Research Progress on Neutron-Induced Fission

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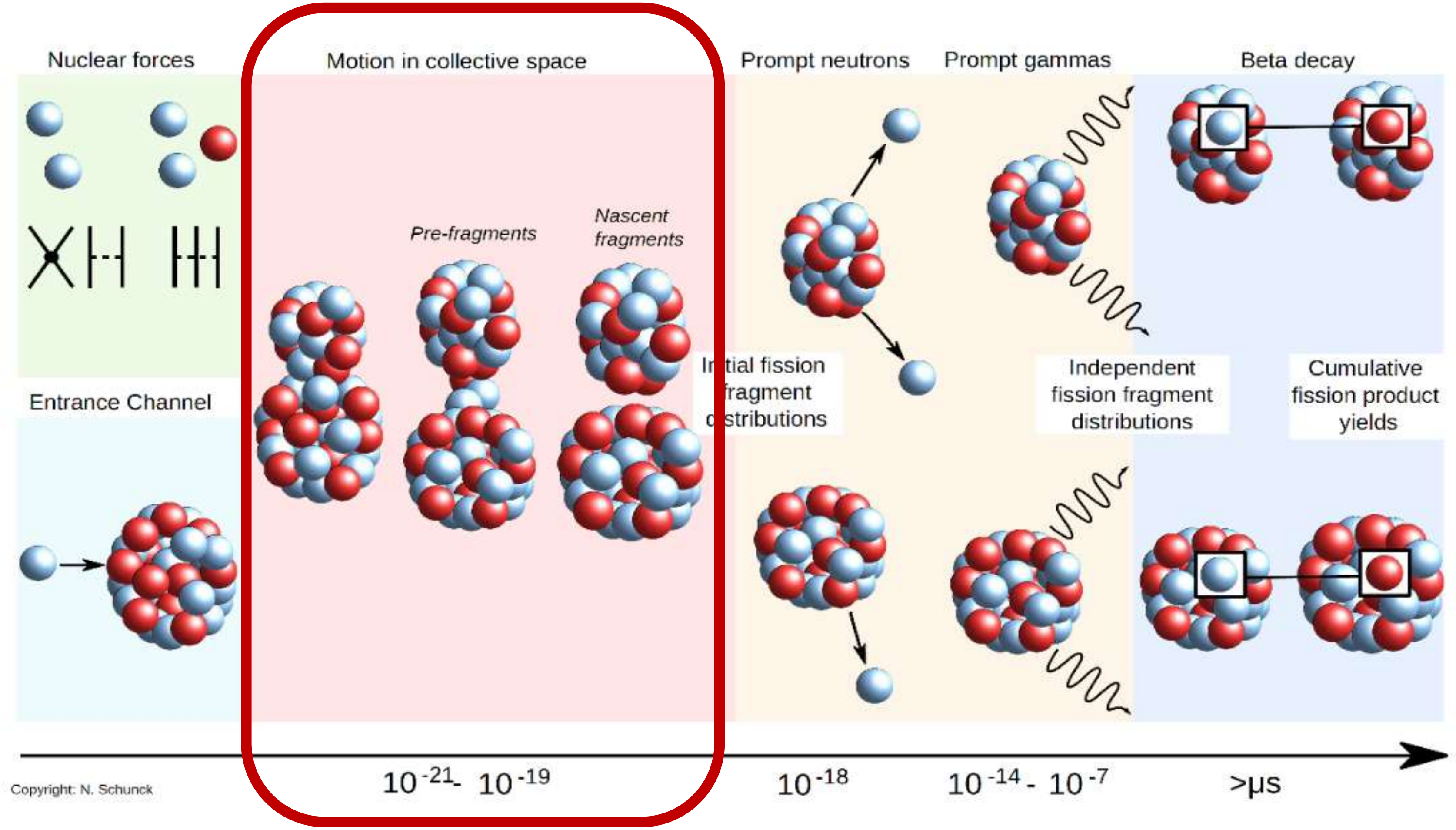
China Nuclear Data Center, China Institute of Atomic Energy

Dongguan, Guangdong, China, May 26, 2025

Outline

Overview of the Nuclear fission process



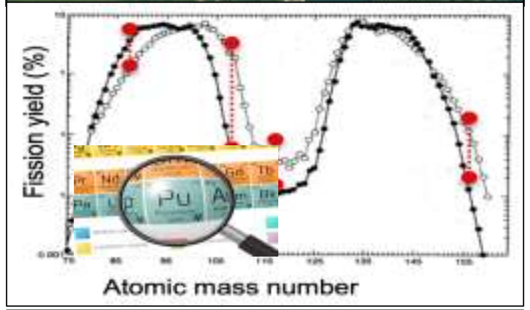
Neutron-induced fission process

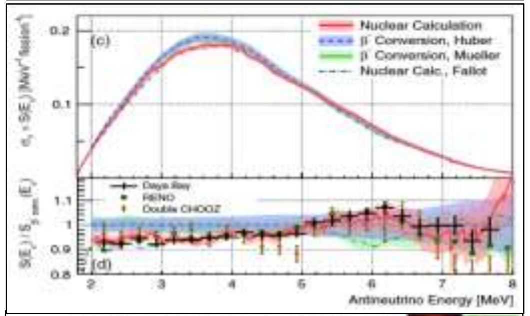
- Nuclear fission refers to the change in which an atomic nucleus splits into several nuclei.
- Nuclear fission is always accompanied by the emission of neutrons, gamma rays, beta decays, etc. (easily detectable)
- The process involves complex correlation, fluctuation, and dissipation...

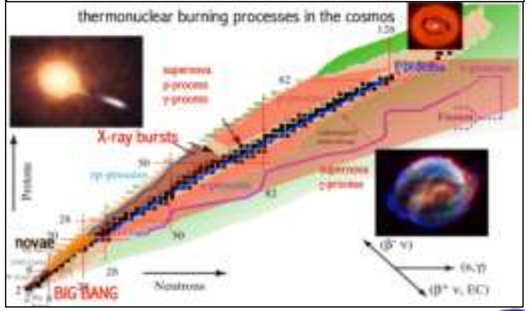
Ref: Michael Bender et al 2020 J. Phys. G: Nucl. Part. Phys. 47 113002

Fission data application (with CS, DD, etc.)

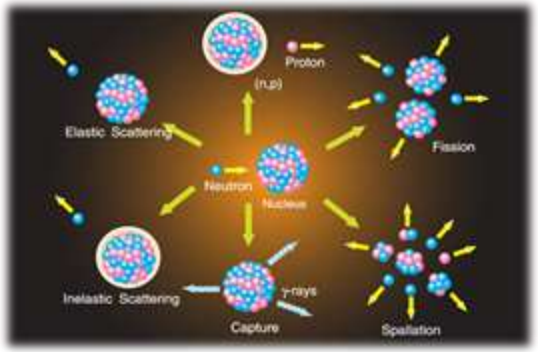
- in reactor design and operation
  - reactivity calculations, fuel and reactor core management, reactor safety (CS, DD, IND and CUM)
- in reprocessing of spent fuel and nuclear waste management
  - fission product inventory, decay heat calculation (CS,DD, IND)
- in safeguard
  - monitor fission products for the verification (CUM,etc)
- in fundamental physics
  - understanding fission physics, r-process nucleosynthesis, antineutrino anomaly (FY)， fission angular momentum …(CS, DD,IND and CUM)
- in other applications
  - ……



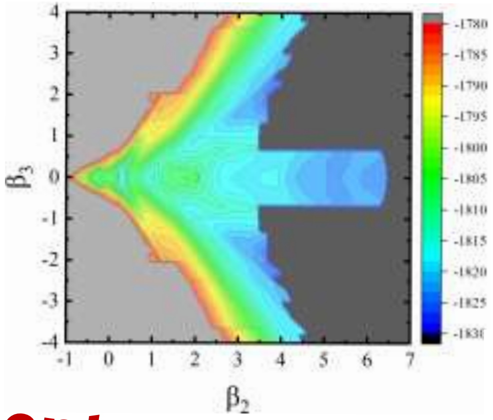




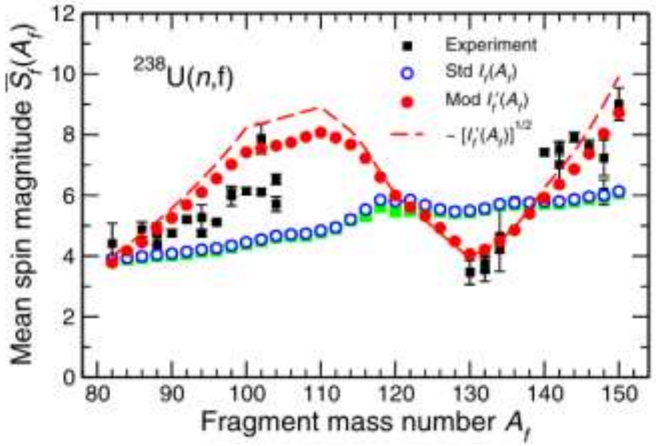
Nuclear fission frontiers



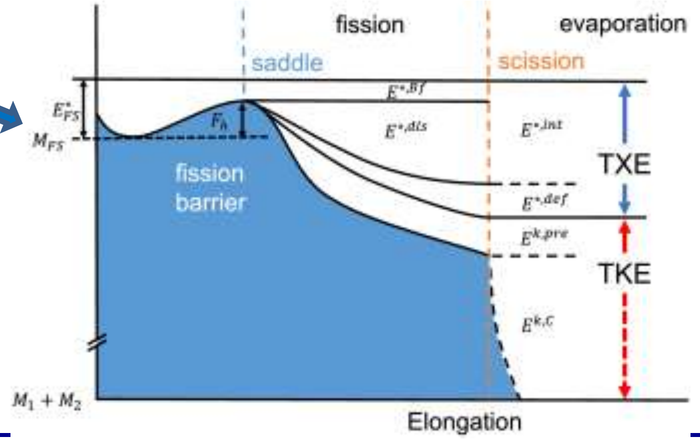
dynamics and yields distribution



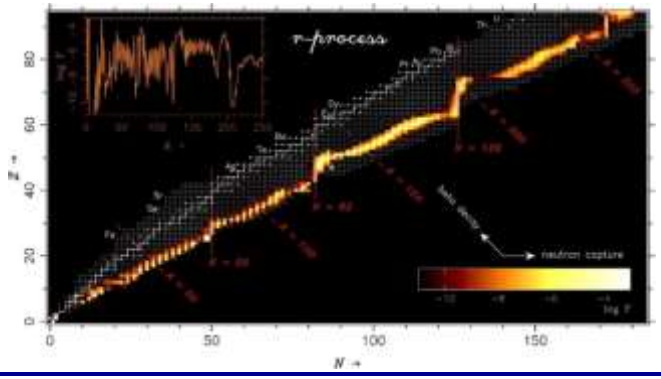
angular momentum generation and correlation



dissipation effects and energy distribution

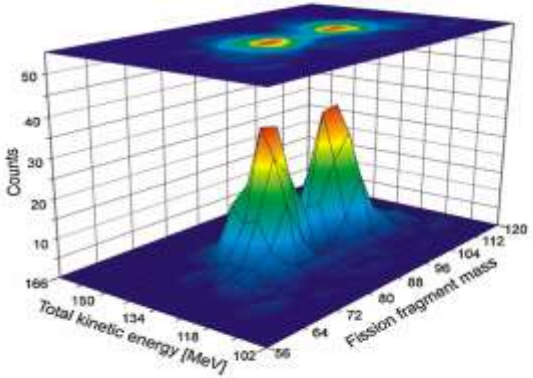


intersection with astrophysics



Progress in nuclear fission experiments (observations)

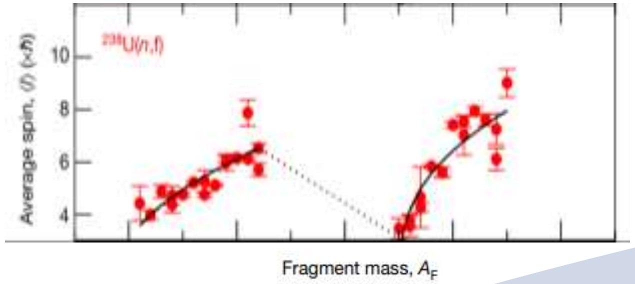
A. N. Andreyev *et al.* PRL 105, 252502(2010)



Novel asymmetric fission in the sub-lead region

2010

J. N. Wilson, *et al.*, Nature 590, 566 (2021)



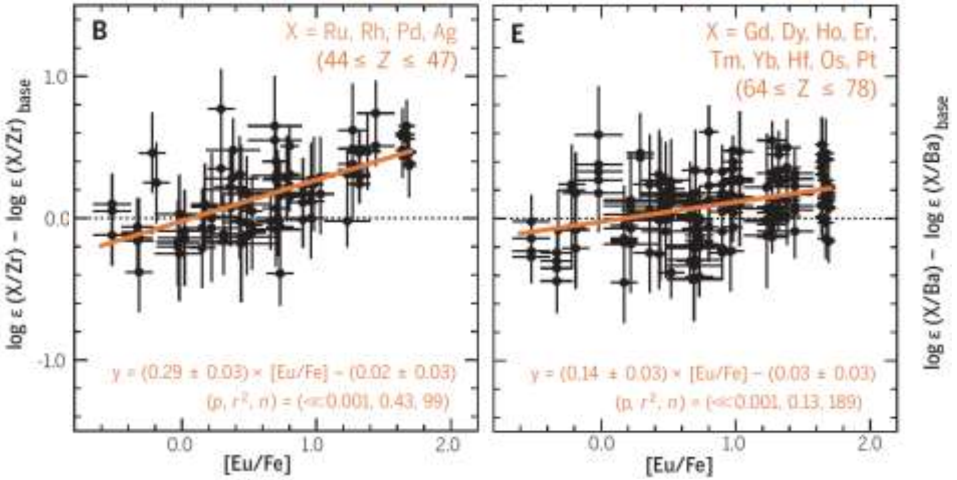
Fragments angular momentum

2021

2023

……

Roederer *et al.*, Science 382, 1177–1180(2023)



Fission of transuranic nuclei is involved in the r-process

Outline

1. Preface
2. **Fission model development**
3. Fission experiment research
4. Fission data evaluation
5. Summary

Advances in nuclear fission theory

Microscopic model

DFT+TDGCM、Generalized-TDGCM-GOA、TDDFT、TDHF、TDHFB、TDHF-BCS、ATDHFB、TDHF+FOA+PNP….

Macro-micro model

Finite Range LDM、WS-Model、LSD、Two Center SM、ISLD (isospin square dependent)、 …
+ Langevin approach、Random walk …

Statistical model

SPY、GEF、Hauser-Feshbach Model、Weisskopf-Ewing Evaporation Model、Statistical Scission-Point Model、Gaussian kernel estimation….

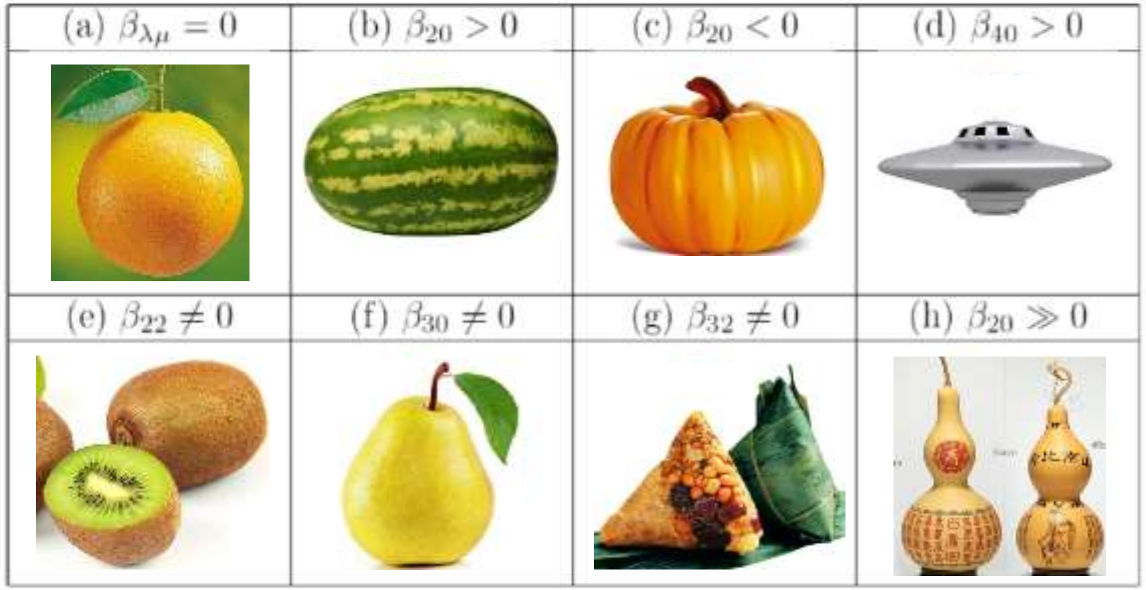
Machine learning

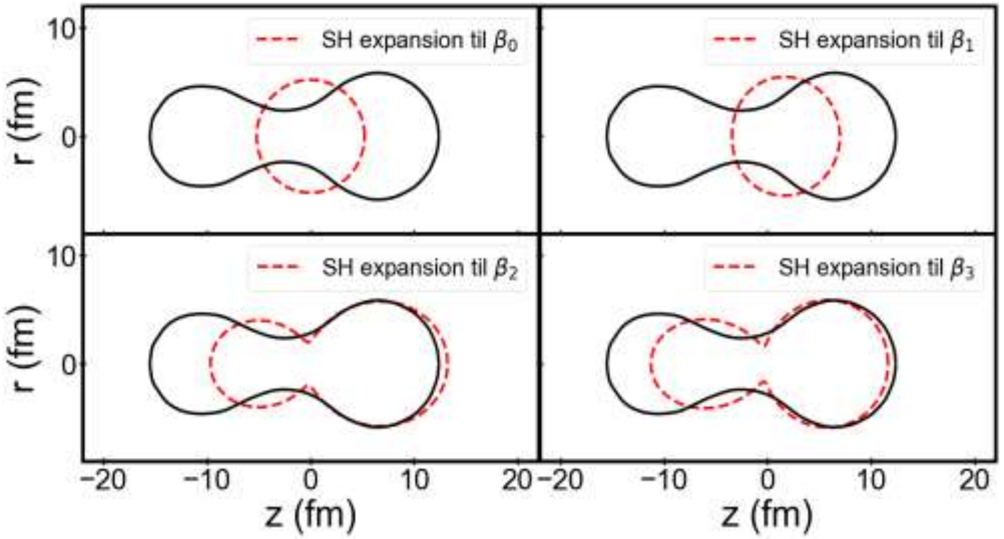
Based on the Bayesian Neural Network evaluation of fission data. etc

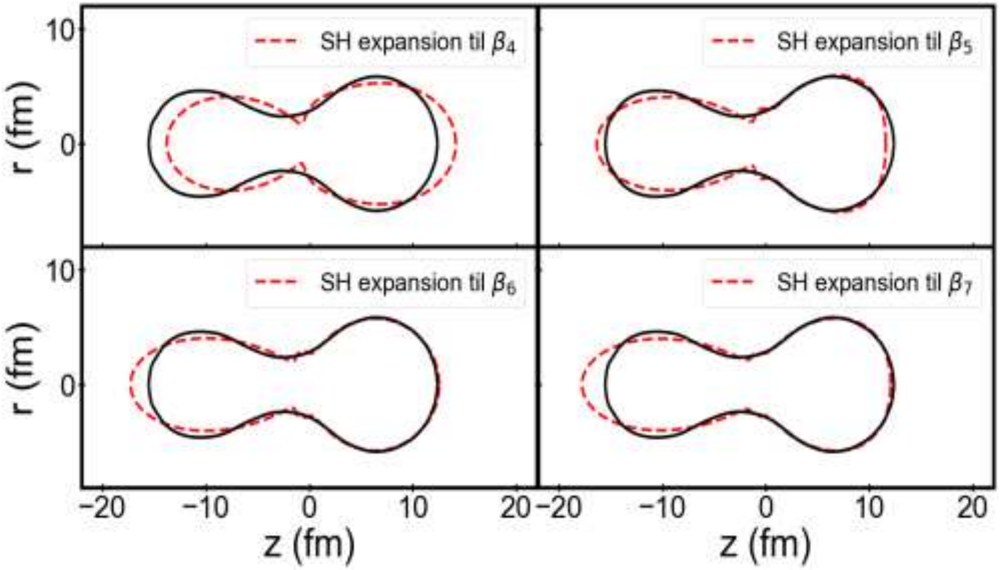
● Microscopic model:

Limitations of Spherical Harmonic expansions

$$R(\theta,\phi) = R_0\left(1+\beta_0+\sum_l\sum_m \beta_{lm}Y_{lm}(\theta,\phi)\right)$$

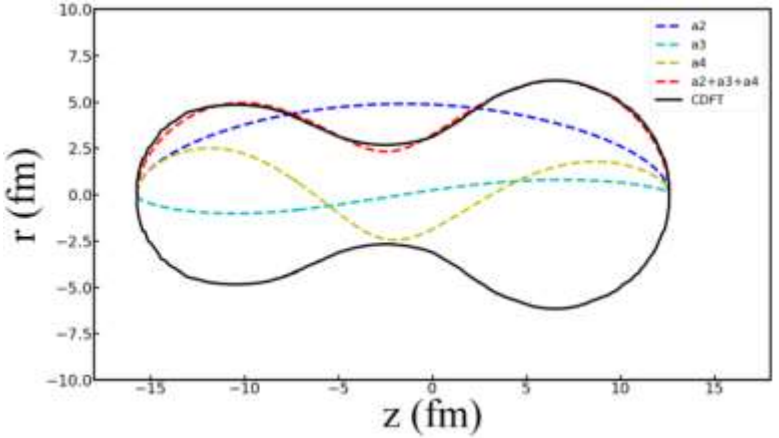




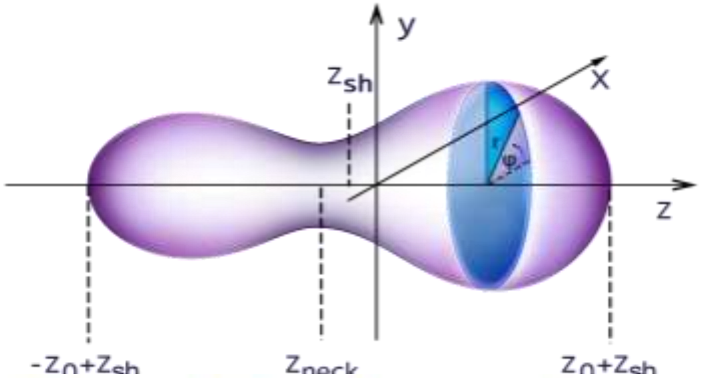


Spherical harmonic (SH) expansion of the nuclear shape is ideal for small to moderate deformations, it cannot characterize separated fragments in fission process.

Two-center harmonic oscillator basis introduced to optimize Dirac equation solutions, overcoming the inherent density mismatch between single-center deformed harmonic oscillator bases and two-body structures when describing large deformation configurations near scission points.



