Time-projection chamber for investigating the spontaneous fission of superheavy nuclei

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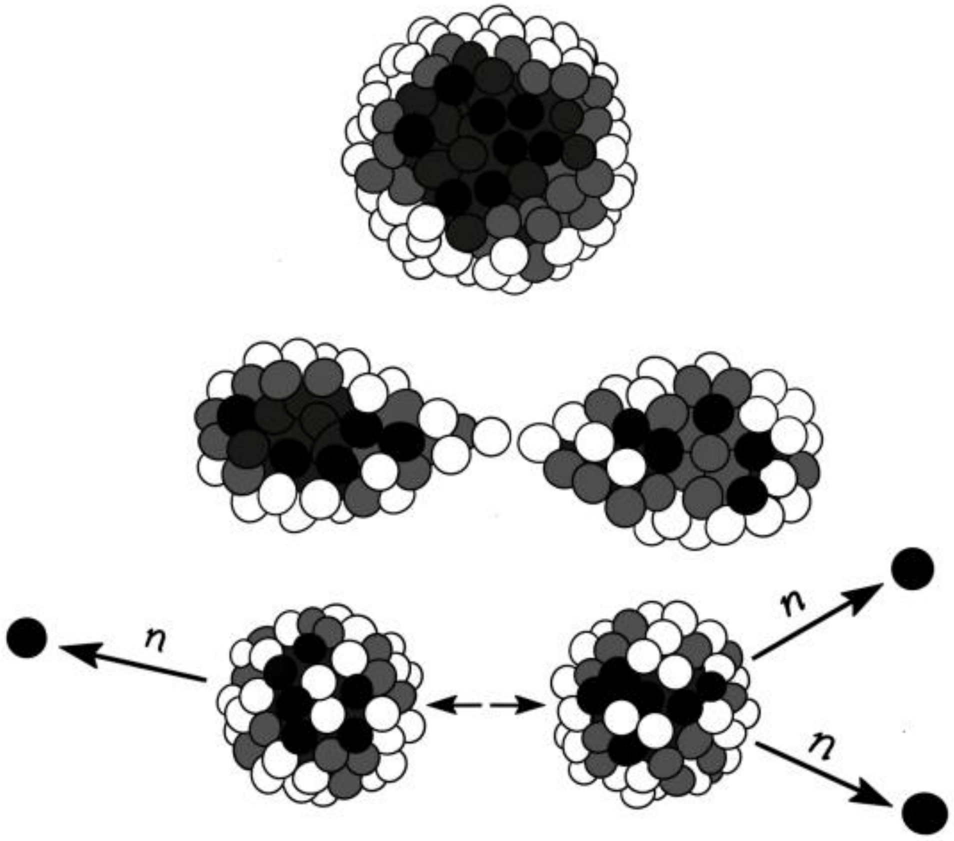
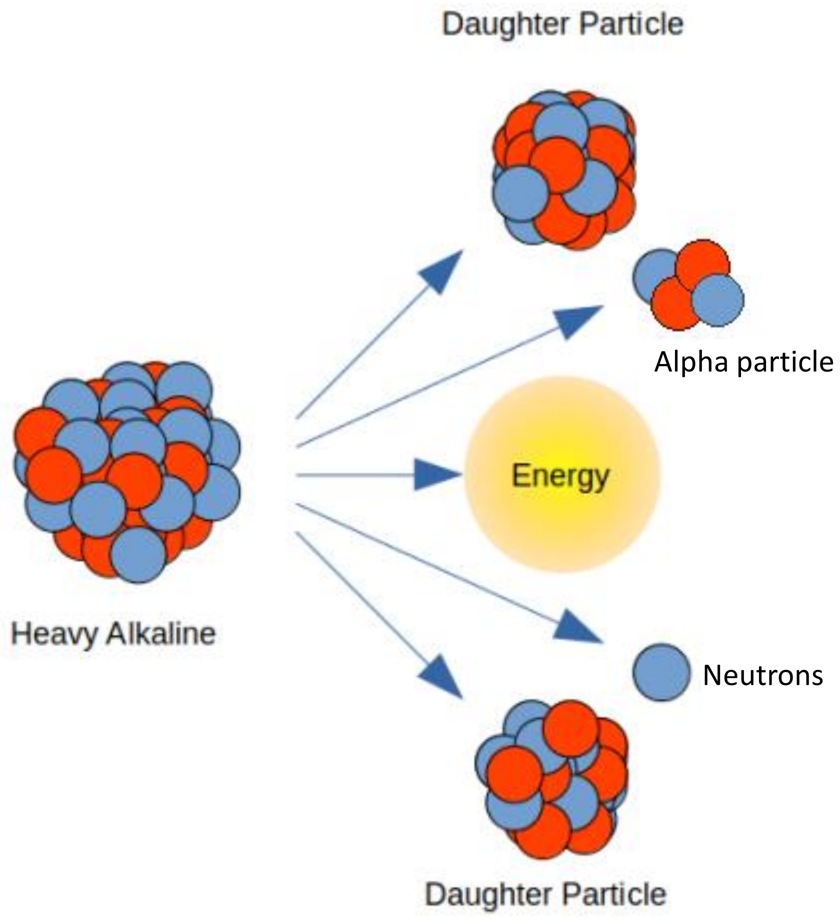
Investigating Superheavy Nuclei

The study of spontaneous fission processes in superheavy nuclei is an important task in nuclear physics. Spontaneous fission provides unique insights into the structure and stability of nuclei. A Time-Projection Chamber (TPC) accurately detects the trajectories and energy of fission fragments. We are developing a TPC-based detector for installation at the focal plane of the GRAND separator at the SHE Factory.



