Synthesis of superheavy nuclei: nearest and distant opportunities

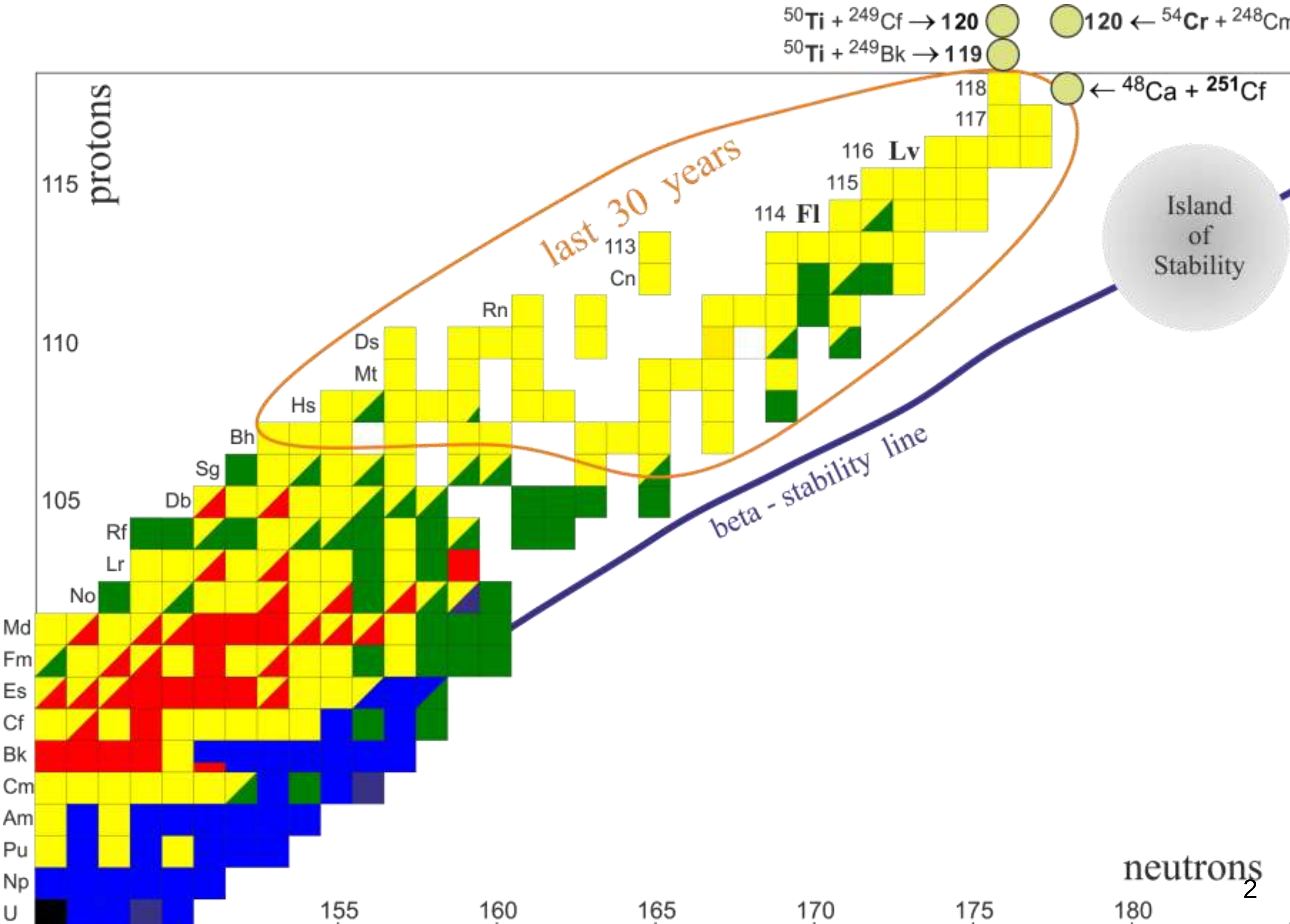
- **Fusion reactions**
  - **Elements 119 and 120 are on the way. What's the next?**
  - **Radioactive ion beams?**
  - **Filling the gap of not-yet-synthesized isotopes of SH elements (Z=106 - 116)**
  - **Narrow (hypothetical) pathway to the Island of Stability**
- **Neutron capture process**
  - **Astrophysical nucleosynthesis, SHE in cosmic rays**
- **Transfer reactions**
  - **Shell effects in damped collisions of heavy ions ?**
  - **Production of new neutron rich SH nuclei in transfer reactions**

Valeriy Zagrebaev

JINR *(Dubna)*

for "Fusion-2014", *February 25, 2014*, New Delhi, India

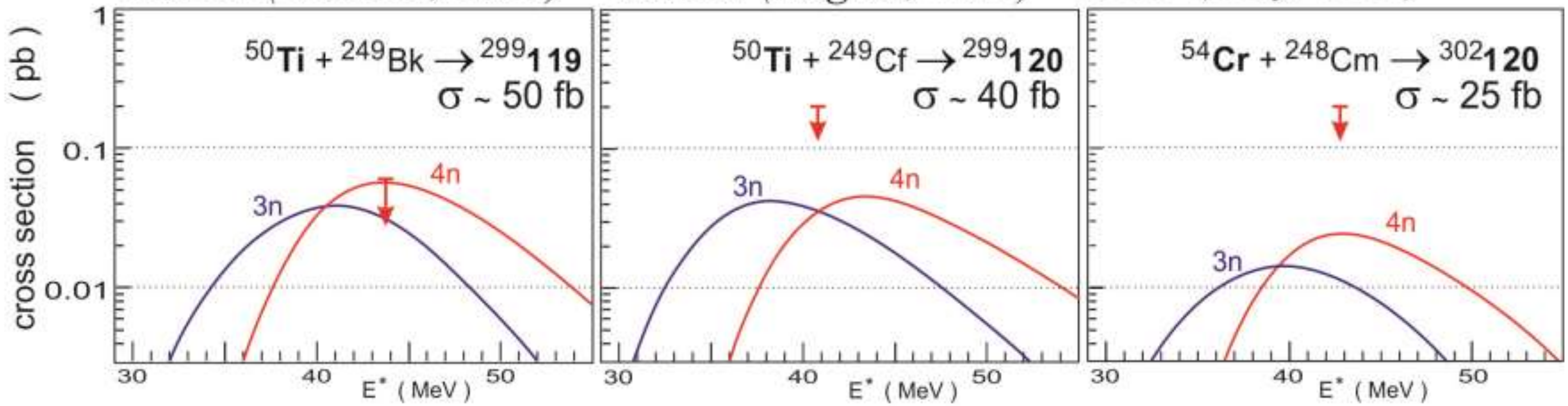
We are still far from the Island of Stability



New elements 119 and 120 are coming !

Ti beam: *TASCA (October, 2012)* *TASCA (August, 2011)*

Cr beam: *SHIP (May, 2011)*

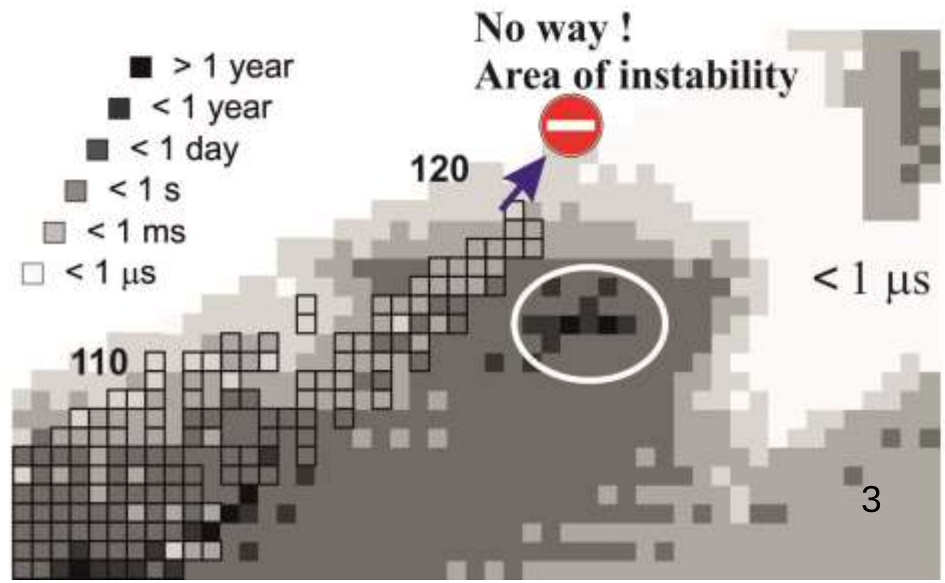


our predictions (PRC 2008):

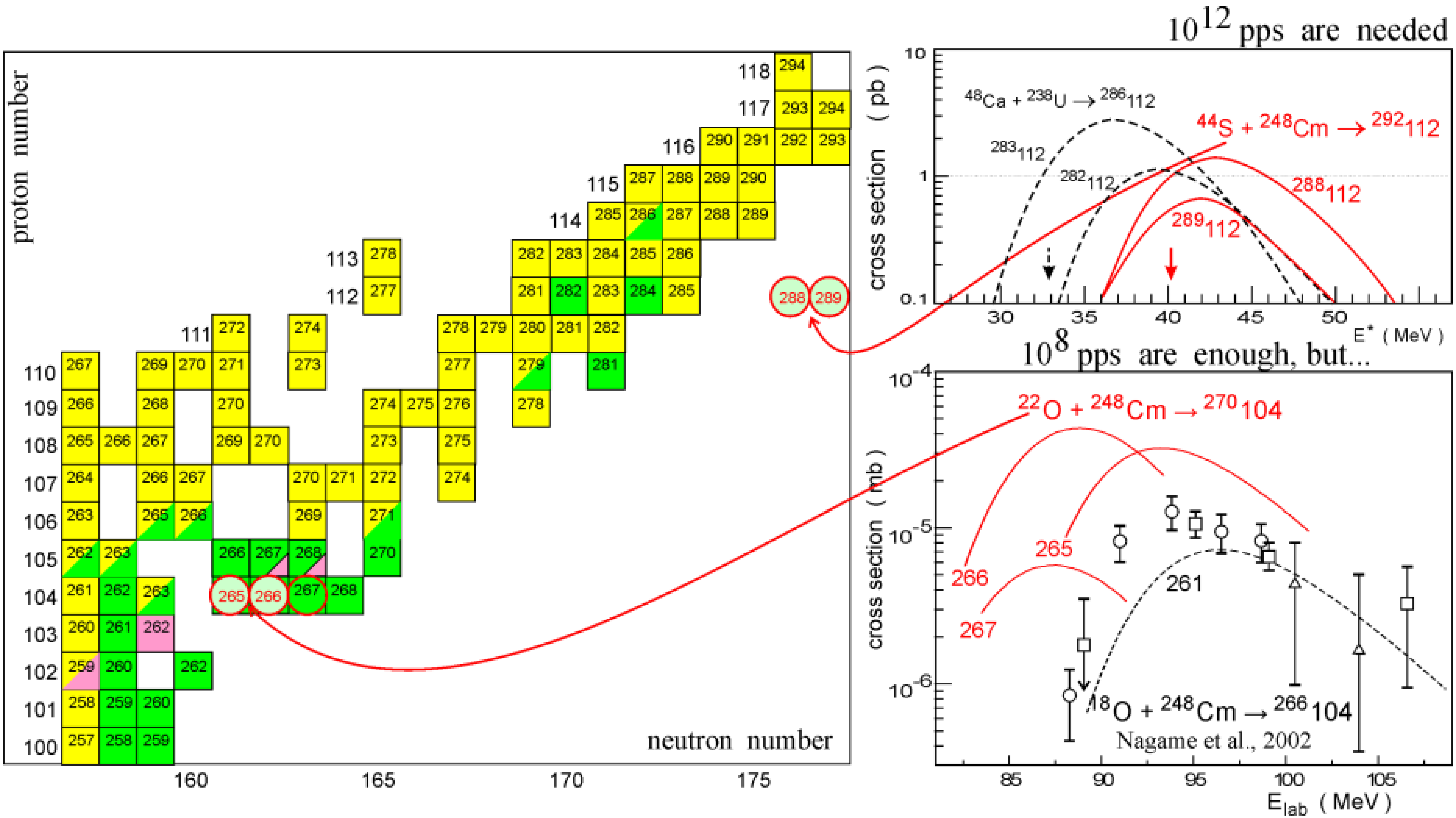
factor $\frac{1}{20}$ as compared to ^{48}Ca

