Dynamical approach to low-energy nuclear fission in terms of Langevin equation

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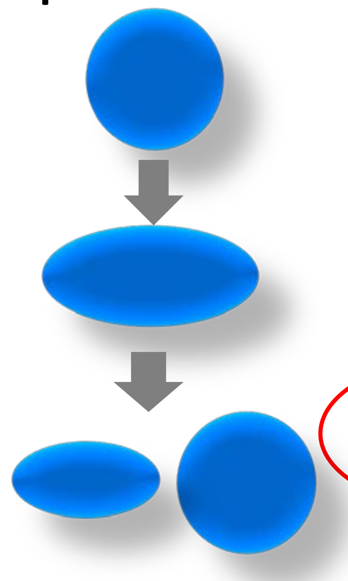
Contents

- Introduction and Background
- Description of nuclear fission by Langevin equation
- Further improvements to the TokyoTech Langevin model
  - Microscopic transport coefficients
  - Charge polarization and its significance on prompt neutron multiplicities
  - Charge-asymmetry degree-of-freedom
  - β-delayed phenomena : IAEA CRP
- Summary

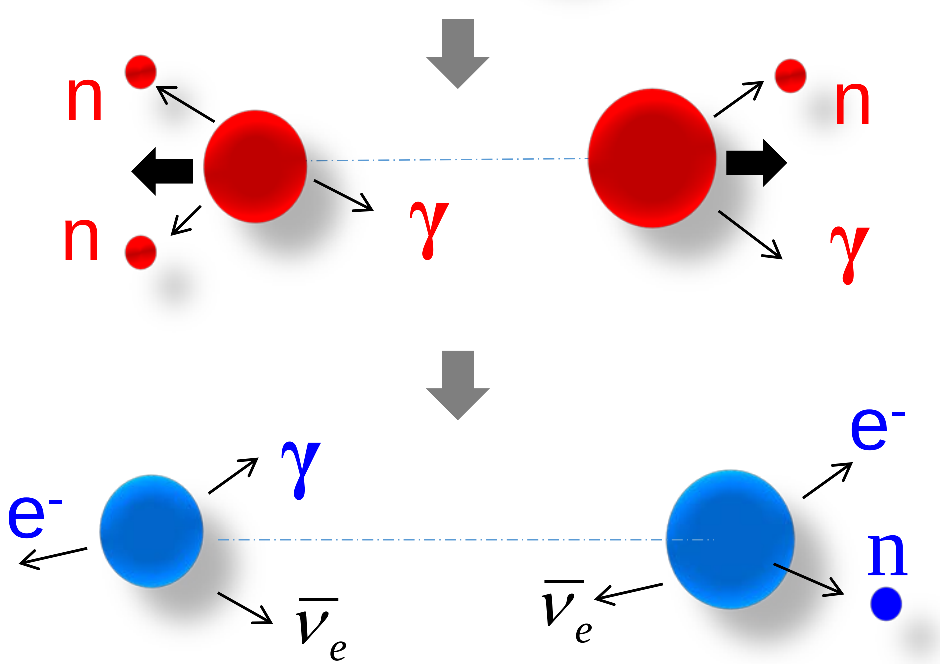
Introduction and Background

Nuclear shape evolution and particle emission during fission



Scission

Dynamical Theory		Static Theory	Phenomenology
Random Walk **Langevin equation**	TDGCM TDDFT	Fong Wilkins	Brosa-model inspired multiple channel fitting