The TPC-based detector will have the capability to register rare ternary fission events, capturing key parameters of the process.



Ternary fission

Is the process in which a heavy nucleus splits into three fragments, rather than two as in standard binary fission.

Fragment Formation

Typically, two large fragments and one smaller one, such as an alpha particle, are formed during ternary fission.

Role of Shell Effects

This process is enabled by strong shell effects that lower the fission barriers. The detector will measure the trajectories and energy release of all three fragments, enhancing our understanding of fission mechanisms.

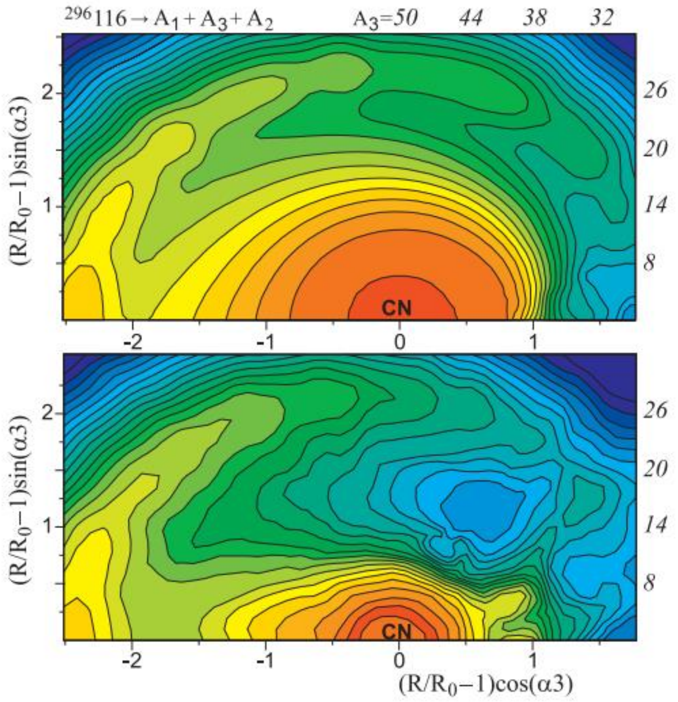
True ternary fission of superheavy nuclei

Role of Shell Effects and Potential Energy Surface

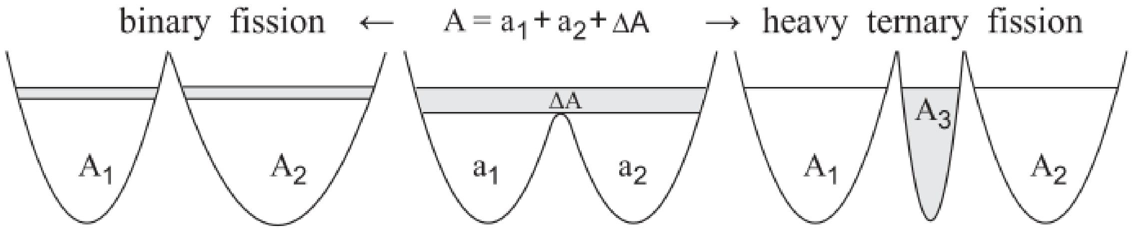
Shell effects play a crucial role in true ternary fission of superheavy nuclei. These effects lower the fission barriers, making the ternary fission process more likely.

For the nucleus ^{296}Lv, theoretical models predict the formation of two tin-like fragments and a smaller third fragment, such as sulfur.

Potential energy surfaces for such nuclei show deep minima, indicating energetically stable configurations where ternary fission becomes feasible.



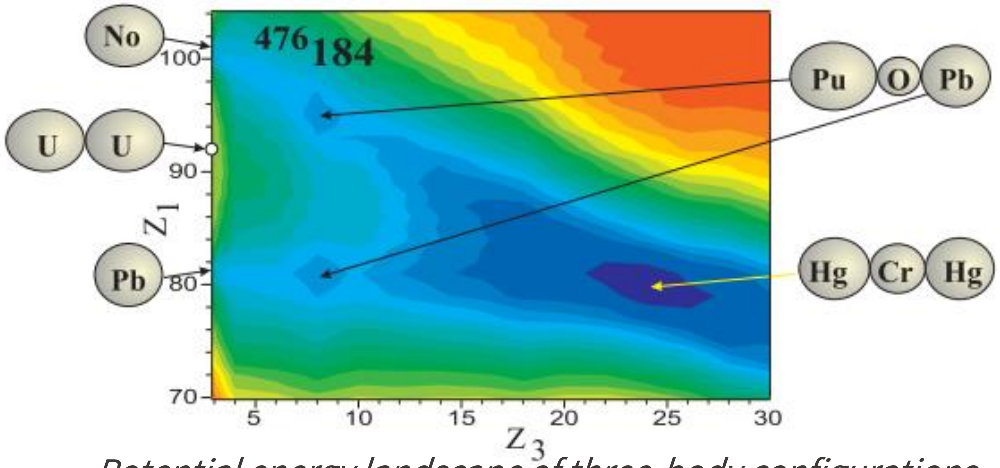
Potential energy surface for the superheavy nucleus ^{296}Lv. Fig. from reference [1].



