Systematic studies to produce heavy above-target nuclides in multinucleon transfer reactions

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India-JINR Workshop on Particle, Nuclear, Neutrino Physics and Astrophysics

November 10-12, 2025

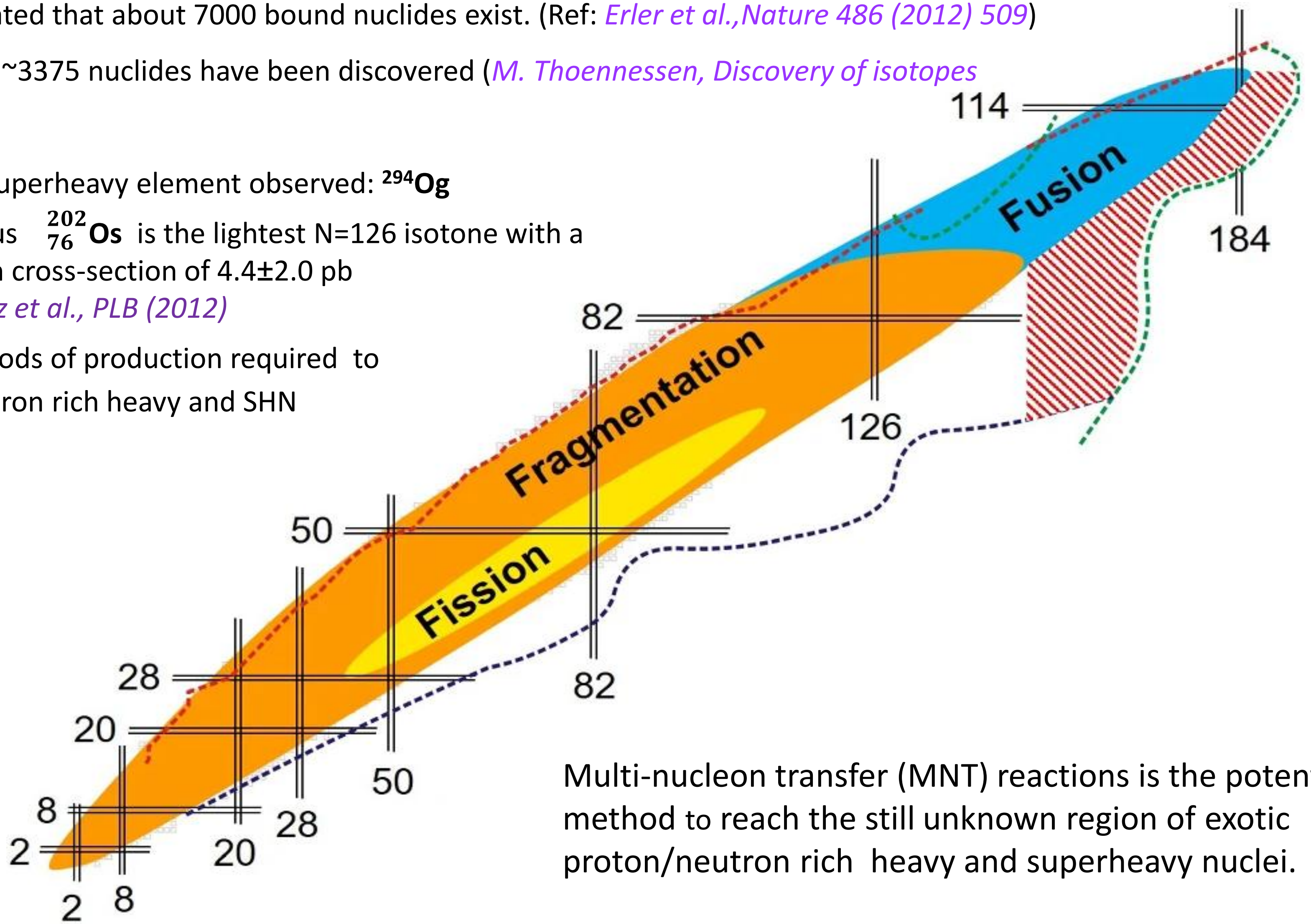
NISER Bhubaneswar, India

Outline

- ✓ Motivation
- ✓ MNT Experiments at velocity filter SHELS
- ✓ Plans for Future MNT Experiments at FLNR

Motivation

- It is estimated that about 7000 bound nuclides exist. (Ref: *Erler et al.,Nature 486 (2012) 509*)
- Until now, ~3375 nuclides have been discovered (*M. Thoennessen, Discovery of isotopes project*)
- Heaviest superheavy element observed: ^{294}**Og**
- The nucleus $^{202}_{76}$**Os** is the lightest N=126 isotone with a production cross-section of 4.4±2.0 pb
  J. Kurcewicz et al., PLB (2012)
- New methods of production required to reach neutron rich heavy and SHN



Multi-nucleon transfer (MNT) reactions is the potential method to reach the still unknown region of exotic proton/neutron rich heavy and superheavy nuclei.

