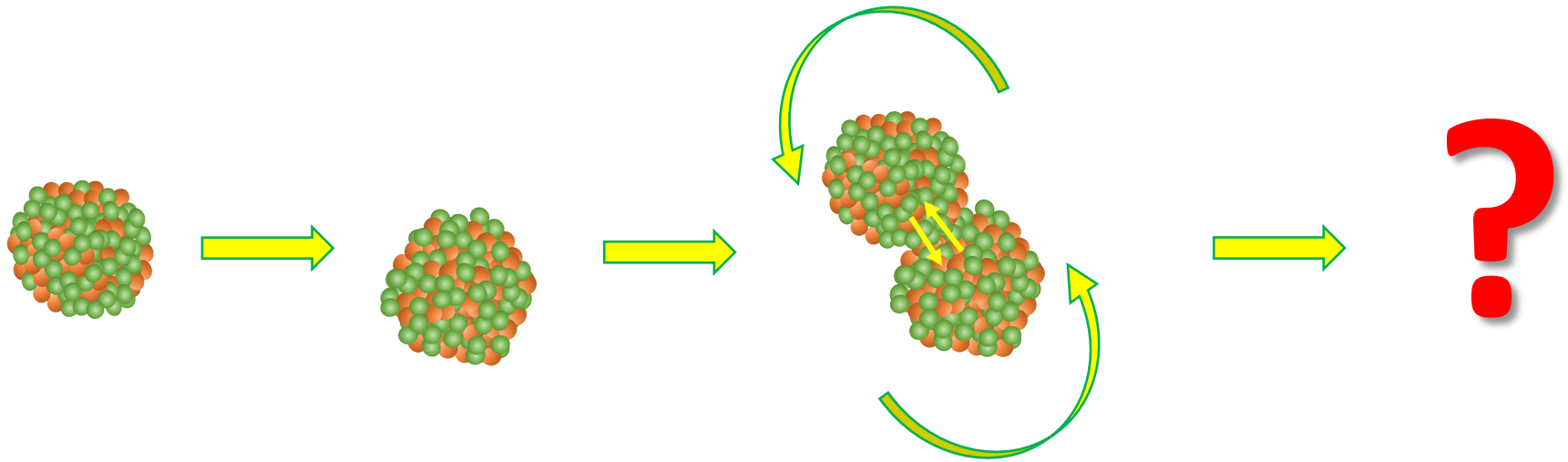
India-JINR Workshop on Particle, Nuclear, Neutrino Physics and Astrophysics

10-12 November, 2025
NISER Bhubaneswar

Experimental investigation of interaction mechanisms in the reactions with heavy ions

Alexey Bogachev



Main directions of the investigations
CORSET Set-Up

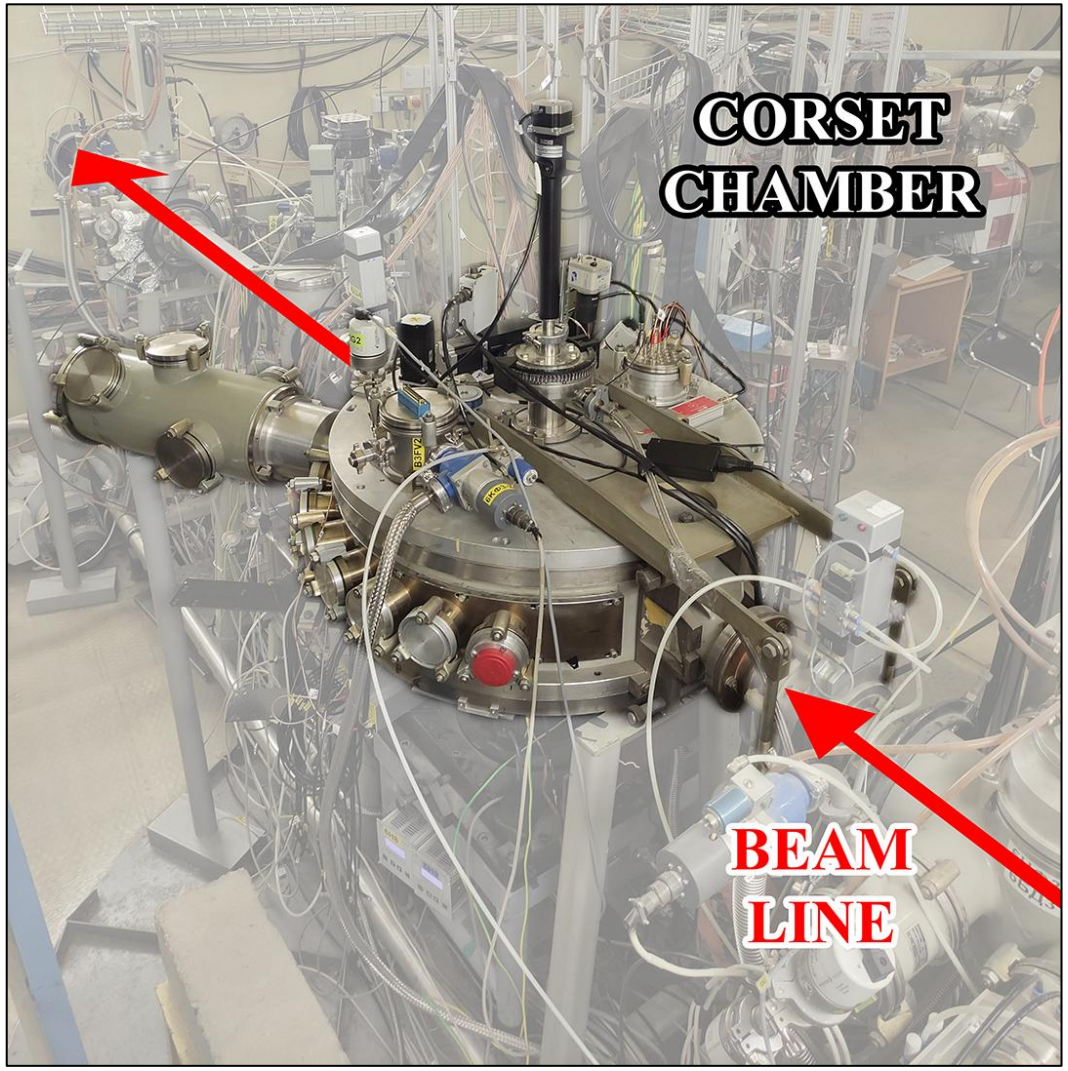
- ✓ Fusion-Fission, Quasifission, Fast fission

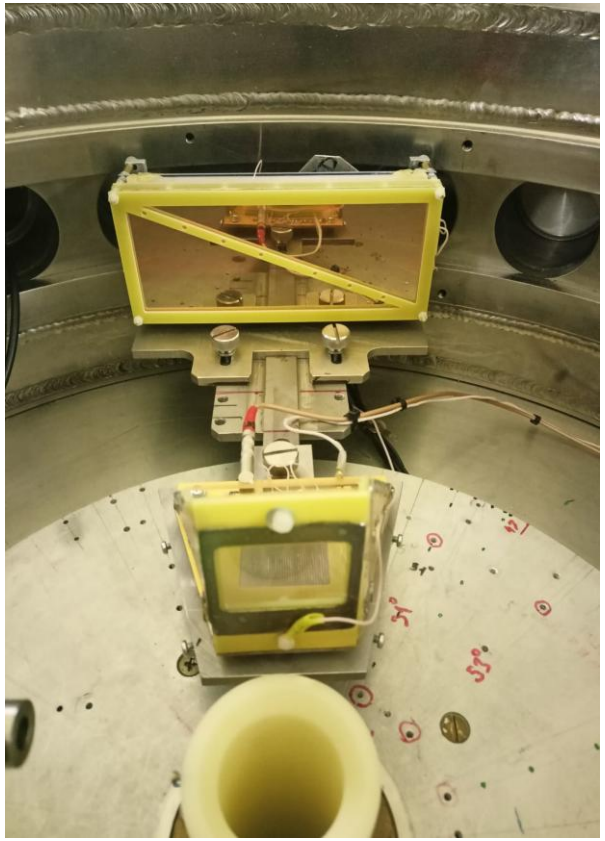
  O+Pb, Ar+Sm, Ca+Pb, Ni+U, Xe+Fe, etc.

