

Fission isomer studies in the actinide region at IGISOL facility

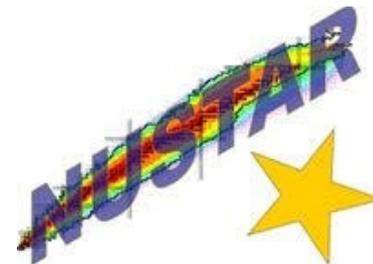
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**Nuclear physics seminar at the Faculty of Physics
University of Warsaw**

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■ **Outline**

- Nuclear fission.
- Research methods.
- Experimental results and discussion.
- Reconstruction of the atomic and mass numbers of fission fragments.
- Conclusions.

■ ***Motivation for fission isomer studies***

➤ Mapping the Nuclear Potential Landscape:

- Multi-Humped Barriers: Allows to extract the heights and widths of these barriers.
- Shell Effects: Evidence for the strong influence of shell corrections on the liquid drop model, which is essential for predicting the stability of superheavy elements.
- Superdeformation: Superdeformed shapes, make them ideal for studying nuclei at extreme elongations.

➤ Refining Nuclear Theory and Models:

- Benchmarking EDFs: Excitation energies and half-lives, are used to fine-tune Energy Density Functionals (EDFs) and other microscopic models.
- Fission Dynamics: Transition from a single nucleus to two separate fragments.

➤ Applications in Astrophysics:

- r-Process Nucleosynthesis: Fission and "fission recycling" are critical in neutron star mergers. Understanding isomeric states helps models to predict the production of heavy elements in the universe.

■ **Nuclear fission: Discovery**

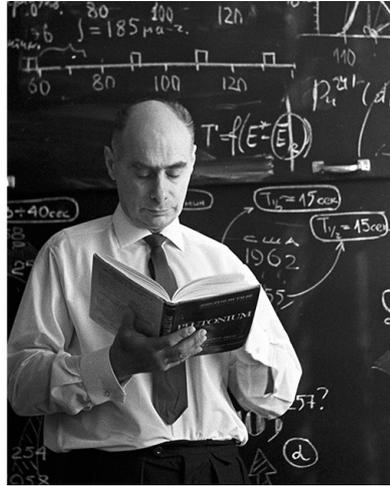


➤ **Induced fission (IF)**

- In December 1938 chemists Otto Hahn and Fritz Strassmann at the Kaiser Wilhelm Institute for Chemistry in Berlin bombarded uranium with slow neutrons and discovered that barium had been produced.
- Lise Meitner and her nephew Robert Frisch theorised, and then proved, that the uranium nucleus had been split and published their findings in *Nature*.
- Meitner calculated that the energy released by each disintegration was approximately 200 megaelectronvolts, and Frisch observed this.
- By analogy with the division of biological cells, Hahn named the process "fission".
- Otto Hahn was awarded the 1944 Nobel Prize in Chemistry for the discovery of nuclear fission.



■ Nuclear fission: **Discovery**



➤ Spontaneous fission (SF)

- G. Flerov and K. Petrzhak are officially discovered in 1940. A group in Calcutta led by S. Chatterjee, actually observed it first. However, their report was withdrawn by their director, leaving the Soviet team to take the historical credit.

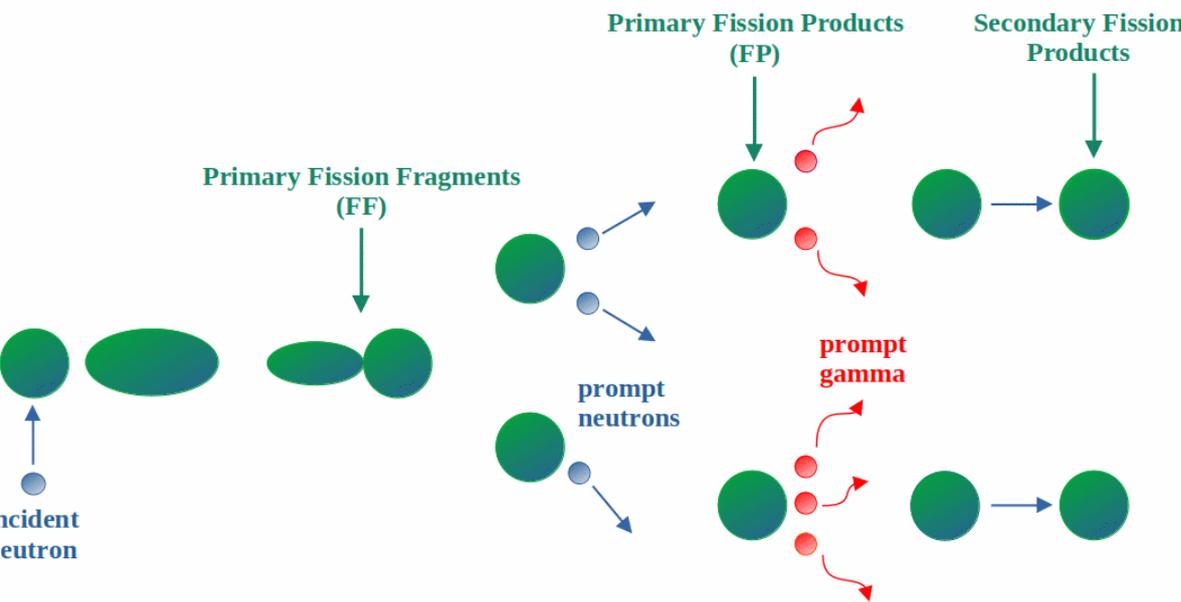
➤ Fission isomers

- In 1962 by S. M. Polikanov and G. N. Flerov at the Joint Institute for Nuclear Research (JINR) in Dubna.
- The first identified fission isomer was ^{242f}Am .
- Have a surprisingly short half-life for spontaneous fission compared to its ground state.
- This was unexpected because the observed fission occurred far faster than traditional theories predicted.
- Theoretical explanation in 1967 by V.M. Strutinsky.



■ Nuclear fission: Induced fission (IF)

- A heavy nucleus is intentionally split by an external trigger, most commonly a slow-moving thermal neutron.
- Releases a large amount of energy and additional neutrons.

