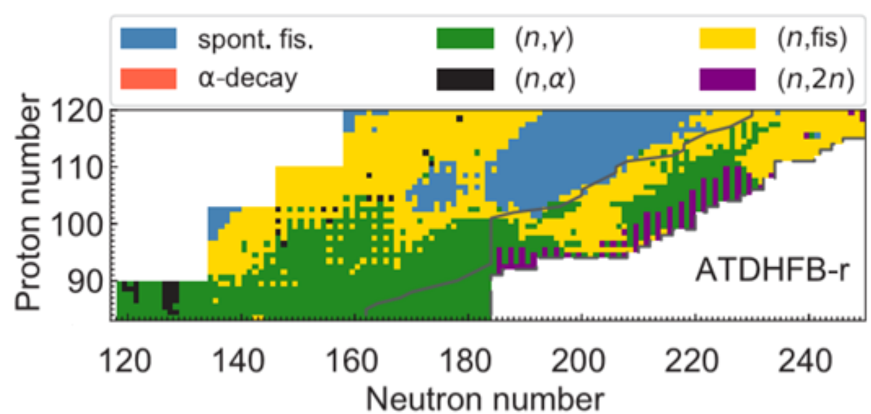
New BCPM EDF, Systematic calculations of fission ~ 3640 nuclei



Potential energy surface *V*

Collective inertia *M*

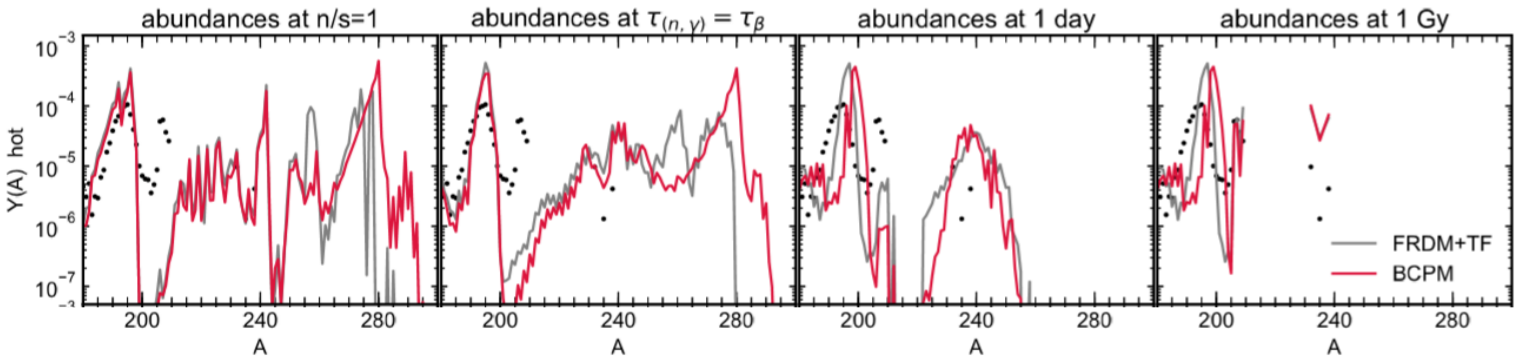
$$S = \int_{s_{\rm in}}^{s_{\rm out}} ds \sqrt{2\mathcal{M}(s)(V(s) - E)/\hbar^2}$$

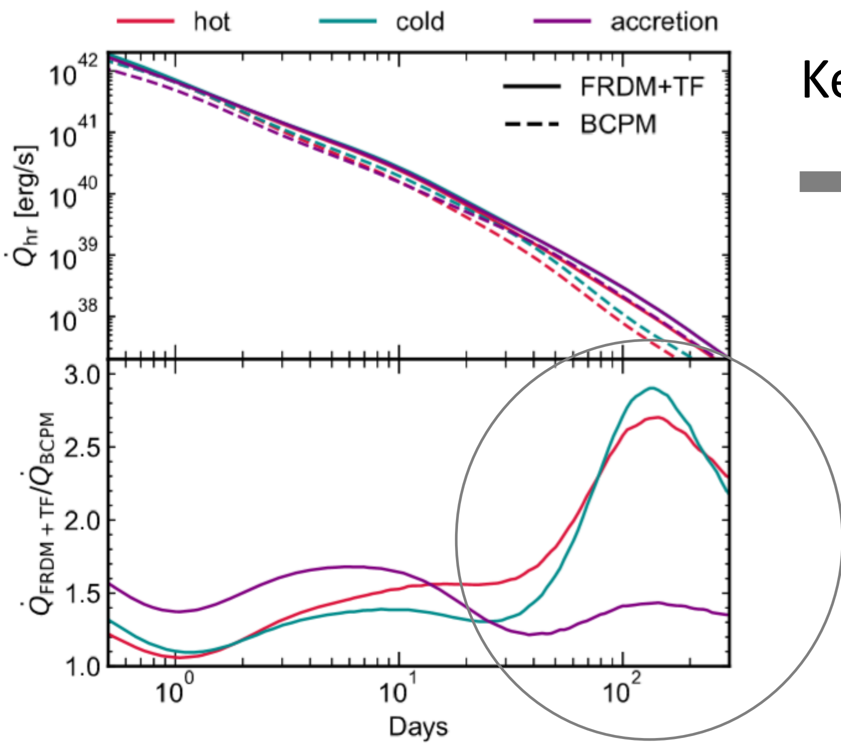


DFT-based r-process nucleosynthesis in NSM

Fission and the r-process nucleosynthesis of translead nuclei arXiv:1904.03733

Samuel A. Giuliani,[1,*] Gabriel Martínez-Pinedo,[2,3,†] Meng-Ru Wu,[4,5,‡] and Luis M. Robledo[6,7,§]





Key nucleus ^{254}Cf, $T_{1/2}$=60.5d

➡ Kilonova lightcurve is sensitive to the amount of ^{254}Cf at t > 10-100 days

A=280 nuclei fission at t<1day, producing neutrons, enhancing n-induced fission of A=254 nuclei

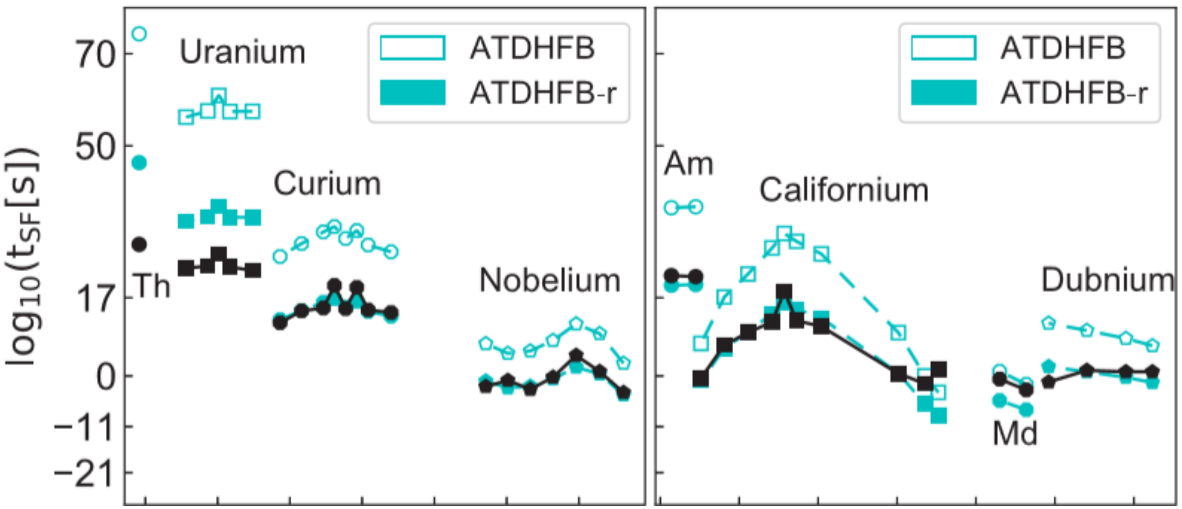
Ambiguity in spontaneous fission

Sadhukhan et al , PRC88, 064314 (2013)

