Flerov Laboratory of Nuclear Reactions
JINR, Dubna, Russia

Transition from heavy-ion reactions involving Ca to Ti , Cr, Kr and Gd ions

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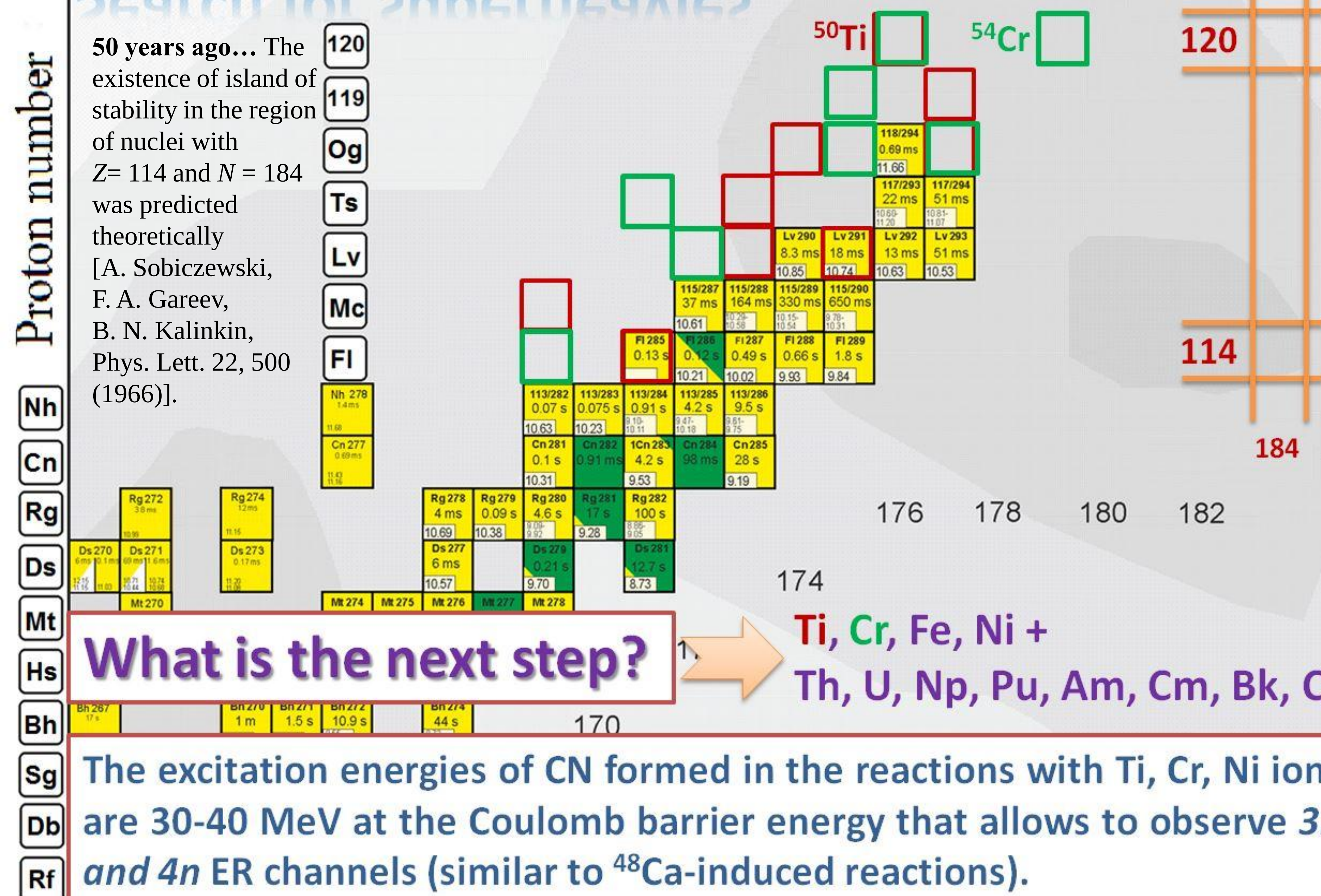
The ENSAR2 – NUSPRASEN Workshop on Nuclear Reactions (Theory and Experiment)

22nd to 24th January 2018, Warsaw, Poland

Search for superheavies

50 years ago… The existence of island of stability in the region of nuclei with Z= 114 and N = 184 was predicted theoretically [A. Sobiczewski, F. A. Gareev, B. N. Kalinkin, Phys. Lett. 22, 500 (1966)].

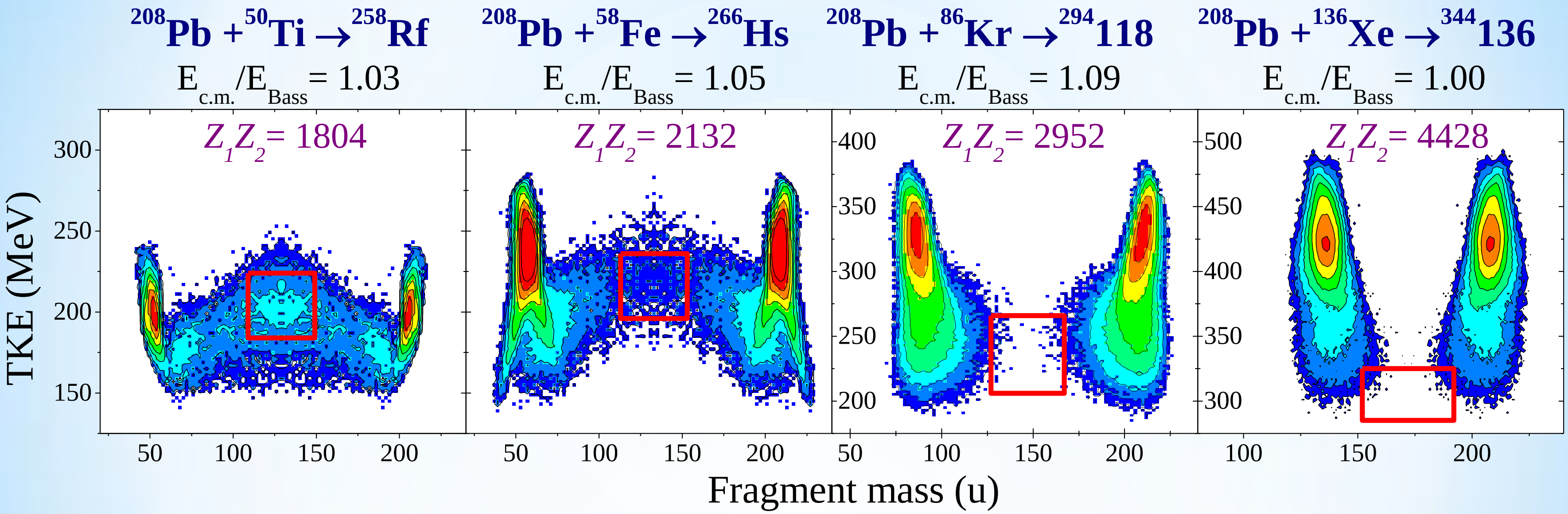


What is the next step?

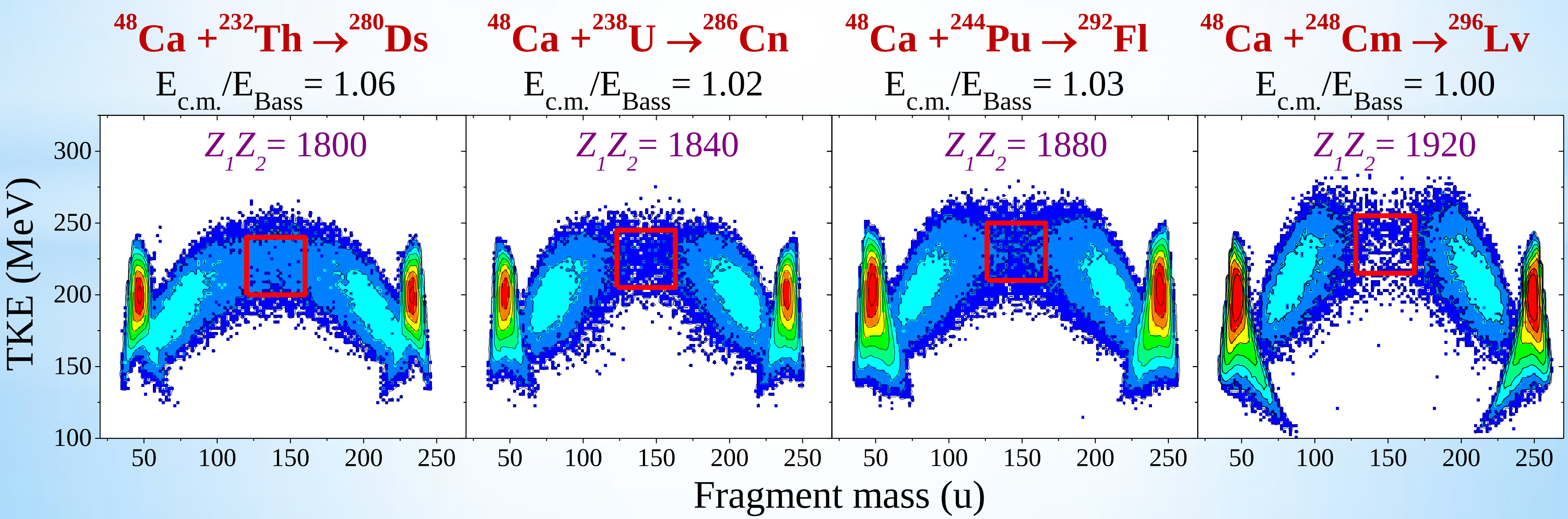
Ti, Cr, Fe, Ni +
Th, U, Np, Pu, Am, Cm, Bk, Cf

The excitation energies of CN formed in the reactions with Ti, Cr, Ni ions are 30-40 MeV at the Coulomb barrier energy that allows to observe *3n and 4n* ER channels (similar to ^{48}Ca-induced reactions).

