The experimental study of MNT process in the reaction $^{136}Xe+^{238}U$ at energy above the Coulomb barrier

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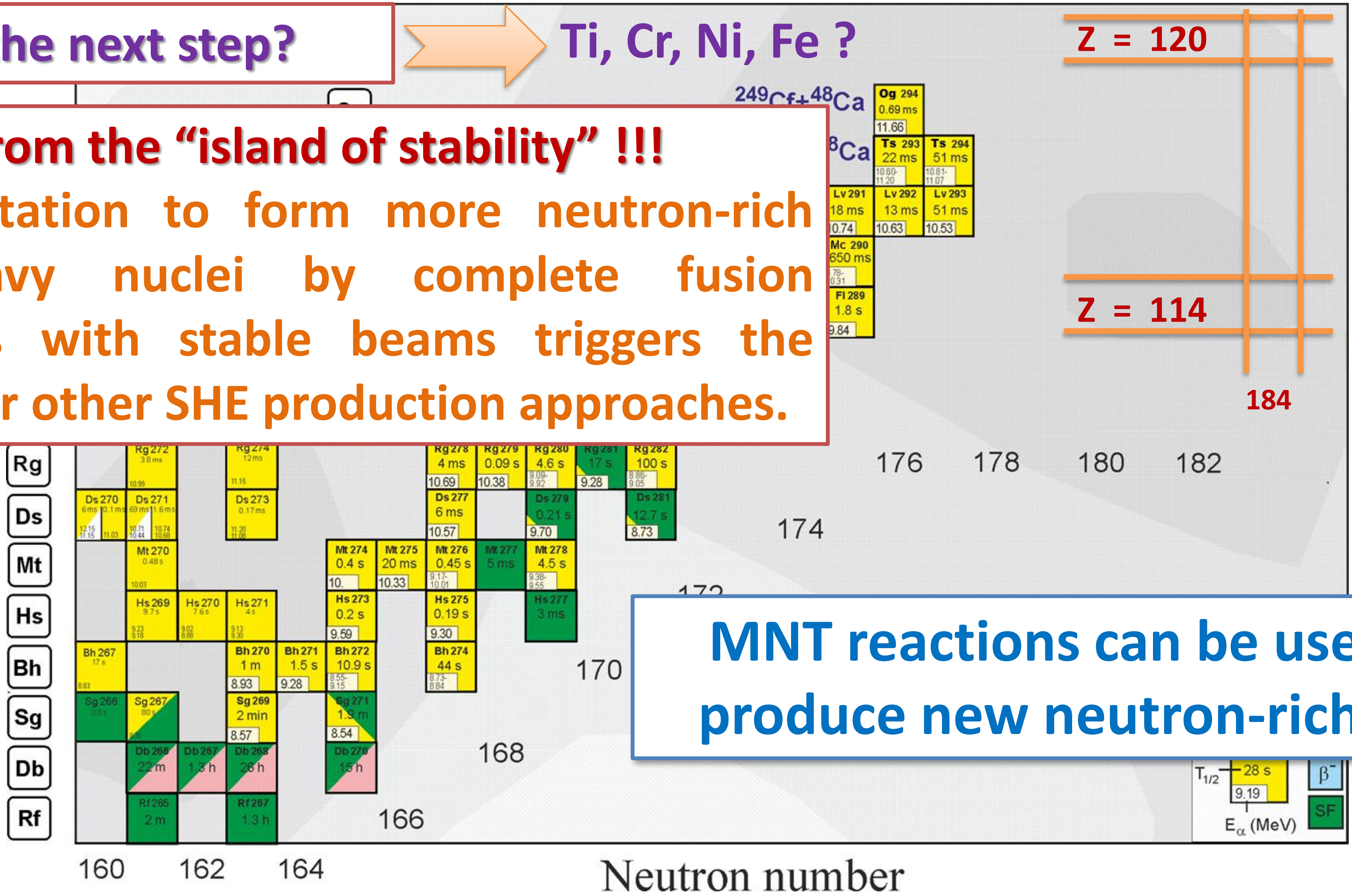
Search for superheaviest nuclei

What is the next step? → **Ti, Cr, Ni, Fe ?**

Still far from the "island of stability" !!!

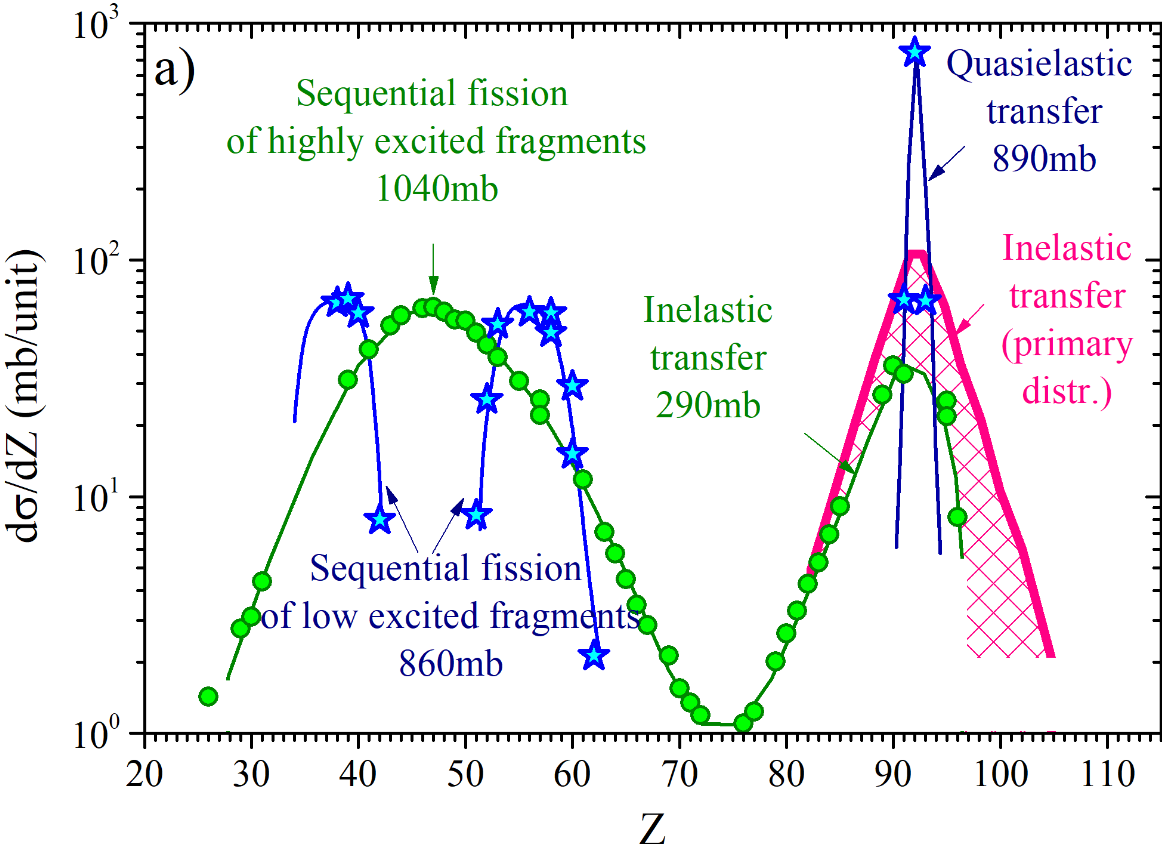
The limitation to form more neutron-rich superheavy nuclei by complete fusion reactions with stable beams triggers the search for other SHE production approaches.