Statistical decay

Sharing of E* between 2 fragments, J^π distribution

Madland-Nix
Weisskopf-Ewing
Hauser-Feshbach

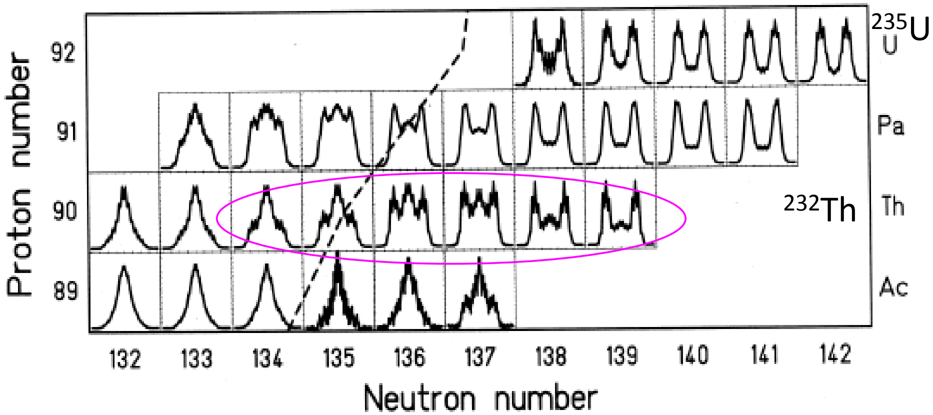
β-decay + statistical decay

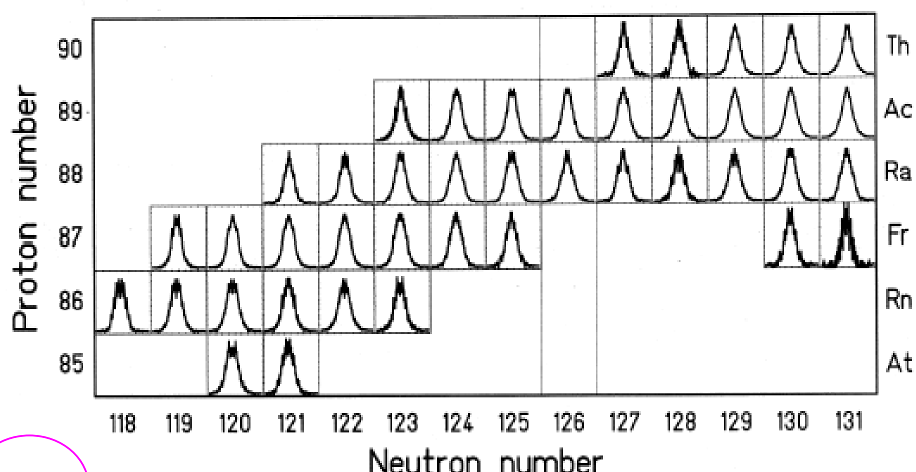
Gross Theory
QRPA
Shell Model

Weisskopf-Ewing
Hauser-Feshbach

Challenges : systematical and regional changes of FFMD

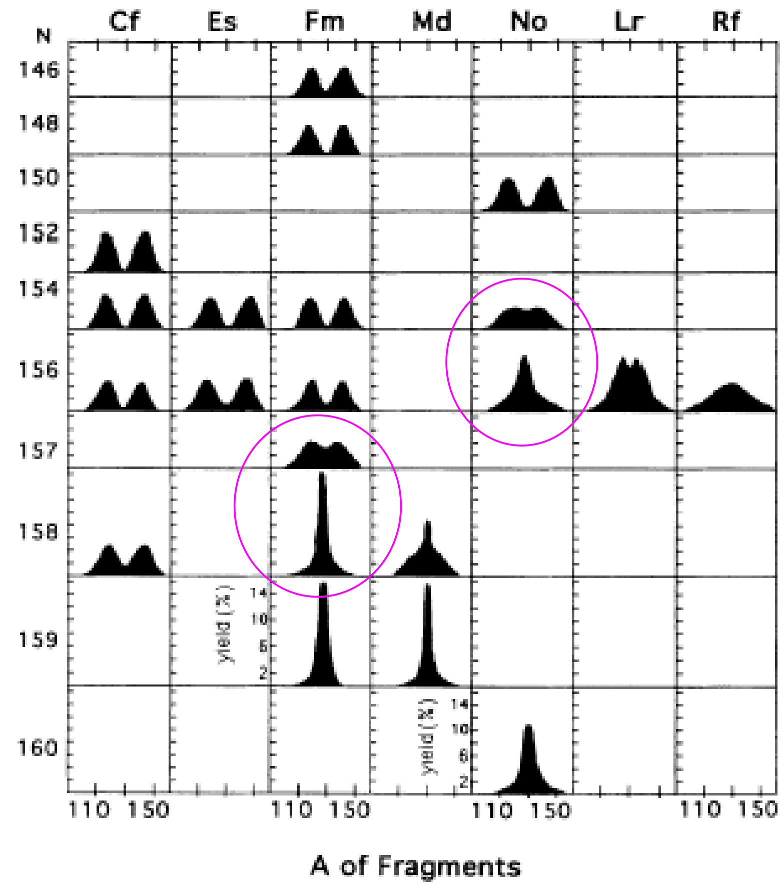
K.-H. Schmidt et al., N.P.A665(2000)221





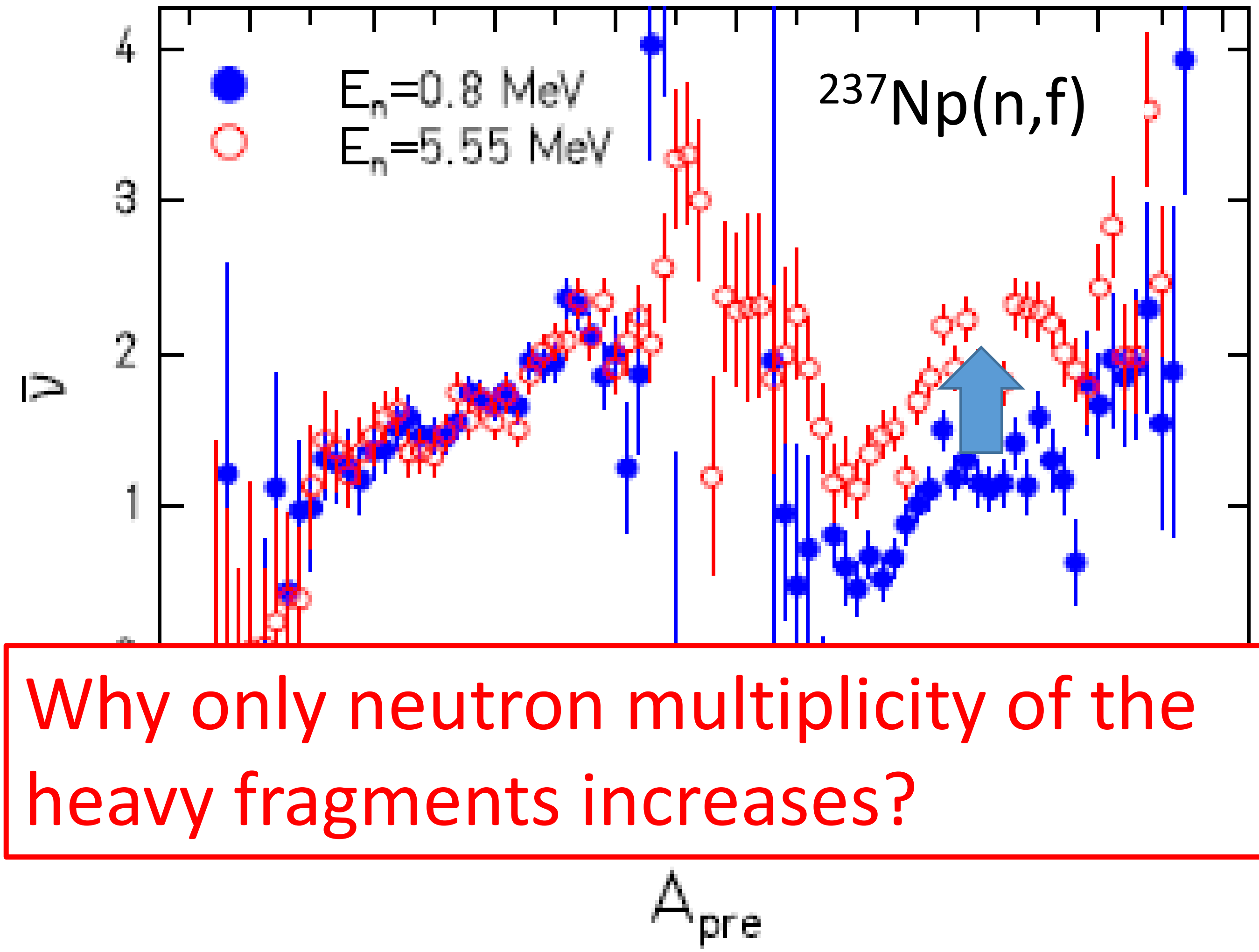
^{180}Hg

T.M.Hamilton et al., P.R. C46(1992)187



Challenges : Neutron multiplicity distribution and its dependence on excitation energy

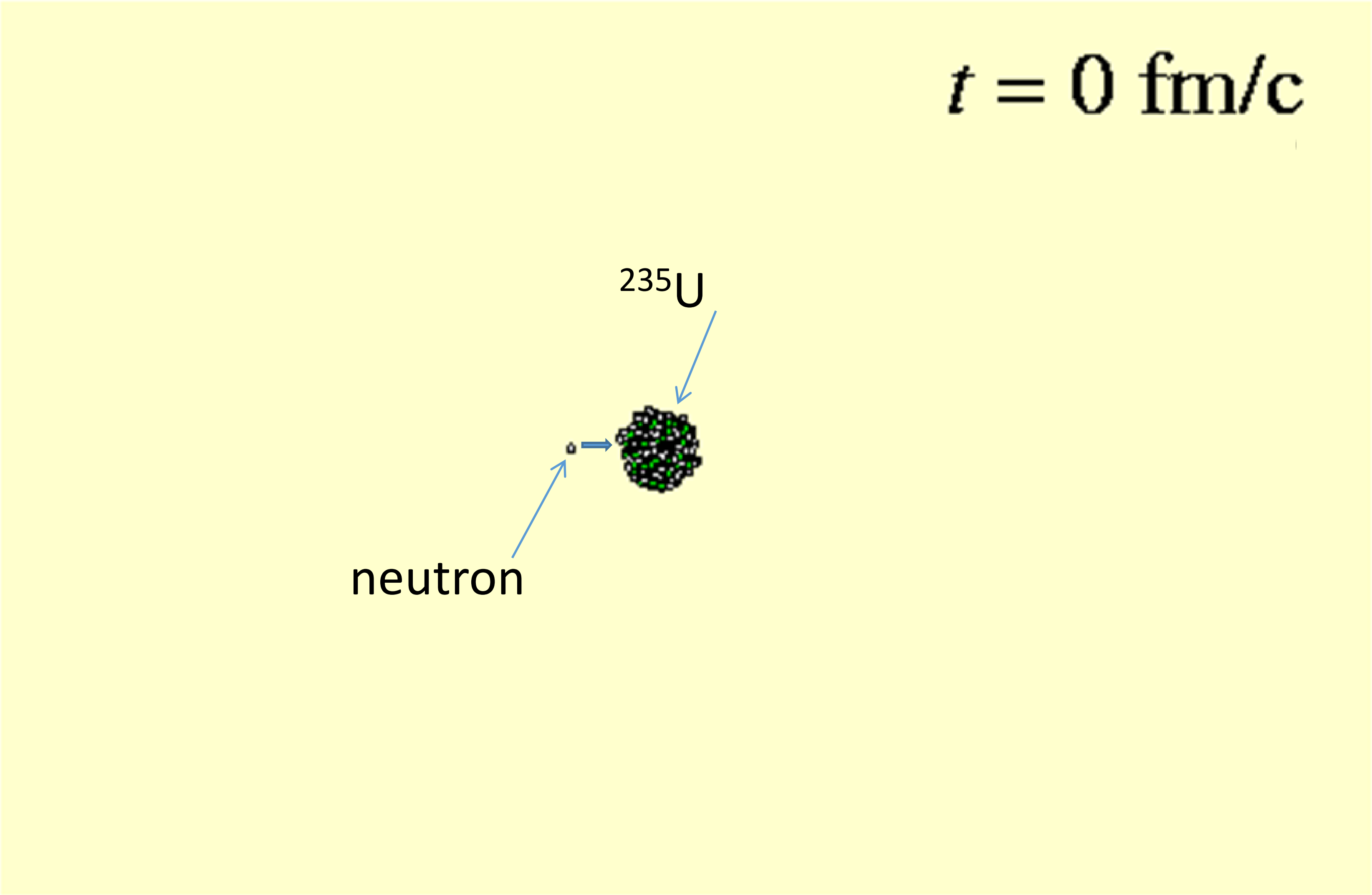
K.-H. Schmidt



Why only neutron multiplicity of the heavy fragments increases?

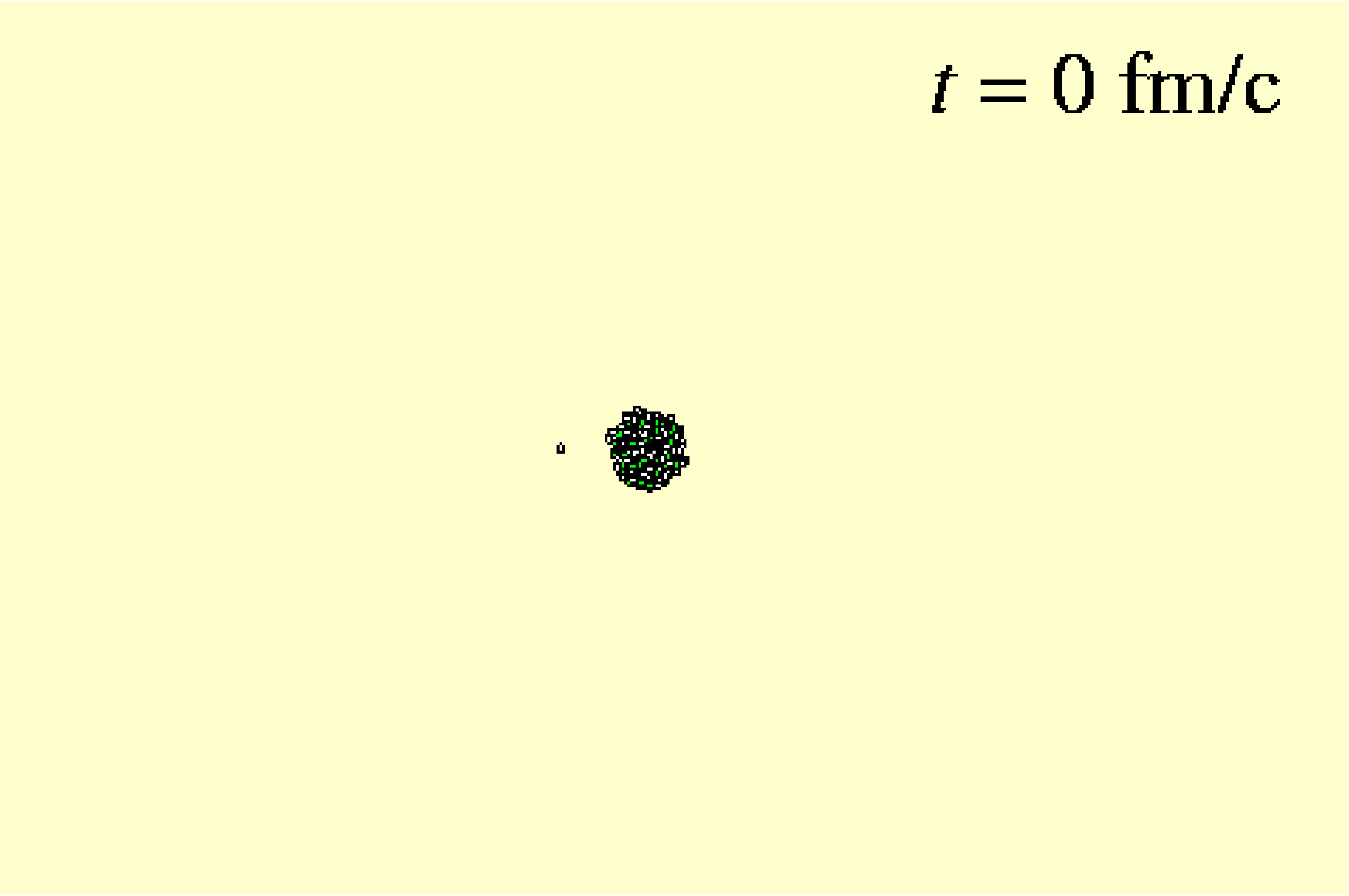
Description of nuclear fission by Langevin equation

MD simulation of nuclear fission (^{235}U + 140 MeV n)



K.Niita, T. Maruyama, Y. Nara, S. Chiba and A. Iwamoto, JAERI-Data/Code 99-042(1999)