Experiment on transfer reaction

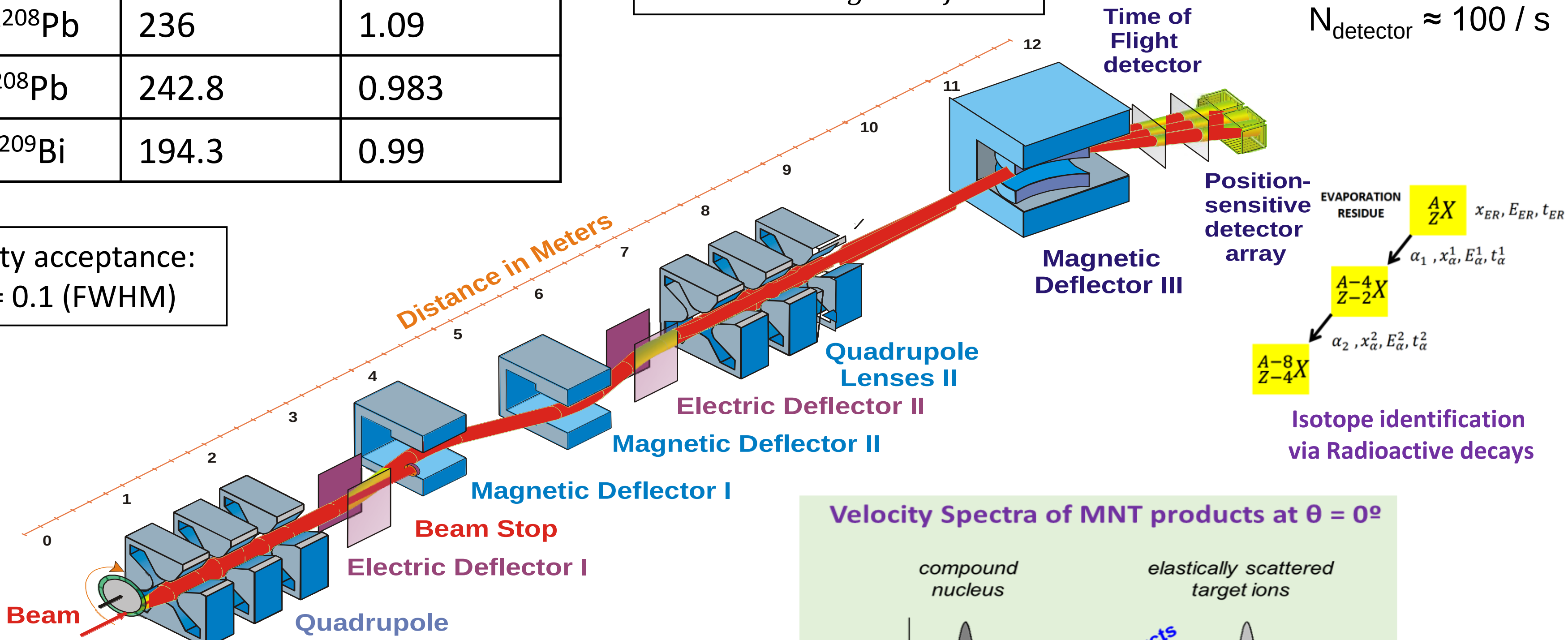
Separator for Heavy ELement Spectroscopy (SHELS) - FLNR

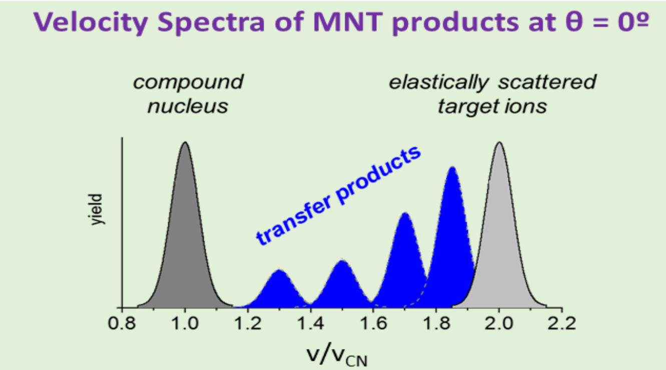
Separation + Single Event Identification

Reactions	E_{lab} / MeV	E_{lab}/B_{int}
$^{48}Ca+^{208}Pb$	236	1.09
$^{50}Ti+^{208}Pb$	242.8	0.983
$^{40}Ar+^{209}Bi$	194.3	0.99

$$velocity \sim \frac{Electric\ field}{Magnetic\ field}$$

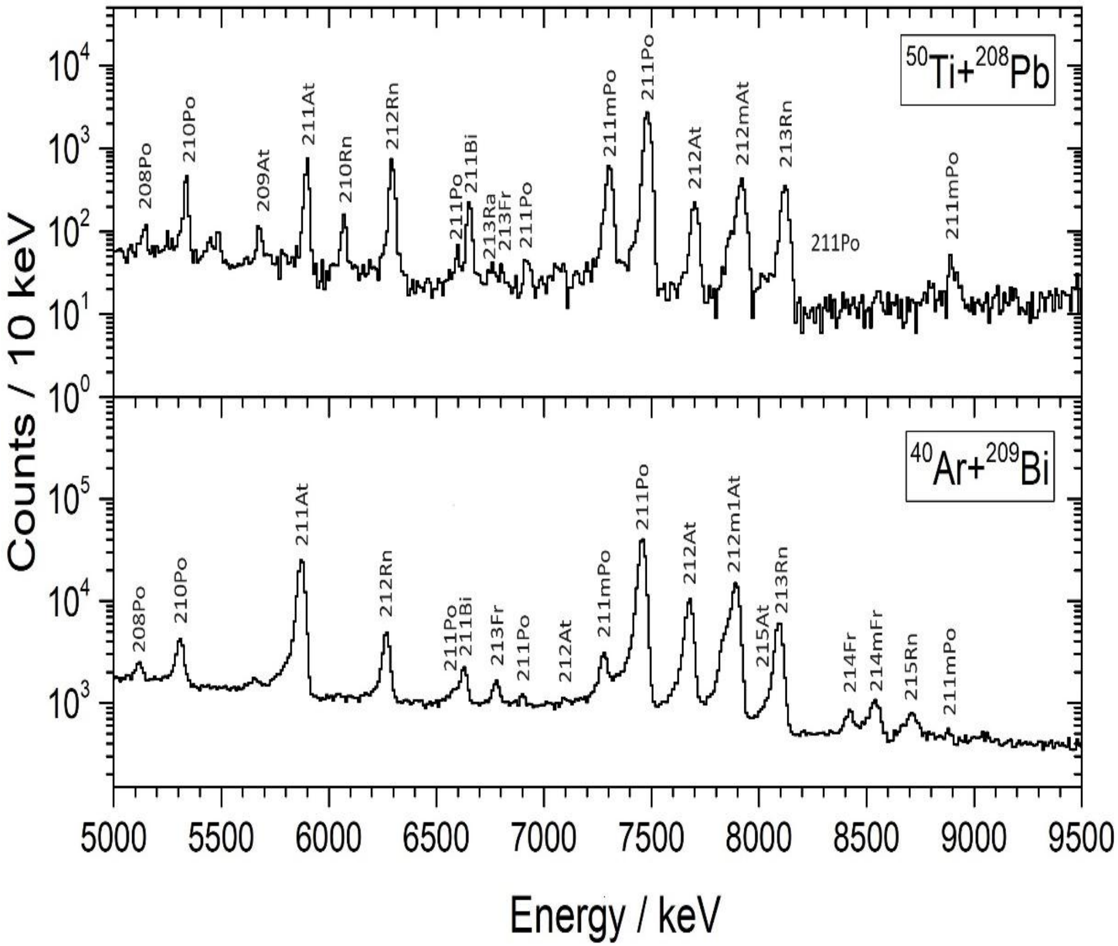
Velocity acceptance:
$\Delta v/v = 0.1$ (FWHM)



