Light and Heavy Fragments Mass Correlation in the $^{197}Au+^{130}Te$ Transfer Reaction

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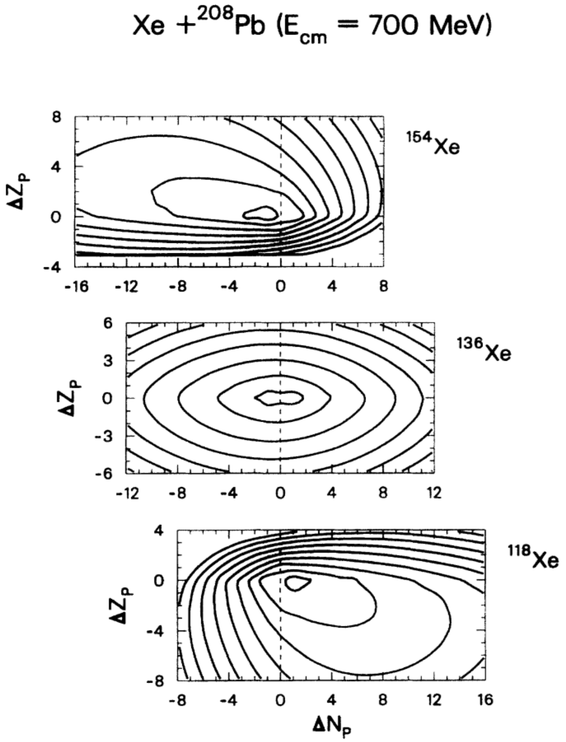
INFN Laboratori Nazionali di Legnaro

2018 European Nuclear Physics Conference

2-7 September 2018

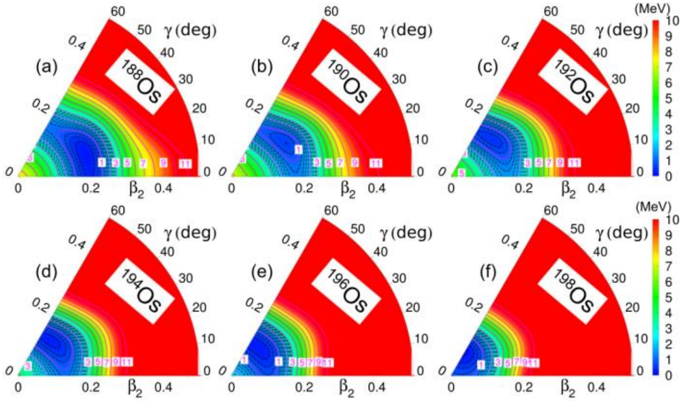
Motivation

More accurate description of the reaction mechanism leading to the population of neutron-rich heavy nuclei



C. H. Dasso, G. Pollarolo, A. Winther, PRL **73** (1994) 1907

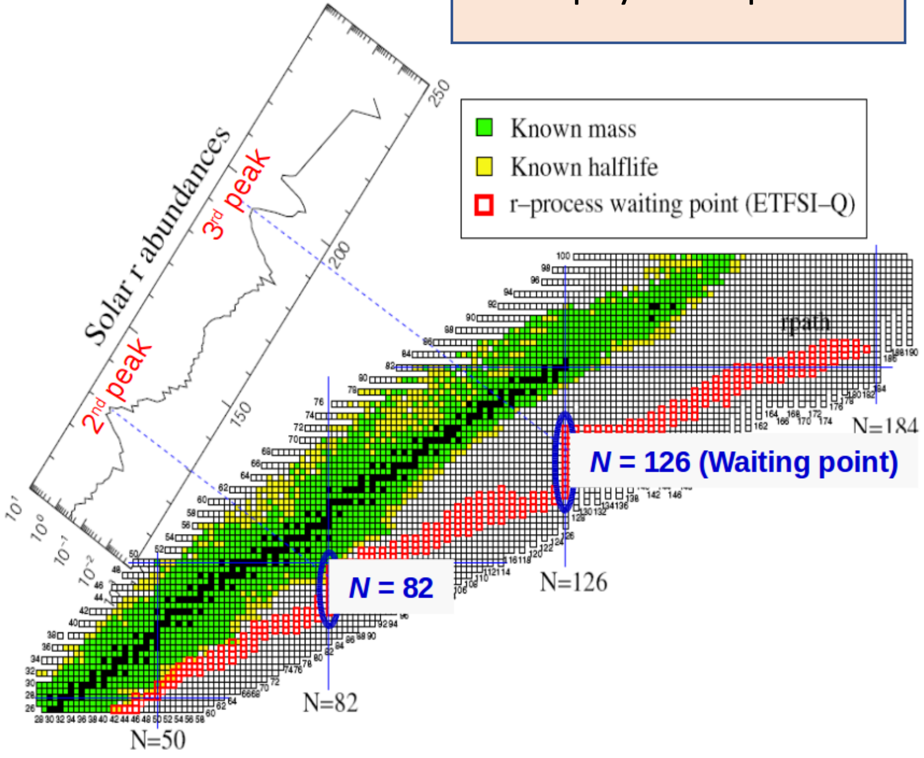
Nuclear structure studies in the vicinity of N=126



Investigation of prolate-to-oblate shape transition moving towards the neutron-rich Pt-Os region

P. R. John et al., PRC **90** (2014) 021301(R); PRC **95** (2017) 064321.

Astrophysical r-process



H.Grawe et al., Rep. Prog. Phys. **70** (2007) 1525

How to access neutron-rich heavy nuclei?

Fusion reactions with neutron-rich radioactive beams → **low beam intensity from accelerators**

Neutron-capture reactions → **low beam intensity from reactors**

Fragmentation reactions at relativistic energy

Multinucleon transfer reactions near the Coulomb barrier

} → **challenging experiments**

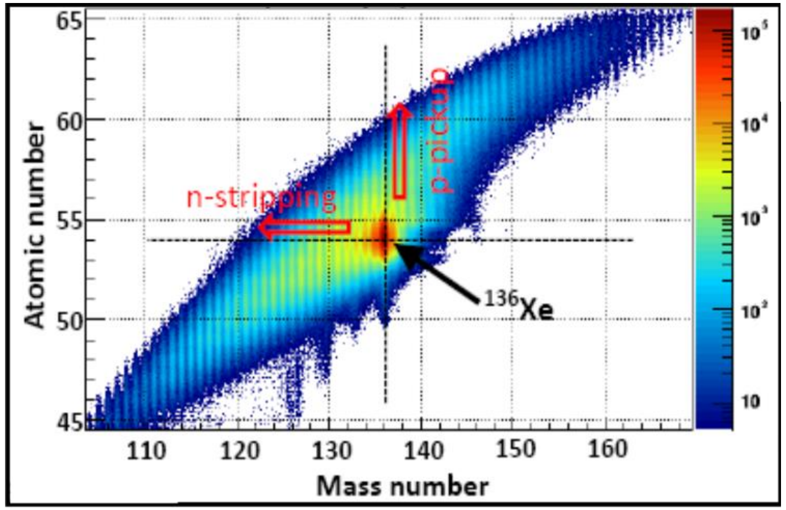
reachable σ in the μb - nb range

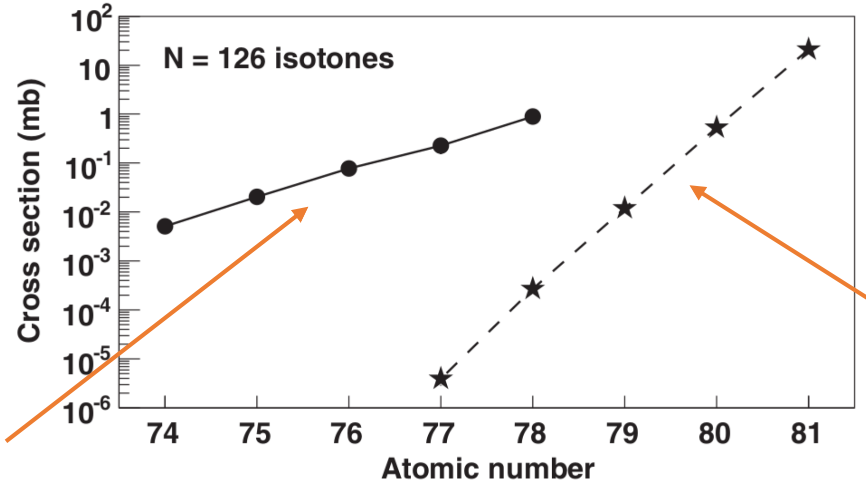
How to access neutron-rich nuclei close to N=126

It is important to understand which is the most suitable mechanism for the production of nuclei close to the Z = 82 and N = 126 region of the nuclide chart.

$^{136}Xe+^{198}Pt$ @ 8 AMeV
VAMOS+EXOGAM
γ-particle coincidences

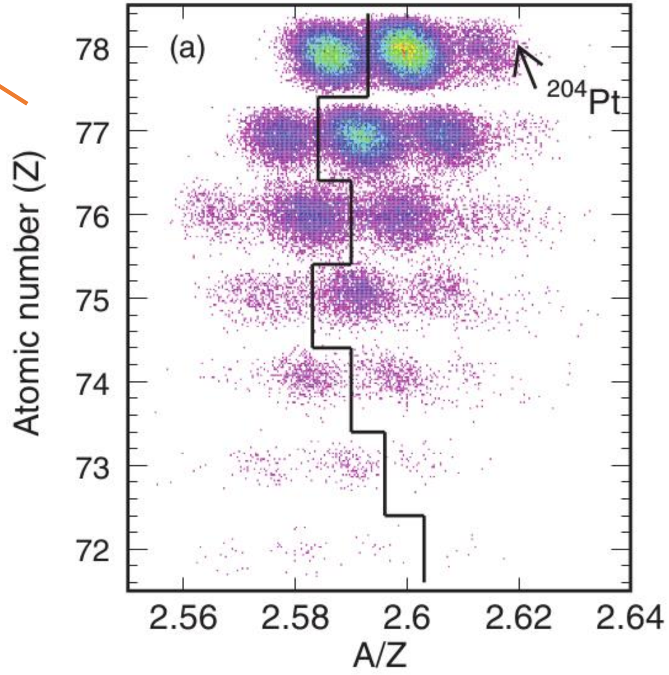
Y. X. Watanabe et al., PRL **115** (2015) 172503





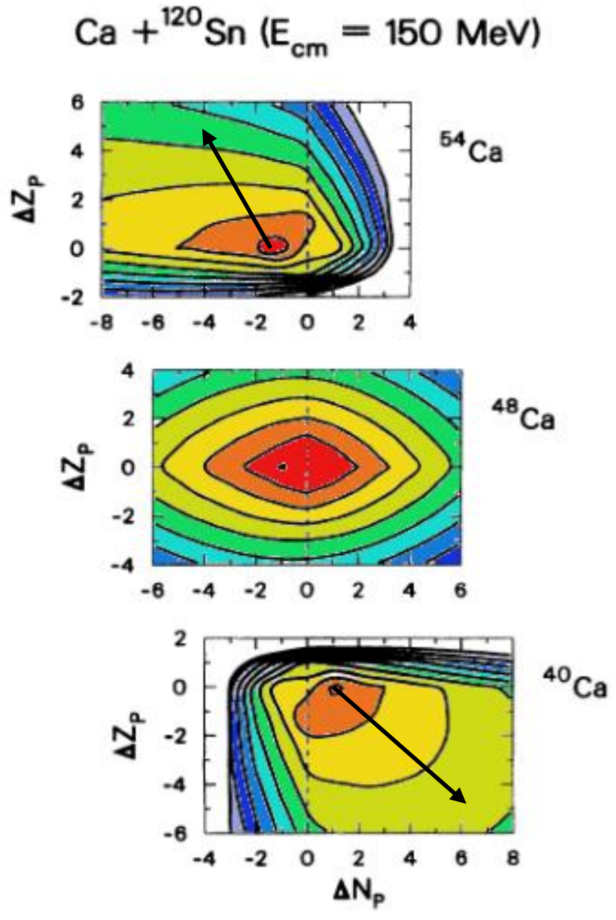
$^{208}Pb+Be$ @ 1 AGeV
Fragment Separator
In-flight separation