MD simulation of nuclear fission (^{235}U + 140 MeV n)

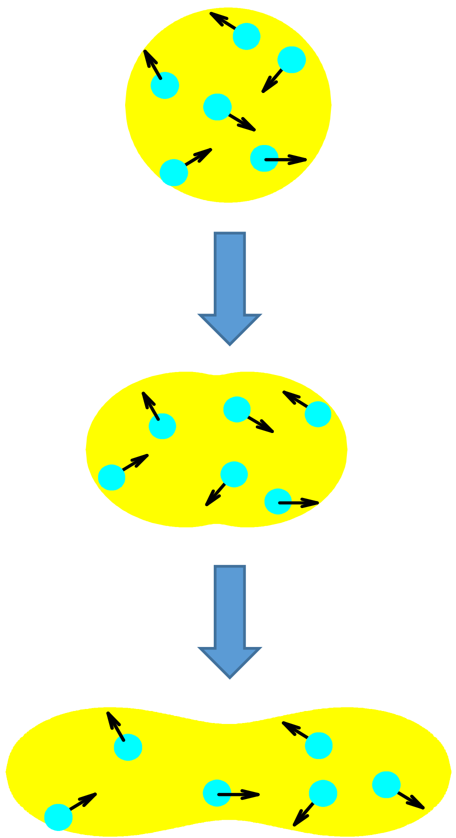


Time evolution of ^{235}U + 140 MeV n reaction by JQMD

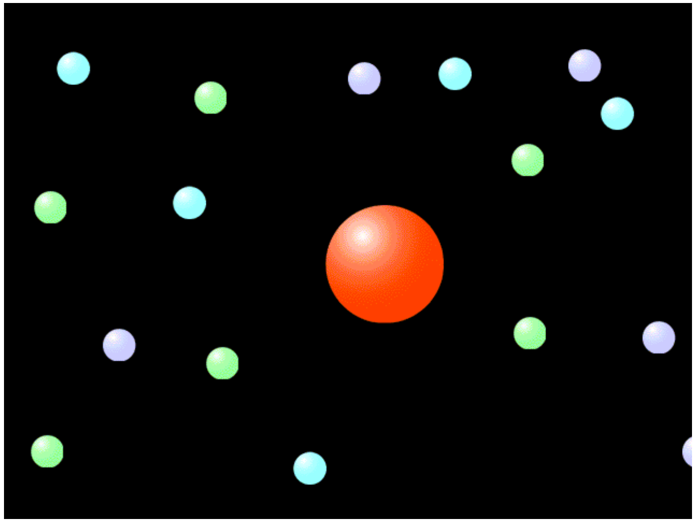
K.Niita, T. Maruyama, Y. Nara, S. Chiba and A. Iwamoto, JAERI-Data/Code 99-042(1999)

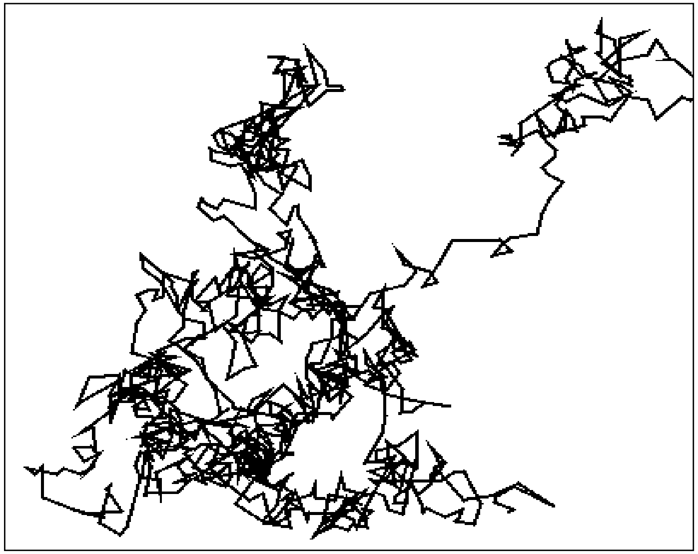
Shape evolution during fission described by MD

2 motions having different time scale:



Browning motion

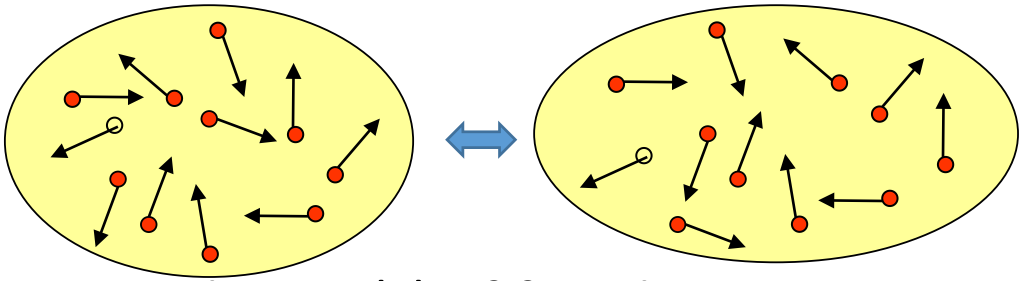




- **single-particle motion : 1 to 10 fm/c**
- **shape change : ～10000fm/c**

Fluctuation-Dissipation Dynamics : Langevin equation

- Brownian picture of nuclear dynamics



  - Macroscopic degree(s) of freedom interacting with microscopic degrees of freedom in thermal motion

dissipation $\Leftarrow$ friction

fluctuation $\Leftarrow$ random force

- Macroscopic degrees of freedom

= Nuclear shape degree of freedom (elongation, deformation, neck, mass asymmetry etc.)

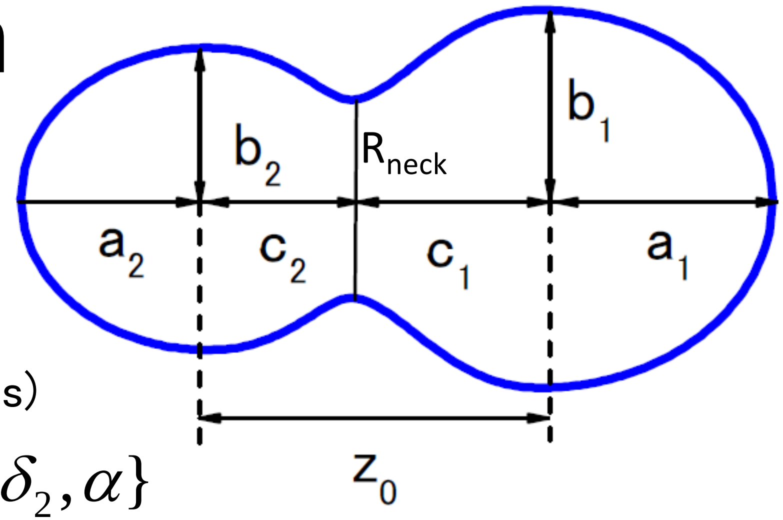
- Microscopic degrees of freedom

= Nucleon thermal motion

Essence of computational method

- Shape parametrization : Two-center model in 3 and 4 dimensions
- Potential energy -- macroscopic-microscopic method
  - Macroscopic part : Krappe-Nix (double-folded Yukawa model)
  - Microscopic part : two-center shell model + Strutinsky + BCS
  - Excitation energy dependence of the shell correction : Ignatyuk or Randrup-Moeller prescription
- Transport coefficients
  - Werner-Wheeler method for mass tensor (3D and 4D)
  - Wall-and-Window model for friction tensor (3D and 4D)
  - Linear response theory for microscopic mass and friction tensors (3D only) (Ivaniuk et al., JNST DOI: 10.1080/00223131.2015.1070111)

Shape parametrization



Two-center oscillator model

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

Collective coordinates (3 or 4 dynamical variables)

$$\{q\}_{3D} = \{ZZ_0, \delta, \alpha\} \qquad \{q\}_{4D} = \{ZZ_0, \delta_1, \delta_2, \alpha\}$$