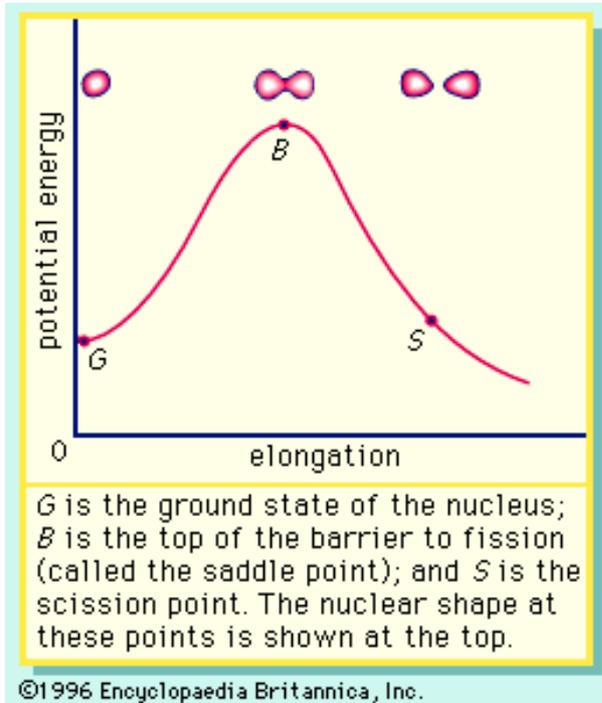


$\sim 10^{-16}$ s	$\sim 10^{-21}$ s	$\sim 10^{-20}$ s	$\sim 10^{-17}$ s	$(10^{-14} - 10^{-7})$ s	$\mu\text{s} - \text{ms}$
Phase 1 Formation of the compound nucleus	Phase 2 Deformation of the nucleus from the saddle point to the scission point	Phase 3 Acceleration of the FF due to the Coulomb repulsion	Phase 4 De-excitation of the FF by prompt neutrons, prompt gamma emission		Phase 5 Decay of the primary FP: (β^- , β^+ , n, γ)

- Excitation & Deformation: After a neutron is captured, the "compound nucleus" becomes unstable. It begins to vibrate and elongate.
- Saddle Point to Scission: The nucleus reaches a critical deformation and quickly thins into a "neck". The break at the neck occurs in roughly 10^{-21} seconds.
- Coulomb Acceleration: The two newly formed, positively charged fragments repel each other violently. This repulsion converts potential energy into the Total Kinetic Energy (TKE) that provides most of the fission's heat.
- Prompt and Delayed Emissions: The timing depends on whether the emission is governed by the Strong Nuclear Force (fast) or the Weak Nuclear Force (slow).

■ Nuclear fission: *Spontaneous fission (SF)*

- In contrast to induced fission, there is no inciting particle to trigger the decay.
- According to classical physics, heavy nuclei shouldn't be able to split without an energy boost. It happens because of quantum tunneling, where particles essentially "ghost" through an energy barrier they don't have enough energy to climb over.

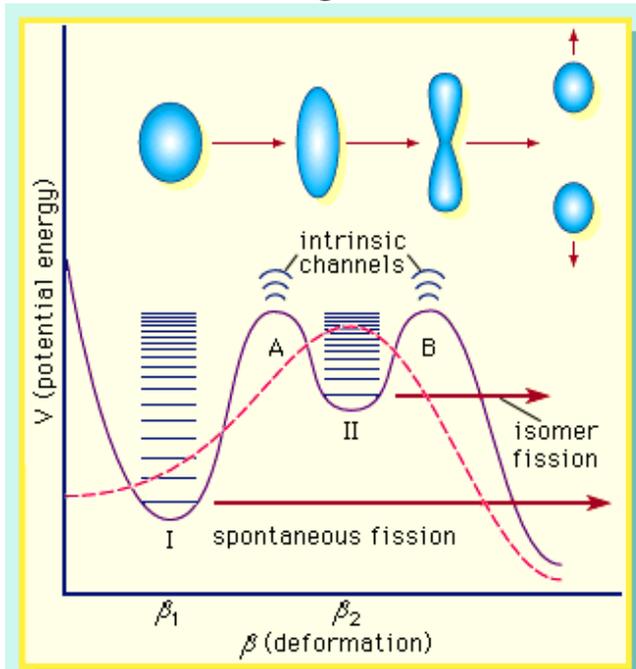


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- It is a purely probabilistic process and the height and shape of the fission barrier are dependent on the particular nucleus and play central role in understanding fission probabilities.
- As elements get heavier, $T_{1/2}$ drop from 10^{17} y for ^{232}Th to ns for ^{252}Rf . The fission barrier gets thinner.
- Nuclei with an even number of both protons and neutrons are much more likely to split.
- If a nucleus has an odd number of nucleons, the fission process is "hindered" and can take 10^3 to 10^7 times longer to happen.
- Spontaneous fission acts as a "practical limit" for the existence of heavy elements.

■ Nuclear fission: *Fission isomers*

- Meta-stable superdeformed excited states located in the second potential minimum of a double-humped fission barrier.
- Large deformations with an axis ratio of roughly 2:1, like a rugby ball.
- Located in the actinide region, specifically from U (Z=92) to Bk (Z=98), for N from 141 to 151.
- Outside this range, the nuclear structure doesn't support that second "trap" in the energy barrier.



- Multi-humped fission barriers is the result of superimposing microscopic shell corrections to the macroscopic liquid drop barrier.
- Half-lives typically from nanoseconds (ns) to milliseconds (ms).
- Based on GSI or using the VESPA data up to 2025 approximately 35 known fission isomers that have been experimentally identified.
- The longest-living fission isomer known is ^{242}Am with $T_{1/2} = 14$ ms. In 2007, an isomer of ^{235}U was found to have a comparable $T_{1/2} = 11$ ms.
- Triple-humped barriers and The "Thorium Anomaly": $^{230-233}\text{Th}$, ^{234}U , ^{236}U , ^{238}U .

■ Nuclear fission: Energy Components

➤ The total energy release Q in binary fission: $Q/c^2 = M_{CN} - M_{light} - M_{Heavy}$

➤ From energy conservation: $E_n + B_n + Q = TKE + TXE$

TKE: Total Kinetic Energy; TXE: Total eXcitation Energy

B_n : neutron binding energy $B_n = M_n + M_{target} - M_{CN}$

E_n : incident neutron energy

In case of spontaneous fission: $B_n = 0$ and $E_n = 0$

➤ The Total Kinetic Energy (TKE) of the Fission Fragments: $TKE = KE_{pre} + E_{Coul}$

KE_{pre} : pre-scission Kinetic Energy

E_{coul} : Coulomb potential energy at scission

➤ At scission, the Total Excitation Energy (TXE):

$$TXE = E_{Light}^{Def, SC} + E_{Heavy}^{Def, SC} + E_{Light}^{*, SC} + E_{Heavy}^{*, SC} + E^{Rot, SC}$$

Intrinsic excitation energy (noted *)

Deformation energy (noted Def)

Collective excitation mode (noted Rot)

➤ After the full acceleration of the FF, the Total Excitation Energy (TXE):

$$TXE = E_{Light}^* + E_{Heavy}^* + E_{Light}^{Rot} + E_{Heavy}^{Rot}$$

■ **Nuclear fission: Observables**

- Half-lives for spontaneous-fission
- Total and differential fission cross sections for the neutron induced fission
- **Primary Fragment Observables:**
 - Fission Yields (Mass and Charge)
 - Total Kinetic Energy (TKE)
 - Total Excitation Energy (TXE)
 - Fragment Angular Momentum
- **Prompt Observables (De-excitation):**
 - Prompt Neutron Multiplicity and Energy Spectrum
 - Prompt Gamma-Ray Multiplicity
- **Delayed Observables Longer-term measurements:**
 - Delayed Neutrons
 - Beta-Decay Spectra
 - Decay Heat
- **Unobservables:**
 - Fission Barrier Height: The energy required to deform the nucleus to the point of splitting
 - Scission Point: The exact configuration and moment when the "neck" between two nascent fragments breaks

▪ **Nuclear fission: GEneral description of Fission (GEF model)**

GEF - A semi-empirical framework designed by Karl-Heinz Schmidt to describe the process of nuclear fission.