Approaching the area of instability:

Probably, these elements are the last ones which will be synthesized in the nearest future

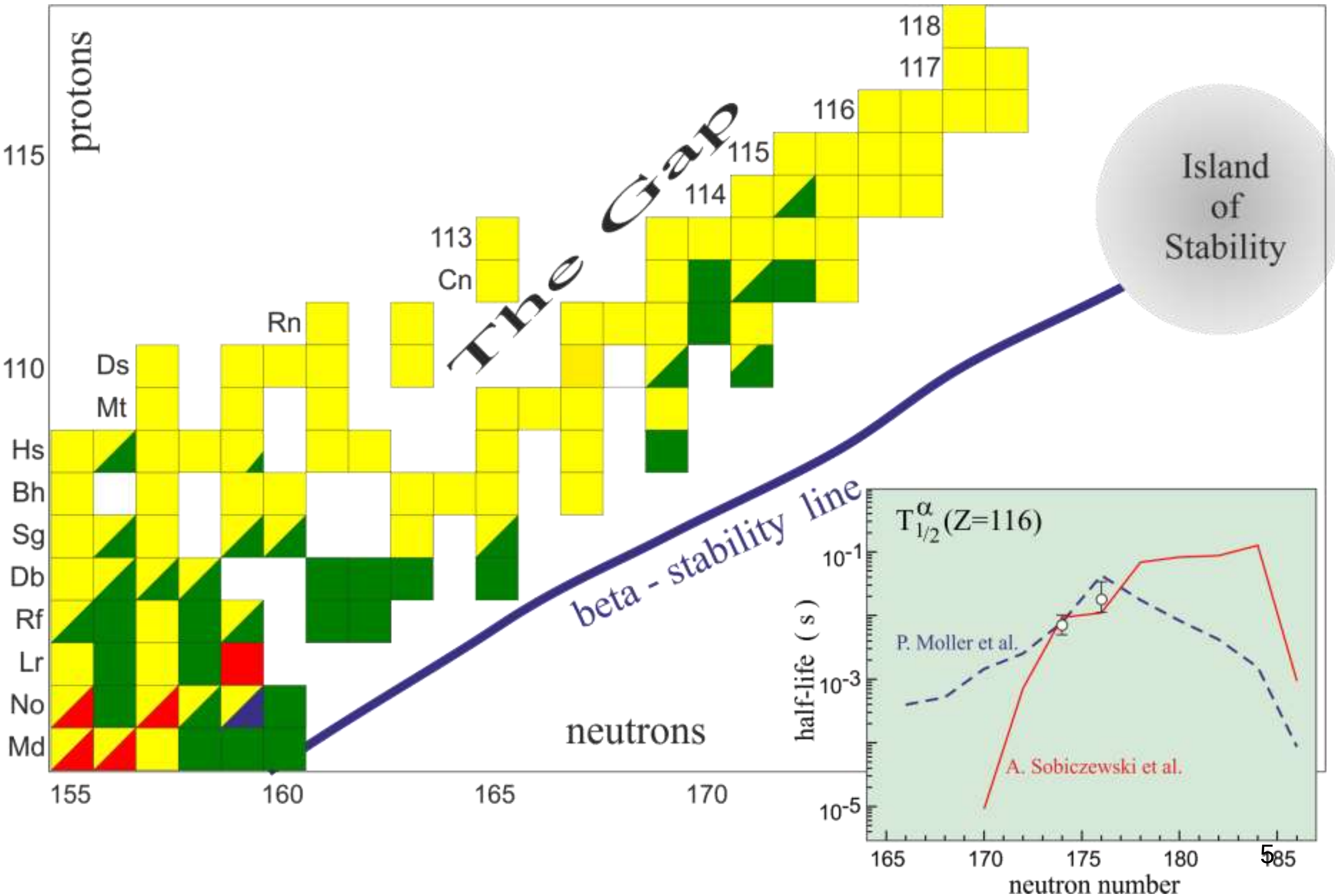


Fusion reactions with Radioactive Ion Beams
for the production of neutron rich superheavy nuclei ?

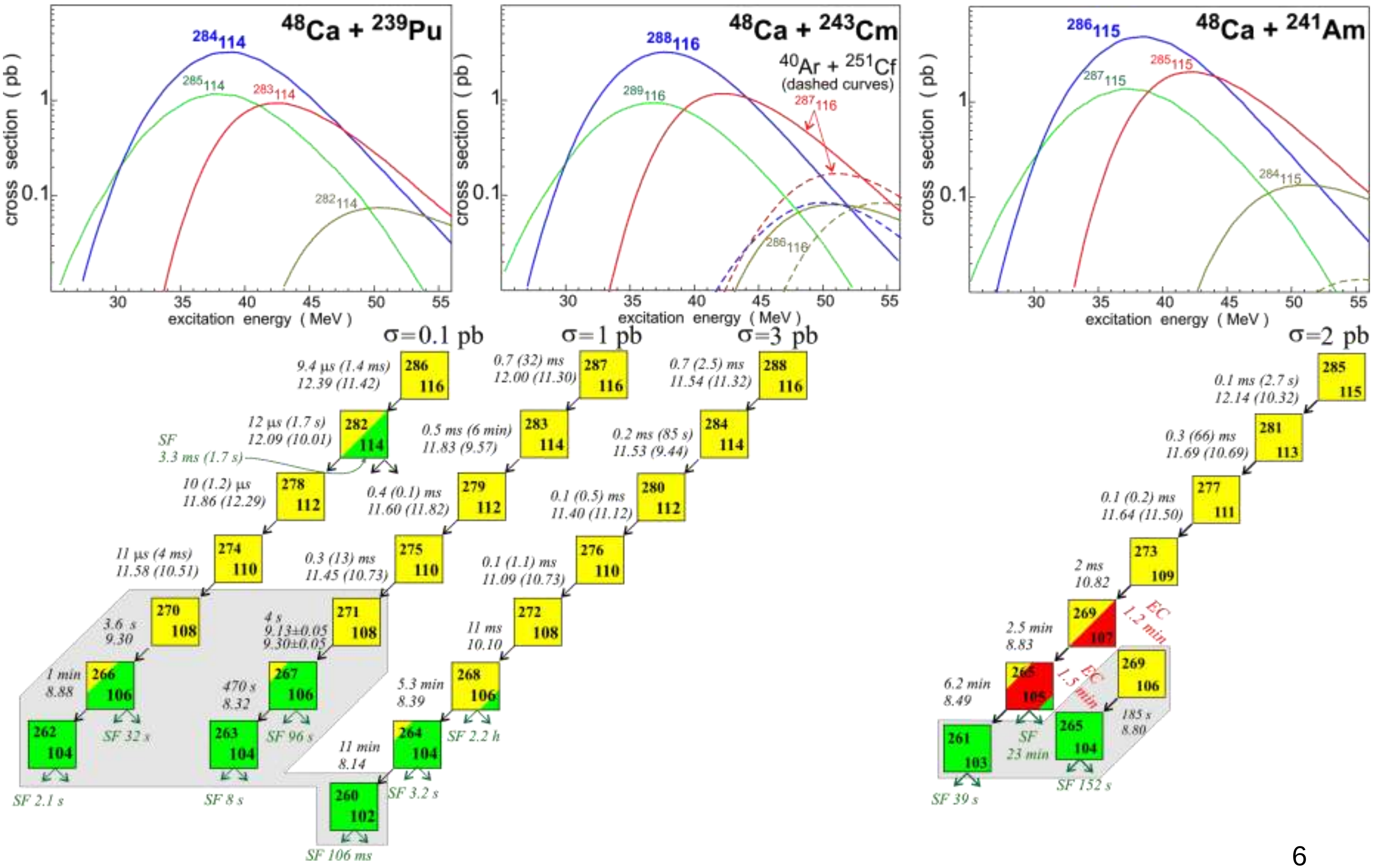


No chances today and in the nearest future

It is important to fill the Gap in superheavy mass area



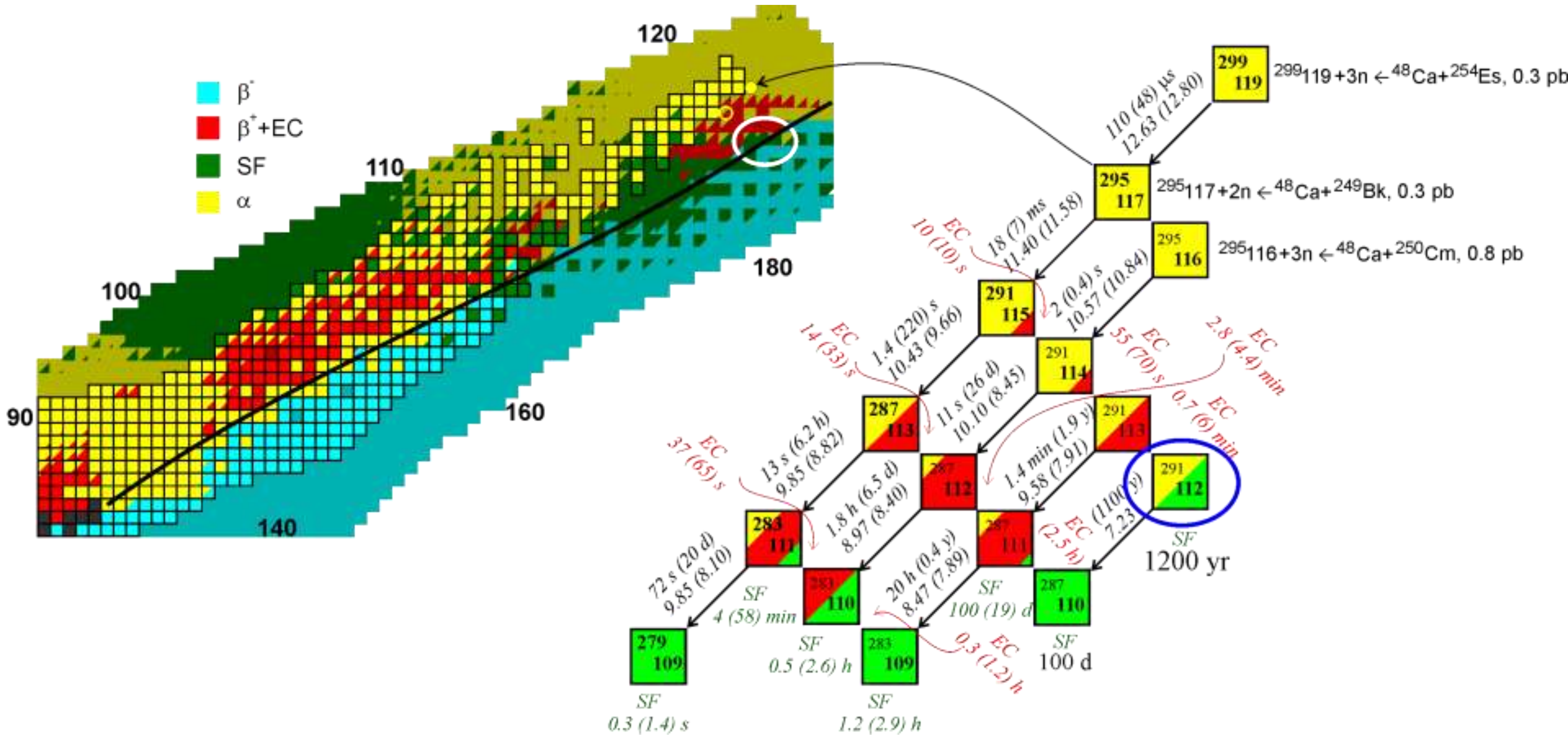
Predicted cross sections are high enough to perform experiments at available facilities just now



