Production of heavy neutron-rich nuclei by multi-nucleon transfer reactions

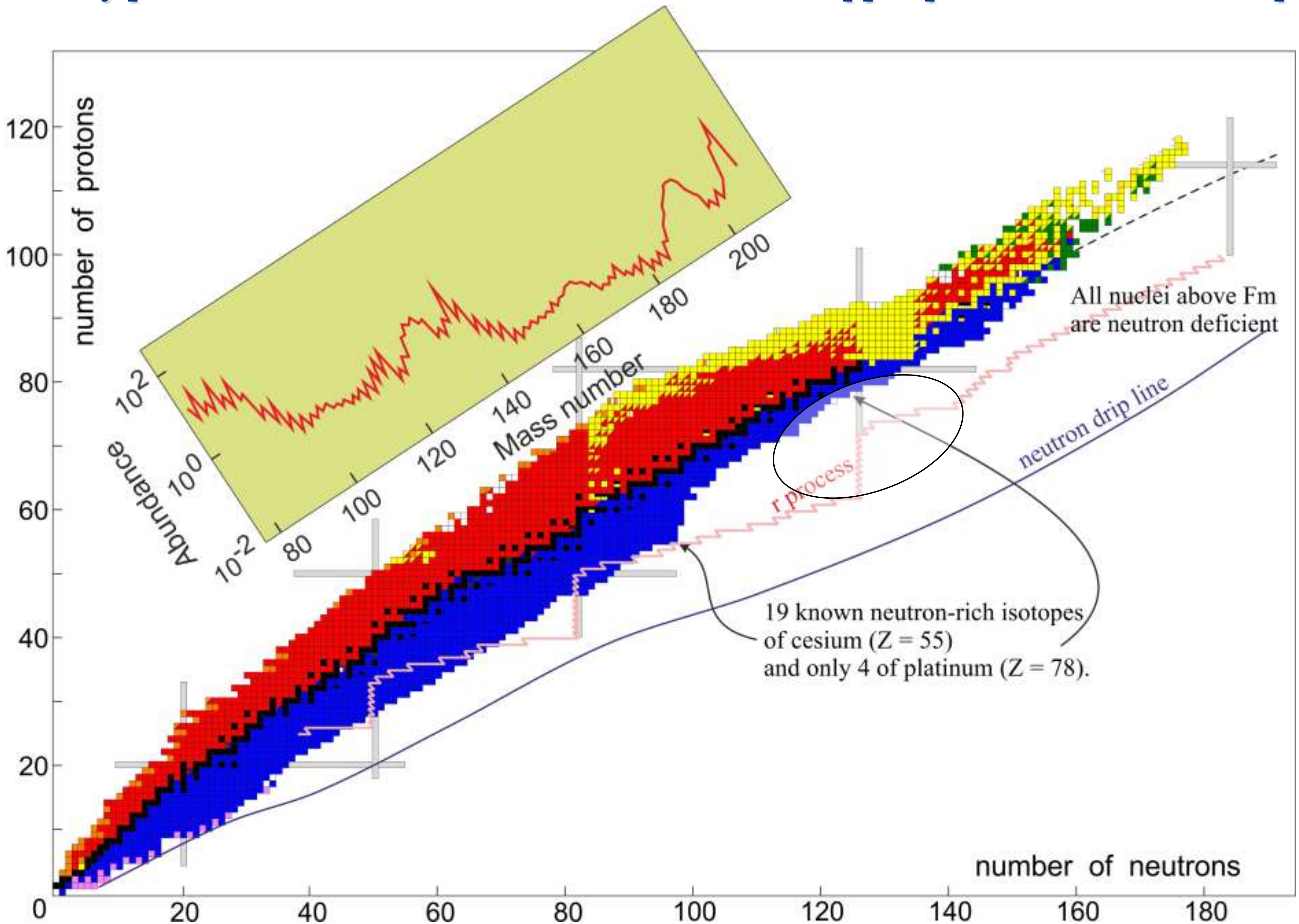
- **State of the art: neutron rich heavy nuclei were not synthesized yet**
- **Outline of the model (3 slides only)**
- **Low-energy multi-nucleon transfer reactions:**
  - **Production of trans-target nuclei**
  - **Shell effects in damped collisions of heavy ions ?**
  - **Production of neutron rich nuclei located along the neutron closed shell N=126**
  - **Synthesis of neutron rich transfermium nuclei**
- **New setup for selective laser ionization of heavy neutron rich nuclei**
- **Summary**

Valeriy Zagrebaev

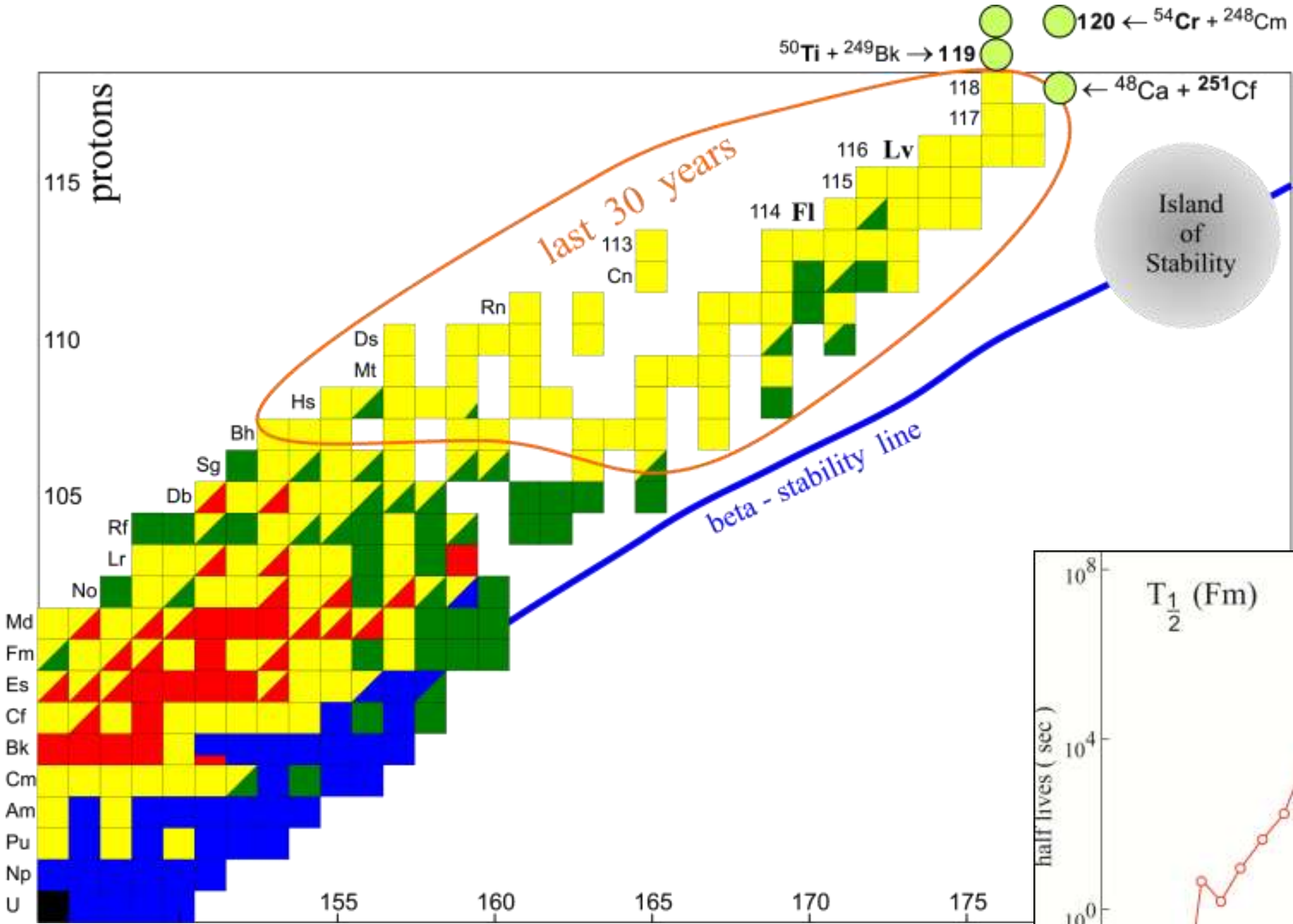
Flerov Laboratory of Nuclear Reactions, JINR, Dubna

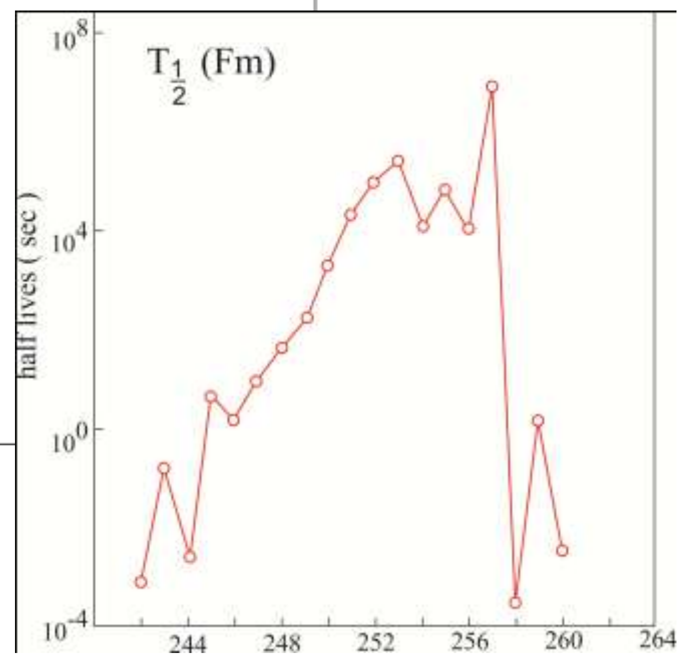
for "Colloque GANIL 2013", September 25, 2013, Port-en-Bessin, France