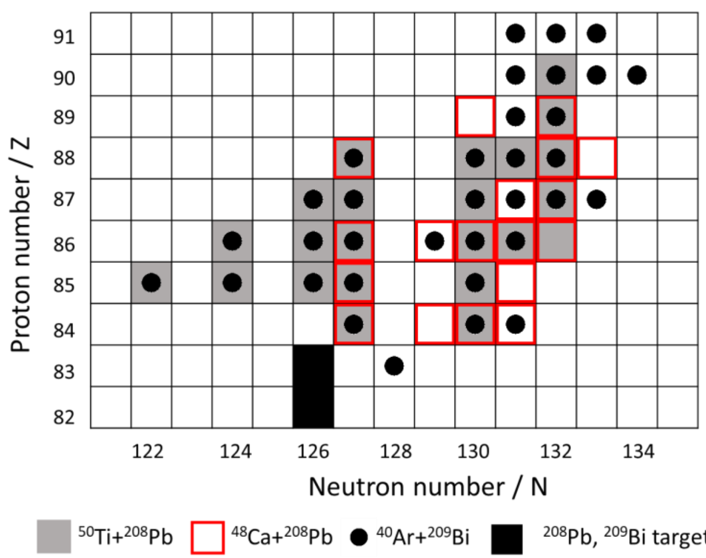


Measured alpha spectra and identified region

SHELS Results: $^{48}Ca+^{208}Pb$, $^{50}Ti+^{208}Pb$ and $^{40}Ar+^{209}Bi$



- Spectrum was taken at the time of the experiment
- Strongly populated reaction products with half-lives up to few minutes were identified unambiguously
- Rarely populated nuclei up to single event identification was performed using Recoil-alpha-alpha correlation method
- Up to the transfer of **8p+7n channels from projectile to the target have been observed**