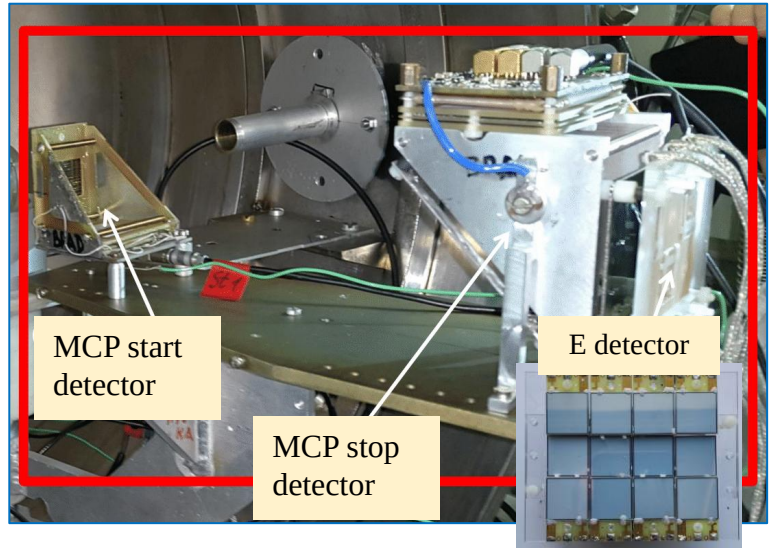
- ✓ Multinucleon transfer reactions

  Xe+U, Bi+U, Bi+Th, Bi+Au

CORSET Set-Up



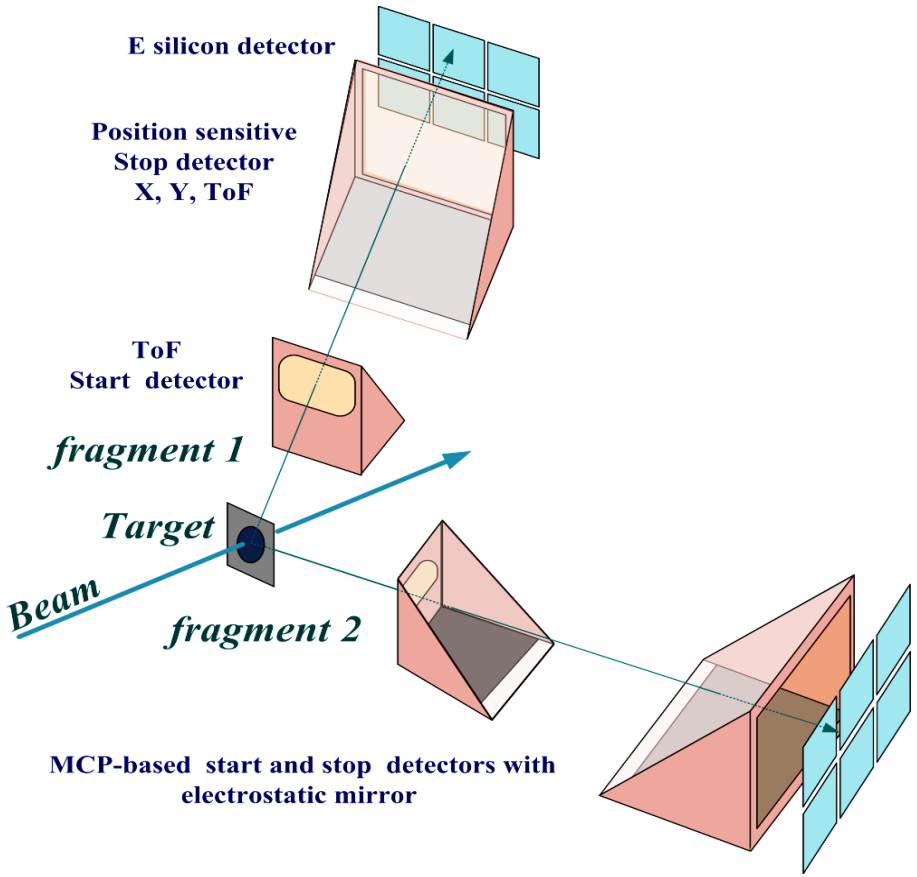




CORSET Set-up

Cor**s**et (**C**orrelation **s**etup) was created in 1995 at Flerov Laboratory of Nuclear Reactions to investigate binary processes.

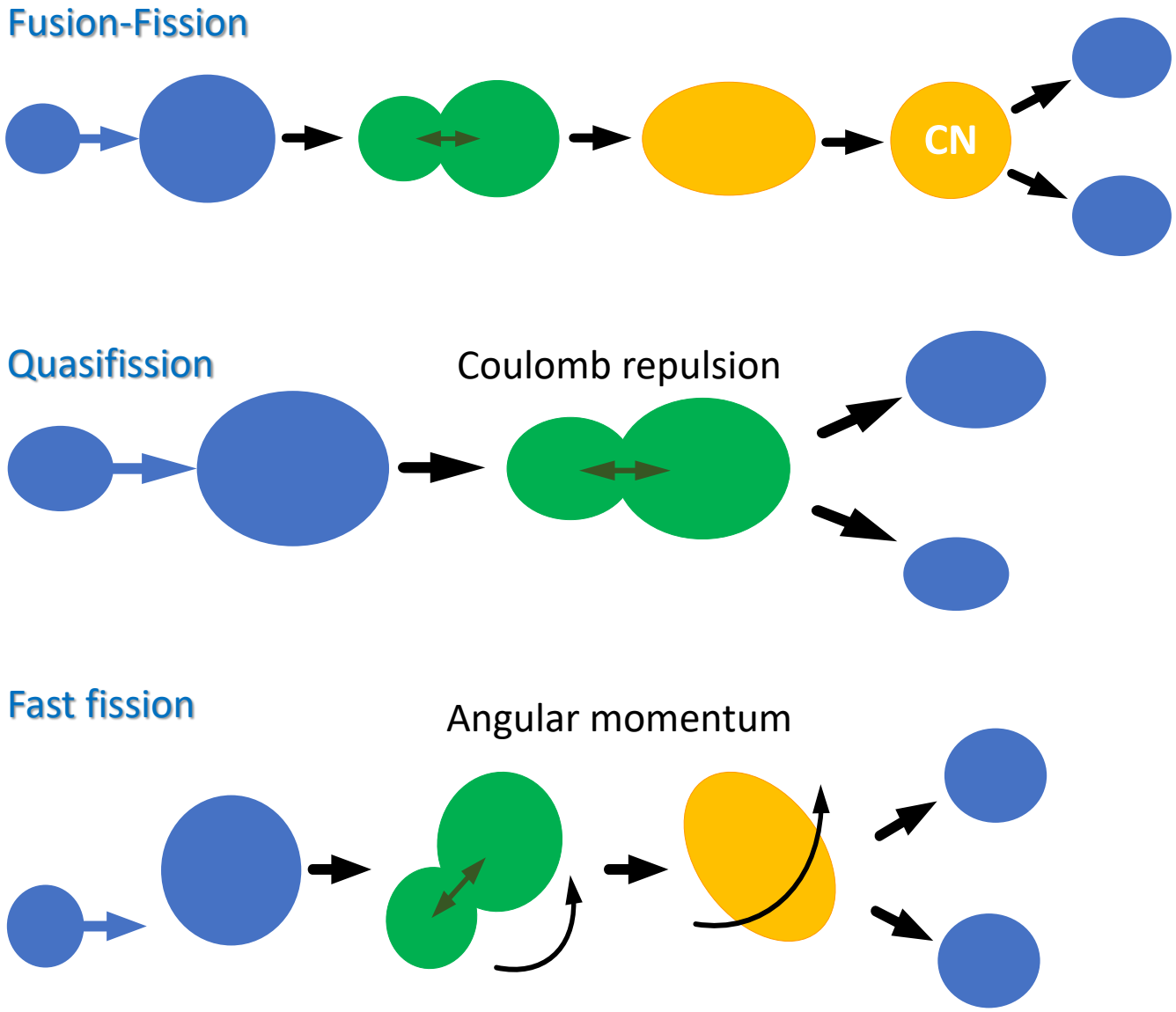
Mass-energy distributions of binary reaction products were measured using the two time-of-flight (TOF) arms consisted of the compact start detectors and the position-sensitive stop detectors



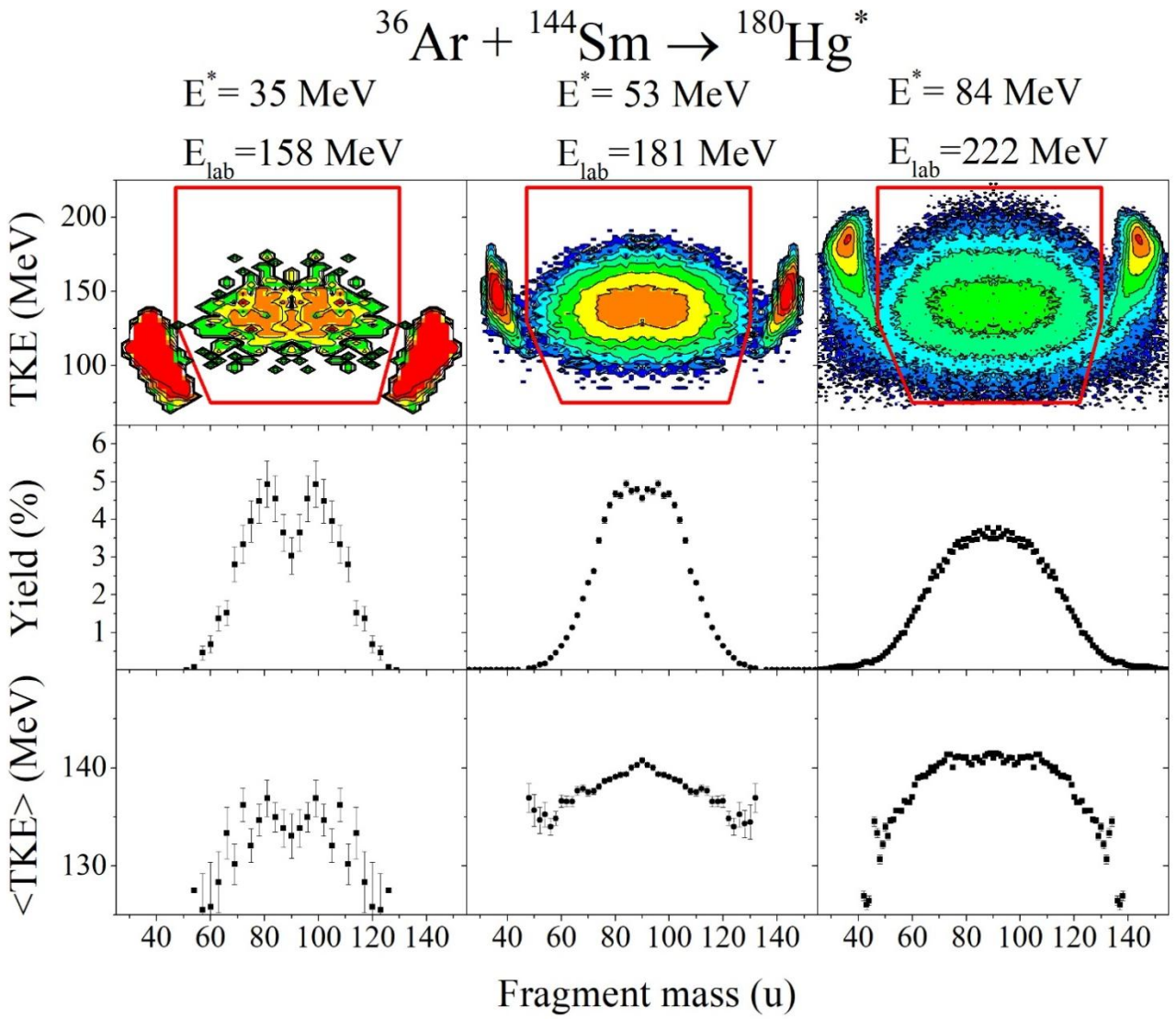
Parameter	
Time resolution	150-200 ps
Time-Of-Flight distance	10-30 cm
Angular range	15°-165°
Angular acceptance	±10 -20°
Solid angle	100-200 msr
Angular resolution	±0.2°
Mass resolution	±2 u
Relative energy resolution	~2%

Э.М. Козулин, А.А. Богачев, М.Г. Иткис и др., Приборы и техника эксперимента, Т. 51, В.1 (2008) с. 44-58.