Mostly proton-rich nuclei were studied so far in the upper part of the nuclear map



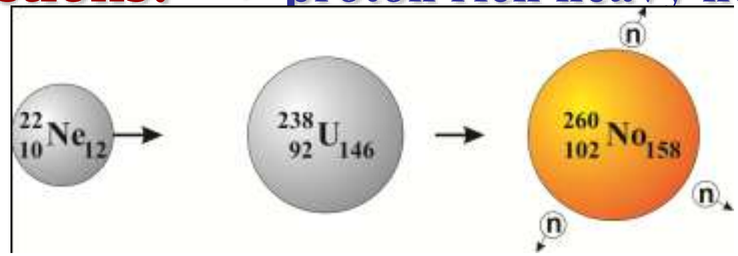
SHE: we are far from the stability line and from the Island of Stability





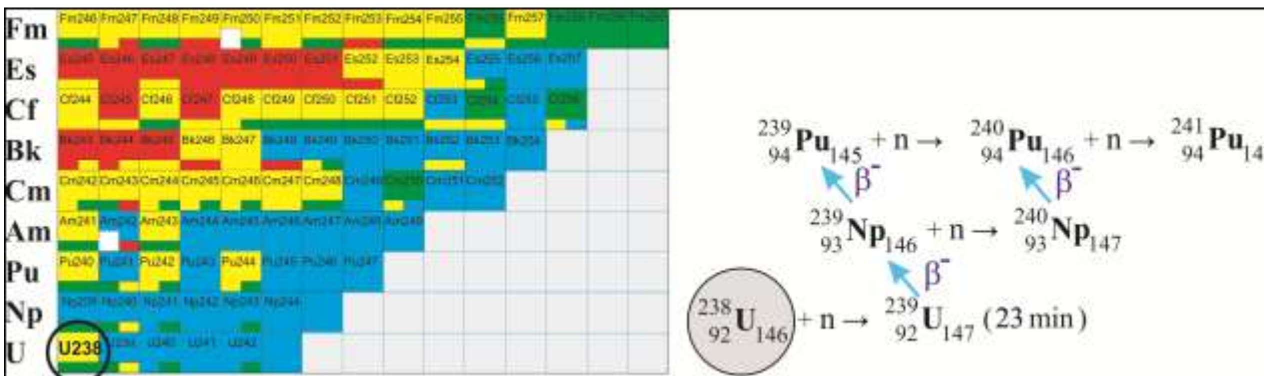
There are only 3 methods for synthesis of heavy nuclei

1. Fusion reactions: → proton rich heavy nuclei

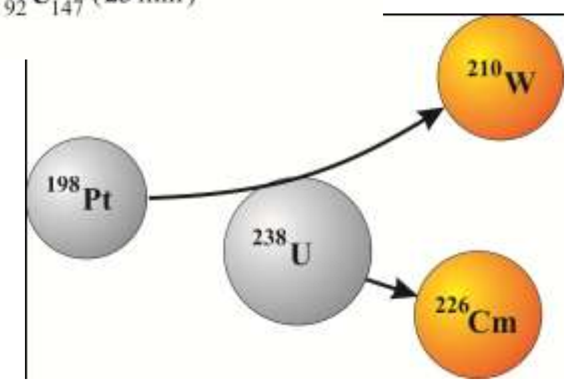


2. Sequence of neutron capture and beta(-) decay processes:

neutron fluxes in reactors are too low, nuclear explosions are forbidden



3. Multi-nucleon transfer reactions



Theoretical models of transfer reactions

Multi-nucleon transfers in damped collisions

Master equation
L.G. Moretto and J.S. Sventek, Phys. Lett. B **58**, 26 (1975)

Fokker-Plank equation
W. Norenberg, Phys. Lett. B **52**, 289 (1974)

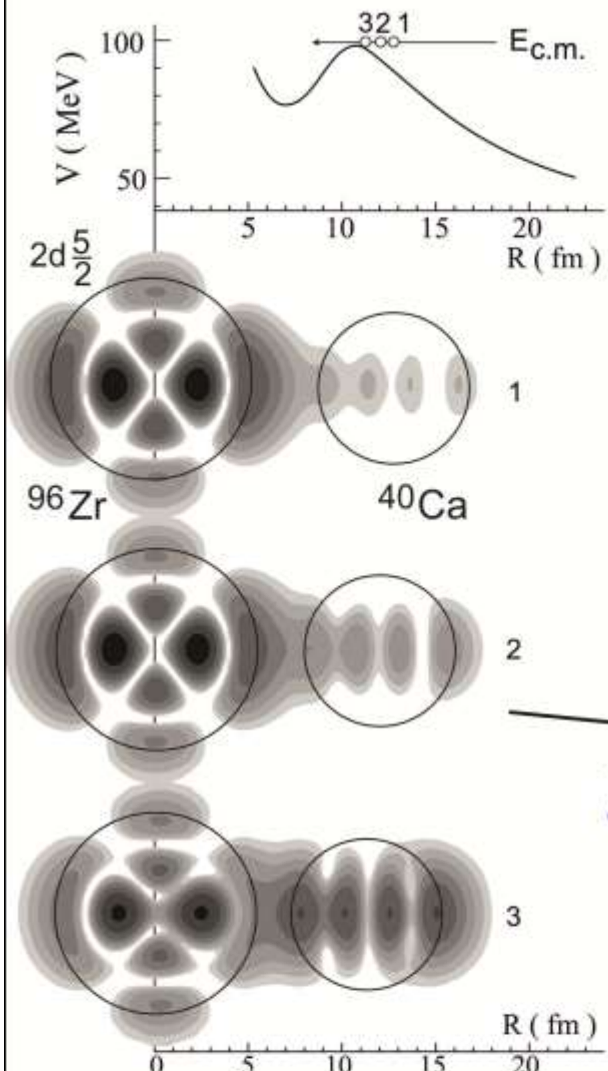
Langevin equations
P. Frobrich and S.Y. Xu, Nucl. Phys. **A477**, 143 (1988)

Semi-classical approaches
E. Vigezzi and A. Winther, Ann. Phys. (N.Y.) **192**, 432 (1989).
V.I. Zagrebaev, Ann. Phys. (N.Y.) **197**, 33 (1990).

Few-nucleon transfers (GRAZING)

A. Winther, Nucl. Phys. **A594**, 203 (1995)
http://personalpages.to.infn.it/nanni/grazing

Adiabatic dynamics of low-energy heavy ion collisions and nucleon transfers

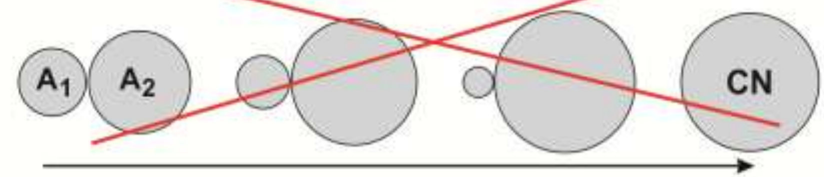


time-dependent Schrödinger equation
for single particle wave functions
(VZ, Samarin, Greiner, 2007);

~~Overlapping of single particle wave functions:~~

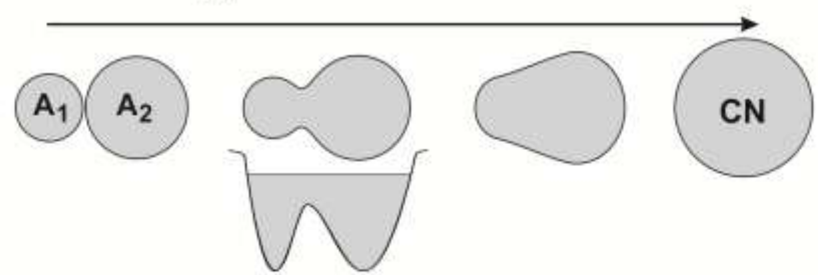
~~$<\Psi^{i}_{A_1}(\mathbf{R}+\mathbf{r}_i)|\Delta V|\Psi^{k}_{A_2}(\mathbf{R}+\mathbf{r}_k)>$~~

~~DNS: frozen nuclei, isolated mean fields~~



Appropriate description:

- overlapped mean fields
- two-center shell model
- rearrangement of nucleons



System of coupled Langevin type Equations of Motion

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

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:

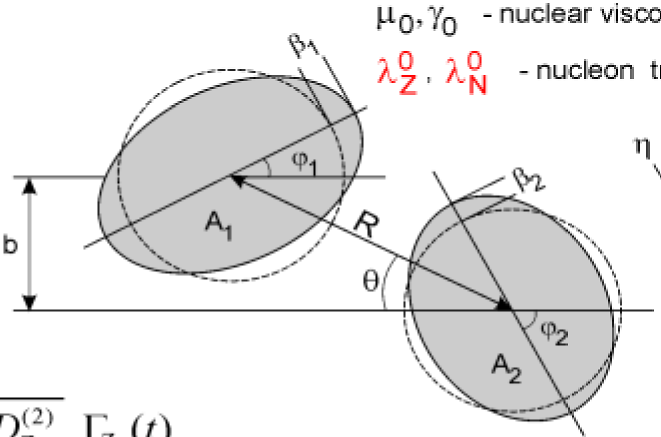
μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate

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

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

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



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

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

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

$$\lambda_Z^0=\lambda_N^0=\frac{\lambda^0}{2}$$

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

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

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

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

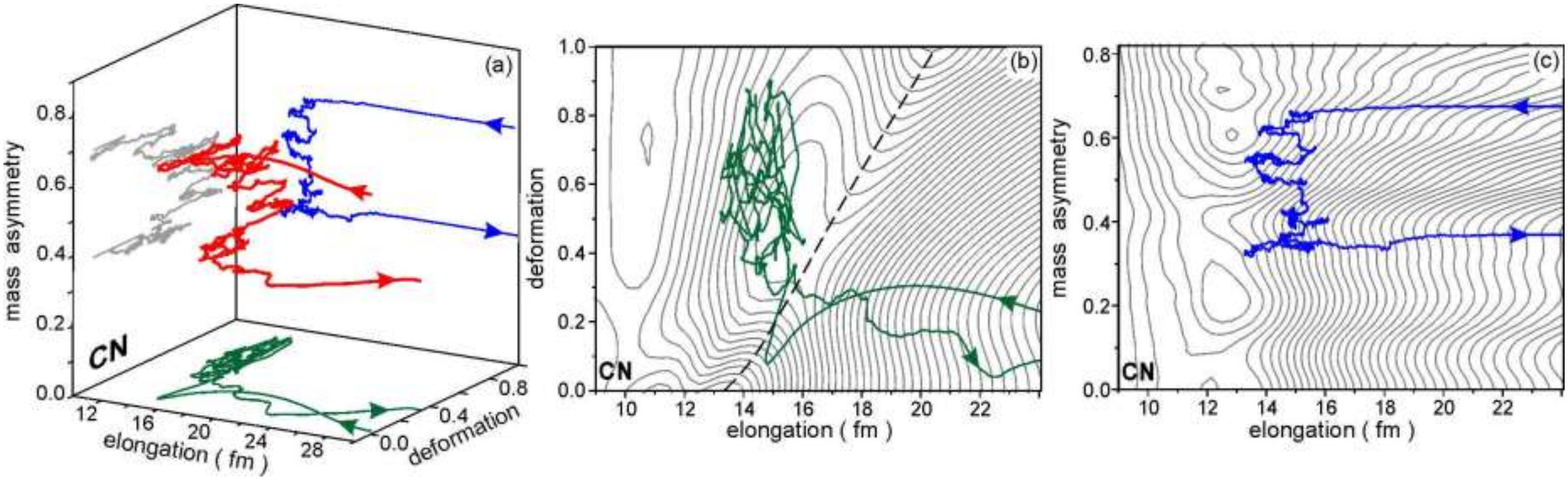
$$\frac{dL_1}{dt}=-\frac{\partial V}{\partial\varphi_1}+\gamma_{\rm tang}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_1-\frac{a_1}{R}\sqrt{\gamma_{\rm tang}T}\,\Gamma_{\rm tang}(t)$$

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

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

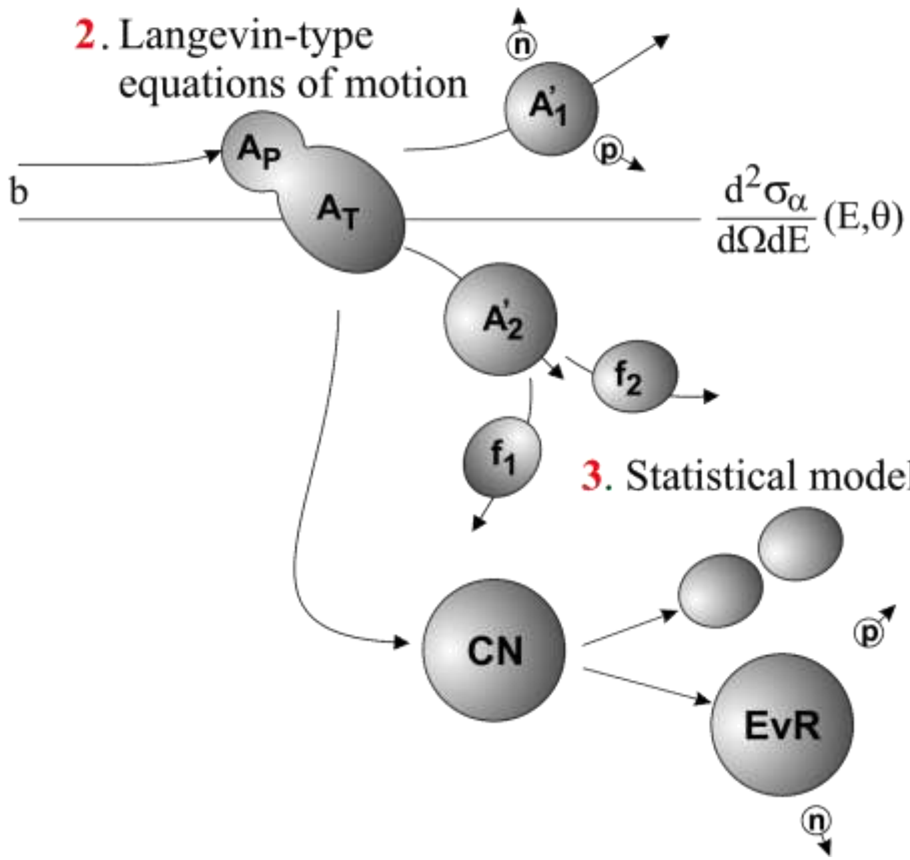
$$\frac{dp_{\beta 2}}{dt}=-\frac{\partial V}{\partial\beta_2}+\frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial\mu_{\beta 1}}{\partial\beta_2}+\frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial\mu_{\beta 2}}{\partial\beta_2}+\left(\frac{\ell^2}{2\mu_R^2 R^2}+\frac{p_R^2}{2\mu_R^2}\right)\frac{\partial\mu_R}{\partial\beta_2}-\gamma_\beta\frac{p_{\beta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

Typical trajectory in the "distance-deformation-mass asymmetry" space (48Ca + 248Cm, E=210 MeV)



Simulation of experiment and cross sections

1. Time-dependent driving potential $V(r,\xi;t)$:
Folding → Adiabatic Two-Center Shell Model

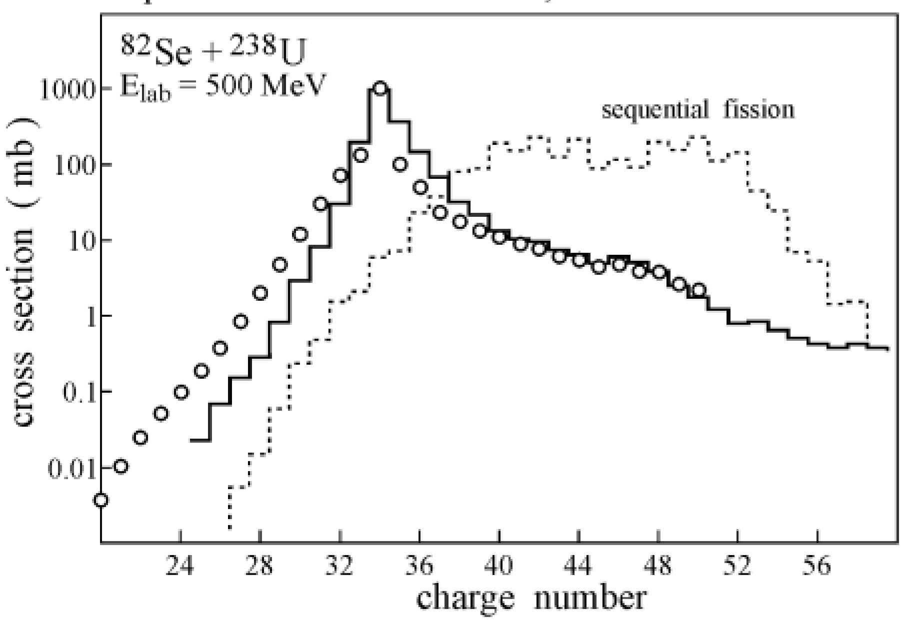


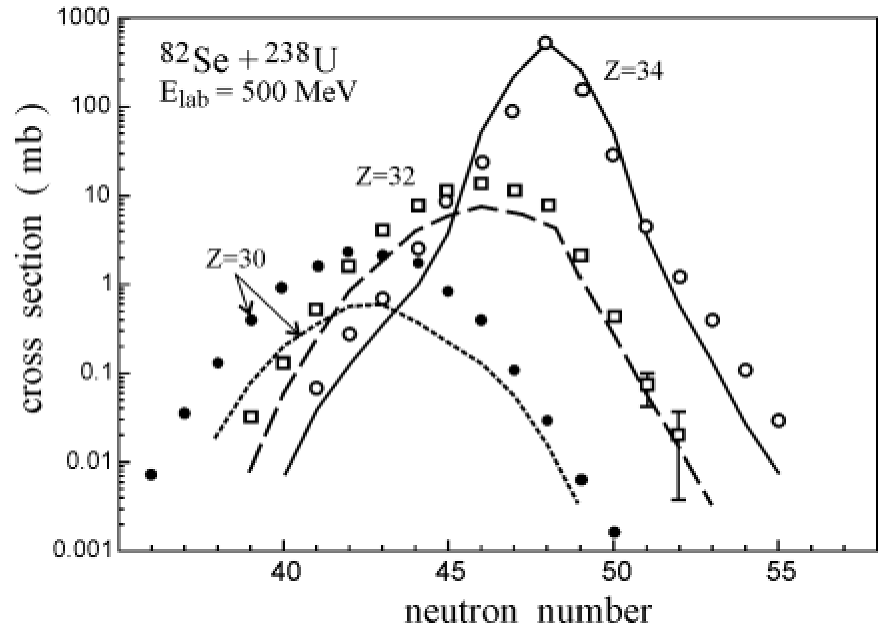
$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