H.M. Devaraja, A.V. Yeremin, et al., *Phys. Lett. B* ***862****, (2025) 139353.*

Isotopic distributions of the observed isotopes

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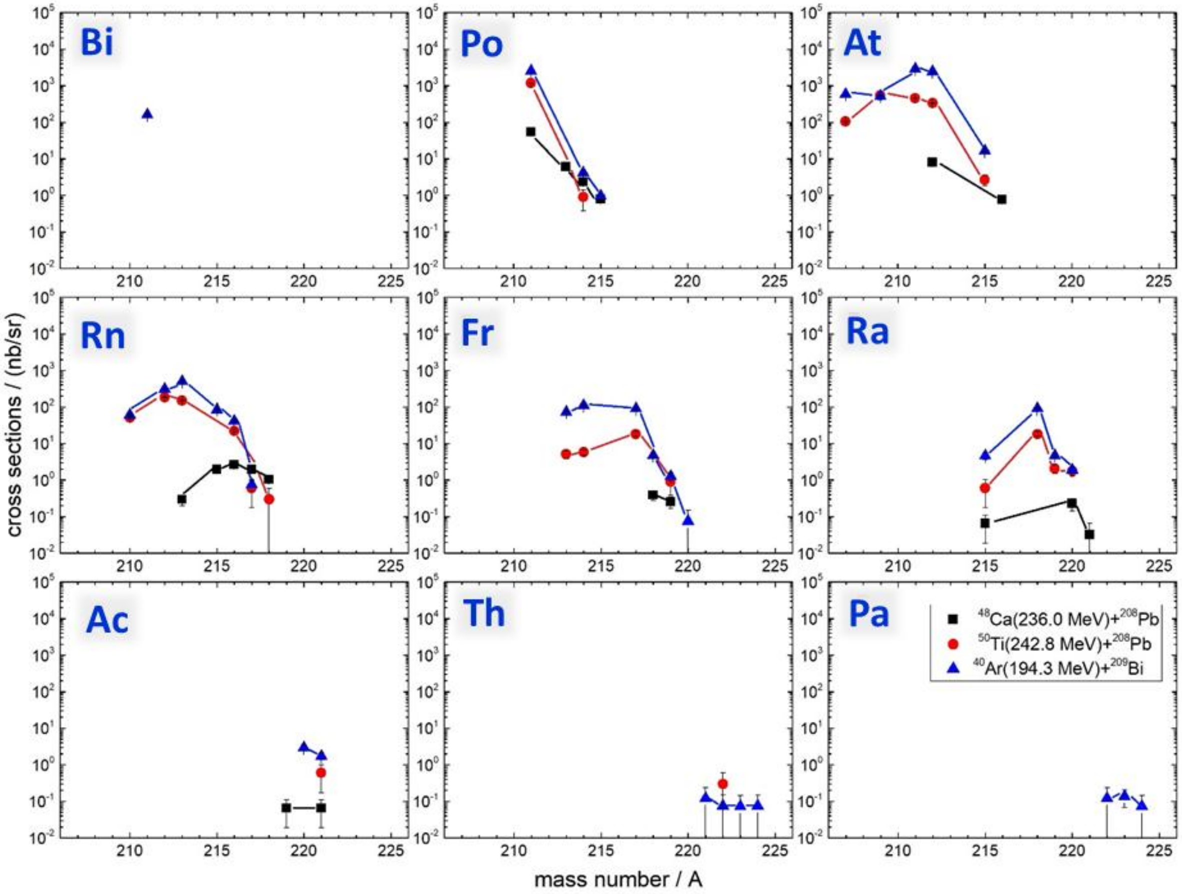
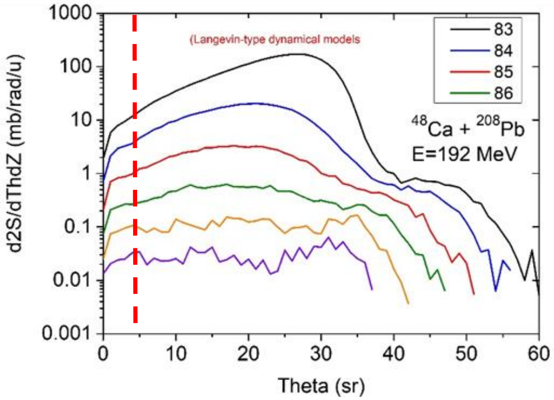


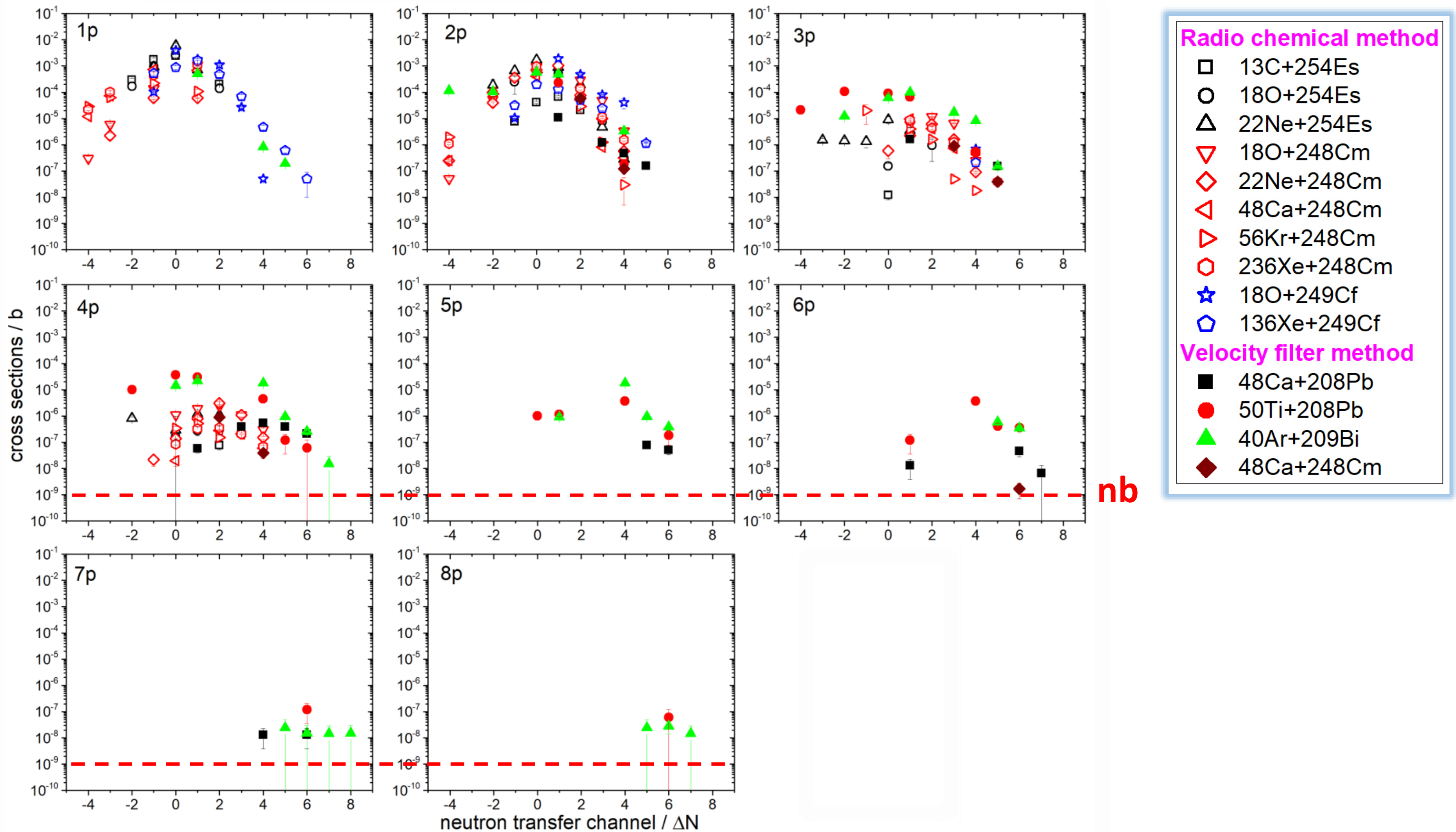
Calculations : V. V. Saiko and A. V. Karpov (2019)