Fusion-fission, quasifission and fast fission in the reactions with heavy ions



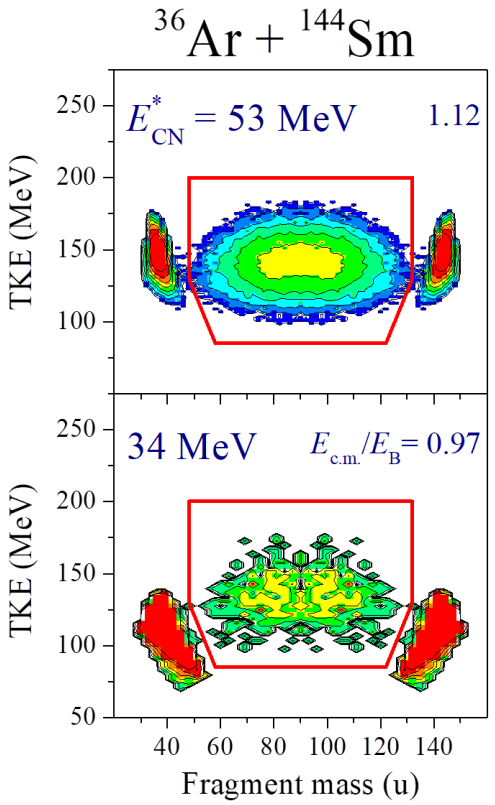
Mass-Total Kinetic Energy distributions of reaction products formed in the reaction $^{36}Ar + ^{144}Sm \rightarrow ^{180}Hg^*$



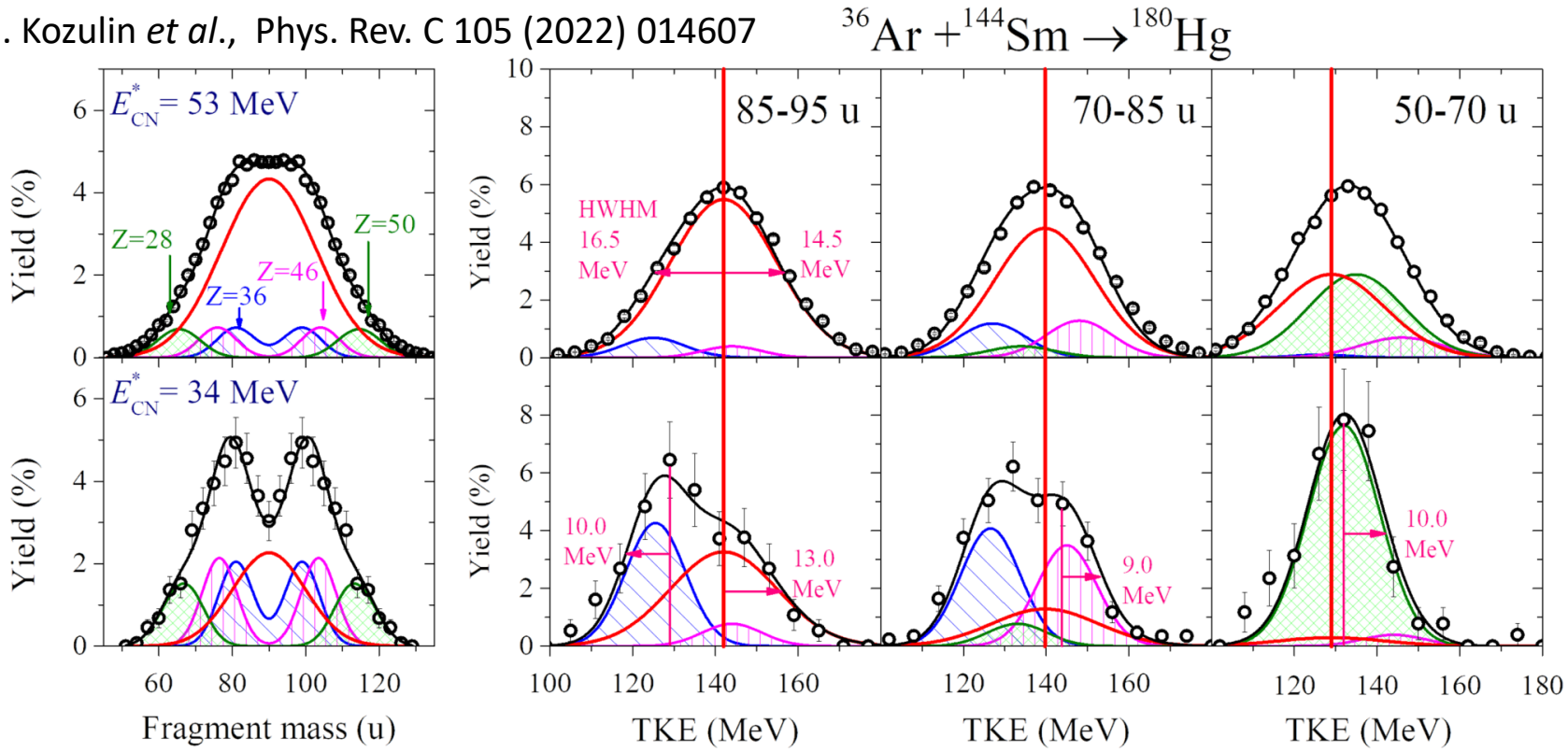
^{180}Hg

Z=80, N=100

Analysis of mass and energy distributions



E. M. Kozulin *et al.*, Phys. Rev. C 105 (2022) 014607



Z_1Z_2 = 1116
x_m = 0.634
η = 0.600
β_2^{proj} = 0.128
β_2^{targ} = -0.135

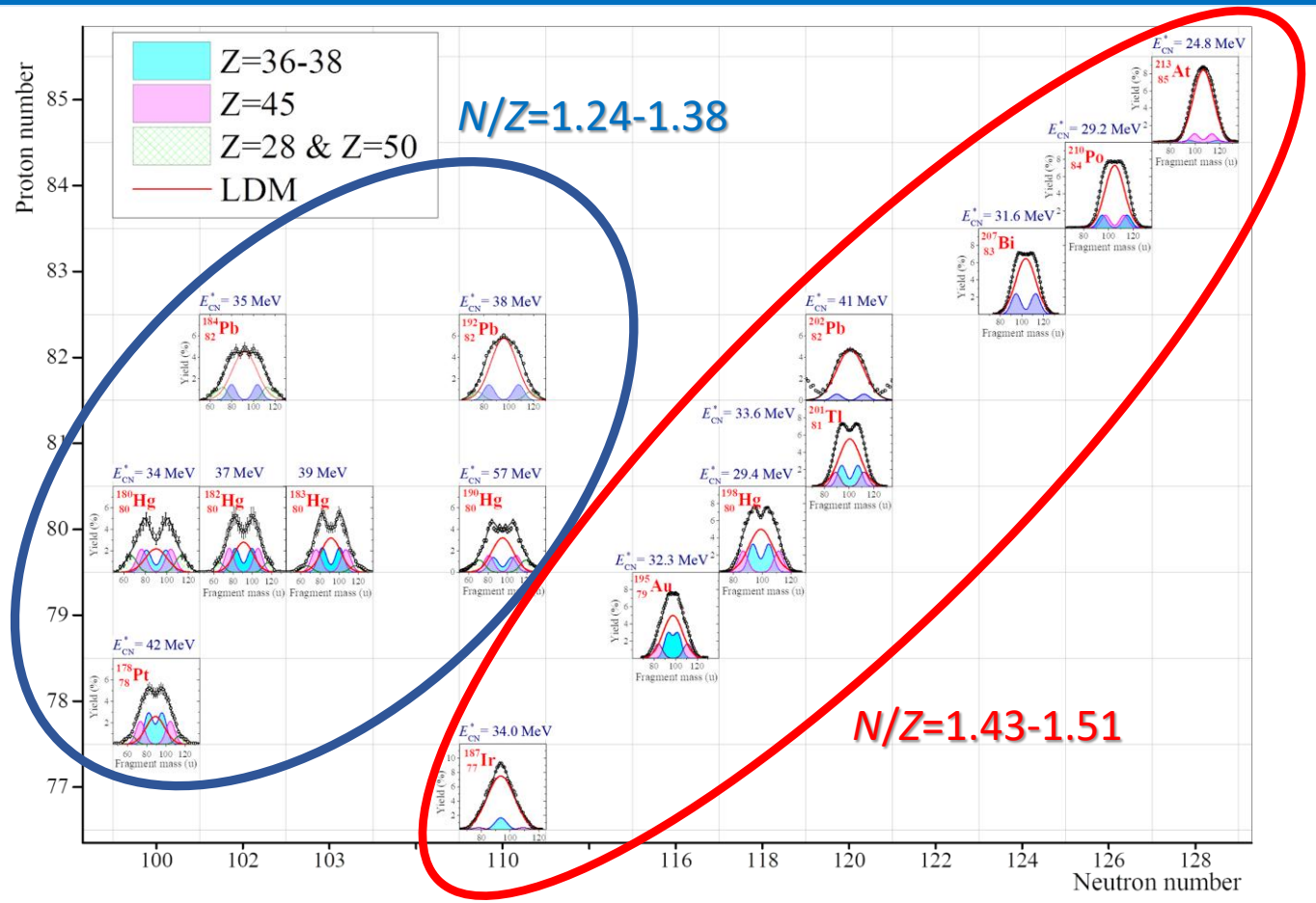
The analysis of the mass and TKE distributions indicates the existence of **one** symmetric (**S**) and **three** asymmetric (**A1**, **A2**, **A3**) modes in the fission of **preactinide** nuclei