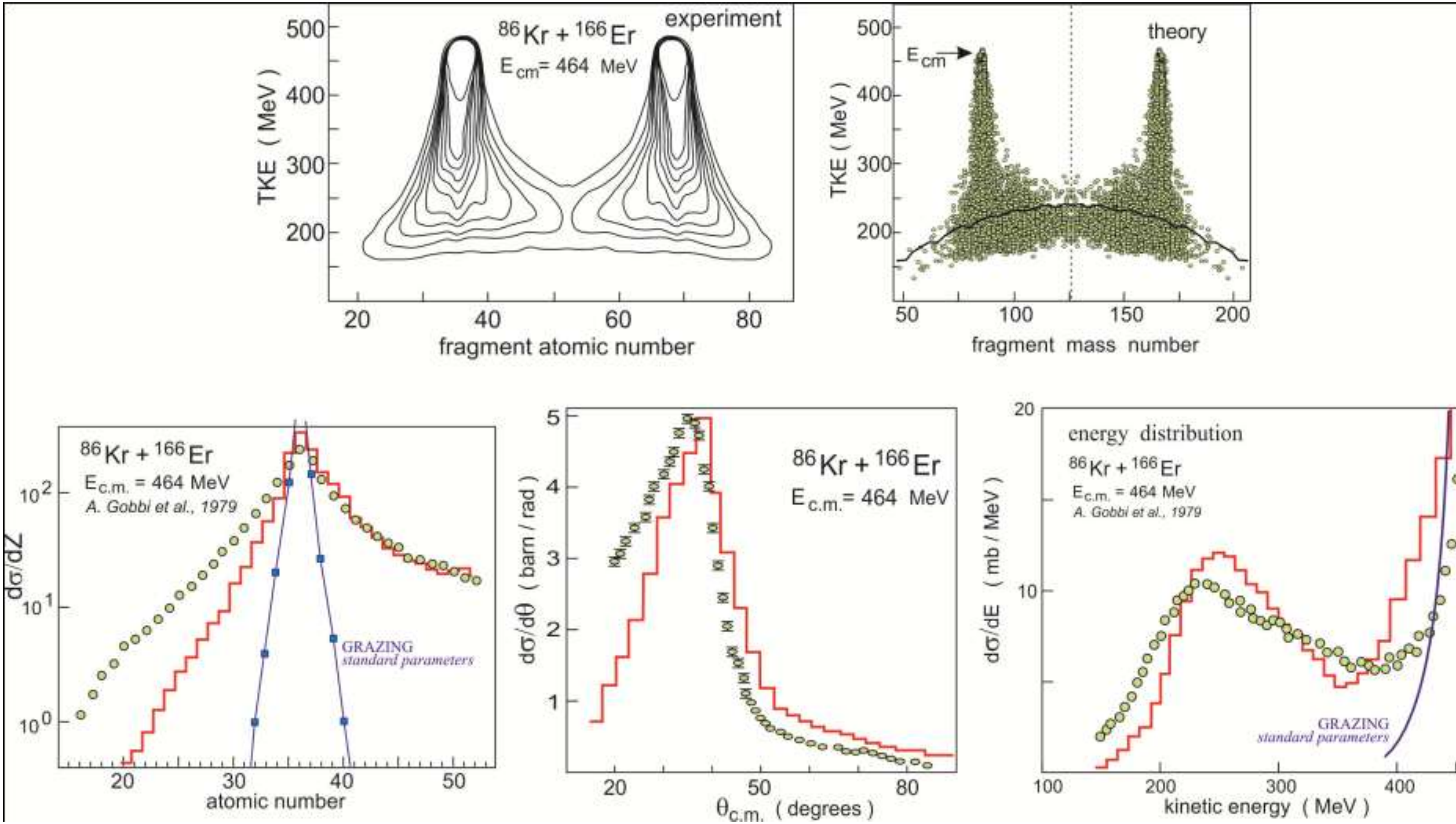
Comparison with experiments on multi-nucleon transfer