➤ **The "Macroscopic-Microscopic" Approach:**

Fission nucleus treated as a system evolving on a potential-energy surface.

- Macroscopic Part: Based on the Liquid Drop Model, describing the smooth, bulk properties of nuclear matter.
- Microscopic Part: Accounts for shell effects and pairing correlations.

➤ **The Concept of Fission Channels:**

The mass and charge distributions is the result of several competing "fission modes" or channels, each represented by a quantum oscillator.

- Standard 1 (S1): Driven by the spherical shell closure (near $Z=50$, $N=82$).
- Standard 2 (S2): Associated with deformed shell closures (near $N=88$ or $N=90$), the dominant asymmetric mode.
- Super-Long (SL): A symmetric mode where the nucleus is highly elongated at the point of scission.

➤ **The Energy Sorting Mechanism:**

- As the nucleus moves toward the scission point, energy sorting occurs due to the constant nuclear temperature of the fragments (superfluid phase).
- Intrinsic excitation energy is transferred from the "warmer" fragment to the "colder" one.
- This explains why the light fragment often carries more excitation energy and consequently emits more prompt neutrons than the heavy fragment.

■ **Nuclear fission: *GEneral description of Fission (GEF model)***

➤ **Monte Carlo Simulation:**

Individual fission events simulated one by one, allowing it to:

- Maintain conservation of energy, momentum, and nucleon number on an event-by-event basis.
- Calculate complex correlations (e.g., how the number of emitted neutrons varies with the total kinetic energy of the fragments).
- Model the de-excitation cascade, including the competition between neutron and gamma-ray emission.

➤ **Calculated global parameters:**

- Describe over 100 different fissioning systems from Polonium to Seaborgium.
- Works for spontaneous fission, thermal neutron-induced fission, and fast fission up to energies of about 100 MeV.
- Provide reliable predictions for nuclei and energies where no experimental data exist, such as for exotic nuclei in the astrophysical r-process.

➤ **Calculated output parameters:**

- Independent Yields: Pre-neutron and post-neutron distributions for mass, atomic number, and neutron number.
- Prompt Neutrons: Total multiplicity, energy spectra, and emission directions for both pre-scission and post-scission neutrons.
- Prompt Gamma Rays: Multiplicities and energy spectra of gamma radiation.

Research methods: IGISOL facility in the JYFL Accelerator Laboratory

➤ The IGISOL facility is a versatile facility equipped with light-ion guide, dipole magnet, MR-TOF and Penning trap etc.

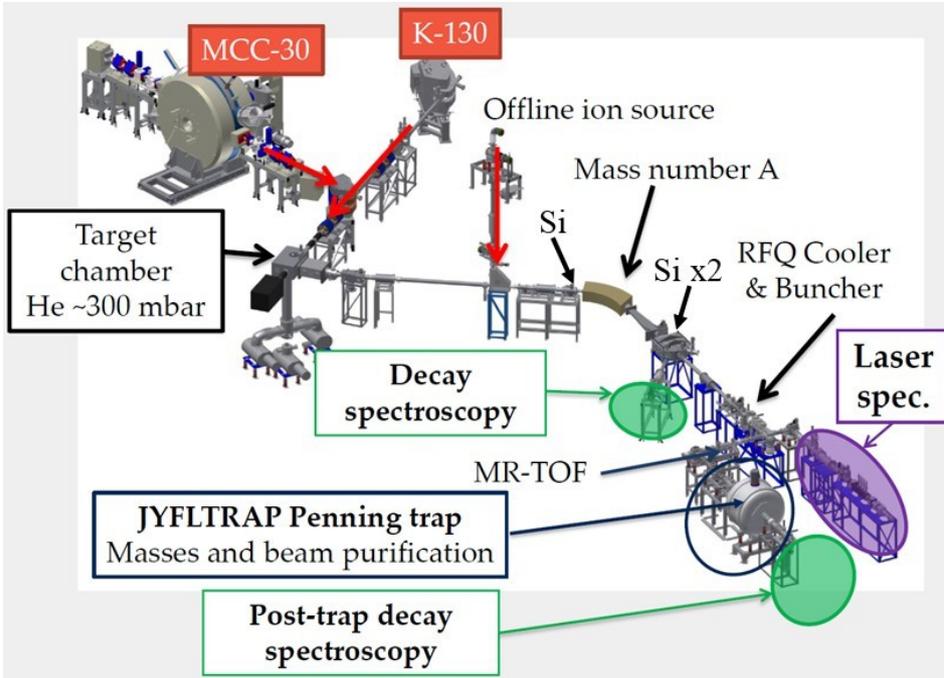
➤ $^{240f,242f}\text{Am}$ were populated via deuteron induced fusion-evaporation reactions on a ^{242}Pu target:



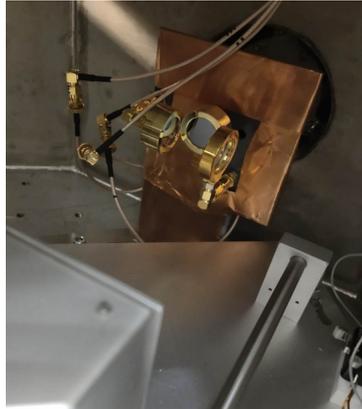
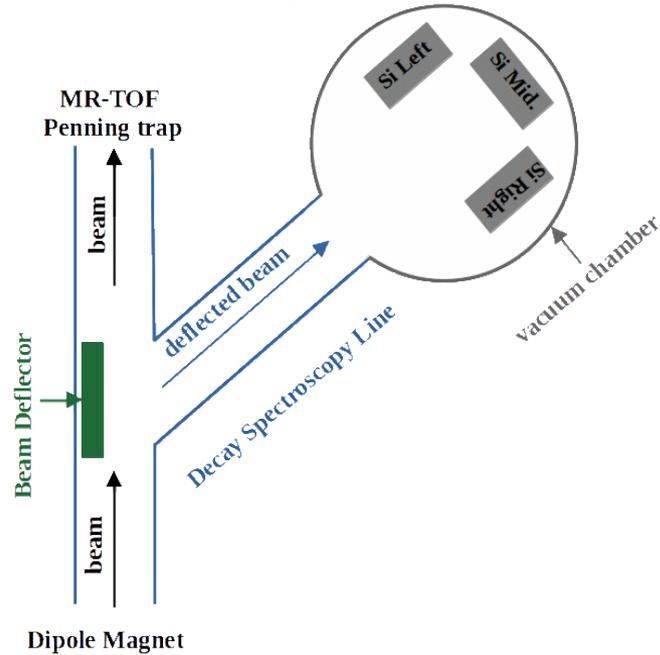
➤ Deuteron beam from the K130 cyclotron with energies from 10 to 28 MeV.