Path	$S(L)$	$\log_{10}(T_{1/2}/\mathrm{yr})$
$\mathrm{DPM} + \mathcal{M}^{C}$	19.1	−11.4
$\mathrm{RM} + \mathcal{M}^{C}$	18.9	−11.6
$\mathrm{DPM} + \mathcal{M}^{C^{p}}$	16.8	−13.4
$\mathrm{RM} + \mathcal{M}^{C^{p}}$	16.8	−13.4

^{264}Fm,
Difference of half lives (order of magnitude) with different models for collective inertia

S.A. Giuliani et al, PRC97, 034323 (2018)



$T_{SF}^{th} >> T_{SF}^{exp}$

Reduced collective inertia (factor 0.5)

Collective inertia

Formulation from Adiabatic TDHFB

Dobaczewski, Skalski, NPA369,123(1981)

→Little practical applications, inverse of huge QRPA matrix

- Neglecting dynamical residual interactions (Time-odd terms)

→ Cranking approximation

→ Practical use with recent DFT-based method

Formulation from Local QRPA

Hinohara et al., PRC82 (2010) 064313

→ Approximation of adiabatic Self-consistent coordinate method

- Properly including residual interactions (Time-odd terms)

→ P + Q force, $\beta-\gamma$ plane

Hinohara et al., PRC82 (2010) 064313, etc

→ Skyrme DFT, axial symmetry

Yoshida, Hinohara., PRC83 (2011) 061302

Aim of this talk 1

Motivation

Understand the origin of this fusion hindrance problem from microscopic point of view

Method

Local QRPA with Skyrme EDF to include dynamical residual effect to collective inertia

Finite amplitude method (FAM)

- Small computational cost
- Equivalent to QRPA response

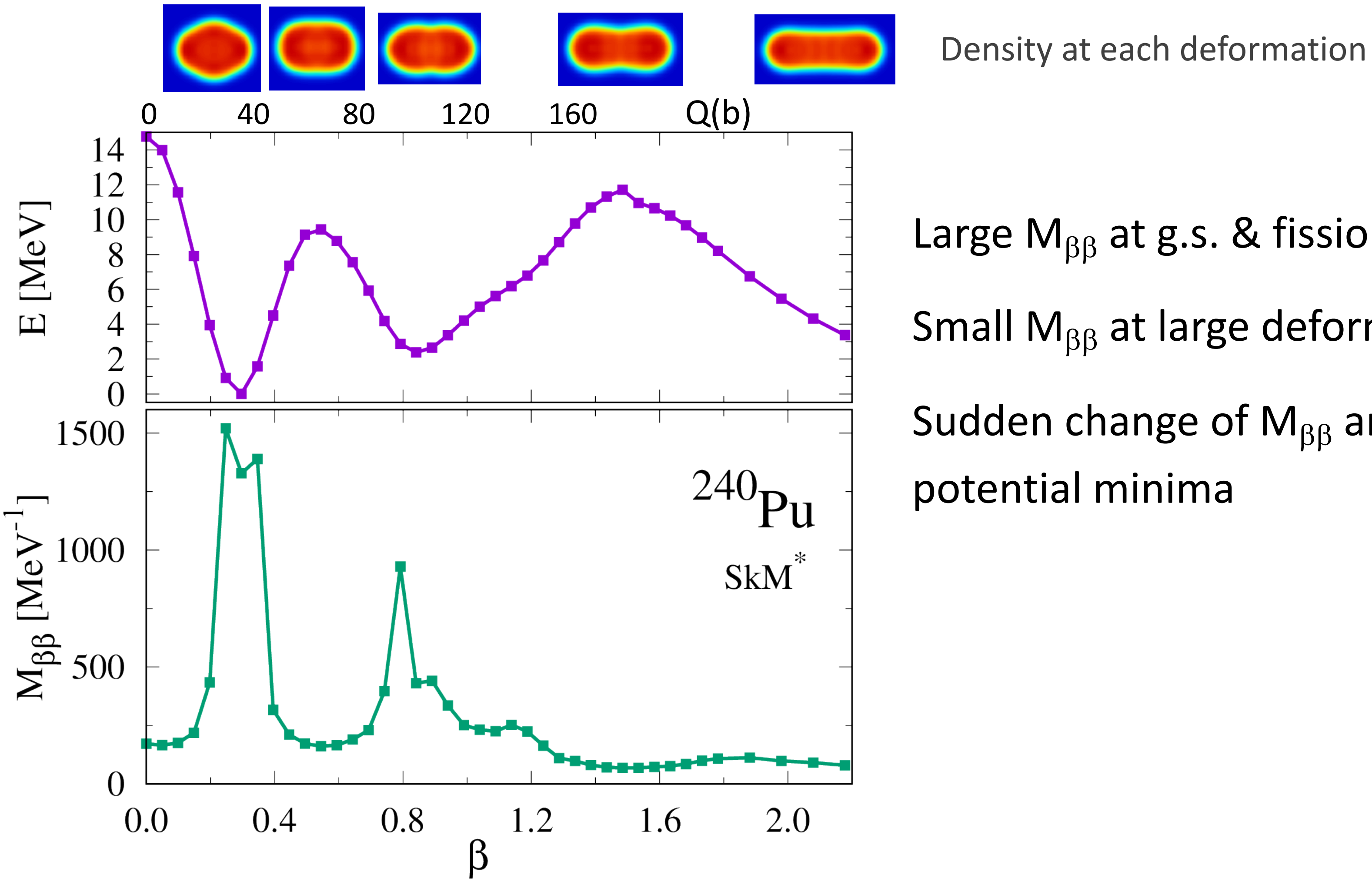
Nakatsukasa et al., PRC76 (2007) 024318
Avogadro & Nakatsukasa, PRC84(2011)014314
Stoitsov et al., PRC84 (2011) 041305
Liang et al., PRC87 (2013) 054310
Niksic et al., PRC88 (2013) 044327

	方程式	次元	解法	cutoff
FAM	$(E_\mu + E_\nu - \omega)X_{\mu\nu}(\omega) + \delta H^{20}_{\mu\nu}(\omega) = -F^{20}_{\mu\nu}$ $(E_\mu + E_\nu + \omega)Y_{\mu\nu}(\omega) + \delta H^{02}_{\mu\nu}(\omega) = -F^{02}_{\mu\nu}$	N x N	反復法	なし
QRPA	$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix} = \omega \begin{pmatrix} X \\ Y \end{pmatrix}$	N^2 x N^2	対角化 固有値 固有ベクトル	E_{2QP}