MNT reactions can be used to produce new neutron-rich SHE

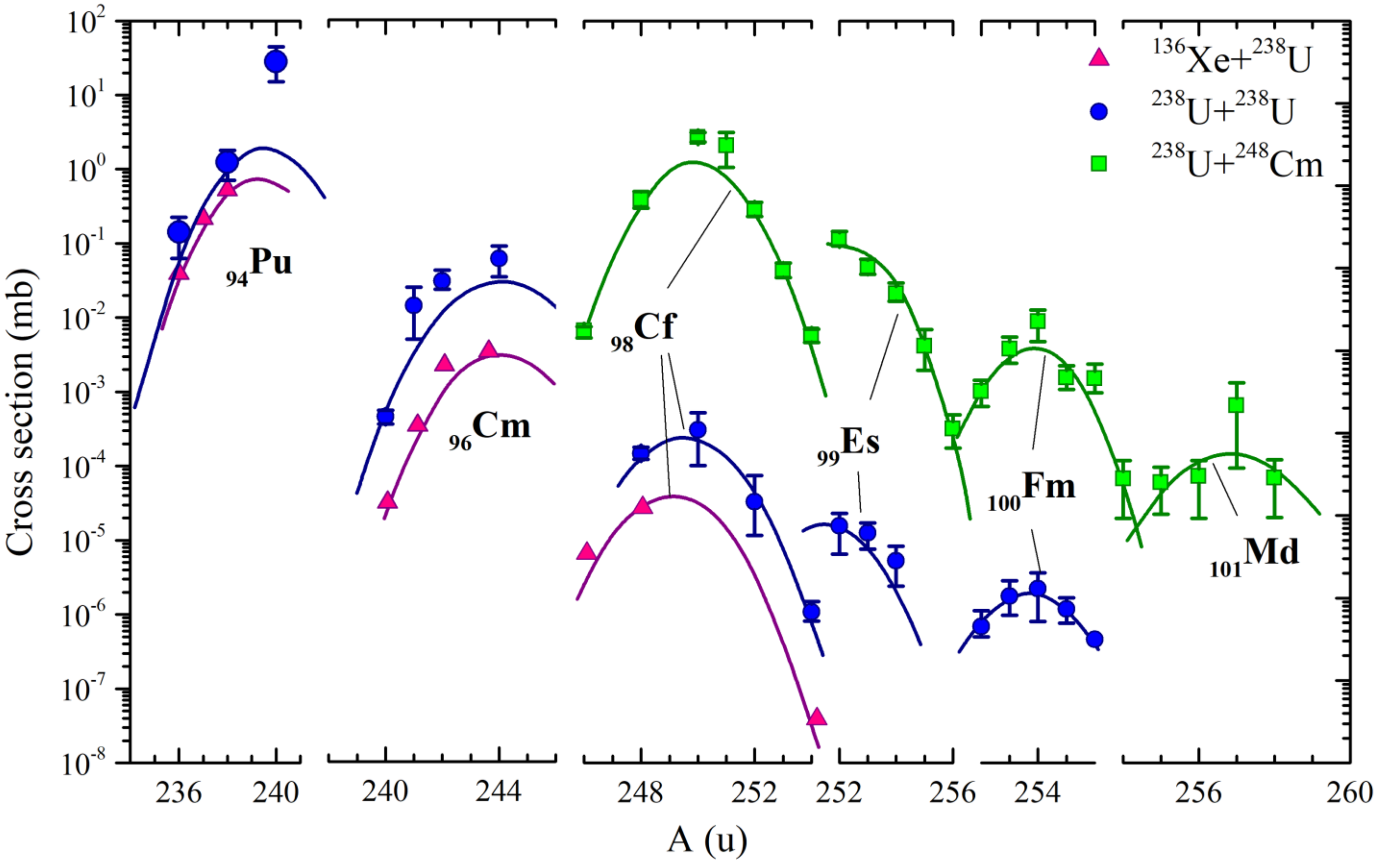
Radiochemical study of the reaction $^{238}U+^{238}U$

M. Schädel et al., Phys. Rev. Lett. 41, 469 (1978)



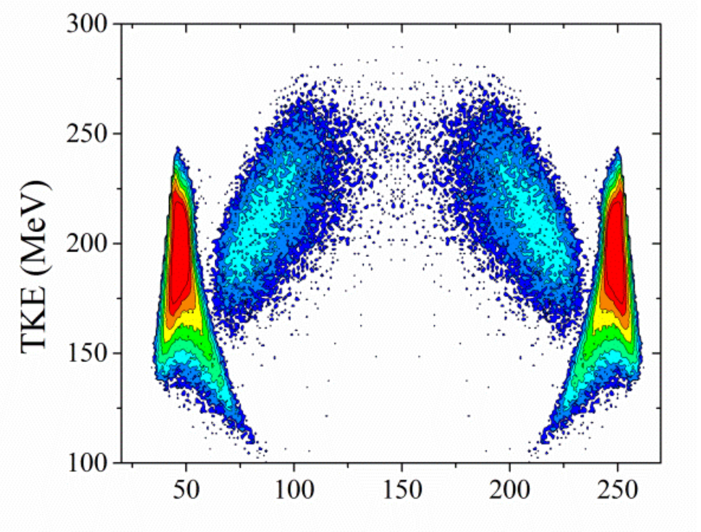
Charge distribution of fragments formed in the reaction $^{238}U+^{238}U$ at the interaction energy $E_{lab} \leq$ 7.5 MeV/nucl.

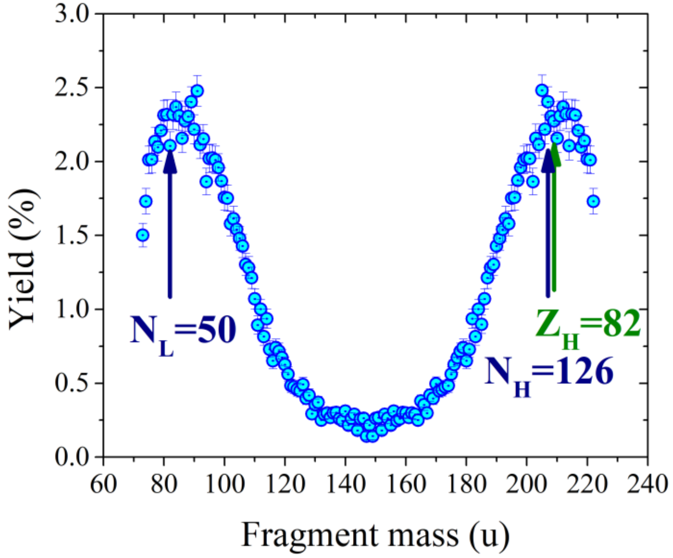
M. Schädel et al., Phys. Rev. Lett. 48 (1982) 852