Experiment: L. Corradi et al., 2006

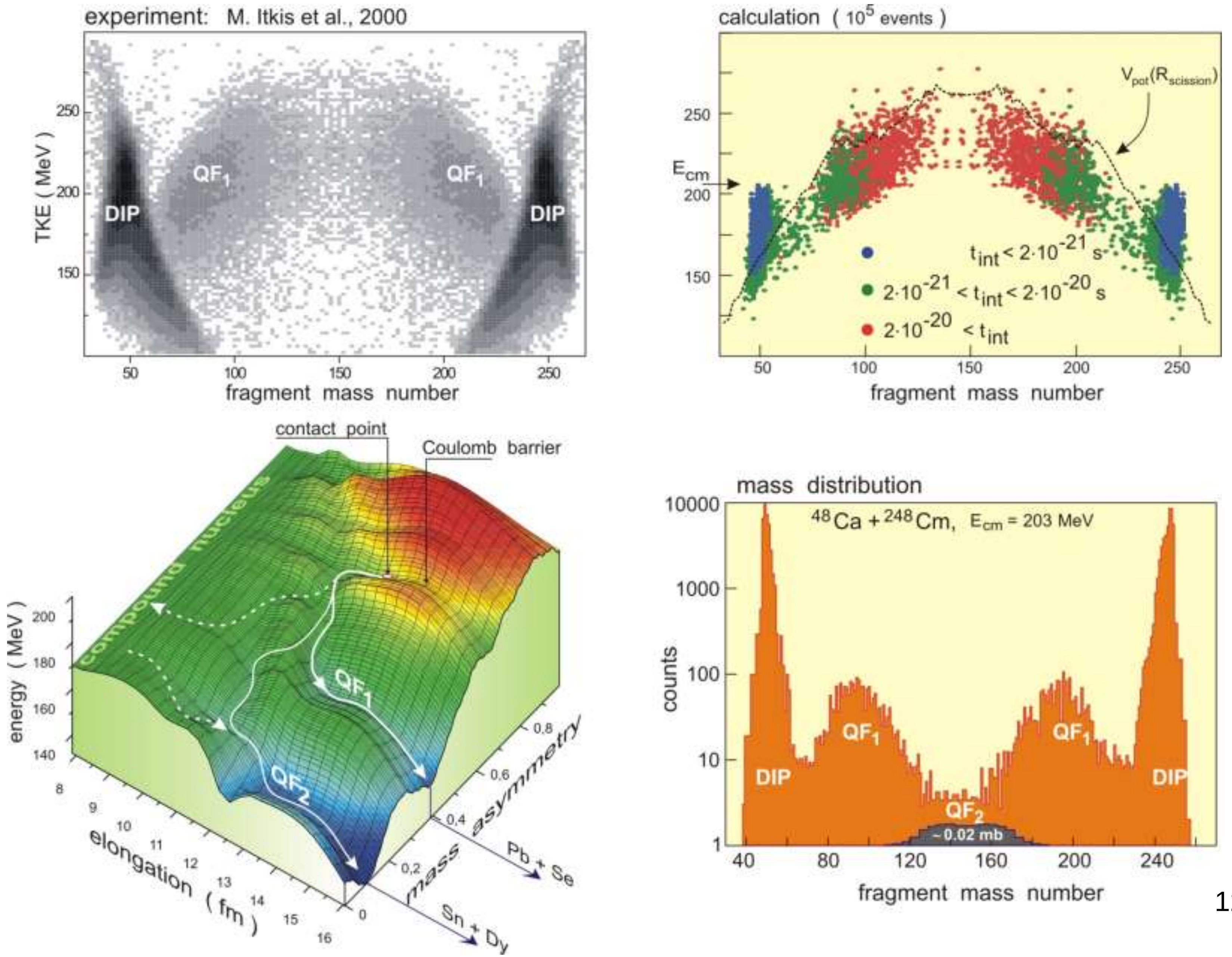




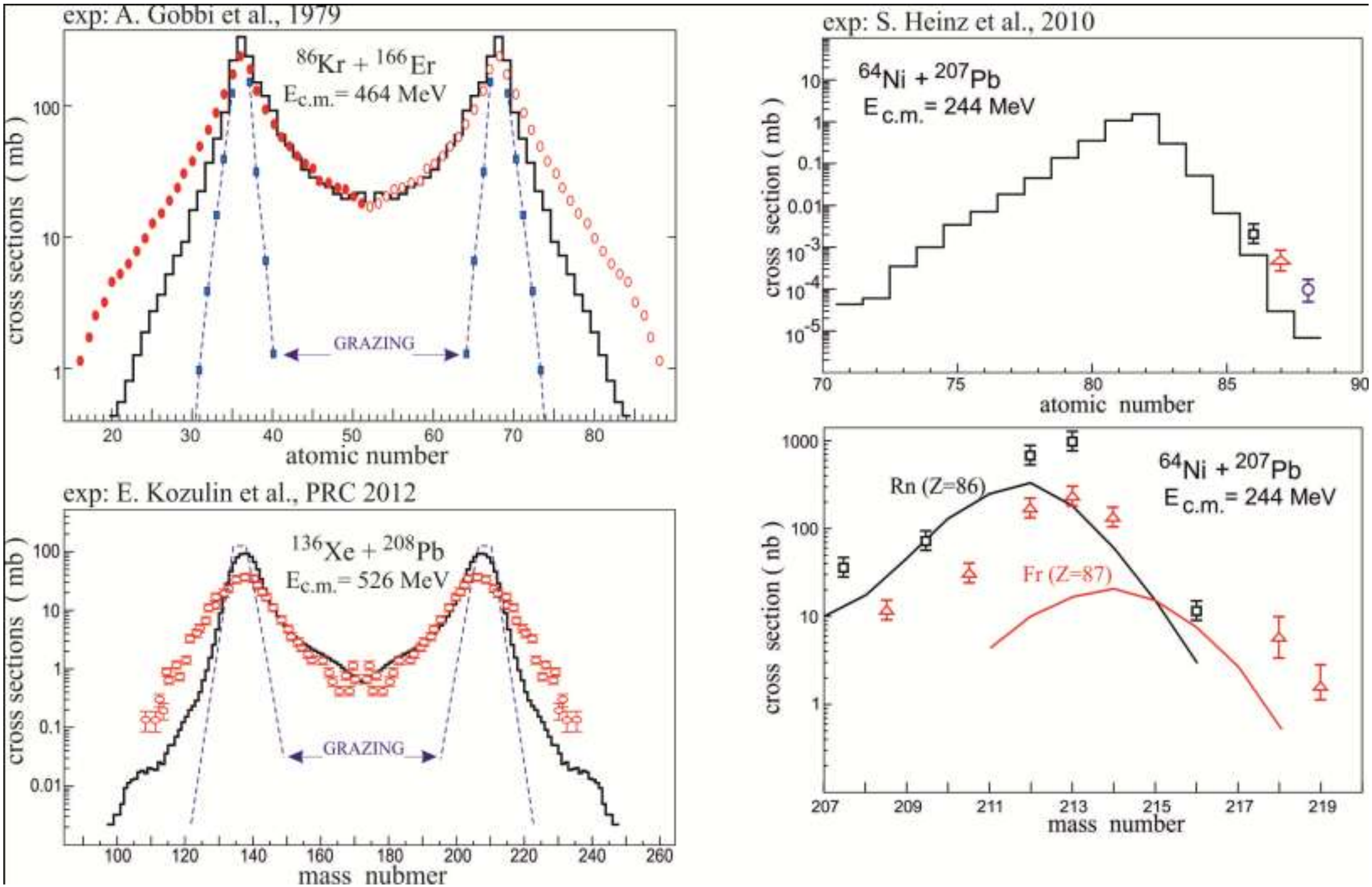
For the first time quantitative description of all the features of Deep Inelastic scattering was obtained



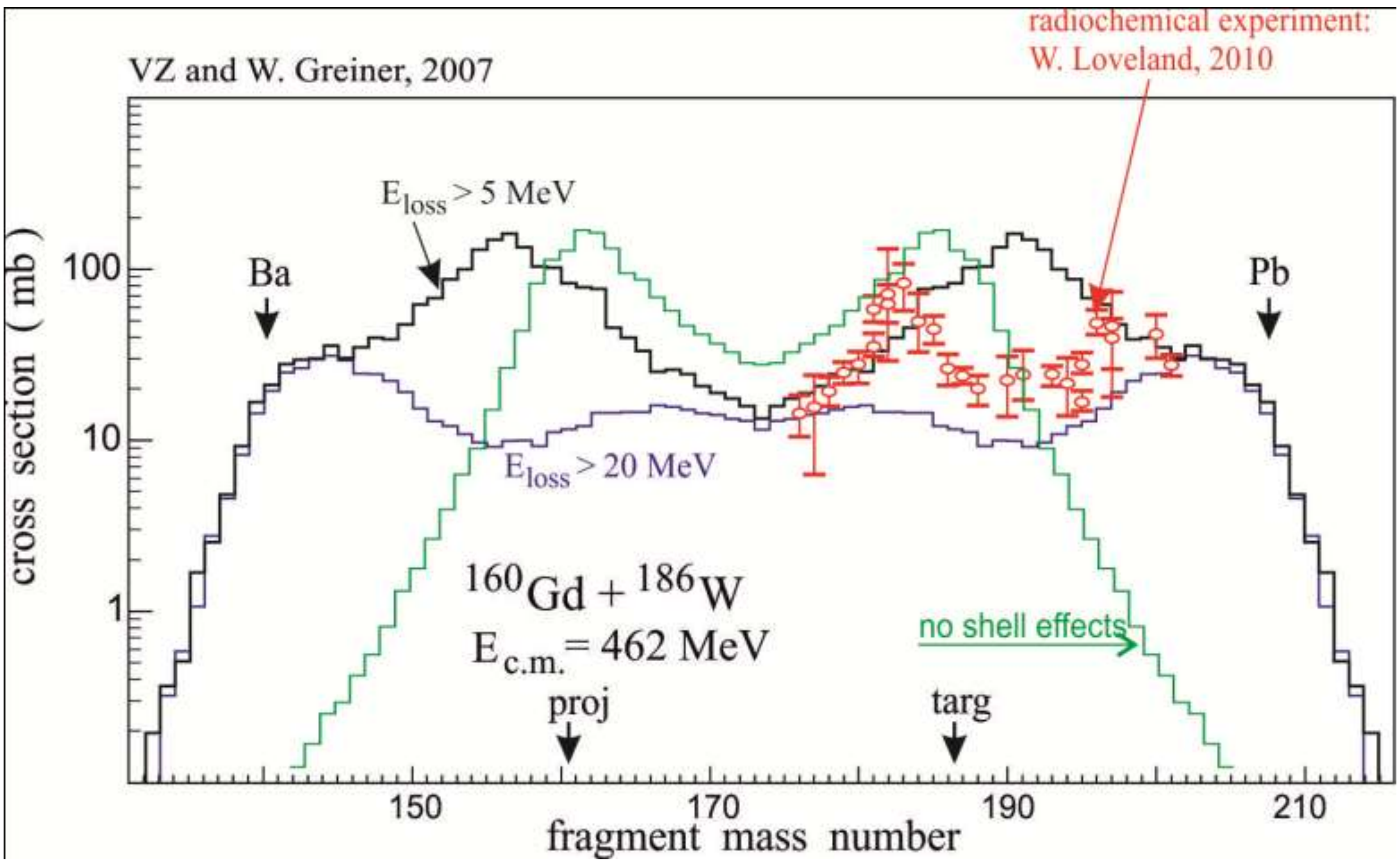
Quasi-Fission process: $^{48}Ca + ^{248}Cm$



Underestimation of the yield of trans-target nuclei ?



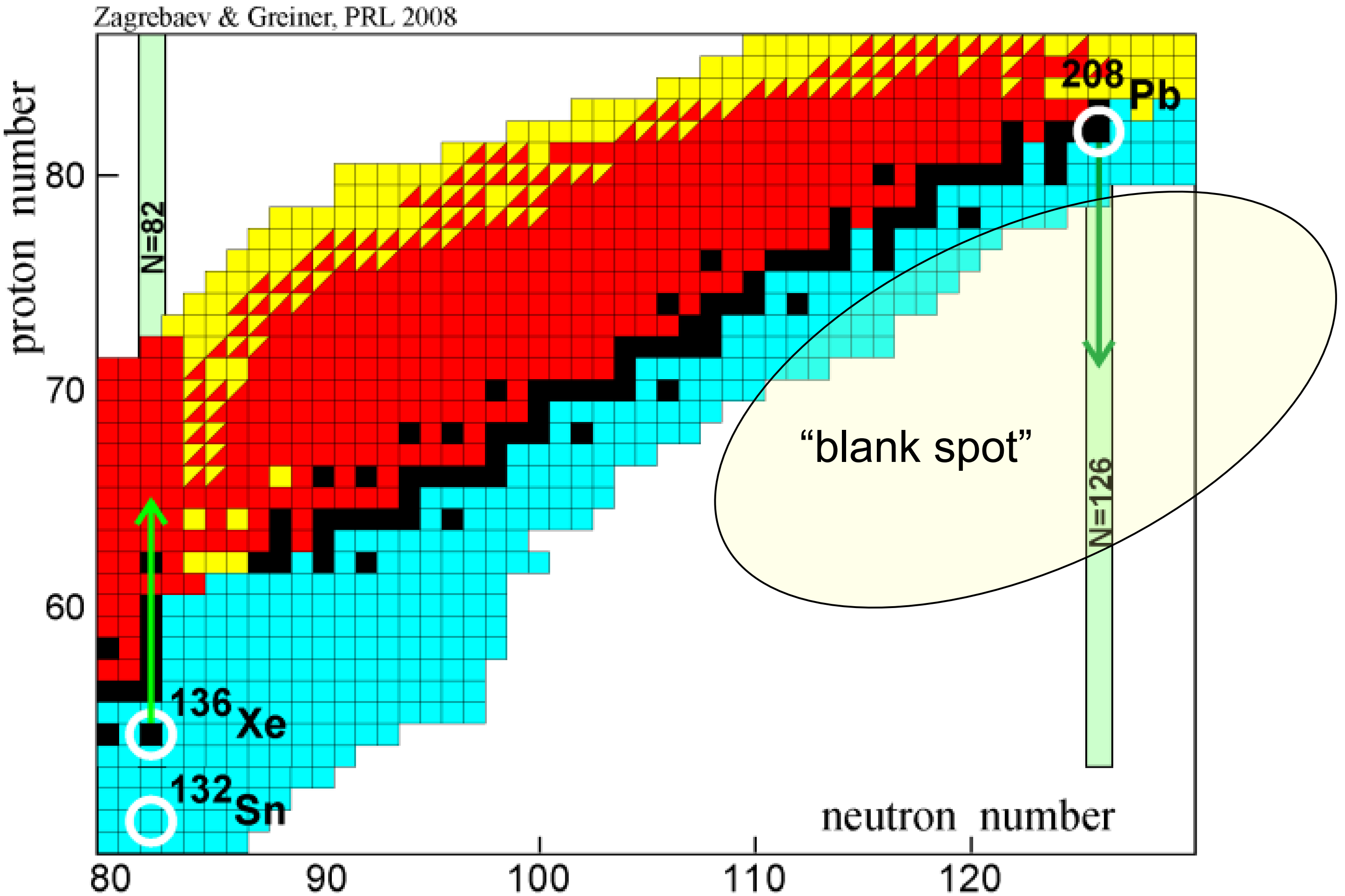
Shell effects in low-energy multi-nucleon transfer reactions ?