N: Dimension of base(~10^3)

Result: Collective inertia along fission path

^{240}Pu Fission barrier, collective inertia $M_{\beta\beta}$



Large $M_{\beta\beta}$ at g.s. & fission isomer

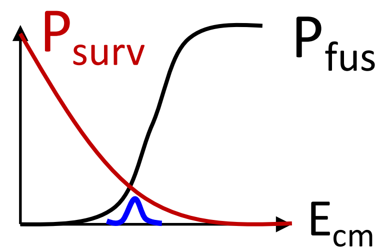
Small $M_{\beta\beta}$ at large deformations

Sudden change of $M_{\beta\beta}$ around potential minima

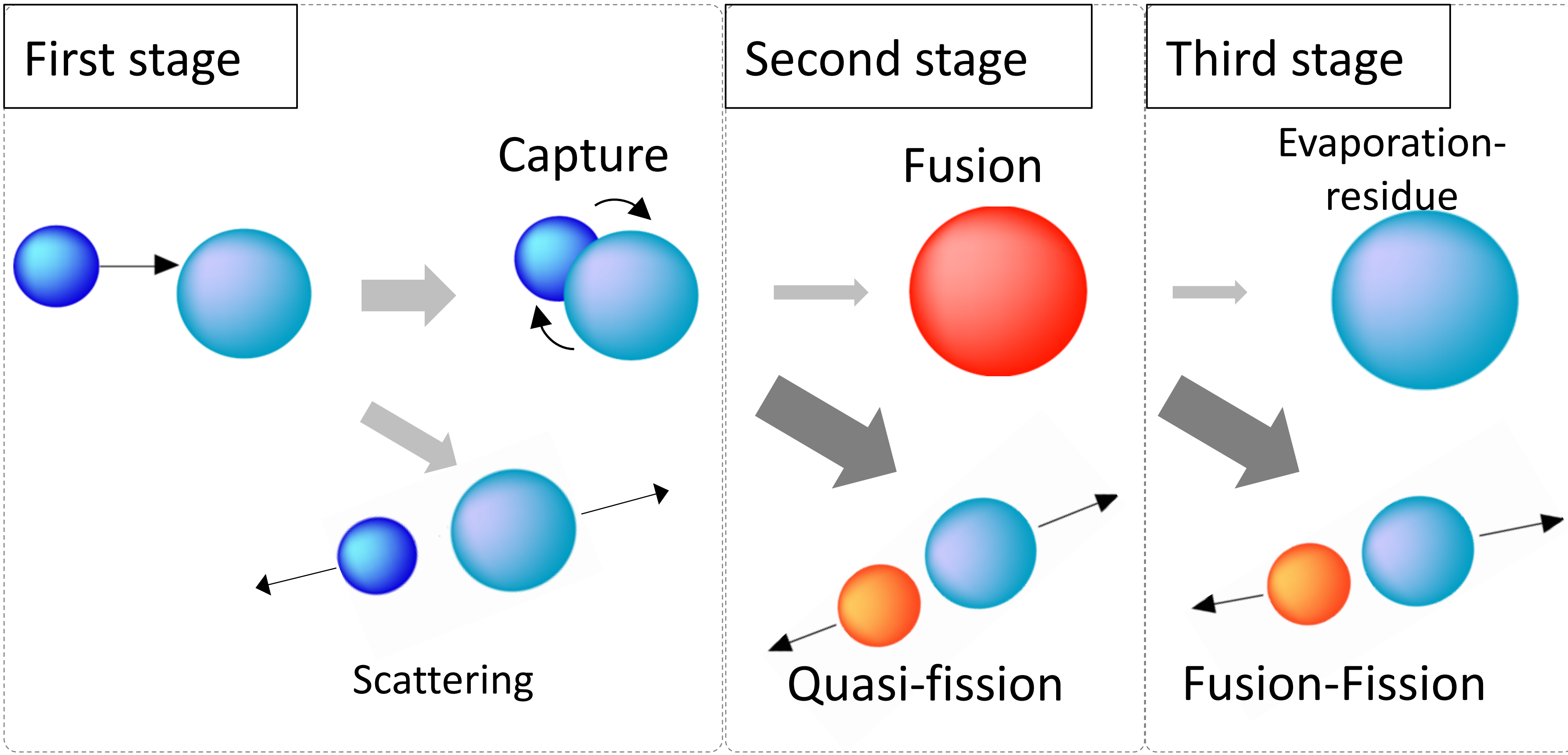
Washiyama et al., in preparation

Formation of superheavy elements

Z≤118 have been synthesized by heavy-ion fusion reactions



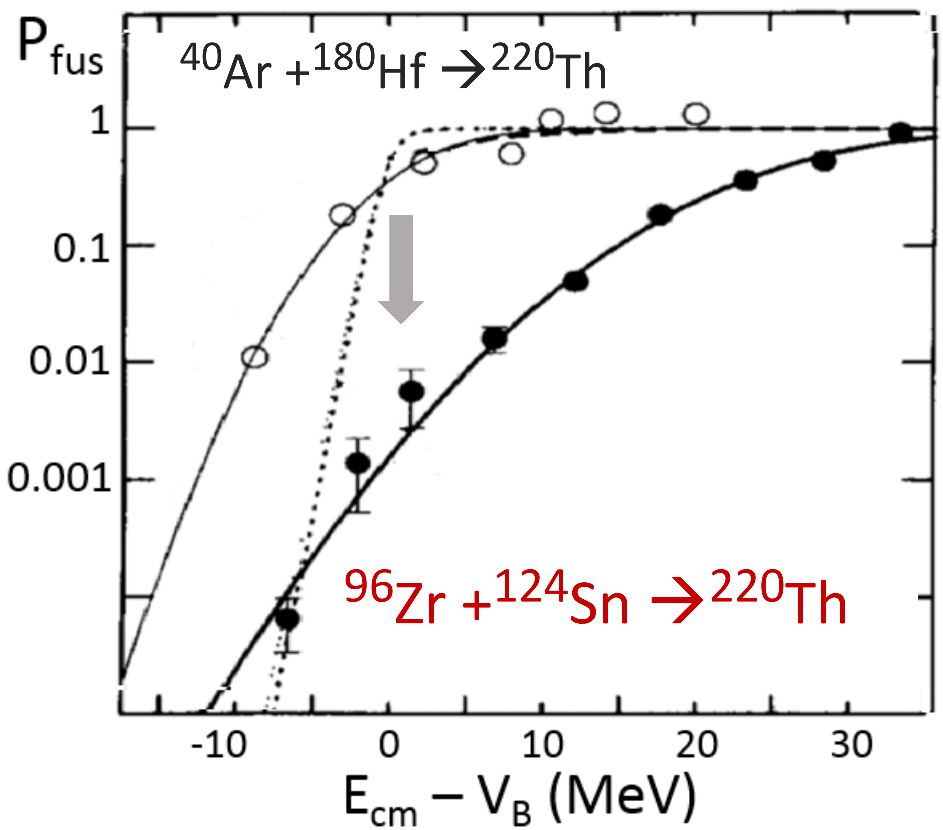
$$P_{ER} = P_{fus} \times P_{surv}$$



Fusion hindrance in heavy systems

Fusion probability

$Z_P Z_T$=1296



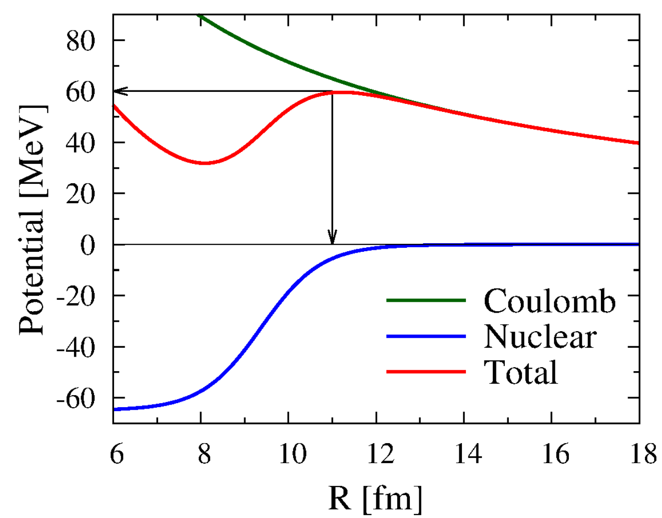
V_B: Bass barrier

C.-C. Sahm et al., NPA441 (1985)316

- Fusion probability is hindered in heavy systems (**$Z_P Z_T$ >1600**)
- Extra-push energy

Swiatecki, NPA376 (1982) 275

- Change in potential?
- Large energy dissipation?



Aim of this talk 2

Motivation

Understand the origin of this fusion hindrance problem from microscopic point of view