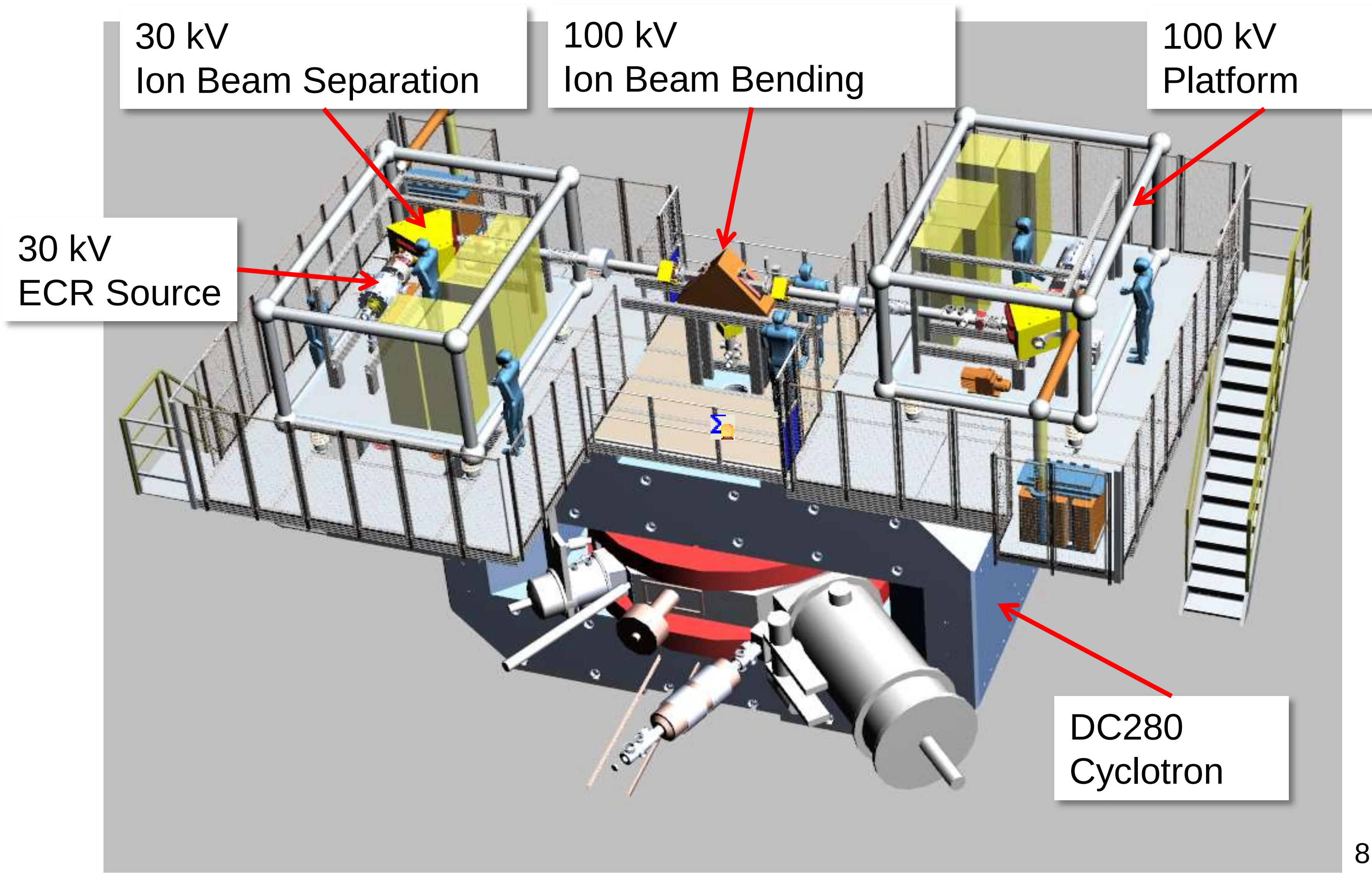
experiment on 48Ca+239Pu is currently going on in Dubna…

Narrow pathway to the Island of Stability ?

[VZ, A. Karpov and W. Greiner, Phys. Rev. C 85, 014608 (2012)]



New DC280 Cyclotron for SHE factory in Dubna

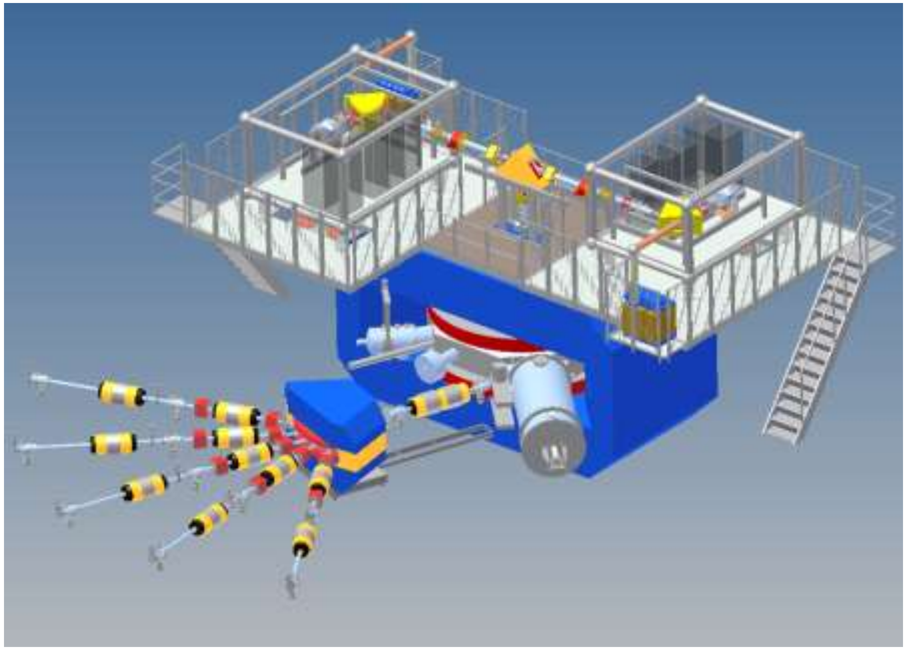


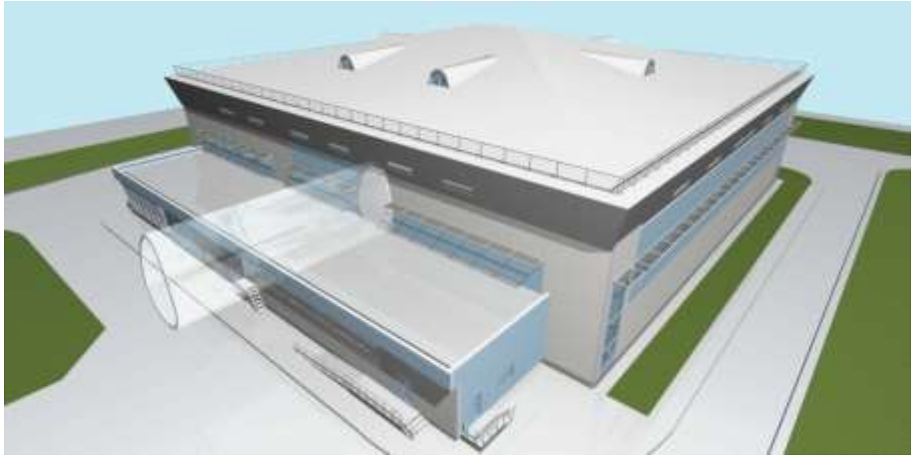
DC280: Intensity of some typical ion beams

20Ne	$1 \cdot 10^{14}$ pps
48Ca	**$6 \cdot 10^{13}$ pps**
50Ti	$3 \cdot 10^{13}$ pps
70Zn	$2{,}5 \cdot 10^{13}$ pps
86Kr	$3 \cdot 10^{13}$ pps
100Mo	$2 \cdot 10^{12}$ pps
124Sn	$2 \cdot 10^{12}$ pps
136Xe	$2 \cdot 10^{13}$ pps
208Pb	$1 \cdot 10^{12}$ pps
238U	$1 \cdot 10^{11}$ pps

Schedule of the SHE Factory creation

	2011	2012	2013	2014	2015	2016
Experimental Building						
Cyclotron DC 280						
Main magnet yoke creation						
Equipment creation, completion.						
Assembling, testing						
First experiment						





Nucleosynthesis by neutron capture

(search for SHE in cosmic rays !)

n_0 is the neutron flux

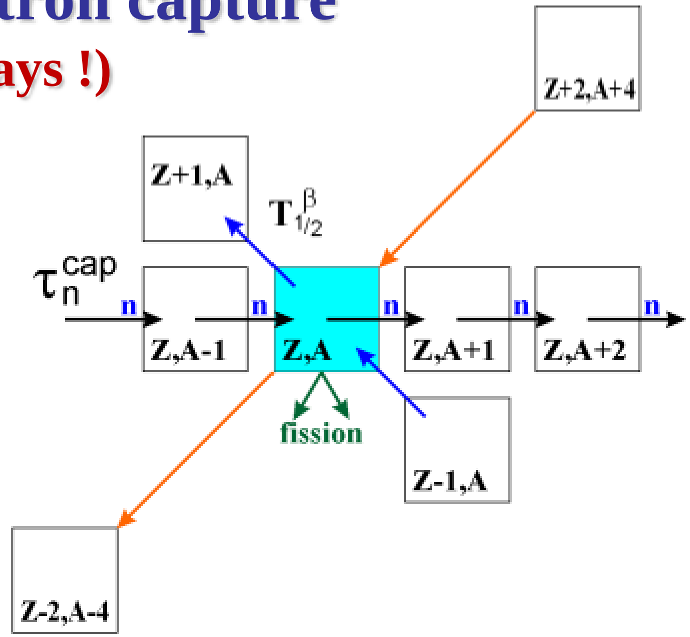
time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