➤ ^{242}Pu target installed in the light-ion guide inside the target chamber. The light-ion guide is a small gas cell (with a stopping volume of $\sim 3 \text{ cm}^3$) filled with He buffer gas.

➤ The separation and selection of ^{242}Am and ^{240}Am was done by the dipole magnet at IGISOL, which resolving power of about 200.

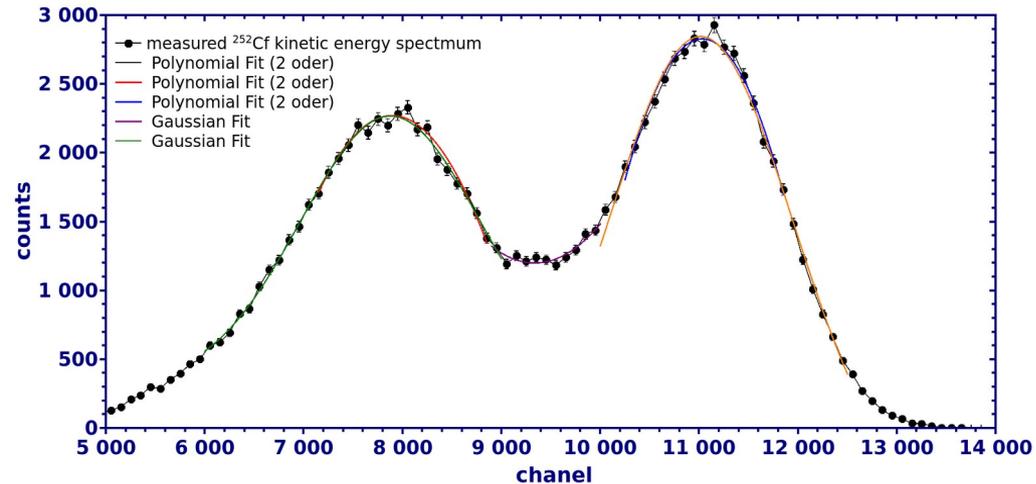
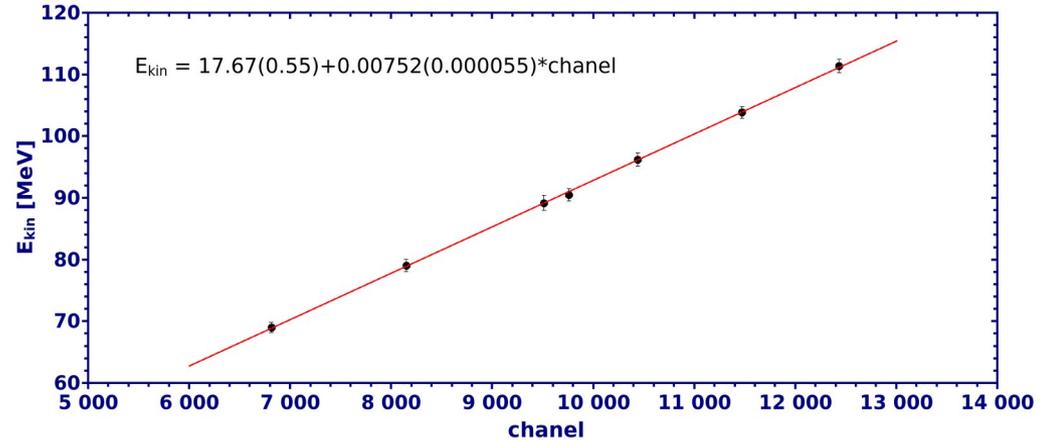
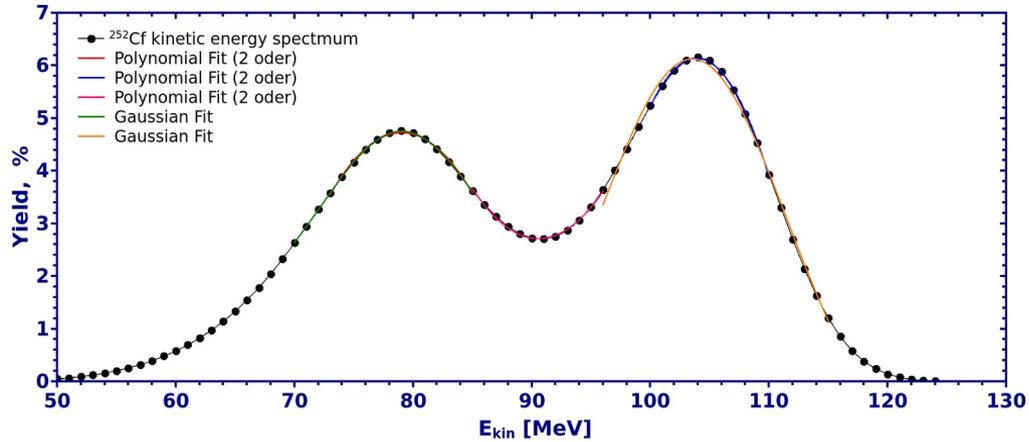


Research methods: Experiment on fission isomer $^{240\text{f}}, ^{242\text{f}}\text{Am}$



- $^{242\text{f}}\text{Am}$: $E^*=2.2$ MeV $T_{1/2}=13.8$ ms
- $^{240\text{f}}\text{Am}$: $E^*=3.2$ MeV $T_{1/2}=0.93$ ms
- With this time scale isomers can be separated and transported sufficiently.
- In order to use the measurements efficiently beam regularly deflects between two lines.
- Fission isomer decays detected by a tree of Si detectors installed after the dipole magnet in the decay spectroscopy line.
- Si Middle detector was used as an implanter for $^{240\text{f}}, ^{242\text{f}}\text{Am}$ isomers.
- Si detectors were calibrated with a ^{252}Cf fission source in order to obtain the kinetic energy spectra of the single fission fragments from fission isomers.