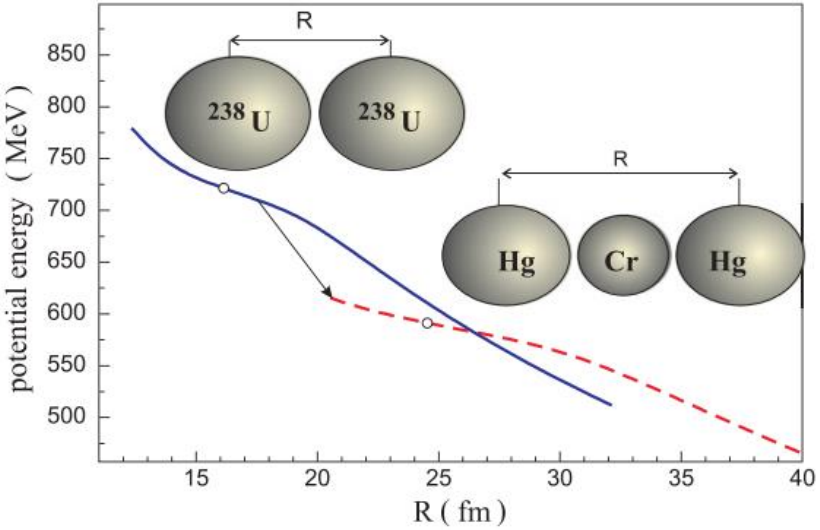
Schematic view of binary and ternary fission. Fig. from reference [1].

[1] Zagrebaev, V. I., Karpov, A. V., & Greiner, W. (2010). True ternary fission of superheavy nuclei. Physical Review C, 81(4), 044608.

Experimental Significance and Detection



Potential energy landscape of three-body configurations formed in U+U collisions. Fig. from reference [1].



Radial dependence of the potential energy of two uranium nuclei (solid curve) and of the three-body nuclear configuration formed in the $^{238}U + ^{238}U$ *collision (dashed curve). Fig. from reference [1].*

True ternary fission remains unobserved in low-energy reactions, but theory predicts its likelihood for superheavy nuclei.

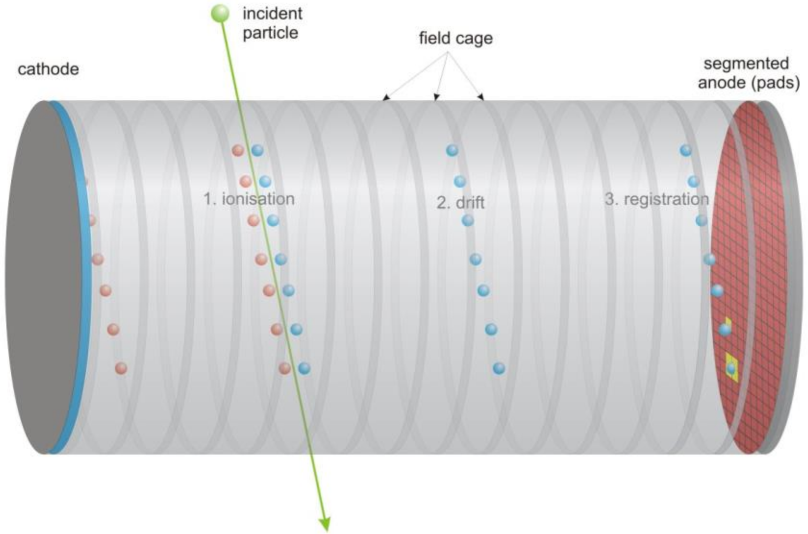
Experimentally, the process could be detected in low-energy *U+U* collisions, where the formation of three fragments is possible.

Advanced detection systems like Time Projection Chambers (TPCs) are required to accurately observe ternary fission by tracking the trajectories and energy release of all three fragments.

[1] Zagrebaev, V. I., Karpov, A. V., & Greiner, W. (2010). True ternary fission of superheavy nuclei. Physical Review C, 81(4), 044608.

What is a TPC Detector?

A Time-Projection Chamber (TPC) is a detector widely used in high-energy and nuclear physics. Its operation is based on the ionization of gas by a charged particle passing through the chamber. Electrons created by ionization drift under an electric field towards the anode, where they are detected, allowing the reconstruction of the particle's track in time and space.



Three Phases of Particle Detection in a TPC: Ionization, Drift, and Registration

One of the main advantages of the TPC is its ability to provide three-dimensional particle tracking and measure ionization density, which offers insights into the particle's energy loss.

TPCs are essential for studying complex interactions, including nuclear reactions and heavy nuclei fission, ensuring highly accurate spatial and temporal event reconstruction.

Fission TPC Example

The chamber described in article [2] is used for offline studies of spontaneous fission with long-lived isotopes, as well as for neutron-induced fission.

Key features of the detector:

1

Operating Principle:

The fission TPC records fission fragment tracks, considering specific ionization energy loss, trajectory angles, and track lengths.

2

Design:

It consists of two internal volumes separated by a target where the neutron beam induces fission.