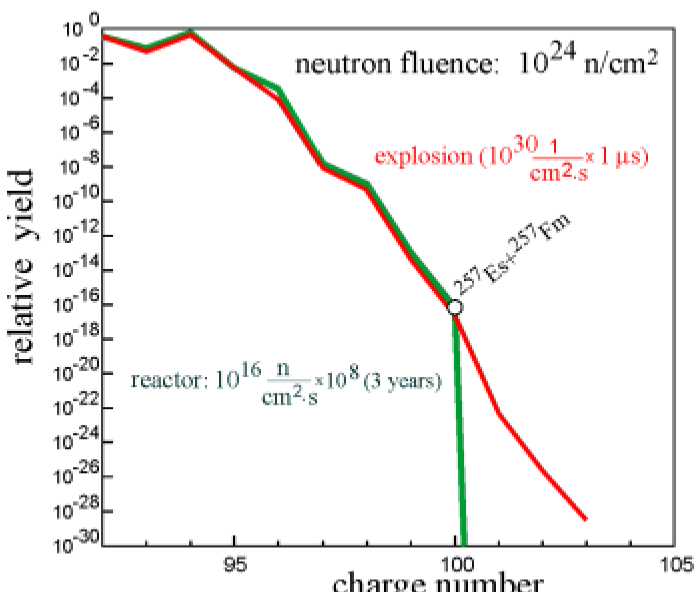
$$(Z,A) \rightarrow (Z,A+1) \text{ if } T_{1/2} > \tau_n^{cap}$$

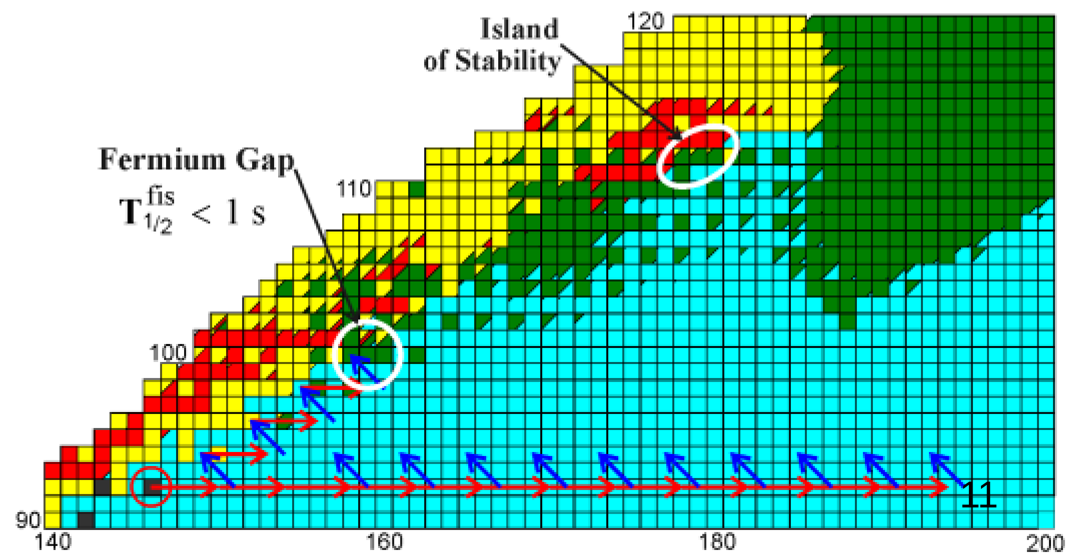
nuclear reactor: $\tau_n^{cap} \sim 1$ year

nuclear explosion: $\tau_n^{cap} \sim 1\ \mu s$



$$\frac{dN_{ZA}}{dt} = N_{ZA-1}\, n_0\, \sigma_{ZA-1}^{n\gamma} - N_{ZA}\, n_0\, \sigma_{ZA}^{n\gamma} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\beta}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\alpha}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{fis}} + N_{Z-1A} \frac{\ln 2}{T_{Z-1A}^{\beta}} + N_{Z+2A+4} \frac{\ln 2}{T_{Z+2A+4}^{\alpha}}$$

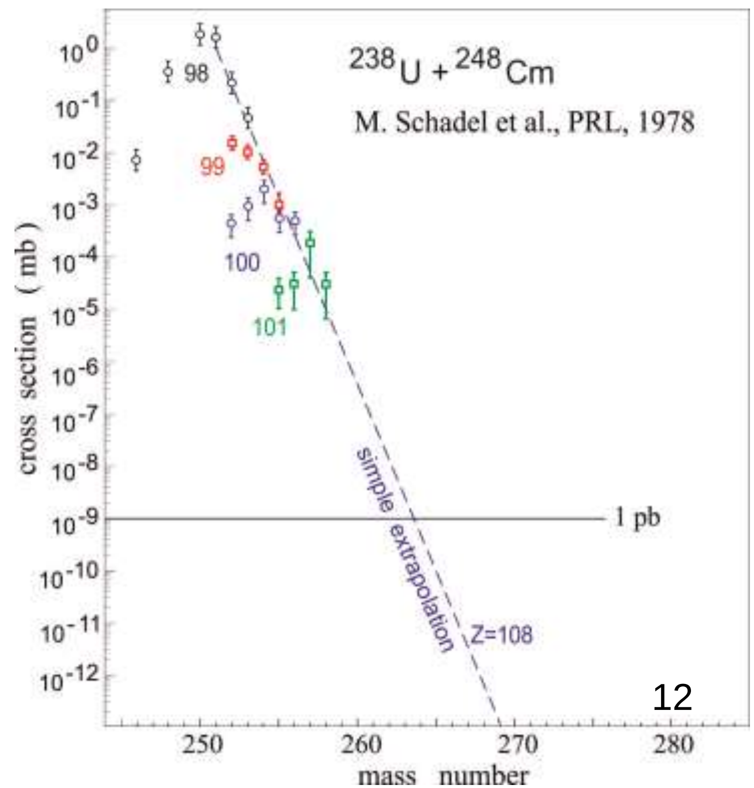




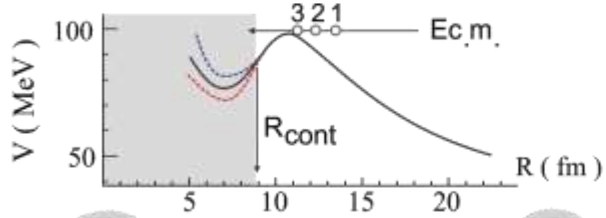
Synthesis of SH nuclei in **transfer reactions**

[1] E. K. Hulet *et al.*, Phys. Rev. Lett. **39**, 385 (**1977**).
[2] M. Schaedel *et al.*, Phys. Rev. Lett. **41**, 469 (**1978**).
[3] H. Essel, K. Hartel, W. Henning, P. Kienle, H. J. Koerner, K. E. Rehm, P. Sperr,W.Wagner, and H. Spieler, Z. Phys. A **289**, 265 (**1979**).
[4] H. Freiesleben, K. D. Hildenbrand, F. P¨uhlhofer, W. F. W. Scneider, R. Bock, D. V. Harrach, and H. J. Specht, Z. Phys. A **292**, 171 (**1979**).
[5] H. Gaeggeler *et al.*, Phys. Rev. Lett. **45**, 1824 (**1980**).
[6] M. Schaedel *et al.*, Phys. Rev. Lett. **48**, 852 (**1982**).
[7] K. J. Moody, D. Lee, R. B. Welch, K. E. Gregorich, G. T. Seaborg, R. W. Lougheed, and E. K. Hulet, Phys. Rev. C **33**, 1315 (**1986**).
[8] R. B. Welch, K. J. Moody, K. E. Gregorich, D. Lee, and G. T. Seaborg, Phys. Rev. C **35**, 204 (**1987**).
…

… a long history.
Isotopes of Fm and Md were synthesized 30 years ago.

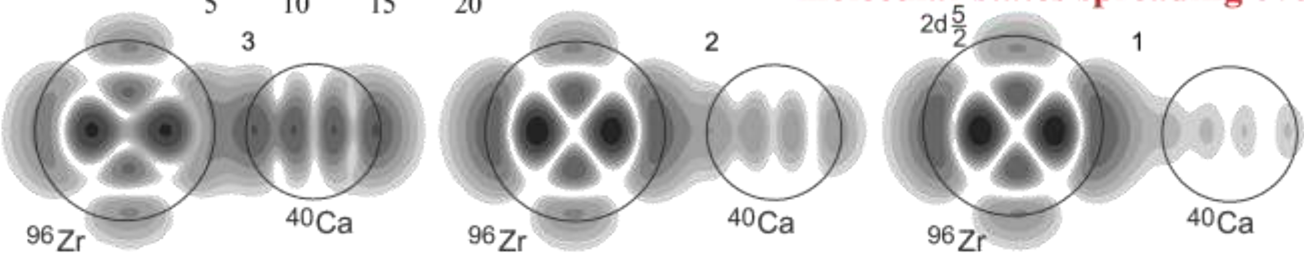


What is real dynamics of heavy-ion collisions ?

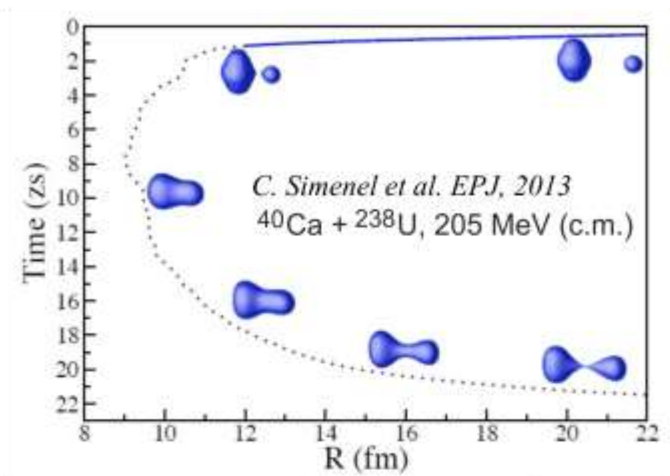


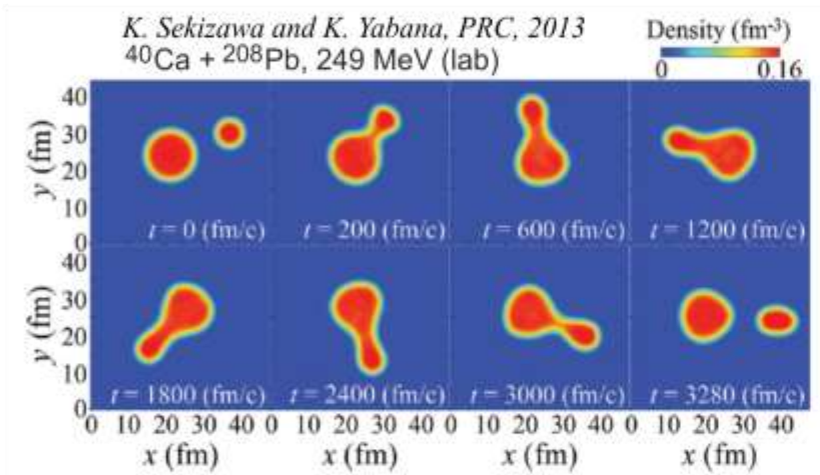
Time Dependent Schrödinger equation
(VZ, V. Samarin and W. Greiner, PRC, 2007)

Wave functions of valence nucleons follow the two-center molecular states spreading over both nuclei.



Time Dependent Hartree-Fock calculations *(A.Umar & V.Oberacker, C.Simenel, K.Yabana)*





Nucleons move in volumes (mean fields) of both nuclei !