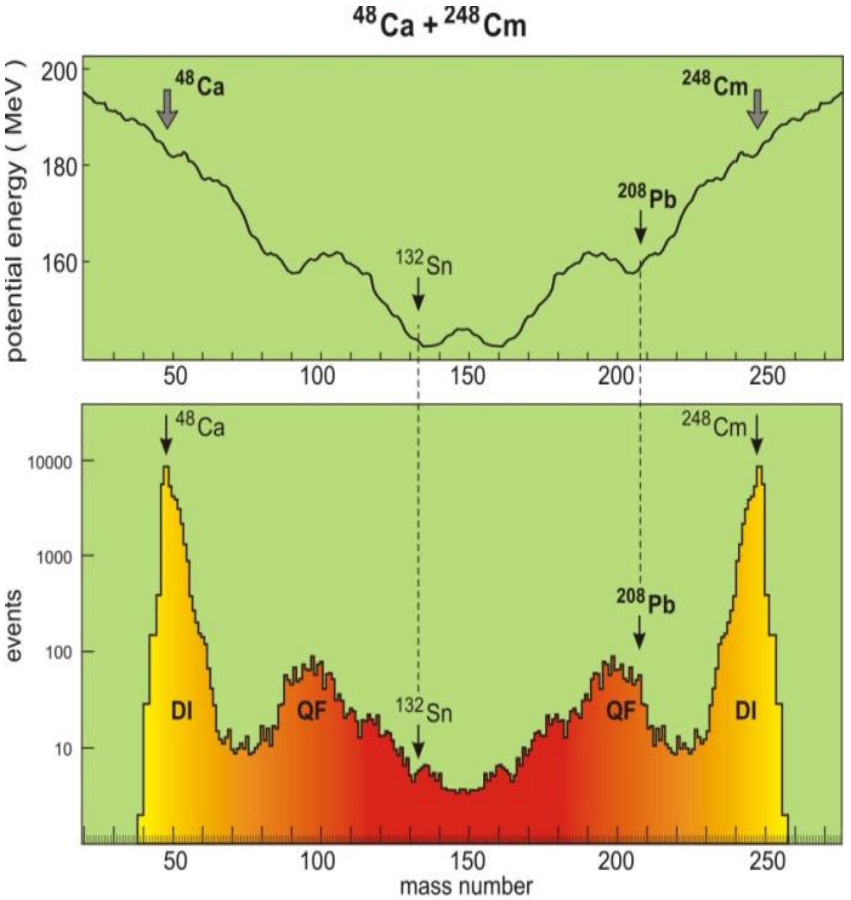


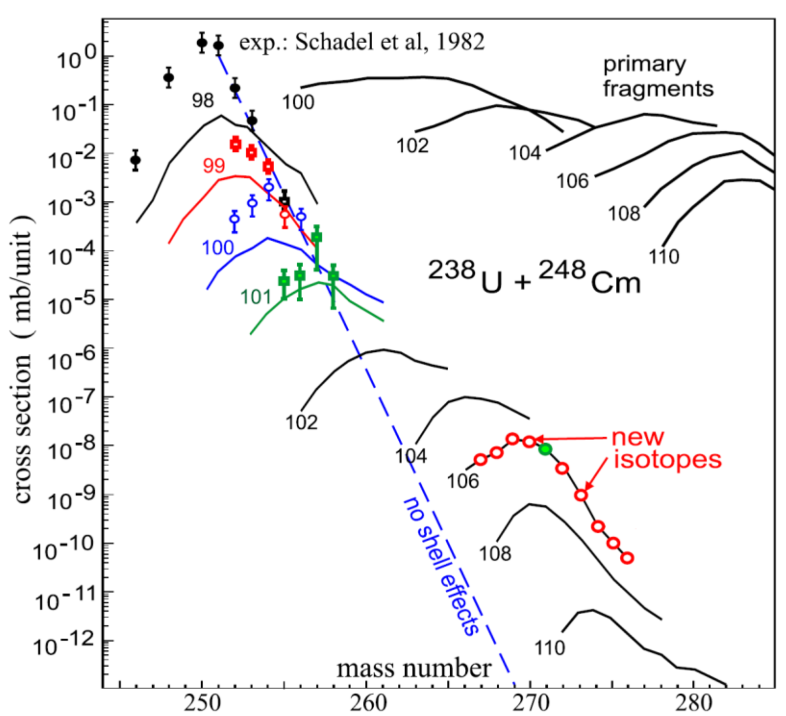
Production cross sections of trans-uranium nuclei in the reactions $^{136}Xe+^{238}U$, $^{238}U+^{238}U$ and $^{238}U+^{248}Cm$ at the interaction energy $E_{lab} \leq$ 7.5MeV/nucl.