on-line Gd+W experiment started in Dubna on September 20

If the shell effects in transfer reactions will be confirmed
it will open a door for the production of neutron rich Superheavy Elements
in U+Cm collisions (inverse quasi-fission)

Production of new heavy nuclei in the region of N=126



proton transfer along the neutron closed shells:

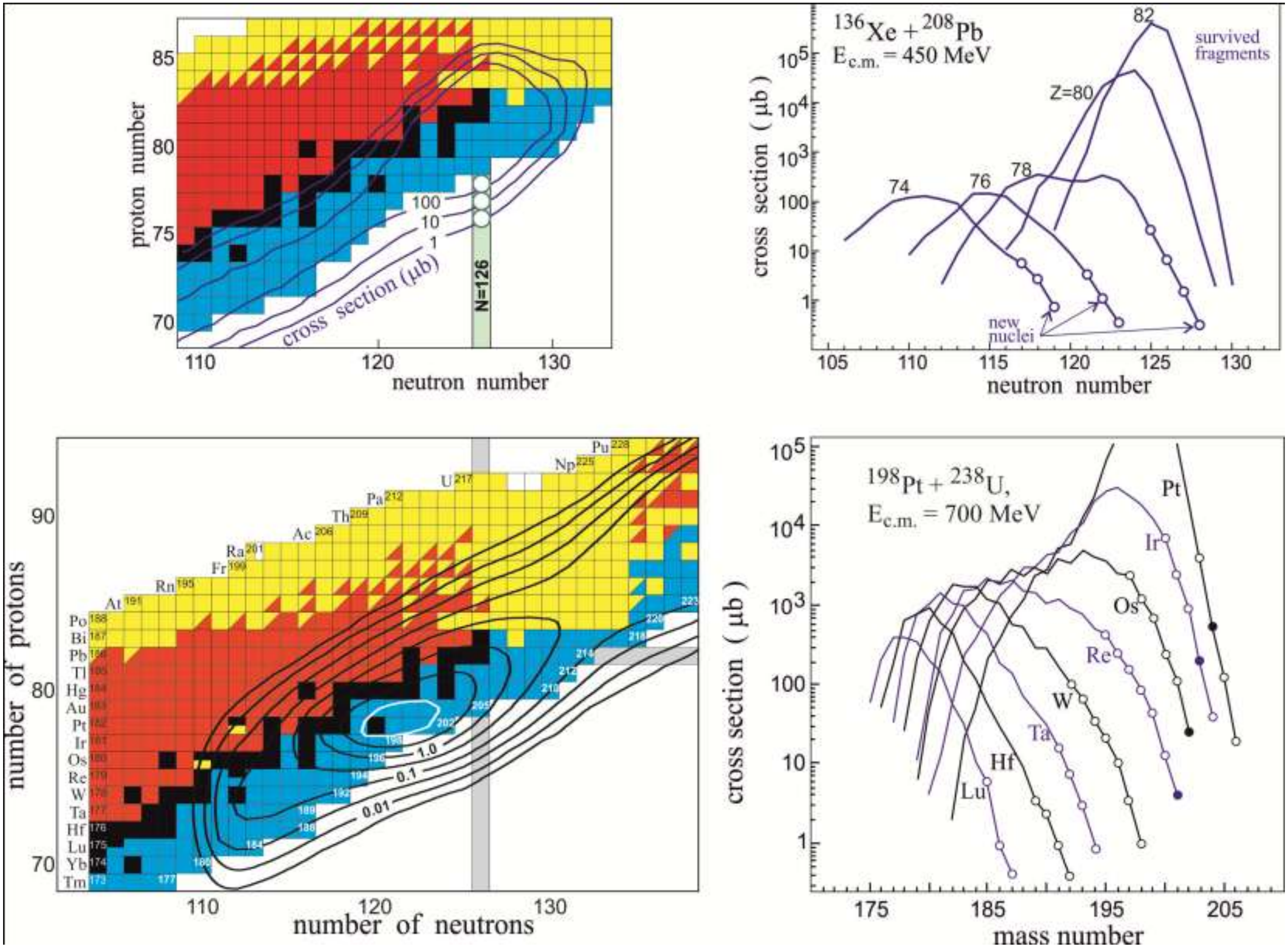
$$^{136}Xe_{N=82} + {}^{208}Pb_{N=126} \rightarrow {}^{136+\Delta Z}X_{N=82} + {}^{208-\Delta Z}Y_{N=126} + Q \approx 0$$

Reactions with $Q \approx 0$ are very favorable for proton transfer

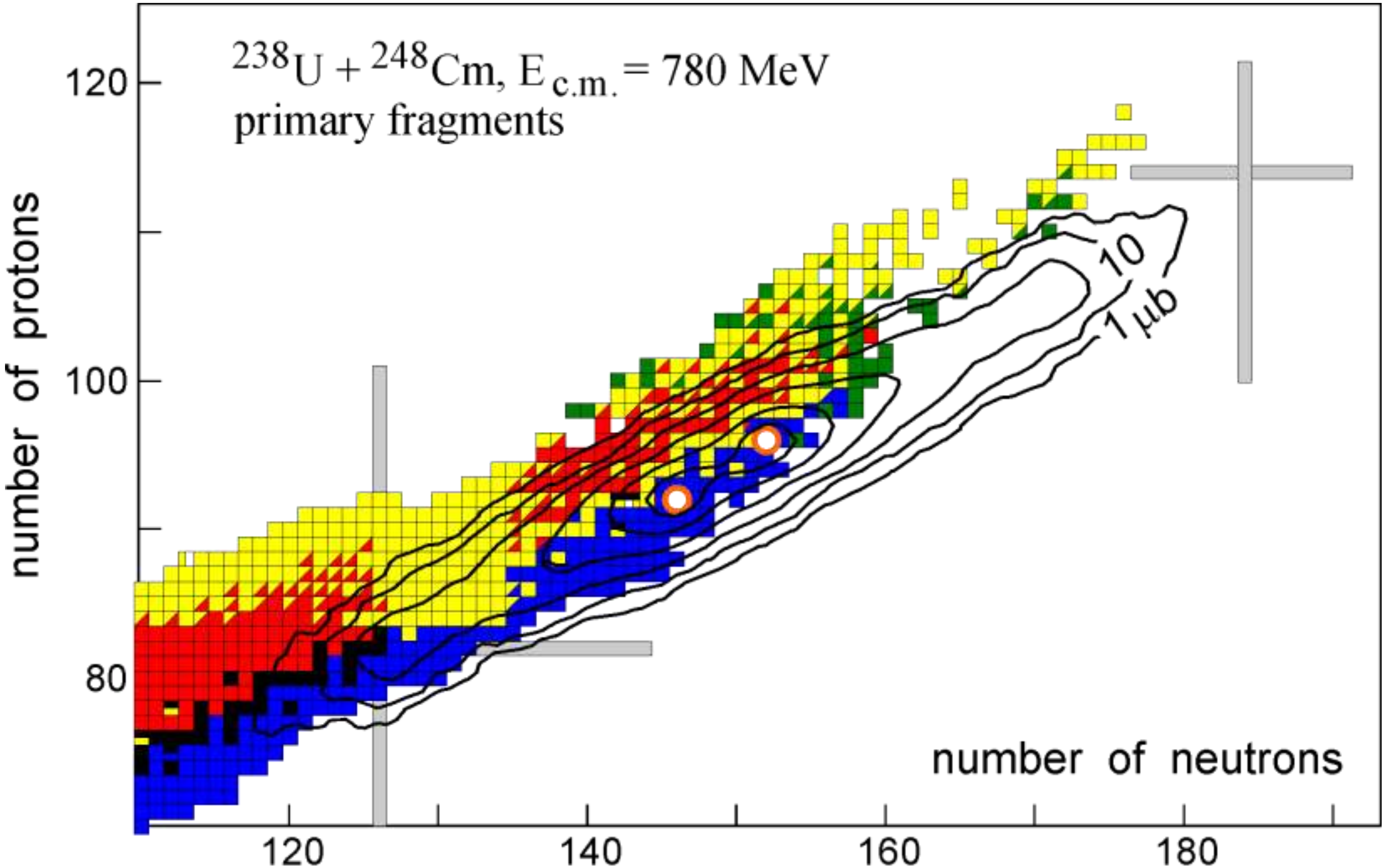
The use of ^{132}Sn is even better !