- Perturbative approches are not applicable for description of nucleon transfers
- DNS model with two isolated mean fields is contrary to physics
- Two body potential energy V(R) has no meaning at R< R contact : V → V(shape)

Microscopic: **TDHF or time dependent Schrodinger calculations**

Semi-microscopic: **Two-Center Shell Model + Langevin-type equations**

System of coupled Langevin type Equations of Motion
(the same for separated and overlapped nuclei)

$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N\}$

$$\frac{d\vartheta}{dt} = \frac{\ell}{\mu_R R^2}$$

Most uncertain parameters:

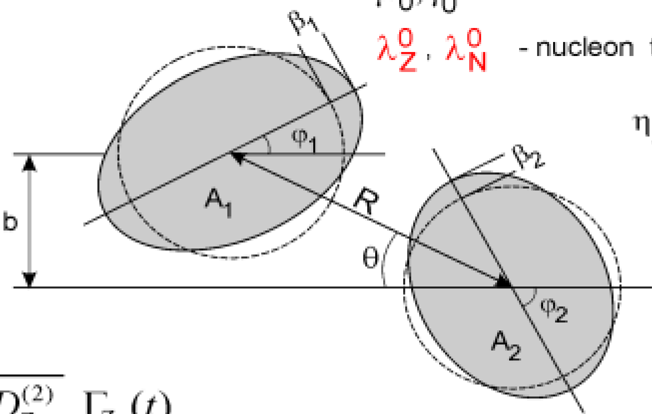
μ_0, γ_0 - nuclear viscosity and friction,

λ^0_Z, λ^0_N - nucleon transfer rate

$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}, \quad \frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta 1}}{\mu_{\beta 1}}$$

$$\frac{d\beta_2}{dt} = \frac{p_{\beta 2}}{\mu_{\beta 2}}$$



$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

$$\eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$$\eta_N = \frac{N_1 - N_2}{N_1 + N_2}$$

$$\lambda^0_Z = \lambda^0_N = \frac{\lambda^0}{2}$$

$$\frac{d\eta_Z}{dt} = \frac{2}{Z_{CN}} D^{(1)}_Z + \frac{2}{Z_{CN}} \sqrt{D^{(2)}_Z}\; \Gamma_Z(t)$$

$$\frac{d\eta_N}{dt} = \frac{2}{N_{CN}} D^{(1)}_N + \frac{2}{N_{CN}} \sqrt{D^{(2)}_N}\; \Gamma_N(t)$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\ell^2}{\mu_R R^3} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial R} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\,\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{\partial V}{\partial \vartheta} - \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) R + \sqrt{\gamma_{\rm tang} T}\,\Gamma_{\rm tang}(t)$$

$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{\rm tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{\rm tang} T}\,\Gamma_{\rm tang}(t)$$

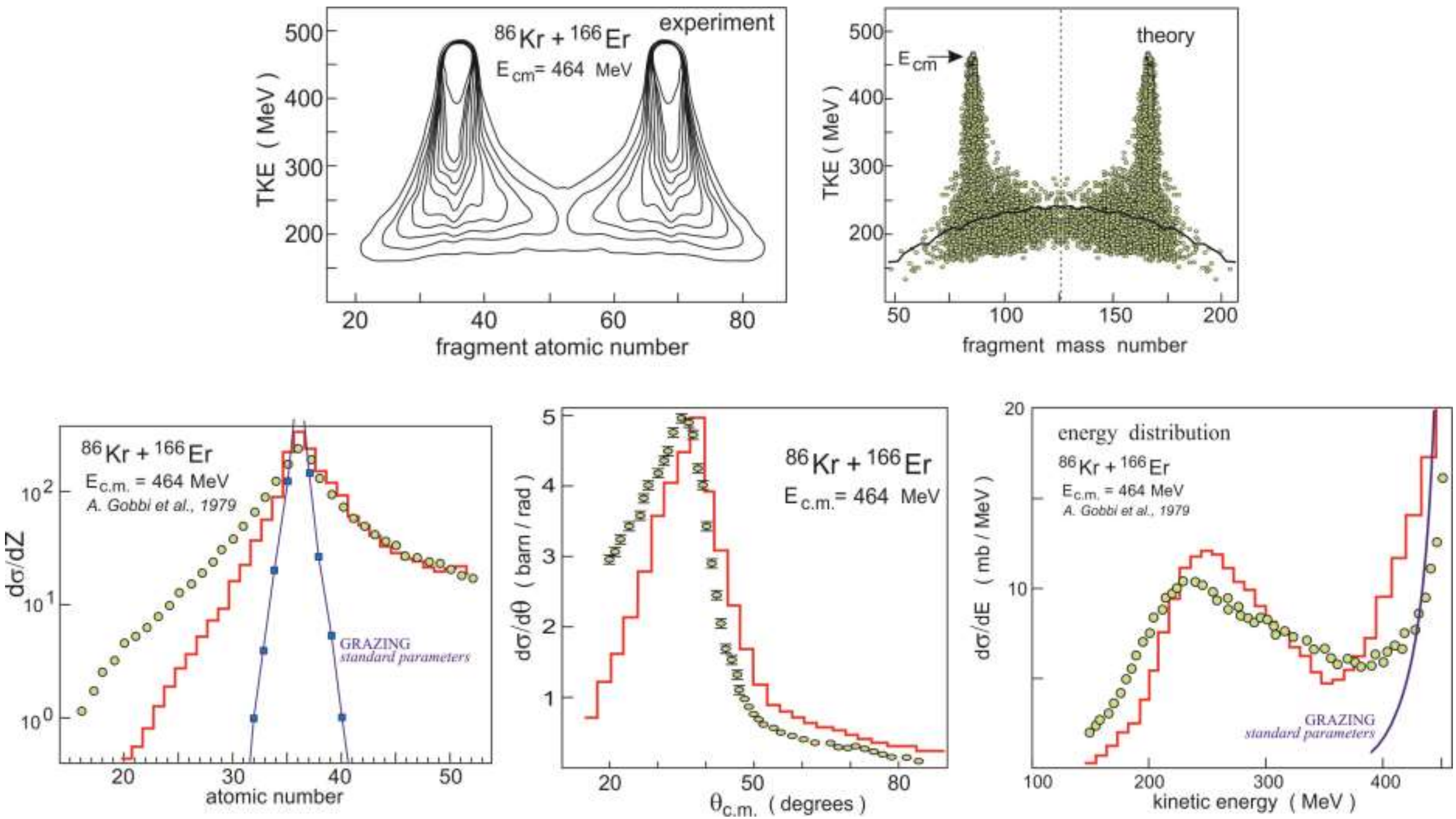
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\rm tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\rm tang} T}\,\Gamma_{\rm tang}(t)$$

$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_\beta \frac{p_{\beta 1}}{\mu_{\beta 1}} + \sqrt{\gamma_{\beta 1} T}\,\Gamma_{\beta 1}(t)$$

$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_\beta \frac{p_{\beta 2}}{\mu_{\beta 2}} + \sqrt{\gamma_{\beta 2} T}\,\Gamma_{\beta 2}(t)$$

Quite satisfactory agreement with experiments on DI scattering

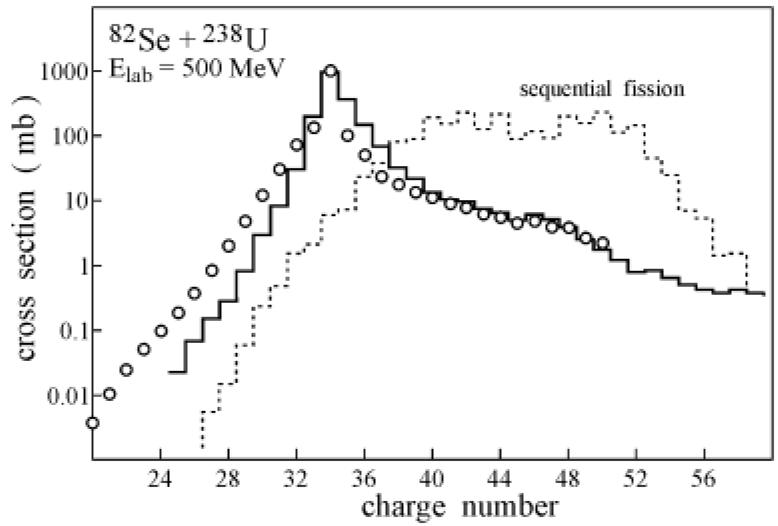
(energy, angular, charge and mass distributions)