T. Kurtukian-Nieto et al., PRC **89** (2014) 024616

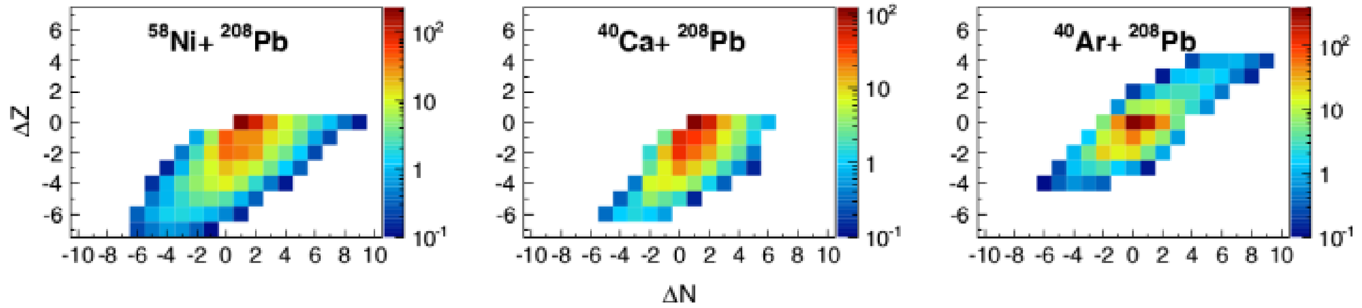


Multinucleon transfer is a complementary mechanism to the fragmentation of actinides or lead on light targets for the population of heavy neutron-rich nuclei
BUT
direct identification is very difficult

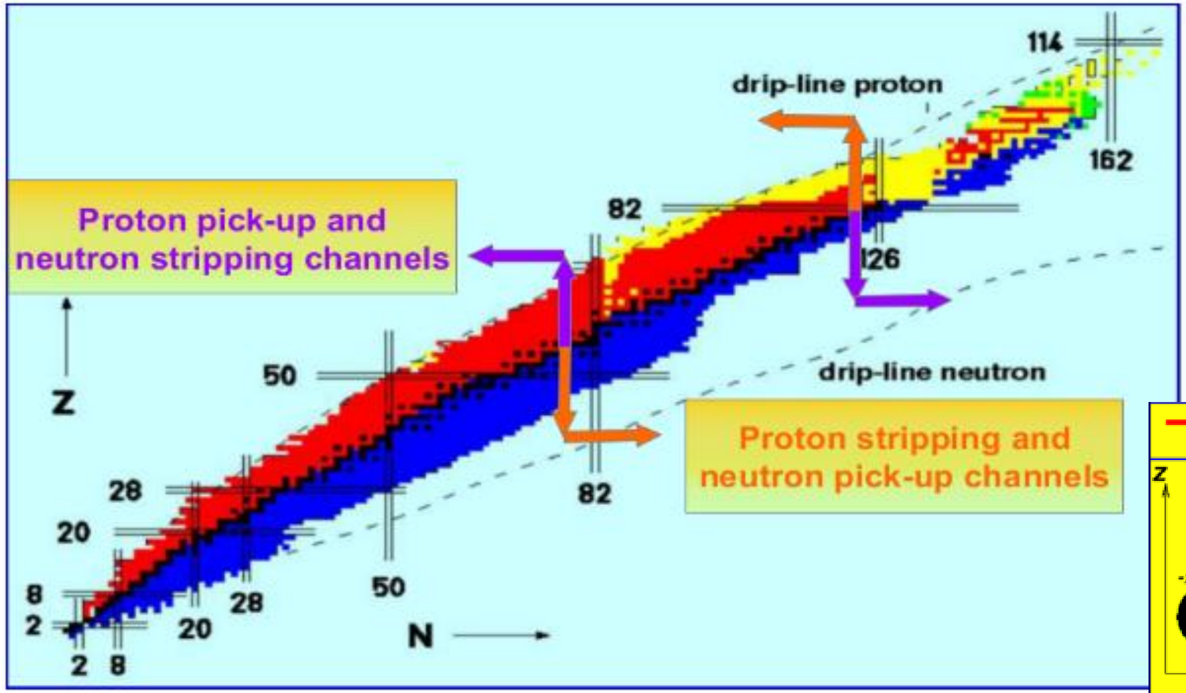
Populating neutron-rich nuclei via MNT reactions