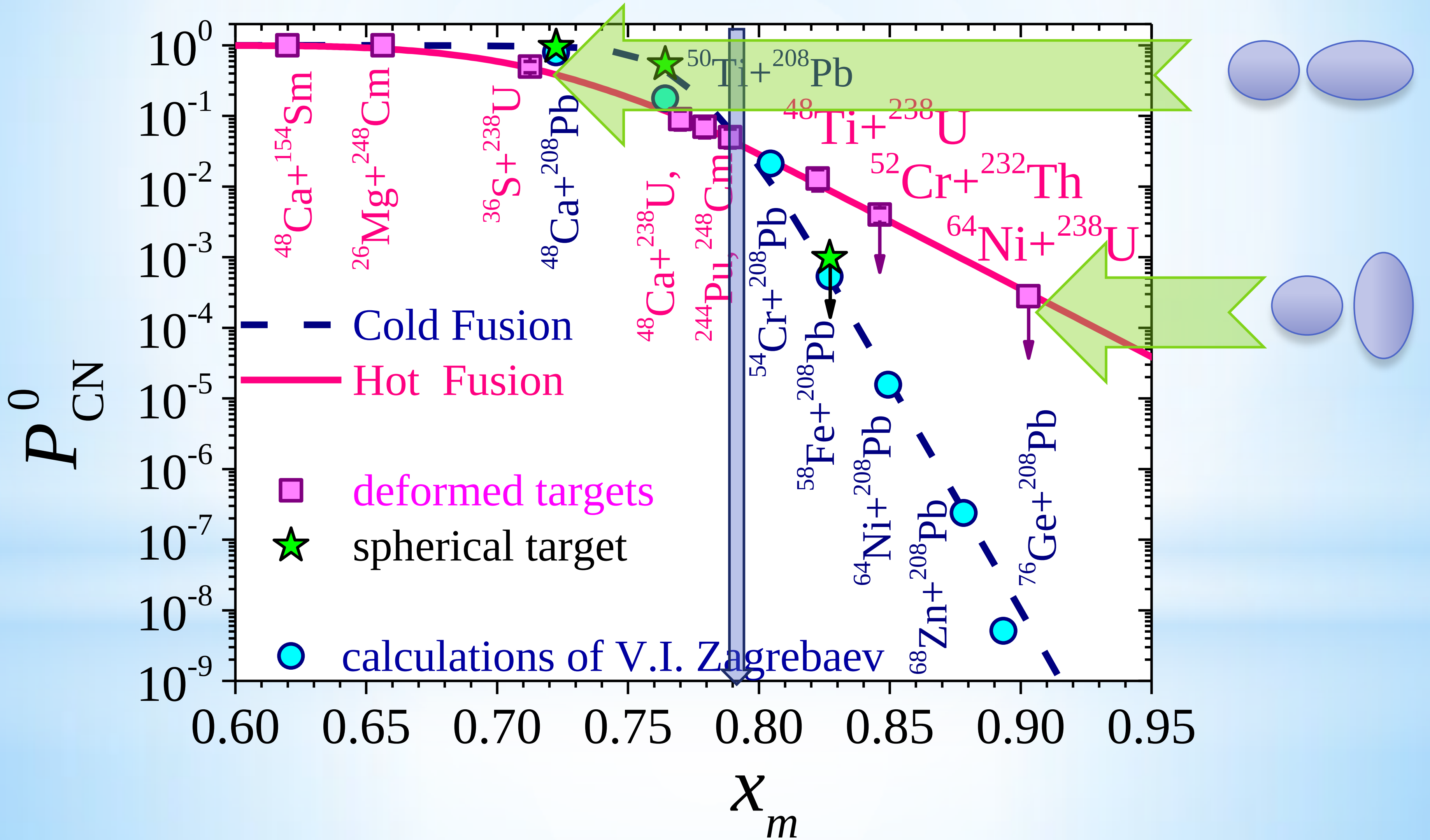
Cold fusion reactions



Hot fusion reactions



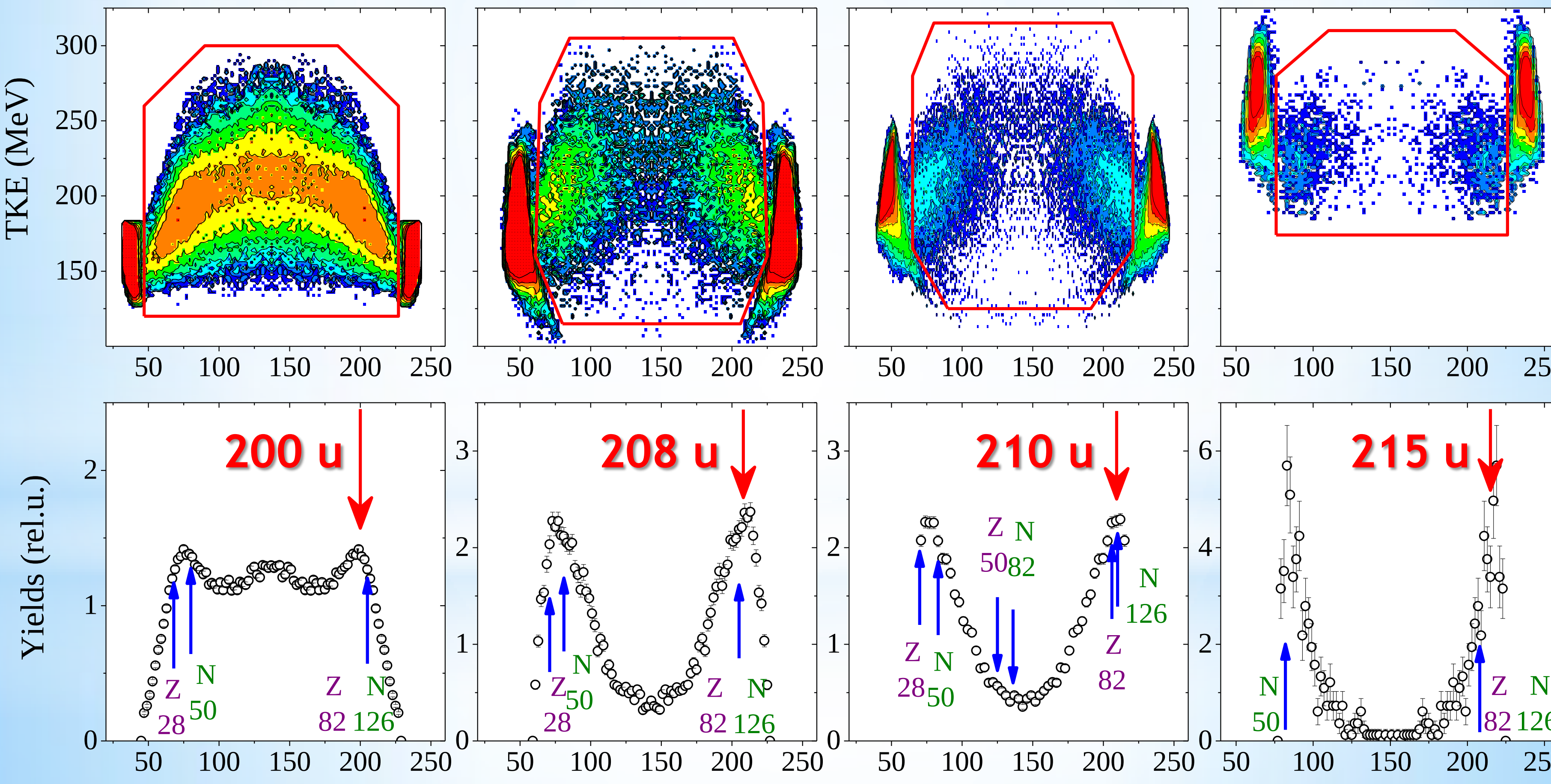
Fusion Probability in Cold and Hot fusion reactions



*Mass and Energy distributions

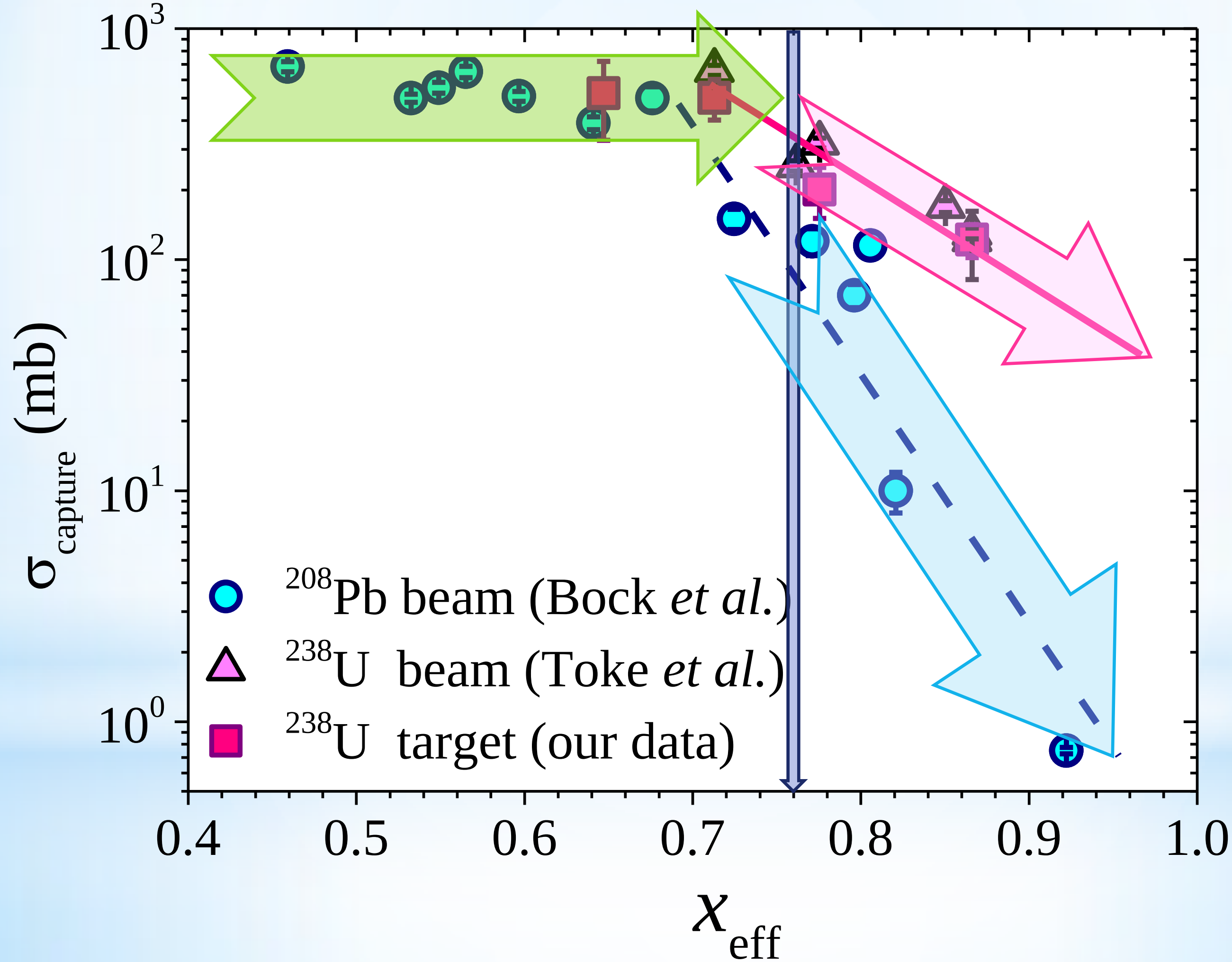
$^{36}S + ^{238}U \rightarrow ^{274}Hs^*$	$^{48}Ca + ^{238}U \rightarrow ^{286}Cn^*$	$^{48}Ti + ^{238}U \rightarrow ^{286}Fl^*$	$^{64}Ni + ^{238}U \rightarrow ^{302}120^*$
$E^* = 46$ MeV	$E^* = 35$ MeV	$E^* = 44$ MeV	$E^* = 31$ MeV