Projectiles	Intensity /pμA		
	Used in present experiment	Max. available at U400	Future U400R
^{40}Ar	0.125	1.44	4.8
^{48}Ca	0.280	1.20	3.2
^{50}Ti	0.05	1.0	3.0

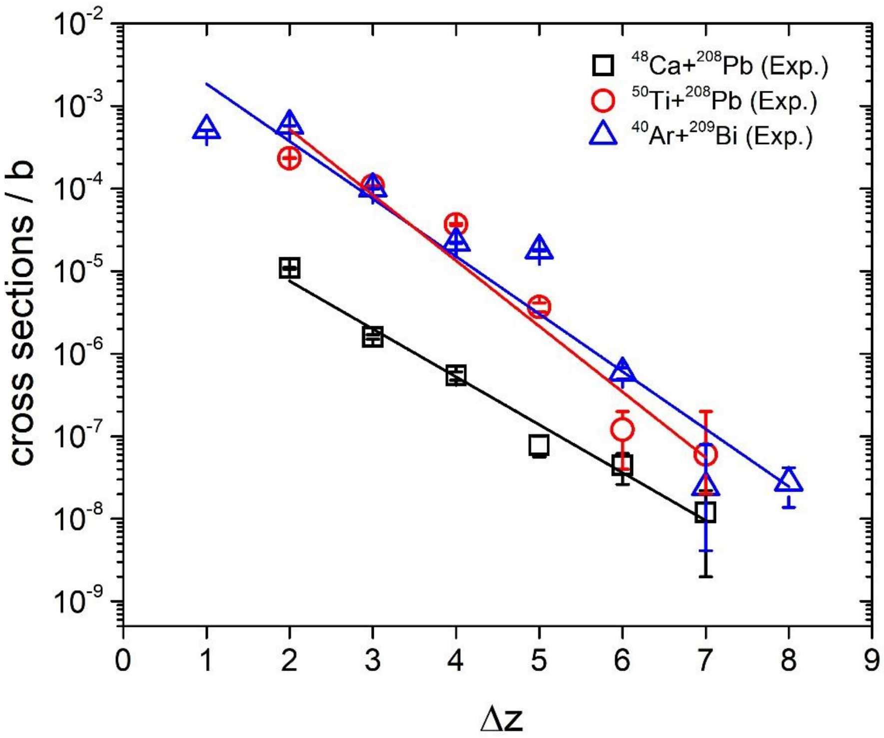
- The cross-sections are differential cross-sections related to the SHELS acceptance angle of **(0±4)** degrees.
- The **lowest measured cross-sections were on the level of 50 pb/sr,** resulting from 5 hours of data taking at the respective velocity setting at the given beam intensity and target thickness, which leads to about **1 nb total cross-sections**
- With our full available beam intensity one could reach up to **0.05-0.1 nb cross-section, with this possible to reach transfer of 10p+10n channel**
- Full angular distribution measurement help us to access **wide range of isotopes of elements**

Comparison with the radiochemical method



- Cross-sections are corresponding to the total cross-sections, **presented in terms of proton and neutron transfer channels**
- All the available experimental data from various neutron rich projectiles incident on the heaviest available actinide targets ^{248}Cm, ^{249}Cf and ^{254}Es are compared with our velocity filter data for the neutron and proton transfer channels

Systematics of above target MNT product cross-sections



- In both above-target regions (Pb or Bi and actinide), we observe a cross-section decrease with increasing number of protons moving from the projectile to the target nucleus.
- The curves diverge with increasing ΔZ when comparing reactions involving Pb or Bi targets with those involving actinide targets. We account this to the larger fissility of the heavier nuclei. With Cm or Cf targets we are entering the sub-nanobarn region if we transfer ≥6 protons.

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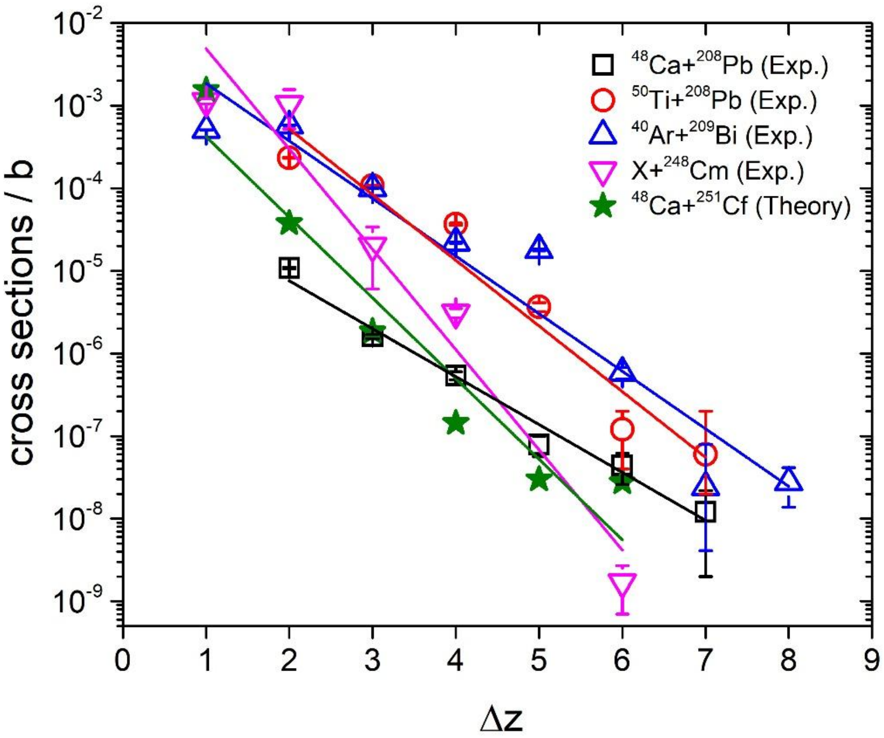