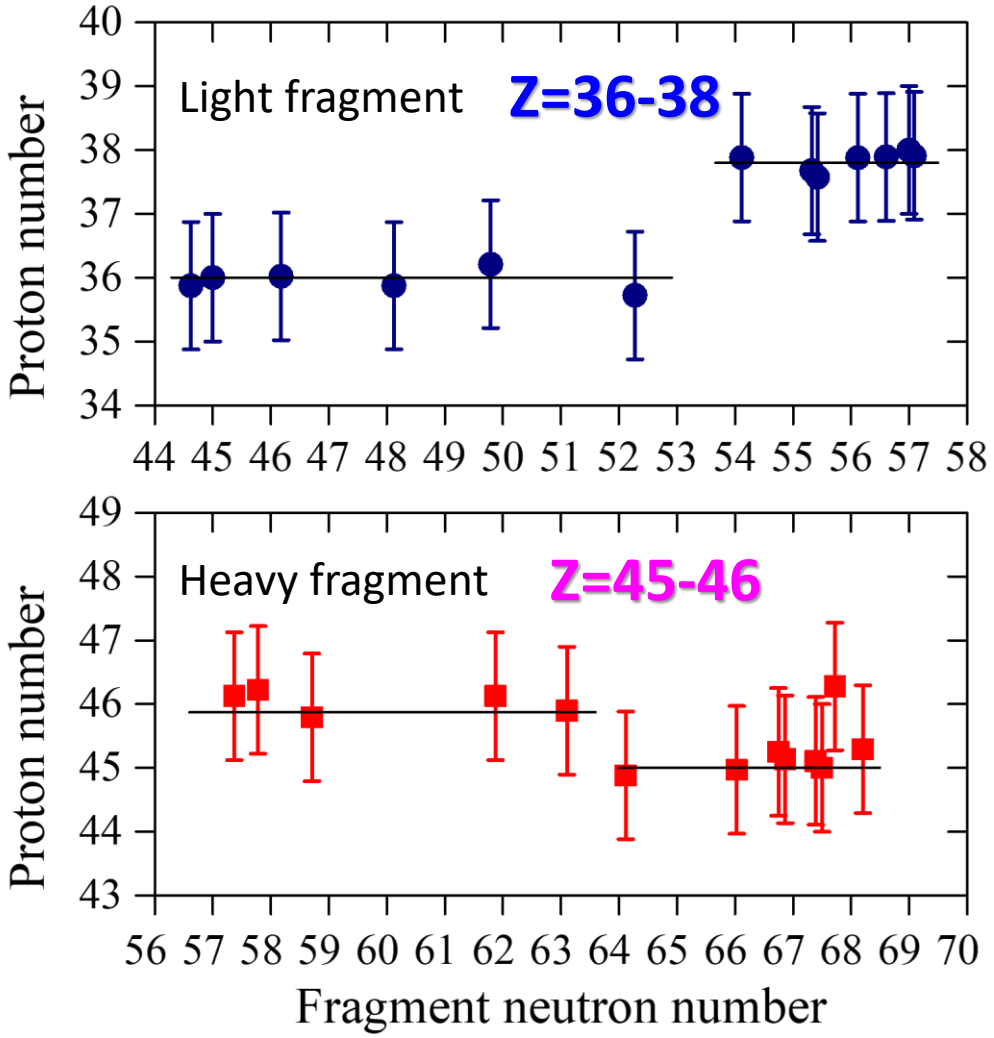
Mode **A1** is connected with nearly symmetric **low-energy** fragments (**Z=36**)

Mode **A2** is connected with **high-energy** fragments with **M_L ≈ 70–85** u (**Z=46, 52**)

Mode **A3** appears for asymmetric fragments with **M_L ≈ 50–70** u (**Z=28, 50**)

Shell effects in fission of preactinides

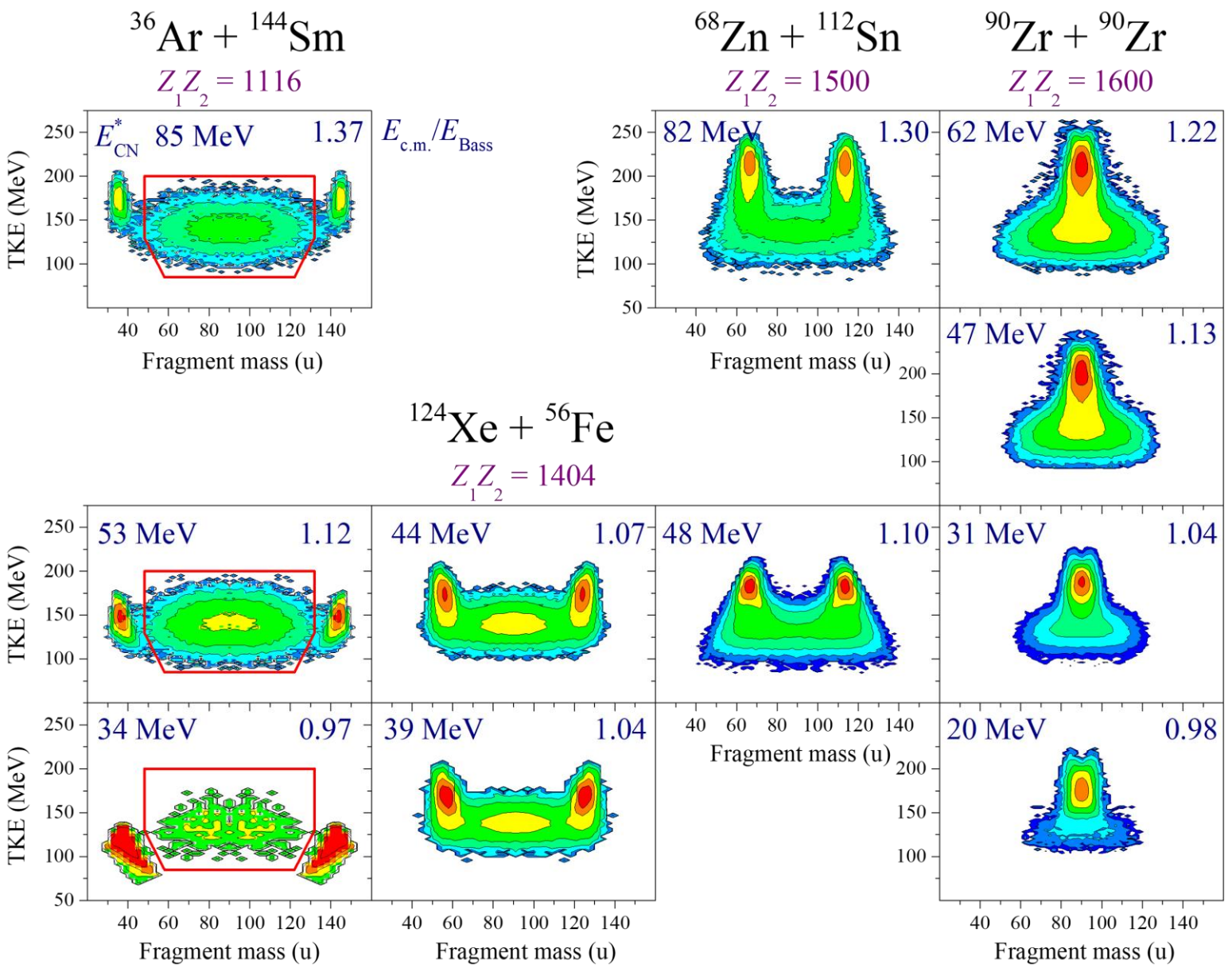


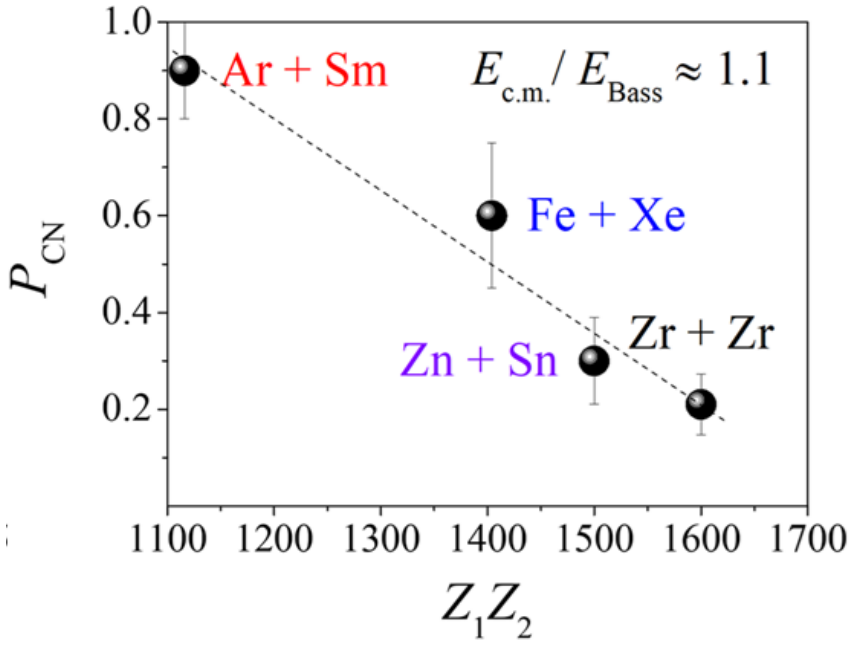


Mass distributions in fission of preactinides. The investigated properties of asymmetric fission of both neutron-deficient and close to the β-stability line preactinide nuclei point out the existence of **well-deformed** proton shell at Z = **36-38** and a **less deformed** proton shell at Z = **45-46**