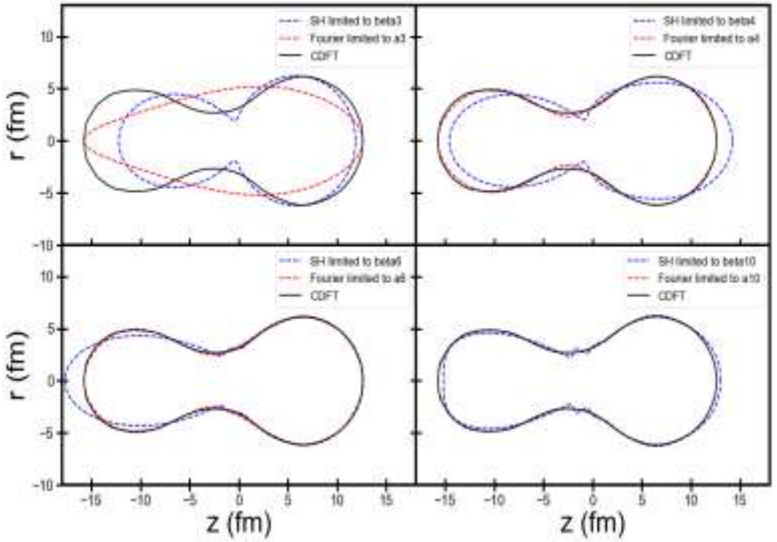
Fourier expansion of nuclear shapes introduced to improve the limitations of the spherical harmonic (SH) expansions for nuclear shape parameterization, when handling large deformation configurations in late-stage fission.



$$r^2(z) = R_0^2 \sum_{n=1}^{\infty} \left[a_{2n} \cos\left(\frac{(2n-1)\pi}{2} \frac{z - z_{sh}}{z_0} \right) + a_{2n+1} \sin\left(\frac{2n\pi}{2} \frac{z - z_{sh}}{z_0} \right) \right]$$

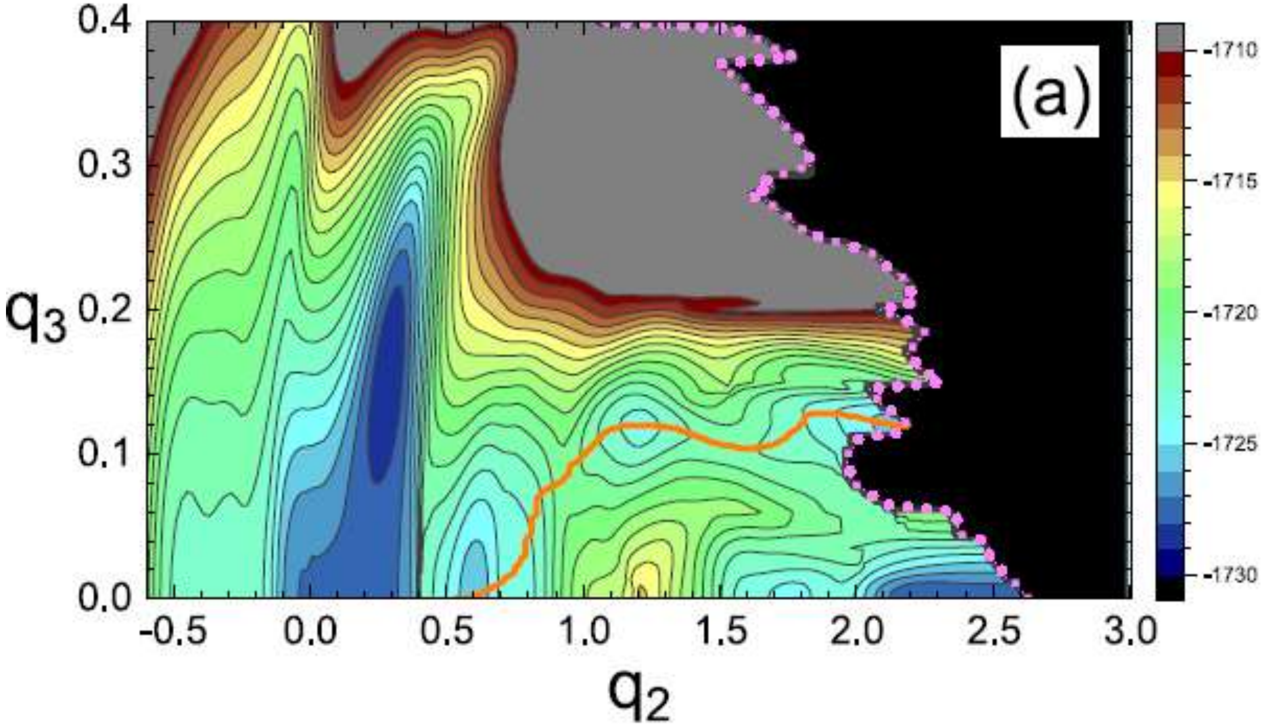
z_0 : Half length of atomic nucleus along z axis. z_{sh}: The geometric center along z axis

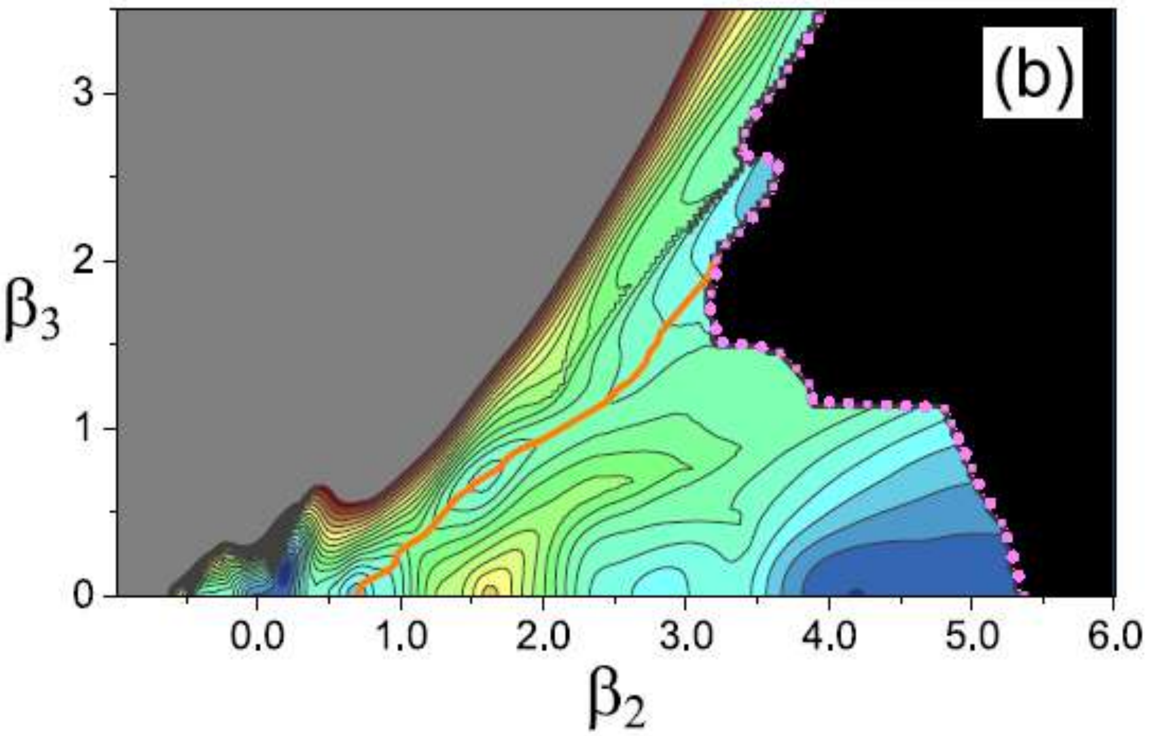
K. Pomorski, et al , Phys.Rev. C 101, 064602 (2020).



Fourier expansion

Spherical Harmonic expansions

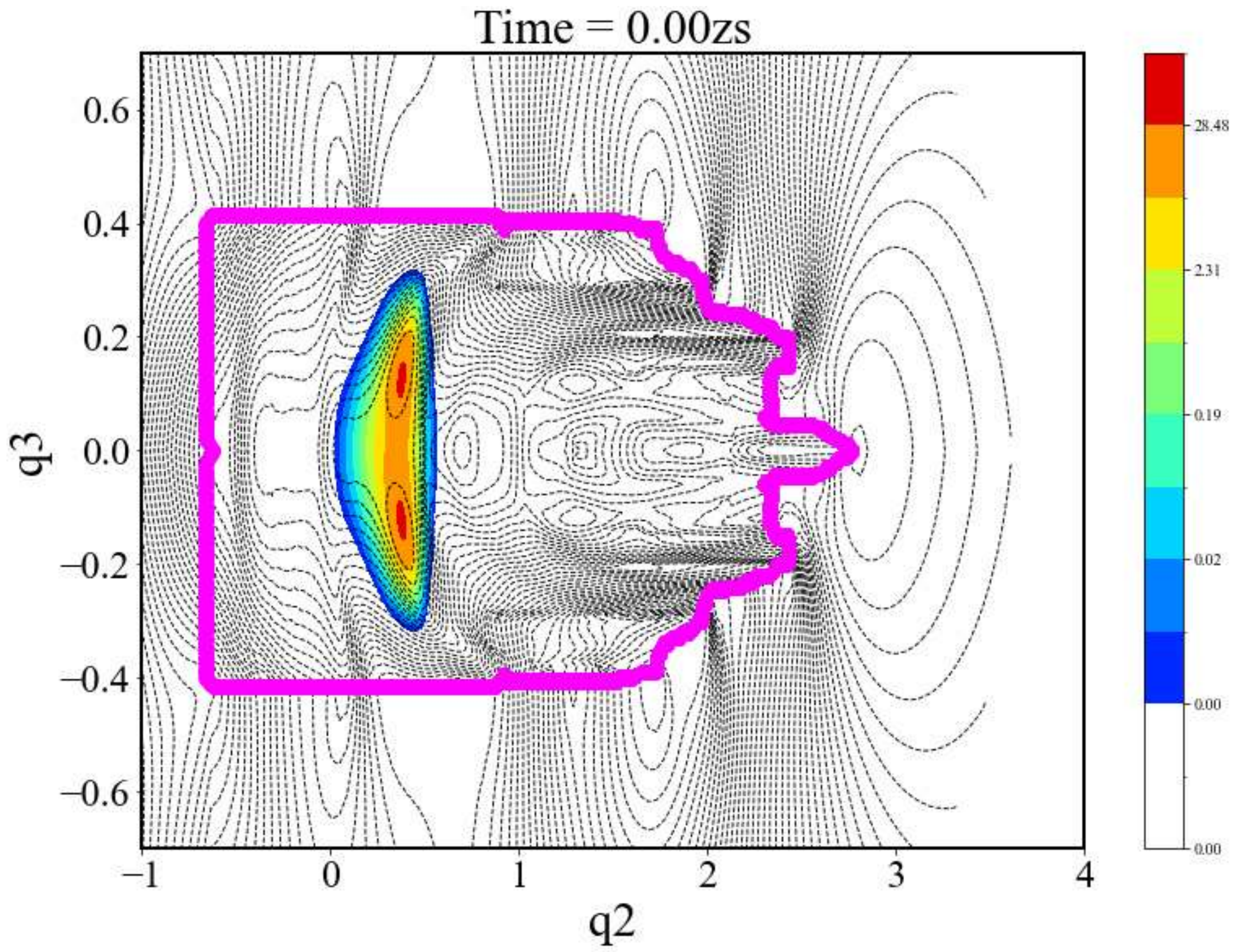




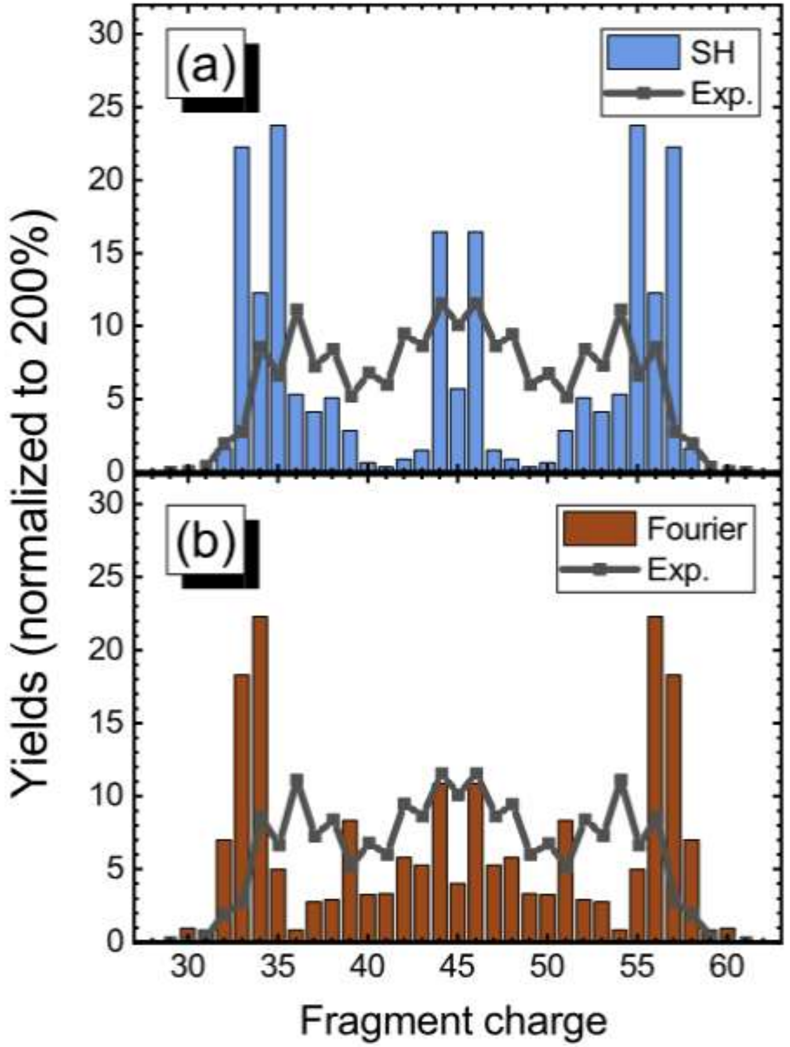
PESs of ^{226}Th

fission dynamics of ^{226}Th within the TDGCM framework

CNDC/CIAE

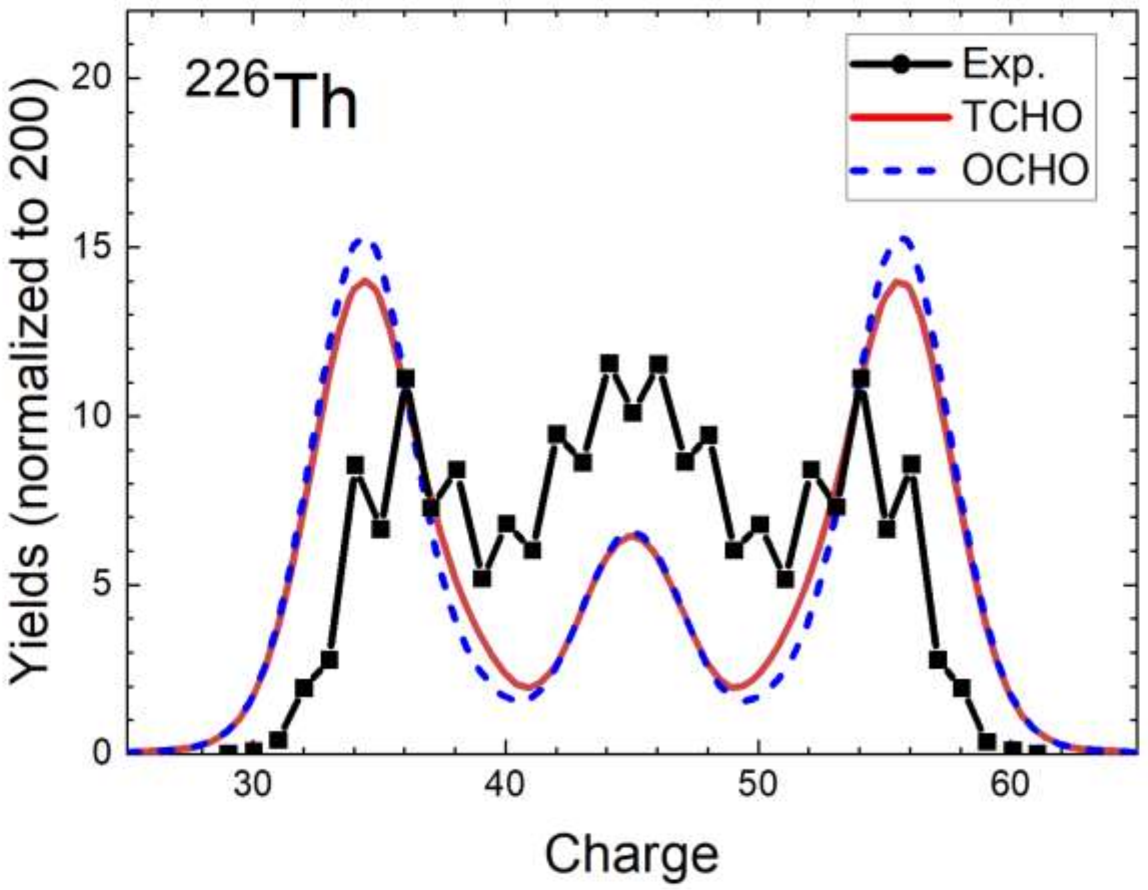


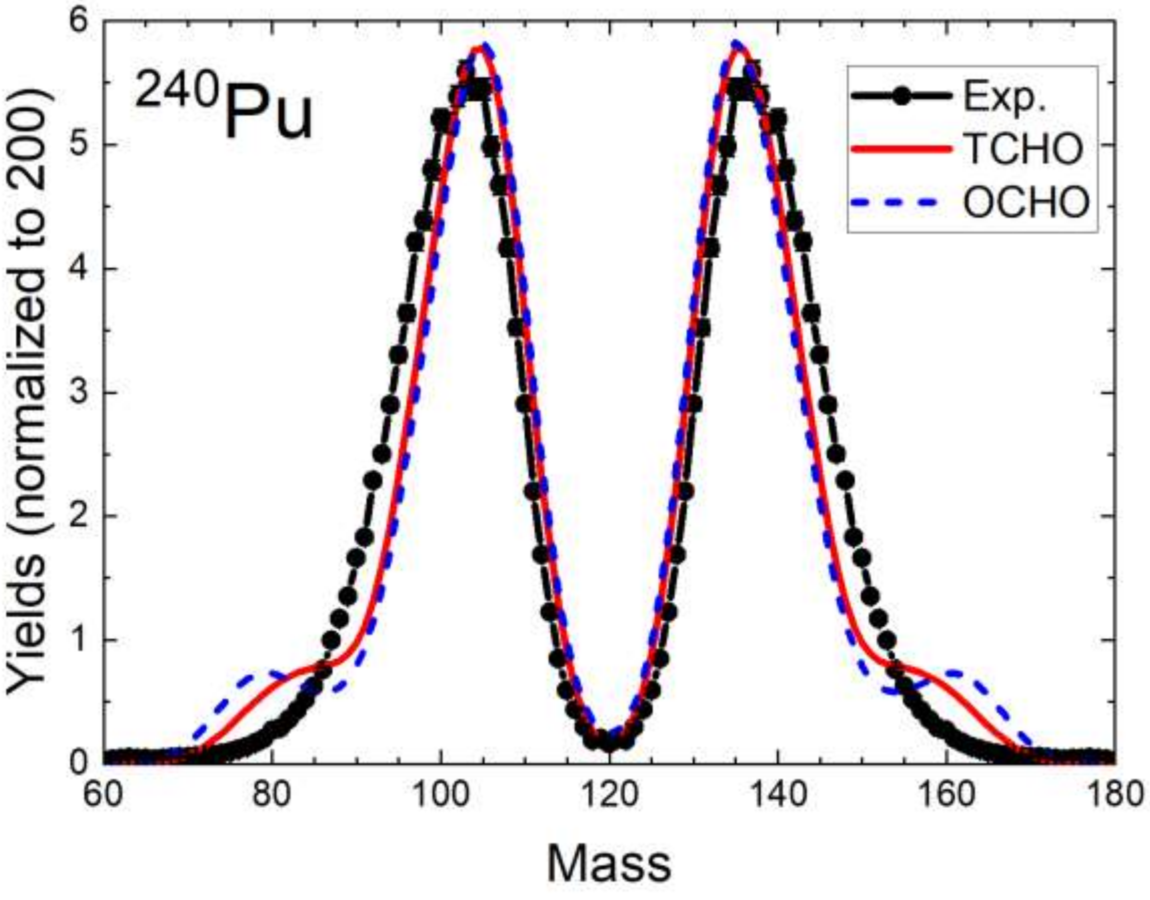
dynamic evolution of the collective wave function at different times



ZY Li, SY Chen,MH Zhou, et al , PRC109, 064310 (2024), *ZY Li, Y Su, LL LIU,YJ Chen, and ZP Li, PLB, 866 , 139509(2025)*

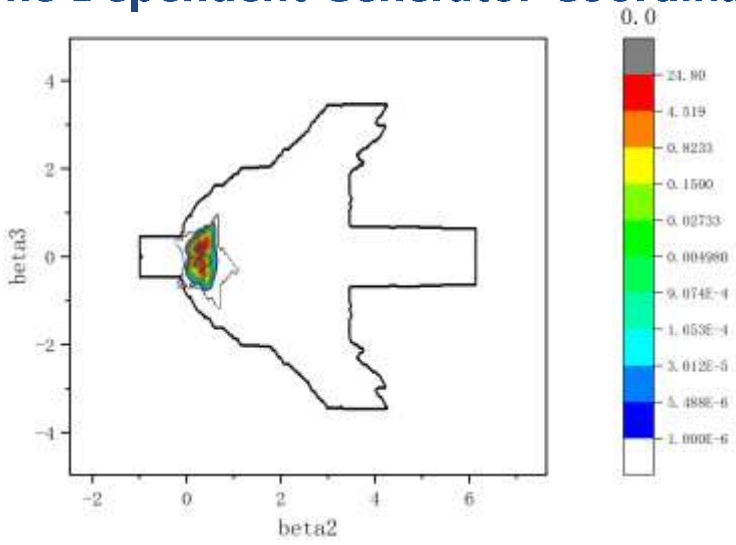
CNDC/CIAE

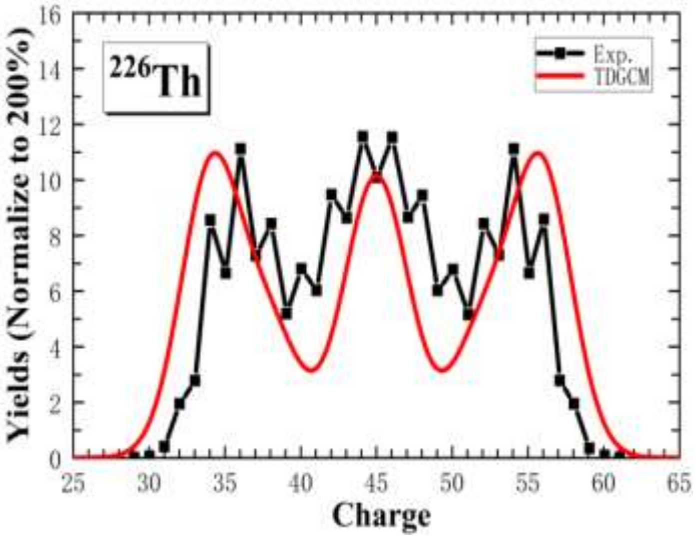

226Th
Exp.
TCHO
OCHO
Yields (normalized to 200)
Charge
0
5
10
15
20
30
40
50
60


240Pu
Exp.
TCHO
OCHO
Yields (normalized to 200)
Mass
0
1
2
3
4
5
6
60
80
100
120
140
160
180

Fission micro-dynamic Model

Time Dependent Generator Coordinates Method(TDGCM)：

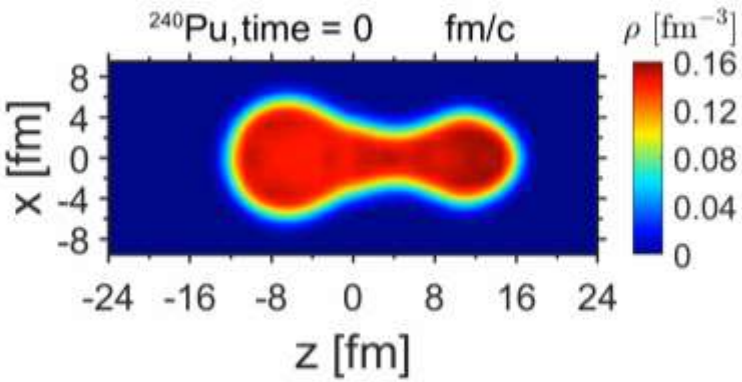


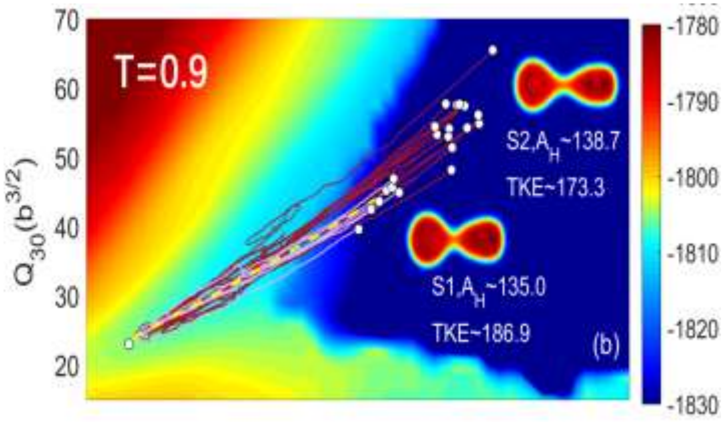


South West University

H. Tao, J. Zhao, Z. P. Li, et al , Phys. Rev. C 96, 024319,(2017).

Time Dependent Hartree-Fock + BCS (TDHF+BCS)



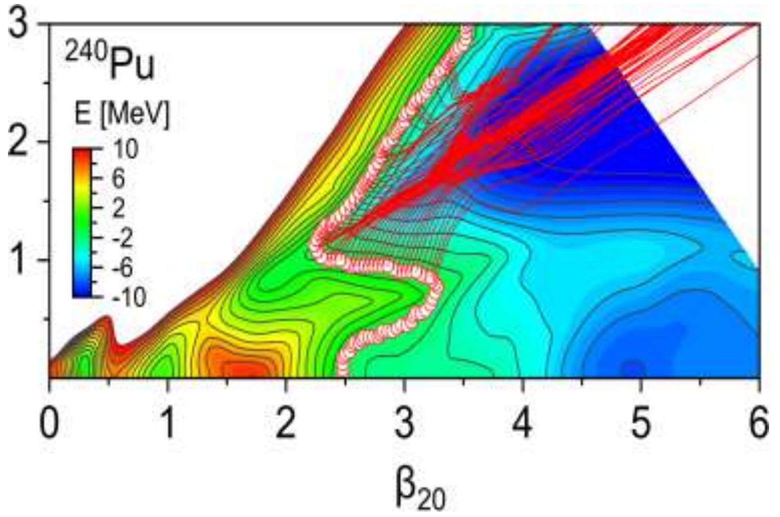


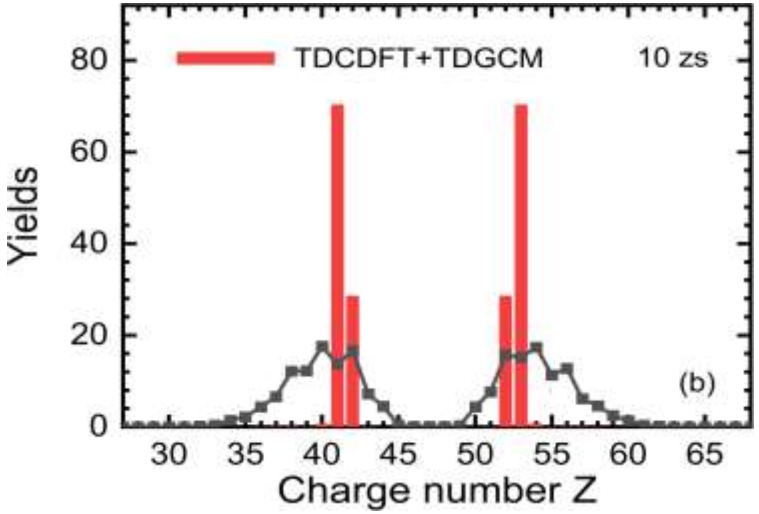
Peking University

Yu Qiang, J. C. Pei, et al, PRC 103, L031304 (2021)