Method

Time-dependent density functional theory , TDDFT

Time-dependent density functional theory (TDDFT)

Bonche et al., PRC13 (1976)
Flocard et al., PRC17 (1978)
Negele, RMP54 (1982)
Kim et al., J. Phys. G23 (1997)
Simenel et al., PRL86 (2001)
Nakatsukasa, Yabana, PRC71(2005)
Umar, Oberacker, PRC73 (2006)
Avez et al., PRC78 (2008)
Ebata et al., PRC82 (2010)
Stetcu et al., PRL84 (2011)

$$i\hbar\frac{\partial}{\partial t}\psi_i(\boldsymbol{r},t) = \hat{h}[\rho(\boldsymbol{r},t)]\psi_i(\boldsymbol{r},t)$$

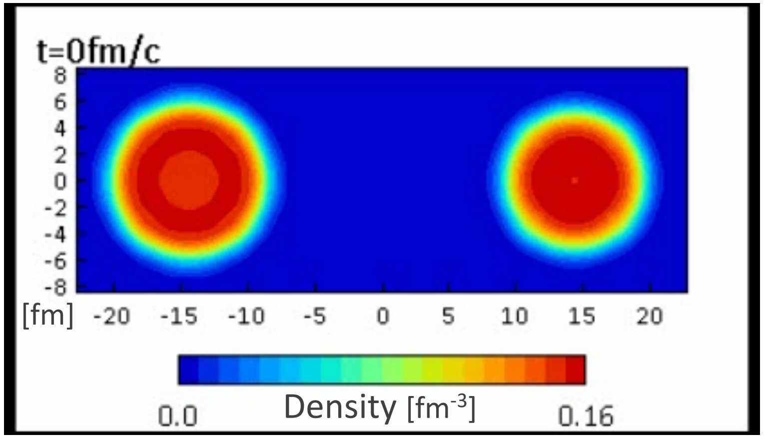
$$\rho(\boldsymbol{r},t) = \sum_{i=1}^{N}|\psi_i(\boldsymbol{r},t)|^2$$

<u>^{96}Zr+^{124}Sn</u>

Central collision

E_{cm}= 225 MeV

V_B~ 214 MeV



- Same description on structure and dynamics
- No phenomenological parameters for dynamics
- Single-particle: quantum, Relative motion: classical

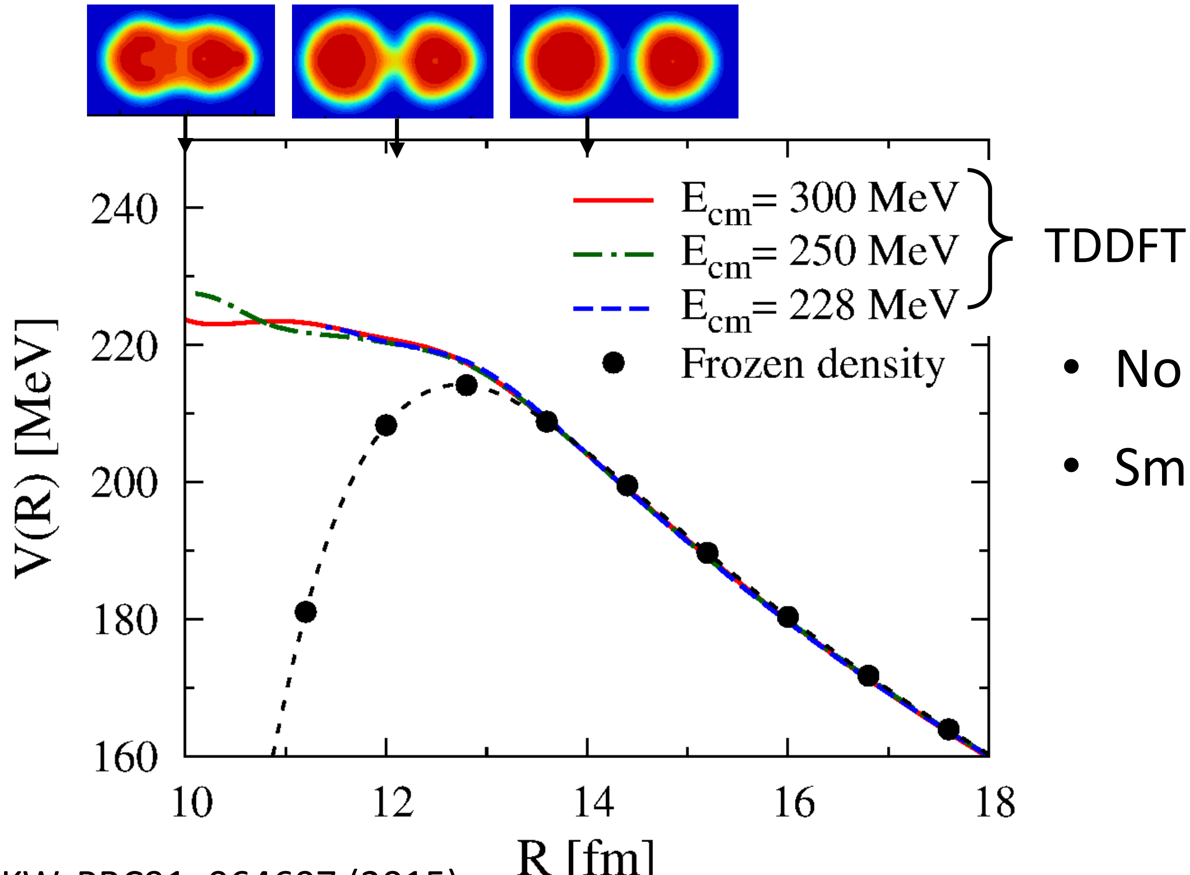
Result: Nucleus-nucleus potential

TDDFT (microscopic) ➡ $$\frac{dP}{dt} = -\frac{dV(R)}{dR} - \frac{d}{dR}\frac{P^2}{2\mu(R)} - \gamma(R)\frac{dR}{dt}$$