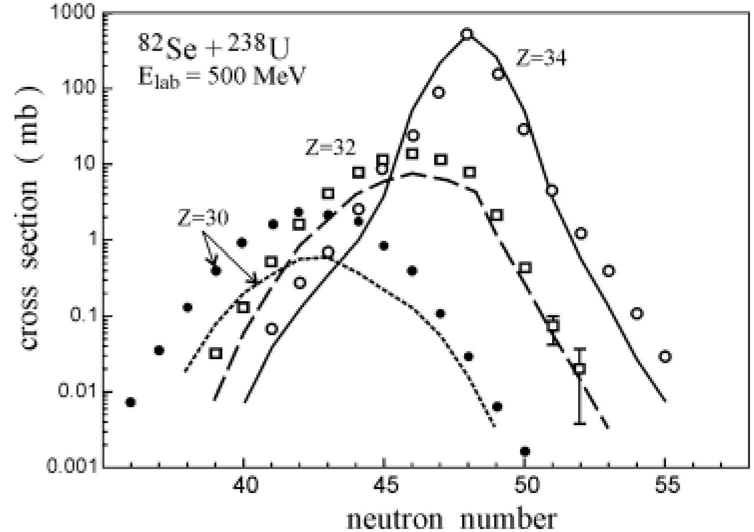


Good agreement with experiment on multi-nucleon transfer

Heavy ions

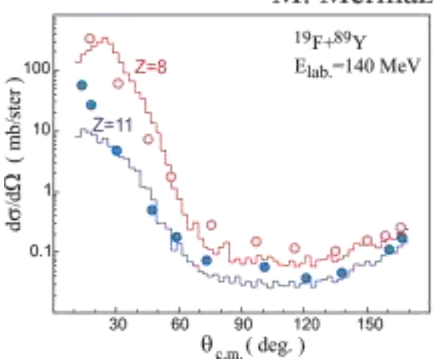
Experiment: L. Corradi et al., 2006

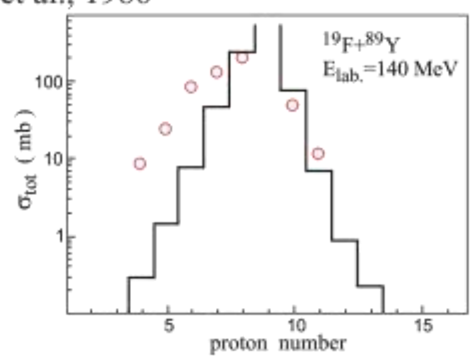




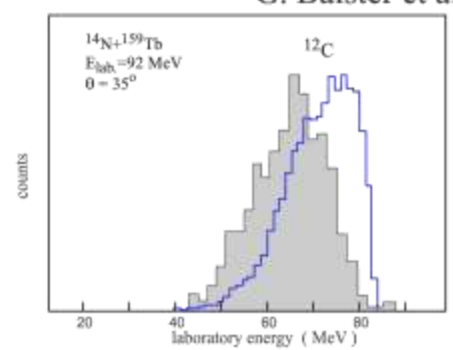
Light ions **(the model works !?)**

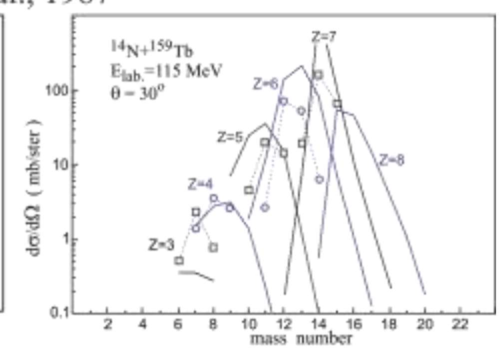
M. Mermaz et al., 1986





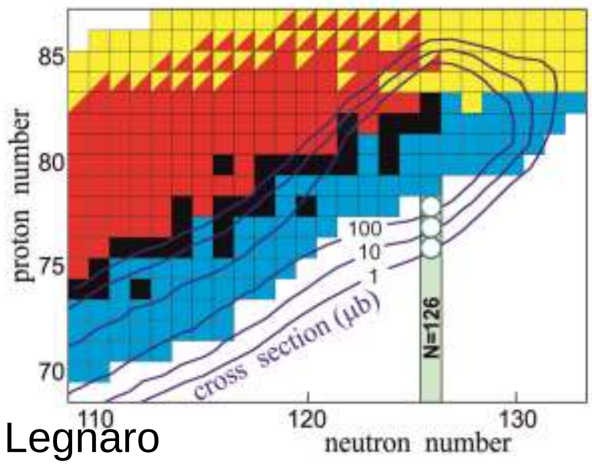
G. Balster et al., 1987

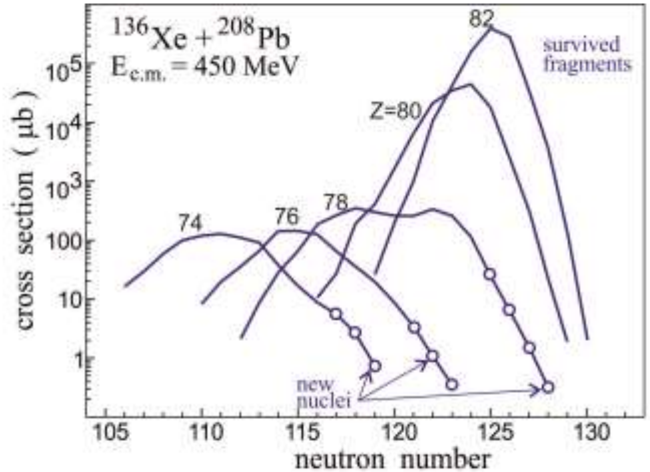




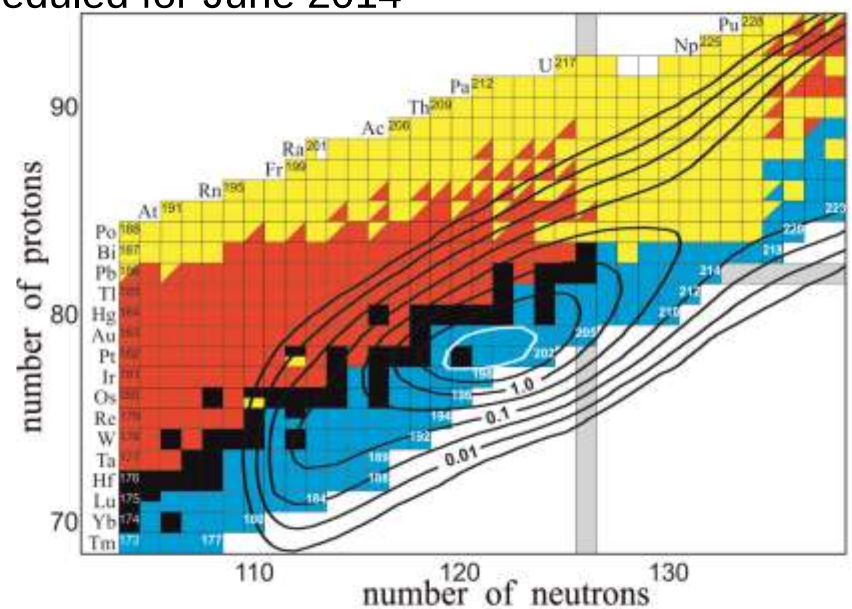
Production of new neutron rich heavy nuclei located along the last “waiting point” of astrophysical nucleosynthesis

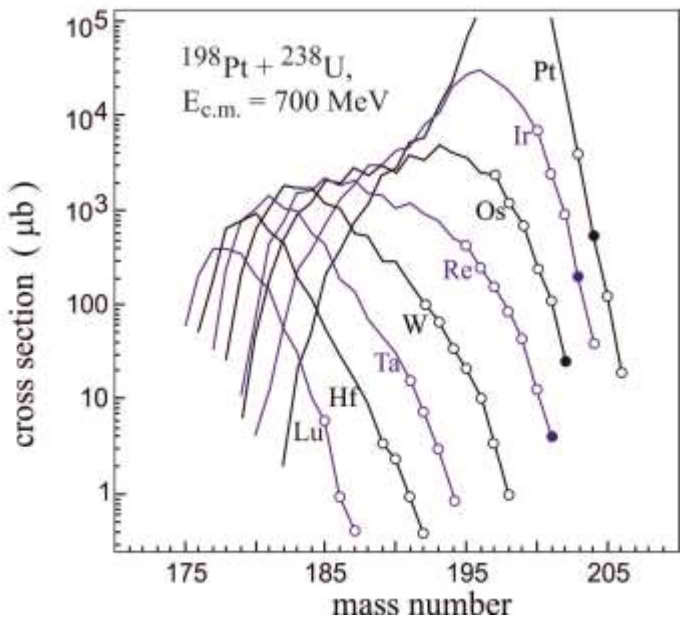
(VZ and W.Greiner, Phys.Rev.Lett., ***101****, 2008)*





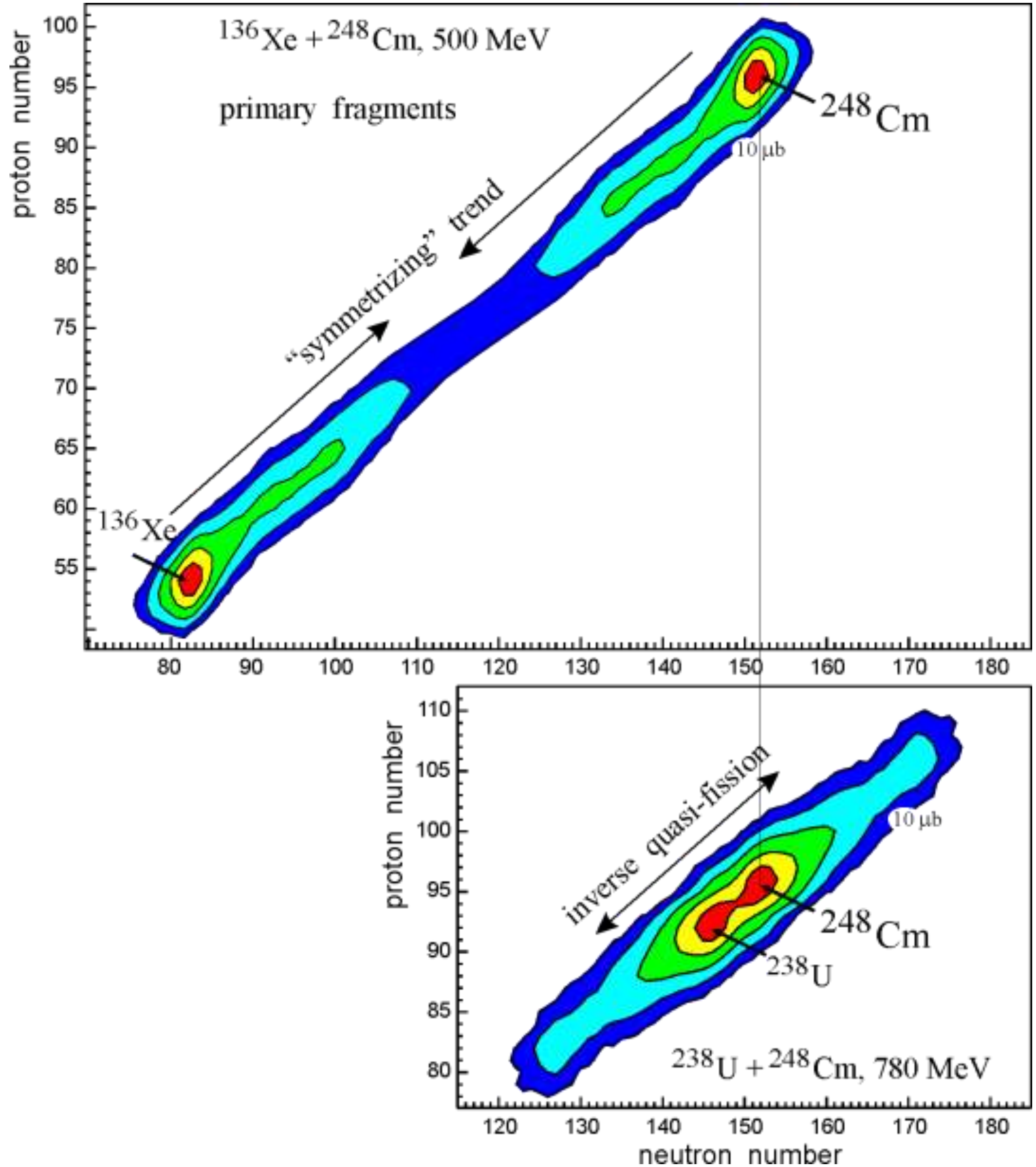
experiment in Legnaro
is scheduled for June 2014





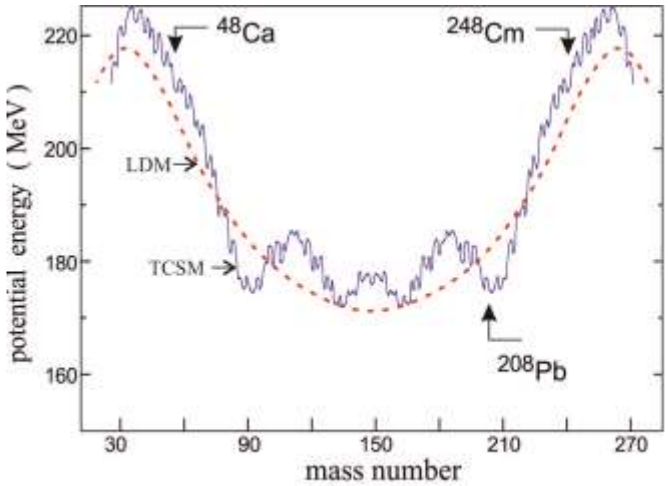
see the talk of Sergei Zemlyanoi

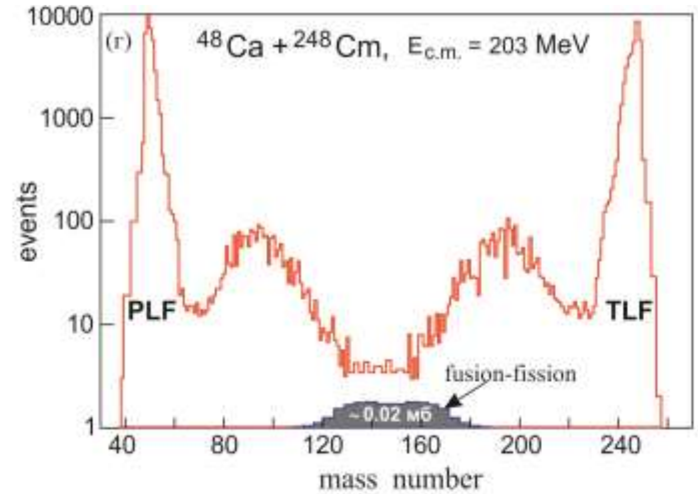
Production of superheavies in multi-nucleon transfers
(choice of reaction is very important)