Fission micro-dynamic Model

TDGCM + TDDFT

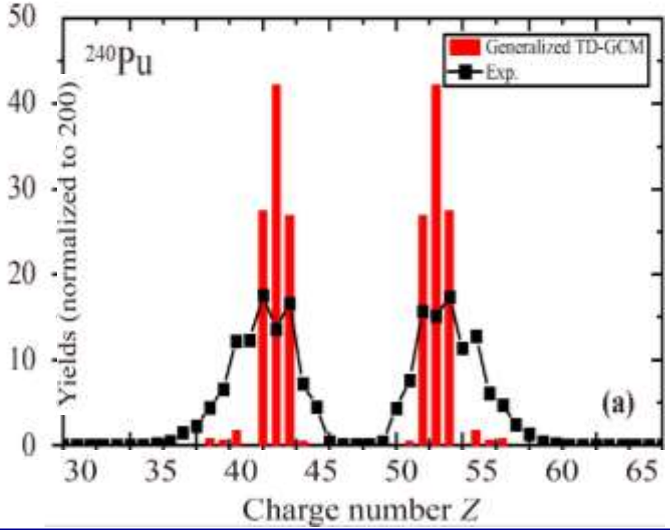


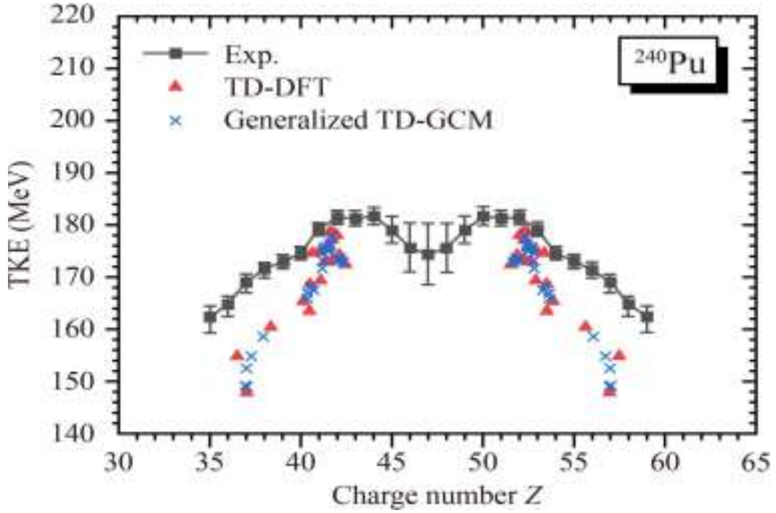


Peking University

ZX Ren , PW Zhao , et al,
PRC 105, 044313 (2022)

Generalized TDGCM





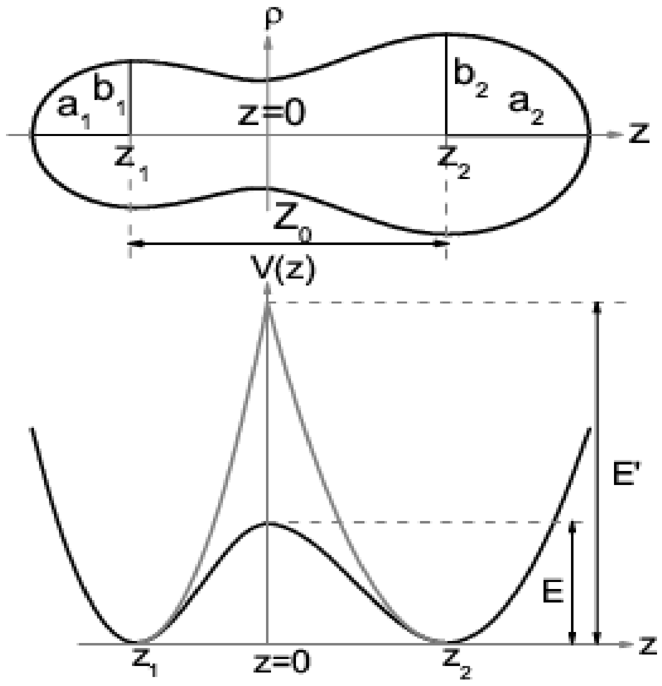
Peking University

Li B, Vretenar, Niksic, Zhao PW, et al
Front. Phys. 19, 44201 (2024)

● Macro-micro model

CNDC/CIAE

Nuclear shape described within the two-center shell model (TCSM)



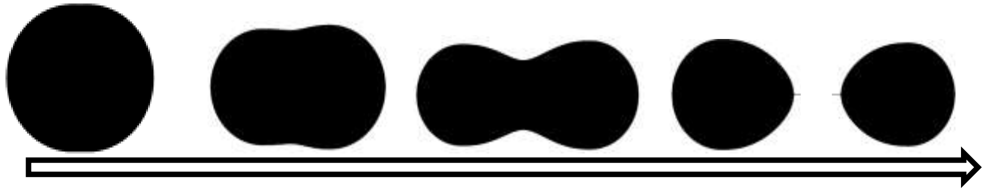
Shape parameters in the model:

The distance between two centers: $Z_0 = (Z_2 - Z_1) / R_0$

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

Fragment deformation: $\delta_i = \dfrac{3(\beta_i - 1)}{2\beta_i + 1}, \beta_i = \dfrac{a_i}{b_i}, i = 1, 2$

Neck parameter— ε=E/E'



Langevin: $\{q_i\}_{3D} = \{Z_0, \delta, \eta\}$

Langevin approach:

CNDC/CIAE

$$\begin{cases} \dfrac{dq_i}{dt} = \sum_j (m^{-1})_{ij} p_j \\ \dfrac{dp_i}{dt} = -\dfrac{\partial V(q,T)}{\partial q_i} - \dfrac{1}{2}\sum_{j,k} \dfrac{\partial (m^{-1})_{jk}}{\partial q_i} p_j p_k - \sum_j \gamma_{ij} \sum_k (m^{-1})_{jk} p_k + \sum_j g_{ij}\Gamma_j(t) \end{cases}$$

Generalized coordinate: $\{q_i\}=\{Z_0/R_0, \delta, \eta\}$ (TCSM)

Generalized momentum conjugate to q_i: p_i

Random force: $g_{ik} g_{jk} = \gamma_{ij} T^*$ (fluctuation-dissipation theorem)

$\langle \Gamma_i(t) \rangle = 0, \langle \Gamma_i(t_1)\Gamma_j(t_2) \rangle = 2\delta_{ij}\delta(t_1 - t_2)$ (white noise)

Intrinsic excitation energy: $E_{int}(q) = E^* - V(q) - E_{coll}(q) - E_{evap}(t)$

The charge and TXE partition:

CNDC/CIAE

- **The charge partition** for a given fragment mass using the Wahl systematics

$$P(Z_f|A_f) \propto exp[\frac{-(Z_f - \bar{Z}_f(A_f))^2}{2\sigma_z^2}] \qquad (\bar{Z}_f(A_f) = \frac{Z_{CN}}{A_{CN}} A_f + \Delta Z)$$

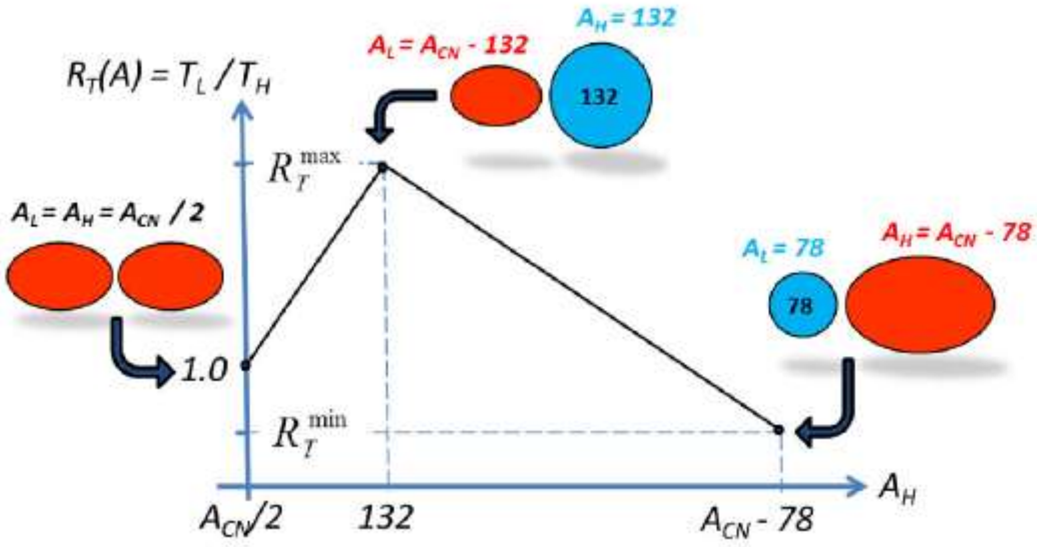
- **The TXE partition** using R_T method

$$\mathrm{TXE} = [E^* + M(A_p, Z_p)c^2 - M(A_L, Z_L)c^2 - M(A_H, Z_H)c^2] - \mathrm{TKE}\,(A, Z)$$

$$R_T = \frac{T_l}{T_h} = \sqrt{\frac{U_l}{U_h}\frac{a_h(U_h)}{a_l(U_l)}}$$

$$a = \tilde{a}\{1 + \frac{\delta W}{U}(1 - e^{-\gamma U})\}$$

$(U_i = E^*_i - \Delta_i,\ i = L, H)$



Eur. Phys. J. A (2015) 51;177

The Weisskopf method:

The emission probability of the neutron with the kinetic energy ε_n for a fragment with an excitation energy E^*_M is given by the Weisskopf formula:

$$\Gamma_n(\varepsilon_n) = \frac{2\mu}{\pi^2\hbar^2\rho_M(E^*_M)}\int_0^{\varepsilon_n}\sigma_{inv}(\varepsilon)\varepsilon\rho_D(E^*_D)d\varepsilon$$

$$\rho(E) = \frac{\sqrt{\pi}exp(2\sqrt{aU})}{12a^{\frac{1}{4}}U^{\frac{5}{4}}}$$

The maximum energy of the emitted neutron: $\varepsilon_n^{max} = E^*_M - B_n$

The excitation energy of the residual nucleus after emitting a neutron with ε_n:

$$E^*_D = \varepsilon_n^{max} - \varepsilon_n$$

In this work, the competition between the neutron and gamma emission is not taken into account.

results

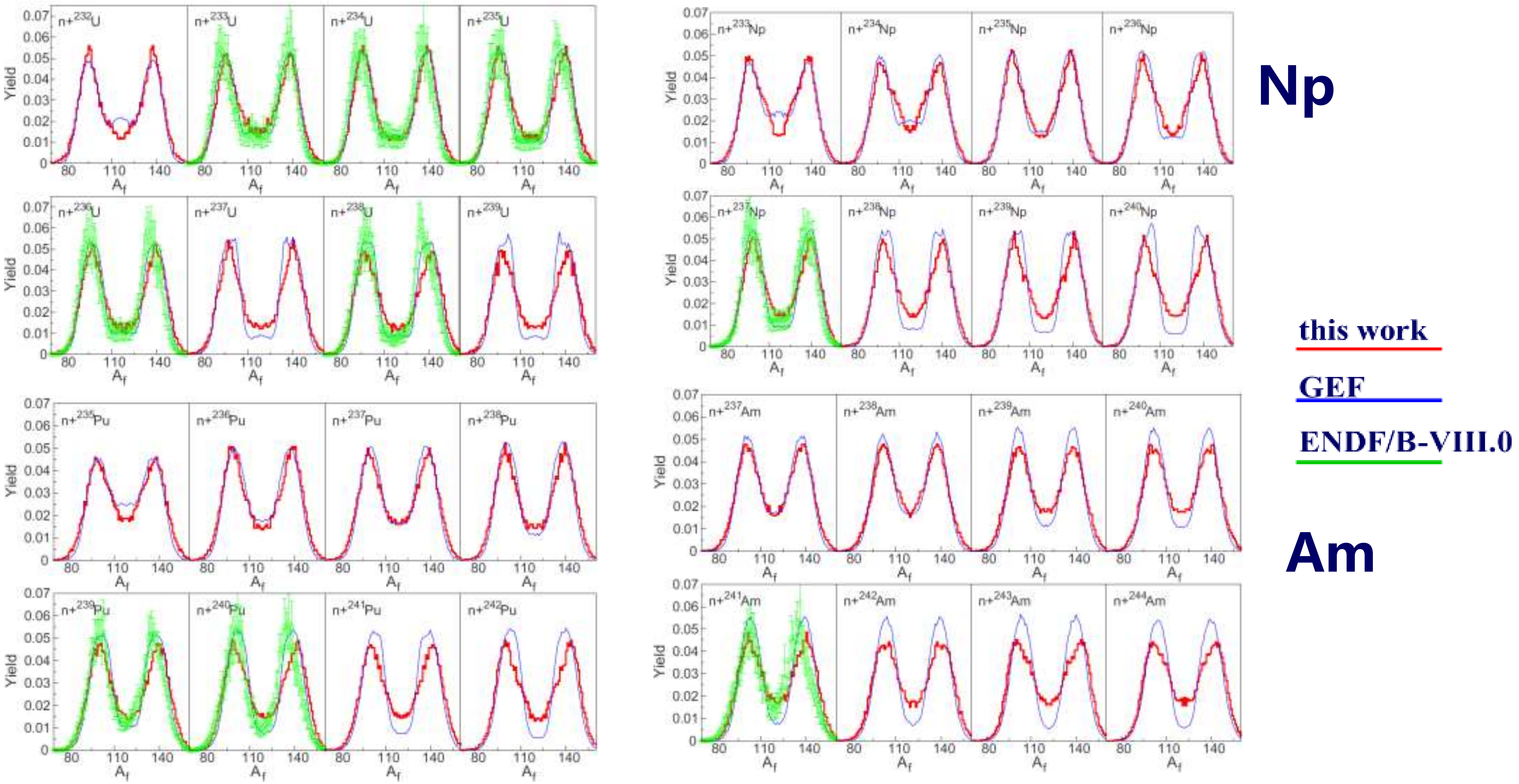
the calculated FFMD (pre-n) of 14 MeV neutron induced actinide fission

U

Np

Pu

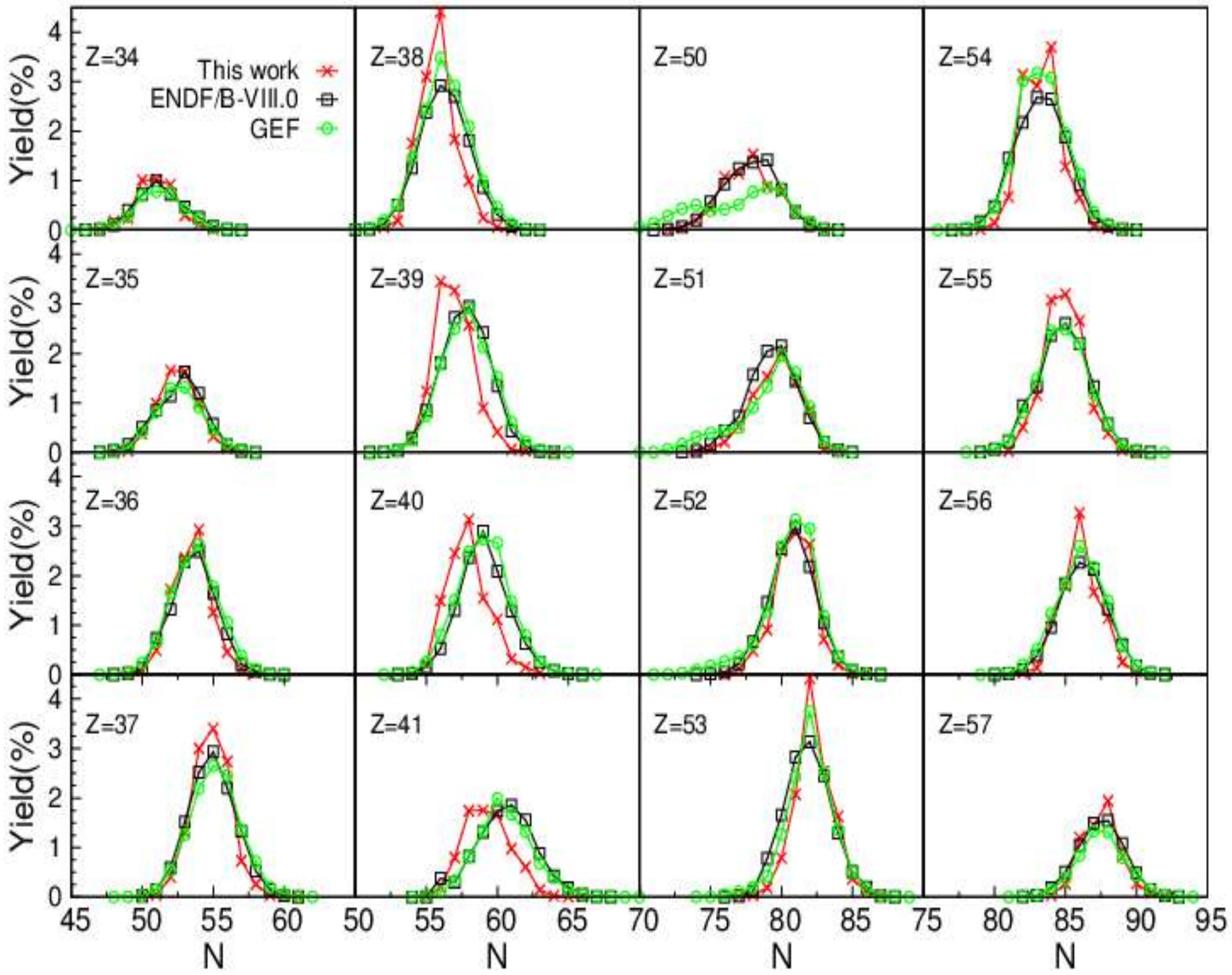
Am

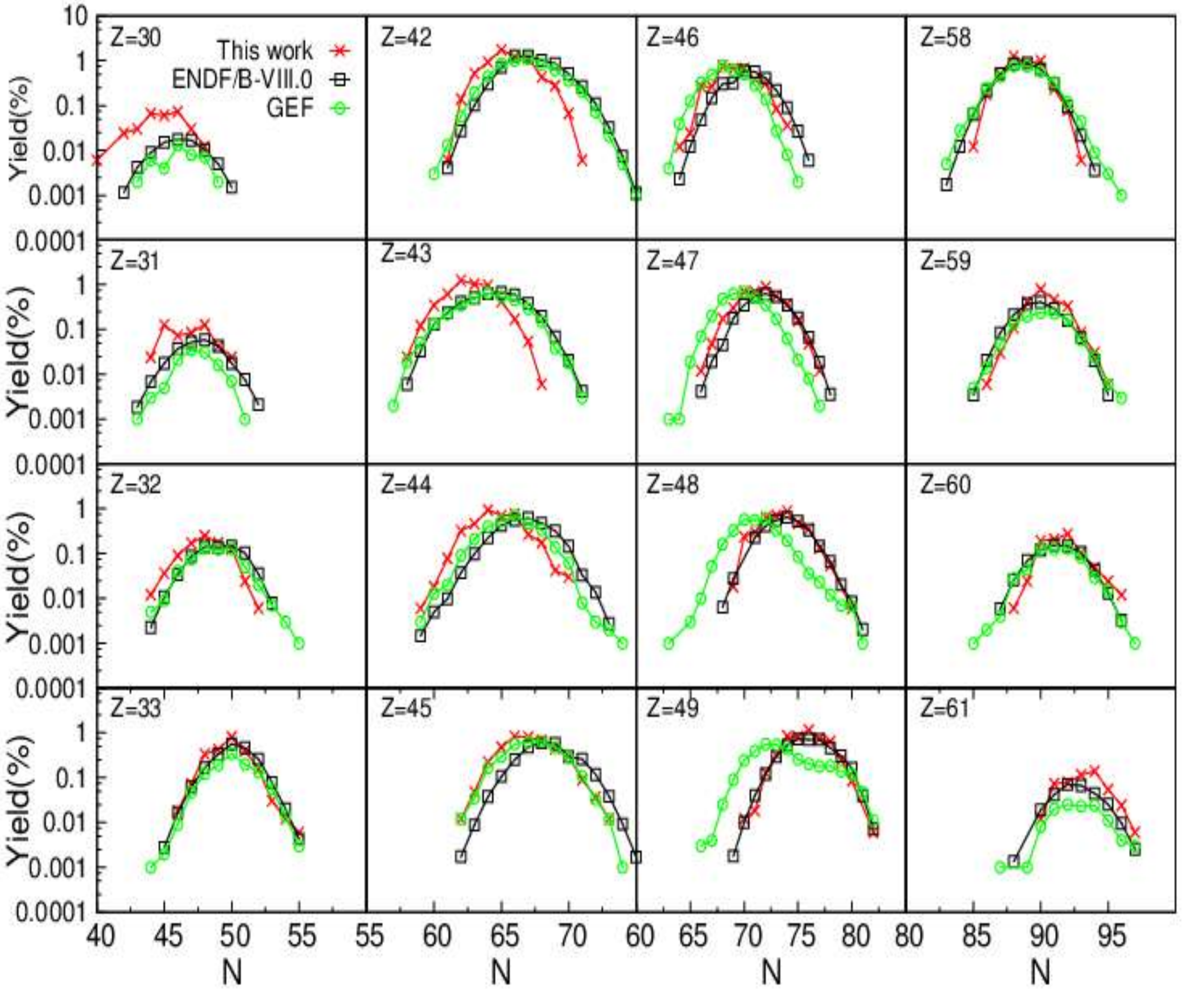


Li-Le Liu,Xi-Zhen Wu, Yong-Jing Chen, et al, Phys. Rev. C 99,044614 (2019), Phys. Rev. C 105,034614 (2022)

results

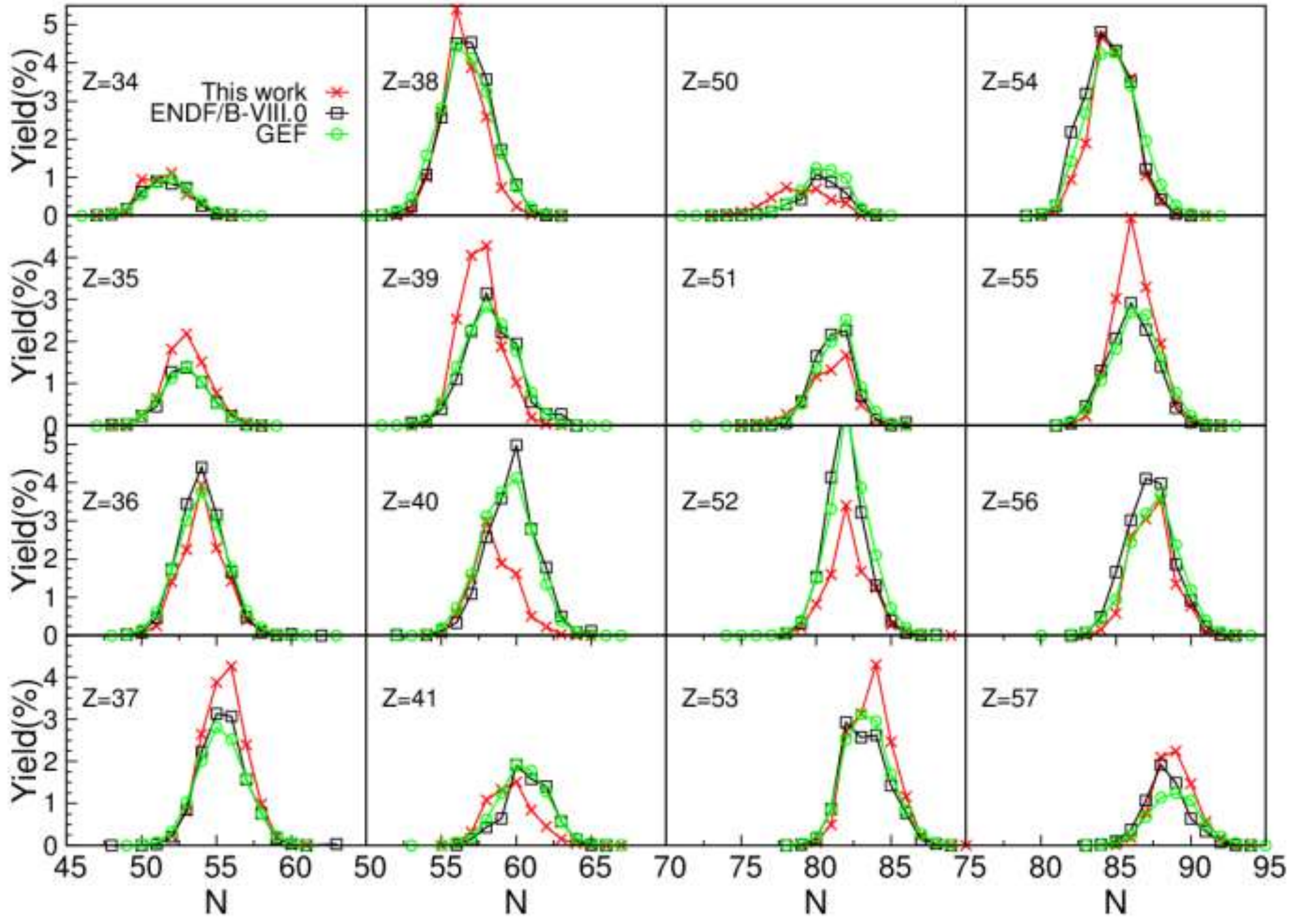
The independent yields of fission products (Z=34-61) in 14 MeV n+^{235}U:

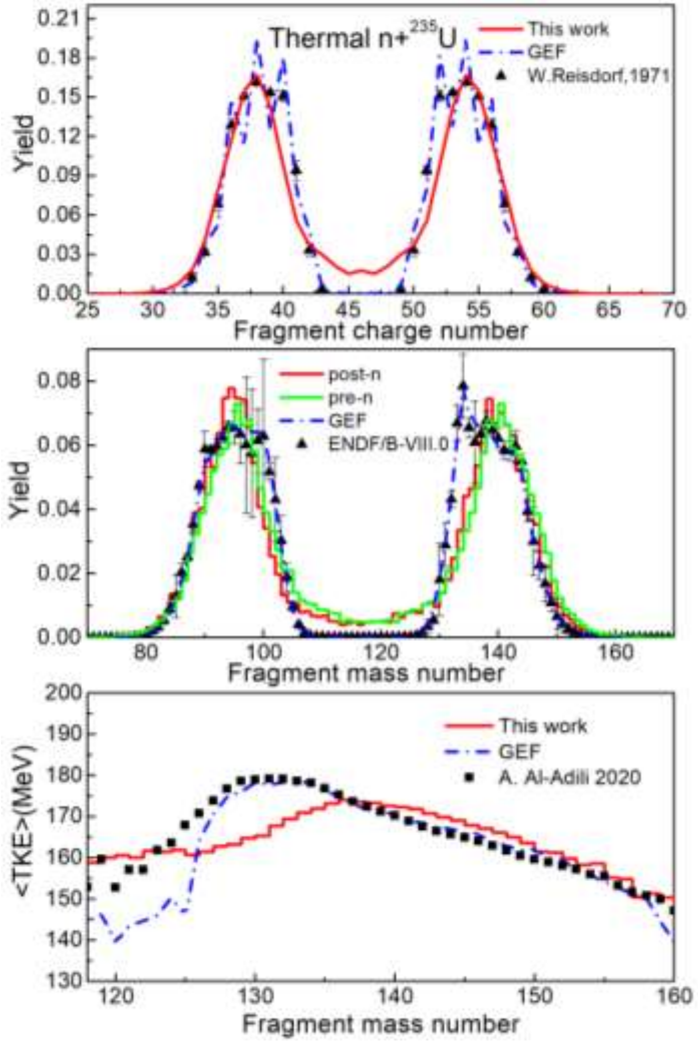




results

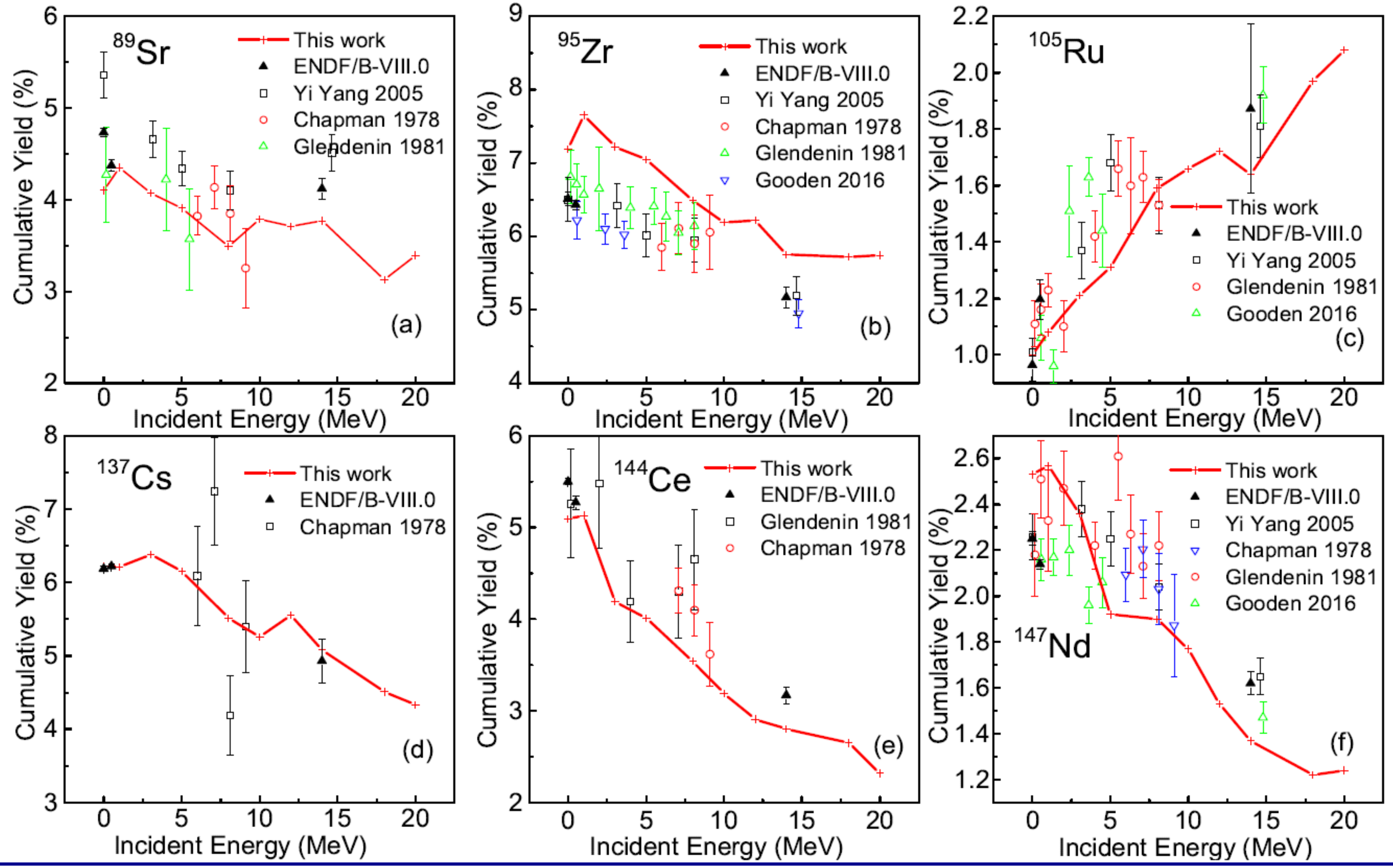
The distributions of fission fragment mass, charge, TKE and independent yields in thermal n+^{235}U:





results

The cumulative fission yield as a function of incident energy in ^{235}U(n, f) for select isotopes

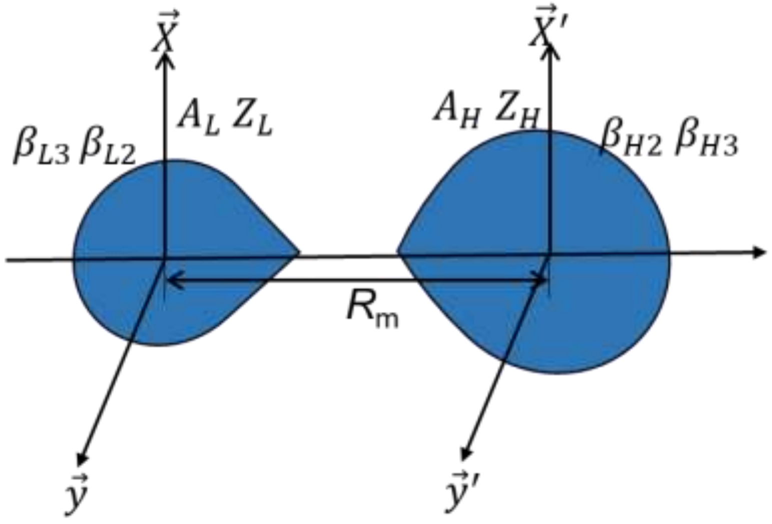


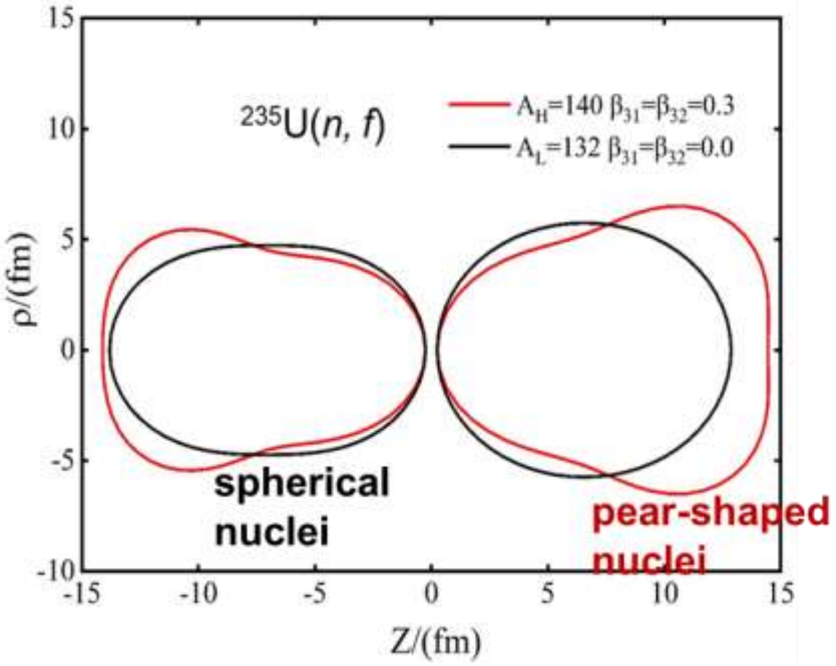
Statistical model

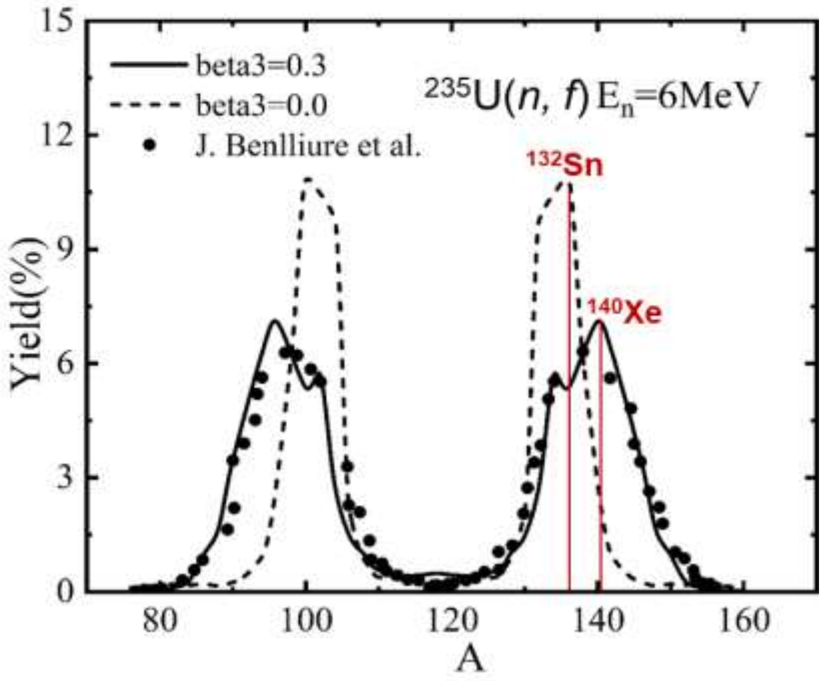
Lanzhou University

Scission point Model

The scission point model is improved by considering the octupole deformations of the fission fragments



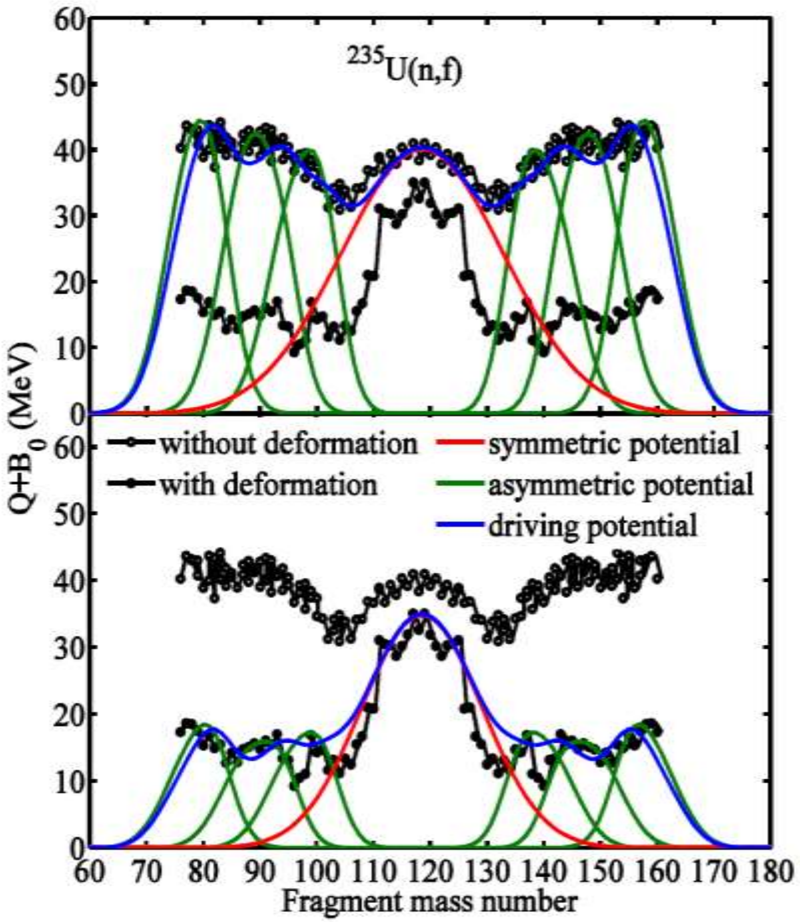




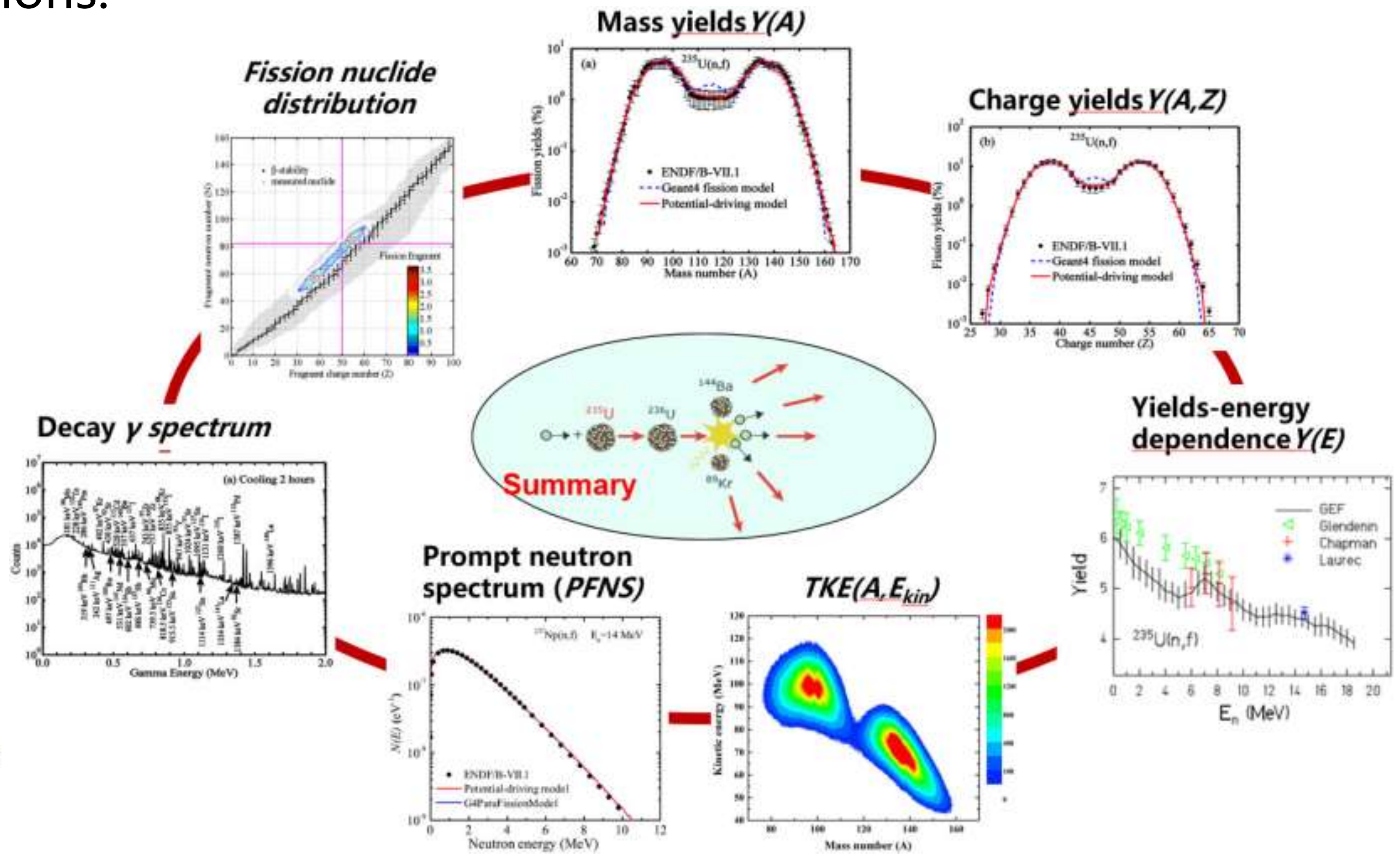
The improved scission point model can accurately calculate the mass distributions of neutron-induced actinides fission with low incident neutron energy.

Potential-driving Model （Lanzhou University)

develop the Potential-driving Model，and Implanted this model in M-C code(Geant4) to describe the FFs distributions.



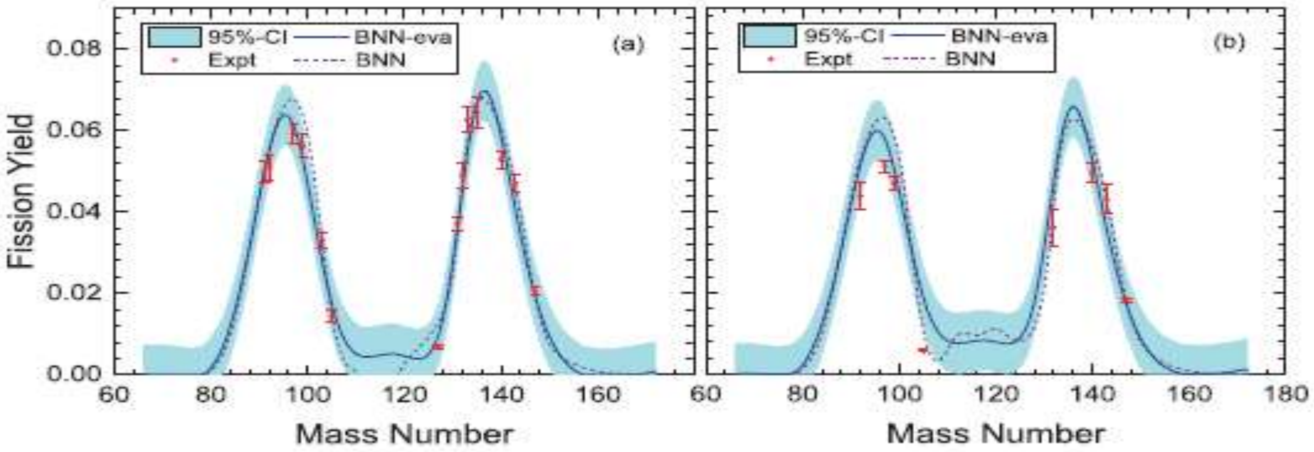
The fission potential energy of ^{235}U(*n, f*).

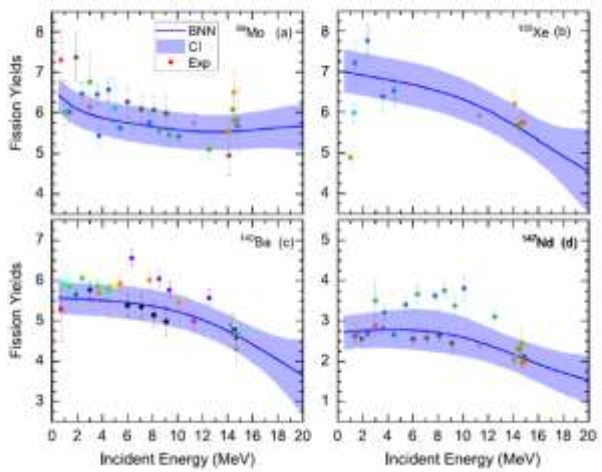


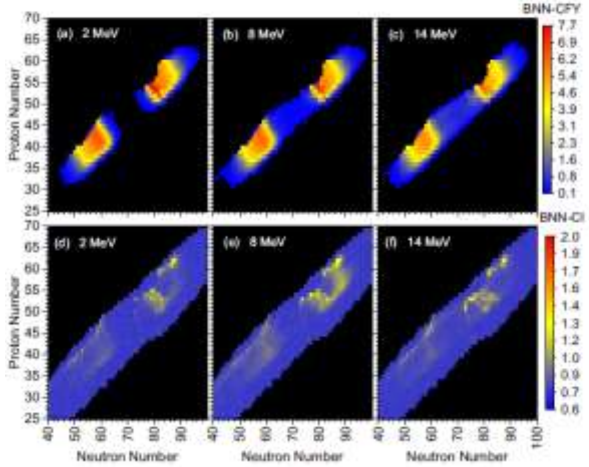
● Machine learning

Peking University, Sun Yat-Sen University, CNDC/CIAE,…

Bayesian Neural Network evaluation of incomplete fission yields

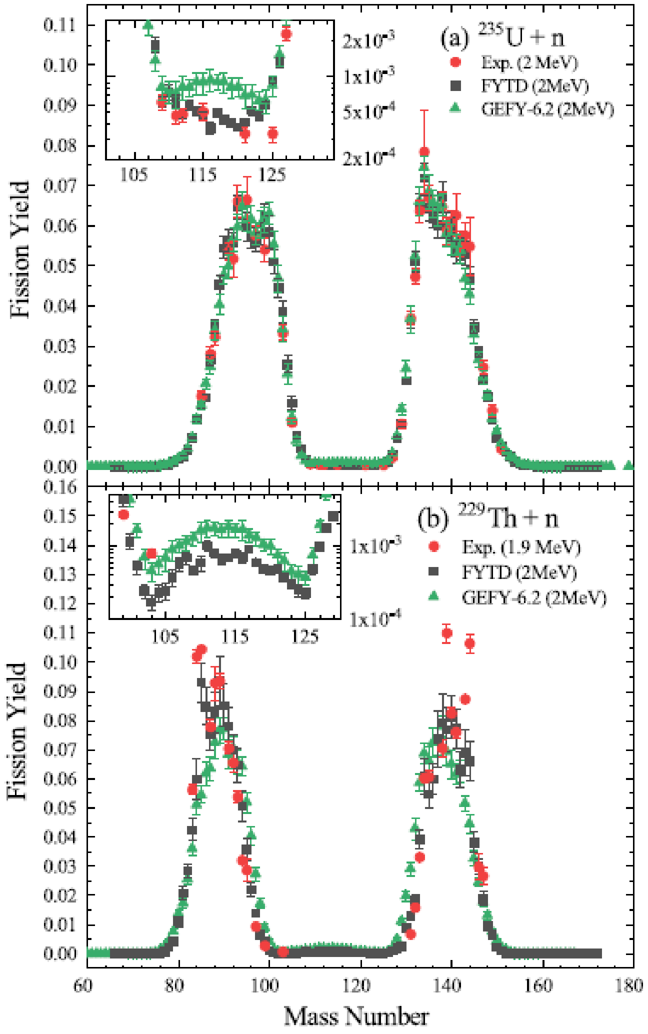






Z.A.Wang,J.C.Pei,Y.Liu,Y.Qiang, PRL.123(12),122501(2019),
Z.A.Wang,J.C.Pei,Y.J.Chen,C.Y.Qiao,F.R.Xu,Z.G.Ge, et al, PRC 106, L021304 (2022)

Fission yield tensor decomposition



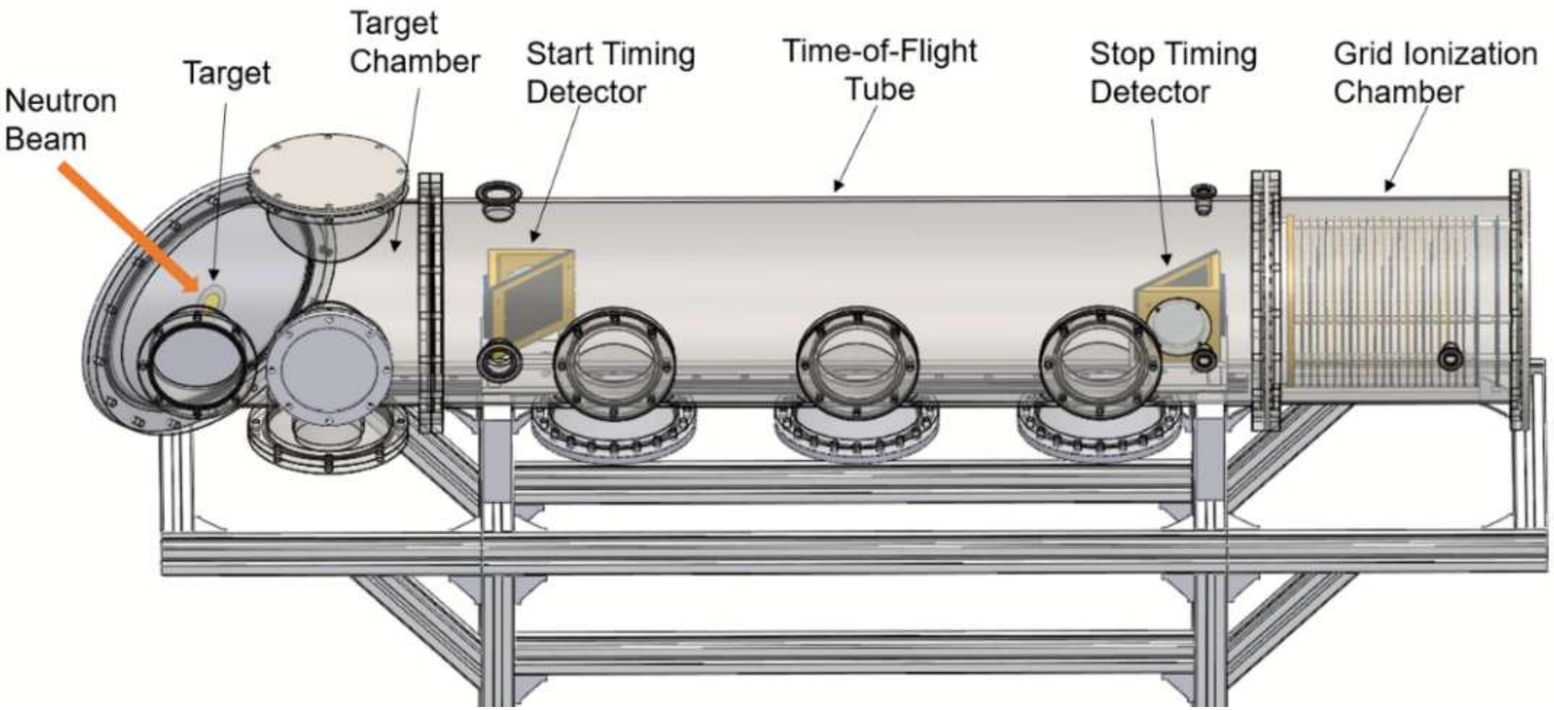
Q.F. Song, L. Zhu, B.S. Cai, et al., PRC107, 044609(2023)