KW, Lacroix, PRC78(2008)024610

KW, Lacroix, Ayik, PRC79(2009)

^{96}Zr+^{124}Sn potential

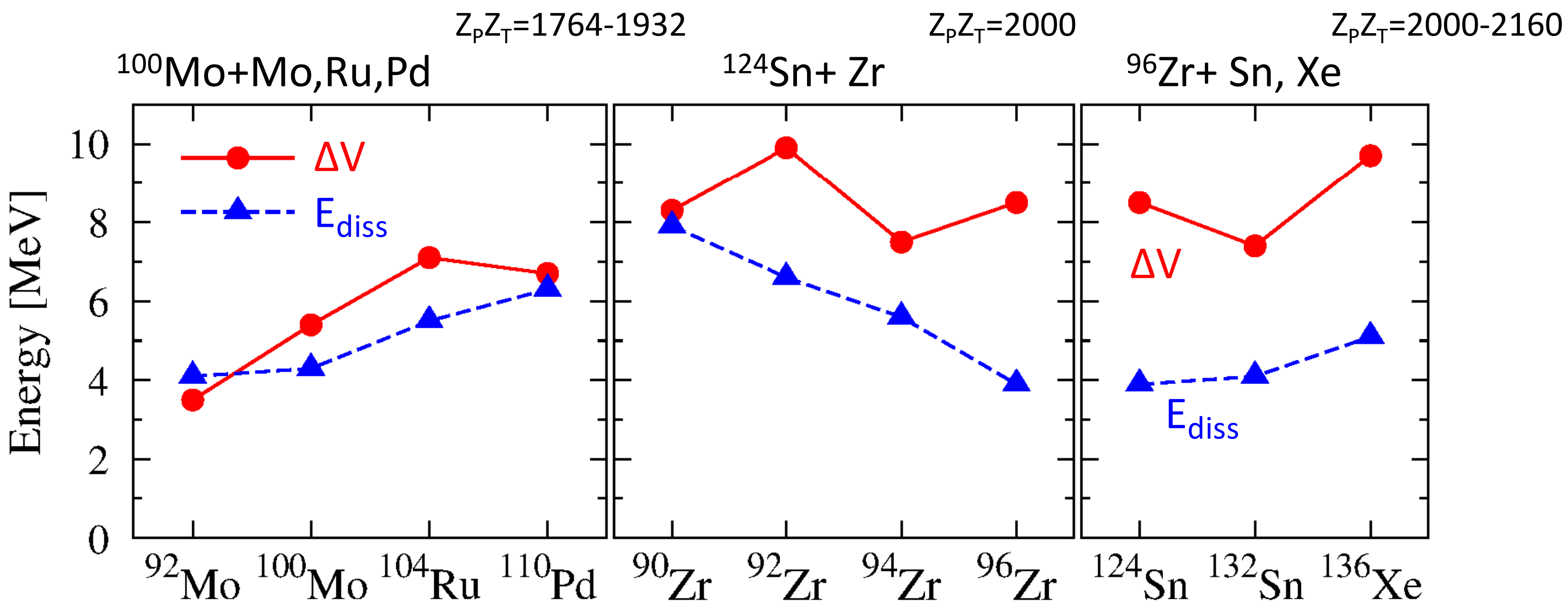


KW, PRC91, 064607 (2015)

- No barrier
- Small energy dependence

Origin of fusion hindrance

E_{extra}= increase in potential (ΔV) + dissipated energy (E_{diss})



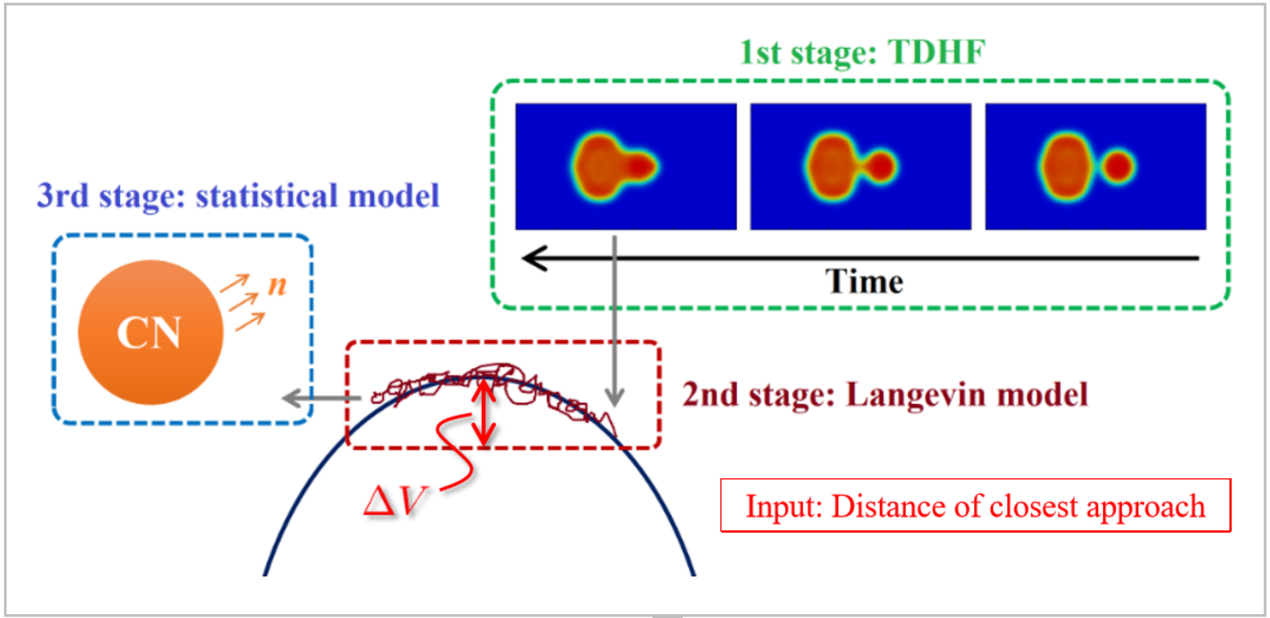
$\Delta V > E_{diss}$

Origin of fusion hindrance is a dynamical increase in potential ΔV at small *R*

KW, PRC91, 064607 (2015)

Hybrid model of SHE formation

Sekizawa, Hagino, PRC99, 051602(R) (2019)
Editors' Suggestions



TDDFT + Langevin + Statistical model

System	CN	E^* (MeV)	$R_{\rm min}$ (fm)	$P_{\rm CN}$ ($\times 10^4$)	$W_{\rm sur}$ ($\times 10^9$)	$P_{\rm CN} W_{\rm sur}$ ($\times 10^{13}$)
^{48}Ca+^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr+^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V+^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca+^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