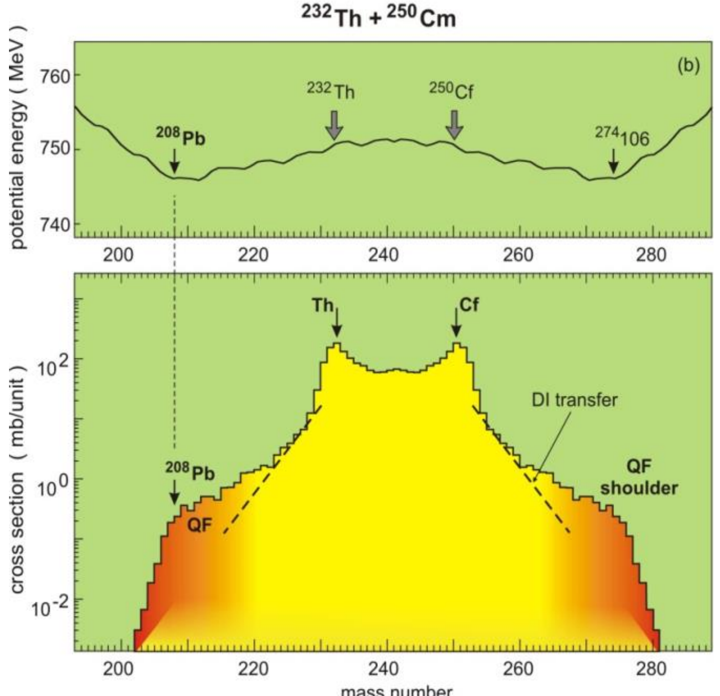
Shell effects in MNT reactions











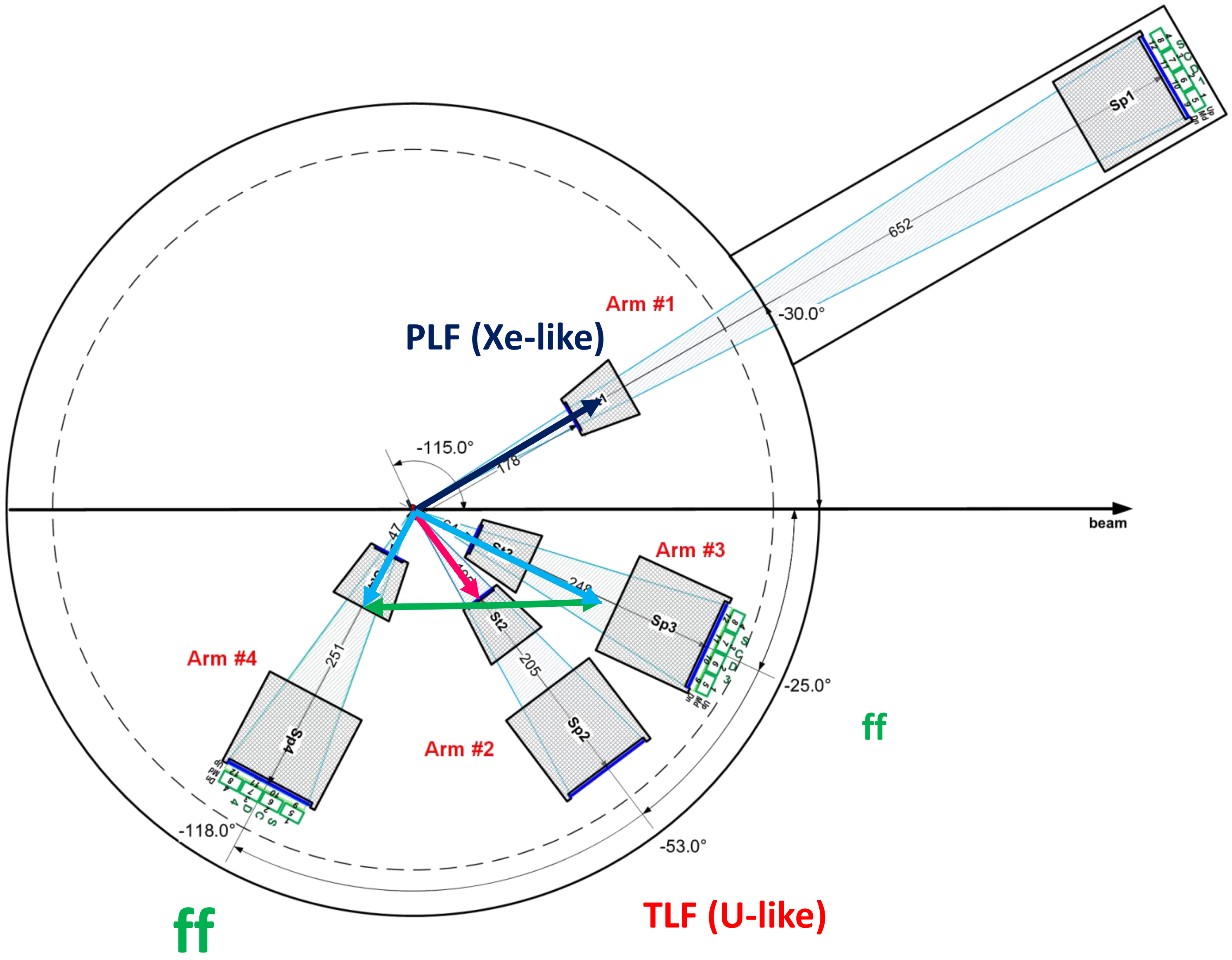
V. Zagrebaev and W. Greiner, Nucl. Phys. A 834 (2010) 366c

MNT reactions as the promising way to synthesize and investigate heavy and superheavy elements

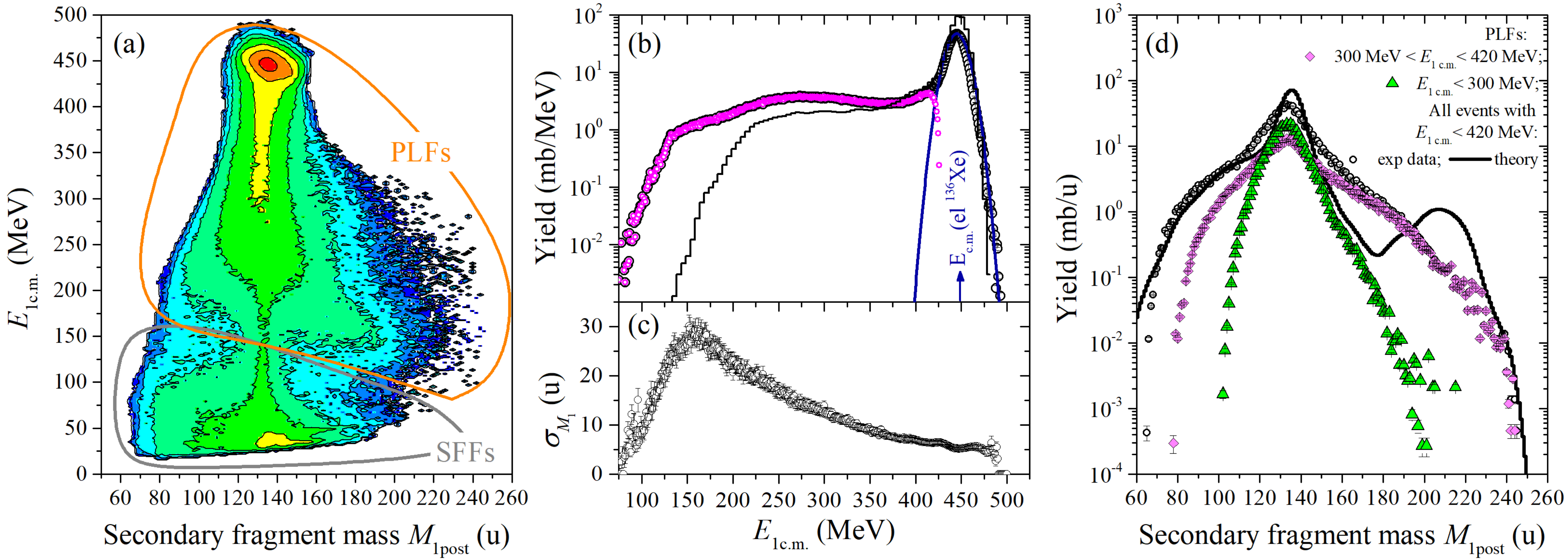
The ^{238}U ions are apparently optimal as projectile particles in the synthesis of superheavy elements in MNT reactions. For deeper understanding of the MNT mechanisms and the best planning the future experiments on the production of new heavy isotopes in the reactions with ^{238}U beam the theoretical calculation has to be checked with experimental data for the reactions like $^{136}Xe+^{238}U$ and $^{209}Bi+^{238}U$.

Primary and secondary mass and energy distributions of projectile-like fragments formed in the reaction $^{136}Xe+^{238}U$ at ^{136}Xe beam energy of 1.11 GeV have been experimentally investigated with the CORSET setup independently and in coincidence with survived heavy targetlike fragments. Since the heavy fragments formed in the reactions is highly excited, the masses, energies and the angles of the both fragments as products of sequential fission of excited heavy MNT fragments have been measured.