Outline

Energy-velocity（E-v）method

CNDC/CIAE

Fission Fragment Identification Spectrometer



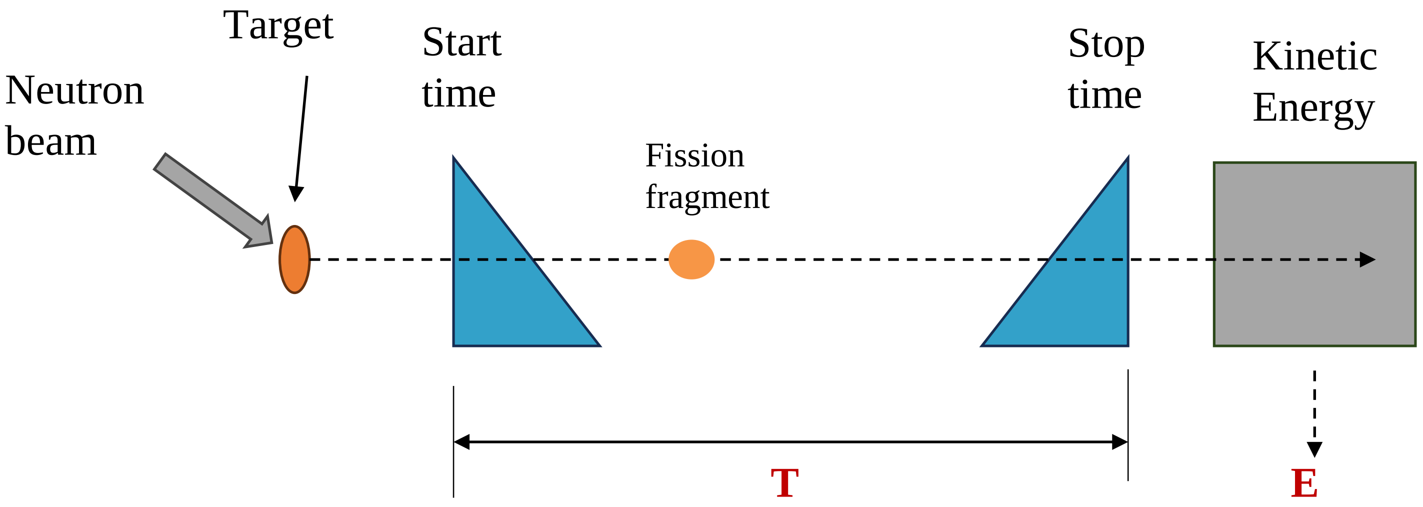
Kinetic energy: Frish Grid Ionization Chamber
Time-of-Flight: micro-channel plates (MCP) timing detector ×2
Flight path length： ~1 m, ΔL < 1 mm

Energy-velocity （E-v） method

- ✓ event-by-event, capable of systematic measurements using white neutrons
- ✓ high mass resolution
- × low detection efficiency
- × need charge identification

$$M = 2E\left(\frac{T}{L}\right)^2$$

$$\frac{\Delta A}{A} = \sqrt{\left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta T}{T}\right)^2 + \left(2\frac{\Delta L}{L}\right)^2}$$



$\Delta A \sim 1$ amu ⇔

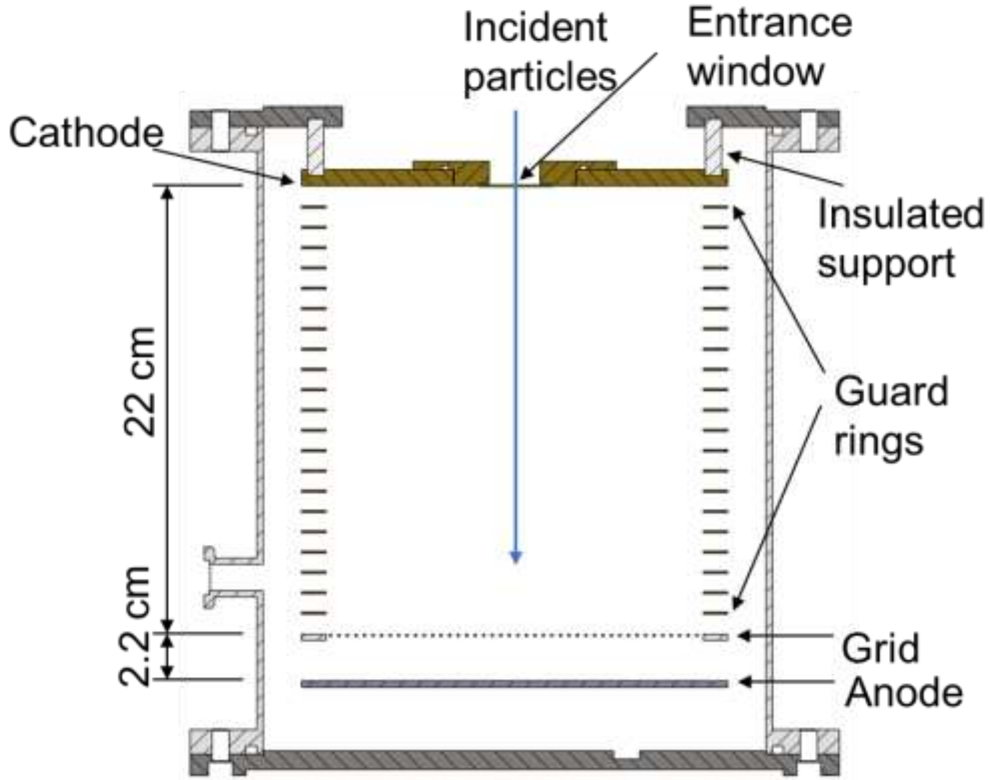
$$\frac{\Delta E}{E} \leq 0.7\ \%$$

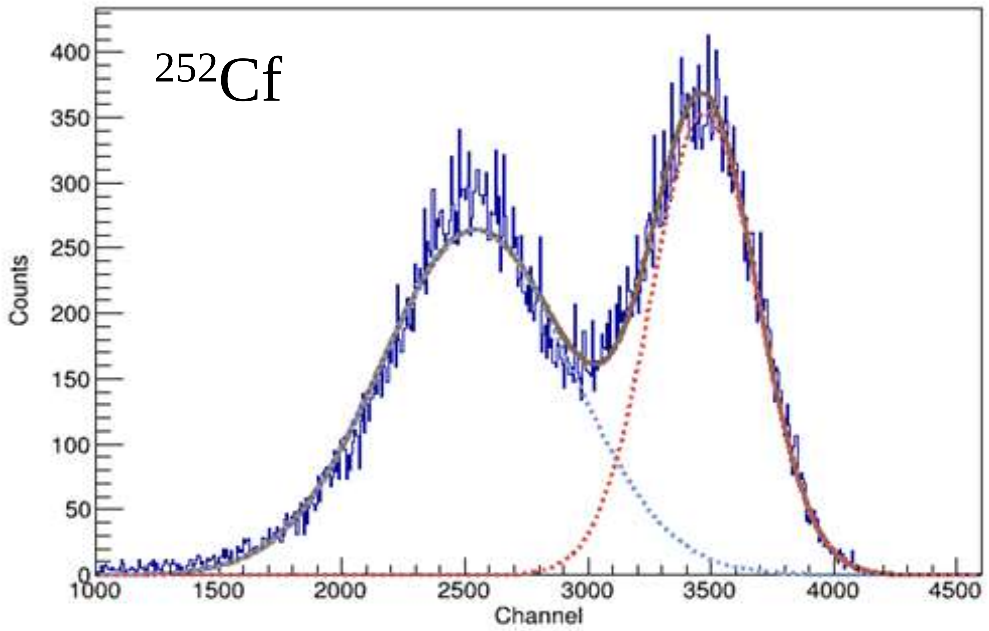
$$\frac{\Delta T}{T} \leq 0.3\ \%$$

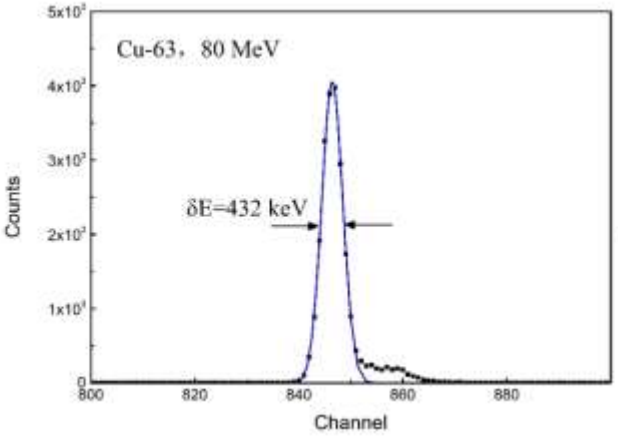
$$\frac{\Delta L}{L} \leq 0.2\ \%$$

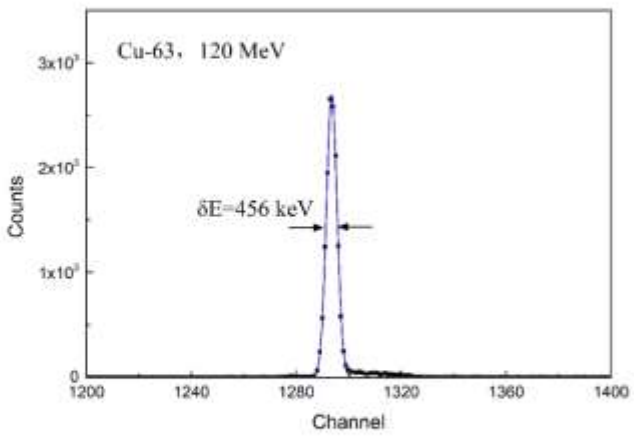
Kinetic energy measurement:

- axial grid ionization chamber with potential particle identification
- thin entrance window: 100 nm Si_3N_4
- low gas pressure: C_4H_{10}, 5300 Pa





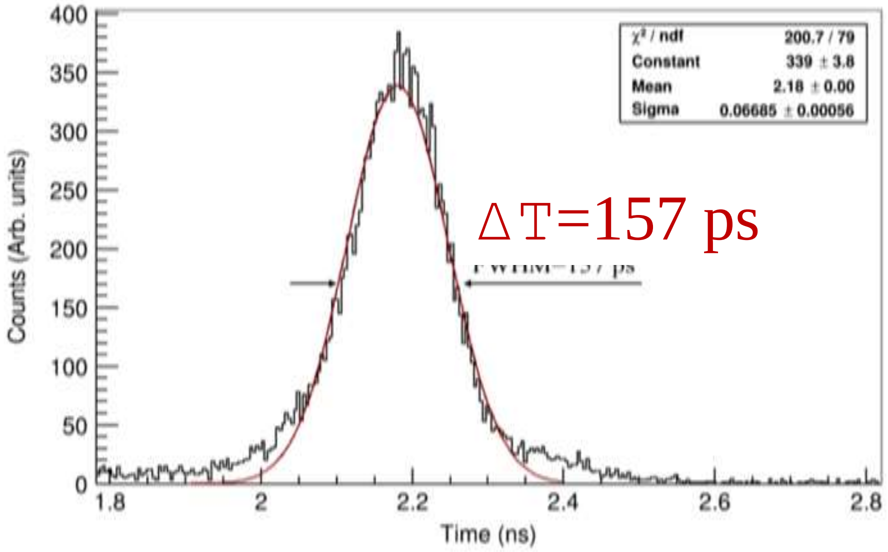


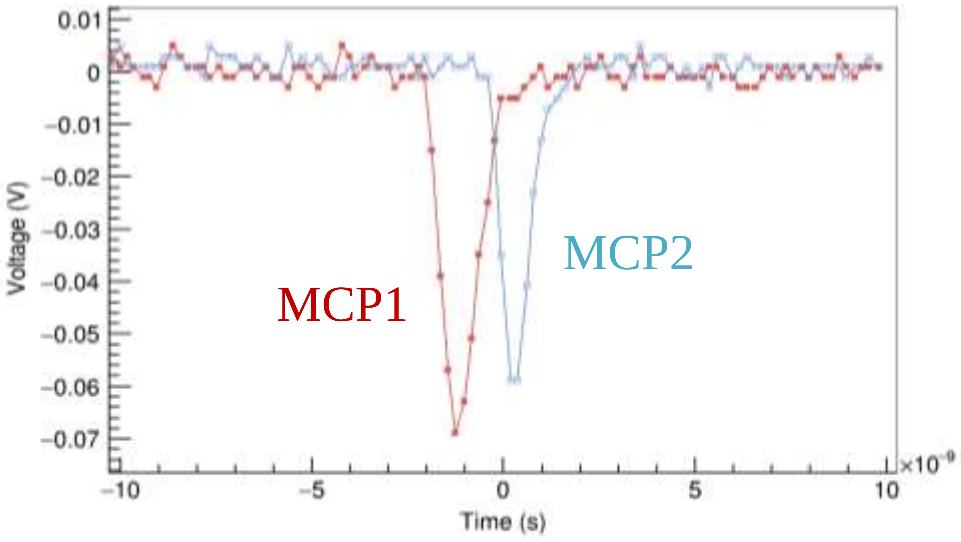


✓ ΔE/E ~0.54%

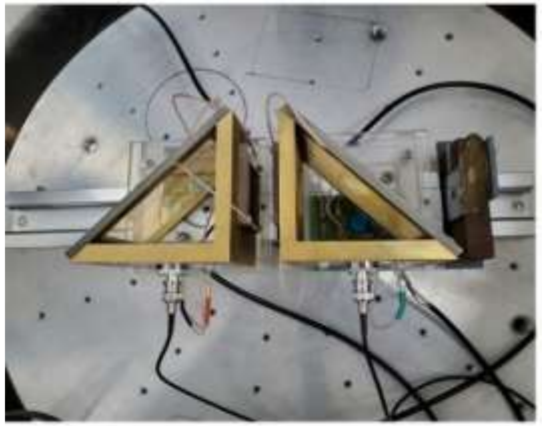
0.7 %

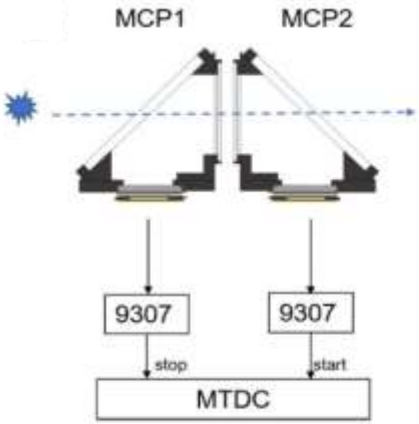
Time-of-Flight measurement:

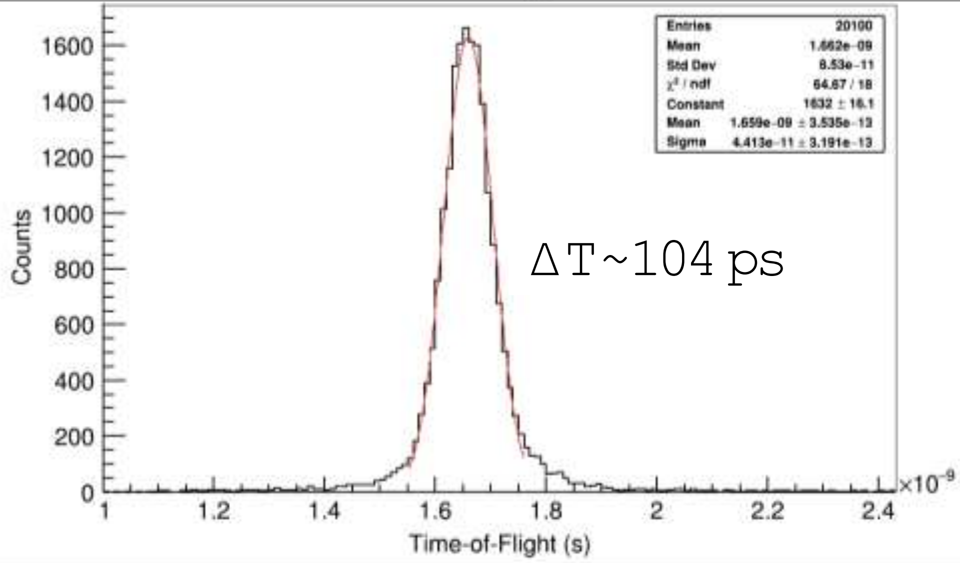




✓ ΔT/T ~ 0.2% @ LF   0.3 %

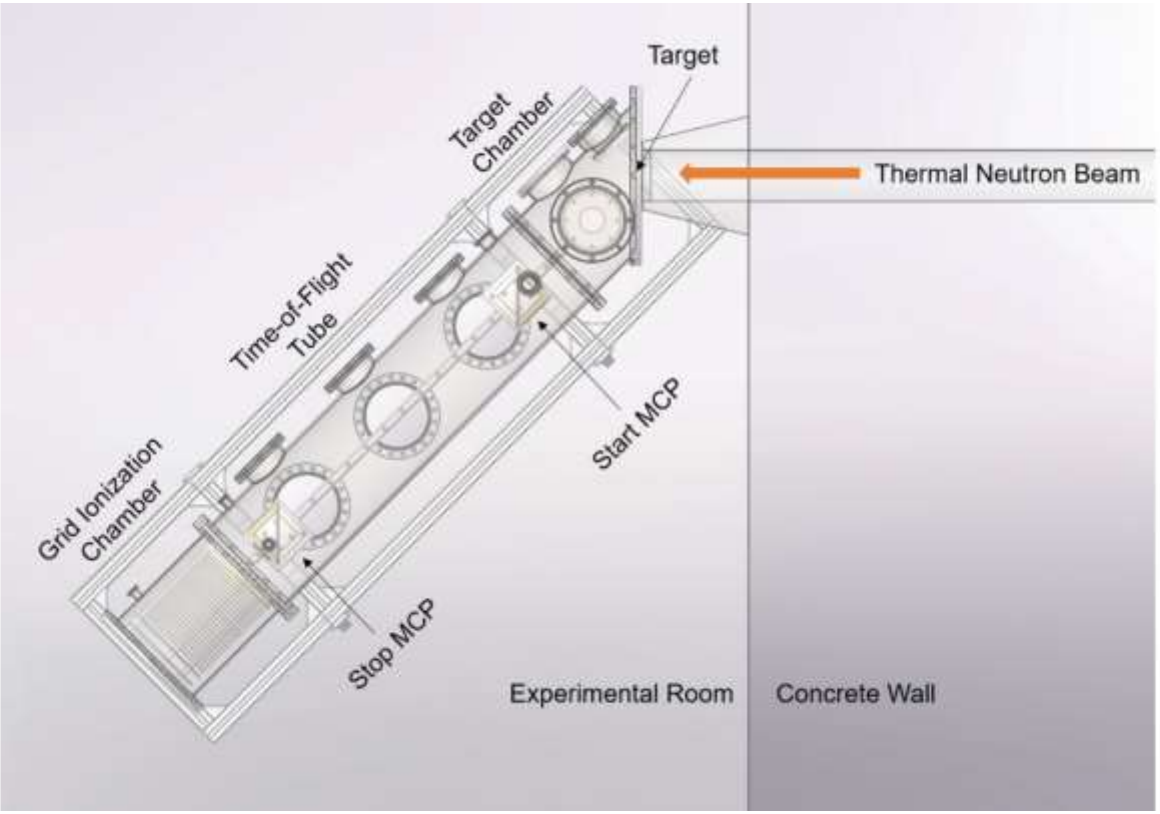




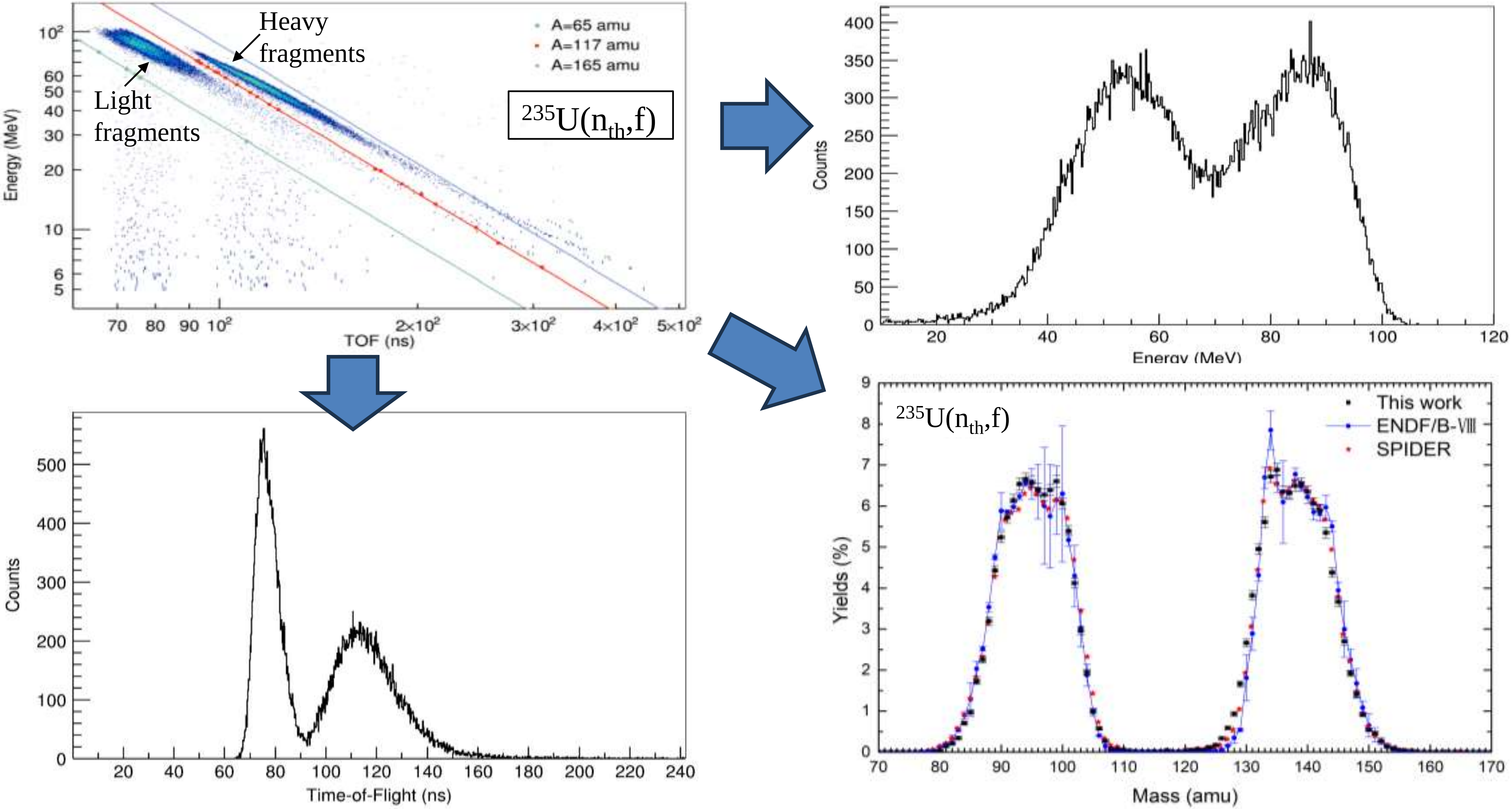


improved Δ *T* with digital timing technique

Experimental setup



- In-Hospital Neutron Irradiator (IHNI) — reactor designed for BNCT
- thermal-neutron beam: $\Phi(n_{th})$=1.92E9 $cm^{-2}s^{-1}$
- Flight path length: 100.45 cm


Heavy fragments
Light fragments
A=65 amu
A=117 amu
A=165 amu
$^{235}U(n_{th},f)$
Energy (MeV)
TOF (ns)
Counts
Energy (MeV)
Counts
Time-of-Flight (ns)
$^{235}U(n_{th},f)$
This work
ENDF/B-Ⅷ
SPIDER
Yields (%)
Mass (amu)

Determination of charge distribution

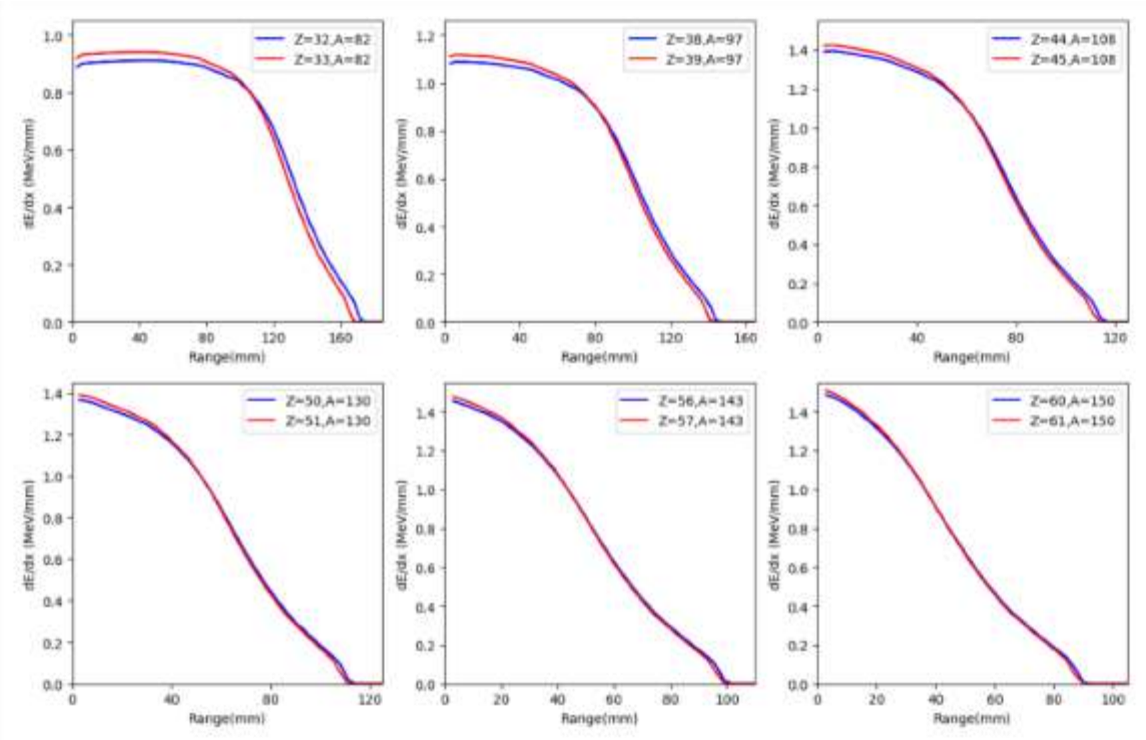
Fragment charge identification is always challenging!