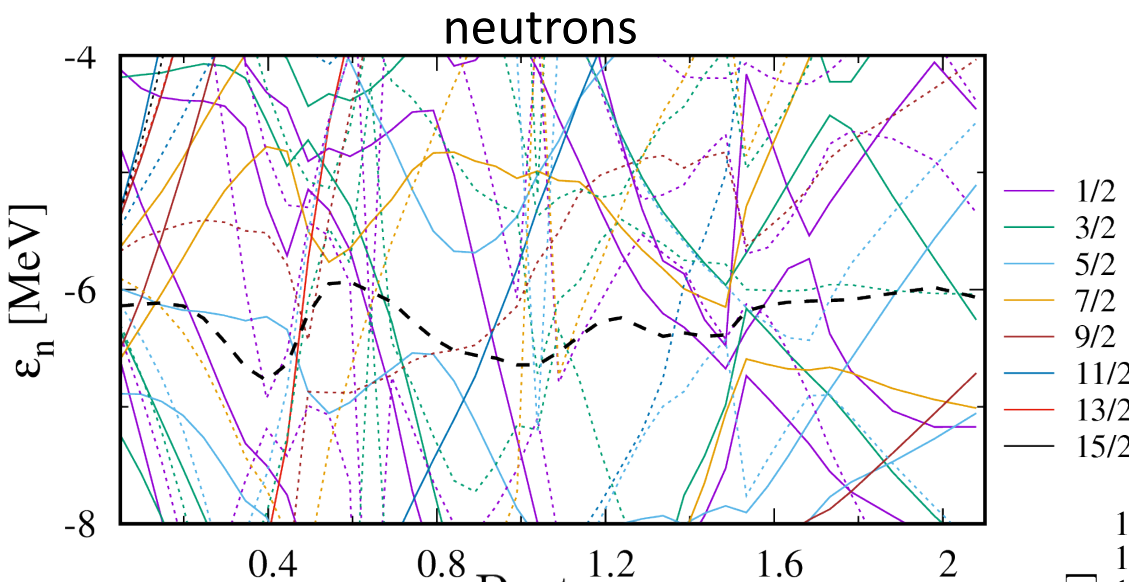
TDHF (for $R_{\rm min}$), FBD (for $P_{\rm CN}$)

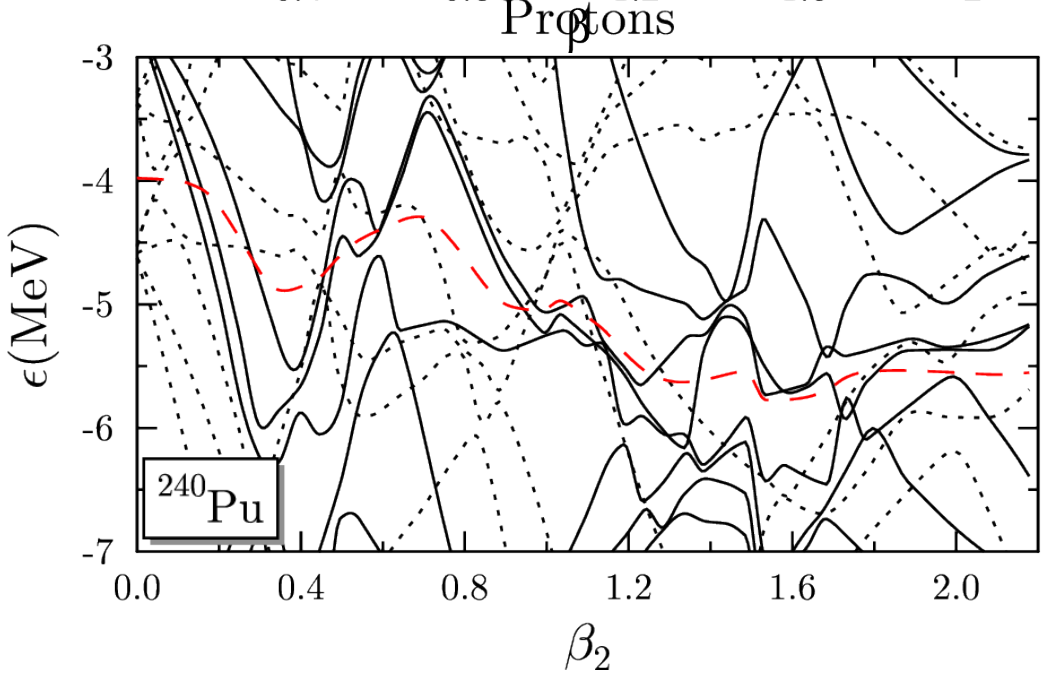
Shell effect of 48Ca affects the probability in the third stage

Summary

- 超重元素の性質、多様な崩壊形式、殻効果で安定化
- 超重元素生成、競合過程
- Fission is a dominant mode against SHE synthesis
- Fission is relevant to r-process nucleosynthesis
- 254Cf is a key nucleus for kilonova lightcurves at t > 10-100days
- Ambiguity in fission: Collective inertia
    - Local QRPA approach to include dynamical effect
- Fusion hindrance problem analyzed by TDDFT
    - Dynamical effect of potential increase is a main origin of this hindrance