A.A. Bogachev, E.M. Kozulin, G.N. Knyazheva *et al.*, Phys. Rev. C 104, 024623 (2021)
E.M. Kozulin, G.N. Knyazheva, I.M. Itkis *et al.*, Phys. Rev. C 105, 014607 (2022)

M-TKE distributions in 4 reactions leading to the formation of ^{180}Hg





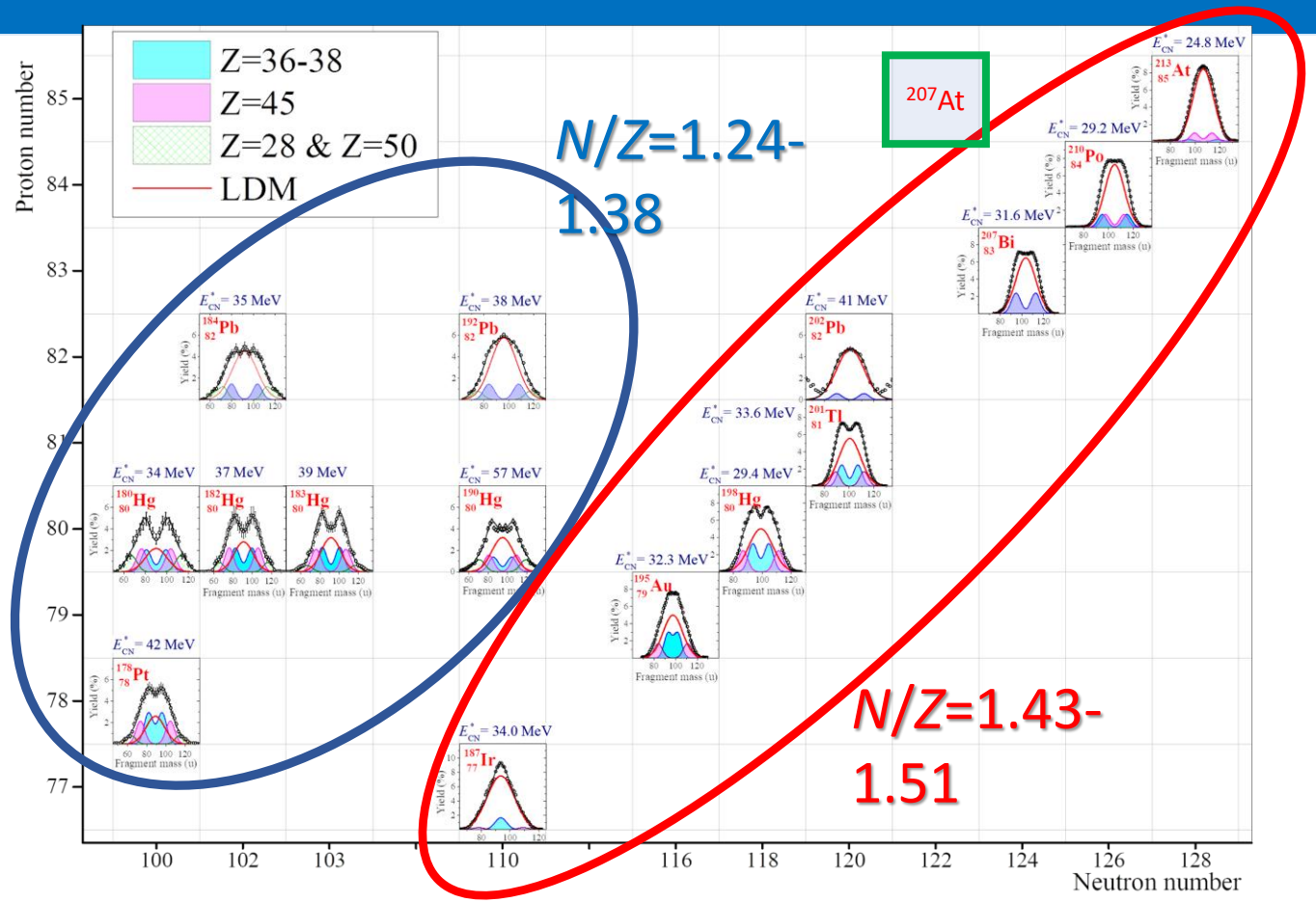
R. du Rietz, Phys. Rev. C 88, 054618 (2013)

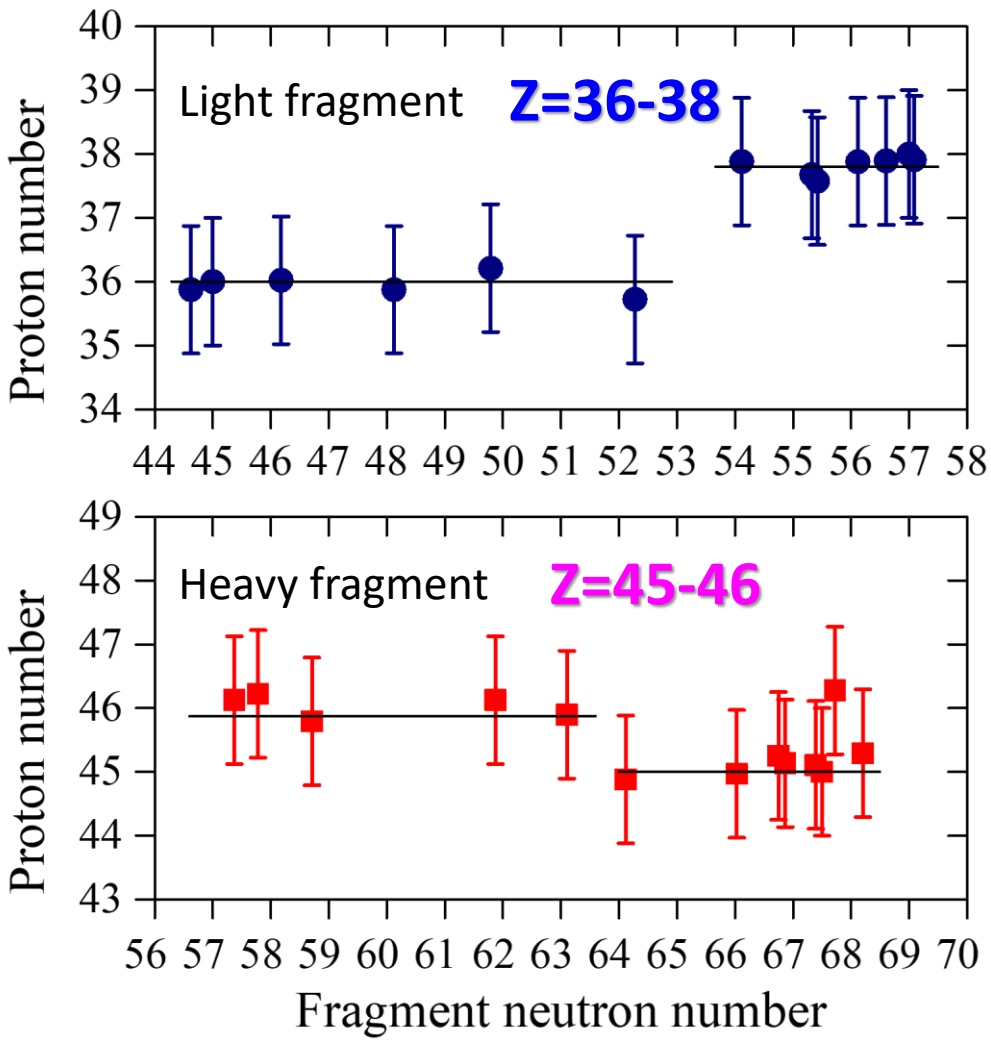
Threshold values for **QF** appearance

Coulomb factor $Z_1Z_2 = 1450 \pm 100$

Mean fissility parameter $x_m > 0.68$

Shell effects in fission of preactinides





Mass distributions in fission of preactinides. The investigated properties of asymmetric fission of both neutron-deficient and close to the β-stability line preactinide nuclei point out the existence of **well-deformed** proton shell at *Z* = **36-38** and a **less deformed** proton shell at *Z* = **45-46**