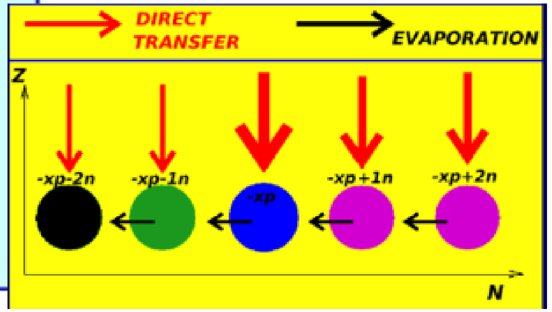


C. H. Dasso, G. Pollarolo, A. Winther, PRL **73** (1994) 1907

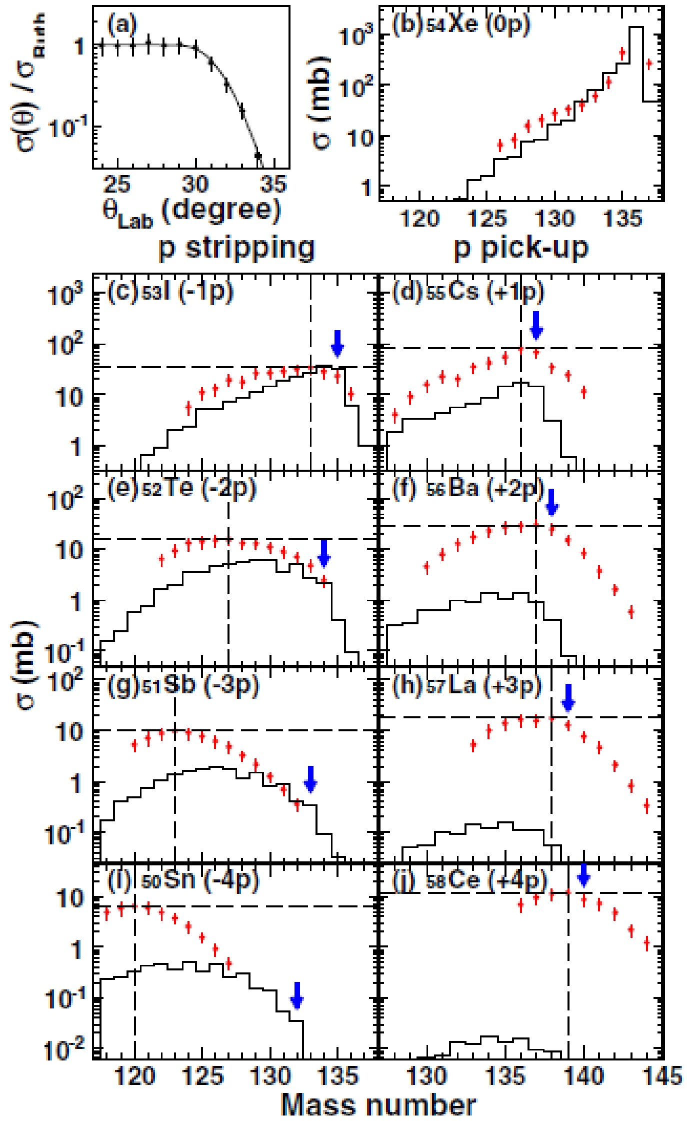


T. Mijatović et al., PRC **94** (2016) 064616

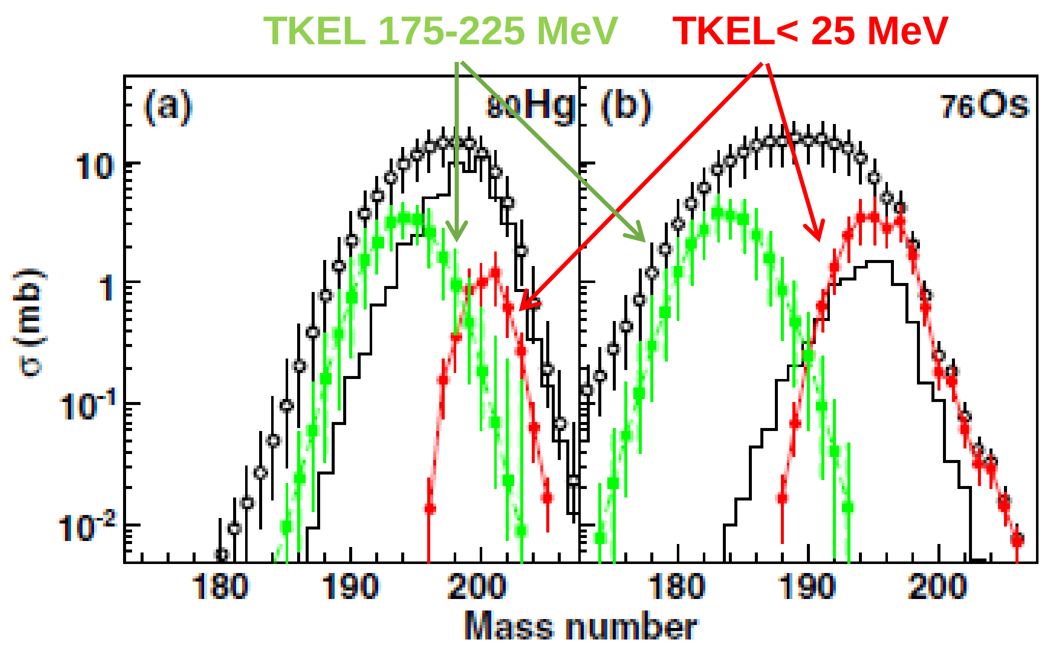




Production of neutron-rich nuclei near N=126 via $^{136}Xe+^{198}Pt$

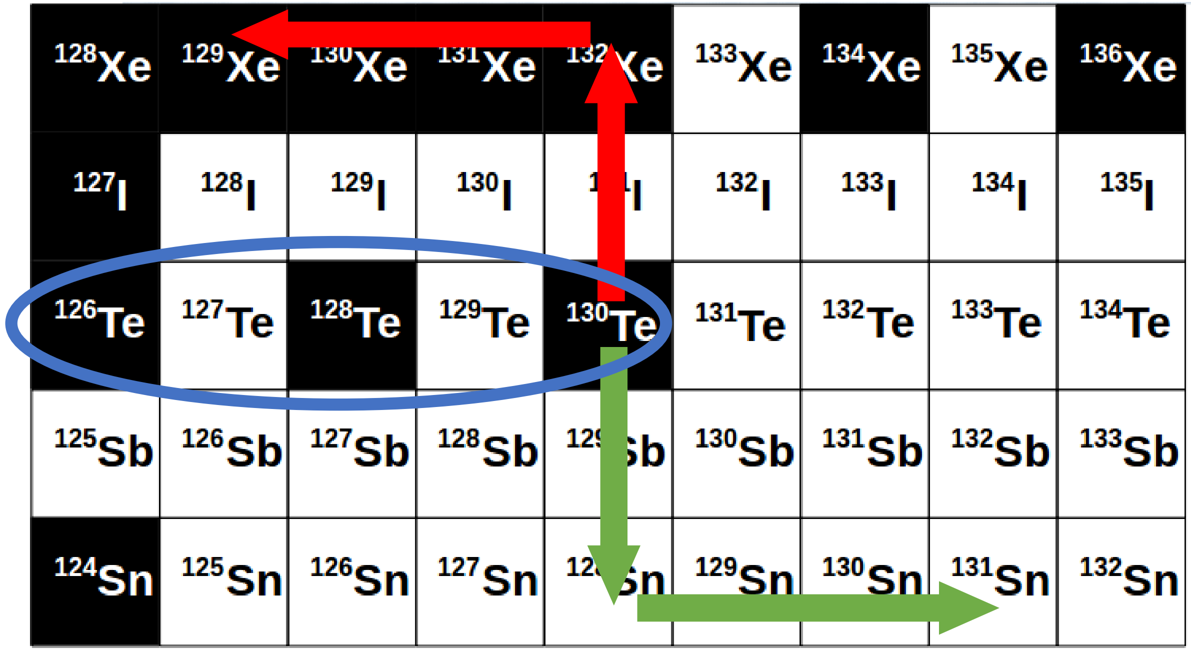


Very neutron-rich nuclei can be populated in transfer with low TKEL.
For large TKEL secondary processes play a major role in the final mass distributions.



Y. X. Watanabe et al., PRL **115** (2015) 172503

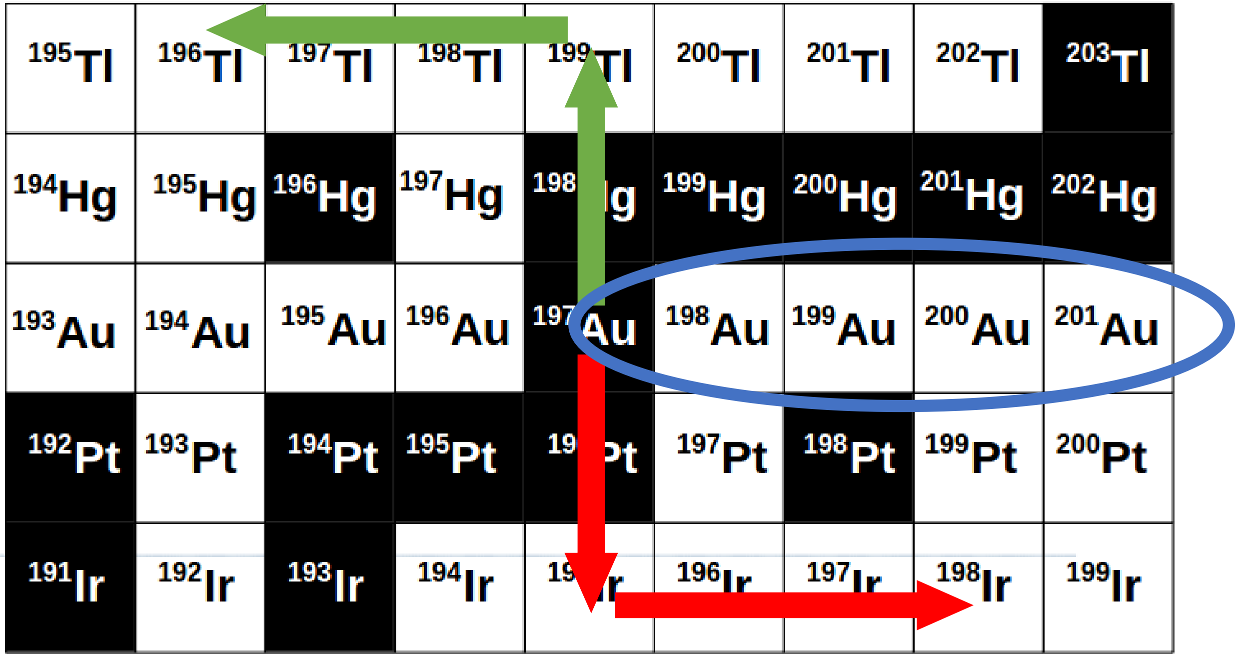
A benchmark system at LNL: ^{197}Au+^{130}Te @ 1.07 GeV



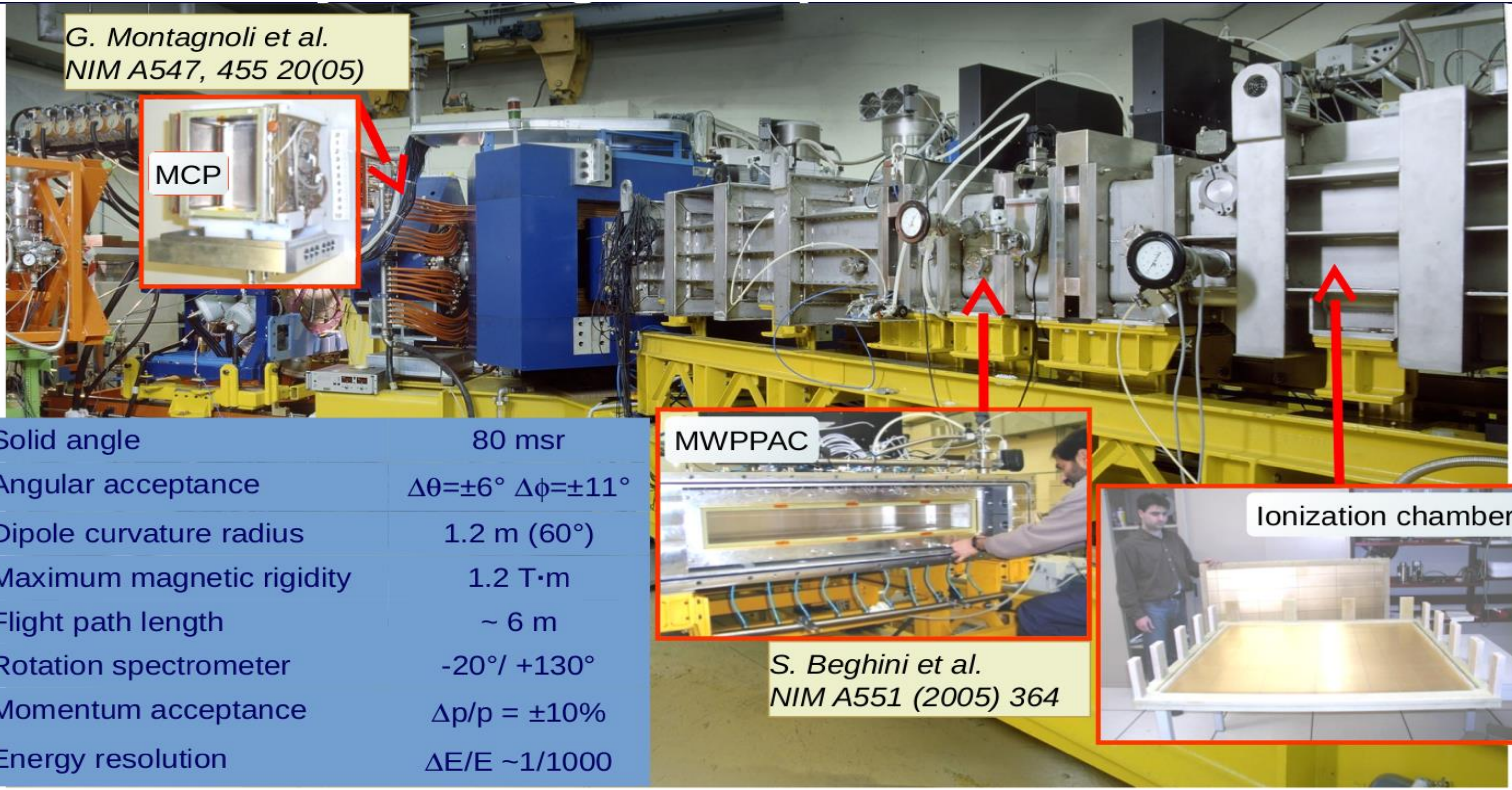
Goal: to understand the production mechanism for neutron-rich nuclei in the A=200 region and the effect of secondary processes on the final yields.

Via proton pick-up and neutron stripping channels from ^{130}Te one produces neutron-rich nuclei around A=200.