Experiment $^{136}Xe+^{238}U$ at $E_{lab}(^{136}Xe)$= 1.11 GeV



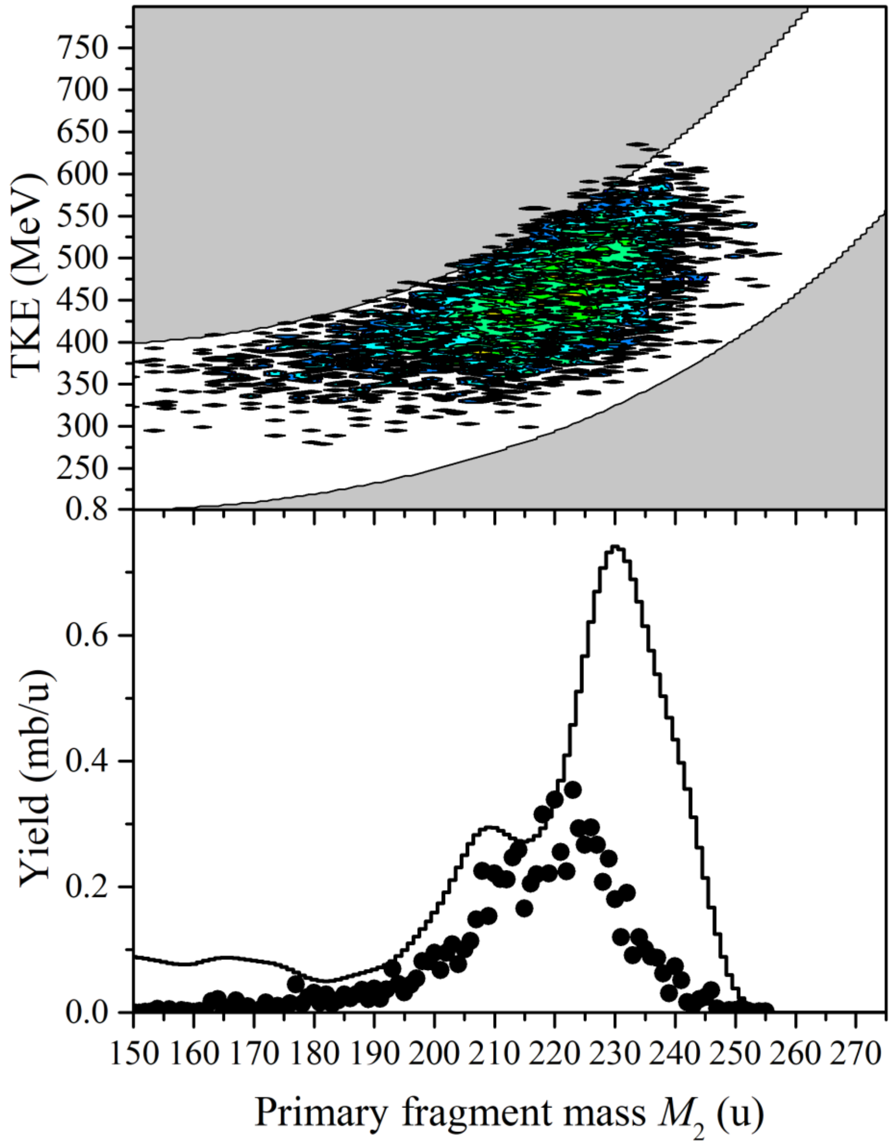
Mass-energy distributions of PLF



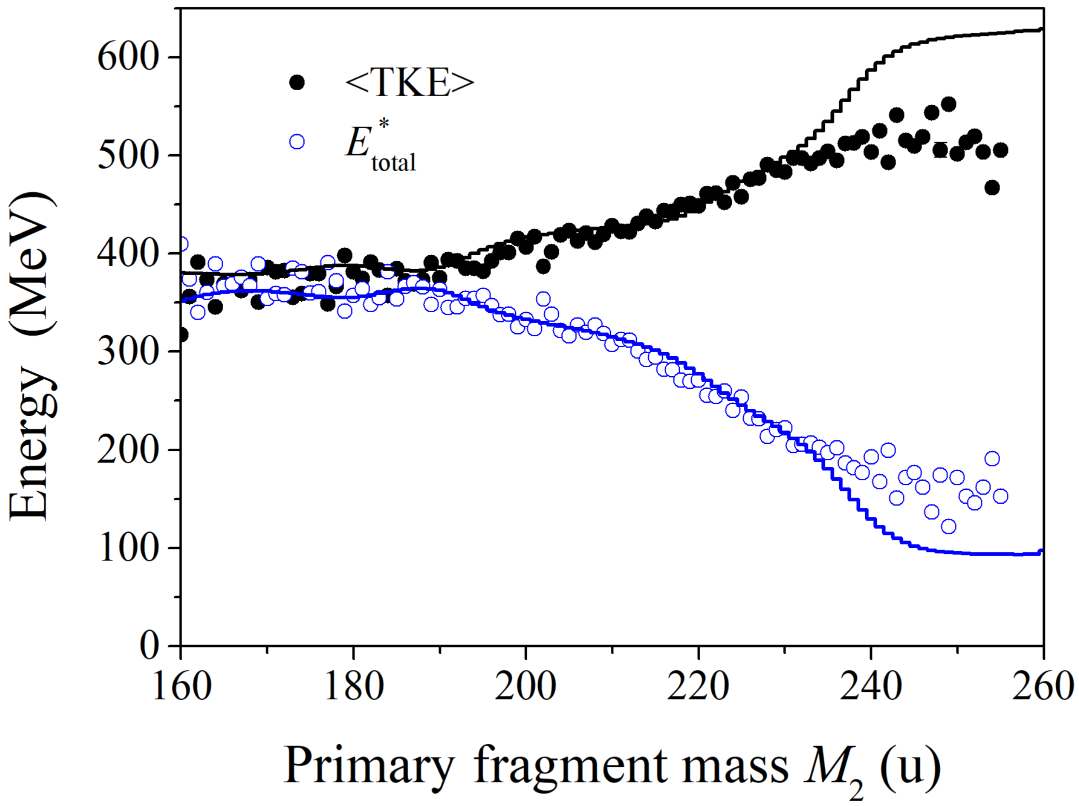
Solid lines are the theoretical calculations by V. Saiko and A. Karpov

The formation cross section of the fragments lighter than 136 u, for which complementary fragments are transuranium nuclei, is about hundred microbarns. The lightest secondary fragment mass found in the mass spectrum for PLF is 82 u.

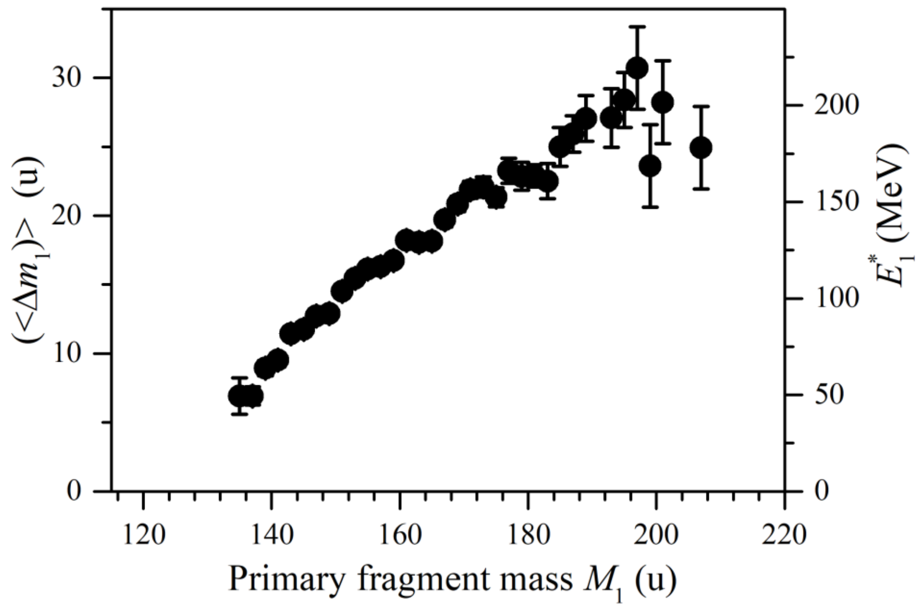
Mass-energy distribution of survived primary MNT fragments