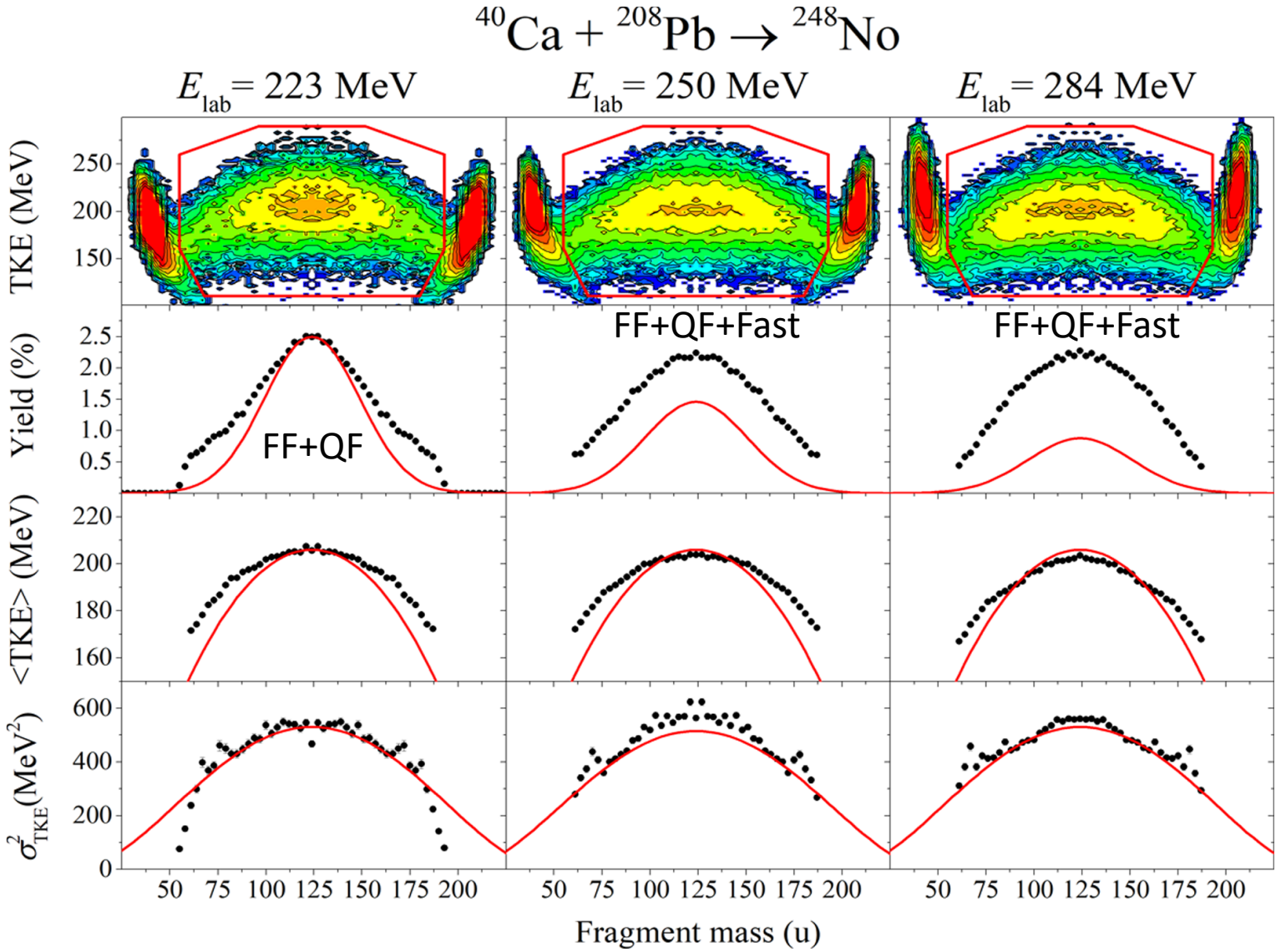
A.A. Bogachev, E.M. Kozulin, G.N. Knyazheva *et al.*, Phys. Rev. C 104, 024623 (2021)
E.M. Kozulin, G.N. Knyazheva, I.M. Itkis *et al.*, Phys. Rev. C 105, 014607 (2022)

Investigation of fission of ^{207}At (in the frame of FLNR-Indian collaboration)

Reaction	V_b, MeV	Energy E_{lab}, MeV	E^*_B, MeV	Z_pZ_t	Entrance channel asymmetry α	X_m
^{16}O+^{191}Ir	82	76-135	48	616	0.85	0.50
^{31}P+^{176}Yb	142	142-160	58	1050	0.70	0.61
^{48}Ca+^{159}Tb (planned)	192	185-230	47	1300	0.54	0.64

All three reactions lead to the formation of ^{207}At

Different mechanisms in the reaction $^{40}Ca+^{208}Pb$

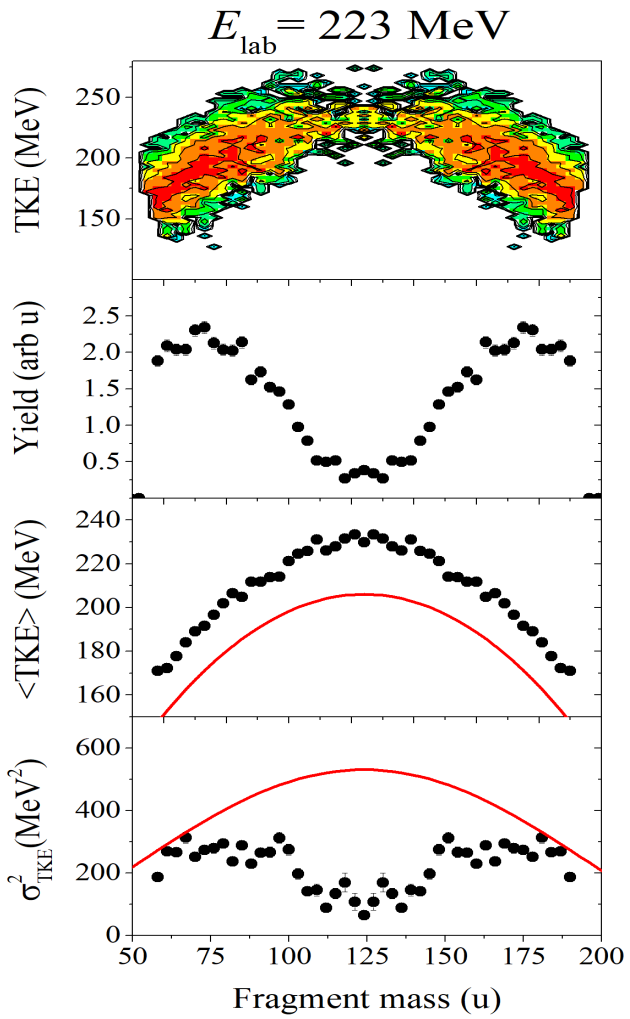


$$(M-TKE)_{QF} = (M-TKE)_{cap} - \frac{\sigma_{fis}}{\sigma_{cap}}(M-TKE)_{fis}$$

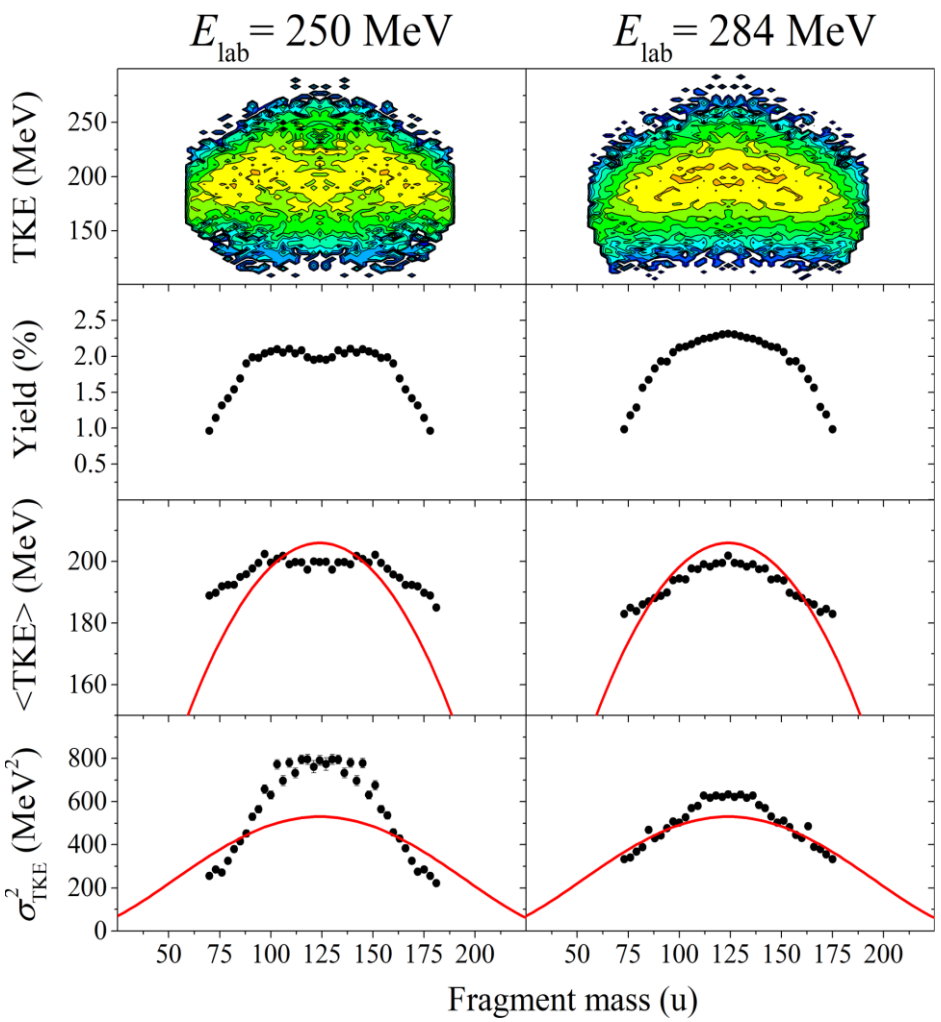
$$(M-TKE)_{\text{fast}} = (M-TKE)_{cap} - \frac{\sigma_{fis}}{\sigma_{cap}}(M-TKE)_{fis} - \frac{\sigma_{QF}}{\sigma_{cap}}(M-TKE)_{QF}$$

E.M. Kozulin, G.N. Knyazheva, A.A. Bogachev et al., Phys. Rev. C**105**, 024617 (2022).

Mass-Total Kinetic Energy distributions for Quasifission and Fast Fission



The mass-energy distributions of extracted QF fragments formed in the ^{40}Ca+^{208}Pb reaction at E_{lab}= 223 MeV.



The mass-energy distributions of fast fission fragments formed in the ^{40}Ca+^{208}Pb reaction at E_{lab}= 250 and 284 MeV

E.M. Kozulin, G.N. Knyazheva, A.A. Bogachev et al., Phys. Rev. C**105**, 024617 (2022).