- $ZZ_0 = \dfrac{z_0}{R}$ Elongation

  R : Radius of compound nucleus $= 1.2 A_{CN}^{1/3}$

- $\delta_i = \dfrac{3(a_i - b_i)}{2a_i + b_i}$ Deformation of fragments

  3D : $\delta_1 = \delta_2 = \delta$ 4D : δ_1, δ_2 are independent

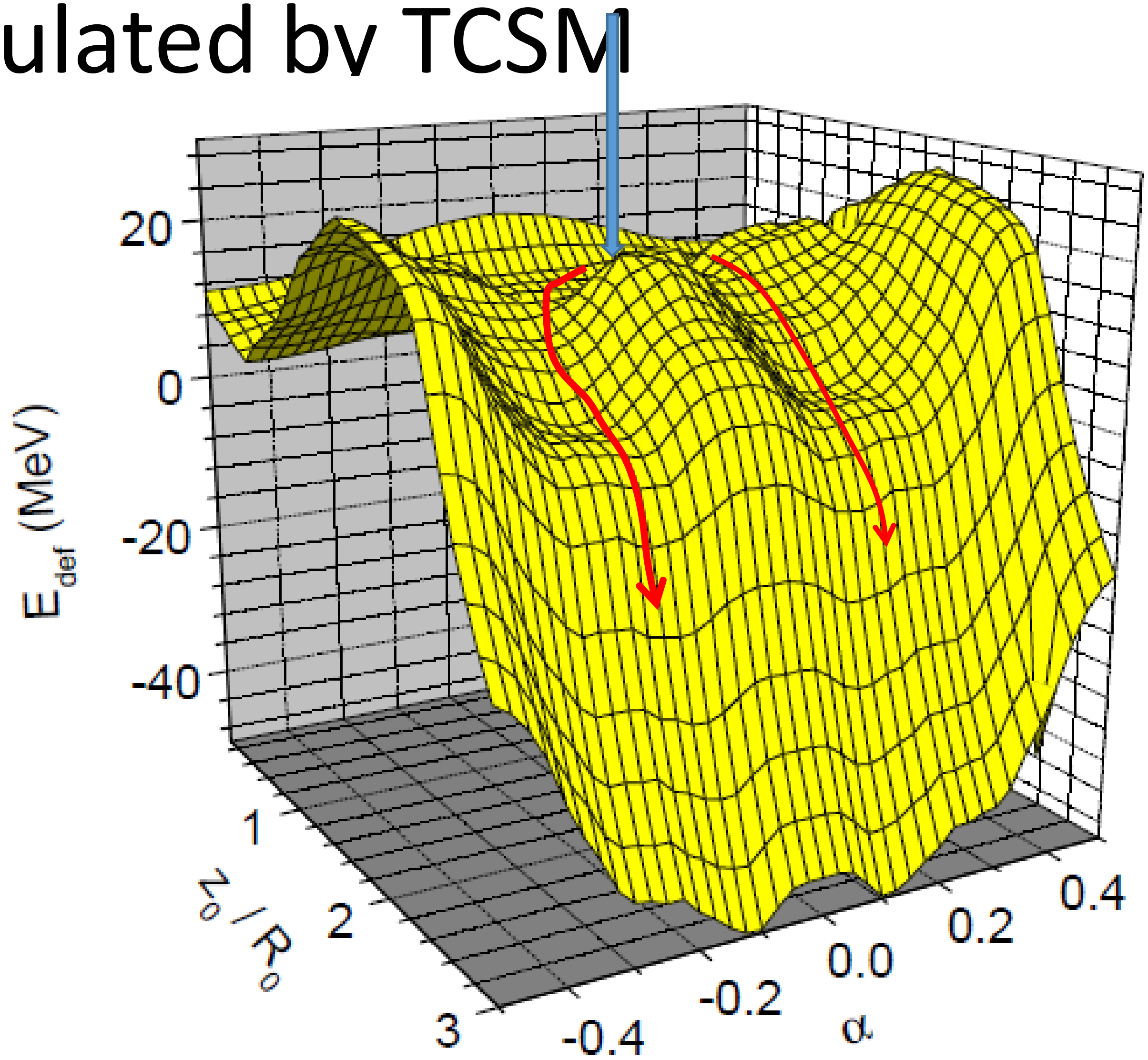
- $\alpha = \dfrac{A_1 - A_2}{A_1 + A_2}$ Mass asymmetry

  A_1 : mass of the right fragment

  A_2 : mass of the left fragment

- $\varepsilon = 0.35$ neck parameter : fixed
- volume conservation condition is applied

Potential energy surface of ^{236}U calculated by TCSM



Langevin Equations for nuclear fission

$$\frac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j$$

Friction　　Random force

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

q_i : deformation coordinates (nuclear shape) in two-center shell-model parametrization $\{q\}_{3D} = \{ZZ_0, \delta, \alpha\}$ $\{q\}_{4D} = \{ZZ_0, \delta_1, \delta_2, \alpha\}$

p_i : momentum conjugate to q_i

m_{ij} : mass tensor : Hydrodynamical mass (Werner-Wheeler)

γ_{ij} : friction tensor : Wall and Window formula (one-body dissipation)

or from Linear Response Theory (microscopic)

Macroscopic transport coefficients

Random force : $\langle R_i(t)\rangle = 0,\ \langle R_i(t_1) R_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$ White noise

$\sum_k g_{ik} g_{jk} = T\gamma_{ij}$ Einstein relation

Intrinsic energy and Temperature : $E_{\text{int}} = E^* - \frac{1}{2}\left(m^{-1}\right)_{ij} p_i p_j - V(q,T) = aT^2$

E_{int} : intrinsic energy, E^* : excitation energy, T : temperature

$\mathrm{V}(q,T)$: potential at deformation q and temperature T

a : level density paramter

Shell and pair correction to the potential energy

Shell correction : Strutinsky's prescription

Pairing correction : BCS theory

$$V(q,T) = V_{LDM}(q) + \Phi_{sh}(E_{\mathrm{int}})E_{sh}^{T=0}(q) + \Phi_{pair}(E_{\mathrm{int}})E_{pair}^{T=0}(q)$$

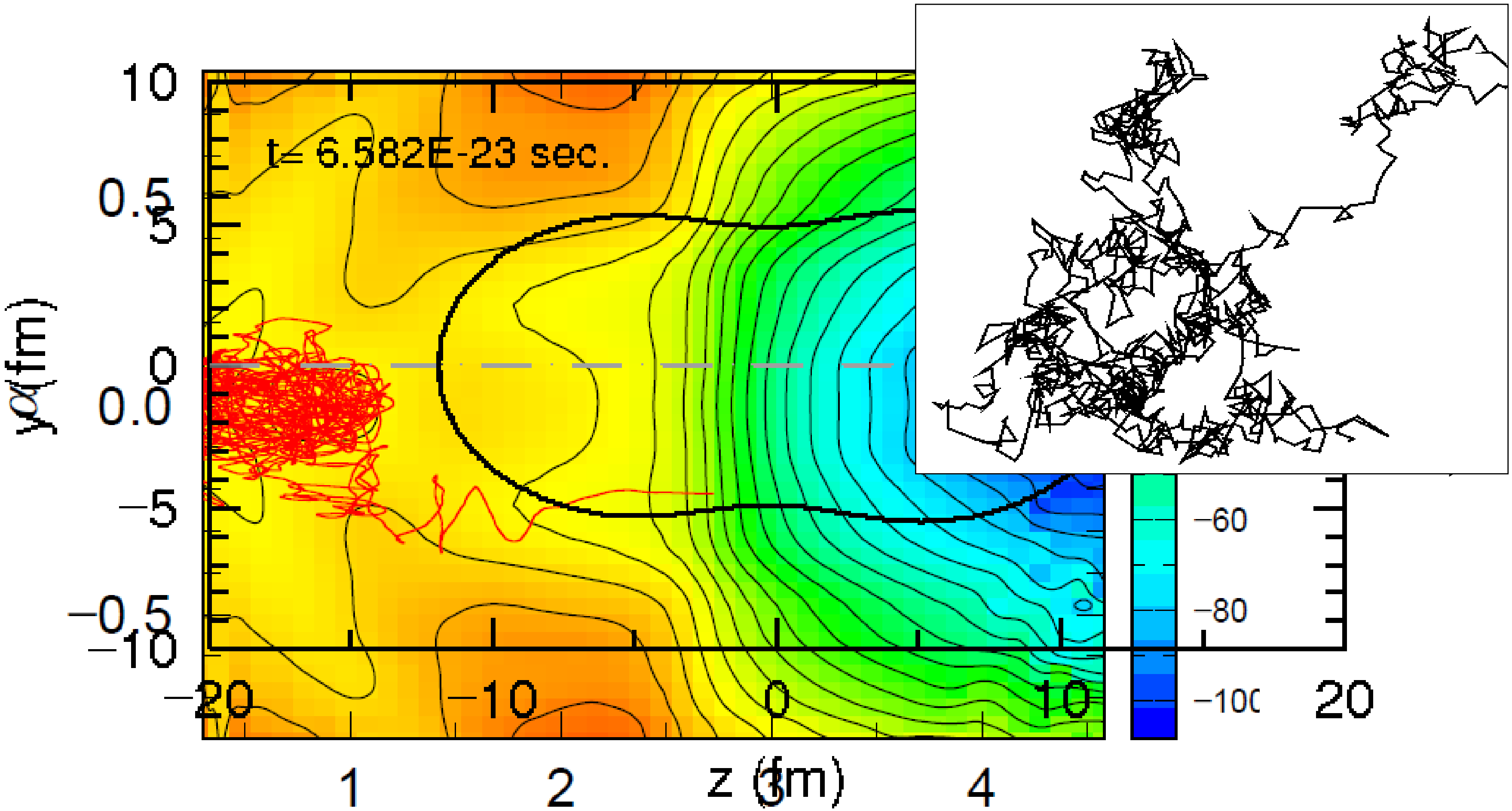
$$\Phi_{sh,pair}(E^*) = \exp\left(-\frac{E^*}{E_D}\right)$$

Iganityuk
Wada, Asano, Aritomo, Chiba

$$\Phi_{sh,pair}(E^*) = \frac{1+e^{-E_1/E_0}}{1+e^{-\left(E^*-E_1\right)/E_0}}$$

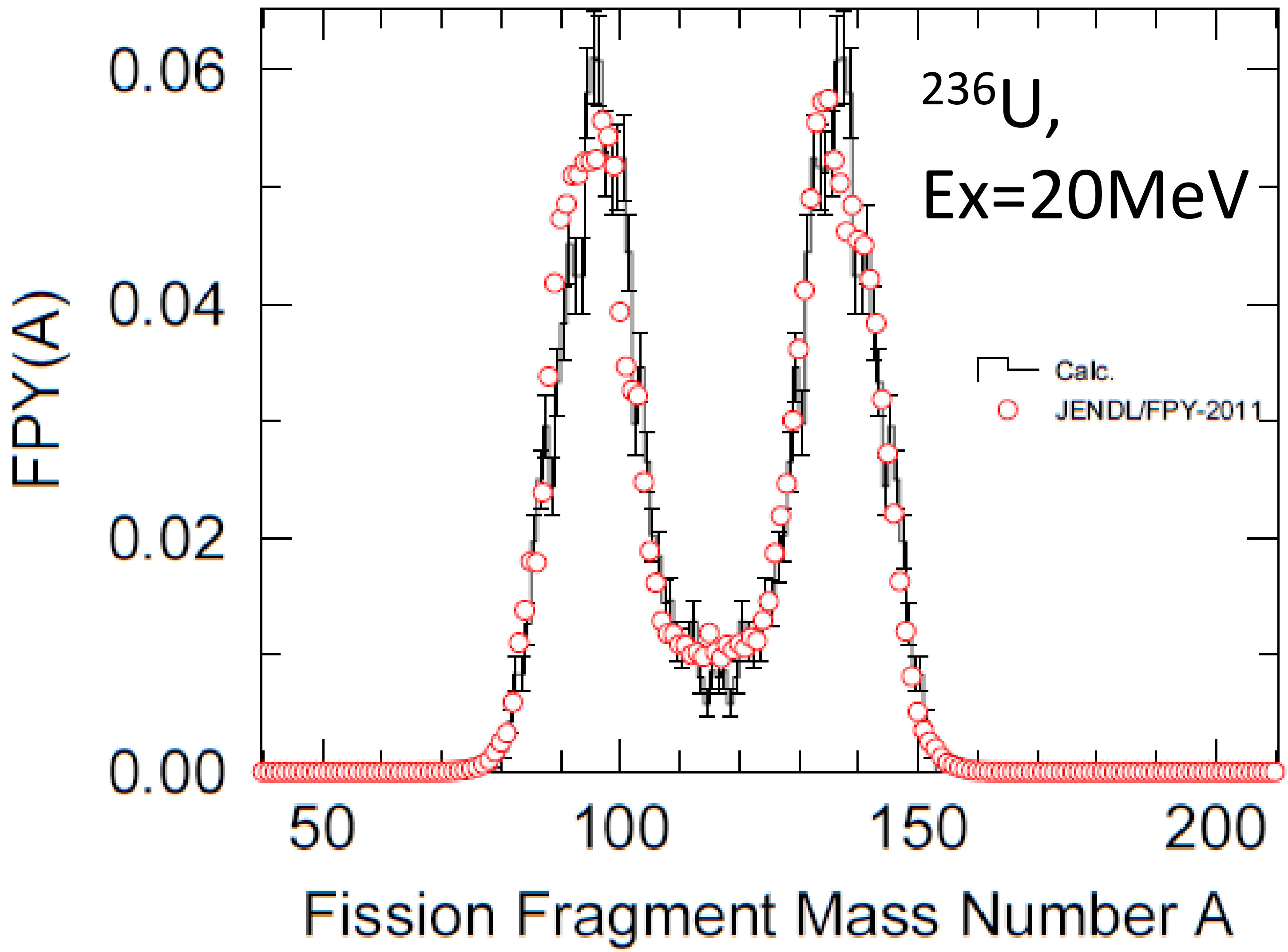
Randrup-Moeller
PRC 88, 064606(2013)