3

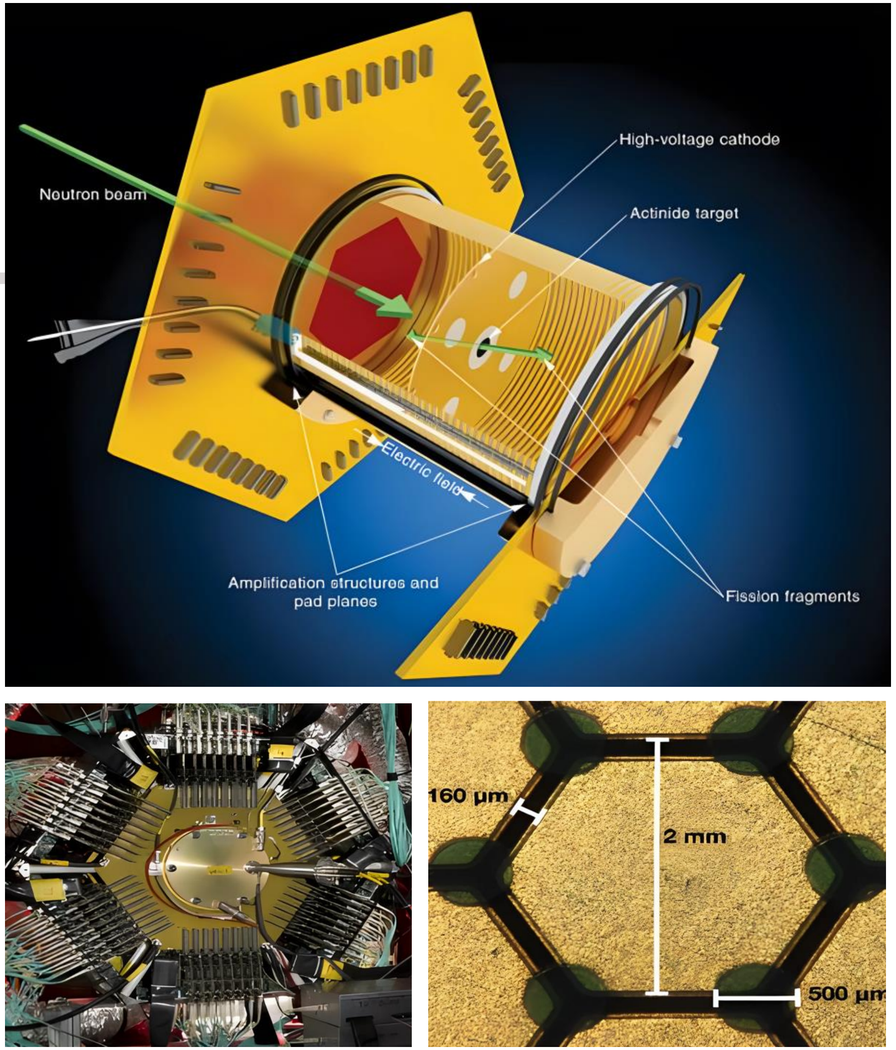
Sensitive Gas:

A mixture of argon and isobutane is employed to facilitate ionization and energy deposition from charged particles.

4

Signal Readout:

Signals from ionization electrons are amplified and read out from hexagonal pads, providing 4π coverage and high measurement accuracy.



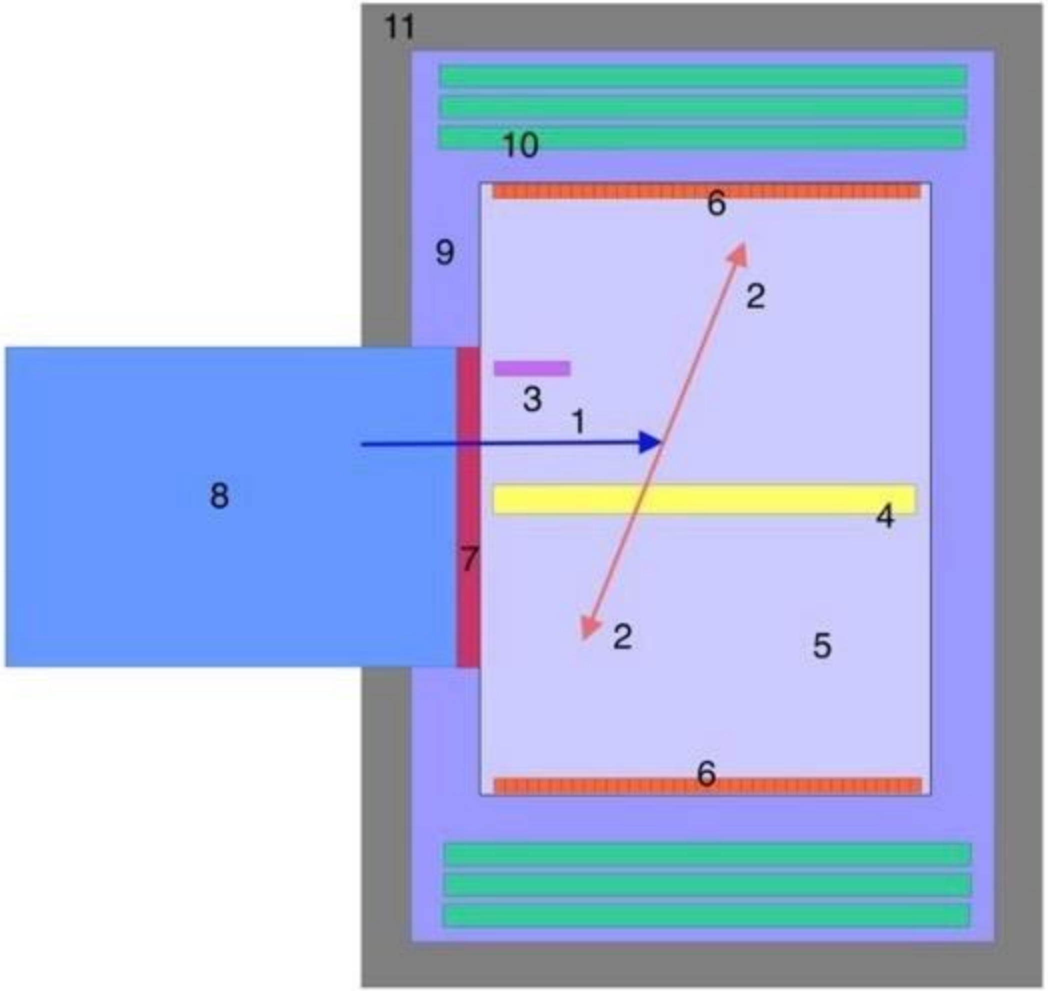
The NIFFTE fission TPC rendering, internal hardware, and pad size. Fig. from reference [2].