$E_{c.m.}/E_B$ **1.01** **1.00** **1.00** **1.01**



E. M. Kozulin, et al, Phys. Rev. C 94, 054613 (2016).

*Capture cross section

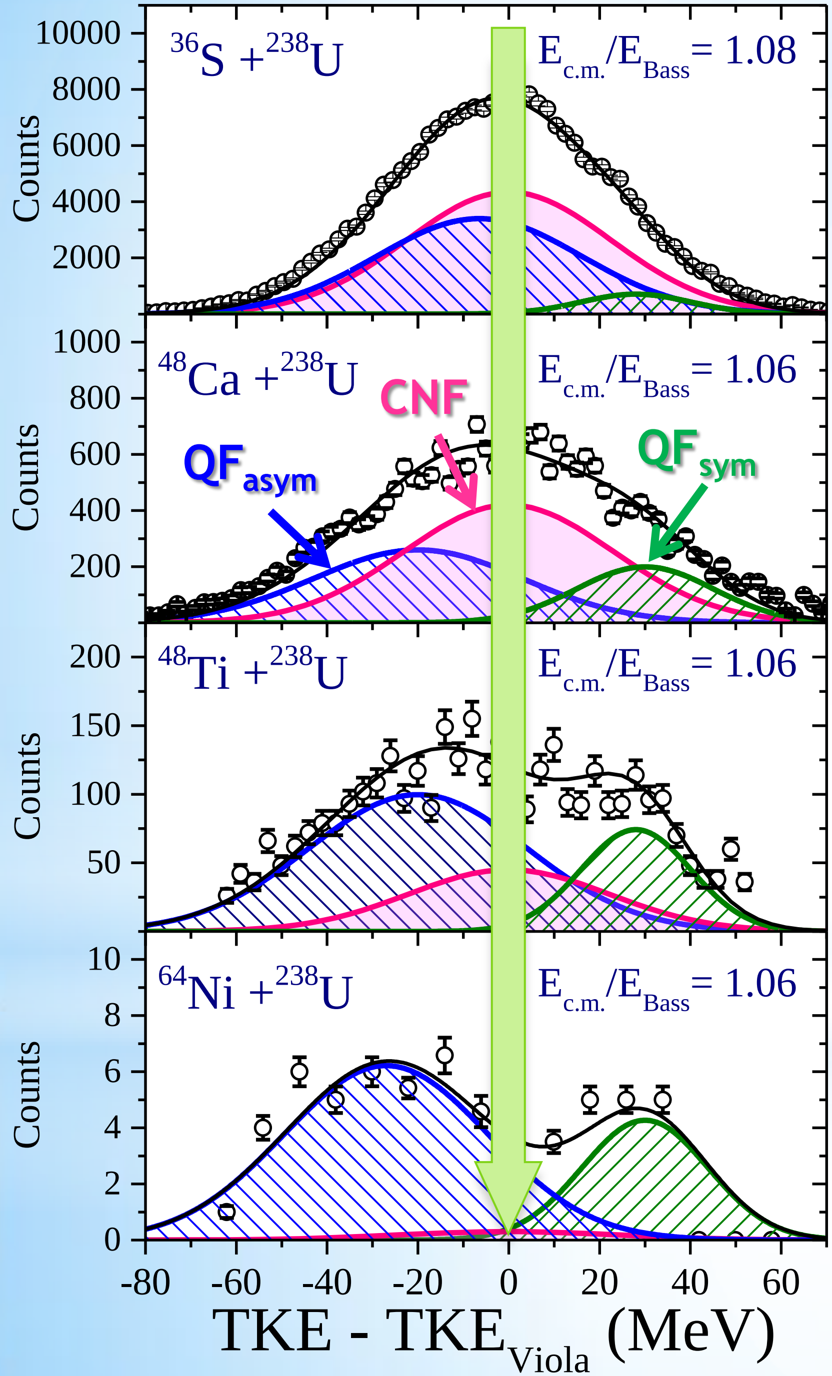


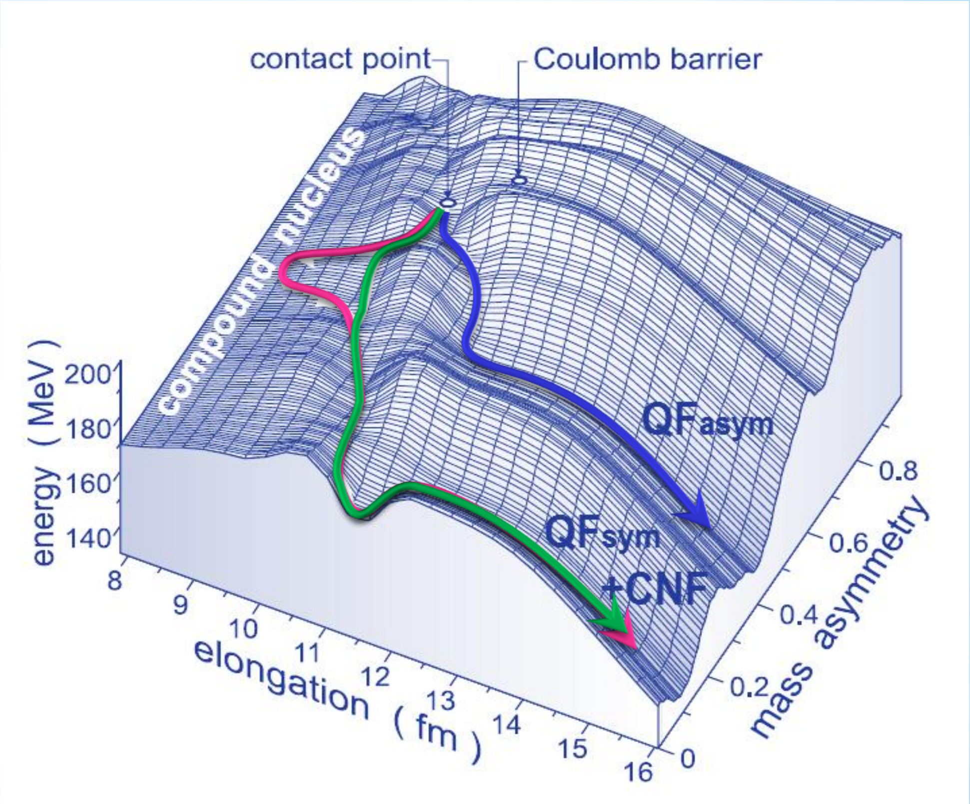
$E_{c.m.}/E_{Bass}$ 1.1÷1.2

^{238}U

$\beta_2 = 0.286$

*TKE distributions

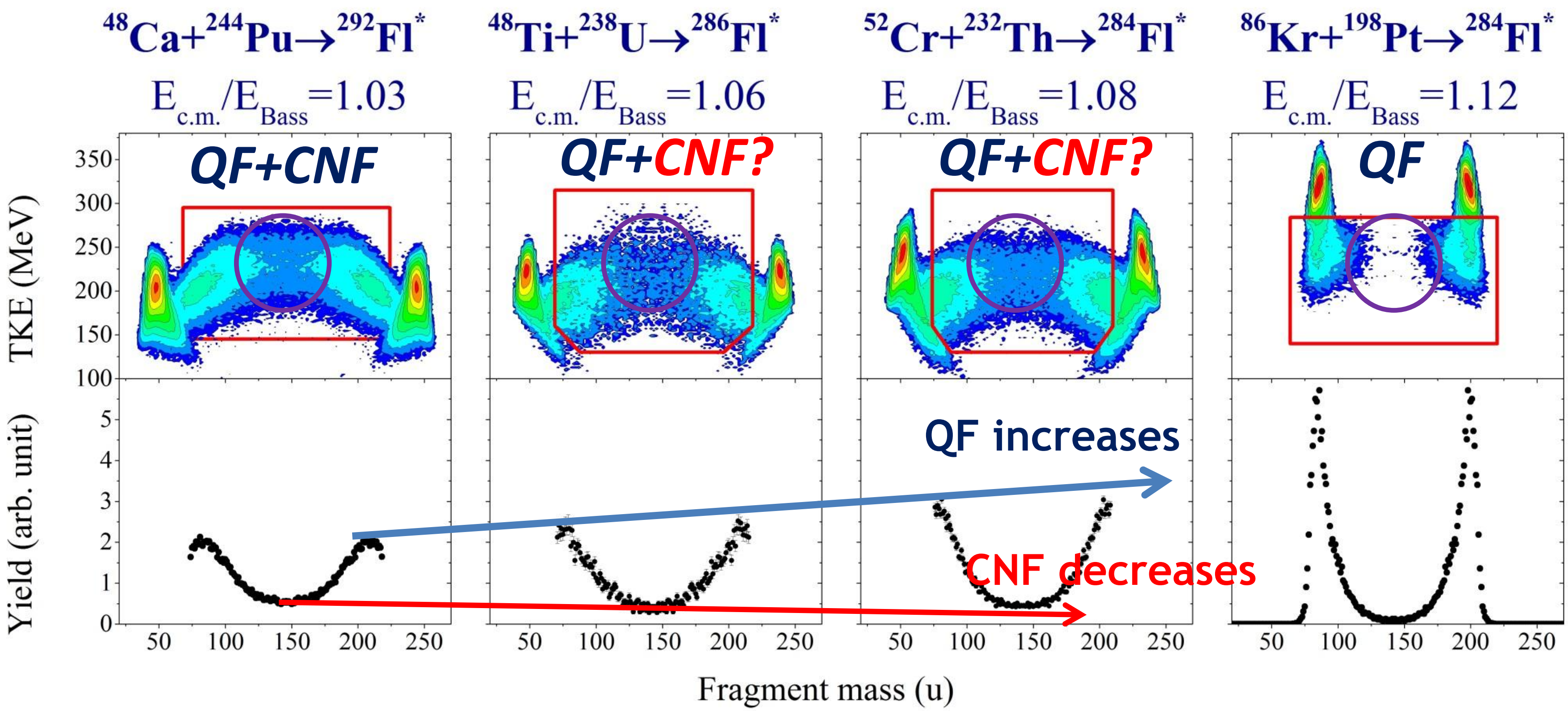




$A_{CN}/2 \pm 20$ u

E. M. Kozulin, G. N. Knyazheva, K. V. Novikov et al, Phys. Rev. C 94, 054613 (2016).

Mass and Energy distributions in the reactions leading to the formation of Z=114



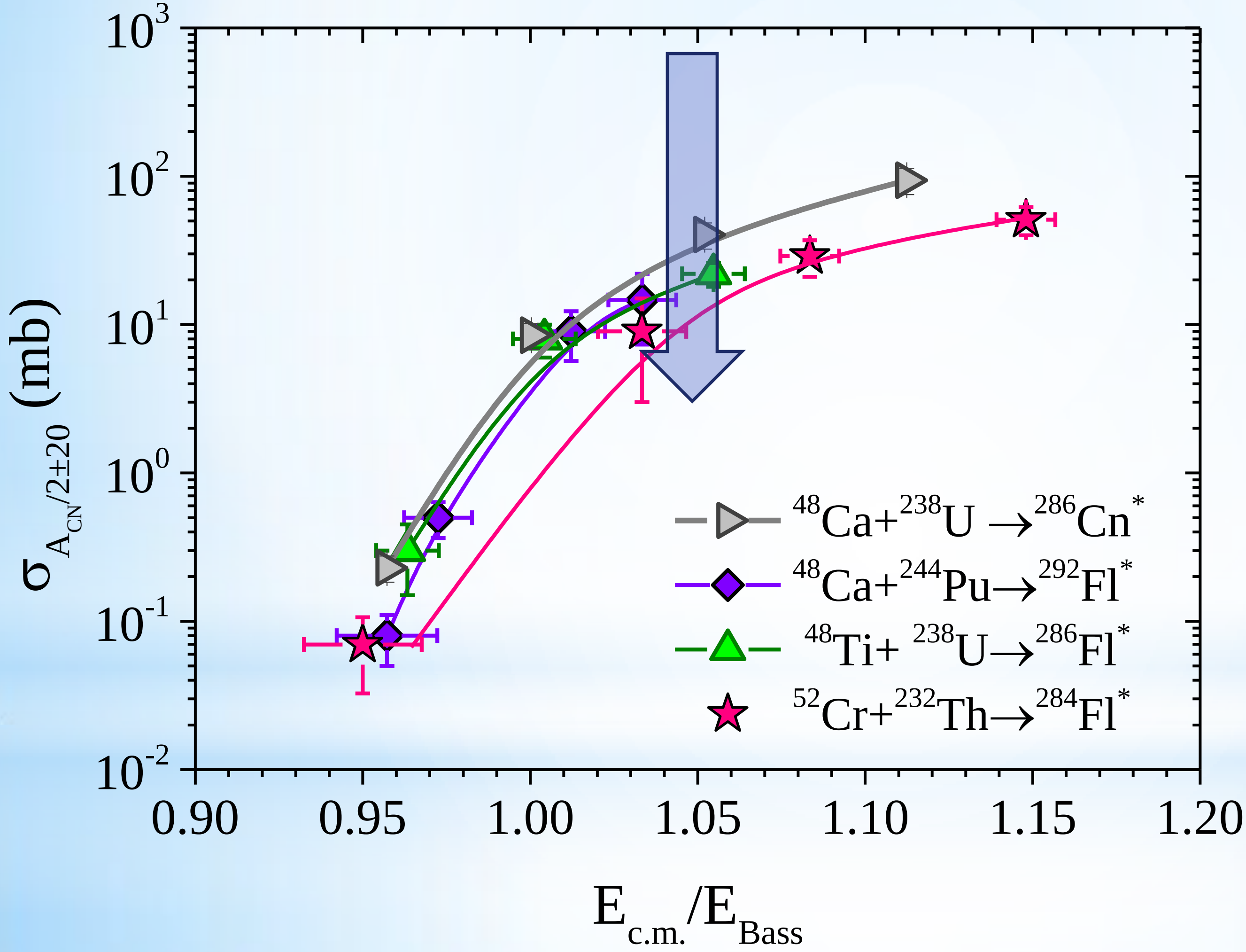
Z_tZ_p=1880 X_m=0.721

Z_tZ_p=2024 X_m=0.776

Z_tZ_p=2160 X_m=0.806

Z_tZ_p=2808 X_m=0.917

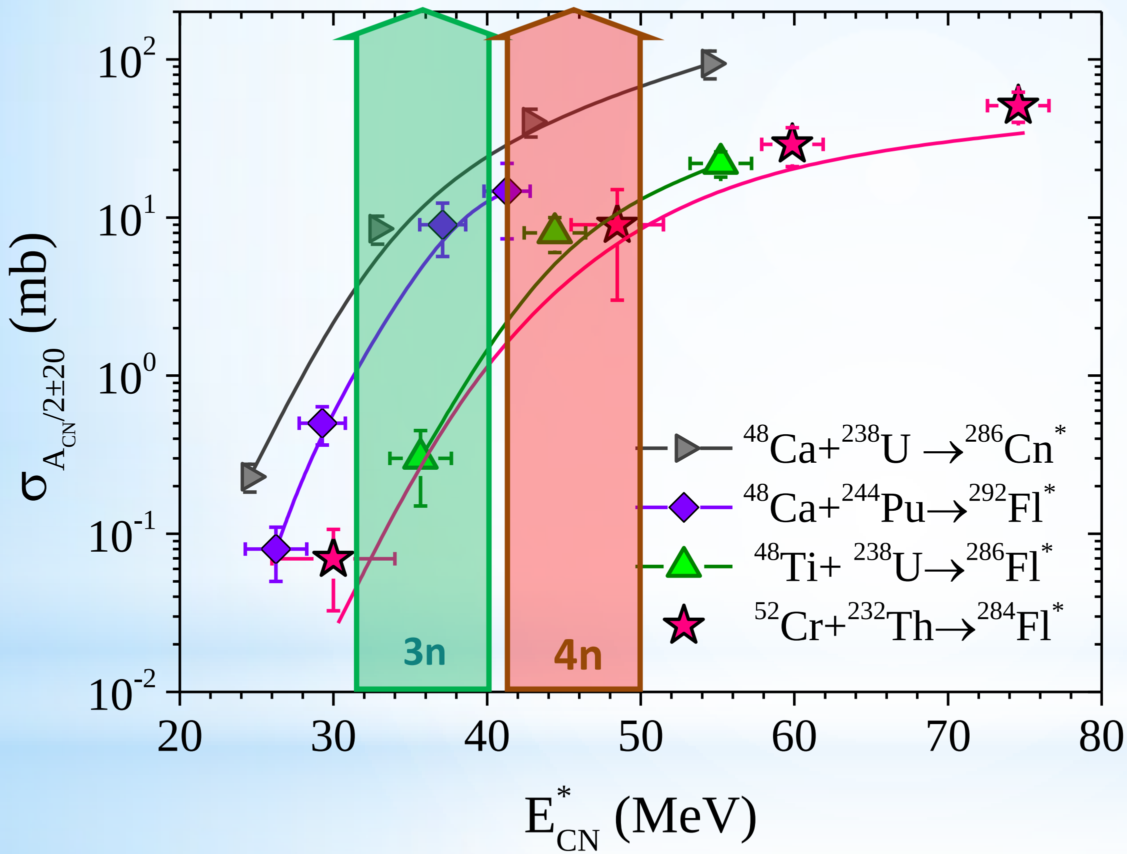
* CS of symmetric fragment formations



At energies above the barrier the CS for symmetric fragments formations decreases 2 times for the reaction $^{48}Ti+^{238}U$ and 4 times for the $^{52}Cr+^{232}Th$ compare with the $^{48}Ca+^{238}U$.