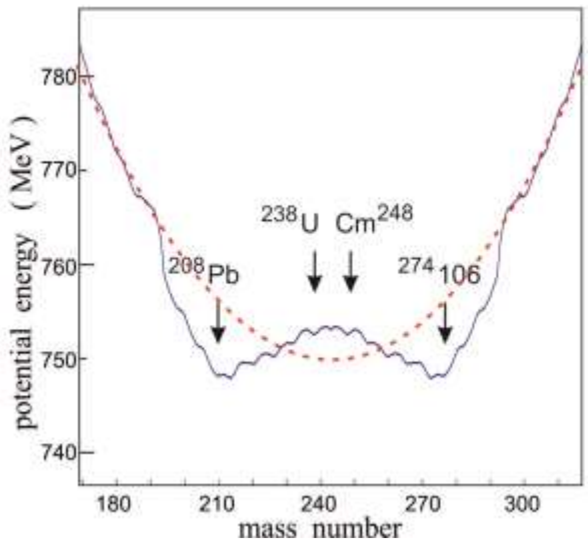
Shell effects: Pb valley

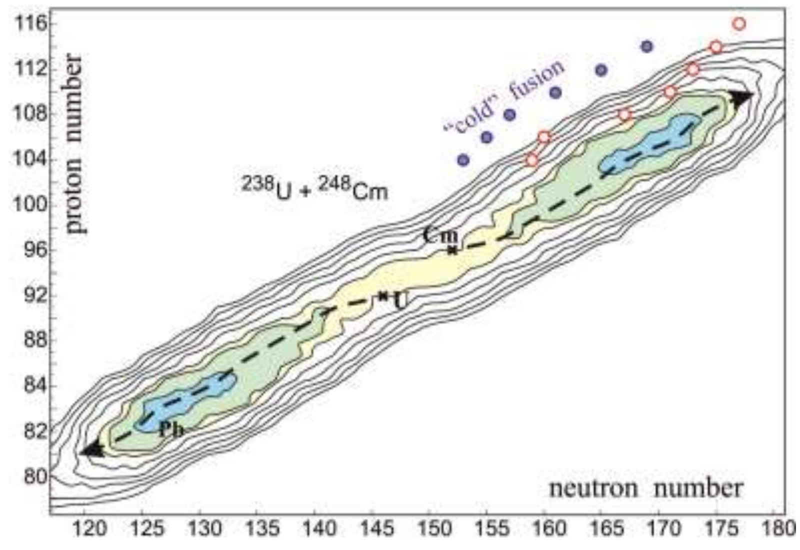
normal (symmetrizing) quasi-fission



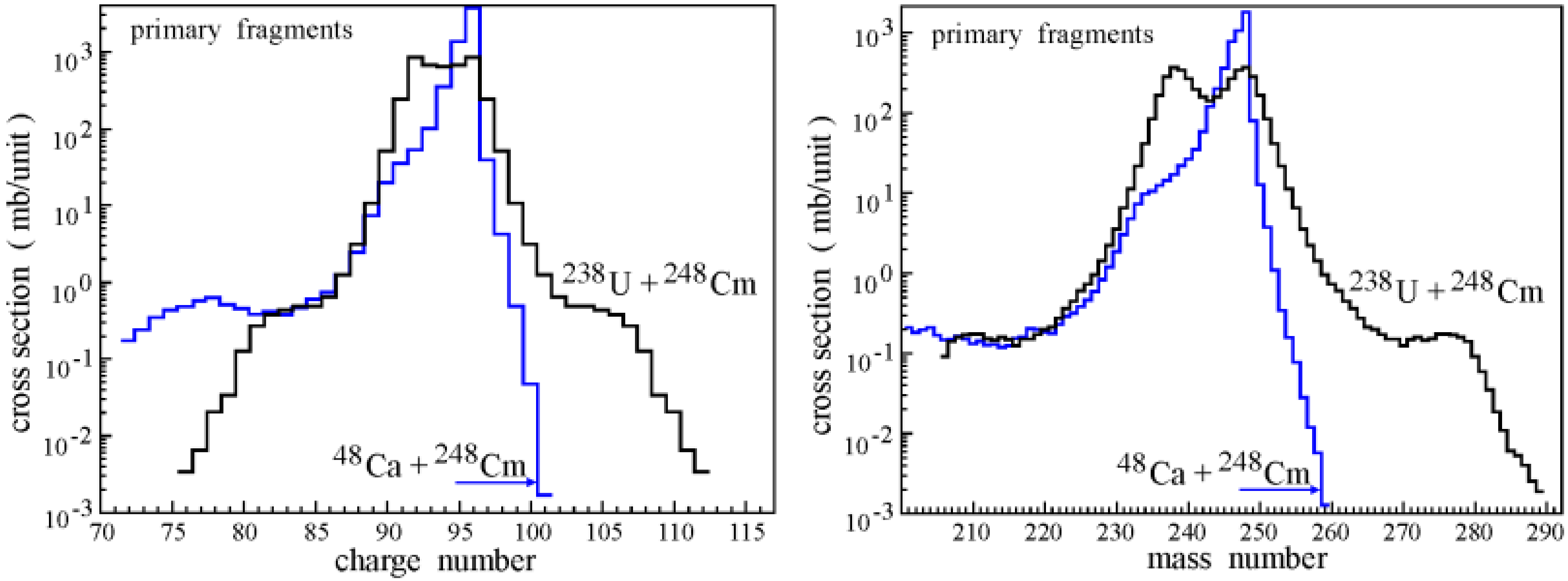


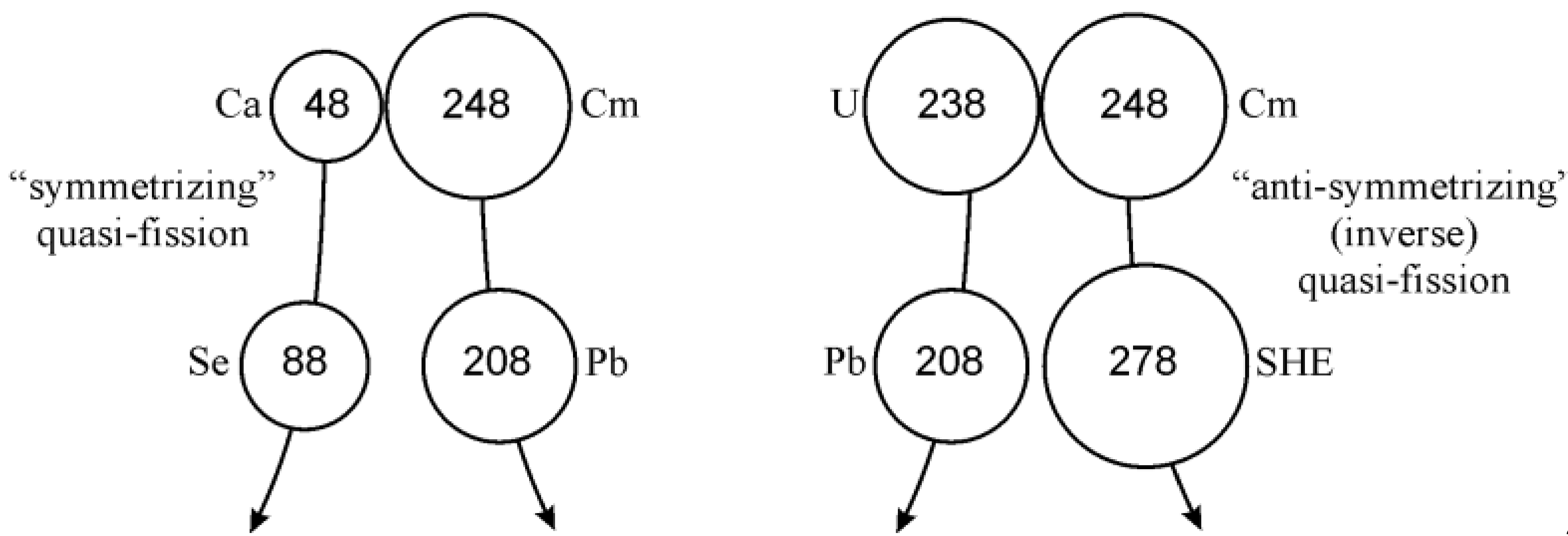
inverse (anti-symmetrizing) quasi-fission





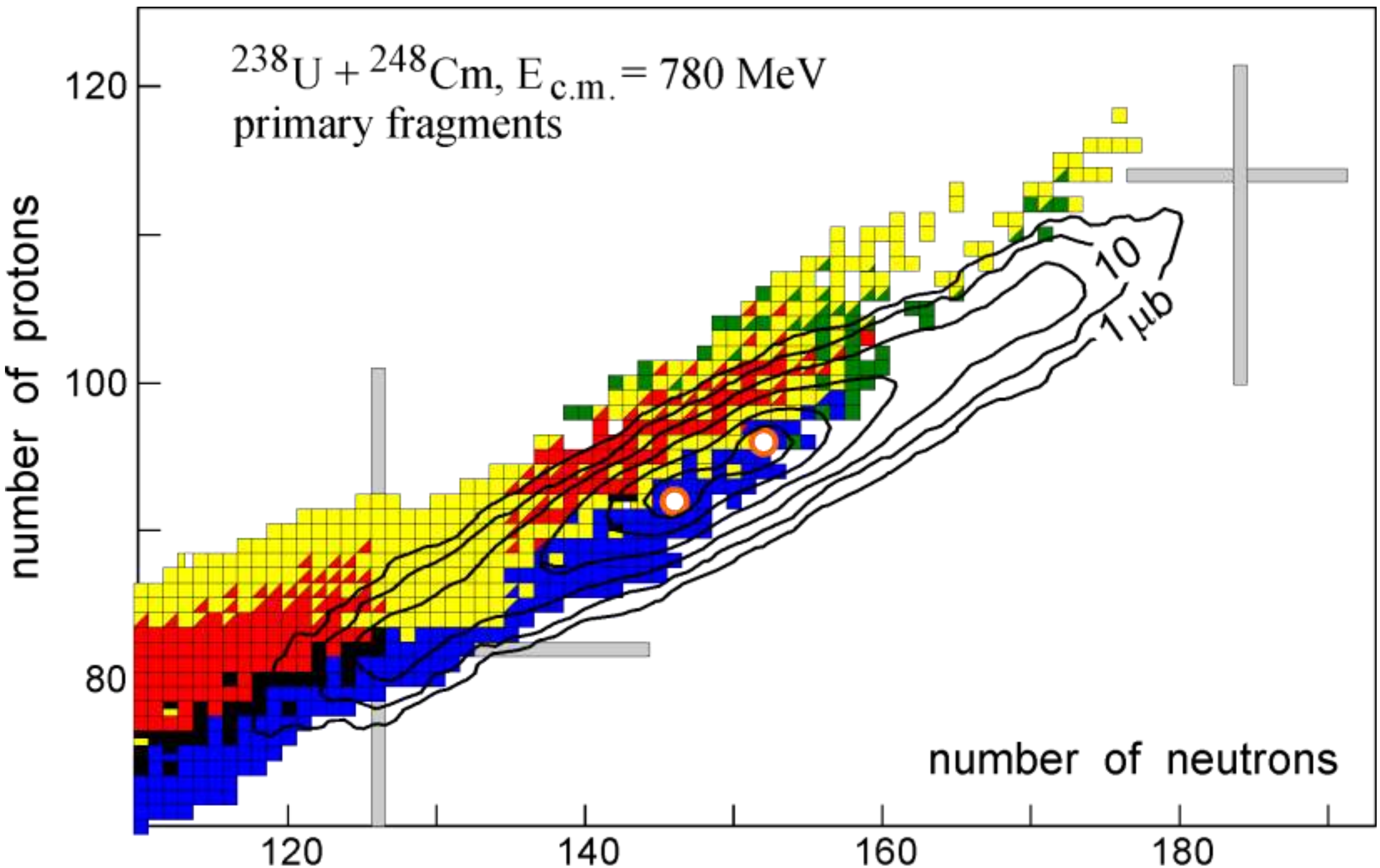
U-like beams give us more chances to produce neutron rich SH nuclei in “inverse quasi-fission” reactions