× many kinds of fission fragments

× low fragment energy: mostly **< 1 MeV/u**

LF

HF



Methods:

(1) specific energy loss

$$\Delta E \cdot E \propto MZ^2$$

(2) characteristic X-ray

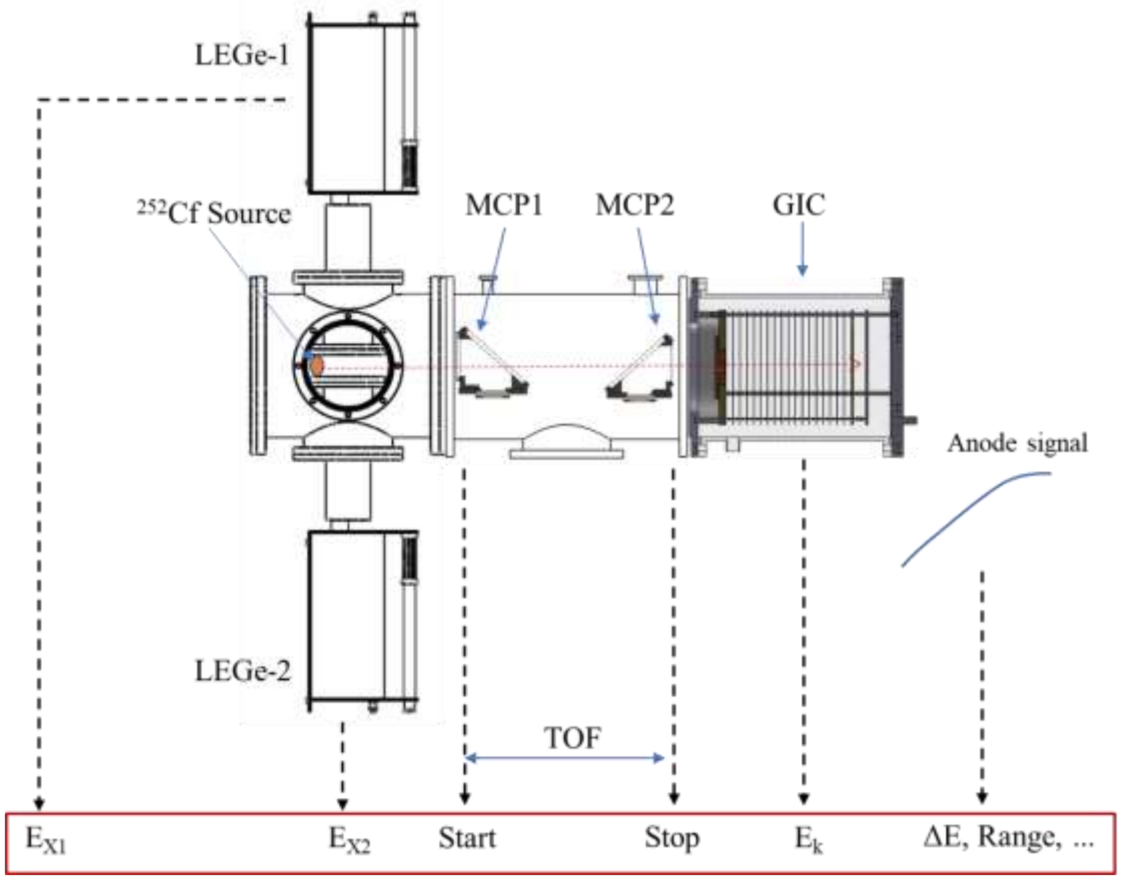
$$Z = a\sqrt{E_X} + b$$

Can we combine these two methods to improve charge resolution?

Multi-parameter charge identification:

- ✓ fragment E-v-E_X-ΔE in coincidence
- ✓ test with ^{252}Cf(sf)

1) **Mass: E-v correlation;**
2) **ΔE extraction: GIC anode signal waveform analysis;**
3) **K X-ray tagging to calibration the ΔE-Z relationship**



Wang Tao-feng, Meng Qing-hua, et al. Equipment to Measure Charge Distributions of Fragments in Low Energy Fission. Atomic Energy Science and Technology, Vol.41,No.4 July 2007

Mariolopoulos G, Bocquet J P, Brissot R, et al. A new experimental method to measure the charge distributions of fission products, Nucl Instrum Methods, 1981,180:141-146.

Djebara M, Asghar M, Bocquet J P, et al. Measurement of charge distributions for ^{229}Th(n_{th},f) and ^{232}U (n_{th},f) Nuclear Physics, 1984, A425:120-140.

Installation for charge distribution measurement of ^{252}Cf(sf)

TOF tube

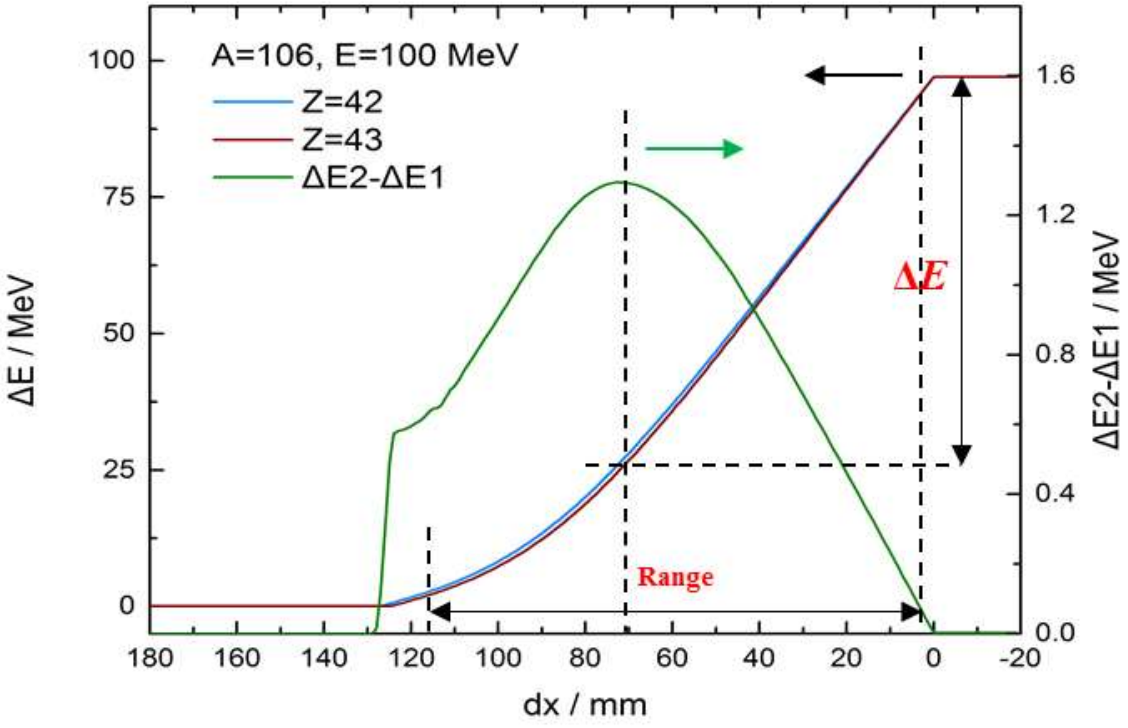
Target chamber

Axial grid ionization chamber

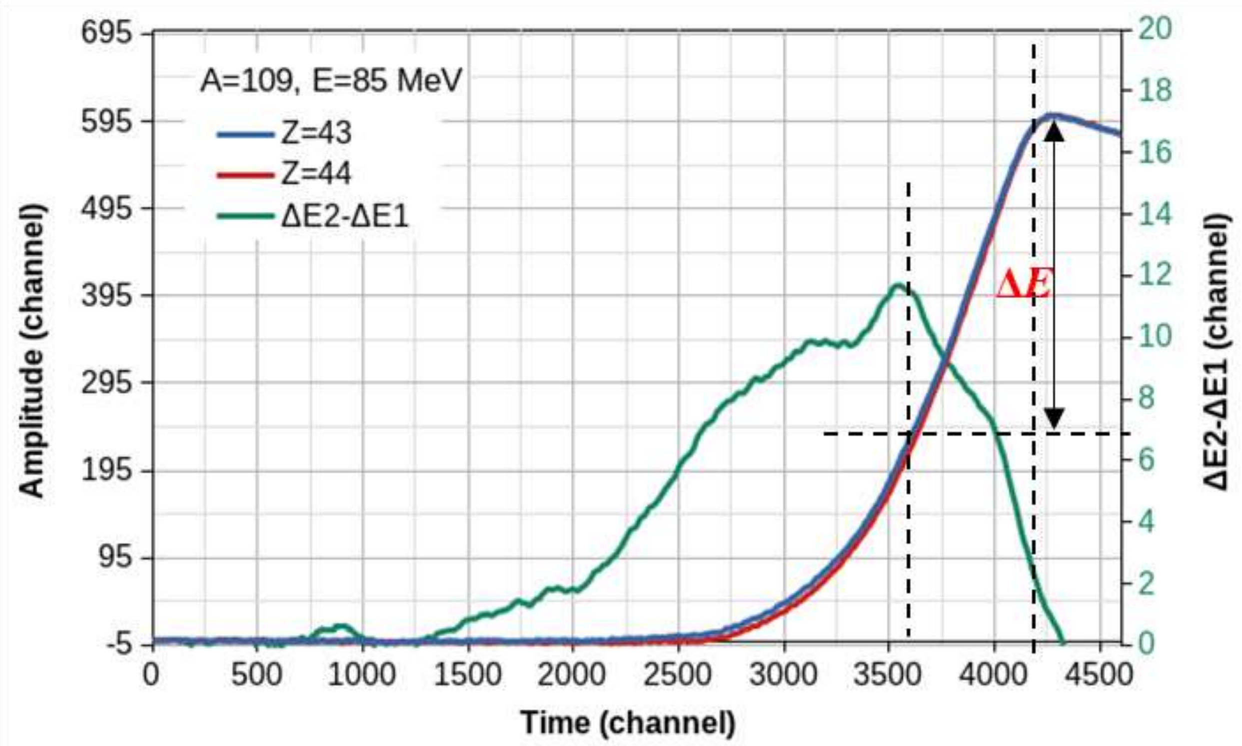
Low Energy HPGe detectors

□ ∆*E* extraction technique

- ✓ max. ∆*E* difference for adjacent Z is ~1.3 MeV (energy resolution~0.45MeV)
- ✓ optimal ∆*E* parameter*:* ~70 % of kinetic energy

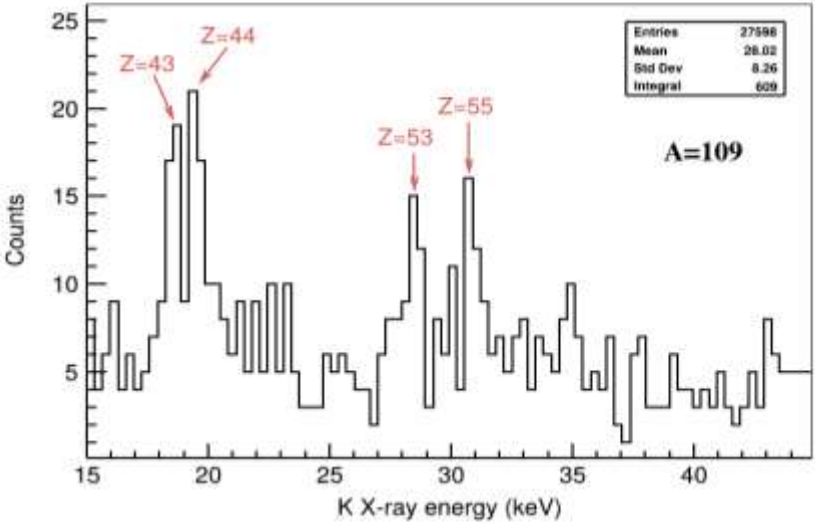


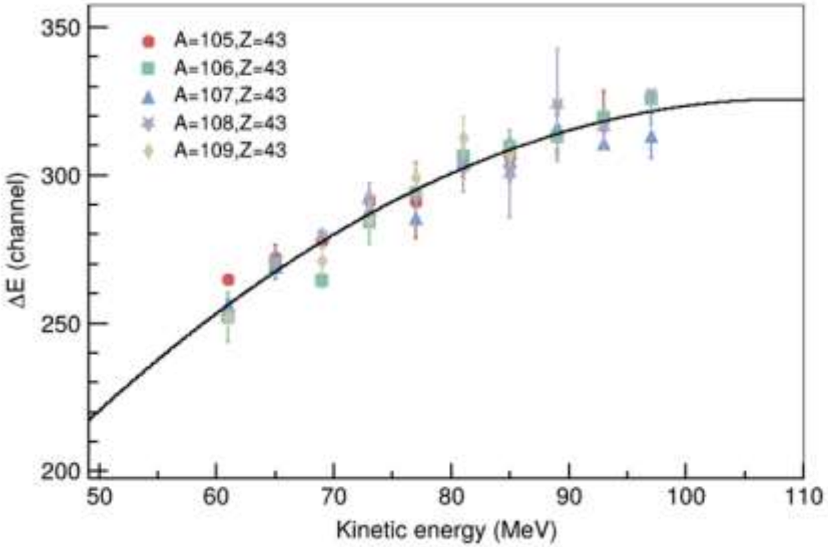
simulated anode signal waveform

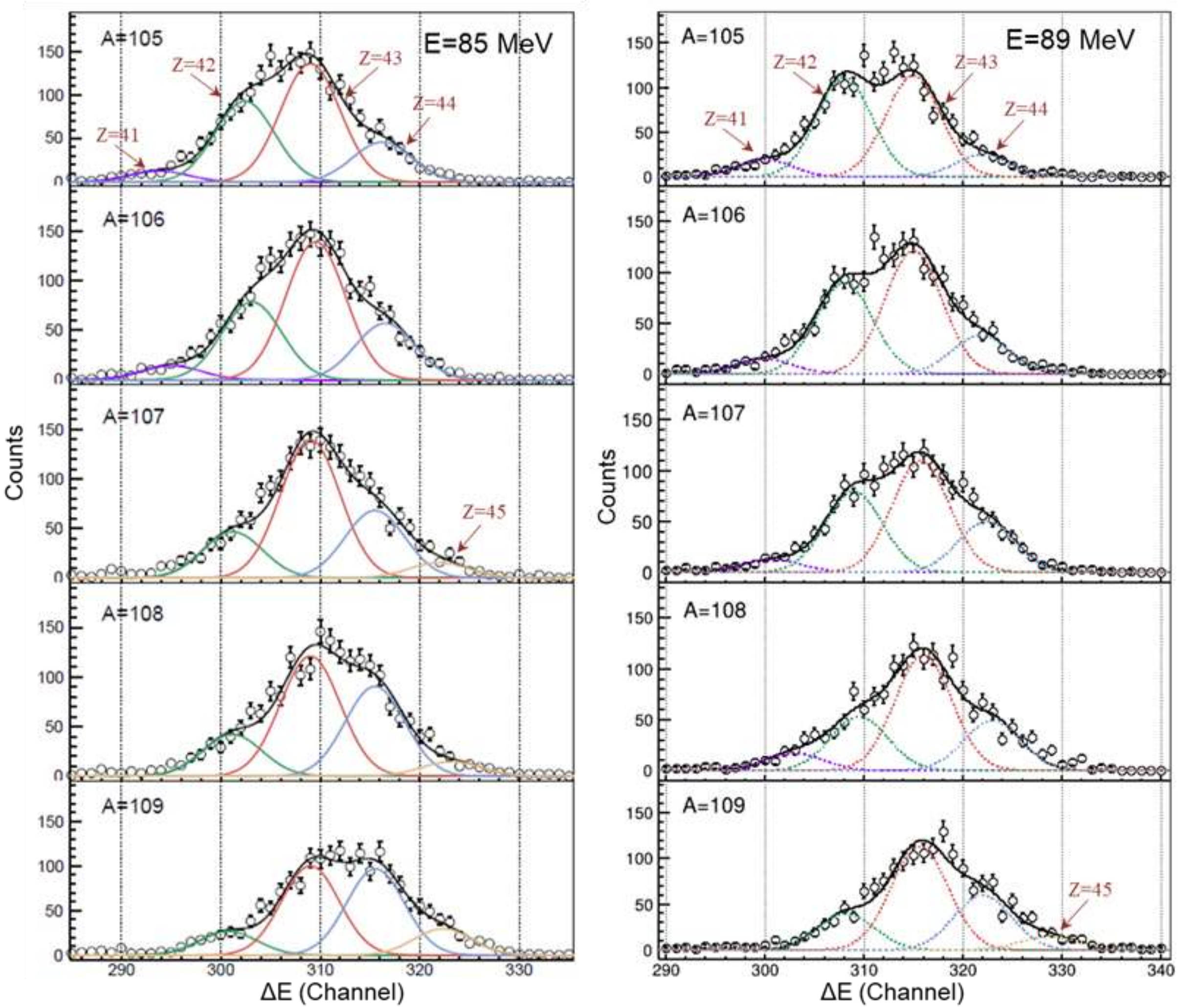


Experimental andoe signal waveforms

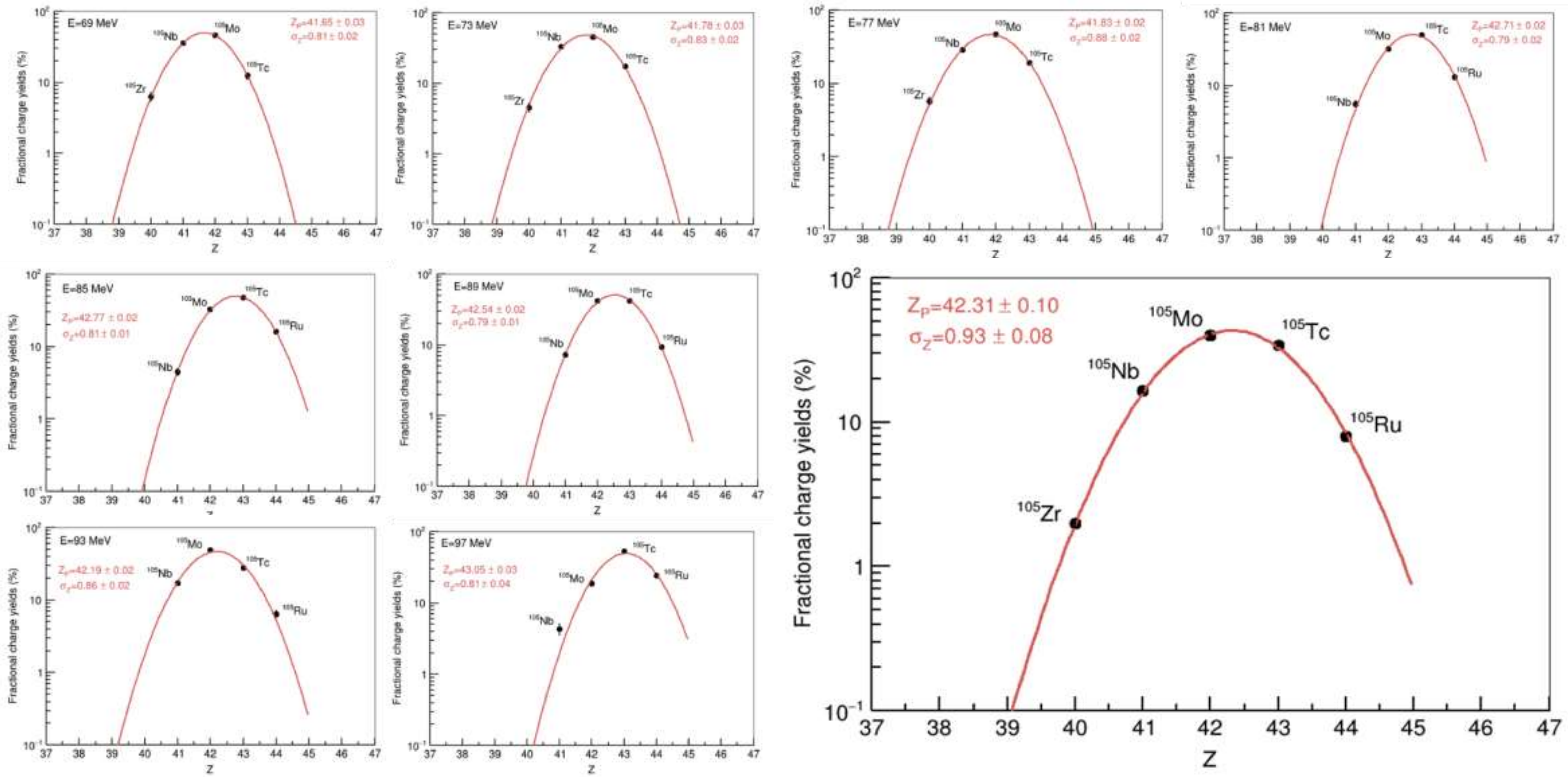
✓ X-ray tagging to improve the reliability of charge identification