The series of experiments with Ar-Ca-Ti-Cr incident ions

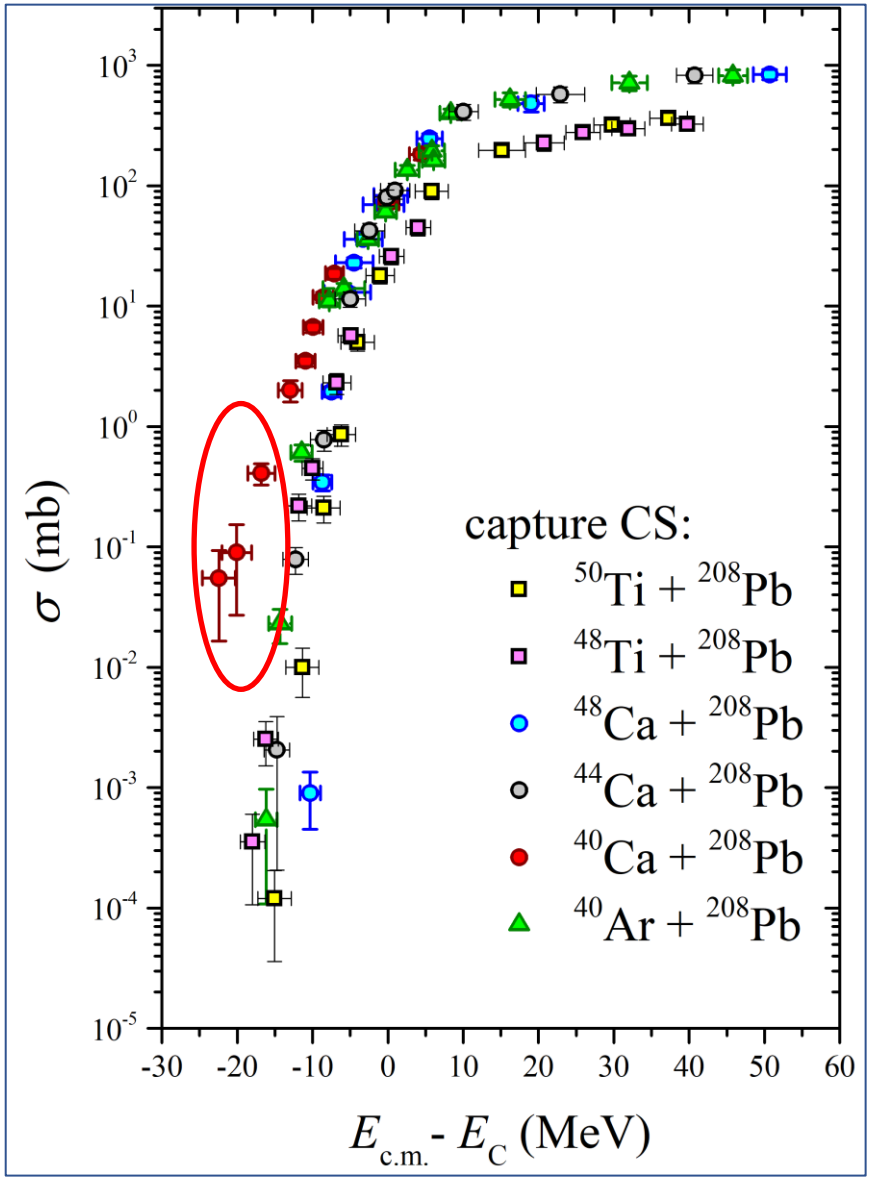
Measured reactions:

^{40}Ar (no closed shells) + ^{208}Pb

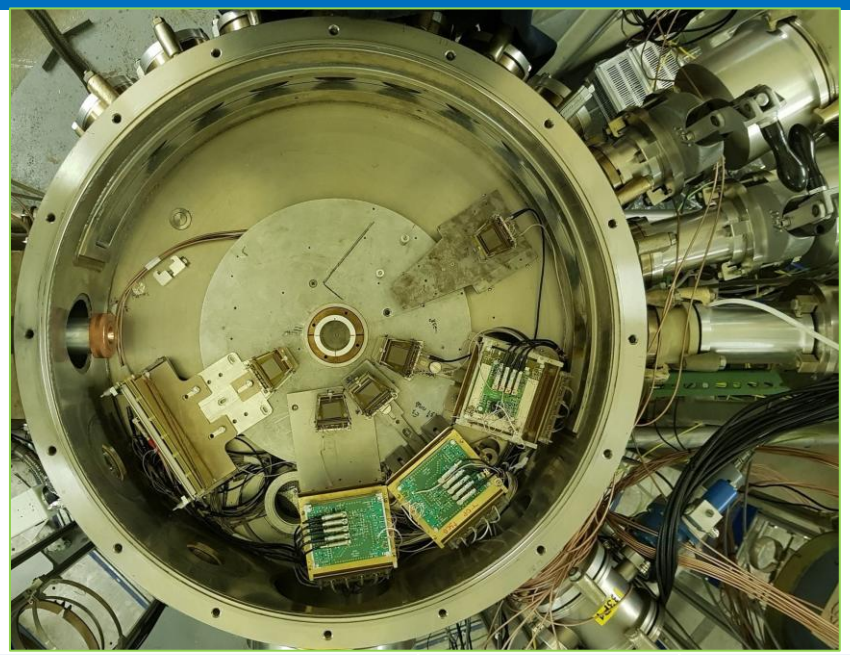
^{40}Ca (Z=20, N=20) + ^{208}Pb
^{42}Ca (Z=20) + ^{208}Pb
^{44}Ca (Z=20) + ^{208}Pb
^{48}Ca (Z=20, N=28) + ^{208}Pb

^{48}Ti (no closed shells) + ^{208}Pb
^{50}Ti (N=28) + ^{208}Pb

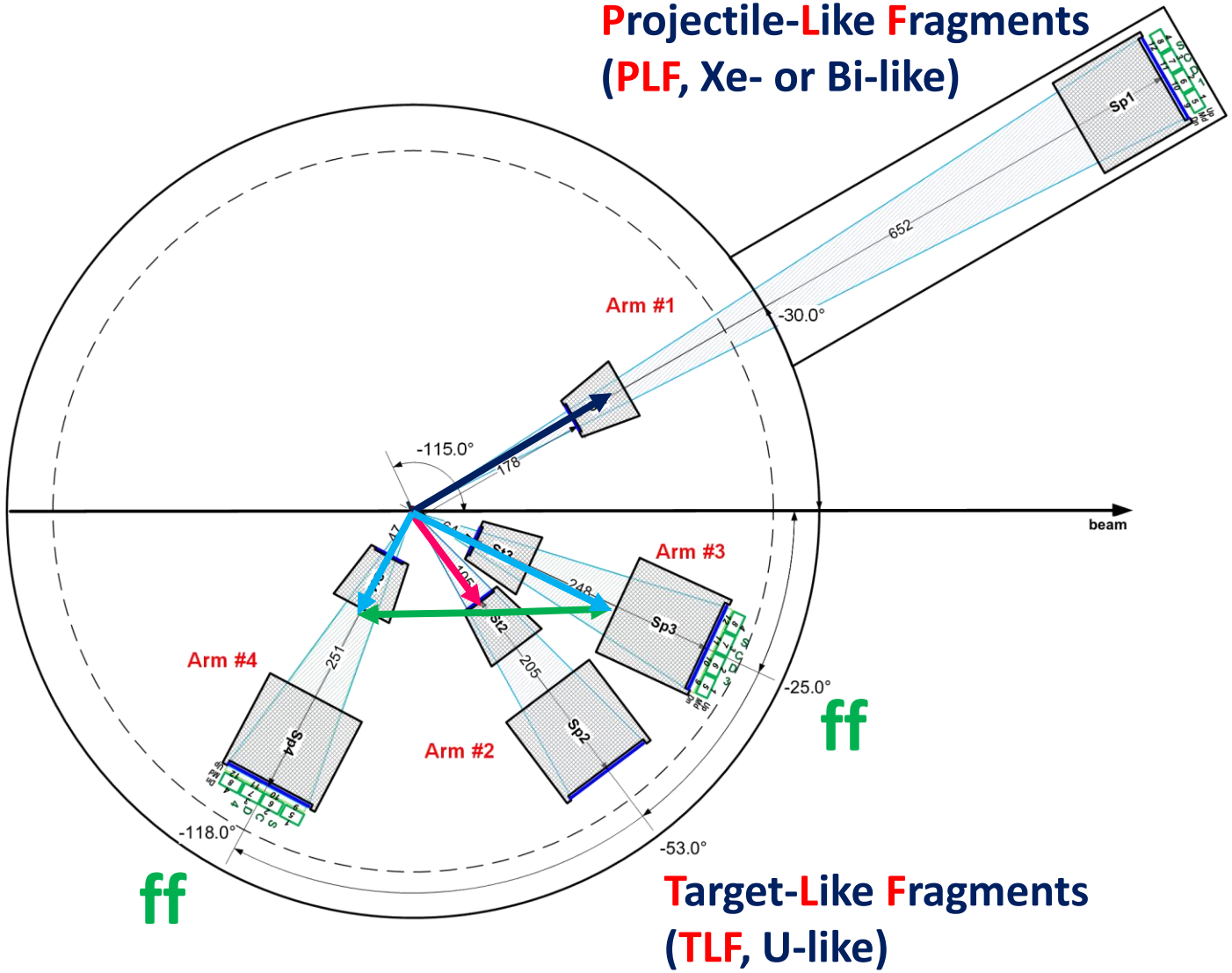
^{52}Cr (N=28) + ^{208}Pb
^{54}Cr (no closed shells) + ^{208}Pb