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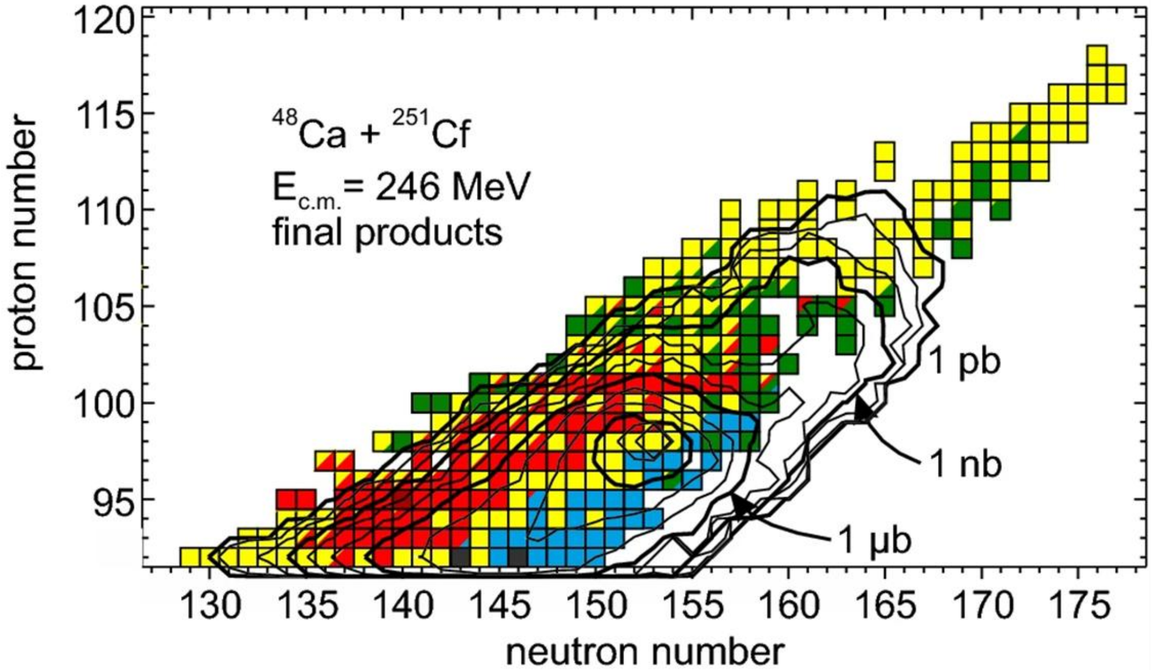
Collision of $^{48}Ca+^{251}Cf$

Calculations : V. V. Saiko and A. V. Karpov (2022)

(Langevin-type dynamical models)