Example of 3D Langevin trajectories (^{236}U, 20MeV)

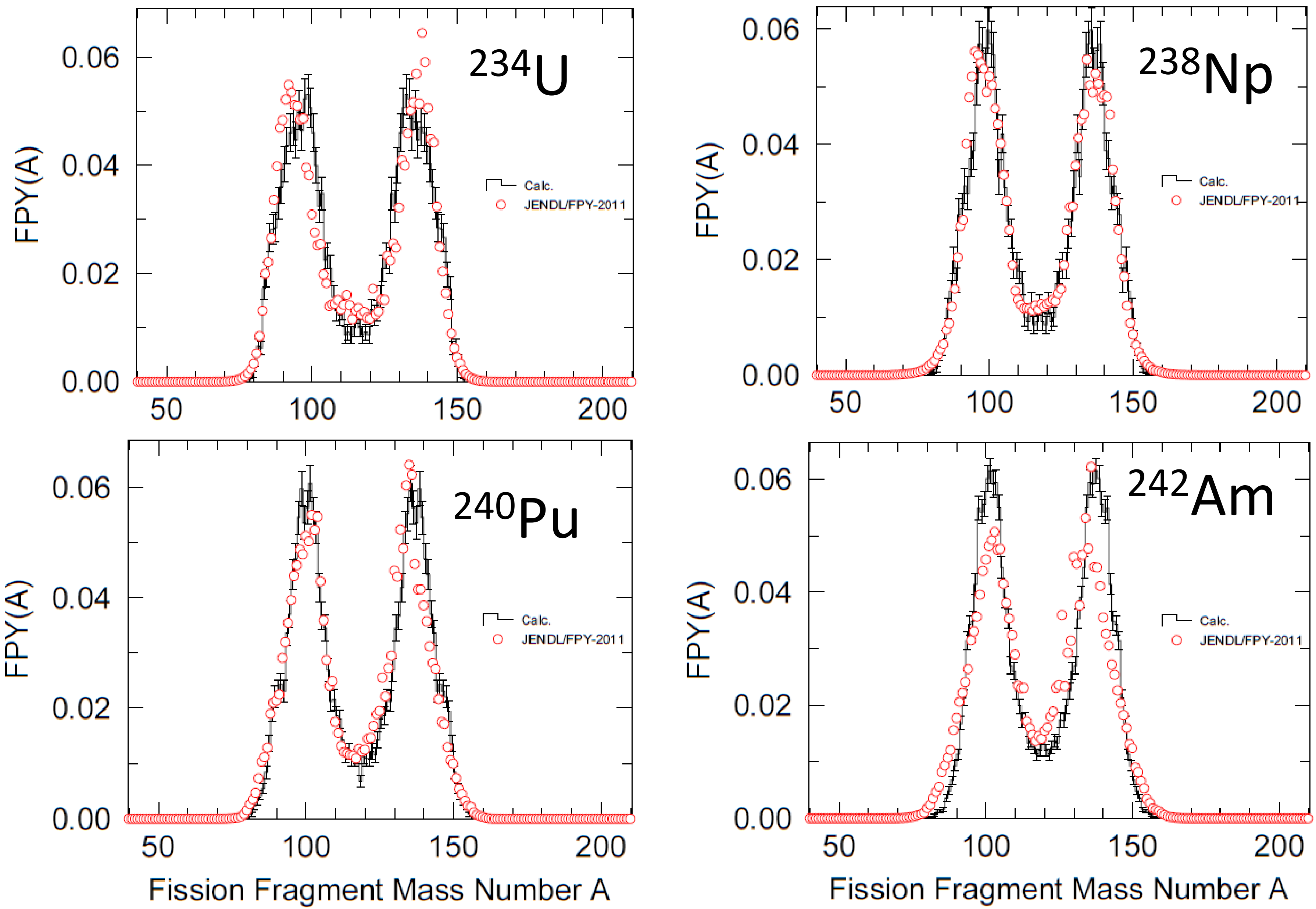


$$ZZ_0 = \frac{z_0}{R}$$

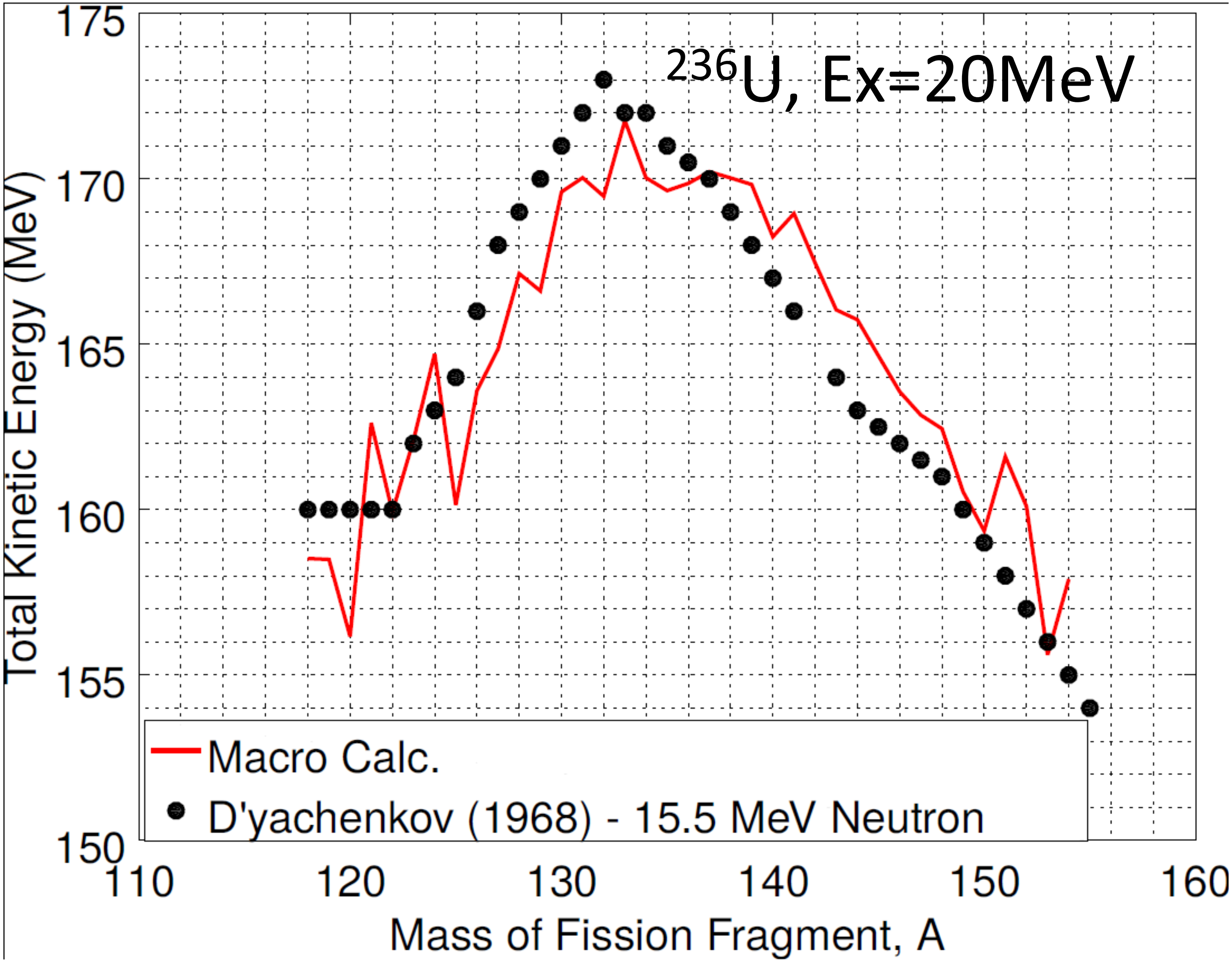
Mass Distribution of Fission Fragments at Ex=20MeV