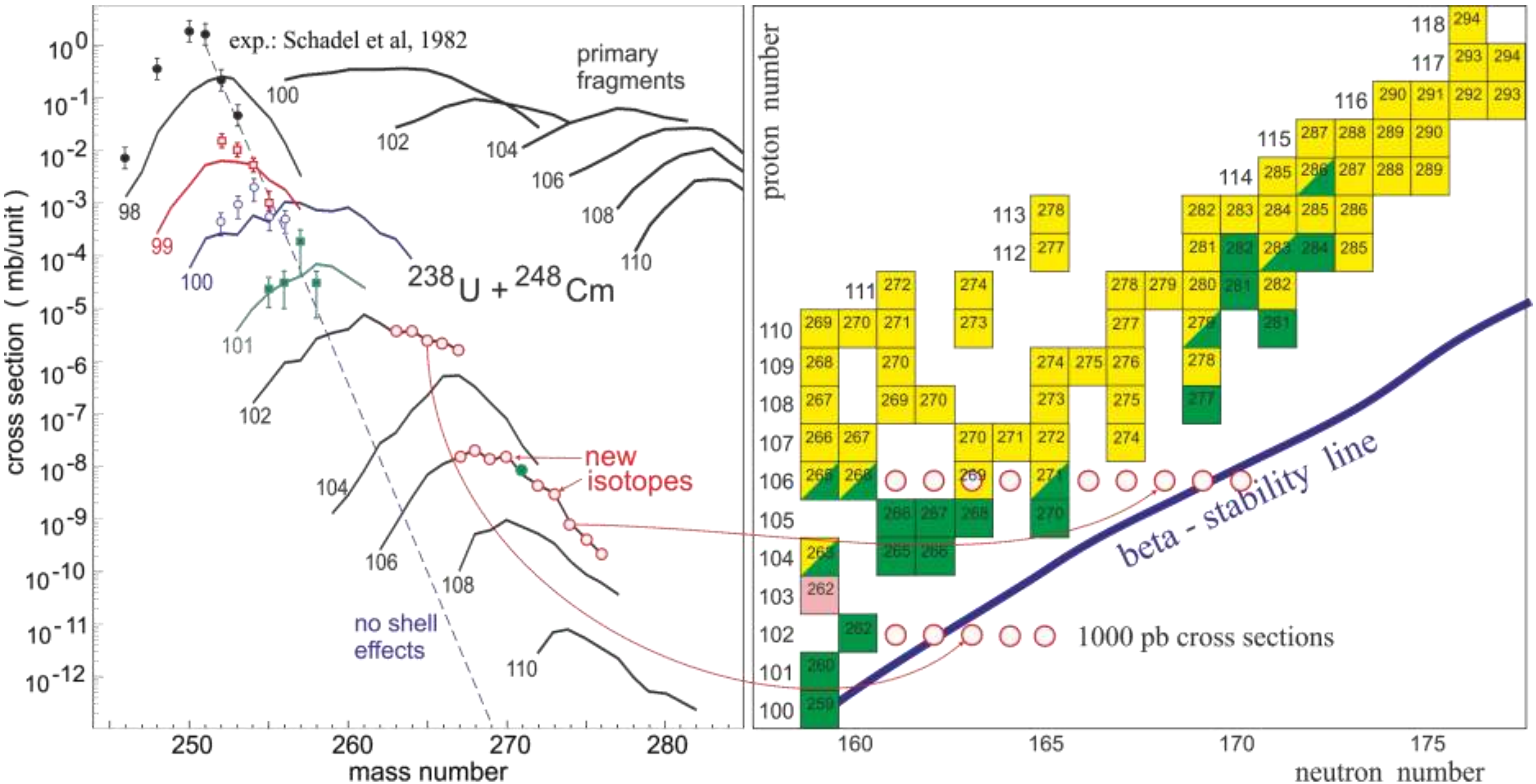


experiment is scheduled for March at GSI (we want to see Pb+x, then Pb+Ca+Pb)

238U + 248Cm. Primary fragments



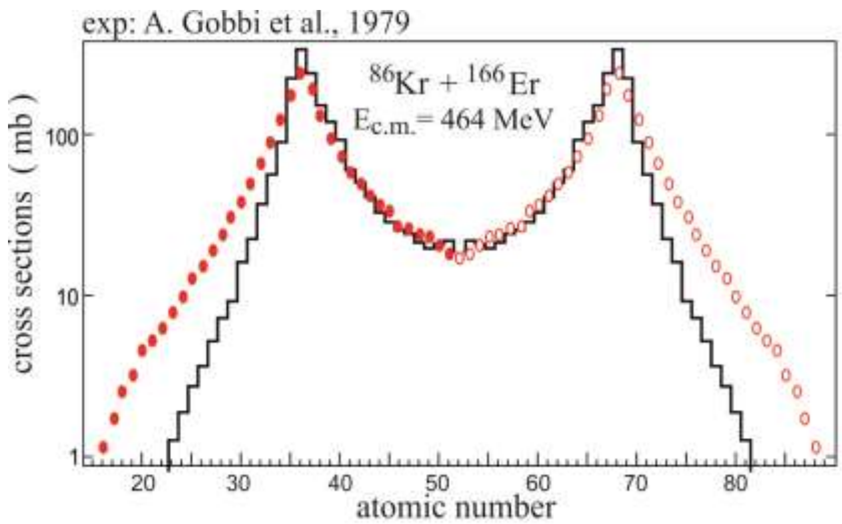
Production of transfermium nuclei along the line of stability looks quite possible (only if there are shell effects!?)

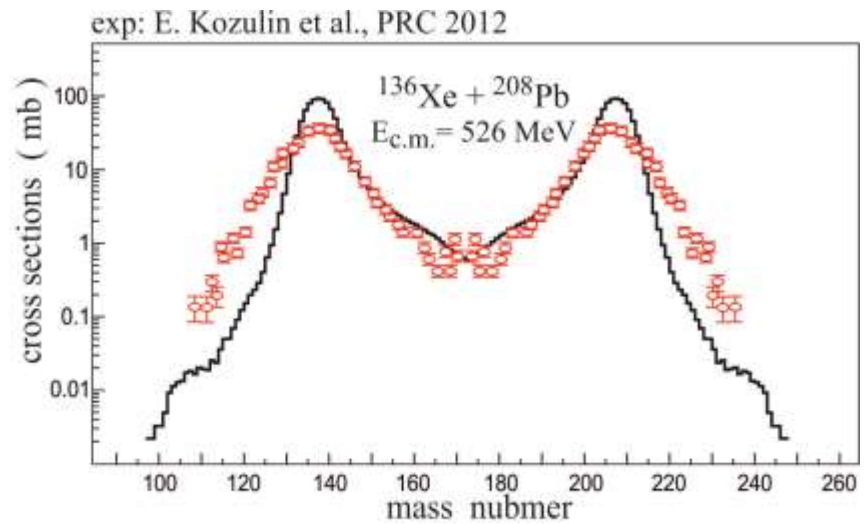


Rather wide angular distribution of reaction fragments:
a new kind of separators is needed

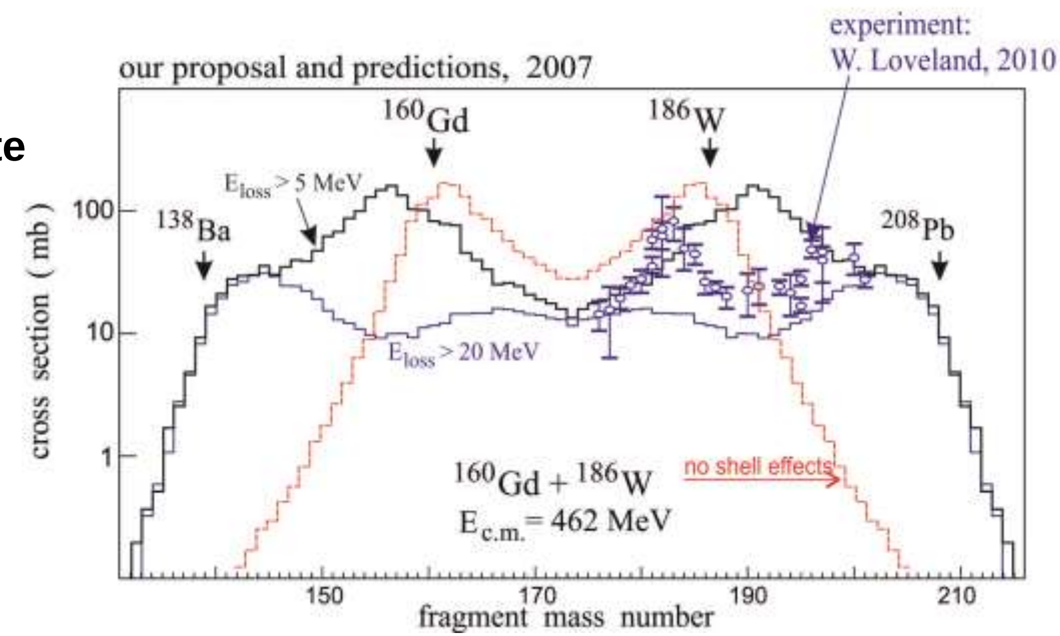
***experiments on Au+Th and U+Th are currently going on in Texas** (without separators)*

Experimental evidences on “inverse” quasi-fission are needed





the best surrogate reaction



experiment is scheduled for May in Dubna

Summary

- Elements 119 and 120 can be really synthesized in the Ti and/or Cr fusion reactions with cross sections of about 0.05 - 0.02 pb.
  Perhaps they are the heaviest SH elements with $T_{1/2} > 1\ \mu s$?

- The gap in SH mass area (Z=106-116) can be filled in fusion reactions of 48Ca with lighter isotopes of actinides (239Pu, 241Am, 243Cm, …).

- The narrow pathway to the island of stability probably exists !?

- Search for long-living SH nuclei in cosmic rays is worth-while.
  Relative yield of SH / Pb in astrophysical r process is about 10^{-12}.

- Multi-nucleon transfer reactions can be really used for synthesis of neutron enriched long-living SH nuclei located along the beta-stability line.
  U-like beams are needed as well as new kind of separators.

- Shell effects in production of trans-target nuclei (inverse quasi-fission) should be proved experimentally at last.