Note that a significant part of symmetric fragments may be connected with QF process. It is only upper limit for fission cross section!

* Cross sections of symmetric fragment formations



For 4*n* channel (E^{*}=40÷50MeV):

$^{48}Ca+^{238}U \rightarrow ^{48}Ca+^{244}Pu$

$\sigma(A_{CN}/2\pm20)$ drops ~2 times

$^{48}Ca+^{238}U \rightarrow ^{48}Ti+^{238}U$

$\sigma(A_{CN}/2\pm20)$ drops ~10 times

For 3*n* channel (E^{*}=30÷40MeV):

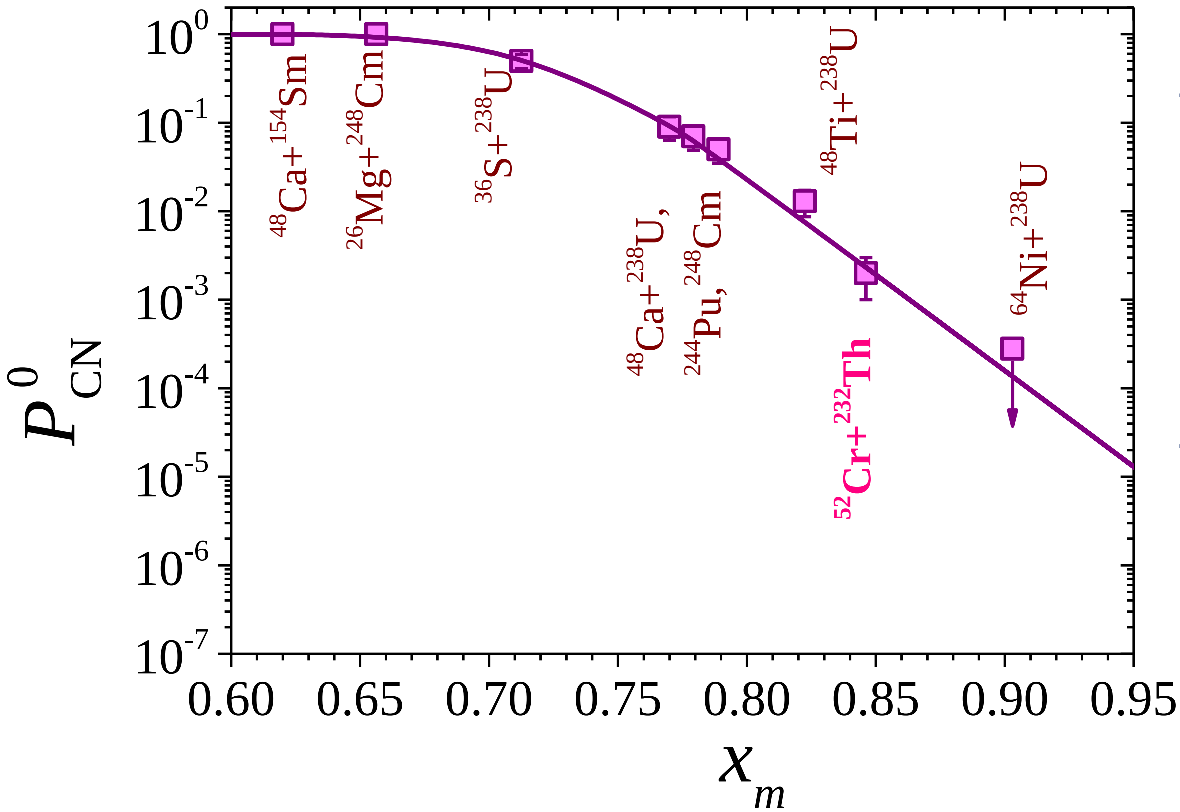
$^{48}Ca+^{238}U \rightarrow ^{48}Ca+^{244}Pu$

$\sigma(A_{CN}/2\pm20)$ drops ~10 times

$^{48}Ca+^{238}U \rightarrow ^{48}Ti+^{238}U$

$\sigma(A_{CN}/2\pm20)$ drops ~100 times

For the studied reactions the excitation energies at the barrier energy vary strongly (36MeV for the Ca+Pu, 44MeV for the Ti+U and 41MeV for the Cr+Th).
It leads to decreasing the CS for the Ti+U and Cr+Th for 3n ER channel.