Mass Distribution of Fission Fragments at Ex=20MeV



Comparison with TKE data

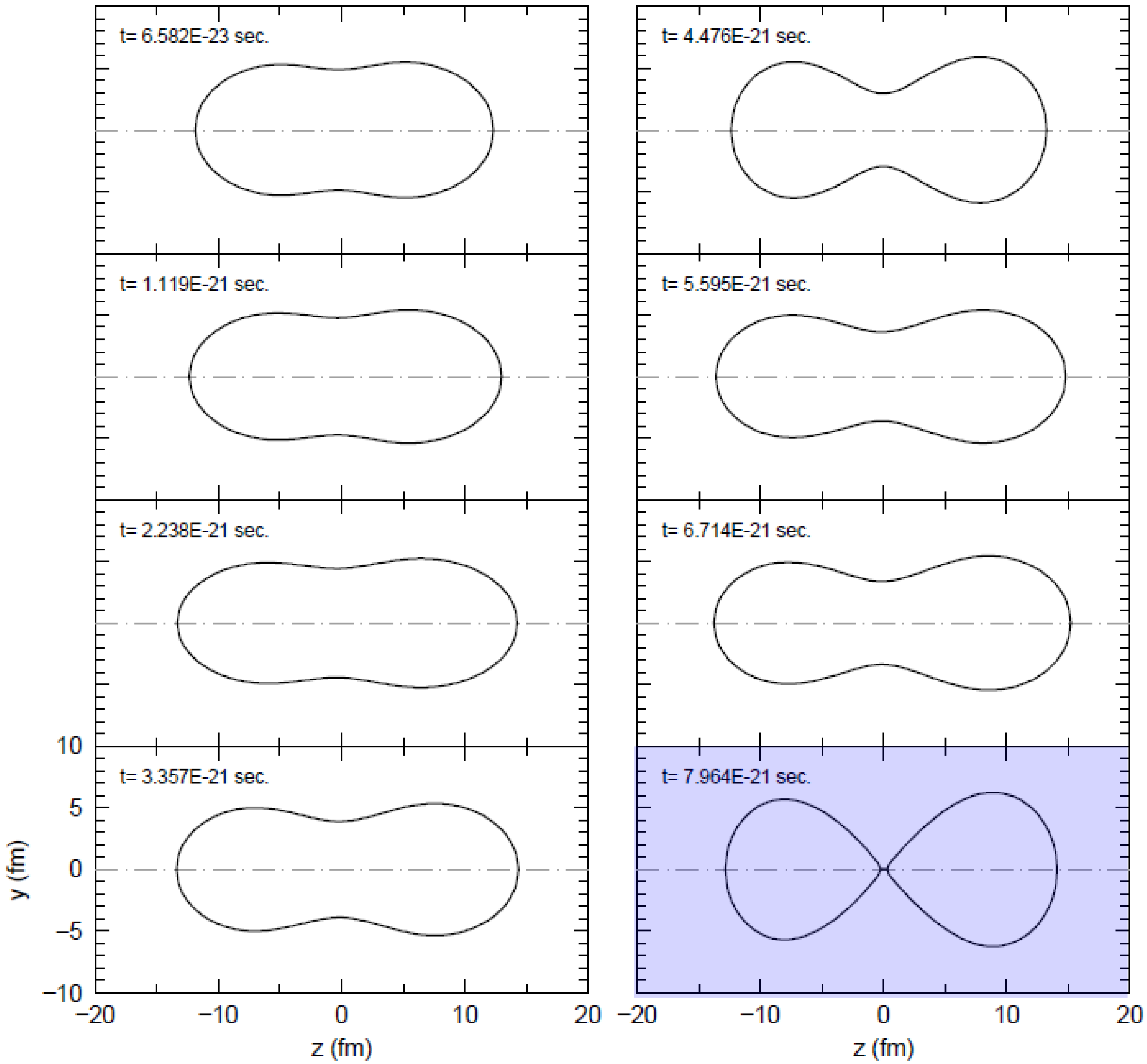


Further improvements to the TokyoTech Langevin model

1. Introduction of microscopic transport coefficients
   - Shell and pairing effects of mass and friction tensors, temperature dependence → talk by Mark Dennis Anak Usang, PRC (in press)
2. Interface to subsequent statistical decay (prompt neutron emission) including effects of charge polarization: sharing of excitation energy between 2 fragments
3. Introduction of charge-asymmetry degree of freedom
   - Calculation of isotope distribution (not only mass distribution)
4. Extension to 4D Langevin model (ongoing)
5. Interfacing to β-delayed phenomena

Charge polarization and prompt neutron multiplicities

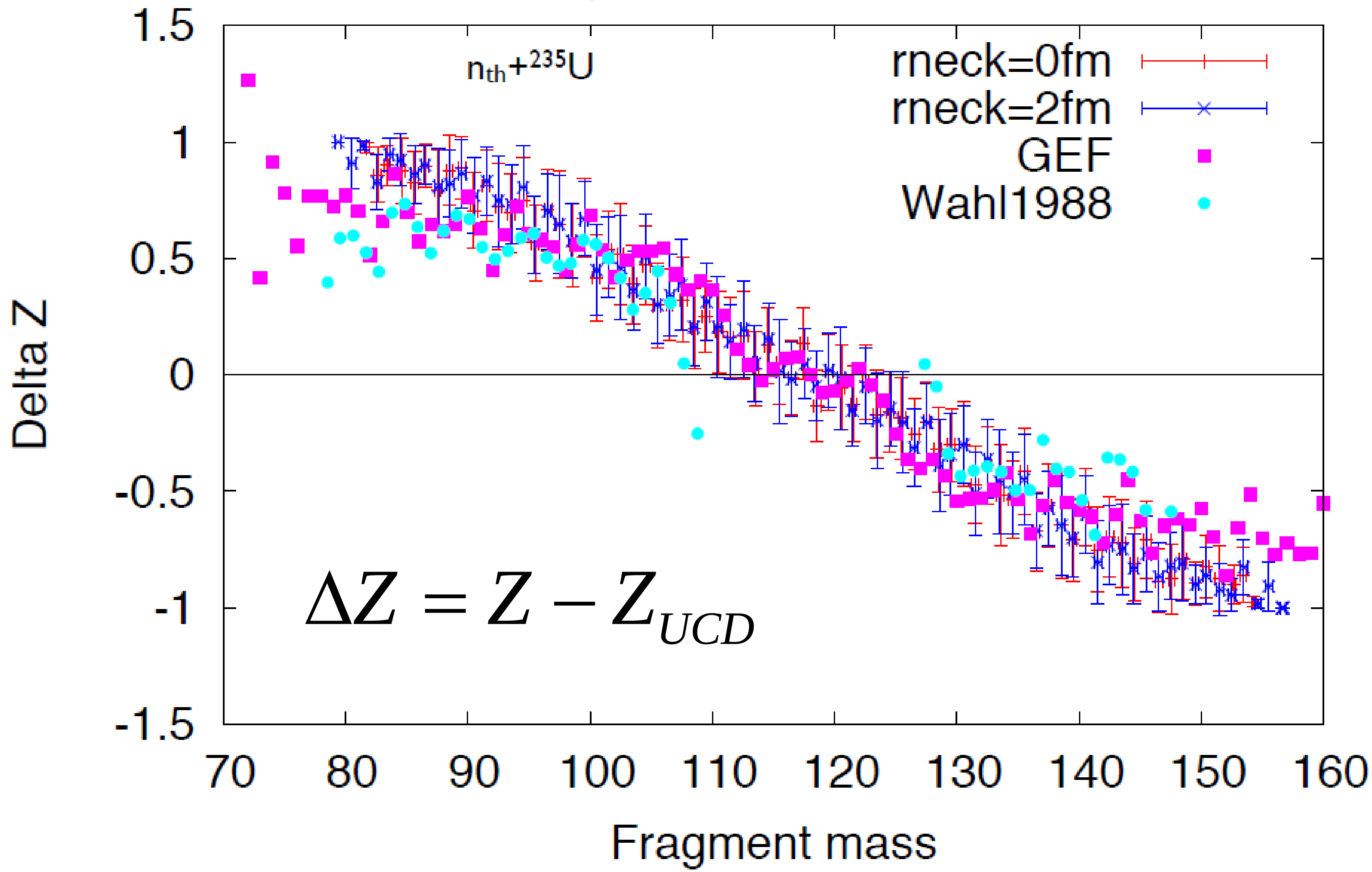
Time evolution of Langevin solutions for ^{236}U at E^* = 20 MeV and charge polarization



We can obtain charge polarization by minimizing the symmetry + Coulomb energy at scission configuration

Charge polarization obtained with scission shape calculated by Langevin equation

Obtained by minimizing the symmetry + Coulomb energy at scission configuration

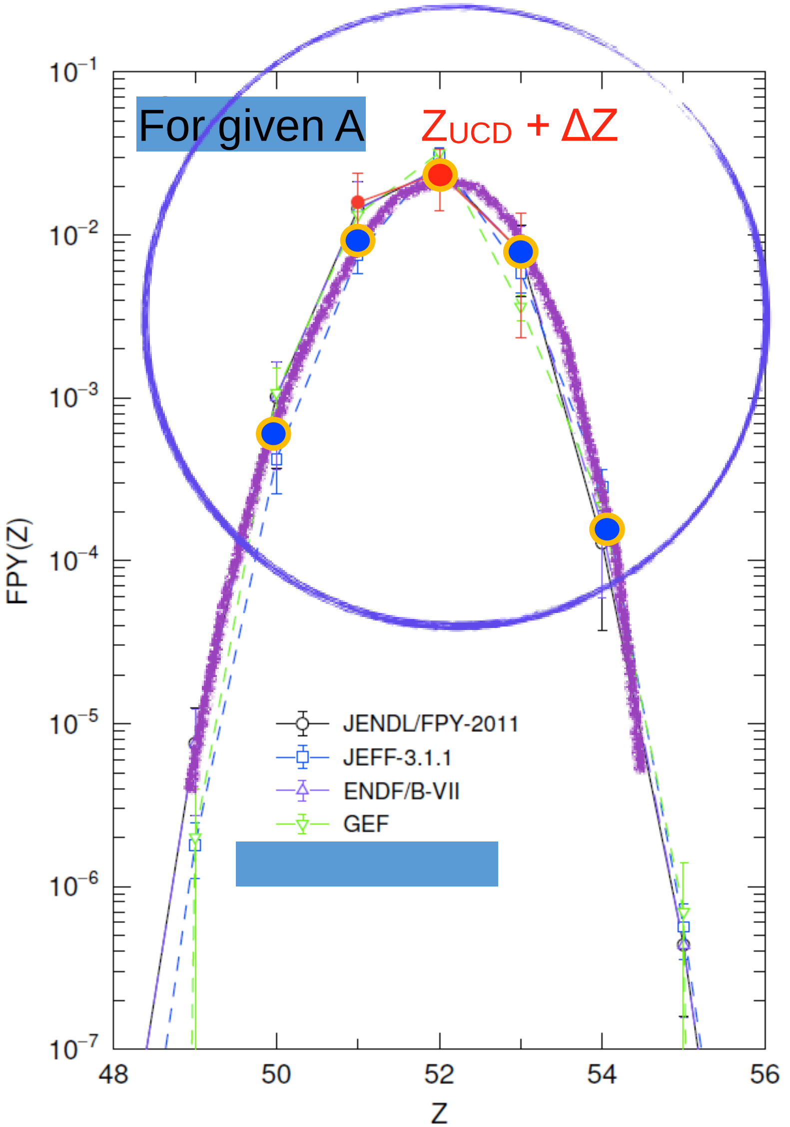


Isotope distribution obtained with charge polarization

$$P(Z_f|A_f) \propto \exp\left(-\frac{(Z_f - \overline{Z}_f(A_f))^2}{2\sigma_Z^2}\right)$$

where σ_Z = 0.4@U-236
[ref] Nucl. Phys. A 177, 337 (1971)

We considered 5 major nuclei around the <Z> for each mass chain to calculate neutron multiplicity



Prompt neutron multiplicity

affected by the charge polarization

TXE(Total excitation energy) =
Q-value + Bn(Neutron binding energy) + En(Incident neutron energy) – TKE(Total kinetic energy taken from Langevin Results)

TXE is shared between each fragments according to Ignatyuk level density parameter ratio.