核分裂経路での質量と一粒子準位

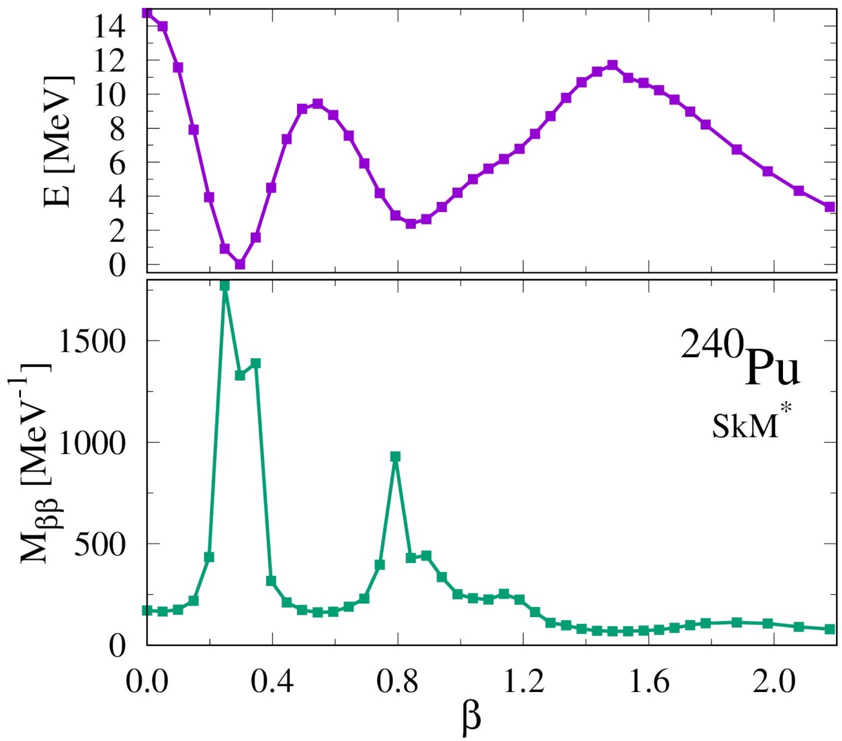




Mass が急激に変化する

β=0.4, 0.7 で level crossing

一方 β=1.0, 1.4 では mass に大きな変化なし。

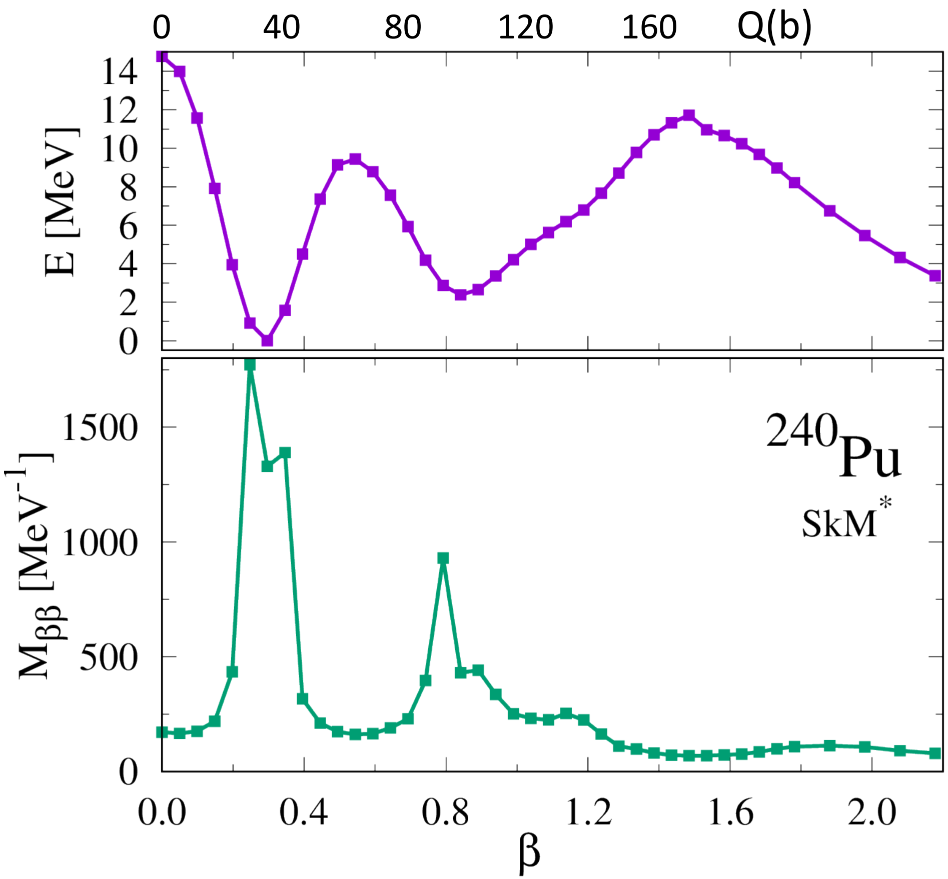


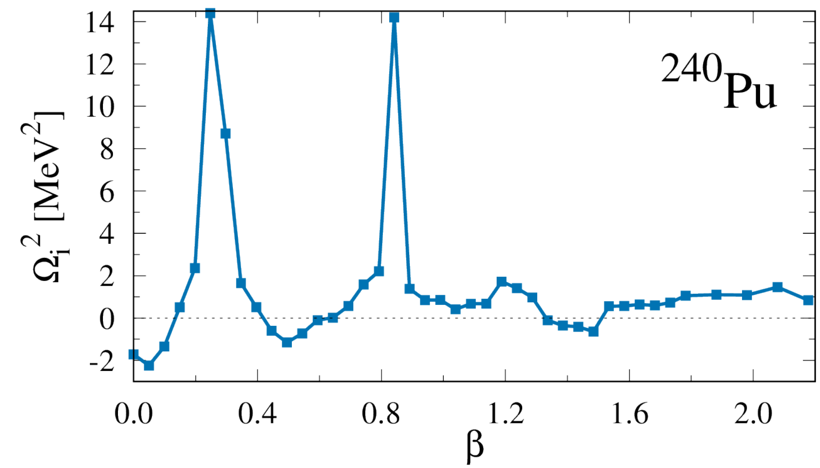
核分裂経路での質量（β 自由度のみ）

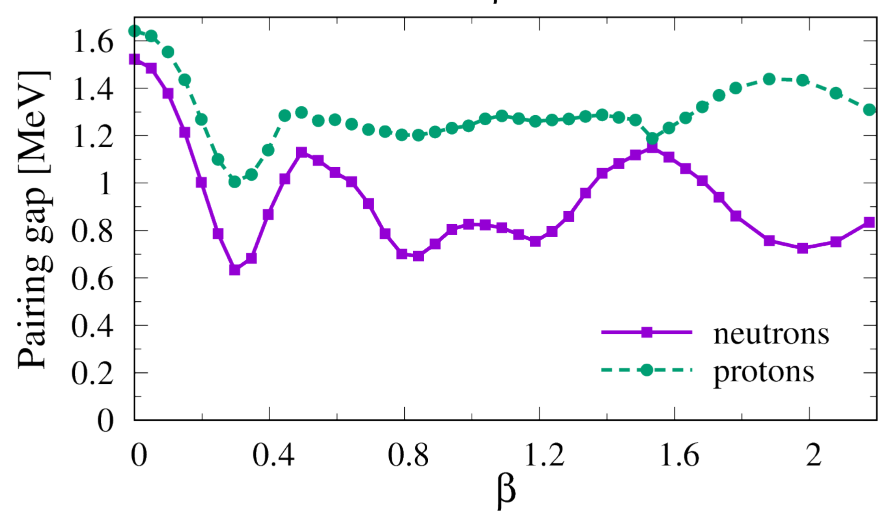
外場：Isoscalar Q_{20}

Ω_i < 4 MeV で最も集団的なモード = 最大の $|\langle P_i|\hat{Q}_{20}|0\rangle|$ を選択

^{240}Pu 核分裂障壁と質量$M_{\beta\beta}$

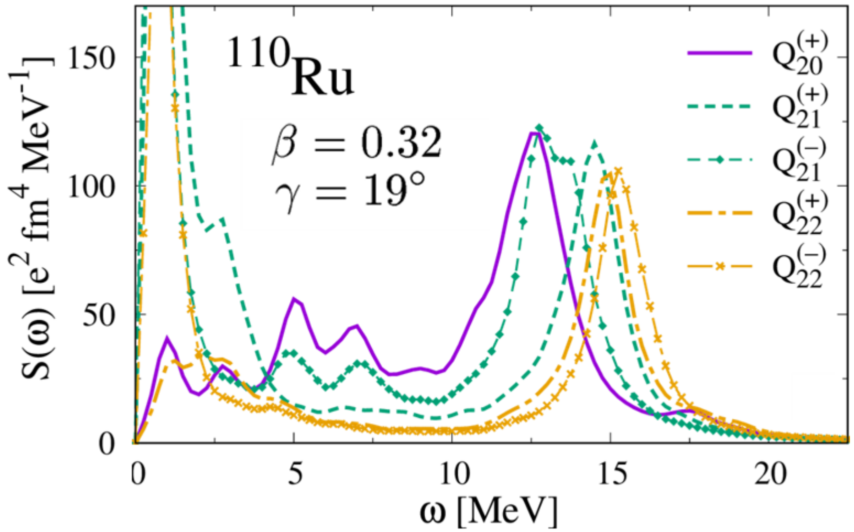






結果：３次元 FAM-QRPA の開発、応用

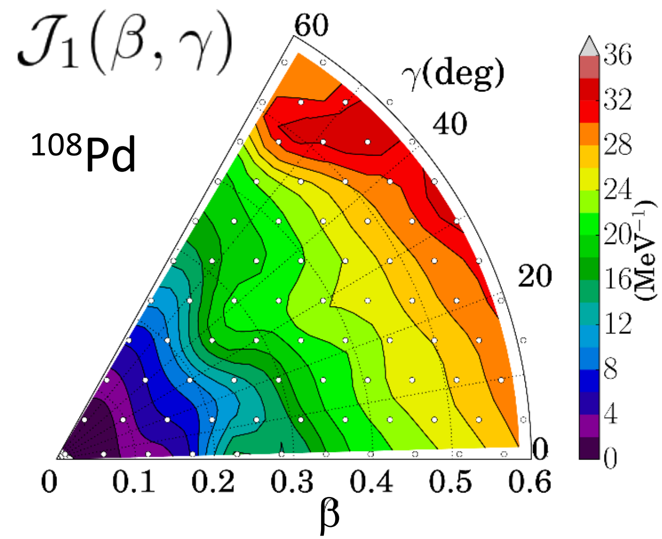
アイソスカラー型四重極強度関数



$$S(\hat{F},\omega) = -\frac{1}{\pi}\mathrm{Im}(\sum_{\mu<\nu} F^{20*}_{\mu\nu} X_{\mu\nu}(\omega) + F^{02*}_{\mu\nu} Y_{\mu\nu}(\omega))$$

回転に対する慣性モーメント

SkM*
Volume
pairing



$$S^{\mathrm{FAM}}(\hat{F} = \hat{J}_k, \omega = 0) = -\mathcal{J}_k$$

- 密度汎関数法に基づく非軸対称核の線形応答計算
- 短いCPU時間で計算実行可能

~15 min/ω (16threads), 3.5 GB memory

KW, Nakatsukasa, PRC96, 041304(R) (2017)
KW, Nakatsukasa, JPS Conf. Proc. 23, 013012 (2018)