$^{48}Ca+^{244}Pu \rightarrow ^{48}Ti+^{238}U$

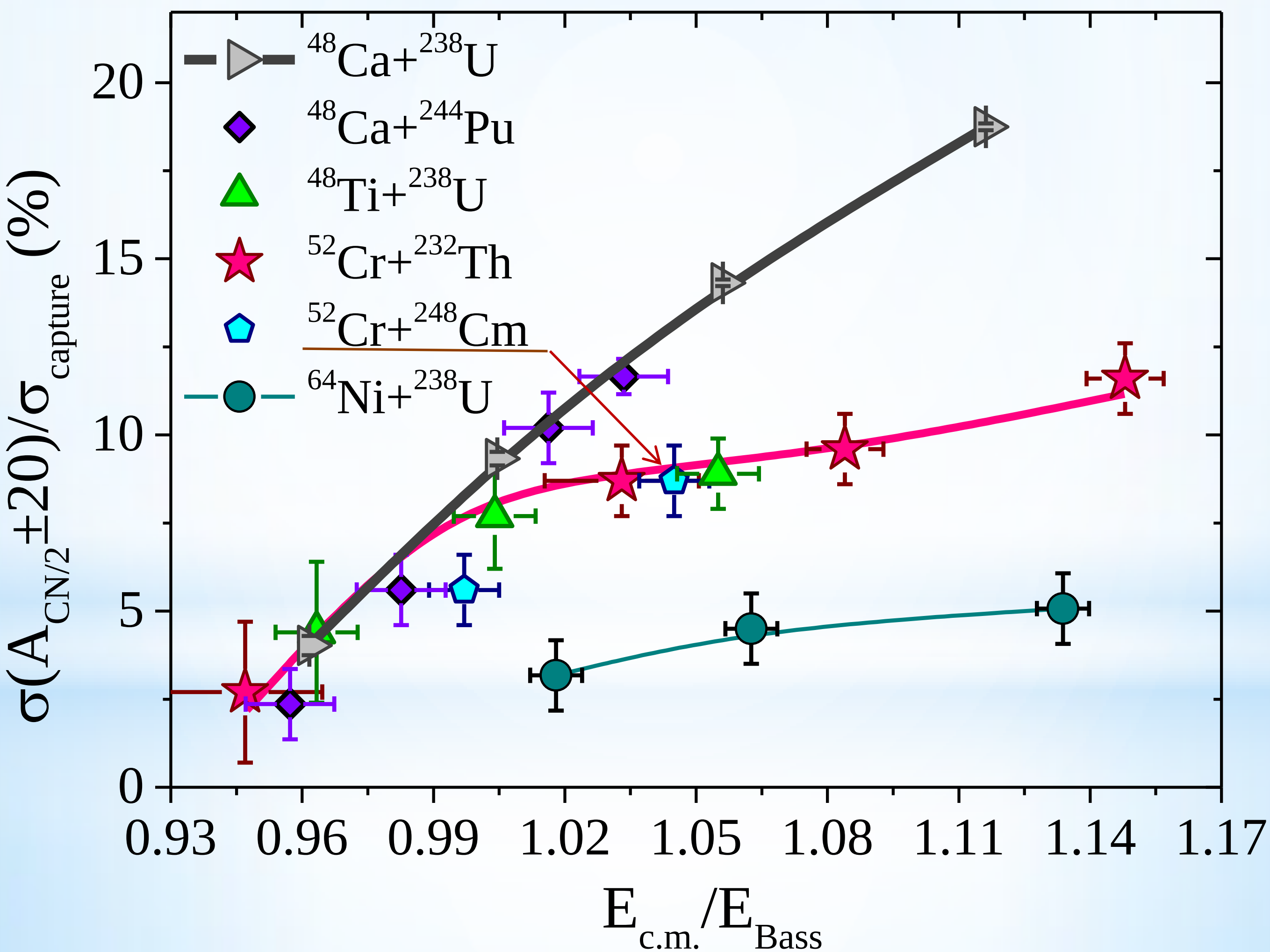
P_{CN} **drops ~ 4 times**

$^{48}Ca+^{244}Pu \rightarrow ^{52}Cr+^{232}Th$

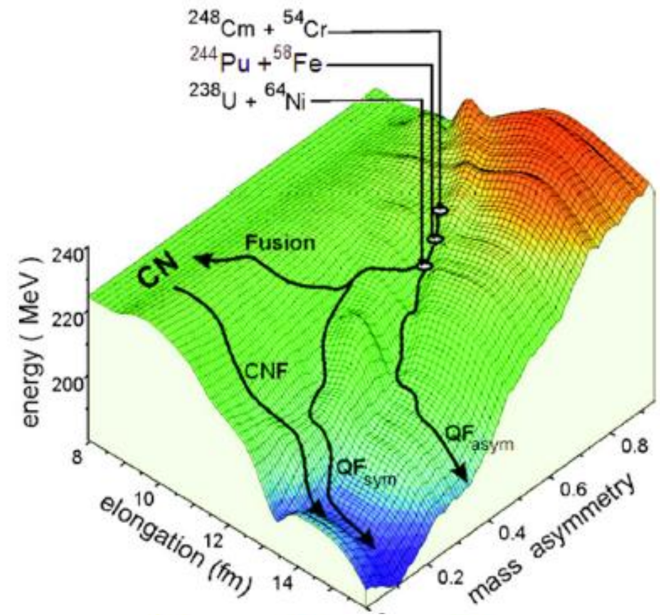
P_{CN} **drops ~ 25 times**

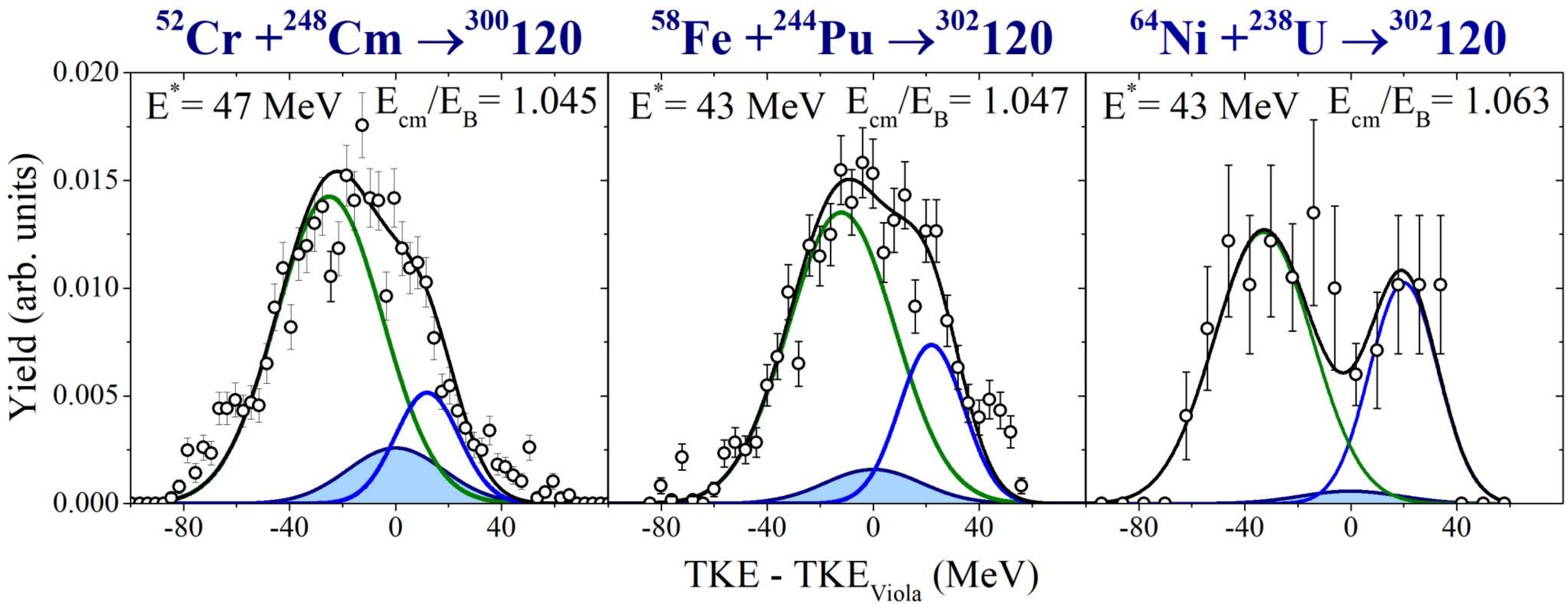
Fusion probability for the reaction $^{52}Cr+^{232}Th$ in comparison with fusion probabilities in hot fusion (strongly deformed target nuclei) reactions at energies above the Coulomb barrier in dependence on the mean fissility parameter of the reaction.