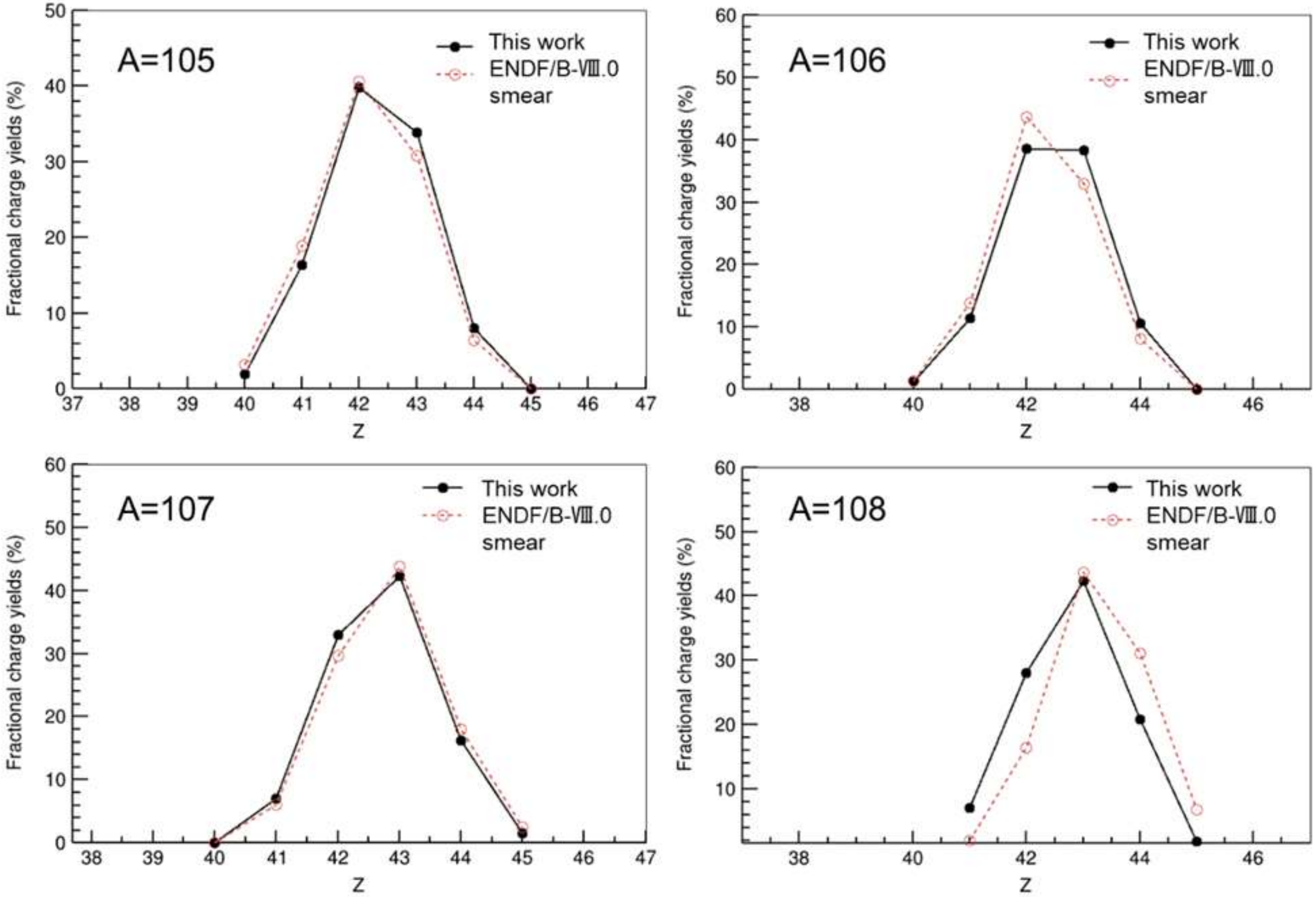


Multi-Gaussian fitting of ΔE spectrum for fragments with a given mass and energy

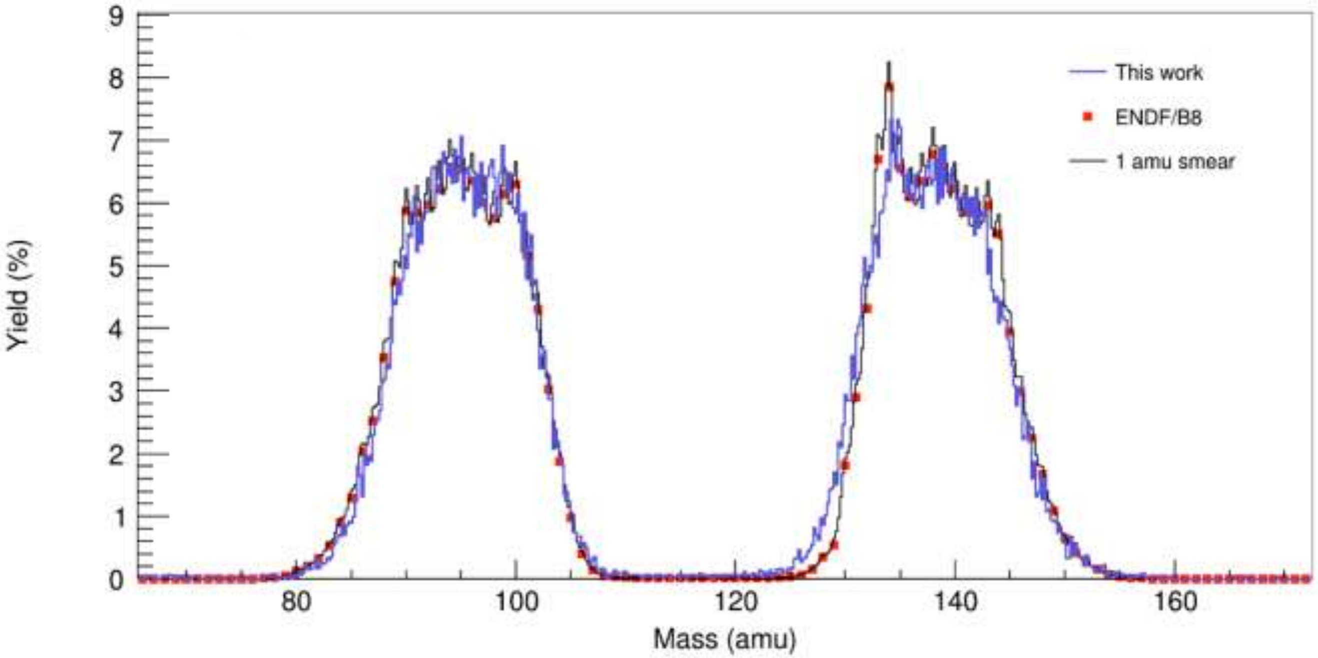


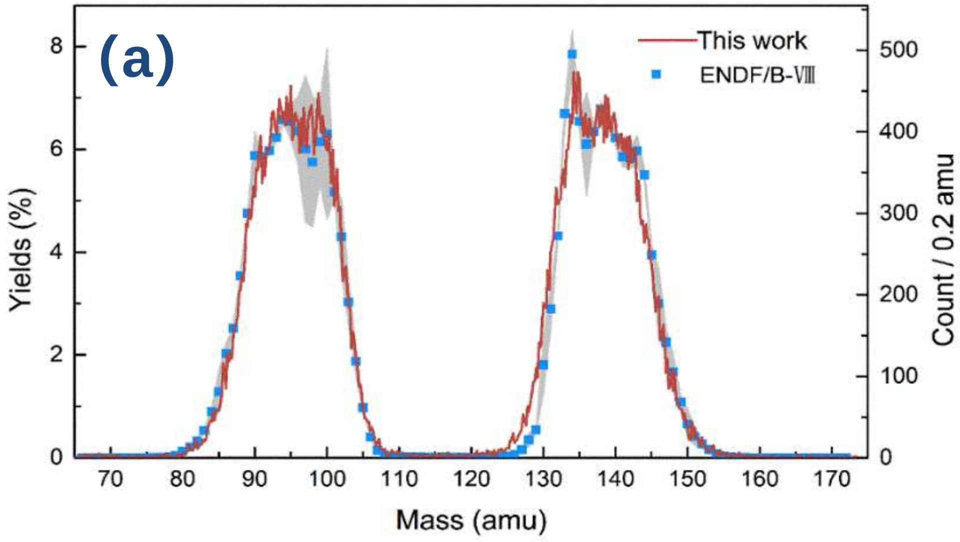
Fractional charge yield distribution for A=105 with a given kinetic energy

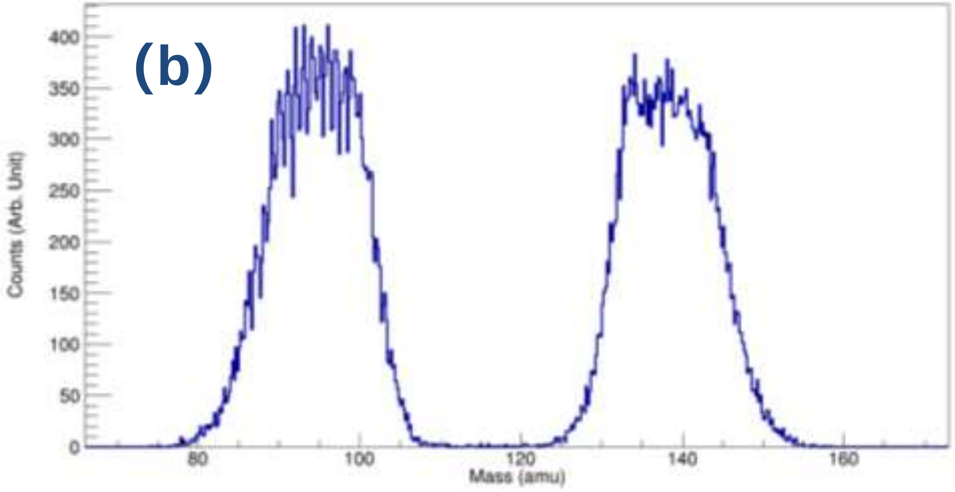
Preliminary results for Fractional Charge Yields:



- $\Delta A=1$ amu may not enough to resolve individual masses;
- Energy loss correction may introduce systematic errors, how to calibrate fragment mass accurately?

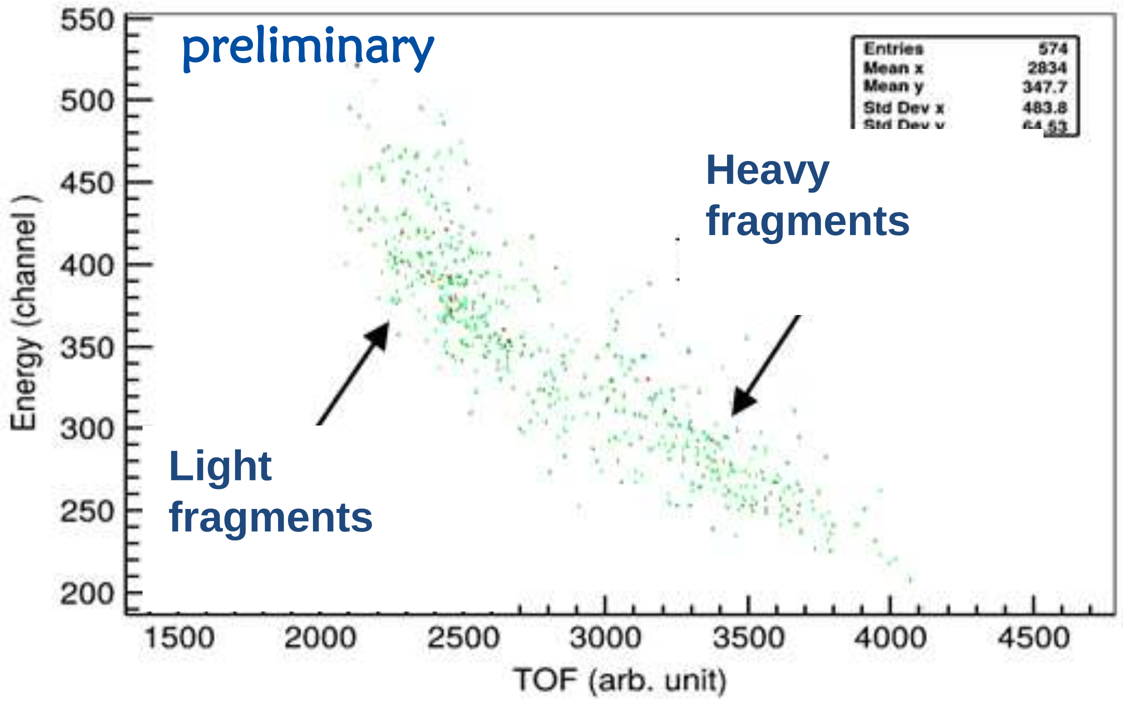


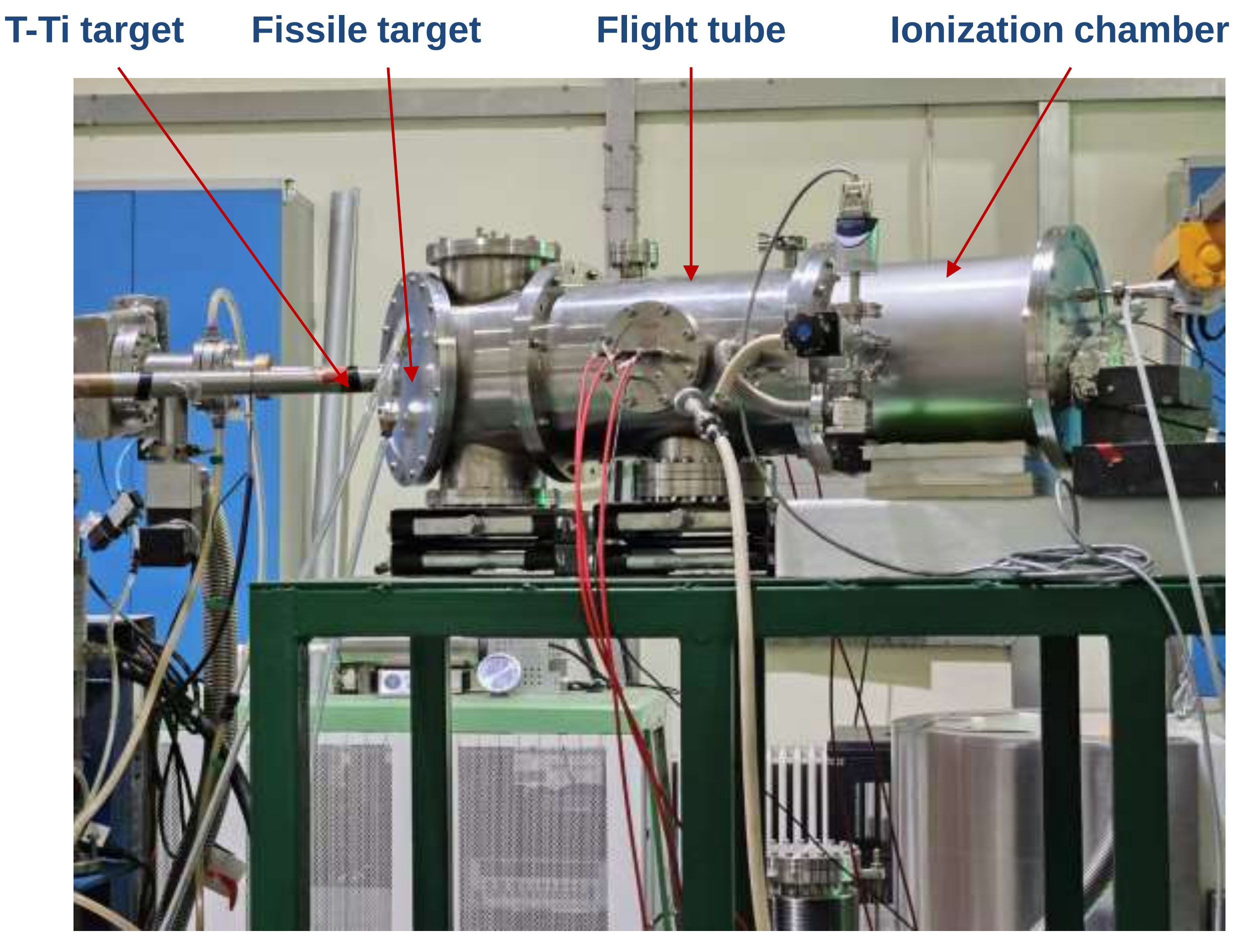




(a) this work (b) Simulation with Geant4

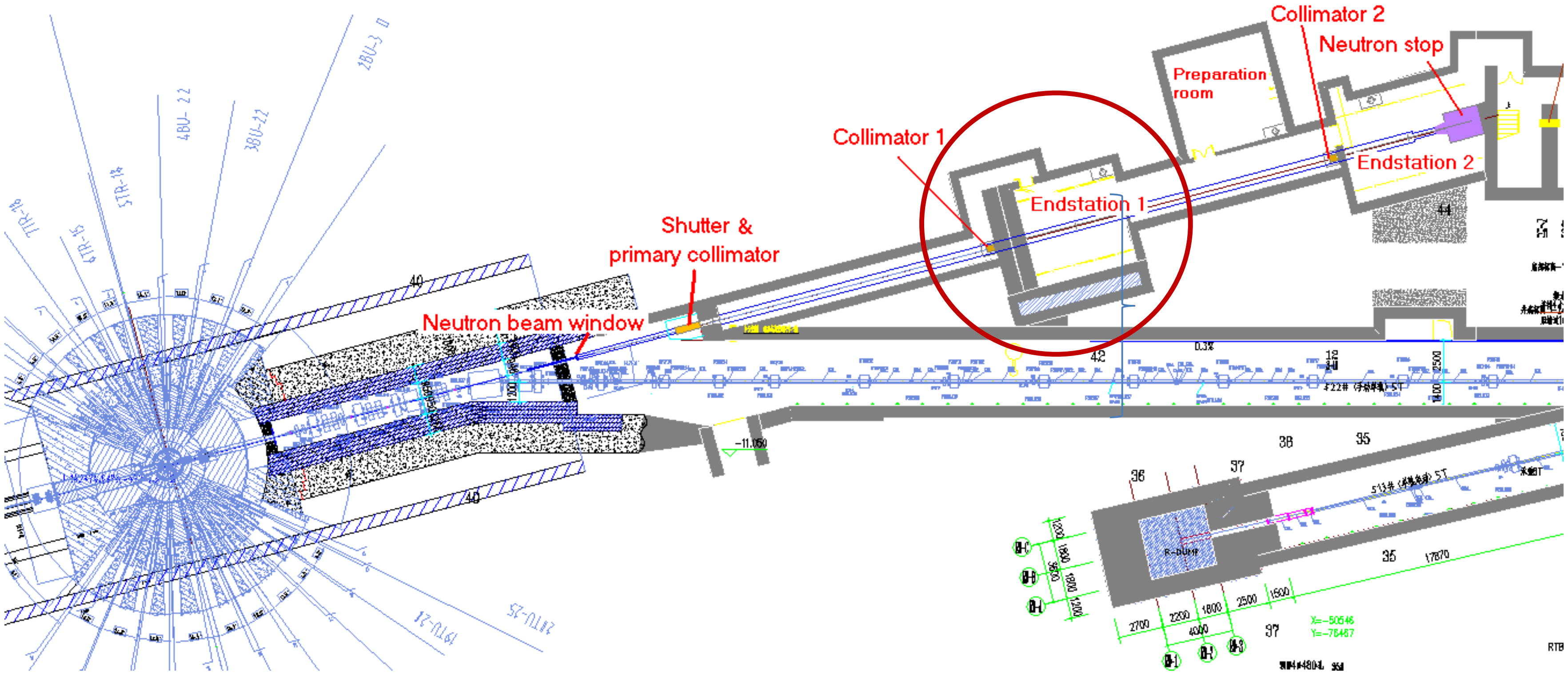
- **Mass resolution and detection efficiency are contradictory;**
- **Lack of high-intensity neutron sources;**
- **Thin fissile targets are required;**
- **……**





A test experiment for 14 MeV neutron-induced fission were carried out at an electrostatic accelerator

The beam power of China Spallation Neutron Source (CSNS) will be upgraded to 500 kW, which makes it promising to study the fission yields as a function of neutron energy.



1 eV~100 MeV, 10E7 n/cm^2/s at Endstation #1 at CSNS BACK-n

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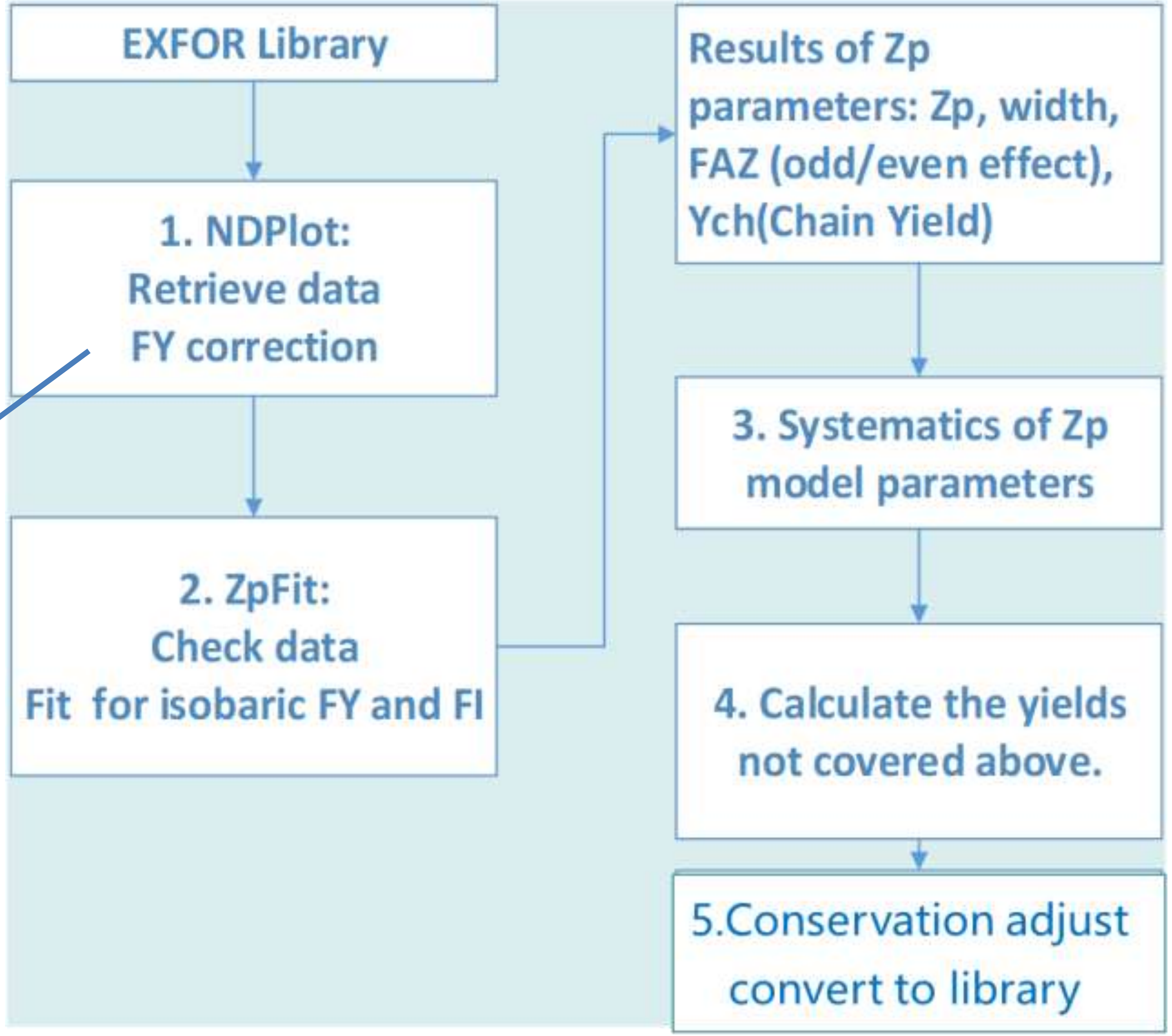
Outline

1. Preface
2. Fission model development
3. Fission experiment research
4. **Fission data evaluation**
5. Summary

Fission yield evaluation

- **Evaluation method and tools**

Gamma intensity correction
Standard /monitor yield correction
Uncertainty adjustment



Fission yield evaluation

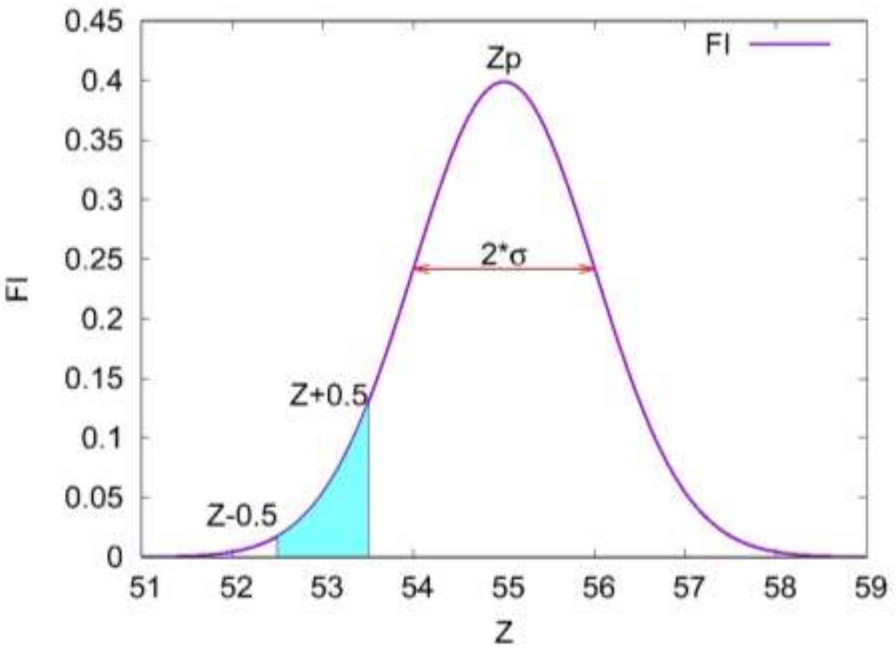
Fit the YI,YC with Zp model

$$\mathrm{FI}(\mathrm{Z}|\mathrm{A},C) = \mathrm{F_{NZ}} \int_{Z-0.5}^{Z+0.5} \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(Z-Z_p)^2}{2\sigma^2}\right) dZ$$

$$\mathrm{YI} = \mathrm{Ych} * \mathrm{FI}(\mathrm{Z}|\mathrm{A},C)$$

$$\mathrm{YC} = \mathrm{M_{IC}} \times \mathrm{YI}$$

$$C = (\mathrm{FNZ}, \mathrm{Ych}, \sigma, \mathrm{Zp})$$



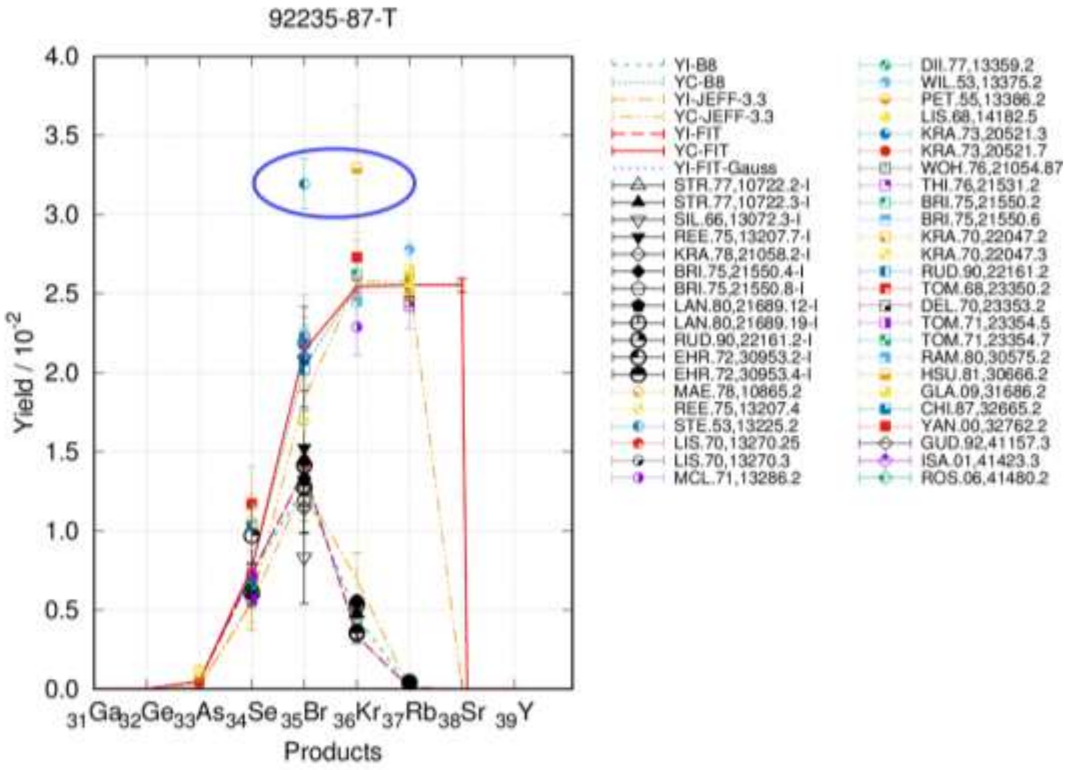
- F_{NZ}： odd and even effect of N and Z,
- σ , $Z_{p:}$ the width and peak of the Gaussian distribution,
- Ych, equal to chain yield approximately,
- C=[F_{NZ}, Ych, Z_p, σ], parameter matrix.
- $M_{IC,}$ matrix to compute YC from YI, deduced from decay branch.