We will mainly focus here on neutron transfer channels

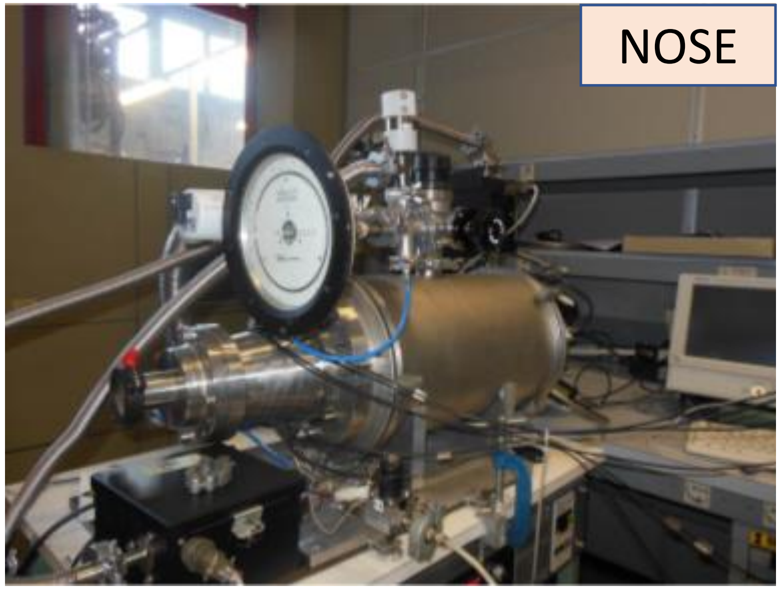


The large-acceptance magnetic spectrometer PRISMA

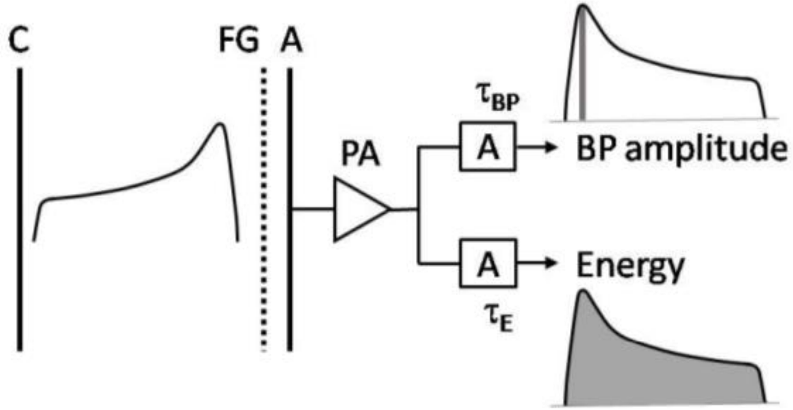


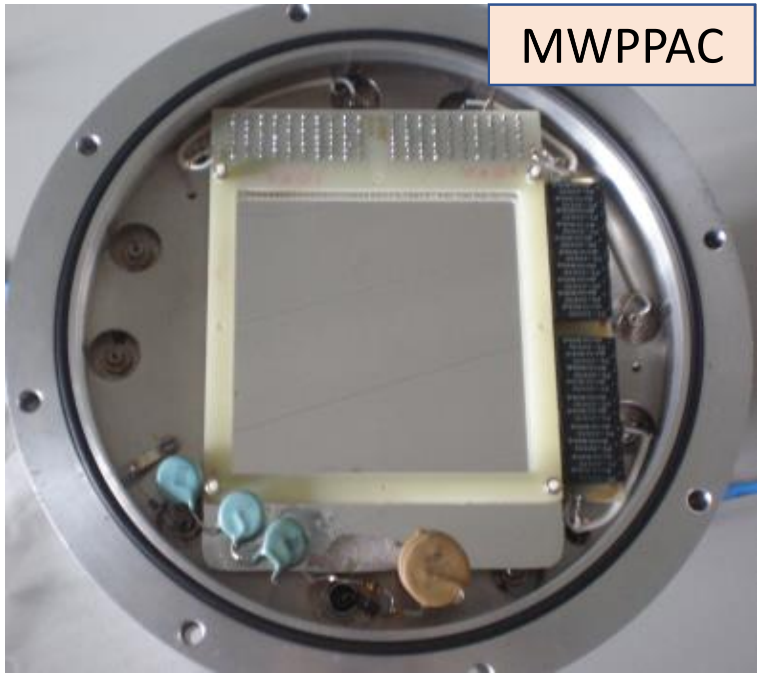
Solid angle	80 msr
Angular acceptance	$\Delta\theta=\pm6°$ $\Delta\phi=\pm11°$
Dipole curvature radius	1.2 m (60°)
Maximum magnetic rigidity	1.2 T·m
Flight path length	~ 6 m
Rotation spectrometer	-20°/ +130°
Momentum acceptance	$\Delta p/p = \pm10\%$
Energy resolution	$\Delta E/E \sim 1/1000$

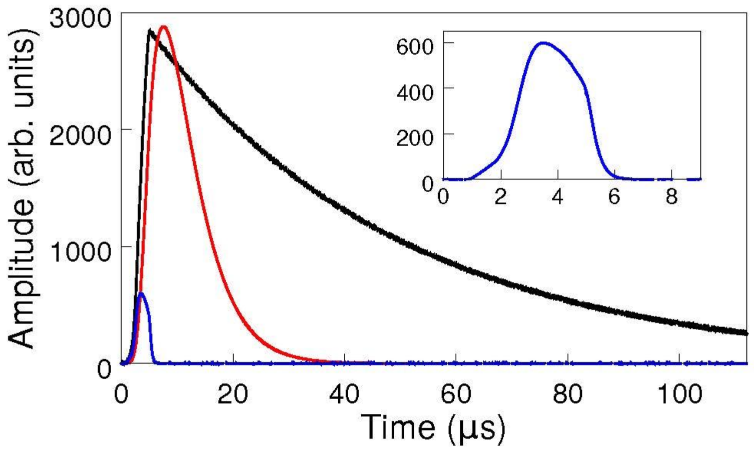
NOSE, an ancillary particle detector coupled to PRISMA



Bragg Curve Spectroscopy

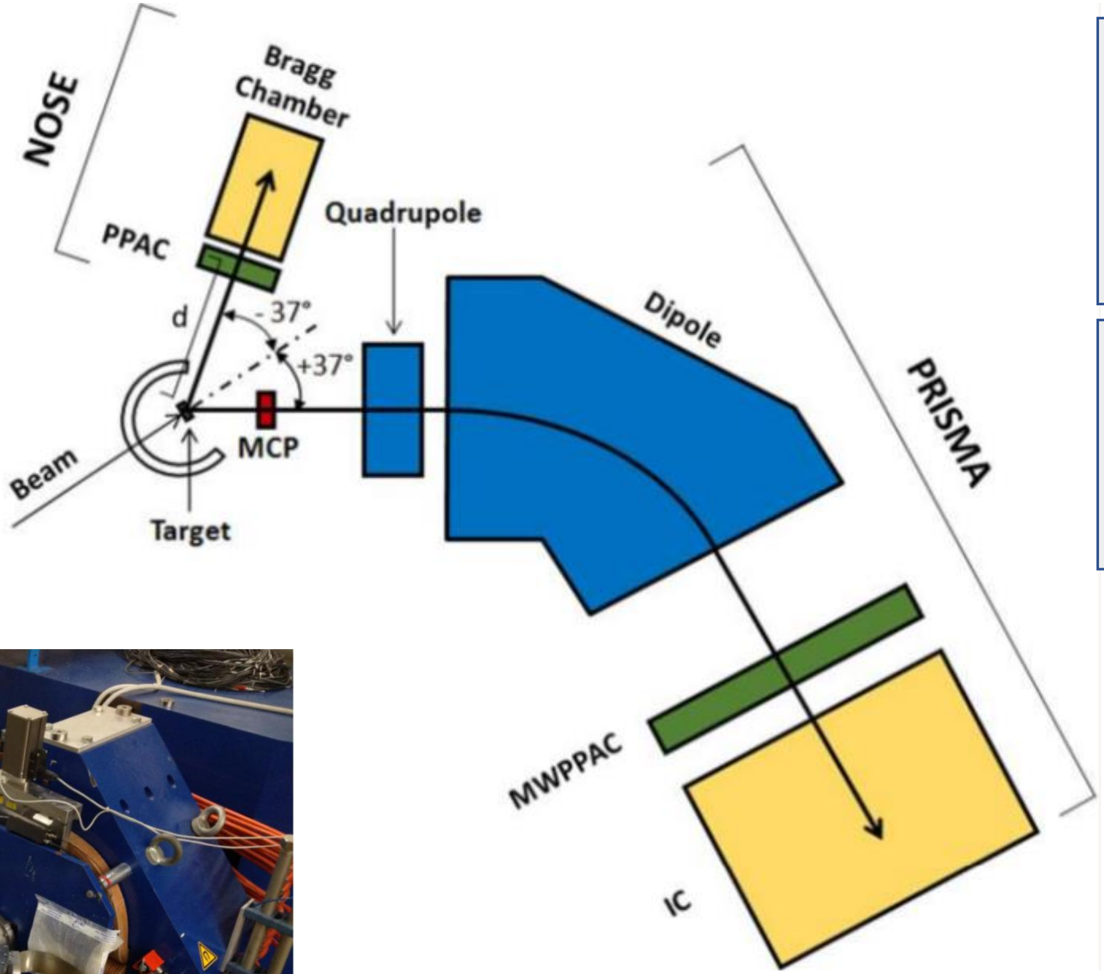


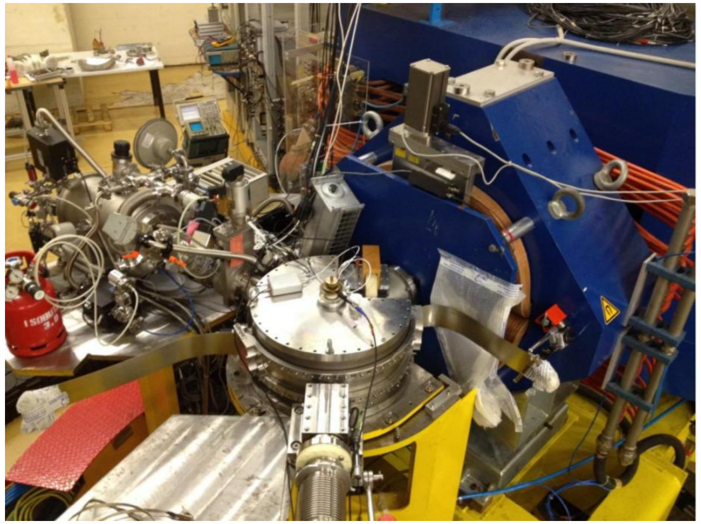




E. Fioretto et al., NIM A **899** (2018) 73-79

The experimental set-up



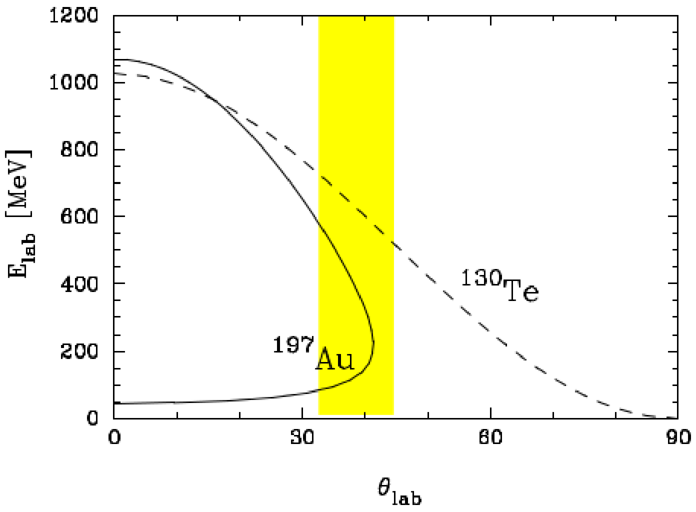


TLF in PRISMA (master trigger)
- (x, y) at the entrance MCP -> (θ, ϕ)
- (X, Y) at the MWPPAC
- ToF between MCP and MWPPAC
- Z from E-ΔE in the IC

PLF in NOSE
- (x', y') at the entrance PPAC -> (θ, ϕ)
- ΔToF between PRISMA MCP and NOSE PPAC
- Z from E-ΔE in the IC