* Contribution of symmetric component into all fissionlike fragments



TKE distribution of symmetric fragments



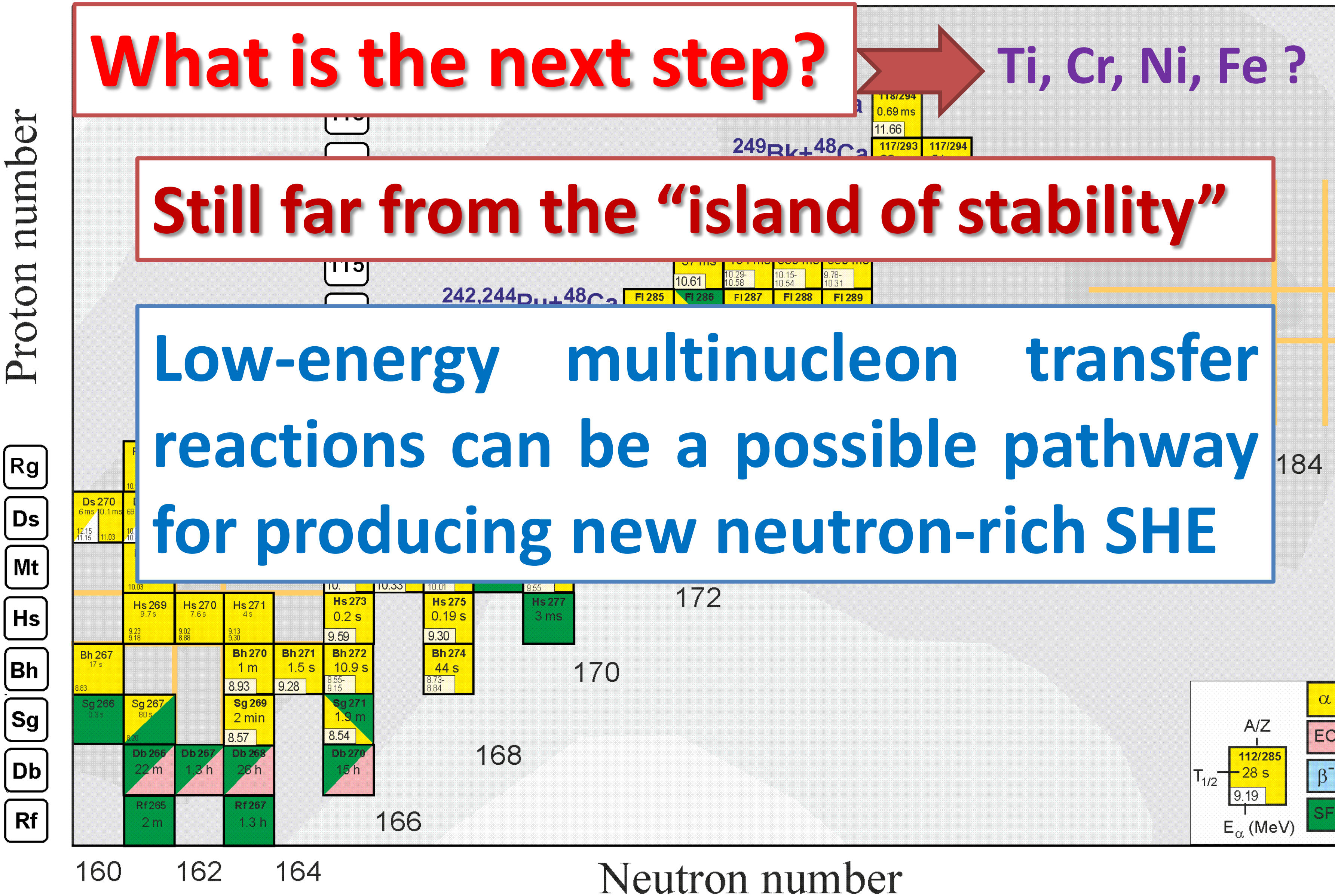


SEARCH FOR SUPERHEAVY

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

Still far from the "island of stability"

Low-energy multinucleon transfer reactions can be a possible pathway for producing new neutron-rich SHE



Normal ← Quasifission → *Inverse*

Normal

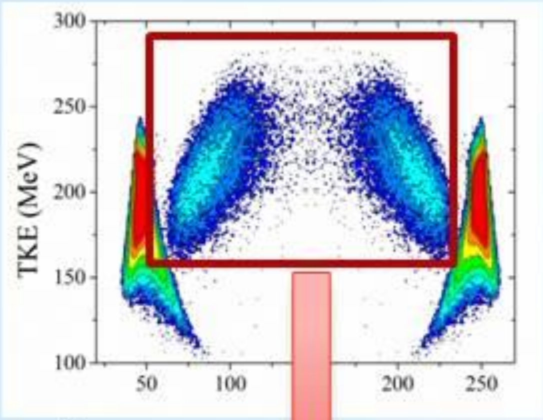
$^{48}Ca + ^{248}Cm$

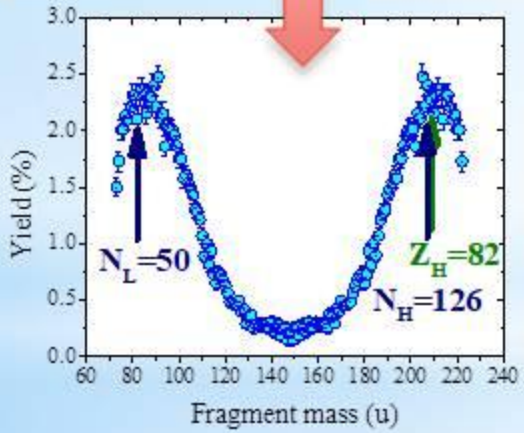
($E_{c.m.}/E_B = 1.00$)

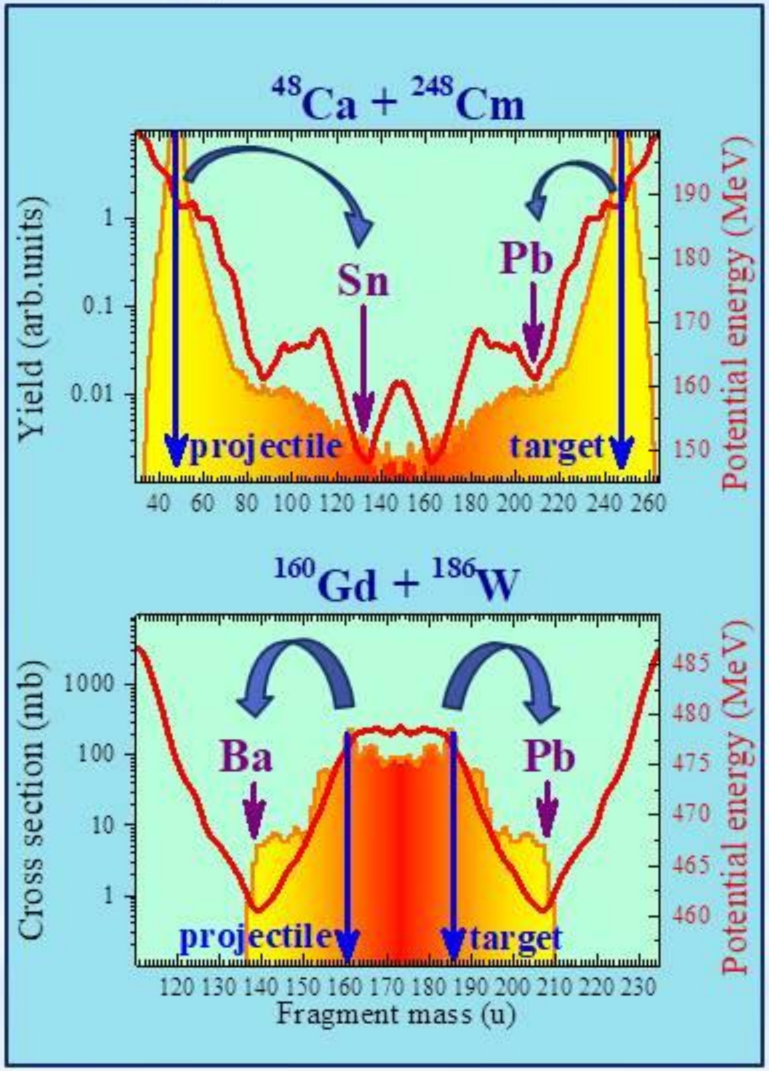
Inverse

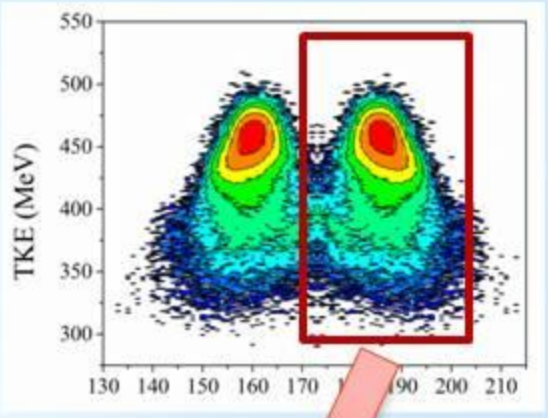
$^{160}Gd + ^{186}W$

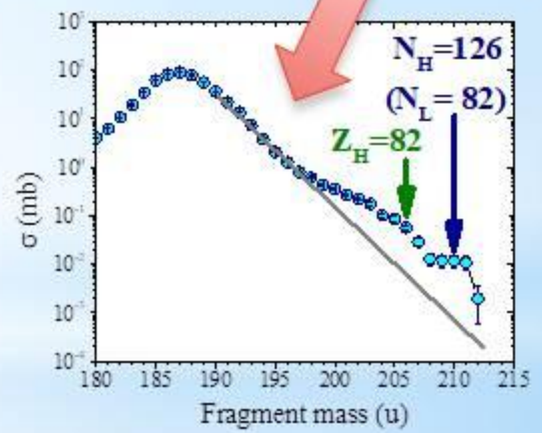
($E_{c.m.}/E_B = 1.01$)