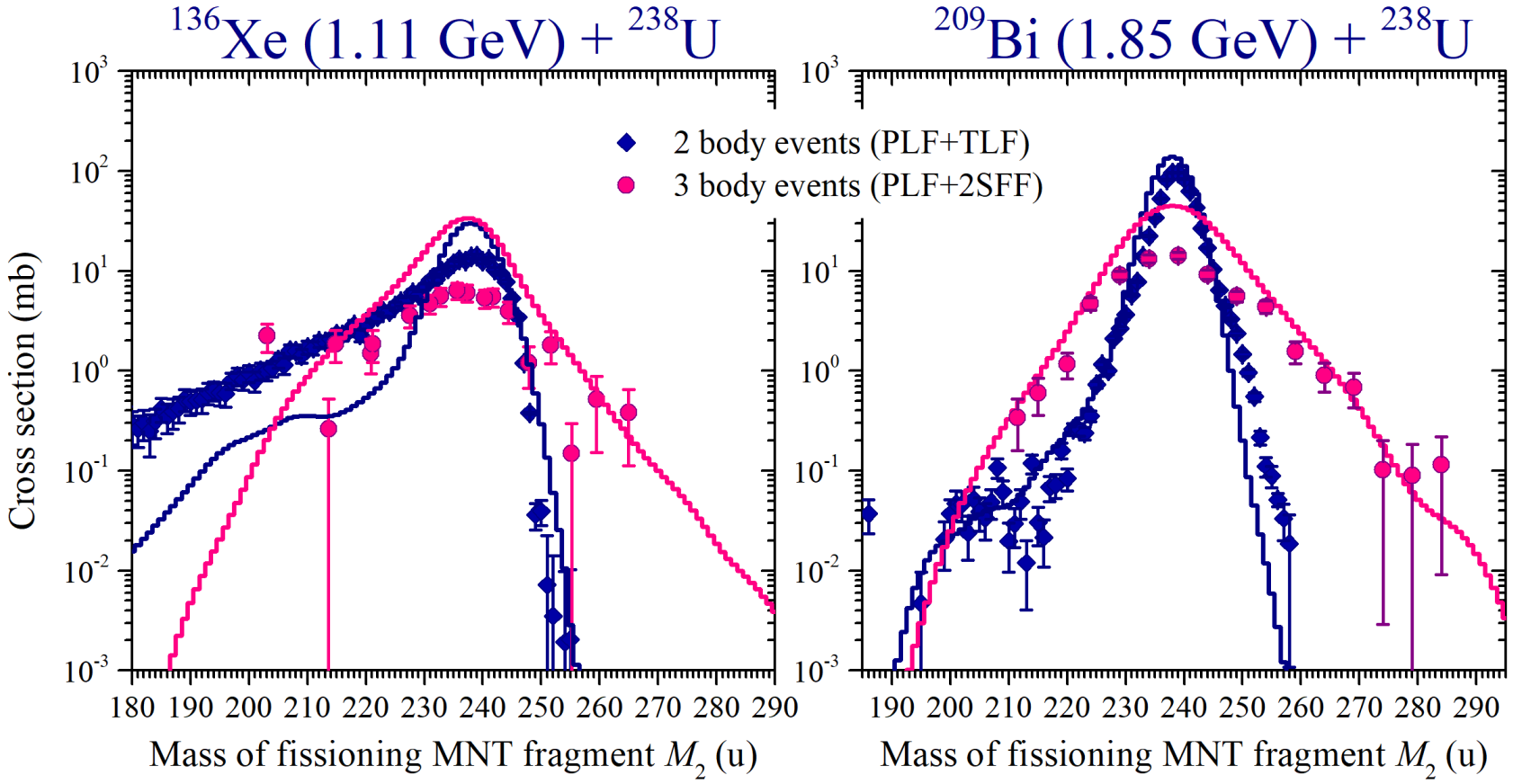
Multinucleon Transfer Reactions
^{136}Xe,^{209}Bi + ^{238}U at energies ~1.4-1.5 E_C



	^{136}Xe+^{238}U	^{209}Bi+^{238}U
E_{lab}	1.11 GeV	1.85 GeV
$E_{c.m.}$	706 MeV	985 MeV
$E_{c.m.}/E_C$	1.48	1.42
$\Theta_{c.m.}$ grazing for Xe/Bi	57°	61°
Θ_{lab} grazing for Xe/Bi	37°	34°
Θ_{lab} grazing of U	61.5°	59.2°



Mass distributions of MNT fragments



^{209}Bi + ^{197}Au, ^{208}Pb, ^{232}Th

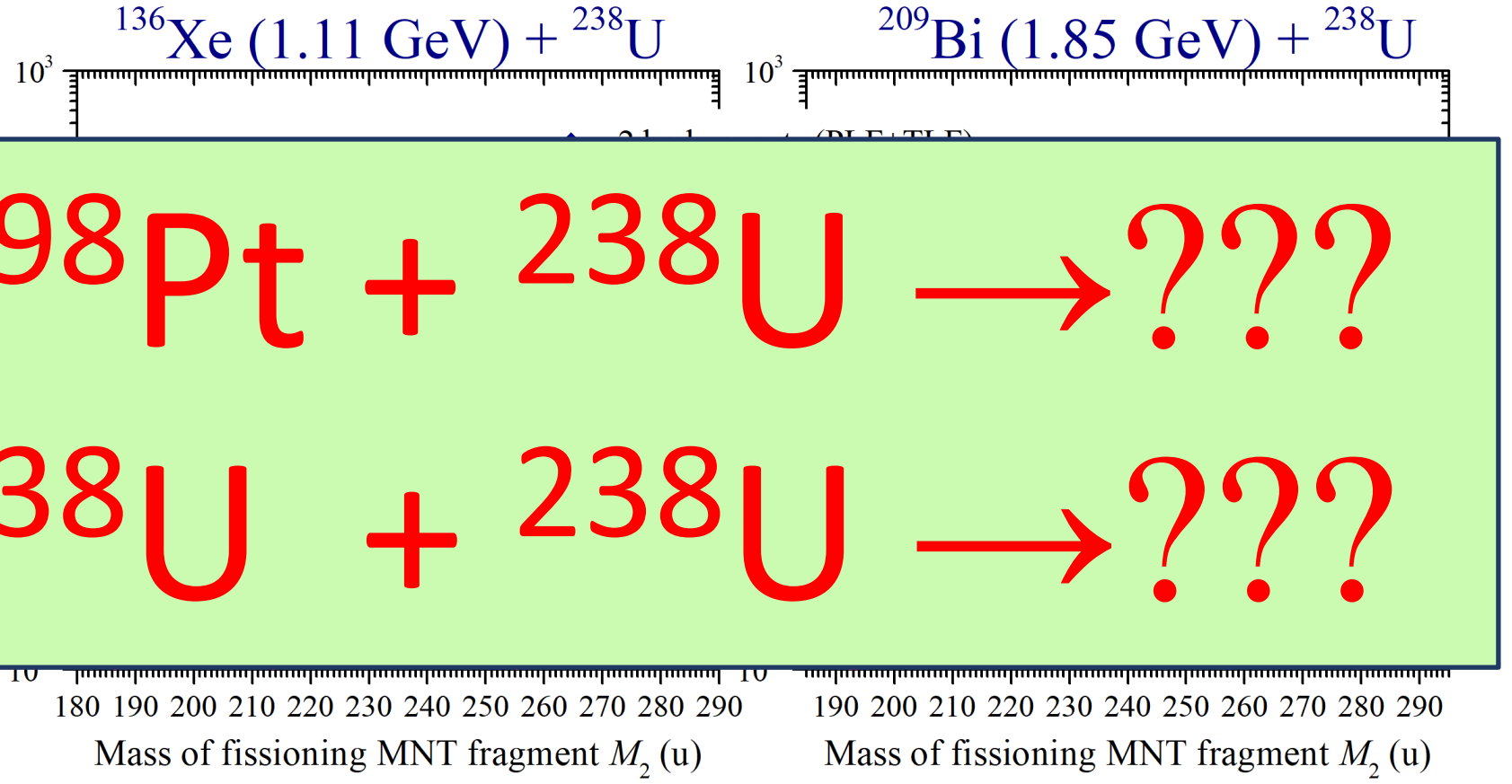
^{136}Xe + ^{238}U - 265 u ($Z \approx 103$, Lr isotopes)

^{209}Bi + ^{238}U - 284 u ($Z \approx 111$, Rg isotopes)

E. M. Kozulin, G. N. Knyazheva, A. V. Karpov et al. PRC **109**, 034616 (2024)

I.V. Vorobiev, E. M. Kozulin, G. N. Knyazheva et al. PRC **112**, 014625 (2025)

Mass distributions of MNT fragments



^{198}Pt + ^{238}U → ???

^{238}U + ^{238}U → ???

^{209}Bi + ^{197}Au, ^{208}Pb, ^{232}Th

^{136}Xe + ^{238}U - 265 u ($Z \approx 103$, Lr isotopes)

E. M. Kozulin, G. N. Knyazheva, A. V. Karpov et al. PRC **109**, 034616 (2024)

^{209}Bi + ^{238}U - 284 u ($Z \approx 111$, Rg isotopes)

I.V. Vorobiev, E. M. Kozulin, G. N. Knyazheva et al. PRC **112**, 014625 (2025)

Summary

- ✓In the sub-lead region of nuclides deformed proton shells Z≈36, Z≈45 and spherical proton shells Z=28/50 play stabilizing role in the formation of fission fragments. Influence of neutron shells is not observed.
- ✓Method for distinguishing fusion-fission, quasi-fission and fast fission processes was developed and successfully applied. This allows to investigate the characteristics of the processes separately and in more detail.
- ✓Capture cross sections were measured in series of experiments with ^{208}Pb target and different incident ions. For ^{40}Ca ions extremely high capture cross section was observed compared to other reactions.
- ✓Multinucleon transfer reactions can be used as one of the ways to obtain new isotopes of heavy and superheavy elements.

CORSET team

Thank you for your attention!