[2] *Kemnitz, A. (2017). Investigation of neutron induced ternary fission with the NIFFTE time projection chamber: A senior project. California Polytechnic State University.*

Limitation: The chamber is not suitable for short-lived superheavy elements.

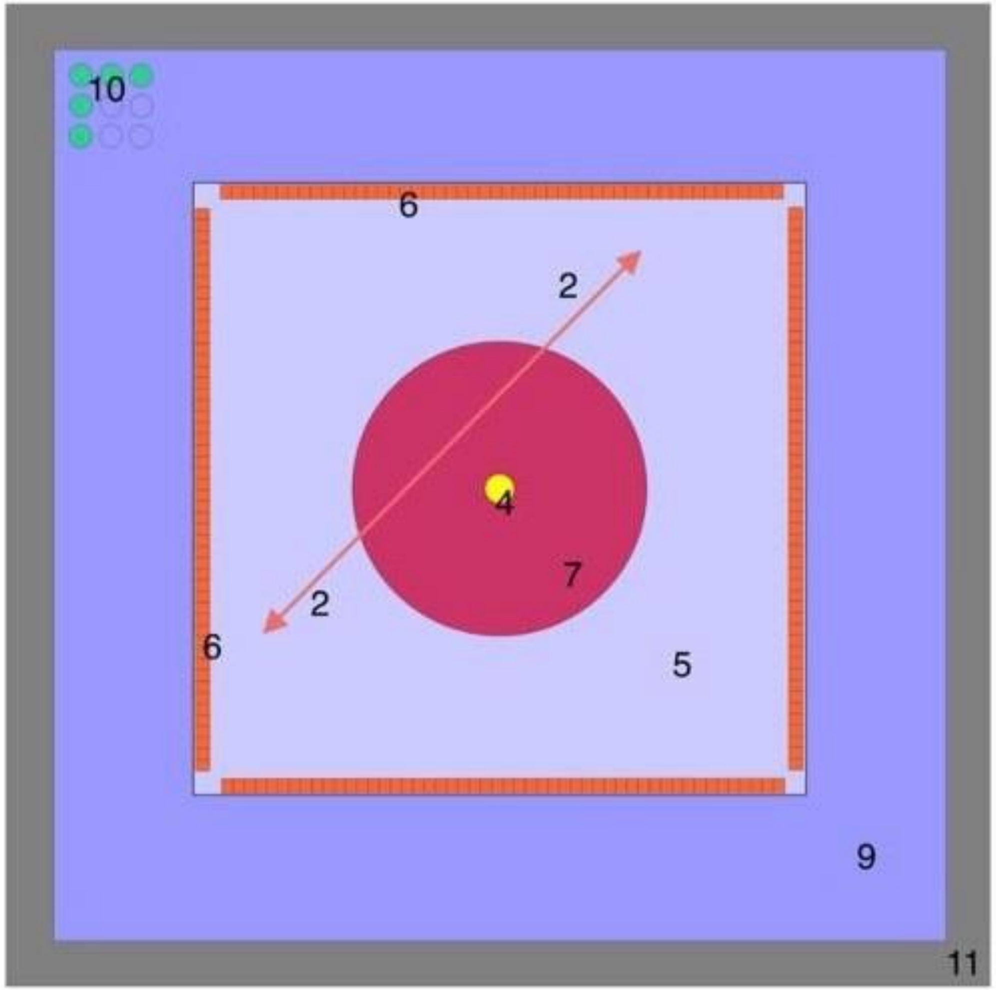
Our Concept: SHE Fission TPC

Detector design based on a TPC with 4 position-sensitive anodes (side view – left; beam view – right). **Legend:** 1 – recoil nucleus, 2 – fission fragments, 3 – position for placing the fission source, 4 – cathode, 5 – gas volume of the Time-Projection Chamber, 6 – anodes, 7 – separating foil (aluminized Mylar), 8 – ion guide of the GRAND separator filled with helium (or hydrogen), 9 – neutron moderator made of polyethylene, 10 – neutron counters filled with ^{3}He gas (7 atm), 11 – neutron background shielding (5% boron-loaded polyethylene).