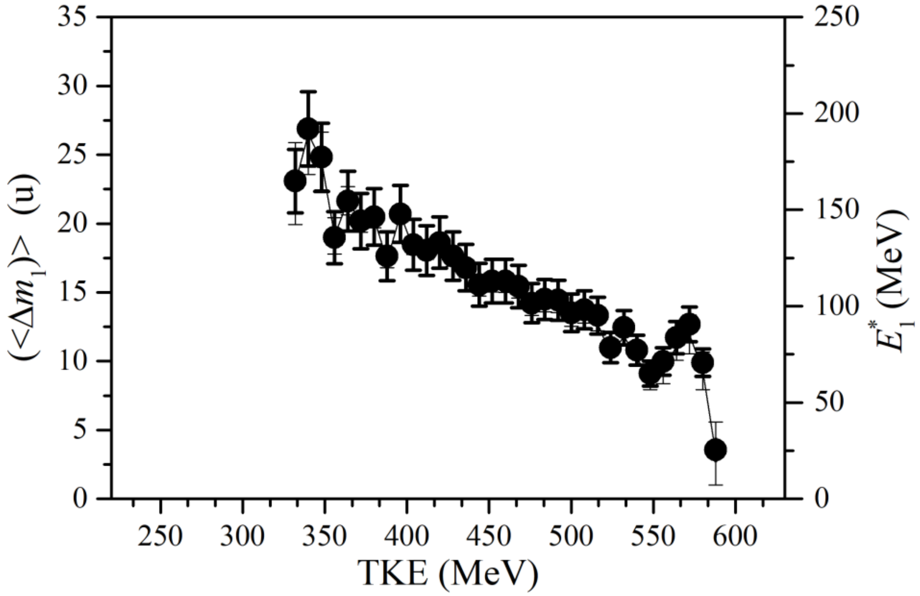


The heaviest survival fragment with primary mass of about 250 u is observed. The cross section formation of these fragments is about 3 μb. The survival probability strongly depends on total excitation energy of the dinuclear system. The excitation energy may be estimated from TKE measurements: $E^*_{\mathrm{total}} \approx E_{c.m.}\text{-TKE} + Q_{\mathrm{gg}}$



Excitation energy of PLFs





The formed primary MNT fragments are excited. Their deexcitation goes via emission of light particles, mainly neutrons. The mass loss Δm of the MNT fragment can be found as:

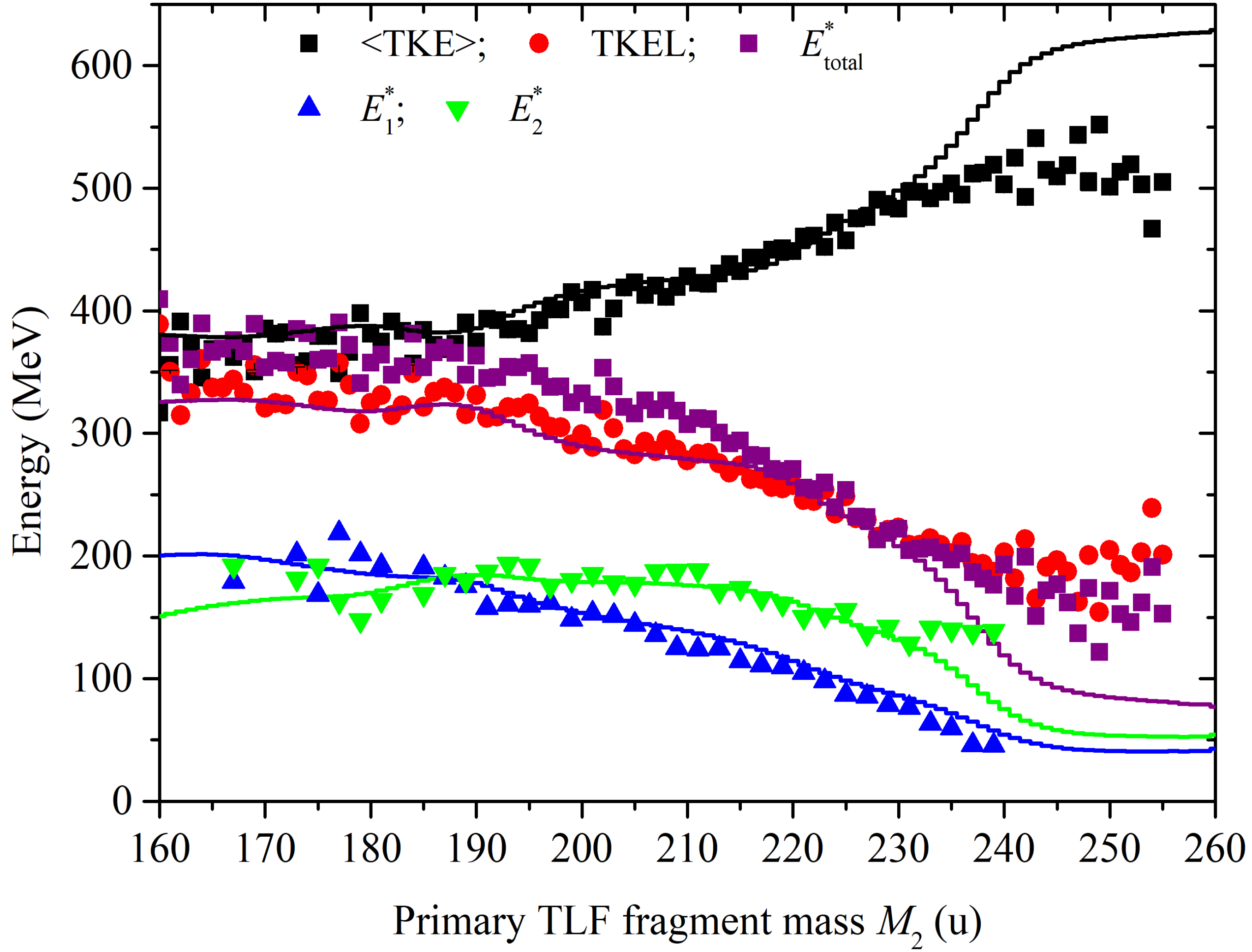
$$\Delta m_1 \left(M_1, \mathrm{TKE} \right) = \frac{1}{N} \sum_{i=1}^{N} \left(M_1^i - M_{1\mathrm{post}}^i \right)$$

M_1 – measured primary mass (via ToF-ToF method)
$M_{1\mathrm{post}}$ – measured secondary mass (via ToF-E method)
N is the number of fragments with given mass M_1 or/and TKE.

The excitation energy of the PLFs can be estimated using the obtained mass loss in assumption that the main evaporation particles are neutrons as

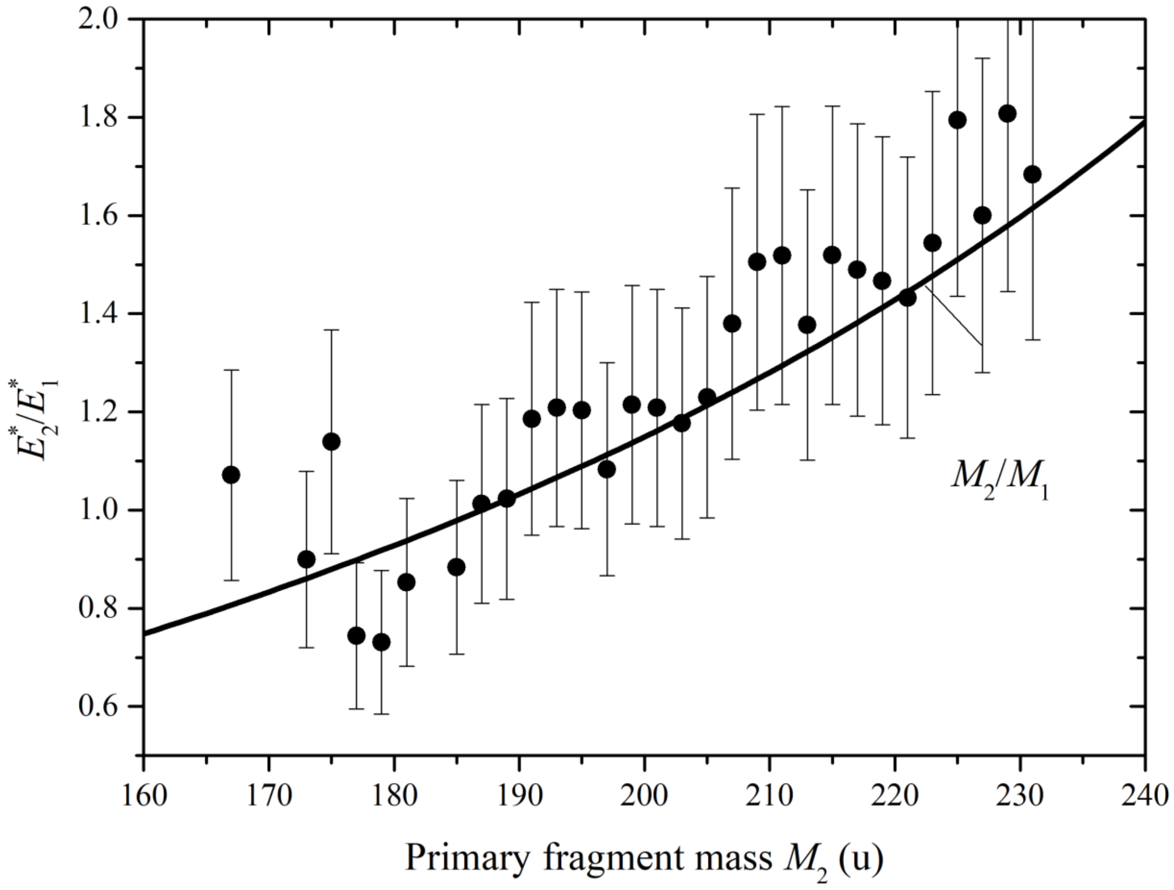
$$E_1^* = \langle \Delta m_1 \rangle \cdot \left(B_\mathrm{n} + E_\mathrm{n} \right)$$