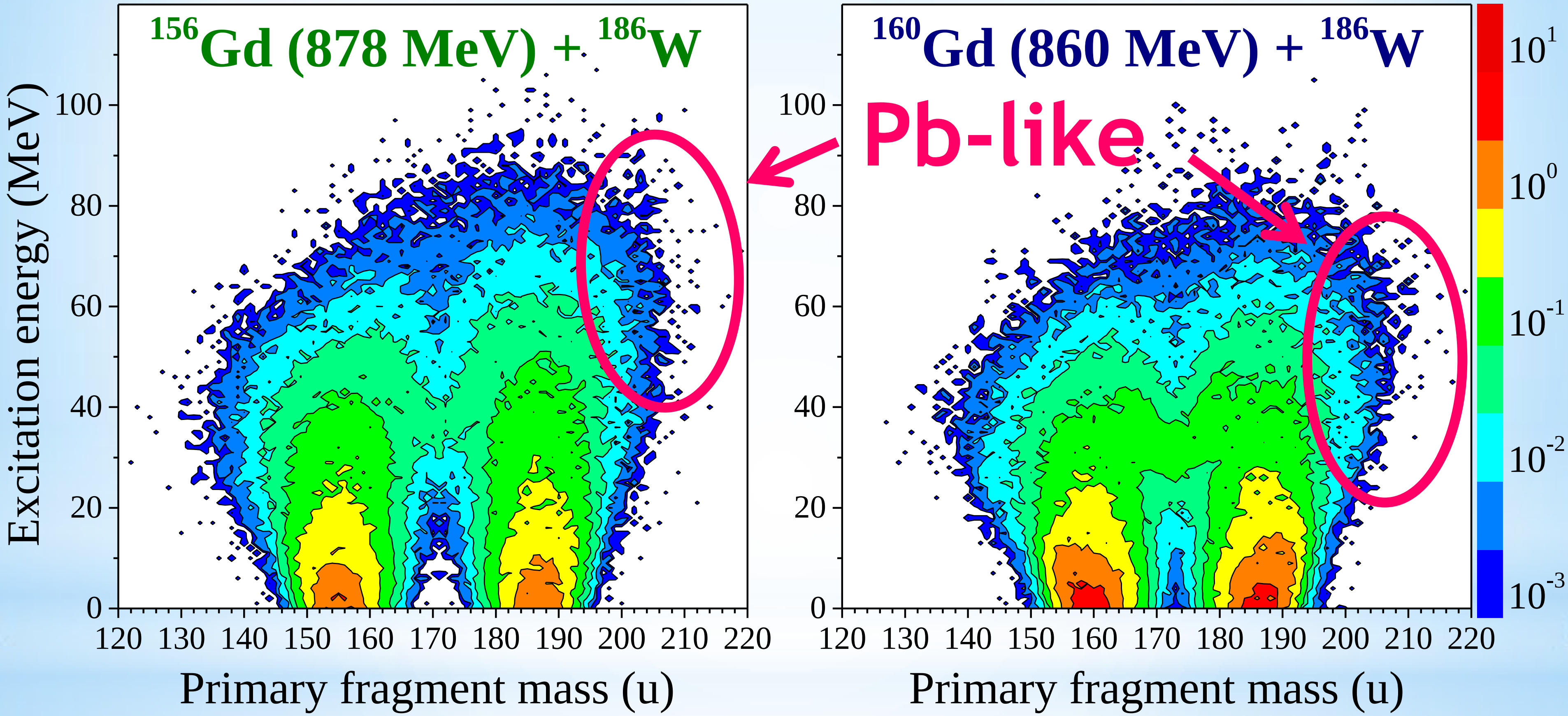
The **inverse** quasifission process, proposed to produce SHE in collisions of transactinides, and the role of shell effects in inverse QF can be studied in the experiments with **less heavy nuclei**

V.Zagrebaev and W.Greiner, J.Phys.G 34 2265 ***(2007)****.*

E.M. Kozulin, V.I.Zagrebaev, G.N.Knyazheva et al. Phys. Rev.C ***96****, 064621* ***(2017)****.*

Excitation Energy of Fragments

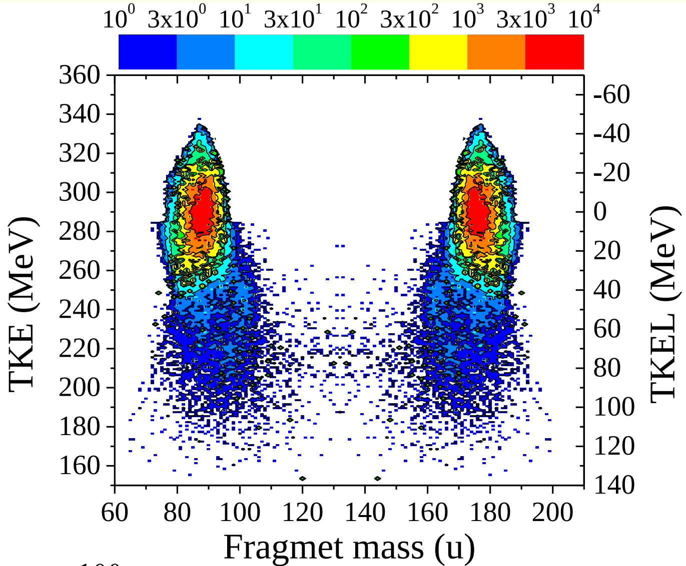
$E_f^* = E_{\mathrm{c.m.}} - \mathrm{TKE} + Q_{gg}$

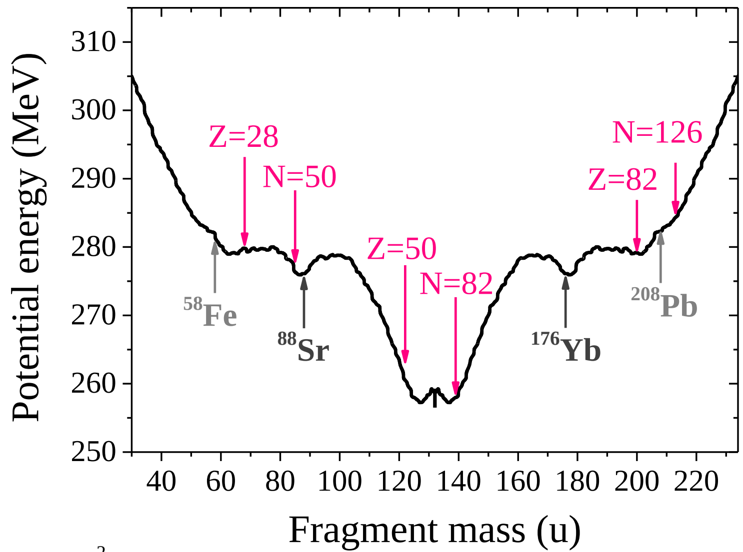


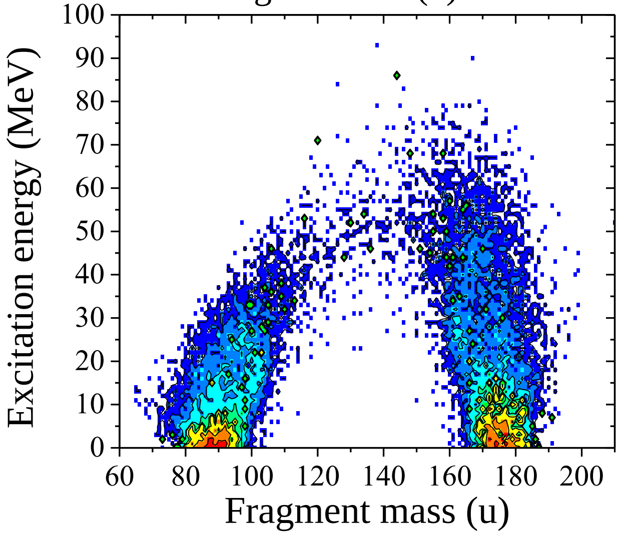
Survival probability is higher!

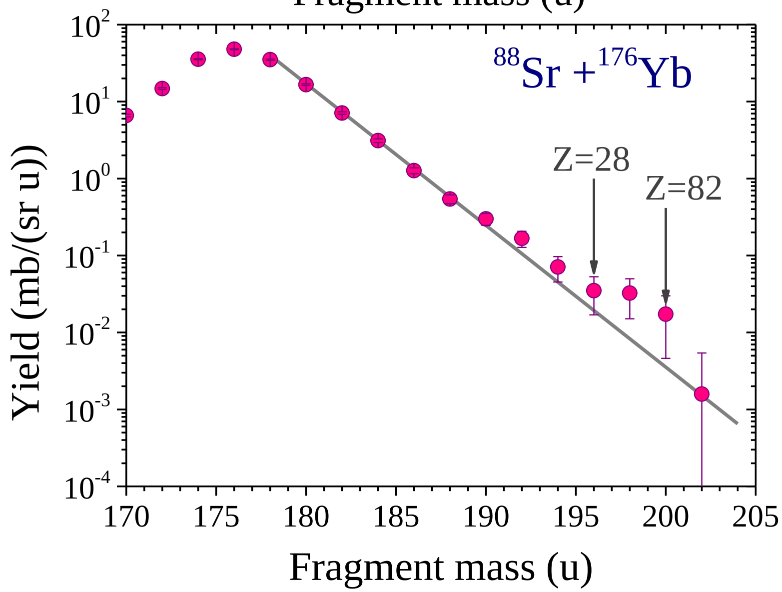
More neutron-rich nuclei!

$^{88}Sr+^{176}Yb$: shell effects in damped collisions









E.M. Kozulin, G.N. Knyazheva, S.N. Dmitriev, I.M. Itkis, M.G. Itkis, T.A. Loktev, K.V. Novikov, A. Baranov, W.H. Trzaska, E. Vardaci, S.Heinz, O. Beliuskina, S.V.Khlebnikov. Shell effects in damped collisions of ^{88}Sr with ^{176}Yb at the Coulomb barrier energy. Phys. Rev. C89, 014614 (2014).

to plan the ISOLDE beamtime for 2018

Experiment IS550 P-344:

Study of the di-nuclear system

$^{A}Rb + {}^{209}Bi$ $(Z_1 + Z_2 = 120)$

Total shifts: 12

SPOKESPERSON:

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GSI Helmholtzzentrum and Justus-Liebig-Universität Gießen

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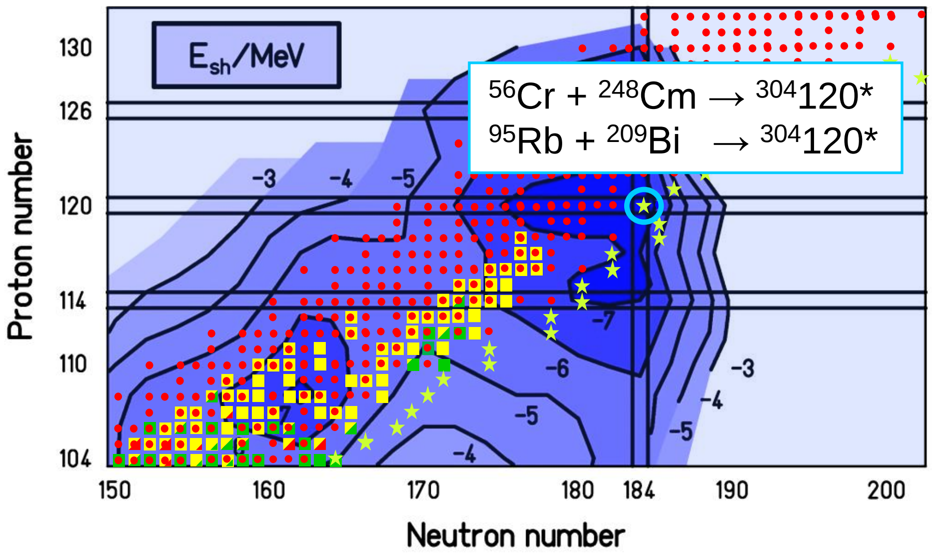
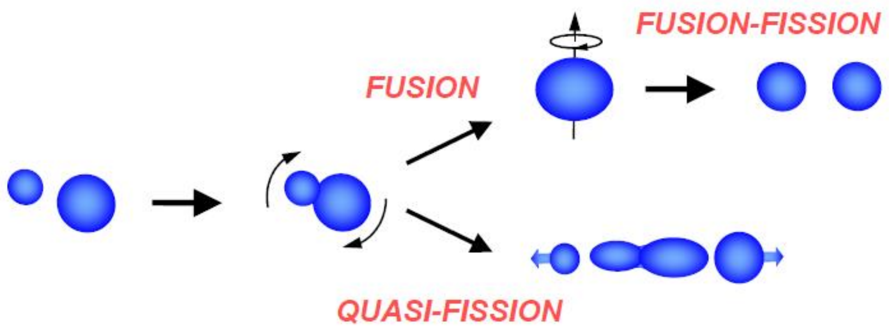
Where are the Next Magic Shells Above ^{208}Pb?