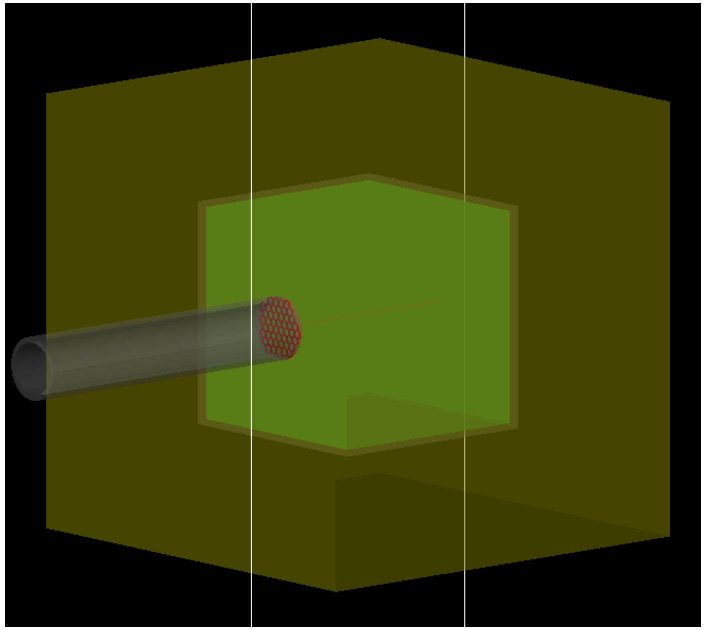
Detector design based on a TPC with 4 position-sensitive anodes (side view – left; beam view – right).

Legend: 2 – fission fragments, 4 – cathode, 5 – gas volume of the Time-Projection Chamber, 6 – anodes, 7 – separating foil (aluminized Mylar), 9 – neutron moderator made of polyethylene, 10 – neutron counters filled with ^{3}He gas (7 atm), 11 – neutron background shielding (5% boron-loaded polyethylene).



Geant4 Simulation

Geant4 is a software tool for simulating the passage of particles through matter, developed at CERN. It is widely used in high-energy physics, medical physics, and space research to model complex particle interactions with materials and radiation.

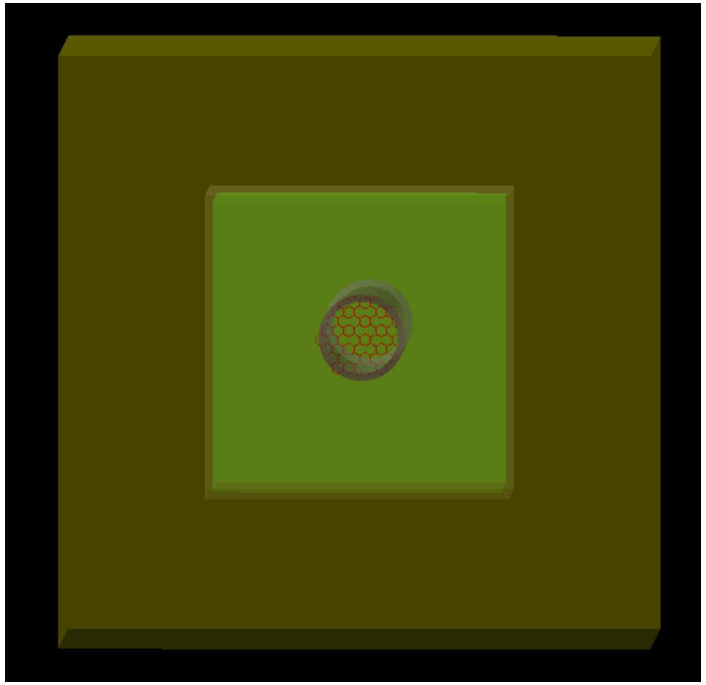


For our project, **Geant4** is used to simulate the behavior of fission fragments within our Time Projection Chamber (TPC) detector system. The primary goals include:

1 **Modeling** how fission fragments interact with the detector materials.

2 **Calculating** energy losses as particles pass through gas and detector elements.

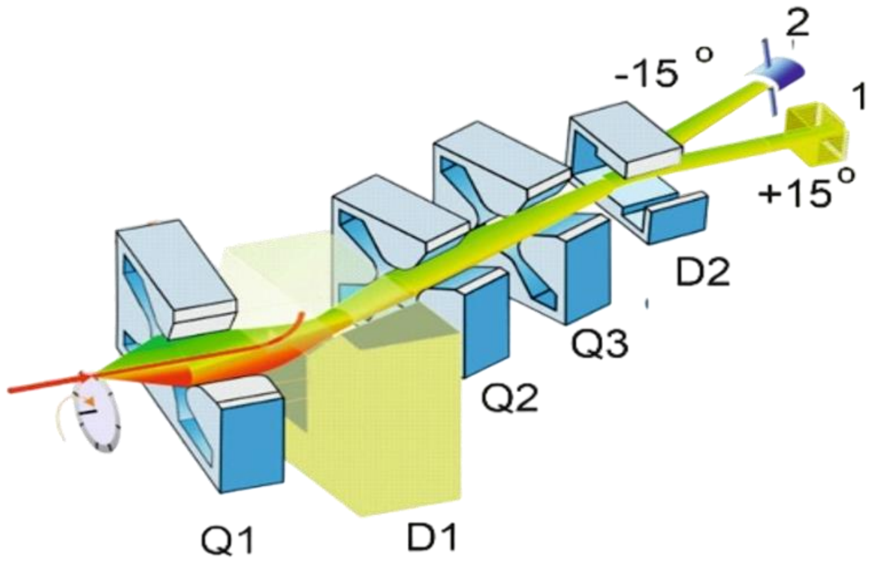
3 **Simulating** the track formation of fission fragments to understand detector efficiency.