In PRISMA: ΔA/A ~ 1/250

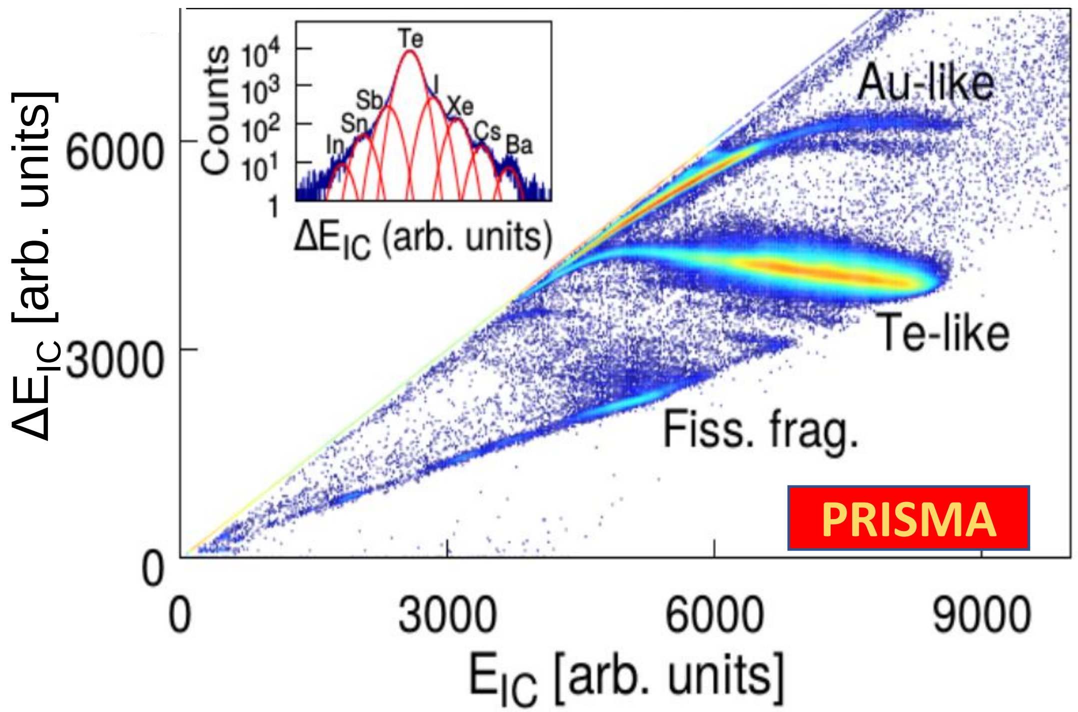
In NOSE: ΔA/A ~ 1/40

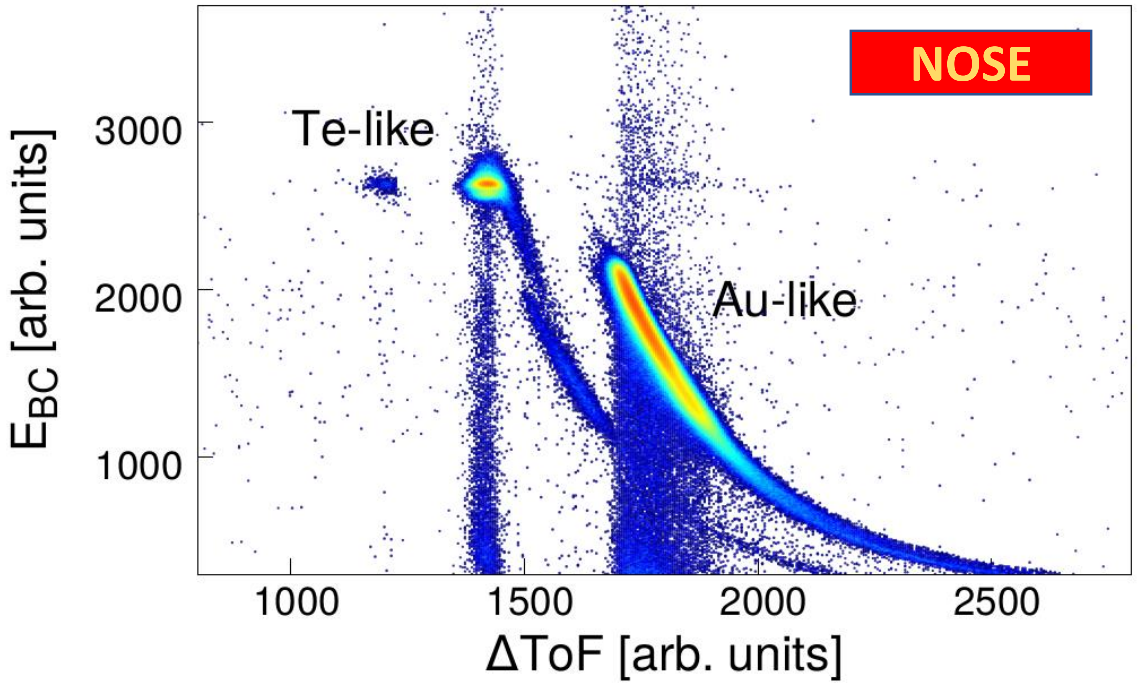


Z identification in PRISMA and NOSE

In PRISMA (optimized for the light partner) the Z resolution is sufficient to distinguish different proton transfer channels, which nonetheless have very low cross section at this low bombarding energy.

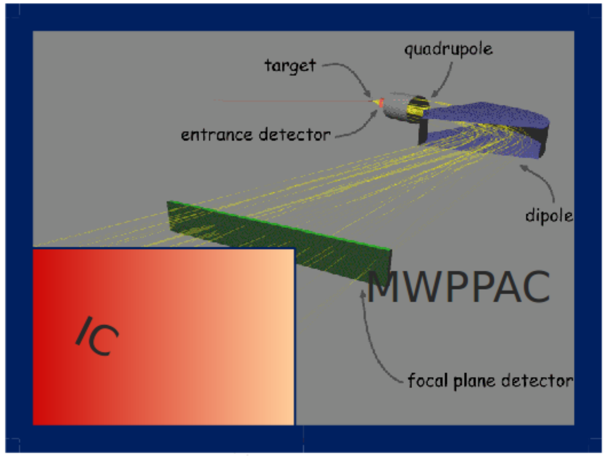
In NOSE (optimized for the heavy partner) the PLF and TLF can be clearly separated but no Z identification is possible due to the very low energy of Au-like ions.

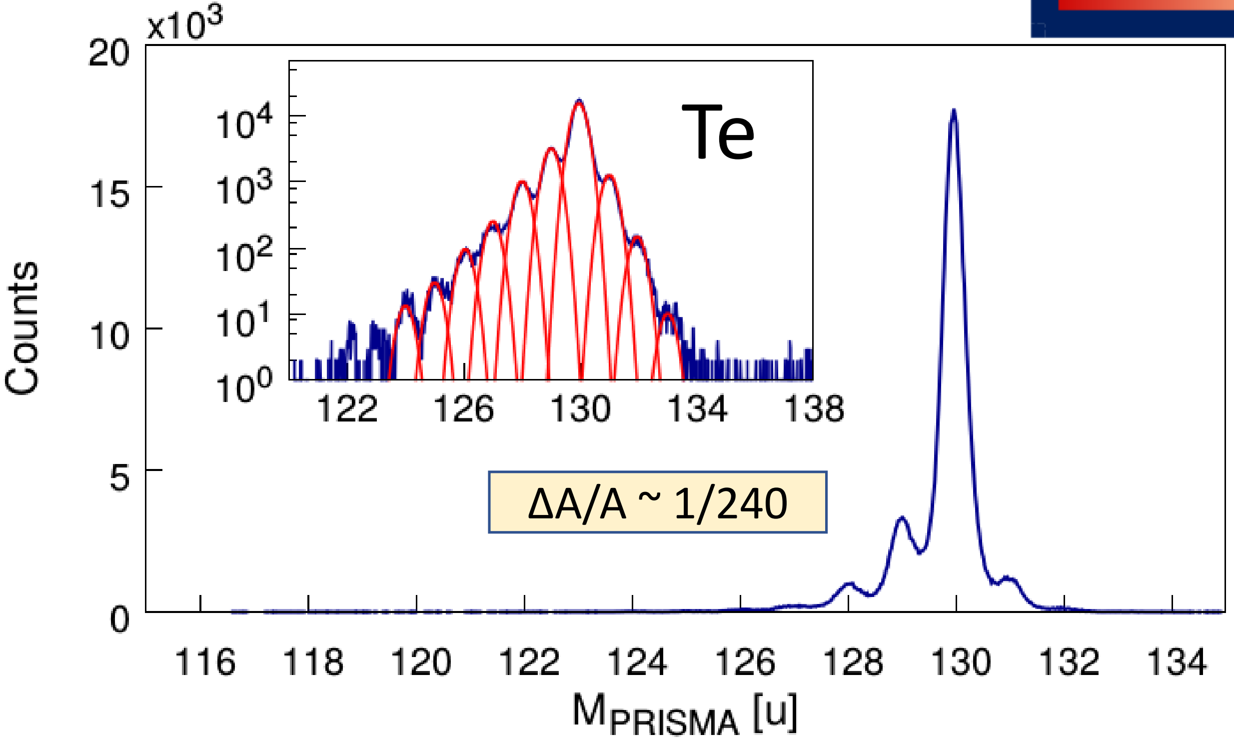


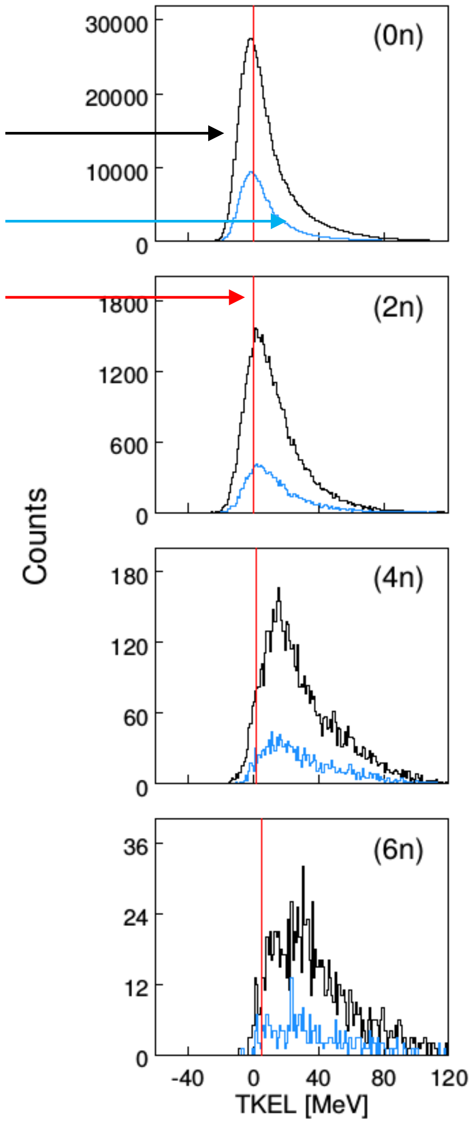


Mass identification of the light partner in PRISMA

Through an event-by-event trajectory reconstruction in PRISMA the mass distribution of Te ions is obtained. The yields are extracted with a multi-Gaussian fit.







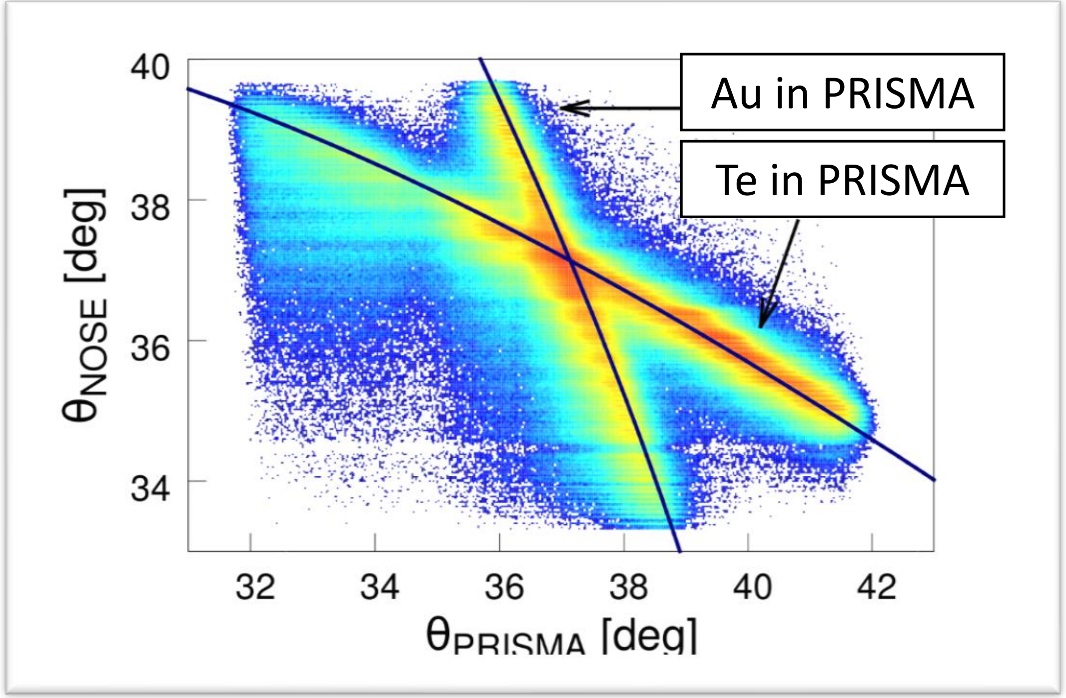
Total kinetic energy loss (TKEL) distributions are obtained for the different transfer channels, showing an increasing contribution of DIC components as more neutrons are transferred.