Excitation energy of MNT fragments



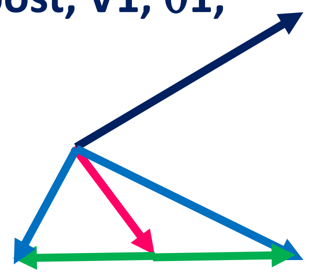
$$E^*_{total} \approx E_{c.m.}\text{-TKE} + Q_{gg}$$

$$E^*_2 = E^*_{total} - E^*_1$$



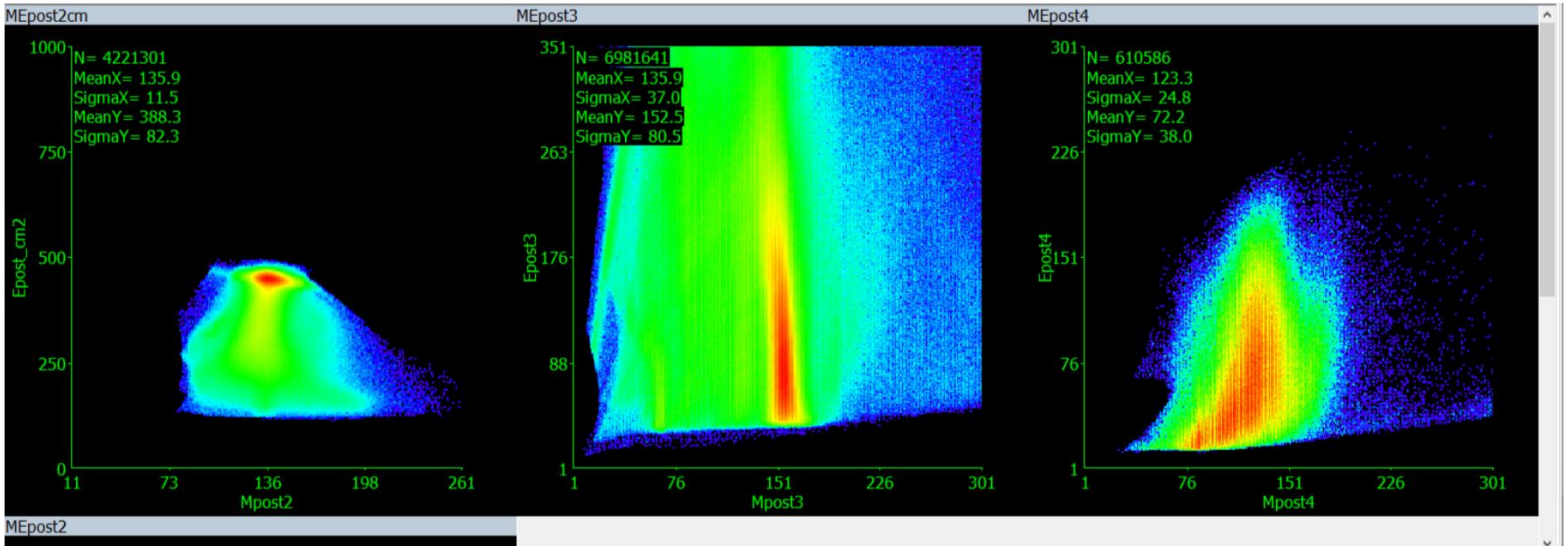
Sequential fission of excited MNT fragment