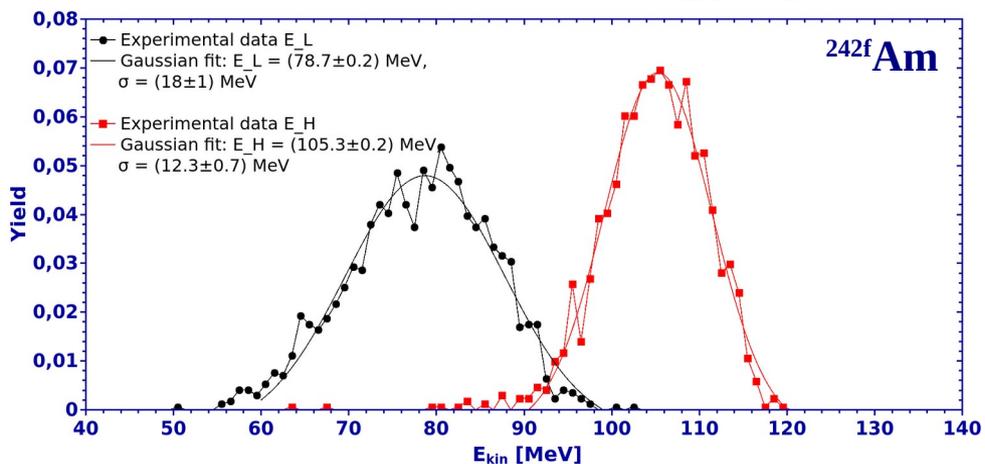
Research methods: Si Detectors calibration



- The kinetic energy spectrum of fission products for ^{252}Cf is the result of a Monte Carlo simulation based on experimental data of $E_k(A)$, $\sigma_{E_k}(A)$, and $Y(A)$.
- 7 points were used to obtain the calibration curve.
 - 3 - obtained from the parabola fit
 - 4 - from the Gaussian fit.

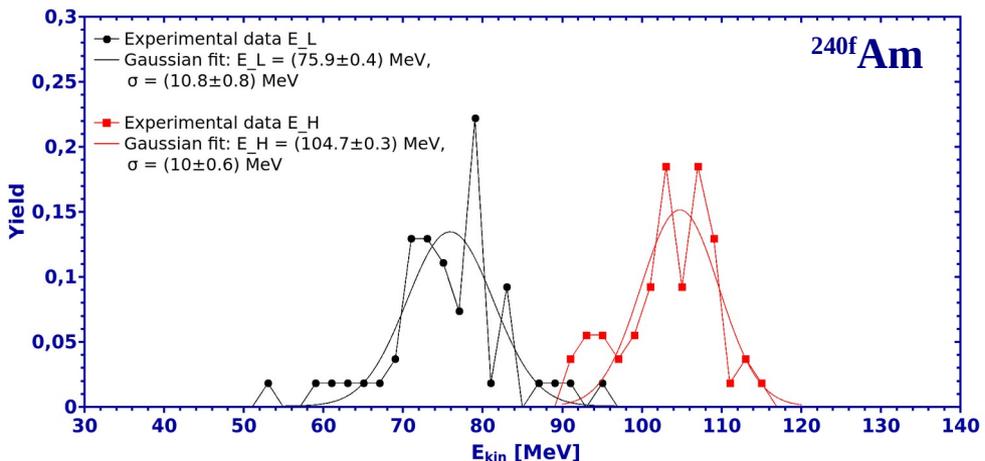
Experimental results and discussion:

Kinetic energy spectra of the single fission fragments of ^{240}f , ^{242}f Am



^{242}fAm fission fragments:

- 12323 - total counts
- 1711 - correlated events (coincident fission fragments)
- Data from: Phys.Rev. C13, 189 (1976) J. Weber et al.
 $E_L = (78.10 \pm 0.11)$ MeV
 $E_H = (105.93 \pm 0.15)$ MeV
Good agreement with previously measurements



^{240}fAm fission fragments:

- 423 - total counts
- 54 - correlated events (coincident fission fragment)

Experimental results and discussion:

Total kinetic energy spectra of ^{240}f , $^{242}\text{f}\text{Am}$

➤ $\text{TKE} = E_{\text{L}} + E_{\text{H}}$ - two fission fragments from the same decay

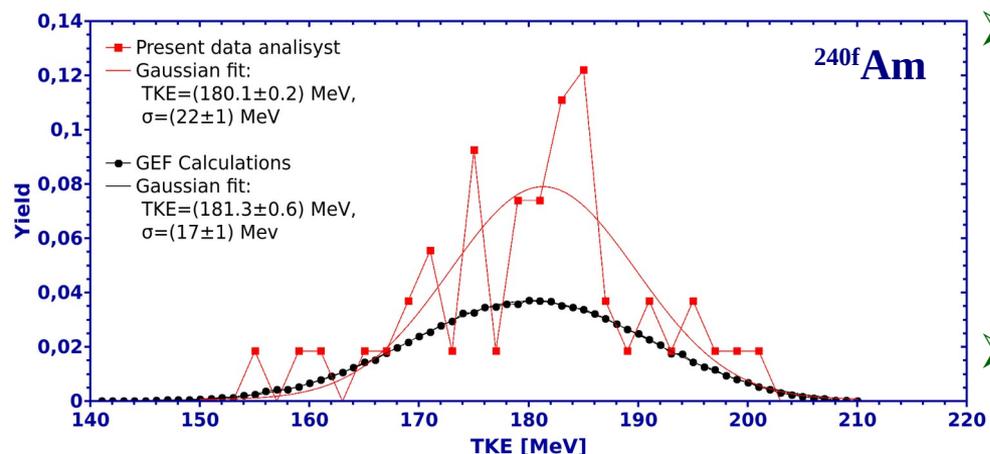
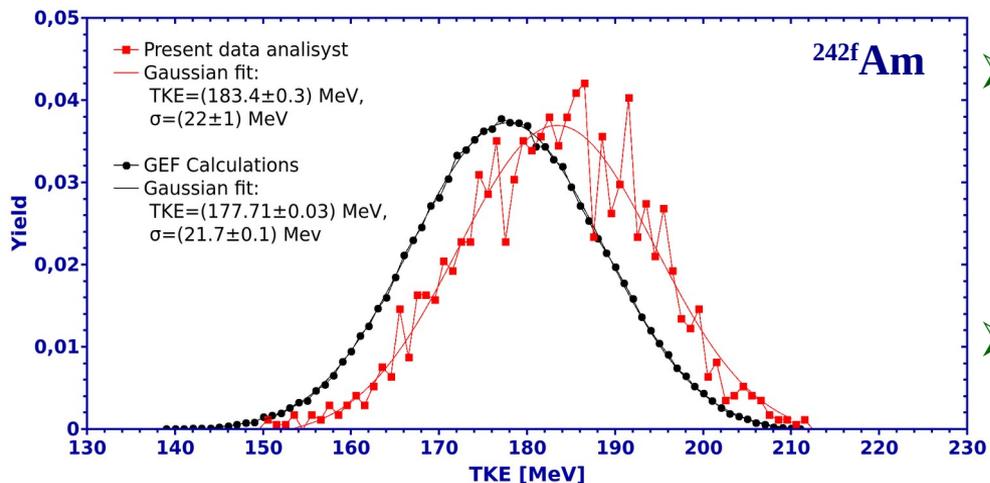
$^{242}\text{f}\text{Am}$ fission fragments:

➤ GEF - A General Description of Fission Observables empirical-theoretical mode by Karl-Heinz Schmidt
The difference in maximal value $\Delta\text{TKE} \approx 6 \text{ MeV}$

➤ Data from: Phys.Rev. C13, 189 (1976) J. Weber et al.
 $\text{TKE} = (184.03 \pm 0.07) \text{ MeV}$
Good agreement with previously measurements

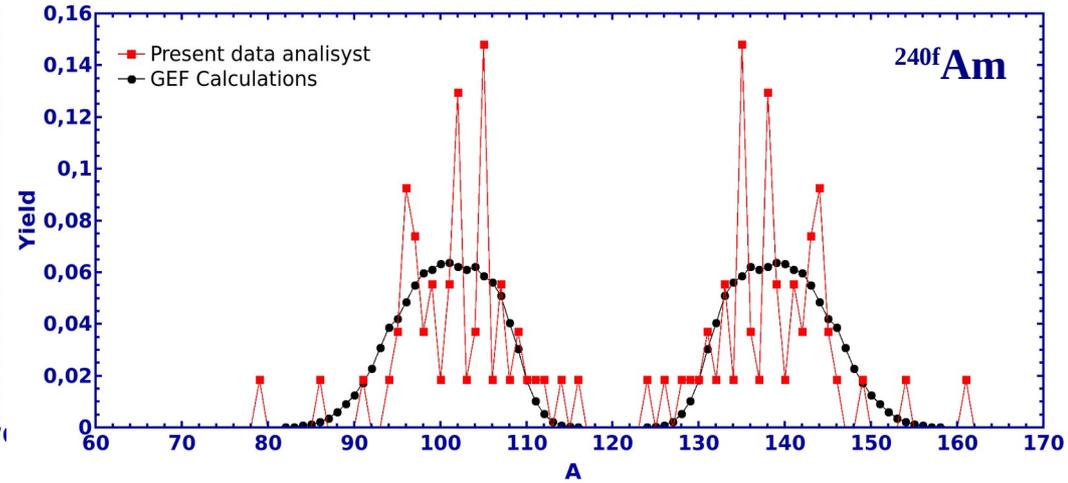
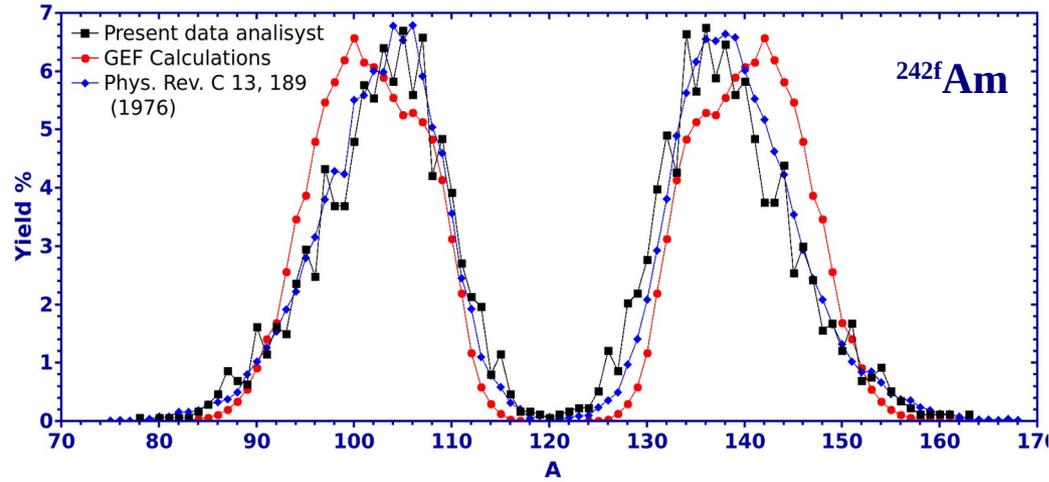
$^{240}\text{f}\text{Am}$ fission fragments:

➤ Statistics must be improve for making conclusions



Experimental results and discussion:

Pre-neutron emission mass distributions of $^{240f}, ^{242f}\text{Am}$



- The pre-neutron emission mass distribution were calculated using 2E method:

$$R = \frac{E_L}{E_H} \quad A_H = \frac{A_m}{(1+R)} \quad A_L = \frac{A_m * R}{(1+R)} \quad \text{were } A_m = 242 \text{ or } 240 \text{ masa number of Americium}$$

- ^{242}Am pre-neutron emission mass distribution to be strongly asymmetric with:

$$A_L = 104.1 \pm 0.2 \text{ and } A_H = 137.7 \pm 0.2$$

- Pre-neutron mass distribution for ^{240}Am exhibit to peak structure with:

$$A_L = 101.9 \pm 0.9 \text{ and } A_H = 138.2 \pm 0.9$$

Reconstruction of the atomic and mass numbers of fission fragments: *Basic assumptions*

➤ The conservation of momentum: $\vec{p}_1 + \vec{p}_2 = \sum_{n_N} \vec{p}_N$

➤ Relativistic relations: $\sqrt{p_1^2 + m_1^2} = m_1 + E_1$
 $\sqrt{p_2^2 + m_2^2} = m_2 + E_2$

➤ The conservation of total energy:

$$m_1 + m_2 + E_1 + E_2 = M_F - n_N m_N - n_N E_N - n_Y E_Y \equiv M$$

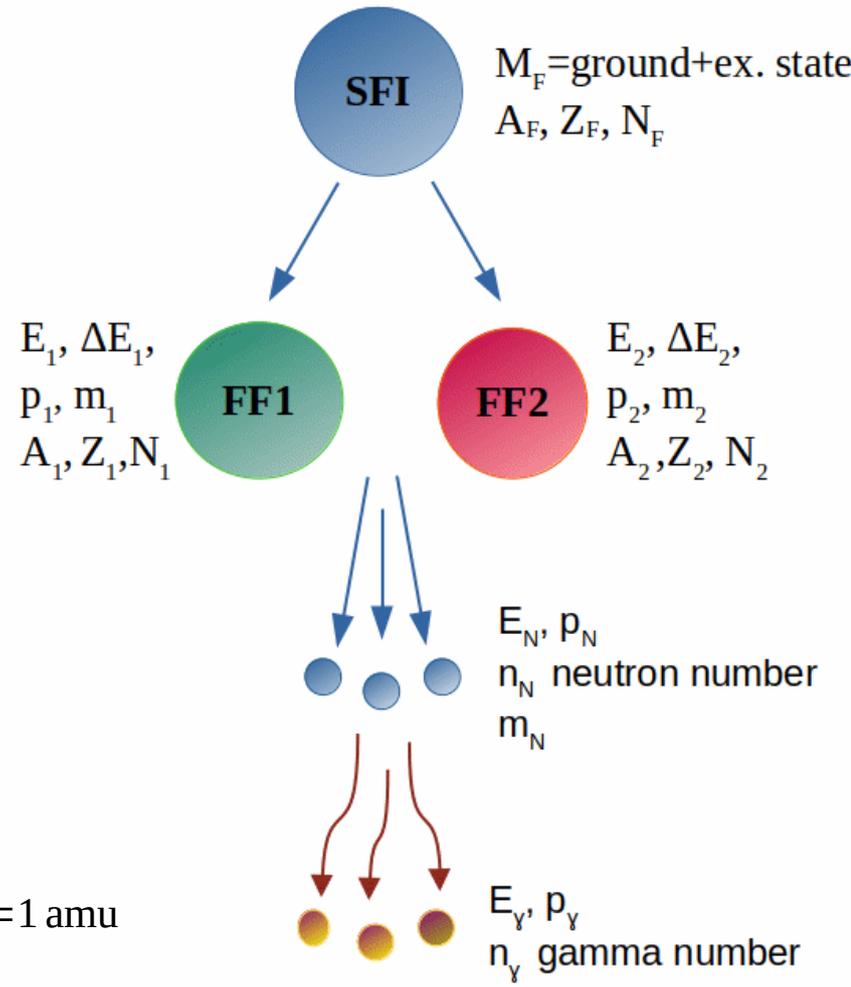
➤ Masses m_1, m_2 :

$$m_1 = \frac{2 E_2 M - (E_1 + E_2)^2}{2 (E_1 + E_2)}$$

$$m_2 = \frac{2 E_1 M - (E_1 + E_2)^2}{2 (E_1 + E_2)}$$

➤ The accuracy of the masses m_1, m_2 :

$$\delta m_{1(2)} = \sqrt{\left(\frac{\delta m_{1(2)}}{\delta E_1}\right)^2 + \left(\frac{\delta m_{1(2)}}{\delta E_2}\right)^2} = \frac{M \sqrt{E_1^2 + E_2^2}}{(E_1 + E_2)^2} \delta E \quad \text{for } \delta E = 1 \text{ MeV } \delta m = 1 \text{ amu}$$



■ **Reconstruction of the atomic and mass numbers of fission fragments:**

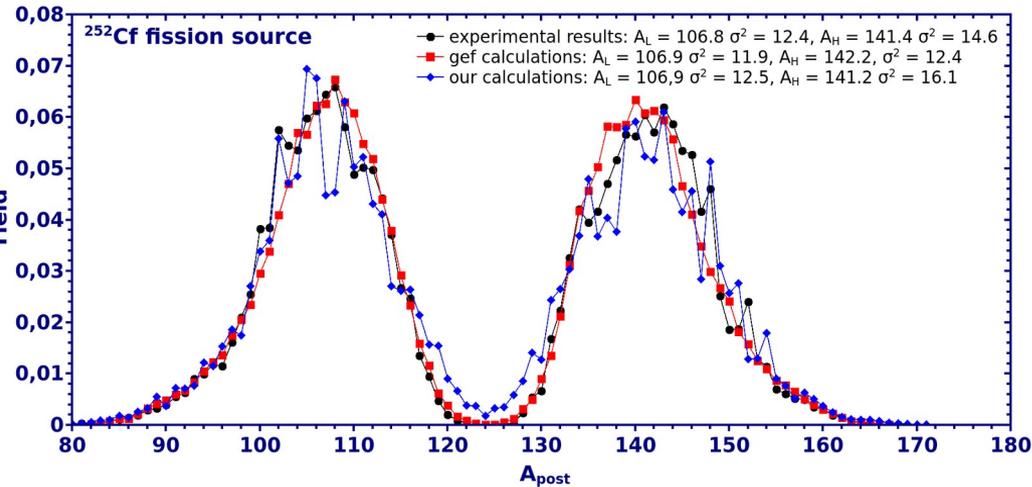
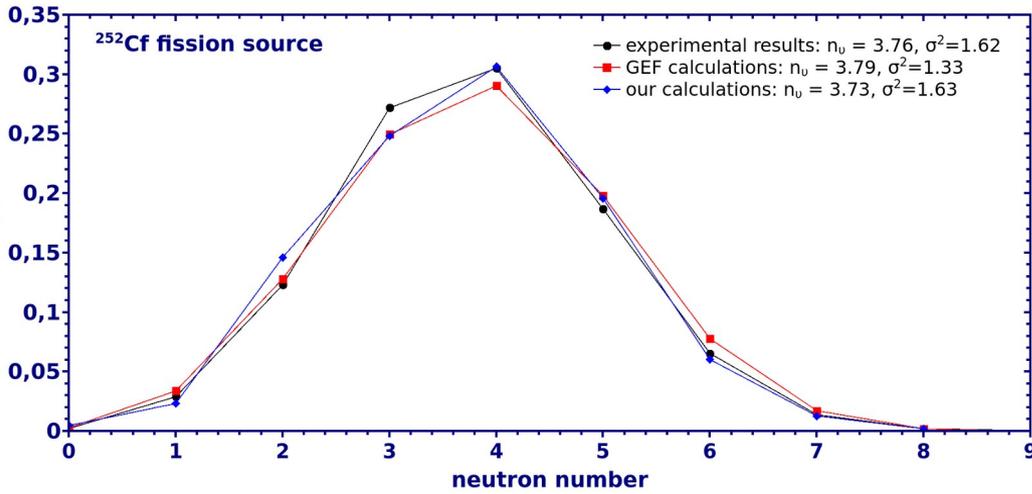
Calculation procedure

- The fragments are not excited (not ionized). During fission n_N neutrons with average kinetic energy E_N and on average n_γ gammas with average energy E_γ are emitted.
- Mass number A_1 and A_2 as an integer, is the closest value to the ratio $m_{1(2)}/\text{amu}$, determined with an accuracy of ± 1 , depends on the number of emitted neutrons n_N .
- Consider all possible pairs of nuclei (Z_1, A_1) and (Z_2, A_2) with known masses, where $A_1 \in \{A_1 - 1, A_1, A_1 + 1\}$ and $A_2 \in \{A_2 - 1, A_2, A_2 + 1\}$, with the constraints:
 $A_1 + A_2 = A_F - n_N, Z_1 + Z_2 = Z_F.$
- For these pairs are further deviations δ calculated from the conservation of total energy
 - $\delta = (M_F - n_N \cdot m_N - n_N \cdot E_N - n_\gamma \cdot E_\gamma) - M_1(Z_1, A_1) - M_2(Z_2, A_2) - E_1 - E_2 (**)$

where $M_1(Z_1, A_1)$, $M_2(Z_2, A_2)$ measured masses from Atomic Mass Data Center (AMDC) 2020

- Obtain the reconstructed atomic and mass numbers for the fragments by minimizing the energy deviation δ , with n_N ranging from 0 to 8. The average E_N, E_γ and n_γ are fixed and depend on the SF nucleus with its decay.