Least-Square Fitting Method is used.
The results include:
1.Optimized parameters C and its covariance
2.YI、YC and their covariance

Results of n+^{235}U fission yield

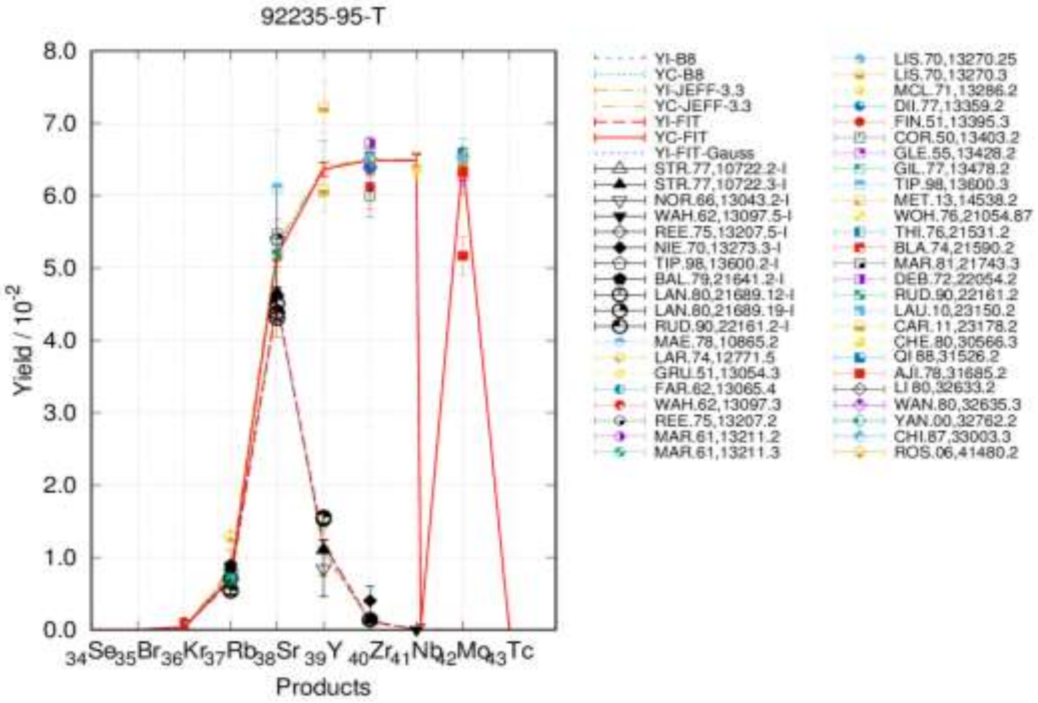
Fission yield evaluation

A=87



Fitting the isobaric YI and YC simultaneously, can tell the rationality easily for the exp. data.

A=95

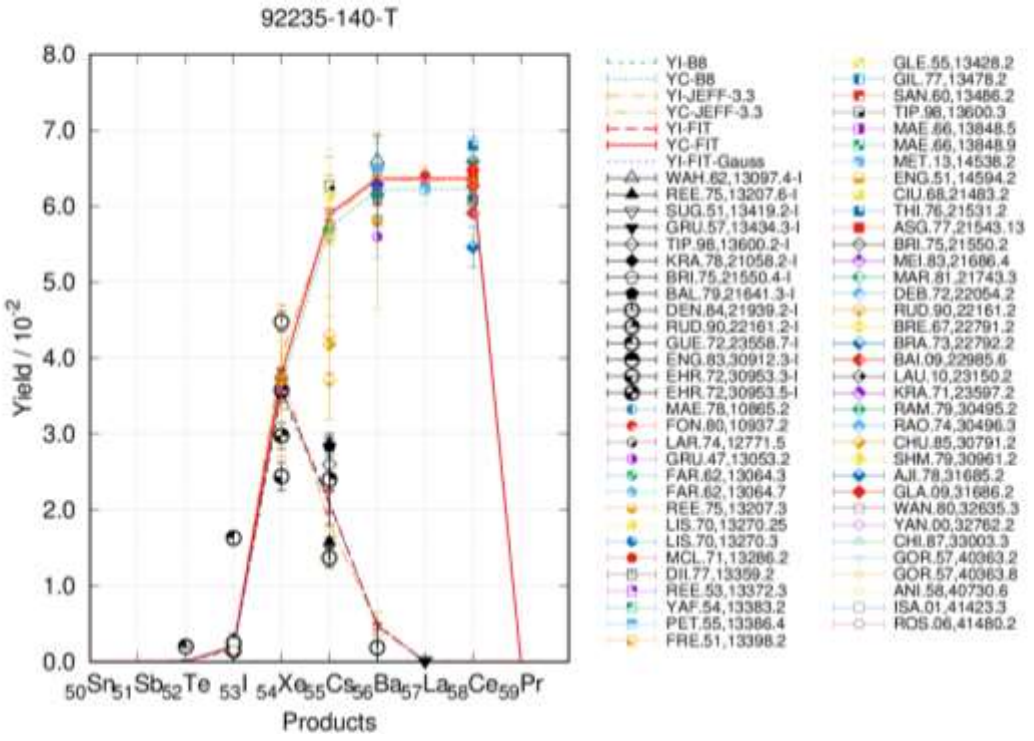


For 95 mass chain， agree well.

Results of n+^{235}U fission yield

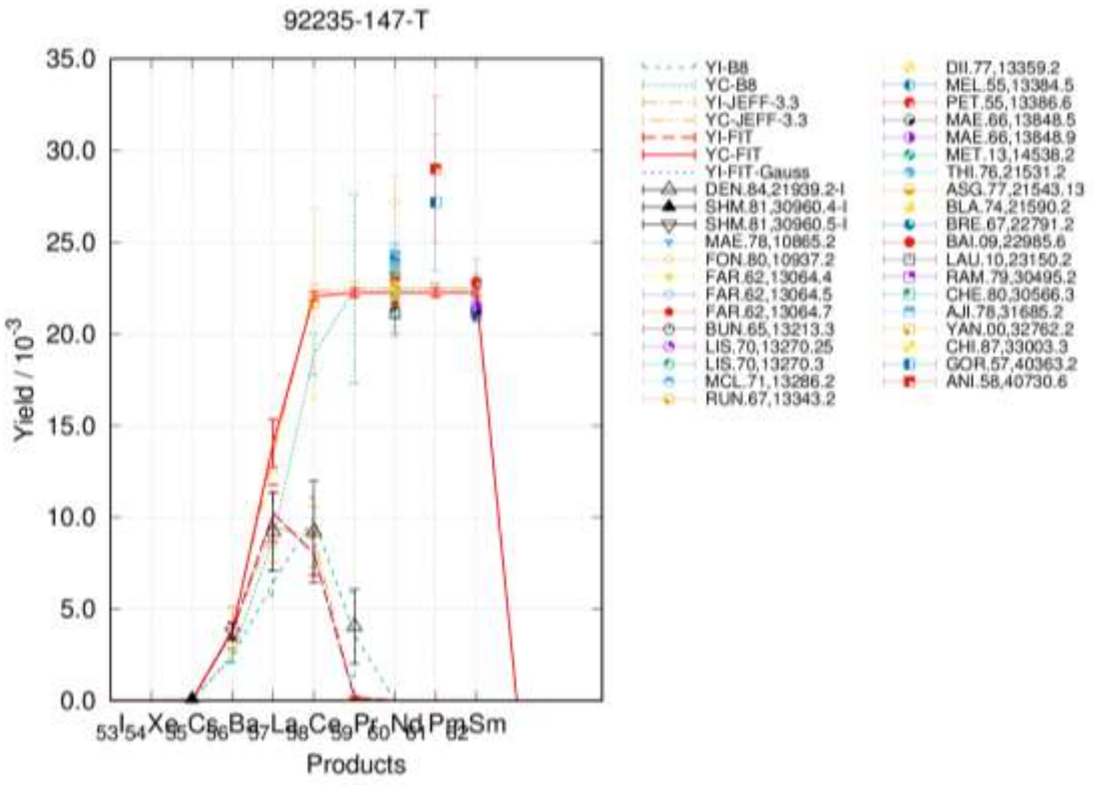
Fission yield evaluation

A=140



This is for the 140 chain, agree within the uncertainties.

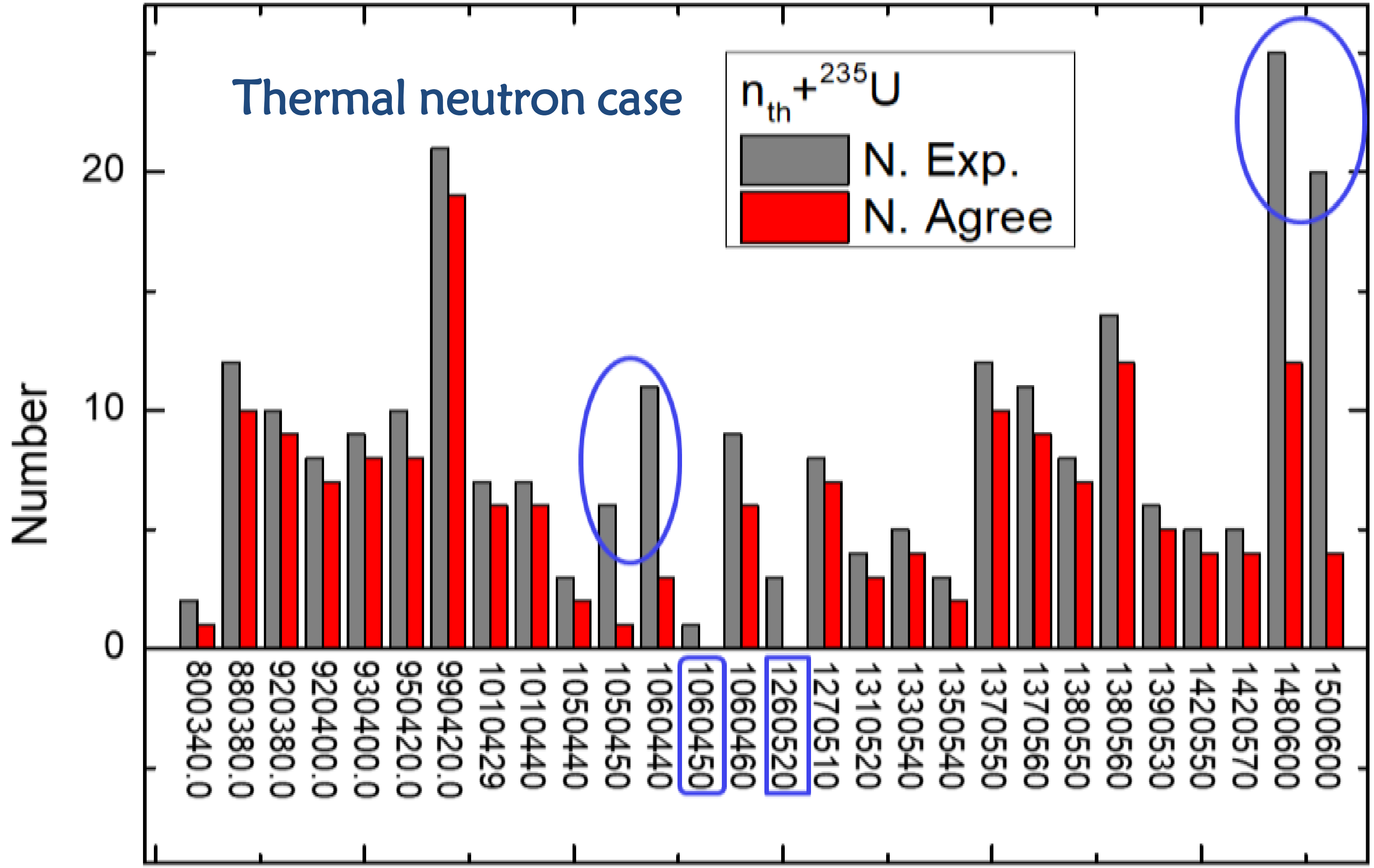
A=147



The cumulative yield agree well, but the position of charge distributions has difference between ENDF and this work.

Fission yield evaluation

Results of of n+^{235}U fission yield



The gray column : the total number of **exp data used.**

the red column : the number agree with the fitted value within the uncertainties.

the consistency between the fitted data and the experimental data

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Summary

- Some fission micro-dynamic models were developed to simulate the fission dynamics and explore the fission mechanism, for example the Fourier shape parametrization within covariant density functional theory, Generalized TDGCM, Time Dependent Hartree-Fock+BCS.
- Macro-micro model, phenomenological model and machine learning method were developed and applied to post-fission phenomena.
- A Fission Fragment Identification spectrometer for determining independent fission yield has been developed, the mass distributions in thermal-neutron-induced fission of ^{235}U were obtained based on the E-v method. Explored a multi-parameter method for charge identification, presented the initial results of charge distribution for ^{252}Cf.
- The update evaluation n+^{235}U、^{239}Pu etc. fission yield has been performed with experimental data by Zp code, which will be included in the updated Chinese Evaluated Nuclear Data Library(CENDL) for application.

Thanks for your attention!

电荷鉴别的基本思路：

$$\Delta E \cdot E \propto MZ^2$$

1. 先通过动能-速度(E-v)得到质量(M)；
2. 选定碎片的M和E后，ΔE（specific energy loss，能量损失）就只和Z相关，通过多高斯拟合解ΔE谱得到电荷鉴别结果；
3. KX射线用来标定ΔE-Z关系，提高ΔE解谱的可靠性。

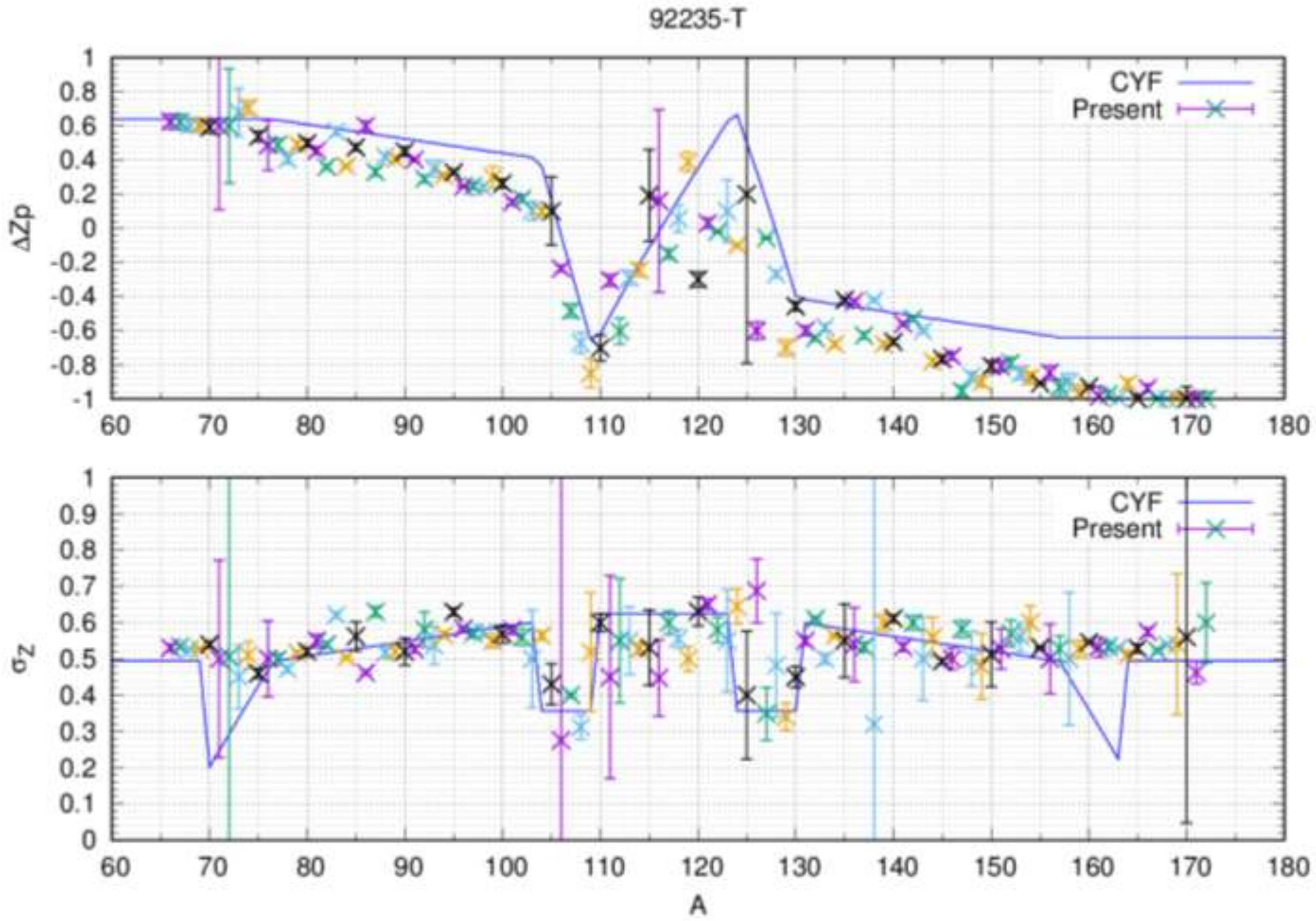
21所研究进展：

基于E-v法开展了热中子能点重要核素的质量分布测量

Results of n+^{235}U fission yield

Fission yield evaluation

Result of the fitted parameters

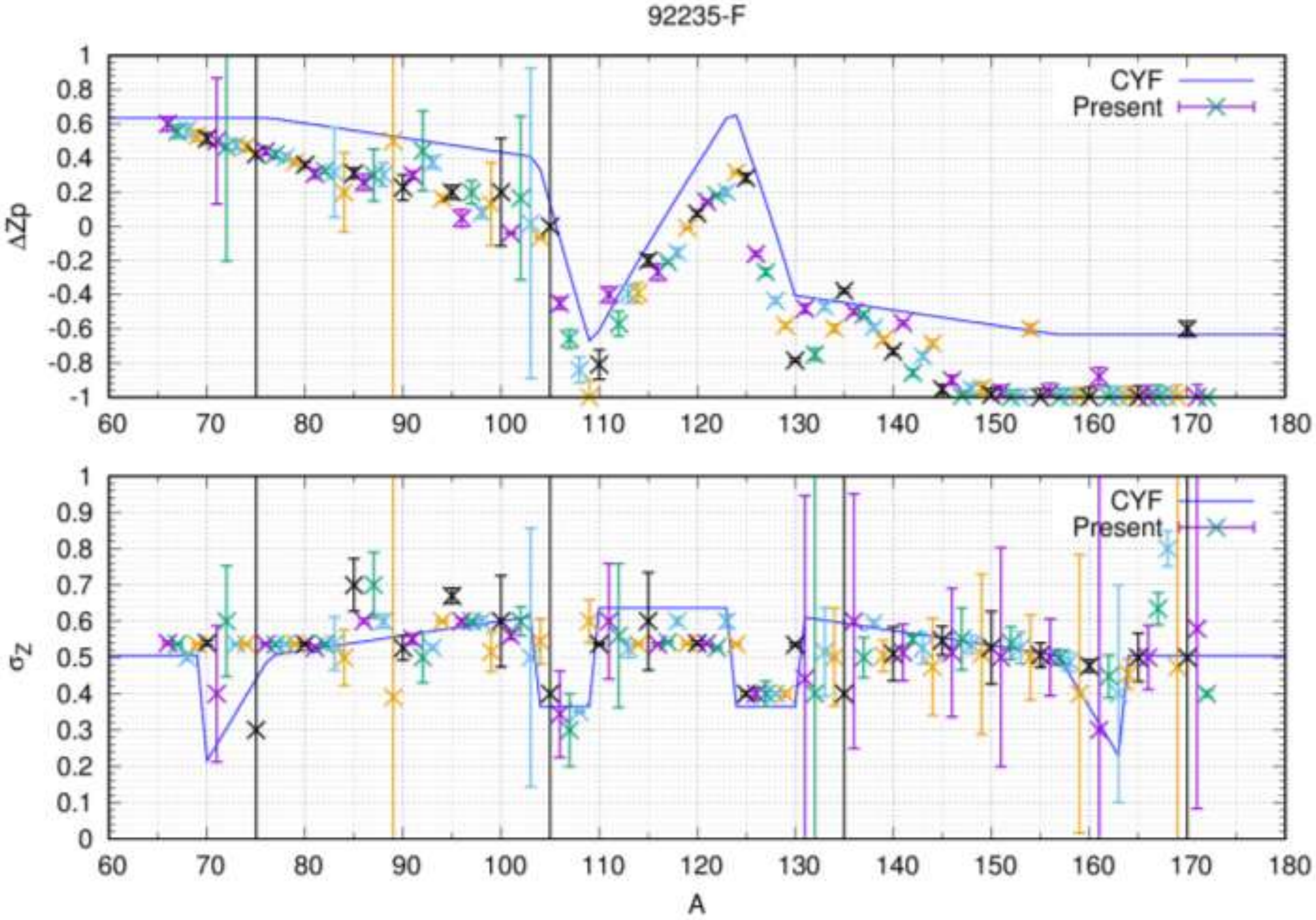


thermal neutron case

Results of n+^{235}U fission yield

Fission yield evaluation

Result of the fitted parameters

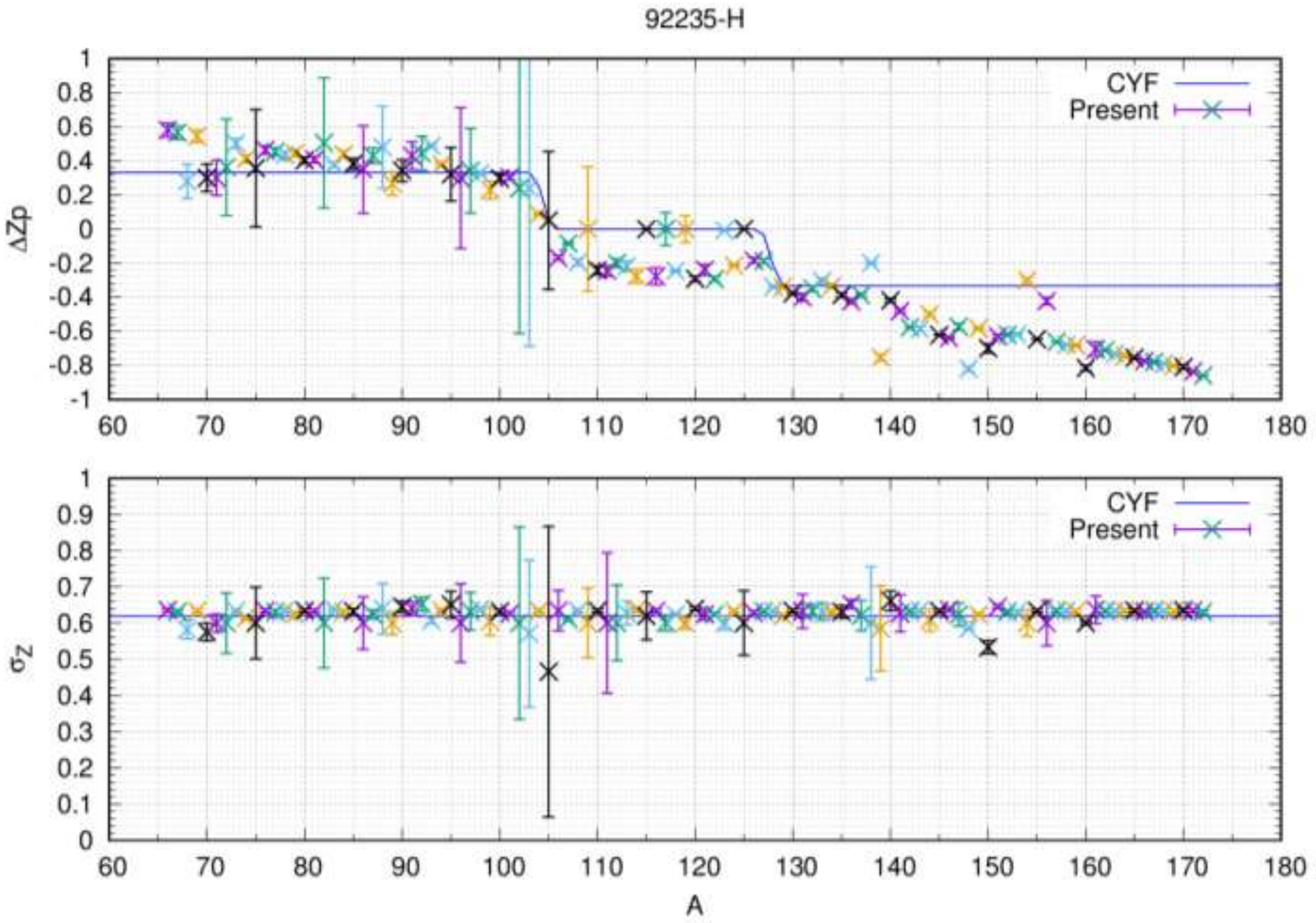


fission spectrum neutron case

Results of of n+^{235}U fission yield

Fission yield evaluation

Result of the fitted parameters



14 MeV neutron case

In general, the fitted parameter delta Zp is lower than Wahl's systematic at heavy fragment, but the width parameter agrees well.

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CFR-600
Gen-IV Reactor

Fission Product Yields:

- input for reactor simulation
- fuel consumption monitoring
- prediction of delayed neutron emission
- to test and improve models for data evaluation
- ……