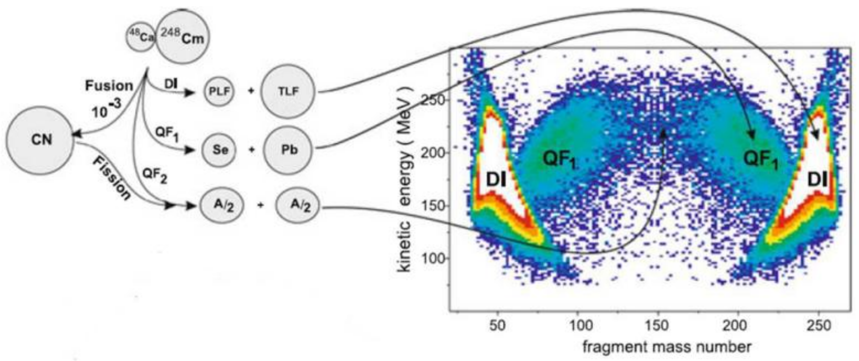
Presented by S.Heinz



- Nuclear systems with N ≈ 184 can be reached in reactions with RIBs
- <u>problem:</u> fusion cross-sections are tiny (σ << 0.1 pb)
- <u>approach:</u> study of quasi-fission (QF) and fusion-fission (FF) reveals the stability of superheavy systems



$$\sigma_{capture} \approx \sigma_{QF} + \sigma_{FF} \approx 100 \text{ mb}$$



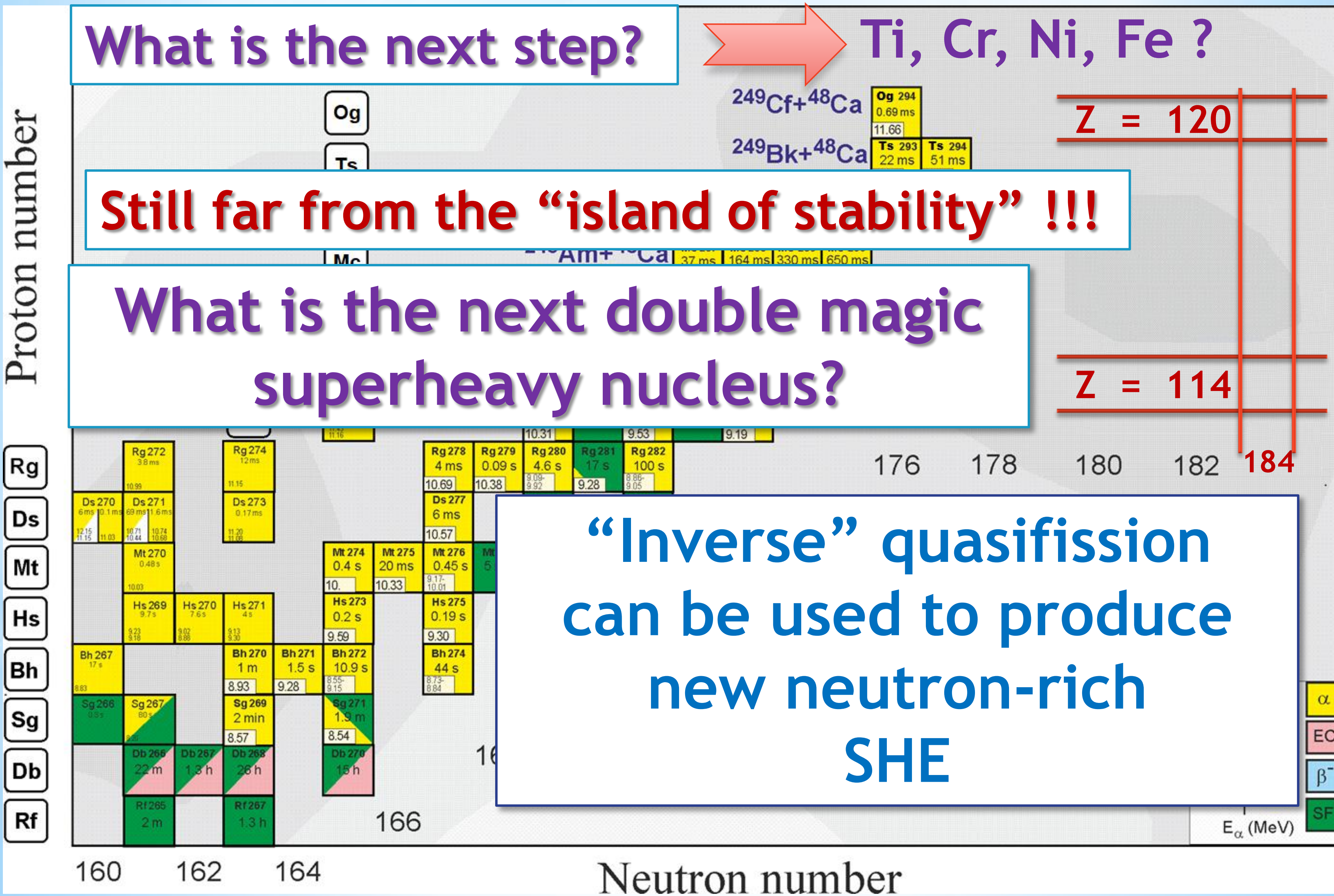
The study of QF and FF as a function of beam energy and neutron number allows a mapping of the potential energy surface

* Search for superheavies

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

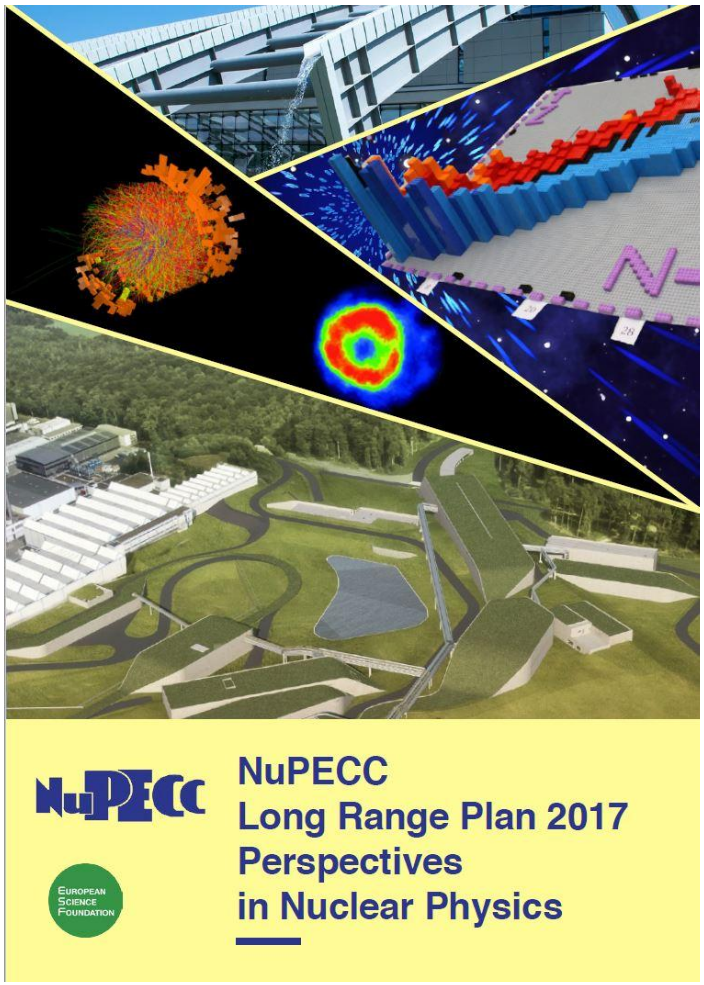
Still far from the "island of stability" !!!

What is the next double magic superheavy nucleus?



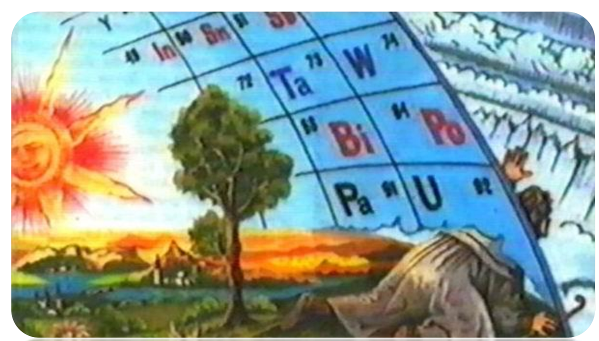
"Inverse" quasifission can be used to produce new neutron-rich SHE

3. NUCLEAR STRUCTURE AND REACTION DYNAMICS



The access to new and complementary experiments combined with theoretical advances allows key questions to be addressed such as:

Where are the limits of stability and what is the heaviest element that can be created?



CONCLUSION

Where is a pathway to the island of stability?

Reactions with Ti, Cr, Ni, Fe ions:

Fusion probability decreases exponentially with the growing mean fissility parameter

Neutron-deficient isotopes - we are still far from the "island of stability"

Multi-nucleon transfer reactions can be used for synthesis of neutron enriched long-living SH nuclei located along the beta-stability line.

U-like beams give us more chances to produce neutron-rich SH nuclei in "inverse quasifission" reactions.

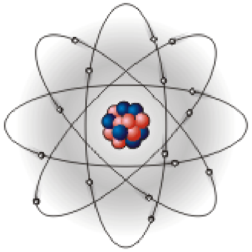
Collaboration Participants

Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research,
(FLNR JINR) Dubna, Russia
Department of Physics (JYFL), Jyväskylä, Finland
Variable Energy Cyclotron Centre, Bidhan Nagar, Kolkata, India
GSI, Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
Dipartamento di Scienze Fisiche and INFN (INFN-Na), Napoli, Italy

The experiments have been performed using the double-arm time-of-flight spectrometer CORSET at U400 and U400M cyclotrons of FLNR Dubna

and

K130 cyclotron *Accelerator Laboratory of Department of Physics (JYFL), Jyväskylä, Finland*



CORSET + LCP + HENDES

Thanks for your attention!