Planned Installation Location: At the focal plane of the GRAND separator (SHE Factory).

The GRAND Separator

The GRAND Separator is a state-of-the-art gas-filled separator designed for studying superheavy elements. It was developed at the Flerov Laboratory of Nuclear Reactions in Dubna and is installed at the **Superheavy Element Factory (SHE Factory)**. The primary function of the separator is to isolate and guide recoil nuclei (reaction products) from background particles that are created in nuclear fusion reactions. GRAND is optimized for experiments involving the synthesis of new superheavy elements, α-, β-, and γ-spectroscopy, and other types of nuclear research.



Schematic of the GRAND Gas-Filled Separator, where: 1 — focal plane; 2 — location of the "chemical" gas cell for stopping recoil nuclei; Q1-Q3 — quadrupole lenses; D1-D2 — dipole magnets. Fig. from reference [3].

How the GRAND Separator Works:

1. **Nuclear Reaction:** Heavy ions collide with a target, creating a range of particles, including recoil nuclei.
2. **Separation:** The nuclei travel through a gas-filled chamber, where magnetic and electric fields guide them towards the focal plane.
3. **Detection:** The recoil nuclei are focused onto the focal plane, where detectors, including the future **TPC detector**, measure their properties.

[3] Eremin A. V., *et al.* Methodology of physical experiment: Universal gas-filled separator GRAND. First experimental results // *PEPAN Letters*. 2024. Vol. 21, No. 3(254). P. 647–659.

The SHE Factory

The Superheavy Element Factory (SHE Factory) is a research facility located at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. It is dedicated to the synthesis and study of superheavy elements (SHEs) with atomic numbers greater than 112. The goal of the facility is to expand the periodic table by synthesizing new elements, such as those with atomic numbers 119 and 120. In 2019, the SHE Factory produced five new isotopes, significantly advancing our understanding of nuclear stability in superheavy nuclei.

DC-280 Cyclotron

The DC-280 cyclotron is the key installation of the SHE Factory, capable of generating powerful ion beams (up to 60×10^{12} ions per second). This beam intensity allows for more efficient synthesis of new elements, especially those with very low production probabilities.

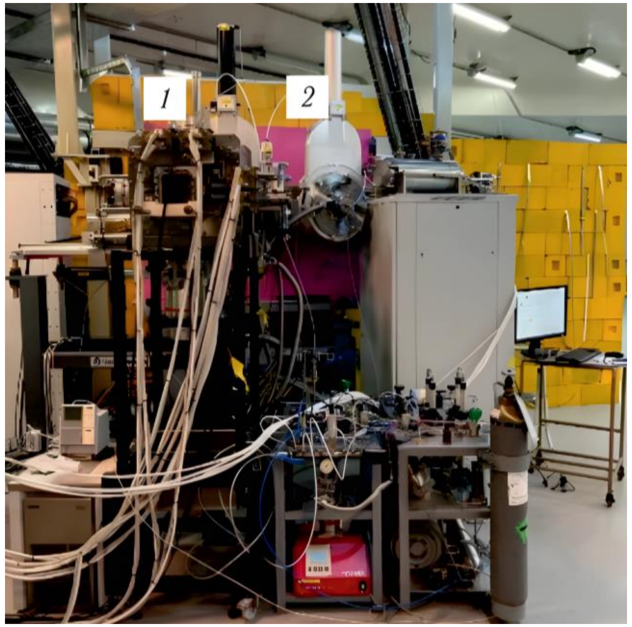


Photo of the detecting devices of the GRAND gas-filled separator. Focal plane - 1, location of the "chemical" gas cell for stopping recoil nuclei - 2.

Measured Quantities:

Fission events are analyzed to determine the kinetic energies, masses, and other properties of the daughter nuclei, providing deeper insights into the nuclear structure of the parent nucleus and the mechanisms of spontaneous fission, including interactions between the fragments and emitted particles.

1

Fission Fragment Energy Release (TKE and Mass Distributions)

TKE is the sum of the kinetic energies of the fragments, providing insight into how fission energy is distributed. Mass distribution shows how fragment masses split.

2

Fragment Trajectories

Are the paths of the fission fragments. Measuring these paths helps understand their movement and reconstruct the fission event.