Reconstruction of the atomic and mass numbers of fission fragments: ²⁵²Cf fission source results



- ²⁵²Cf properties:
 - Half-Life: 2.645 years.
 - Decay Modes: Alpha Emission (~96.9%)
Spontaneous Fission (~3.1%)
 - Neutron Yield: 1 mg emits $\sim 2.3 \cdot 10^6$ neutrons/second

- * Ex. data: Eur. Phys. J. A (2025) 61: 5 V. Piau, et al.

- * Measured pairs of energies (E_1, E_2) for two fission fragments: $1.732 \cdot 10^9$ events.
Ex. values: $E_N = 2.1$ MeV, $E_Y = 0.8$ MeV, $n_Y = 9$.

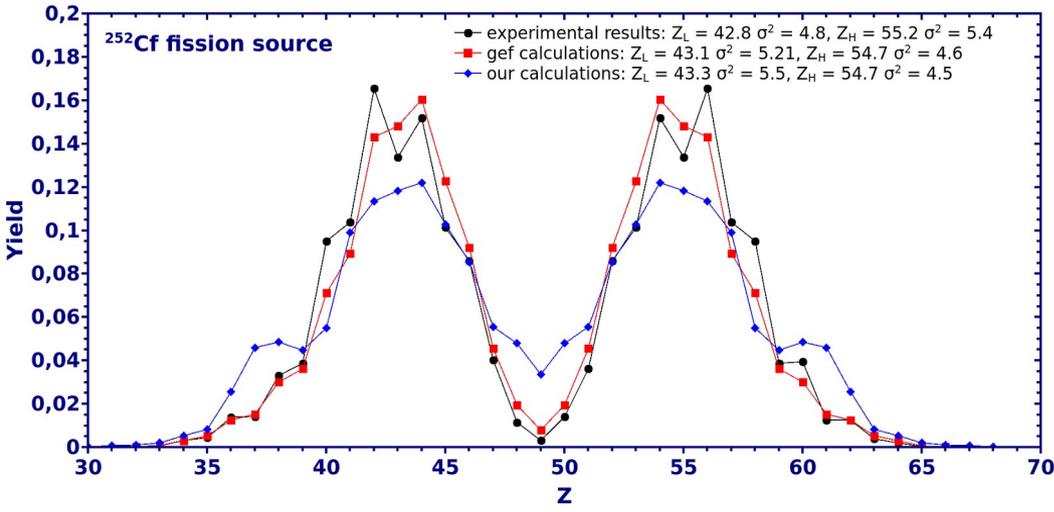
- A_{post}, Z, N and $Y(n)$ reconstructed using equation (**).

- The probability distribution of the number of prompt neutrons reaches a maximum at 4 neutrons.

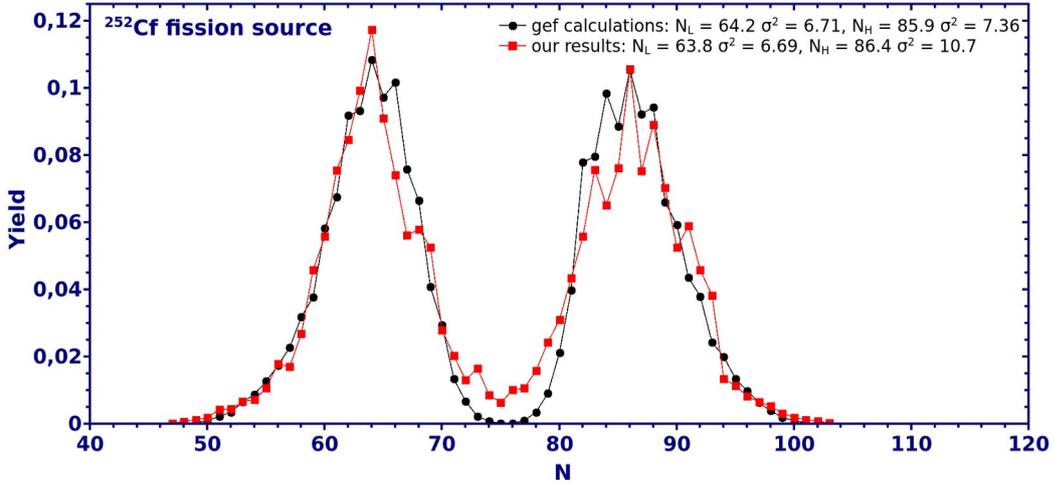
- The A_{post} distribution of the fragments exhibits two peak structure at $A_L \approx 107$ and $A_H \approx 141$.

- $A_L + A_H + n_v = A_{252Cf}$

Reconstruction of the atomic and mass numbers of fission fragments: ²⁵²Cf fission source Results



- The proton distribution of the fragments, displaying two distinct maxima. The left maximum corresponds to $Z_L \approx 43$ and the right one to $Z_H \approx 55$.
- $Z_L + Z_H = Z_{252\text{Cf}}$.
- Observed maximum is shifted by 4 protons from this magic number.



- The neutron distribution of the fragments to peak structure. The left maximum corresponds to $N_L \approx 64$ and the right one to $N_H \approx 86$.
- $N_L + N_H + n_v = N_{252\text{Cf}}$.
- Reconstructed A_{post} , Z , N and $Y(n)$ distributions well reproduce shapes and position of the maximums those from the experimental data and GEF calculations.

■ **Conclusions**

- Study fission isomers properties of $^{240f, 242f}\text{Am}$ were performed at the IGISOL facility.
- It was possible to measured the kinetic energy spectra of the single fission fragments from fission isomers. Typical for fission two peak distribution of kinetic energy yield were received.
- The pre-neutron emission mass distributions were calculated from the kinetic energy spectra of the single fission fragments using 2E method. Distributions to be strongly asymmetric.
- Method of reconstruction of the atomic and mass numbers of fission fragments were proposed.
- Obtained results were compered with GEF calculations and previously measurements, which are in good agreement.
- The proof-of-principle investigations done successfully for the deuteron induced reactions on the ^{242}Pu target proposed in the present experiment, there will be a series of potential experiments can be done at IGISOL for studies on fission isomers in the near future.

Thank you for your attention!