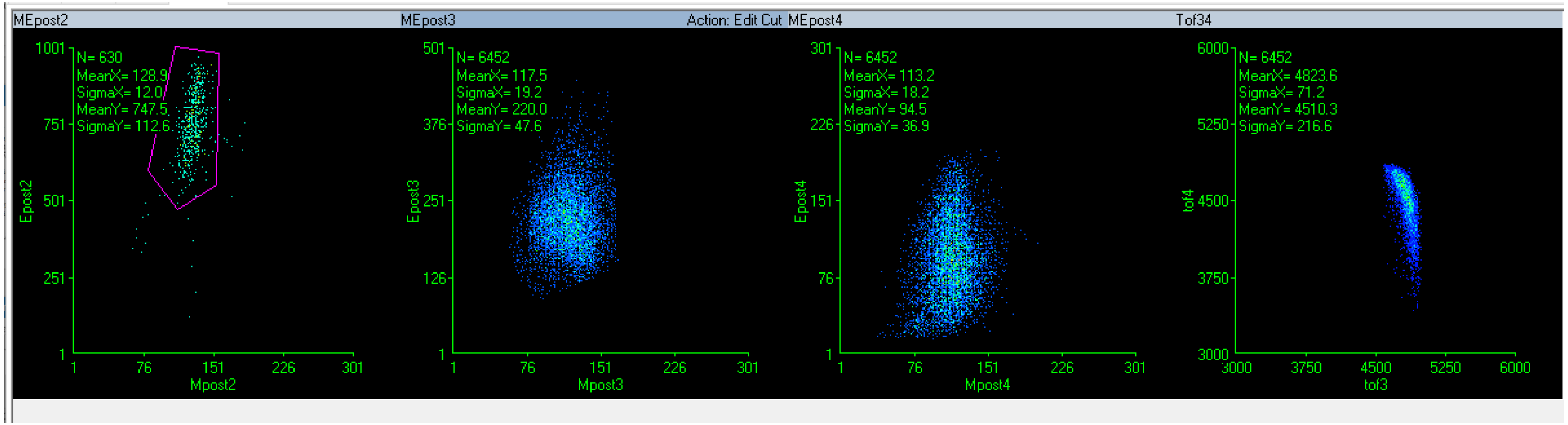
PLF: m1post, E1post, V1, θ1, φ1



FF2: m4post, E4post, V4, θ4, φ4

FF1: m3post, E3post, V3, θ3, φ3





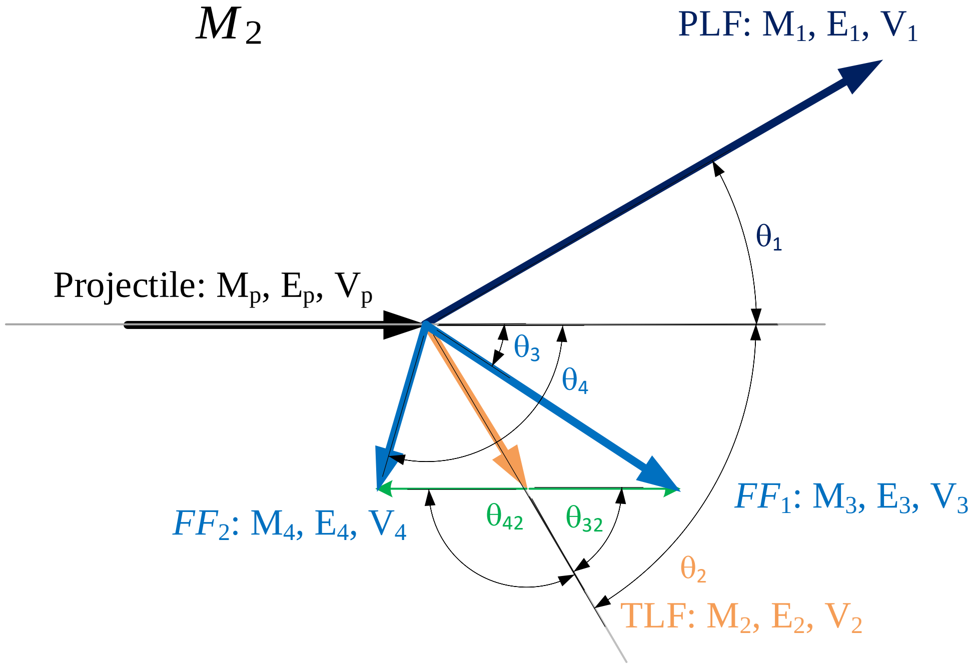
Sequential fission of excited MNT fragment

Properties of TLFs via **M1post, E1post, V1, θ1, φ1 on the basis of momentum conservation low:**

$$M_2 = (M_{target} + M_{projectile}) - (M_{1post} + \Delta m_1)$$

$$\theta_{2cm} = 180 - \theta_{1cm}$$

$$V_{2cm} = \frac{(M_{1post} + \Delta m_1)V_{1cm}}{M_2}$$



Properties of TLFs via **M3post, E3post, V3, θ3, φ3 and M4post, E4post, V4, θ4, φ4 :**

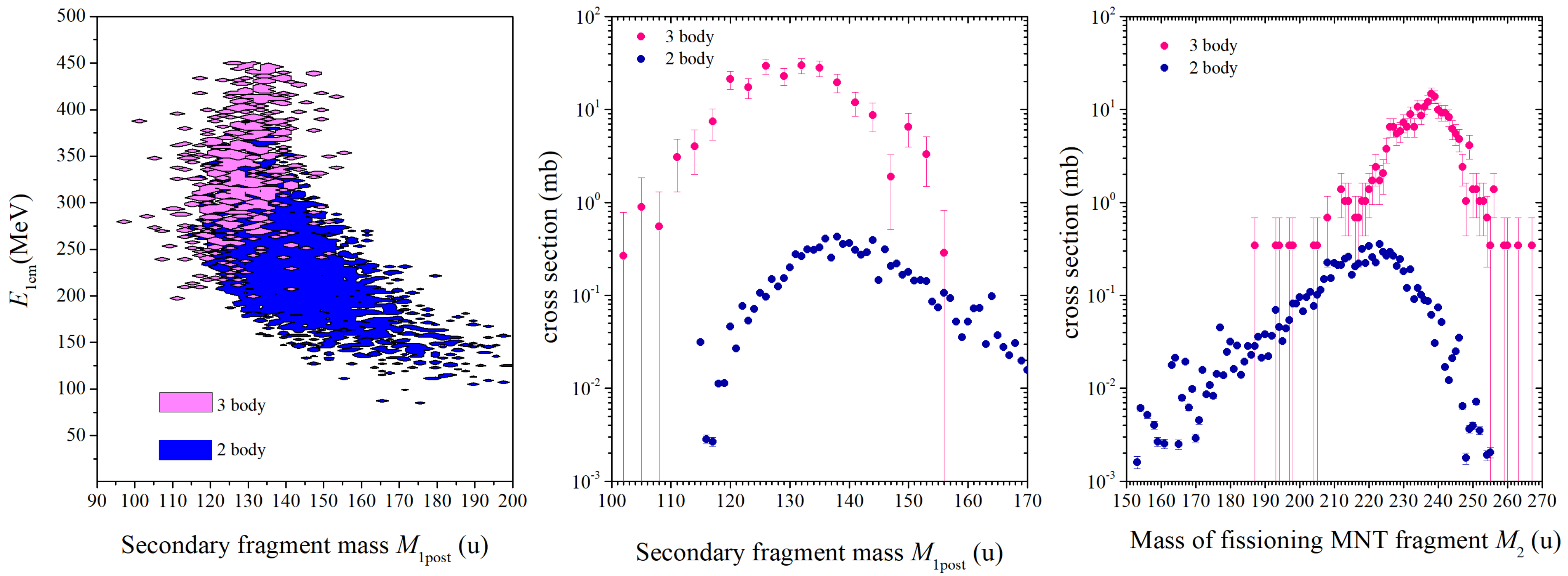
$$M_{2post} \approx M_{3post} + M_{4post}$$

$$V_2 = \frac{V_3 \sin(\theta_2 - \theta_3) V_4 \cos(\theta_4 - \theta_2) + V_3 \cos(\theta_2 - \theta_3) V_4 \sin(\theta_4 - \theta_2)}{V_3 \sin(\theta_2 - \theta_3) + V_4 \sin(\theta_4 - \theta_2)}$$

$$\theta_{32} + \theta_{42} = 180^\circ$$

$$\frac{V_{32}}{V_{42}} = \frac{M_4}{M_3} \approx \frac{M_{4post}}{M_{3post}}$$

Sequential fission of excited MNT fragment



3 body events: PLF + both fission fragments of excited TLF

2 body events: PLF + survived TLF

Conclusion

As a first step in the investigation of MNT reactions as a possible tool to produce new isotopes of heavy and superheavy nuclei, the measurements of mass, energy and angular distributions of fragments formed in the $^{136}Xe+^{238}U$ reaction at E_{lab} = 1.11 GeV have been performed. Modified CORSET setup allows studying binary fragments, as well as 3 body events (projectile-like + sequential fission of heavy MNT fragment).

The measurements of TKE of reaction fragments together with primary (via ToF-ToF) and secondary (via ToF-E) masses of projectile-like fragments allow to estimate the excitation energies of each fragment. It is obtained that the excitation energy divides proportionally to the fragments' masses. Therefore, we should expect that the reactions with heavier projectiles give the opportunity to reduce the excitation of trans-target nuclei and, as a result, to increase the survival probabilities of these fragments.

It is found that the cross section of MNT reaction is about 860 mb. The main part of heavy MNT fragments undergoes fission. The heaviest survived fragments are isotopes of Bk and Cf with cross section of about 3 μb. The analysis of 3 body events shows that the heaviest MNT fragments formed in the reaction is Fm-No isotopes with cross section formation of about 300 μb.

With decreasing interaction energy the excitation of formed fragments also decreases. Thereby, low-energy MNT reactions may be considered as a promising pathway for producing new neutron-rich heavy isotopes.

CORSET team

Thank you for your attention!