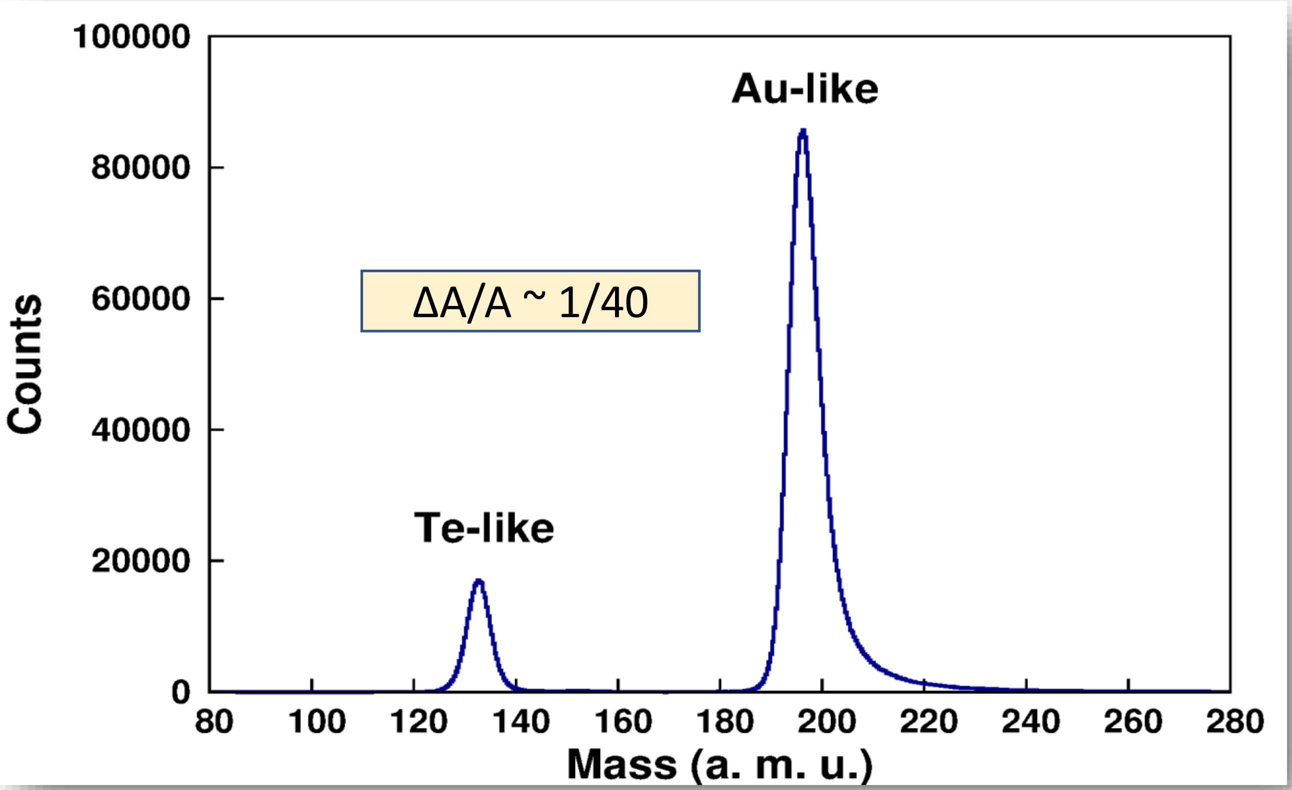
Mass reconstruction of the heavy partner

A+a → B+b, where A is the heavy projectile (Au) and a the target nucleus (Te).
The mass M_B of the heavy PLF can be deduced from momentum conservation assuming a binary character of the reaction.

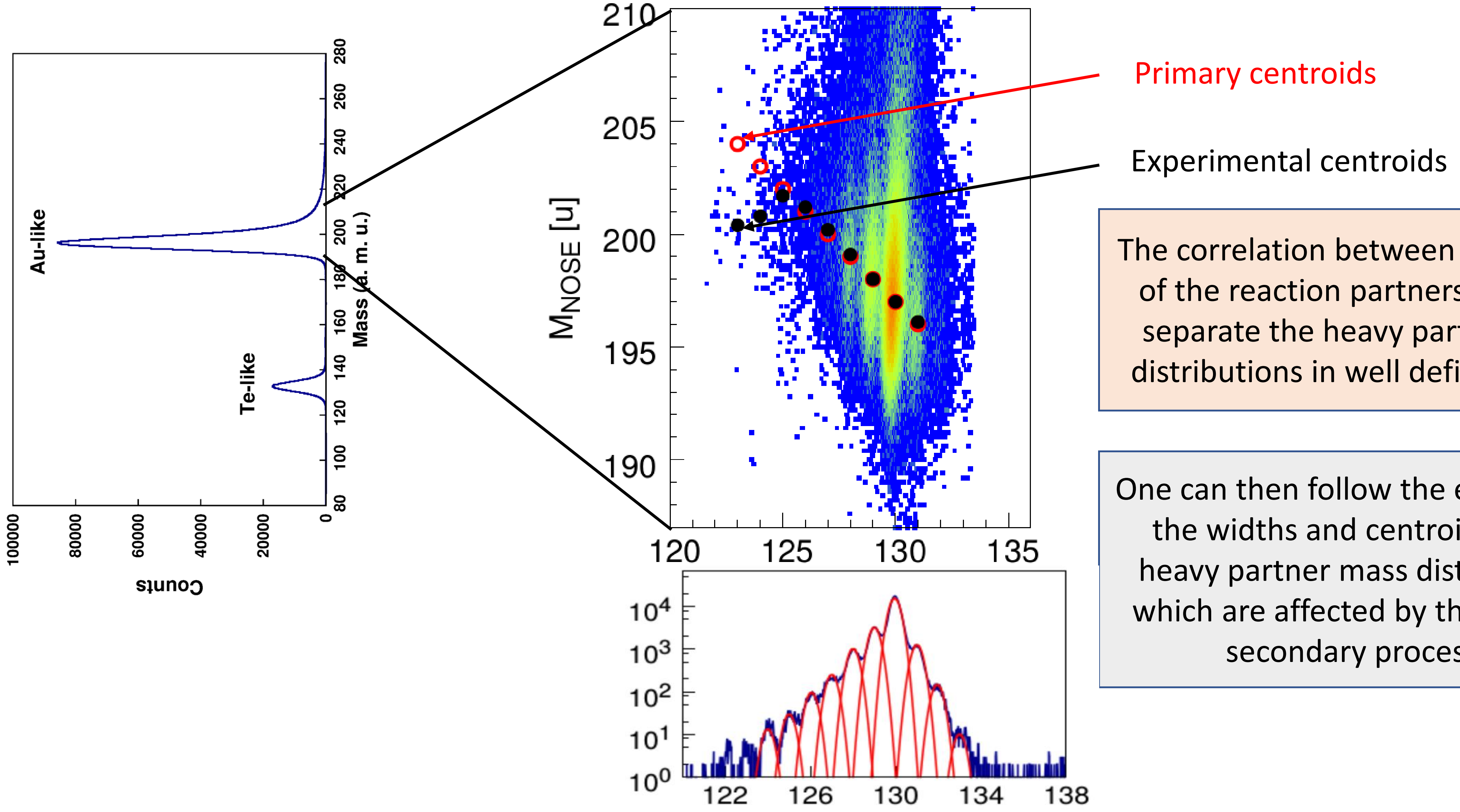
$$M_B = \frac{p_A}{d} \frac{\sin\theta_b}{\sin(\theta_B + \theta_b)} \tau_B$$