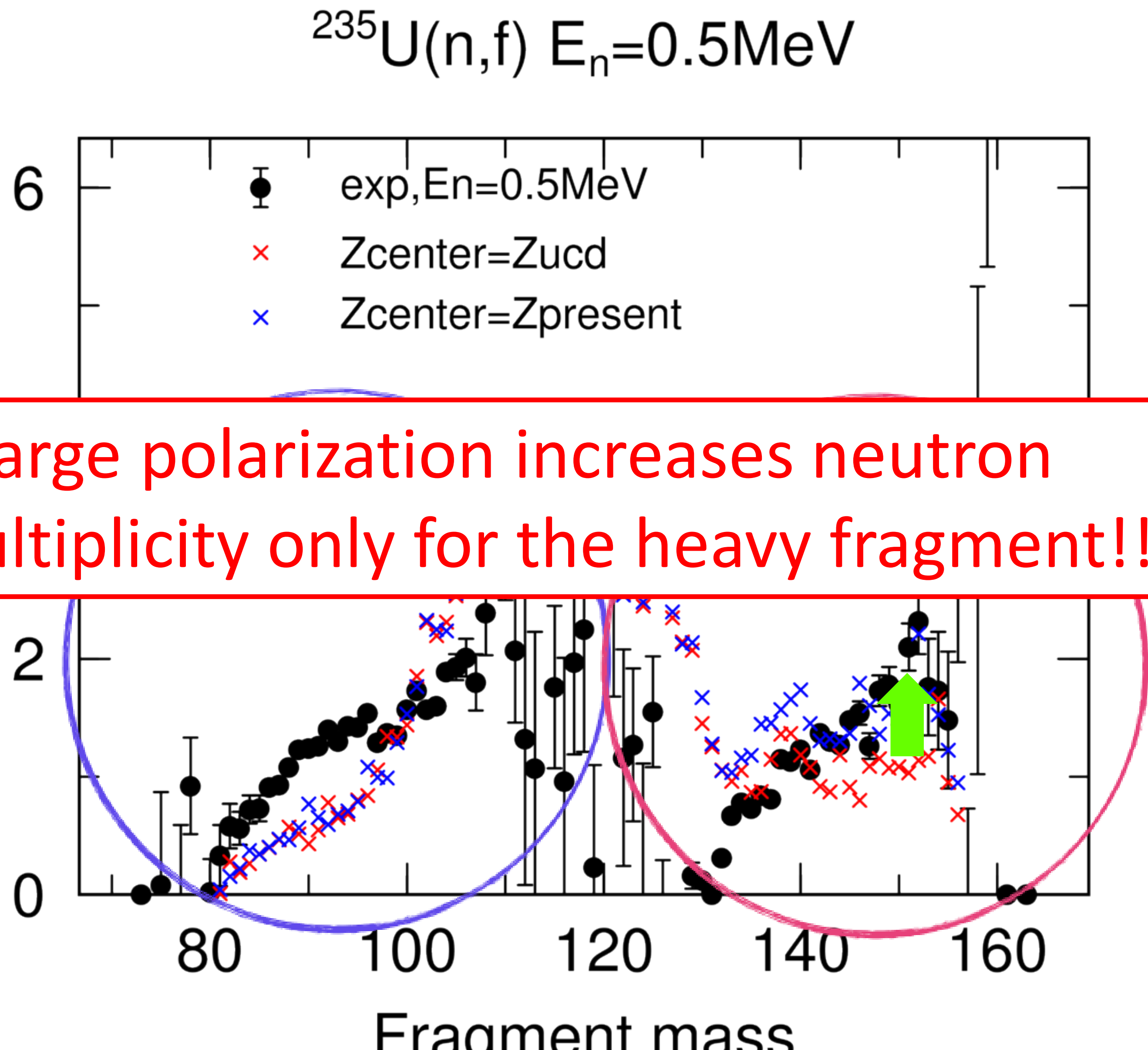
$$a(U) = a^*\left(1 + \frac{\delta W}{U}\left(1 - e^{-\gamma U}\right)\right)$$ (δW:Shell correction, γ:damping factor)

$$\bar{\nu}(A_1) = (E(A_1) - S_{2n}(A_1)/4)/(S_{2n}(A_1)/2)$$

$E(A_1)$: Excitation Energy of fragment A_1

$S_{2n}(A_1)$: Two neutron separation energy of fragment A_1

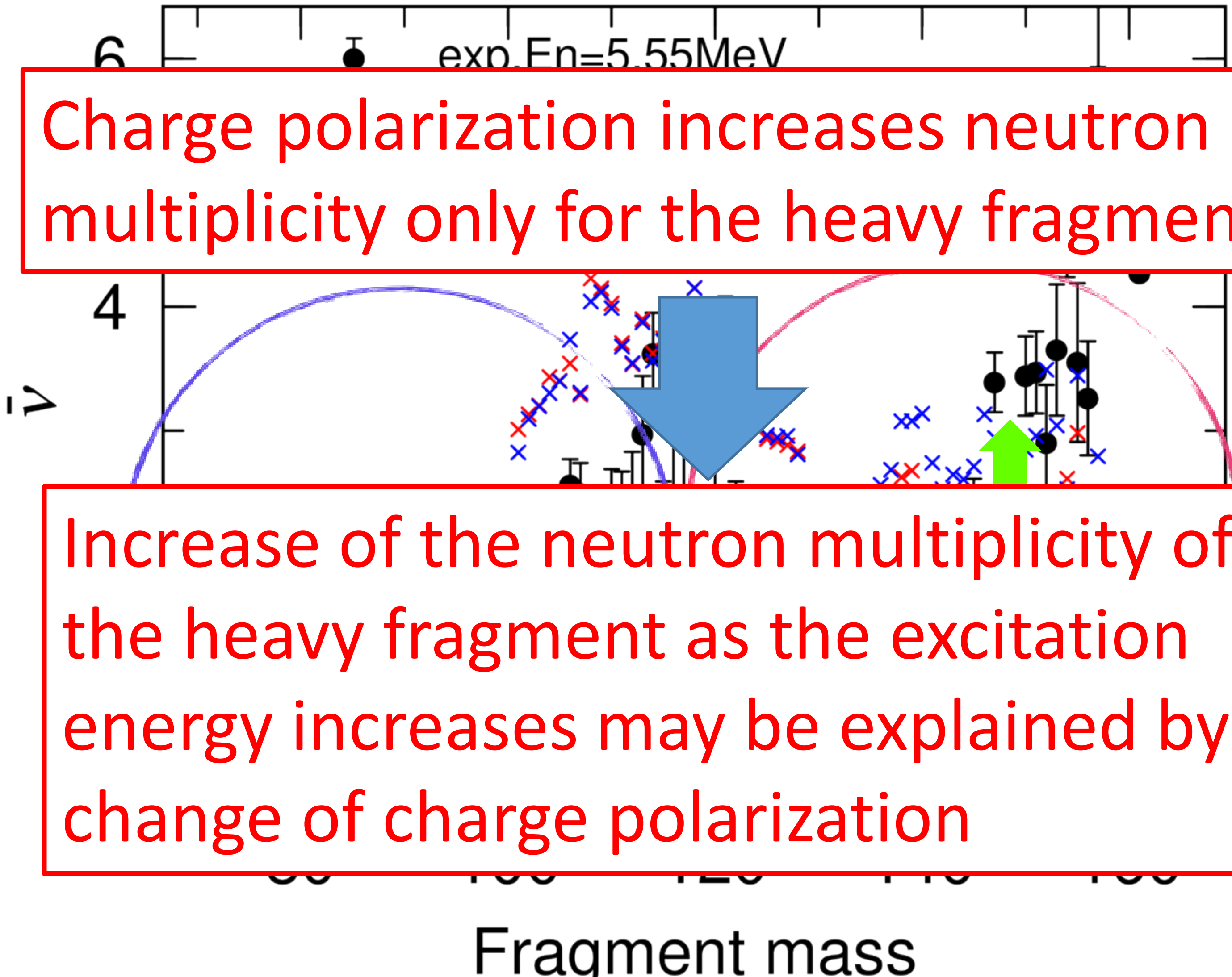
Effect of charge polarization on prompt neutron emission (1)



Charge polarization increases neutron multiplicity only for the heavy fragment!!