Numerical set up

^{110}Ru,^{108}Pd: 17^3 mesh, R_{max}=14.0fm, N_{base}=1120

BCPM energy density functional

$$E_0 = \min_{\rho} E[\rho]$$

$$E = T_0 + E^{\text{s.o.}} + E_{\text{int}}^{\infty} + E_{\text{int}}^{\text{FR}} + E_C.$$

$$E_{\text{int}}^{\text{FR}}[\rho_n, \rho_p] = \frac{1}{2} \sum_{t,t'} \iint d\mathbf{r} d\mathbf{r}' \rho_t(\mathbf{r}) v_{t,t'}(\mathbf{r} - \mathbf{r}') \rho_{t'}(\mathbf{r}') - \frac{1}{2} \sum_{t,t'} \gamma_{t,t'} \int d\mathbf{r} \rho_t(\mathbf{r}) \rho_{t'}(\mathbf{r}),$$

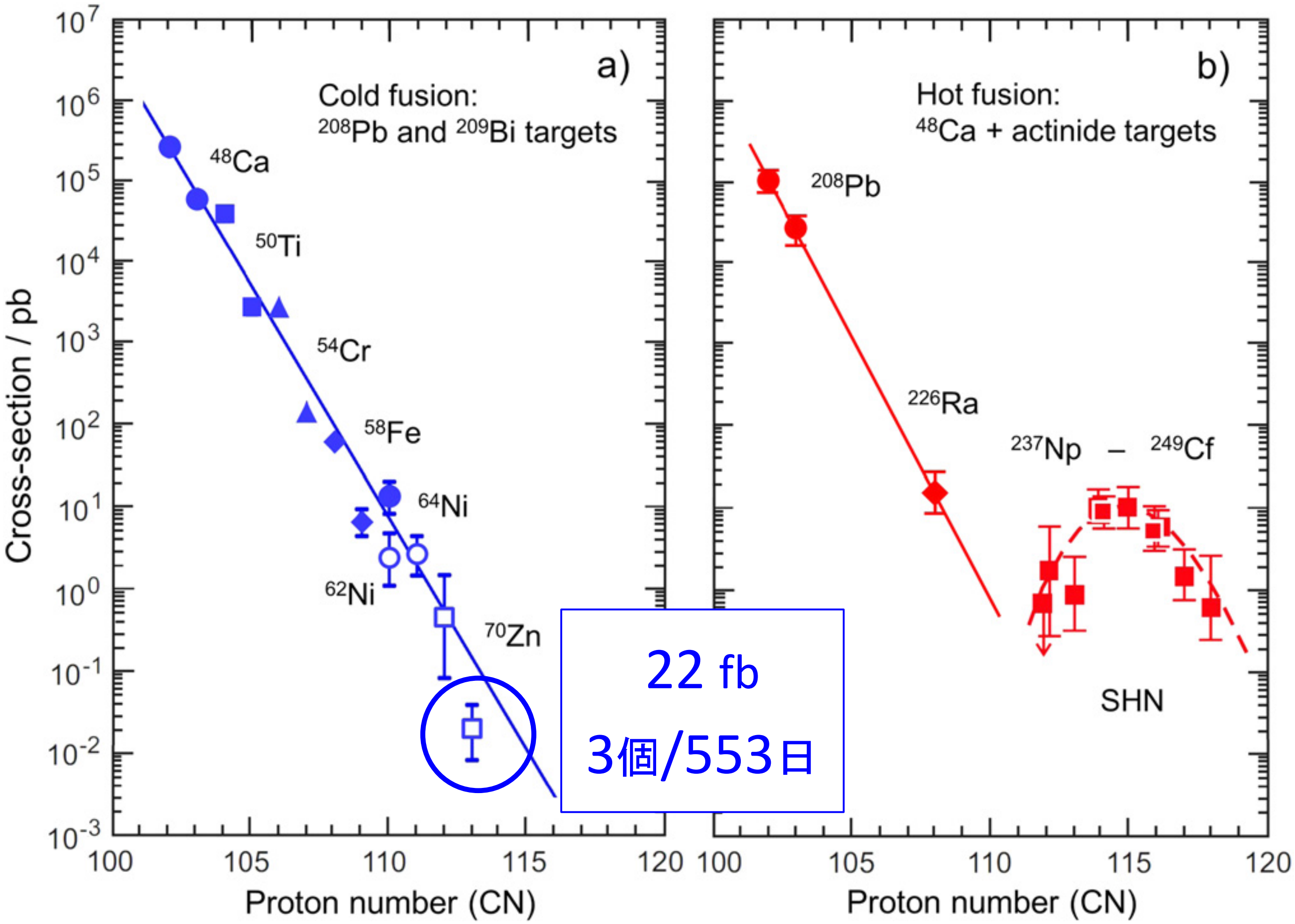
$$E_{\text{int}}^{\infty}[\rho_p, \rho_n] = \int d\mathbf{r}[P_s(\rho)(1-\beta^2) + P_n(\rho)\beta^2]\rho$$

$$P_s(\rho) = \sum_{n=1}^{5} a_n \left(\frac{\rho}{\rho_0}\right)^n, \quad P_n(\rho) = \sum_{n=1}^{5} b_n \left(\frac{\rho}{\rho_{0n}}\right)^n$$

Baldo et al., PRC87 (2013) 064305

Introduction: Superheavy element research

Cold fusion　　Hot fusion



安定の島に
近づいている？

Hofmann, JPG42, 114001(2015)