Isotope production with radioactive beams, Dasso, Pollarolo, Winther, PRL 1994

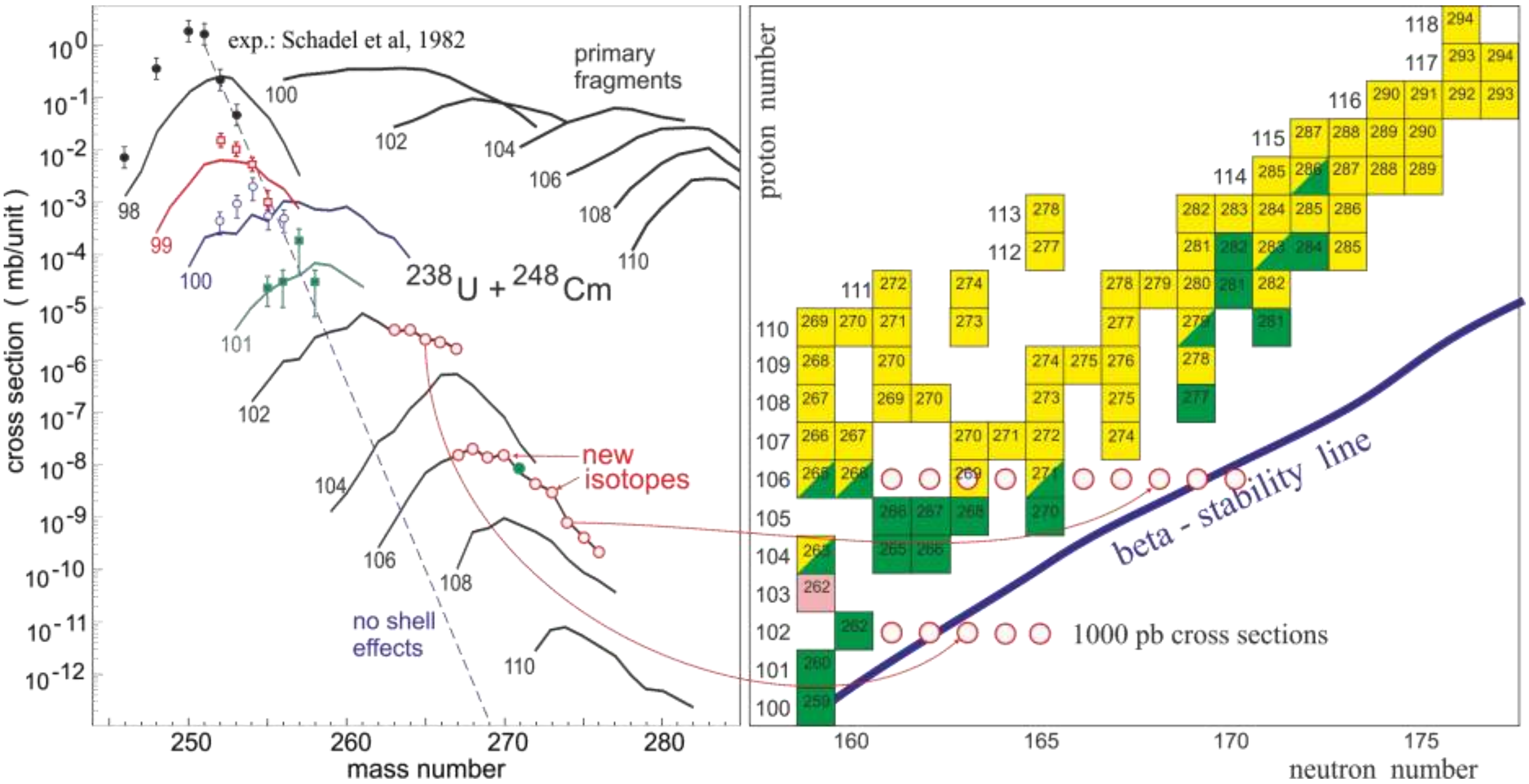
Production of neutron rich heavy nuclei located along the last "waiting point" of astrophysical nucleosynthesis



238U + 248Cm. Primary fragments

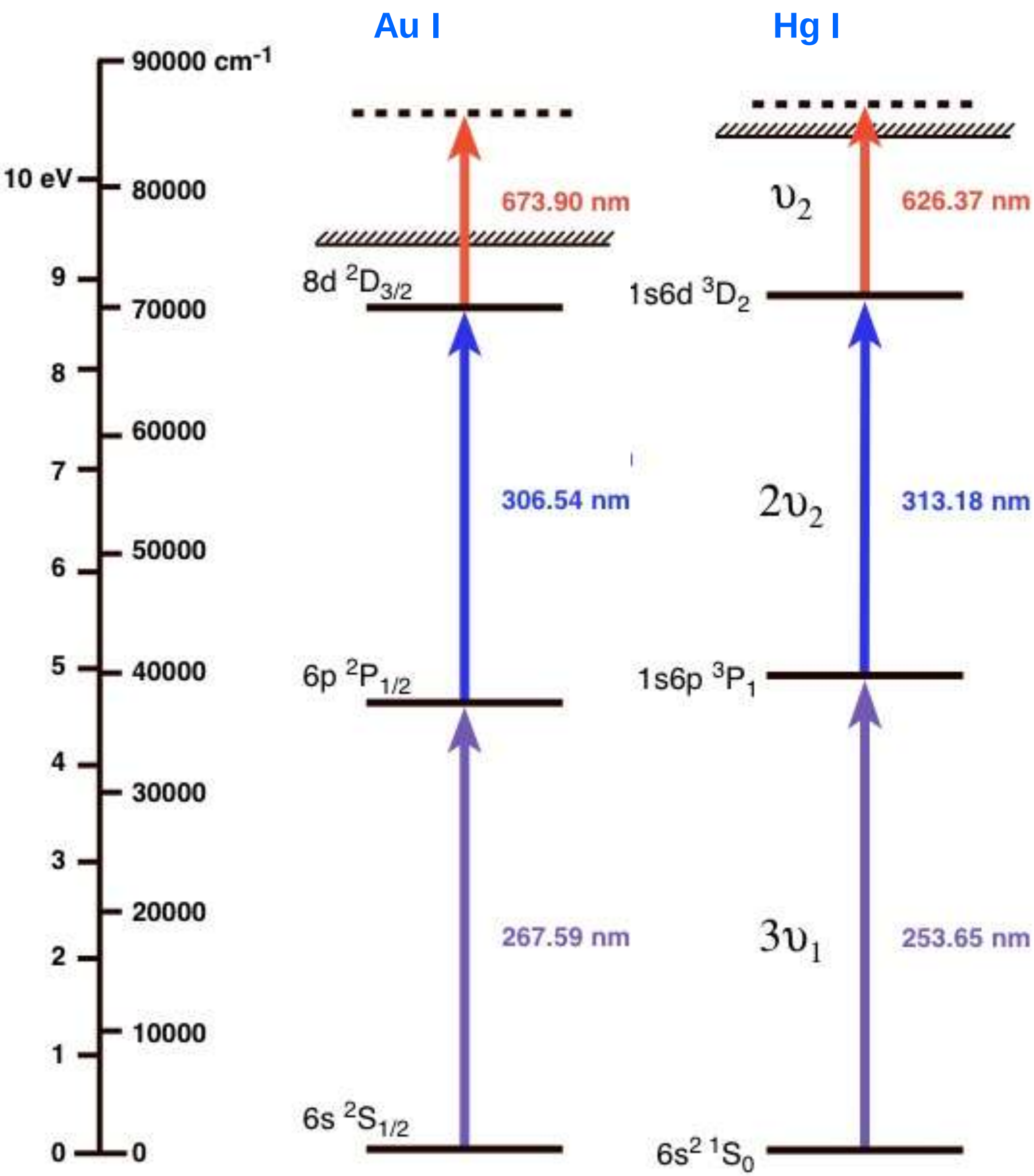


Production of transfermium nuclei along the line of stability looks quite possible



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

Selective laser ionization of Au & Hg atoms



Ionization Schemes

Au I

Level	Energy, cm^{-1}	Configuration	Wavelength, nm	
E_0	0	$6s\ ^2S_{1/2}$	λ_1	267.6
E_1	37358.99	$6p\ ^2P_{1/2}$	λ_2	306.5
E_2	69971.42	$8d\ ^2D_{3/2}$	λ_3	673.9

Chemical series	Transition metals
Group, Period, Block	11, 6, *d*
Atomic mass	196.96655(2) g/mol
Electron configuration	[Xe] $4f^{14}\ 5d^{10}\ 6s$
Ionization potential	74408.88 cm^{-1} (9.22553 eV)