Effect of charge polarization on prompt neutron emission (2)

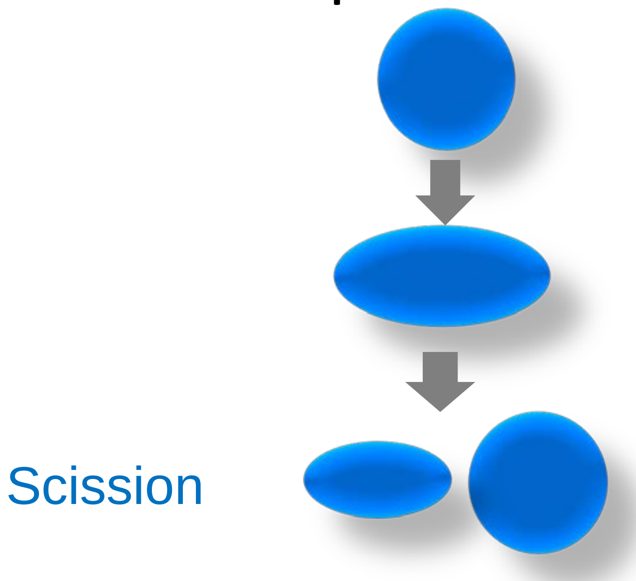
$^{235}U(n,f)$ En=5.55[MeV]



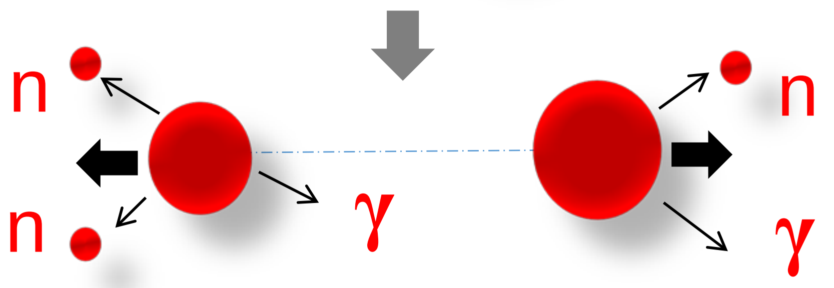
Charge polarization increases neutron multiplicity only for the heavy fragment!!

Increase of the neutron multiplicity of the heavy fragment as the excitation energy increases may be explained by the change of charge polarization

Nuclear shape evolution and particle emission during fission



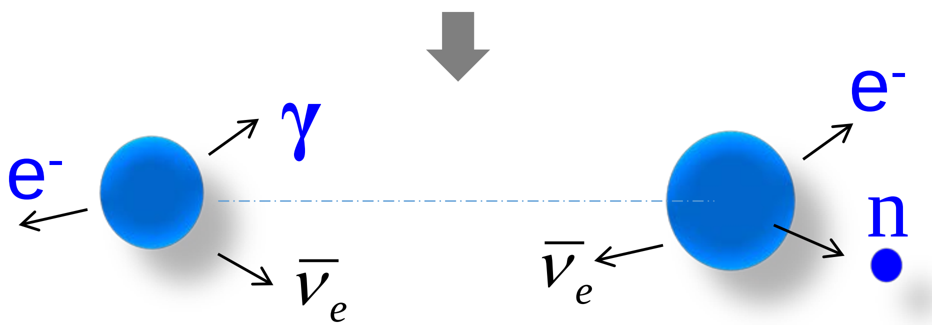
Dynamical Theory		Static Theory	Brosa-inspired
Random Walk **Langevin equation**	TDGCM **TDHF** **AMD**	Fong Wilkins	Multi-modal analyses



Statistical decay

Sharing of E*
between 2 fragments,
J^{π} distribution

Madland-Nix
Weisskopf-Ewing
Hauser-Feshbach



β-decay + statistical decay

Gross Theory
QRPA
Shell Model

Weisskopf-Ewing
Hauser-Feshbach

Participants

- Ivan Borzov
- Daniel Cano
- Satoshi Chiba
- Iris Dillmann
- Muriel Fallot
- Paul Garrett
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- Xiaolong Huang
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- Balraj Singh
- José L. Tain
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Advisers

- Daniel Abriola
- Tim Johnson
- Libby McCutchan
- Alejandro Sonzogni

See attached file

IAEA CRP on a Reference Database for Beta-Delayed Neutron Emission Data

Project Officer: Paraskevi Demetriou

http://www-nds.iaea.org/beta-delayed-neutron/

Objective:

Create a Reference Database for Beta-Delayed Neutron Emission that contains both a compilation of existing data as well as recommended data for individual precursors and aggregate quantities (nu-bars, group constants)

IAEA Meetings

- 2nd RCM 2015
- 1st RCM 2013
- Consultants Meeting 2011

INDC (NDS) Documents

- INDC(NDS)-0683
- INDC(NDS)-0643
- INDC(NDS)-0599
- INDC(NDS)-0107/G

Workshops

- 2nd Workshop on The Status of Reactor Antineutrino Flux Modelling 2015
- 3rd North-American Workshop 2014
- Workshop on Reactor Neutrinos 2013
- 2nd North-American Workshop 2013
- 1st North-American

Reviews | **New Data** | Compilation/Evaluation | Systematics | Neutron Spectra | Macroscopic Data | Summation Method | Group Spectra

#	Year	Author	Title	Link
			New experimental data for β-delayed neutron emission from Individual Precursors	
1	2013	Mazzocchi et al	New half-life measurements of the most neutron-rich arsenic and germanium isotopes	Physical Review C 87, 034315
2	2013	Miernik et al	β-decay study of neutron-rich bromine and krypton isotopes	Physical Review C 88, 014309
3	2013	Miernik et al	Large βNudear Data Sheets 128, 131 (2015)-Delayed One and Two Neutron Emission Rates in the Decay of ^{86}Ga	Physical Review Letters 111, 132502
4	2013	Korgul et al	Experimental study of the β-γ and β-n decay of the neutron-rich nudeus ^{85}Ga	Physical Review C 88, 044330
5	2014	Miernik et al	Excited states in ^{82}As studied in the decay of ^{82}Ge	Physical Review C 90, 034311
6	2014	Korgul et al	Structure of Neutron Rich-Nudei Beyond N = 50	Acta Physica Polonica B 45, 223
7	2014	Grzywacz et al	Hybrid-3Hen-New Detector for Gammas and Neutrons	Acta Physica Polonica B 45, 217
8	2014	K. Rykaczewski	Decay Studies of ^{238}U Fission Products at the HRIBF (Oak Ridge)	Nuclear Data Sheets 120, 16-21
9	2014	A. Fijalkowska	First Results from the Modular Total Absorption Spectrometer at the HRIBF	Nuclear Data Sheets 120, 26-29
10	2014	Miernik et al	No Evidence of Isomerism for the First Excited State of ^{93}Rb	Nuclear Data Sheets 120, 56-58
11	2014	Rajabali et al	β decay of ^{72}Co and microsecond isomers in even-mass neutron-rich nickel	J. Phys. G: Nucl. Part. Phys. 41,

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A. Sonzogni, E. McCutchan	BNL	USA

Work done: 2nd RCM 23-27 March 2015:

INDC(NDS)-0683, July 2015

- Compilation and evaluation microscopic data for Z = 2-28
  - M. Birch, *et al.*, First Compilation and Evaluation of Beta Delayed-neutron Emission Probabilities and Associated Half-lives for A ≤ 72 Nuclei, Nucl. Data Sheets 120 (2014) 66-69.
  - M. Birch, *et al.*, Evaluation of Beta Delayed-neutron Emission Probabilities and Half-lives for Z = 2-28, Nucl. Data Sheets 128 (2015) 131-184.
- DN spectra: analysis by J-L. Tain, INDC(NDS)-0683;

  Digitization by VECC (Banerjee/Mukherjee); NDS-IAEA
- Systematics
  - E.A. McCutchan, *et al.*, Improving Systematic Predications of β^- Delayed-neutron Emission Probabilities, Phys. Rev. C86 (2012) 041305.
  - E.A. McCutchan, *et al.*, A New Approach to Estimating the Probability for β^- Delayed-neutron Emission, Nucl. Data Sheets 120 (2014) 62-65.
- Theoretical calculations
  - Marketin et al, PRC 93 (2016) 025805;
  - Minato, JPS Conference Proceeding Vol.6 030053 (2015)
- Sensitivity studies of macroscopic quantities: nu-bars, DN spectra

  V.M. Piksaikin, *et al.*, IAEA report INDC(NDS)-0646, October 2013; INDC(NDS)-0689, June 2015.

Work in progress (3^{rd} RCM in 2017)

- Measurements:

  RIKEN (2016-2017)

  1. first measurement of $P_{1n} \rightarrow$ ^{76}Co, $^{78,79}Ni$, $^{80,81}Cu$, $^{83,84,85}Zn$, $^{85,87}Ga$, $^{87-90}Ge$, $^{88-91}As$, $^{90,92}Se$
     first measurement of $P_{2n} \rightarrow$ $^{80,81,82}Cu$, $^{83,84}Zn$, $^{84,85,87}Ga$, $^{87,88}Ge$, $^{88-91}As$,
  2. first measurement of P_{1n}, P_{2n}, $P_{3n} \rightarrow$ $^{121-127}Rh$, $^{128,129}Pd$, $^{130,131}Ag$, $^{133,134}Cd$, $^{135,136}In$, $^{138,139,140}Sn$, $^{140,141}Sb$, $^{142,143}Te$, $^{144,145,146}I$, $^{147,148}Xe$, $^{149,150,151}Cs$, $^{150,151,152}Ba$

  ISOLDE (July/Oct 2015)

  $^{40-53}K$, $^{130,131,132}Cd$

  CARIBU (2015-2018)

  1. $^{109,110}Mo$, A=136,137
  2. $^{98m,99-103}Y$, $^{134,135,136}Sn$

  TRIUMF (2015-2016)

  ^{9}Li, ^{49}K, $^{130,131,132}Cd$, $^{133,134}In$, $^{145,146}Cs$

  ALTO (2015-2016)

  $^{130-134}In$, $^{133,134,136}Sn$

- Compilation and evaluation of microscopic data for → Z = 29-57 (T1/2 ~ 300 nuclides) and Z > 57
- Systematics and theory → various models are being assessed/pursued and comparison of delayed neutron spectra will be added
- Benchmarking of Pn wrt macroscopic DN properties: nu-bars, DN spectra

Summary

- Dynamical description of fission by Langevin equation is explained
  - Calculations are performed for actinides at Ex=20MeV by a 3D version
  - Mass and TKE distribution of fission fragments are reproduced with a high accuracy, including their systematical trends
  - With this degree of accuracy, this method can be considered to be one of the data production tool
- Possible ways to extend the current methodology were presented
  - introduction of charge polarization, charge-asymmetry d.o.f., microscopic transport coefficients, and 4D calculation so that deformation of 2 fragments can be independent
  - Interfacing to subsequent statistical decay is in progress, and our first results on prompt-neutron multiplicities are promising
- Activity through IAEA CRP on β-delayed neutron emission was briefly introduced

Thank you for your attention!!

For further information or collaboration, please contact

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