ToF in NOSE





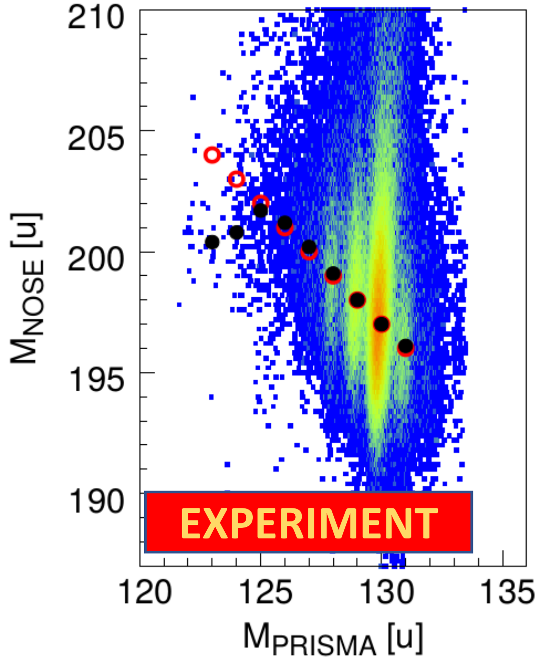
Mass-mass correlation matrix

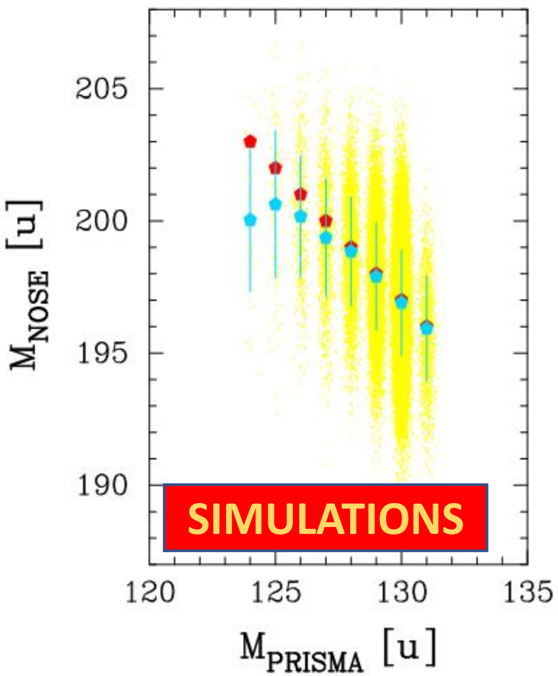


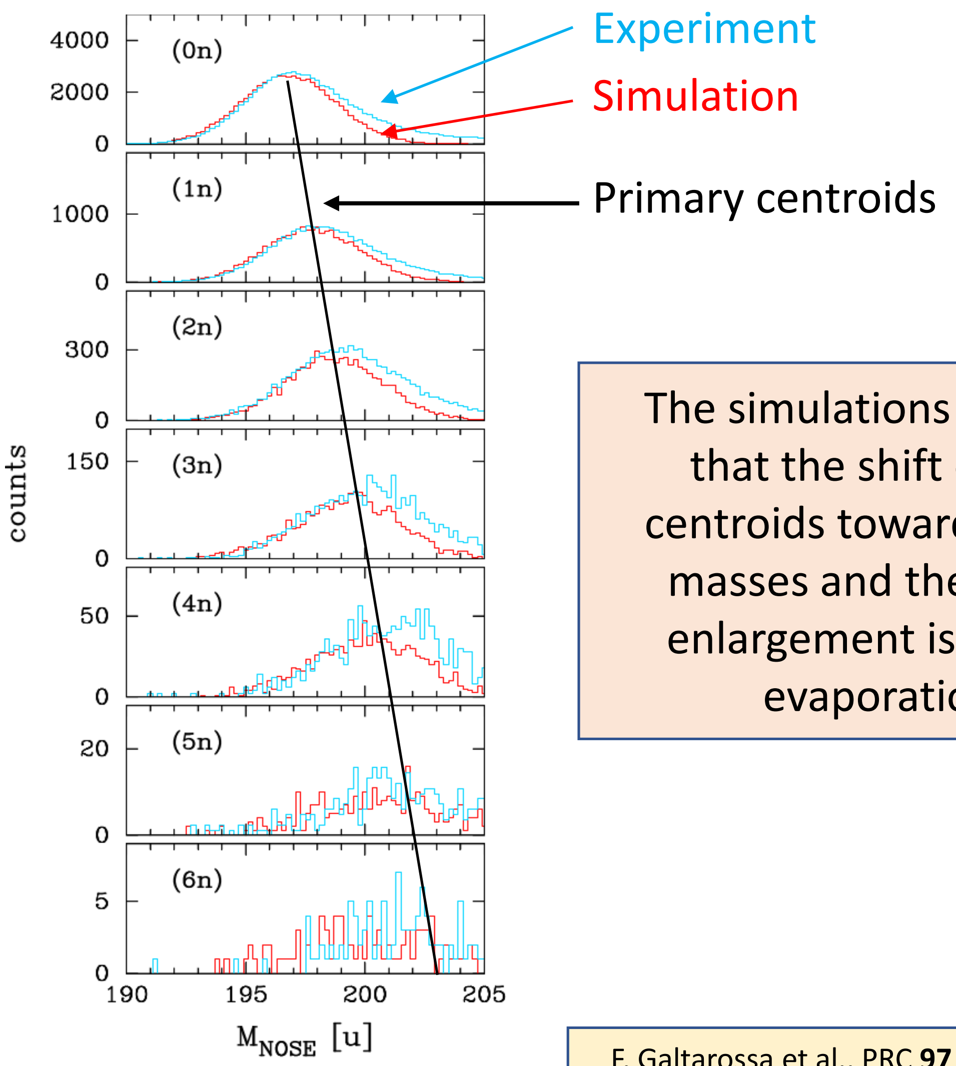
The correlation between the masses of the reaction partners allows to separate the heavy partner mass distributions in well defined bands

One can then follow the evolution of the widths and centroids of the heavy partner mass distributions, which are affected by the effect of secondary processes

Mass-mass correlation matrix







The simulations incorporate a successive evaporation of neutrons taking into account the experimental TKEL distributions (to compute evaporation), the cross sections measured in PRISMA and the experimental resolution.

The simulations indicate that the shift of the centroids towards lower masses and the width enlargement is due to evaporation

F. Galtarossa et al., PRC **97** (2018) 054606

Theoretical models for MNT reactions

- **GRAZING**

Program GRAZING. http://www.to.infn.it/nanni/grazing. A. Winther, NPA **572** (1994) 191; NPA **594** (1995) 203.

- **Langevin-type dynamical equations of motion**

V. Zagrebaev, W. Greiner, PRL **101** (2008) 122701

- **Time-Dependent Hartree-Fock (TDHF) theory**

K.Sekizawa, K.Yabana, PRC **88** (2013) 014614

- **DiNuclear System (DNS) model**

L. Zhu, Z.-Q. Feng, and F.-S. Zhang, Journal of Physics G: Nuclear and Particle Physics, **42** (2015) 085102

- **Improved Quantum Molecular Dynamics (ImQMD)**

N. Wang, Z. Li and X. Wu, PRC **65** (2002) 064608. C. Li et al., PLB **776** (2018) 278.

The GRAZING code

The GRAZING code calculates distributions in masses, charges, energies and angular momenta of fragments in collisions between heavy nuclei according to a semiclassical model. This model has been successfully applied in the description of transfer reactions and can reproduce the near-barrier fusion excitation functions and extract barrier distributions.

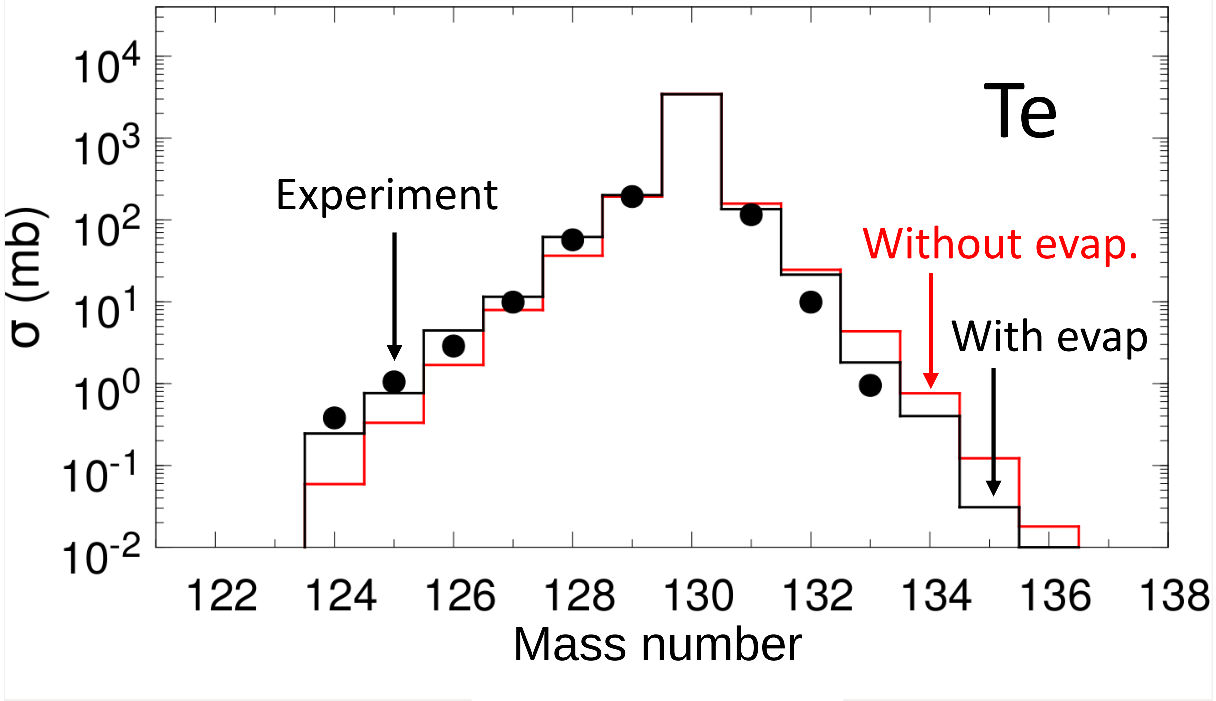
- The trajectory is calculated by solving the system of classical equations for the variables of relative motion and the deformation parameters for the surface modes. The two ions interact via a Coulomb plus nuclear interaction and may exchange nucleons.
- The exchange of many nucleons proceeds via a multi-step mechanism of single nucleons (both, protons and neutrons, via stripping and pick-up processes). The different single-particle states that are participating to the transfer process are described by introducing average single-particle level densities.
- The model includes the low-lying $2+$ and $3-$ states of both projectile and target.

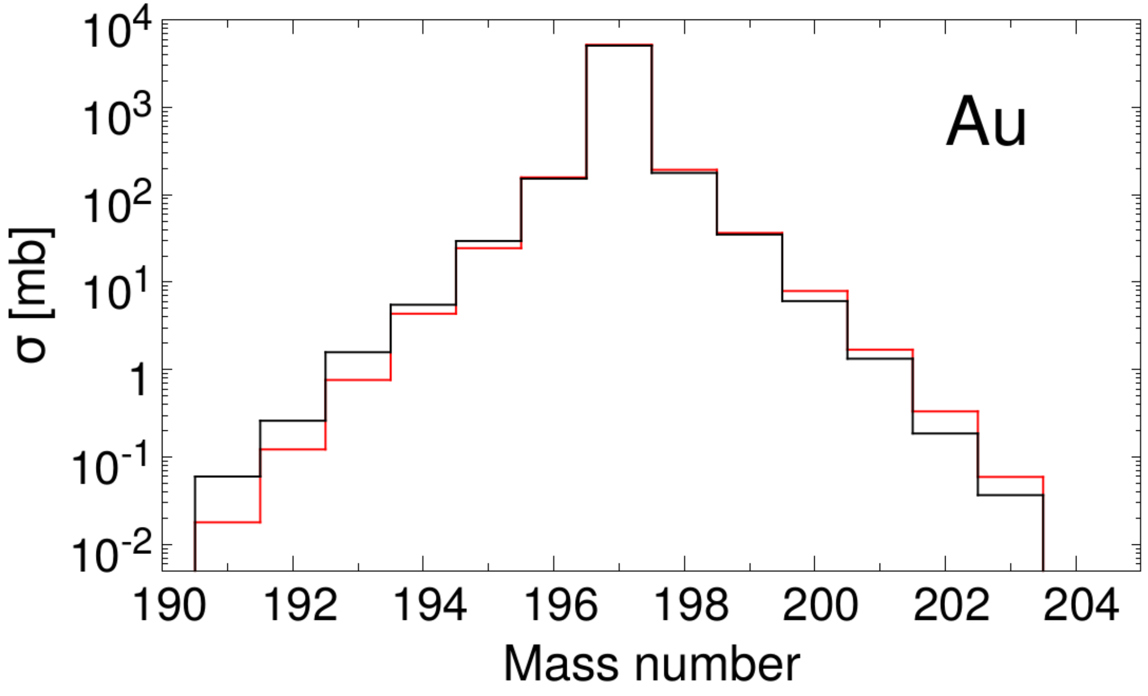
program GRAZING. http://www.to.infn.it/nanni/grazing
A. Winther, NPA **572** (1994) 191; NPA **594** (1995) 203.

Comparison with GRAZING predictions

The cross sections for neutron transfer channels were compared to GRAZING after normalizing to the (1n) channel. GRAZING calculations include the effect of neutron evaporation.

The good agreement between experimental and theoretical cross sections and between experimental and simulated mass distributions of the heavy partner allows us to show the predictions of the same code for the production of Au isotopes.