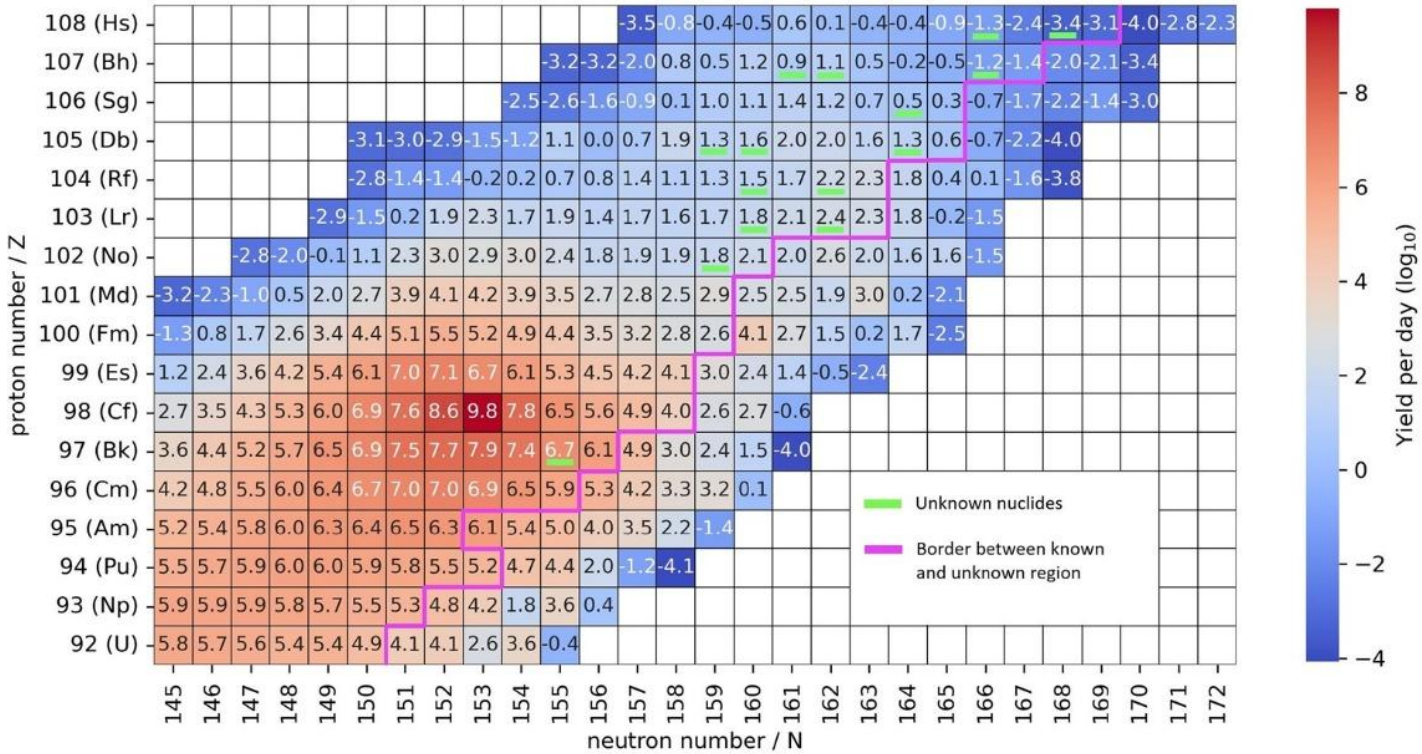


- As per the estimation, $^{48}Ca+^{249}Cf$ reaction a large area of unknown neutron-enriched isotopes of elements from **U (Z=92) to Sg (Z=106) can be explored with the cross sections exceeding 1 nb**. Which can still be measured at the present velocity filters.
- At velocity filters separation of primary beam from target-like reaction products fails more and more with **increasing symmetry of the collision** system. Hence reactions like Xe+U, U+U, U+Cm, U+Es are difficult to investigate

Expected yields at velocity filters

^{48}Ca (E_{lab} = 293 MeV, 1.2 pμA) + ^{251}Cf (500 μg/cm^2)

Transmission efficiency of 1% was assumed.

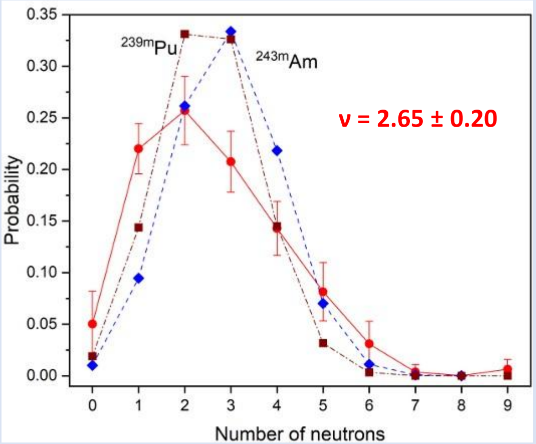


- **About 15 still unknown nuclides** are situated between the region of nuclei discovered in cold and hot fusion reactions. These isotopes can potentially be observed using MNT reactions at the present velocity filters.
- Additionally, **around 50 still unknown neutron-rich nuclides in the transuranium region**, directly joining the known region, are expected to be produced with sufficient yields to study them at the current velocity filters.

Other Major Investigations

1) $^{26}Mg + ^{238}U$ MNT reaction:

First investigation of **prompt neutrons from spontaneously fissioning isomers** (^{239m}Pu and ^{243m}Am) produced in multinucleon transfer reactions.
(Manuscript submitted to Physics Letters B)



Prompt neutron probability distributions (circles) compared with predictions by GEF model

2) $^{48}Ca + ^{238}U$ MNT reaction:

- Studied about **50 nuclides below and above the target** populated in MNT reactions.
- Cross-sections are measured and isotopic distributions are studied

3) $^{136}Xe + ^{238}U$ MNT reaction:

- Found that **beam–reaction product separation** at velocity filters becomes increasingly difficult with **more symmetric systems**.
- Reactions such as Xe+U, U+U, U+Cm, and U+Es are **challenging to study**

Overview on separation and detection techniques for MNT products:

experimental technique	σ_{min}	τ_{min}
E-dE-TOF-Bρ	$\sim 1\,\mu$b	0.1 - 1 μs
velocity filter + α decay tagging velocity filter + γ decay tagging	~ 0.5 nb $\sim 1\,\mu$b	$\sim 1\mu$s $\sim 1\mu$s
radiochemistry + α decay tagging	~ 20 nb	~ 1 min. (online tech.) ~ 30 min. (offline tech.)
laser ionization		~ 1 s
precision mass measurements		~ 1 s

- σ_{min} is the smallest MNT cross-sections which was so far measured with the respective technique
- τ_{min} is the minimum necessary lifetime of a reactions product to be detected with the respective technique

New kinematic separator for the MNT reactions studies

- The experimental limits for cross-sections and yields are already reached with beam intensities of the order of 10^{12} particles per second.

Requirements:

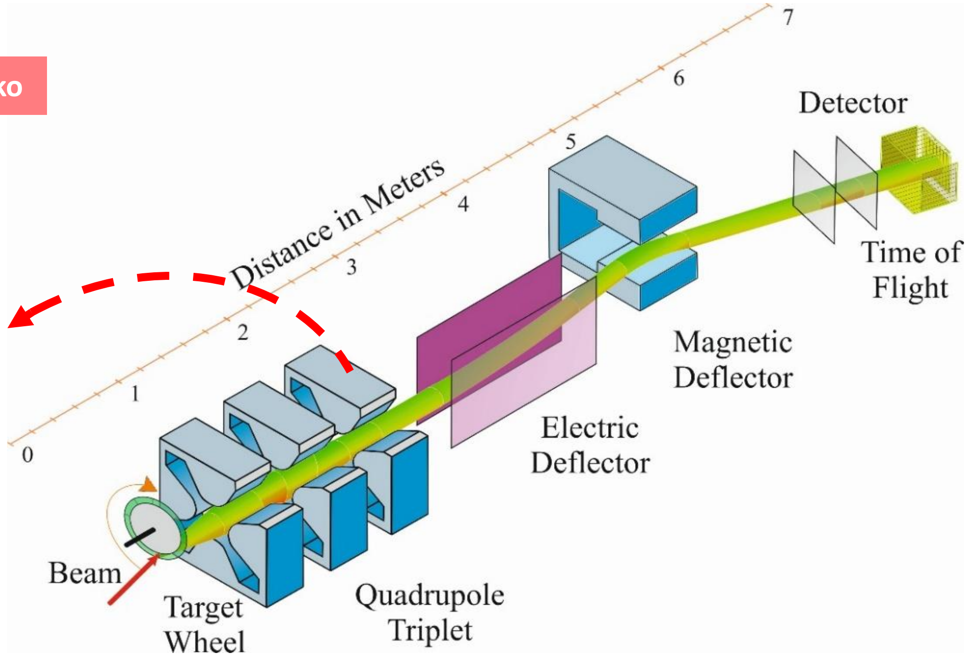
- the development of upgraded ion sources and modern accelerators able to provide high beam currents of more than 10^{14} particles/s
- development of advanced detection techniques, which allow the identification of nuclei through the simultaneous measurement of their decay properties
- development of efficient in-flight separators for both complete fusion and deep inelastic transfer products

- Within this framework a New Kinematic Separator, which is named as **Separator for TransActinide Research (STAR)** was proposed together with **the modernization of U400 cyclotron (U400R)**
- Modernized U400R will deliver **increase of beam intensity by factor of 3 and allow smooth energy variation**

STAR – Separator for TransActinide Research

Proposed conceptual plan of the new kinematic separator

Figure Courtesy: A.G. Popeko



- Optimized for **high beam intensities, high background suppression, large transmission** of heavy and superheavy nuclei produced in fusion or transfer reactions and measurement of all decay modes and mass.
- It allows analysis of MNT products under **different angles**
- After in-flight separation an investigation based on the **decay properties** of the desired nuclei can be performed using an **implantation detection system**
- To investigate very symmetric collision like U+U
- Alternatively, **multiple reflection time-of-flight mass spectrometers (MR-TOF-MS) or penning traps** can be used for non alpha-emitters with a long half-life to identify them via **mass measurements**

Conclusions and Outlook

MNT with SHELS:

- MNT studies with the in-flight separator SHELS show strong potential for producing unexplored very heavy neutron-rich nuclei, particularly with optimized setups and high intensity beams.
- However, its narrow angular acceptance of ±4° captures only forward-moving products, whereas MNT near the Coulomb barrier has a broad angular spread, limiting collection efficiency.

STAR Separator and U400R Upgrade:

- To overcome this, a new facility, the Separator for TransActinide Research (STAR), is under construction at FLNR, Dubna. STAR will allow efficient detection over a much wider angular range.
- Simultaneously, the U400 cyclotron is being upgraded (U400R) to deliver beam intensities up to 10 pμA, enabling sensitivity to production cross sections down to the picobarn level.
- Together, these upgrades will significantly expand experimental access to previously unexplored neutron-rich heavy and superheavy nuclei.

Plans for future experiments

- Carry out investigation of MNT products by performing new experiments for the reactions using various projectiles from O up to U incident on actinide targets.
- **Interested regions:** Neutron rich/deficient heavy and superheavy and Below lead N=126 astrophysical interesting region

Formation reaction and structure of heavy nuclei group at FLNR

H.M. Devaraja, M.L. Chelnokov, V.I. Chepigin , A.V. Isaev, I.N. Izosimov, A.A. Kuznetsova, O.N. Malyshev, R.S. Mukhin, A.G. Popeko, Yu.A. Popov, B. Sailaubekov, E.A. Sokol, A.I. Svirikhin, M.S. Tezekbaeva, and A.V. Yeremin

Thank you

Early studies of MNT reactions

Discoveries of new isotopes in MNT reactions

- Between 1970 and 1995, **75 new nuclides were discovered** in MNT reactions.
- Major contributing laboratories:
  - **Dubna (Russia):** Bρ–ΔE–E method
  - **LBNL (California) and Orsay (France):** TOF–ΔE–E telescopes
  - **GSI (Germany):** Online Mass Separator and Decay Spectroscopy
- The Bρ–ΔE–E and TOF–ΔE–E methods provide mass (charge) resolutions of about 1%. Therefore, they are only applicable for **lighter nuclei**, whereas the **heavy MNT products** were identified through **decay tagging.**

Radiochemical methods for isotope separation and identification in the actinide region:

- **Experimental limitations**

  Cross-section σ ≈20 nb;

  Half-lives $T_{1/2}$> 30 min.

Inflight separation:

- In recent years, using the velocity filter SHIP, MNT reactions such as: $^{58,64}Ni + ^{207}Pb$, $^{48}Ca+^{248}Cm$, and $^{48}Ca+^{238}U$ have been investigated.
- A large region of populated MNT products, both below and above the target, has been identified.
- Studies include isotopic distributions, excitation energies, and the influence of nuclear shell effects on the reaction prodcuts
- In the $^{48}Ca + ^{248}Cm$ reaction, high sensitivity allowed identification of **several new neutron-deficient transuranium isotopes**.

- **Experimental limitations**

  Cross-section σ ≈0.5nb;

  Half-lives $T_{1/2}$≥ 1 μS

The expected cross-sections **for the production of new heavy and superheavy isotopes** reach far below microbarn range. As a consequence efficient separation and detection techniques have to be applied.