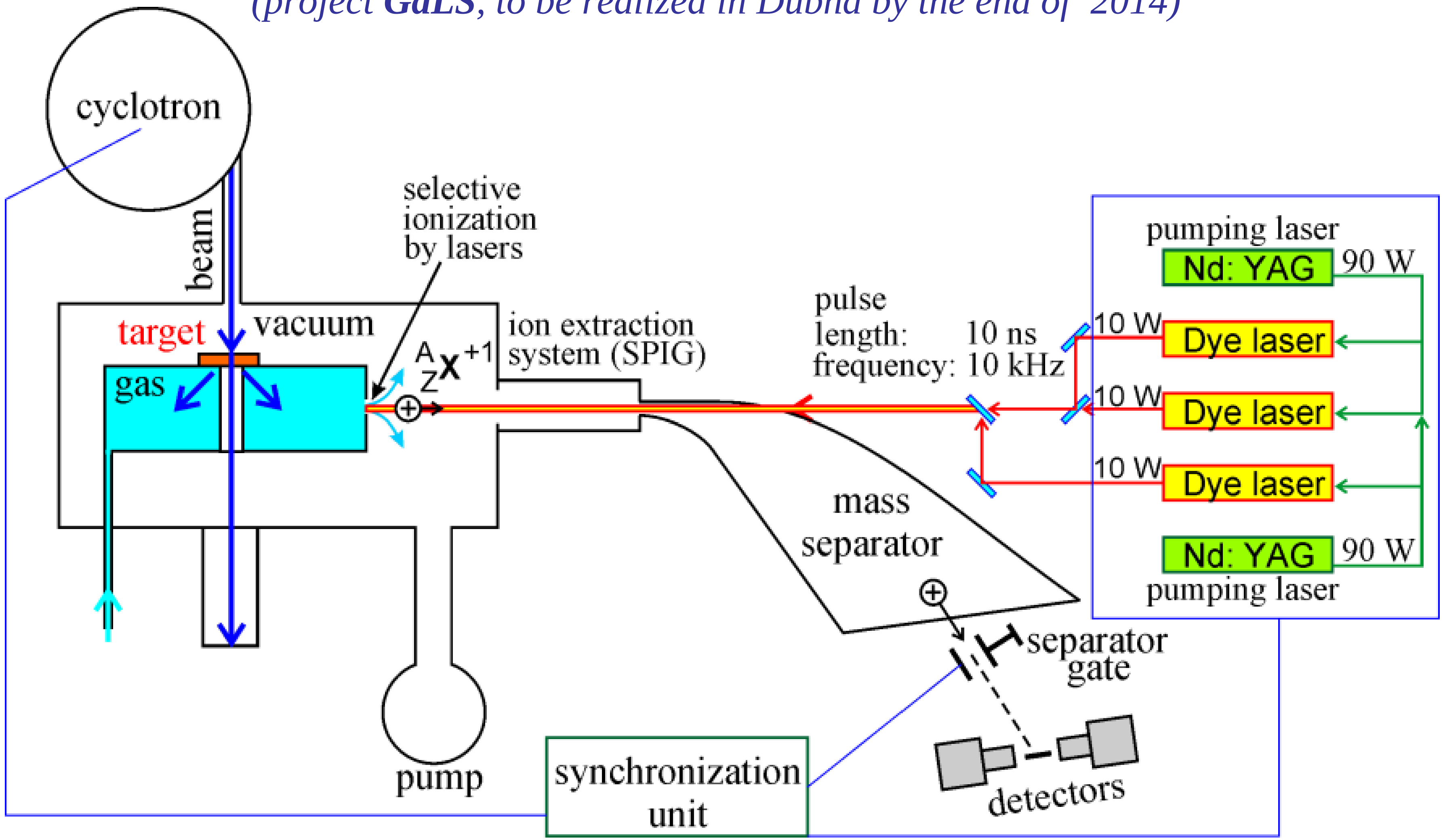
Hg I

Level	Energy, cm^{-1}	Configuration	Wavelength, nm	
E_0	0	$6s^2\ ^1S_0$	λ_1	253.65
E_1	39412.30	$6s\ 6p\ ^3P_1$	λ_2	313.18
E_2	71396.22	$6s\ 6d\ ^3D_2$	λ_3	626.37

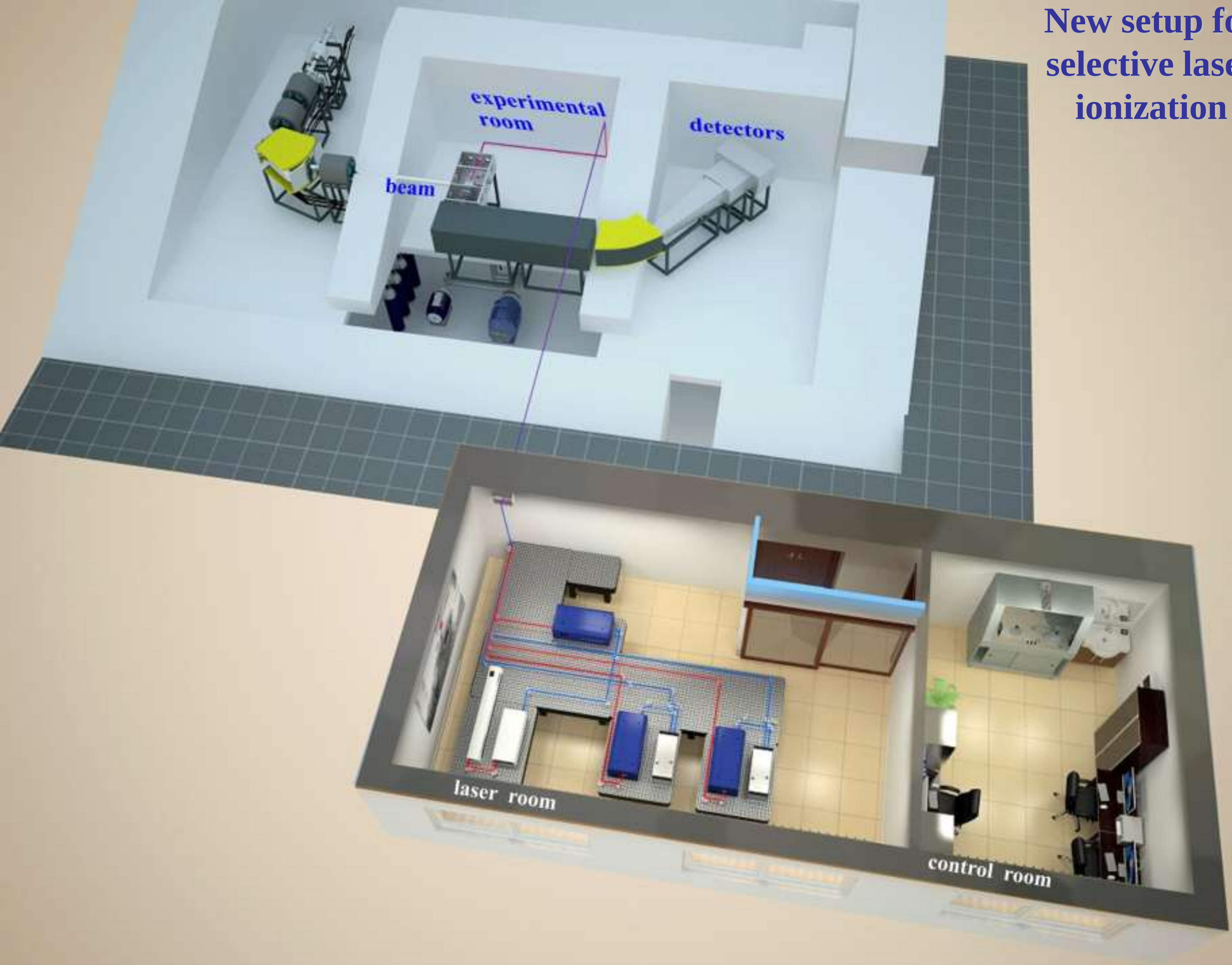
Chemical series	
Group, Period, Block	12, 6, *d*
Atomic mass	200.59(2) g/mol
Electron configuration	[Xe] $4f^{14}\ 5d^{10}\ 6s^2$
Ionization potential	84184.1 cm^{-1} (10.4375 eV)

New setup for selective laser ionization of multi-nucleon transfer reaction products stopped in gas

*(project **GaLS**, to be realized in Dubna by the end of 2014)*



New setup for selective laser ionization



Summary

- **North-east part of the nuclear map is still "terra incognita".**
  Heavy neutron rich nuclei are not synthesized and studied yet.

- **Multi-nucleon transfer reactions can be used for synthesis of new neutron rich nuclei located along the closed neutron shell N=126 having the largest impact on the astrophysical r-process. Cross sections are higher than 1 μb.**

- **Multi-nucleon transfer reactions can be used also for synthesis of new neutron enriched transfermium nuclei located along the beta-stability line. U-like beams are needed as well as a new kind of separators!**

- **Shell effects and dynamics of the "inverse quasi-fission processes" in HI damped collisions should be studied much better. There are several quite promising experiments to be perform just now.**

Valeriy Zagrebaev (FLNR, Dubna)

Walter Greiner (FIAS, Frankfurt)

JINR *(Dubna)*

FIAS *(Frankfurt)*