3

Bragg Curves

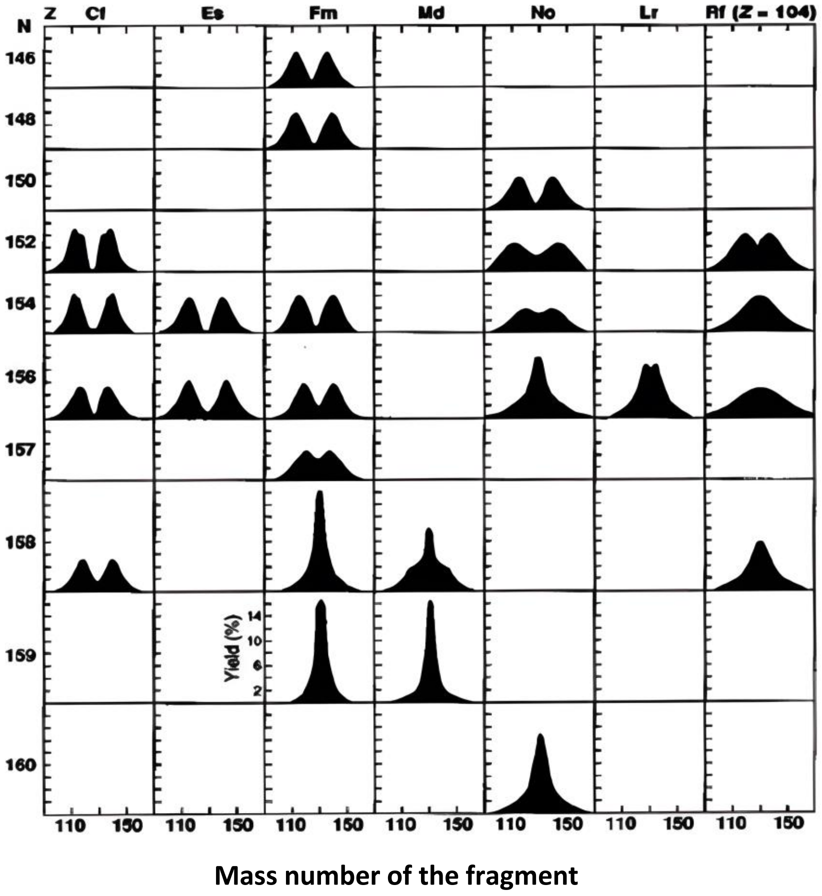
Illustrate how fission fragments lose energy as they travel. This is crucial for determining their total energy and deceleration in the detector gas.

4

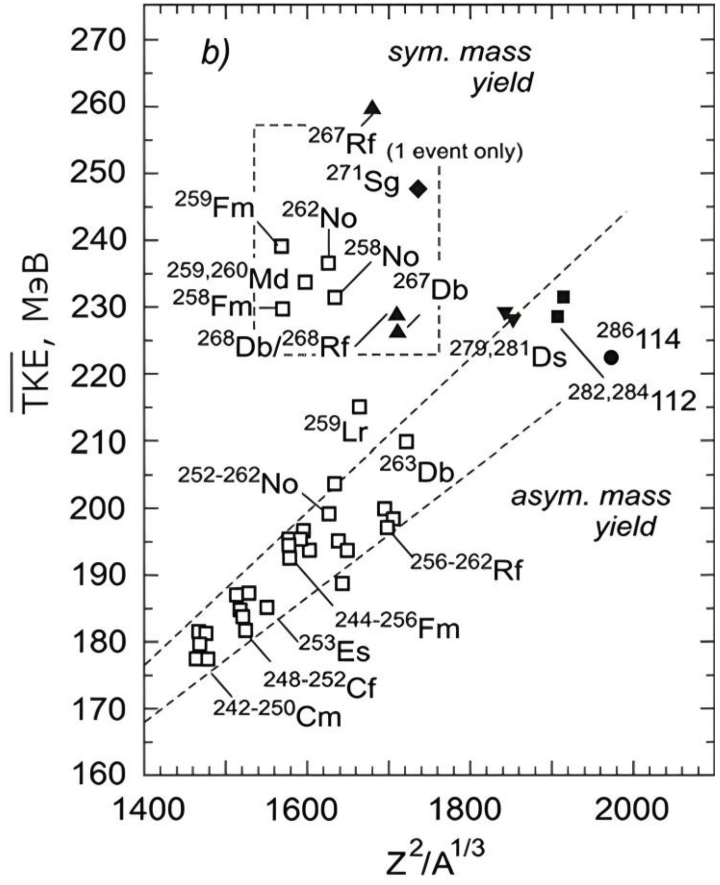
Multiplicity of Prompt Fission Neutrons

Refers to the number of neutrons emitted during fission. Measuring this is important for understanding fission energetics and reactions in superheavy nuclei.

Conclusion: The Need for a New Detector



Mass Yield Distributions for Fission Fragments Across Different Heavy Isotopes. Fig. from reference [4].



Total Kinetic Energy (TKE) of Fission Fragments vs. $Z^2/A^{1/3}$ or Various Heavy and Superheavy Nuclei. Fig. from reference [5].

Fission Fragment Mass Distributions, Neutron Data and TKE:

Mass distributions for fission fragments, total kinetic energy (TKE), and neutron data are well-documented for certain isotopes. However, current data on superheavy nuclei, especially regarding neutron emission and TKE, remain limited, restricting our ability to advance fission models.

Next Step:

A new detector is essential to capture mass distributions, TKE, and neutron data with higher precision. This will enable more detailed studies of fission mechanisms and improve our understanding of superheavy nuclei.

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[4] Hoffman D. C., Lane M. R. Spontaneous fission, RCA 70/71 (1995) P. 135–146
[5] Oganessian, Yu. Ts. "Heaviest nuclei from 48Ca-induced reactions." Journal of Physics G: Nuclear and Particle Physics, vol. 34, no. 4, 2007, pp. R165–R242.

Thank you for your attention!