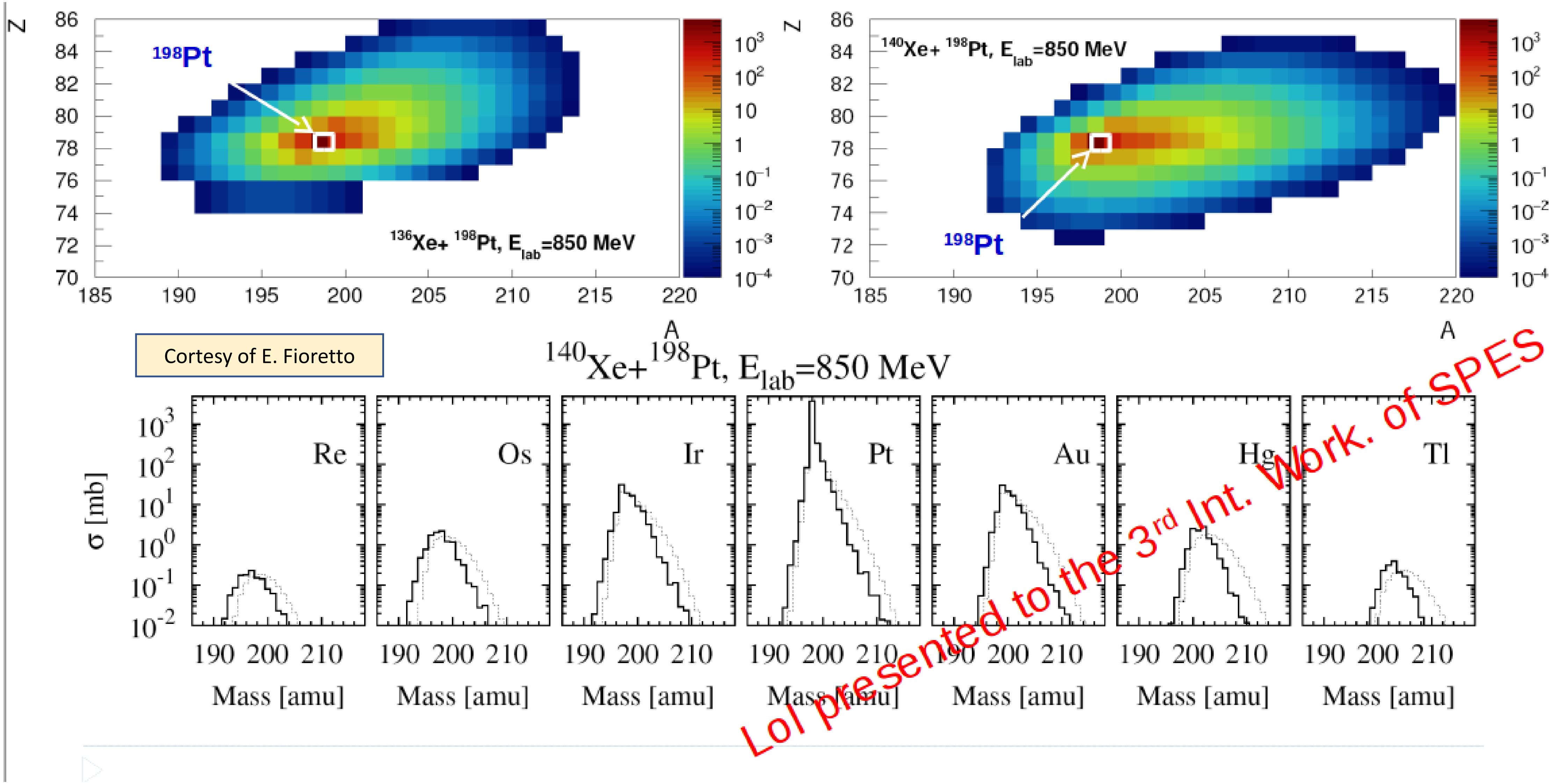




Conclusions

- We studied MNT processes in the $^{197}Au+^{130}Te$ system at E_{lab} = 1.07 GeV with a kinematic coincidence where one of the two detectors was a high-resolution large-acceptance magnetic spectrometer;
- We determined the mass of the light partner in PRISMA through an event-by-event trajectory reconstruction and the mass of the heavy partner in NOSE from momentum conservation in a binary collision;
- We correlated the masses of the light and heavy partner in a mass-mass correlation matrix and through the comparison with a simple Monte Carlo simulation we could follow the behavior of the heavy partner and infer about the effect of evaporative processes;
- The measured cross sections for neutron transfer channels of the light partner are in good agreement with GRAZING calculations which take into account the effect of neutron evaporation

Perspectives: towards SPES, a RIB facility @ LNL



Collaboration

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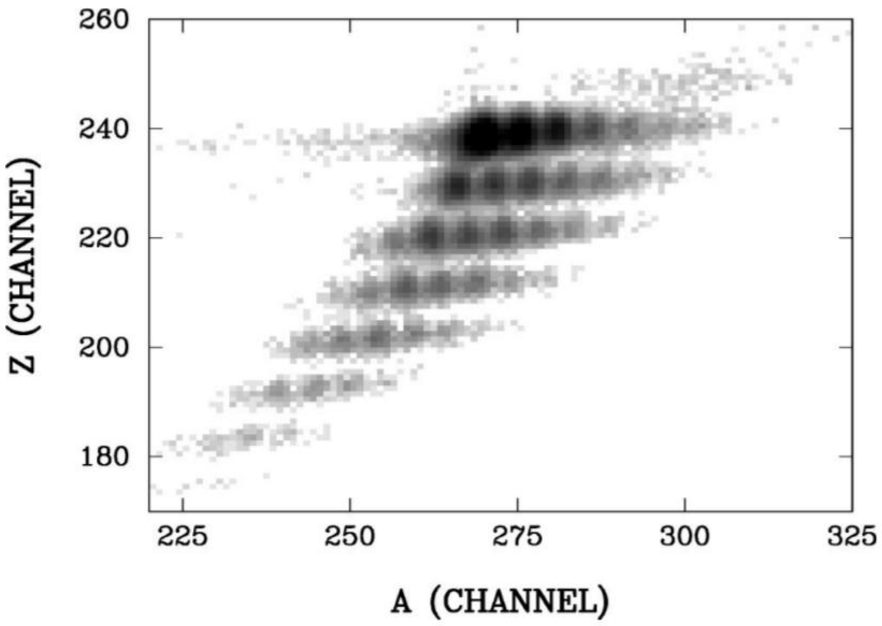
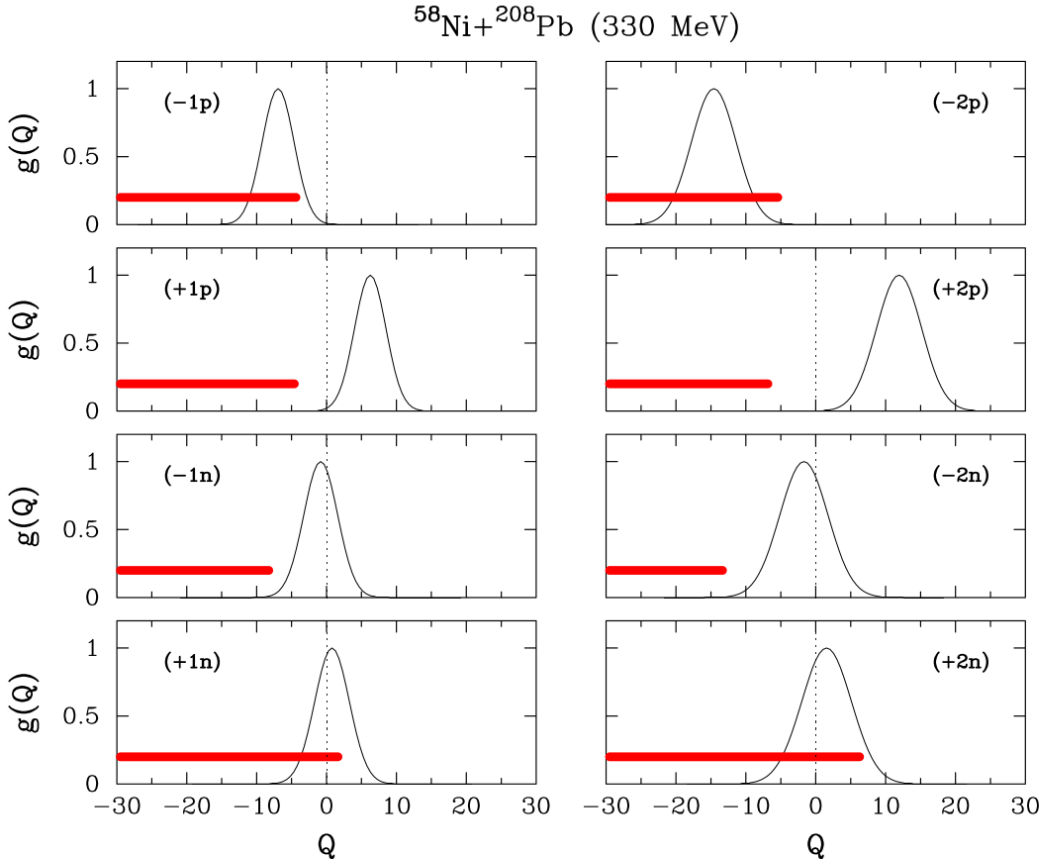
Backup slides

Multinucleon transfer reactions at barrier energies

Multinucleon transfer reactions at energies around the Coulomb barrier are governed by optimum-Q-value considerations.
With a neutron-poor projectile only proton stripping and neutron pick-up channels are open.

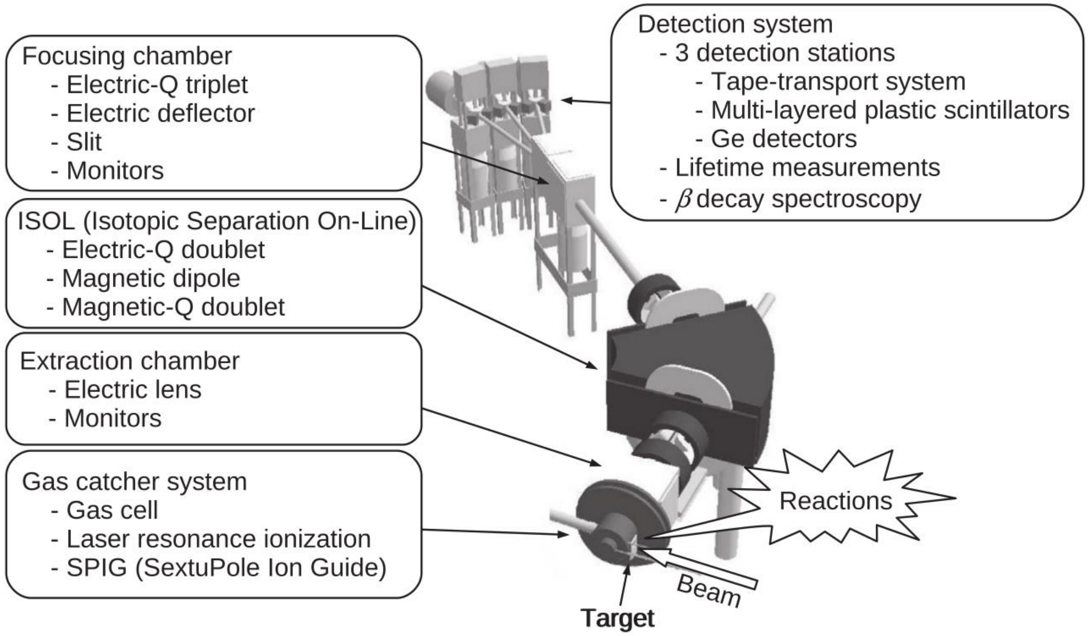


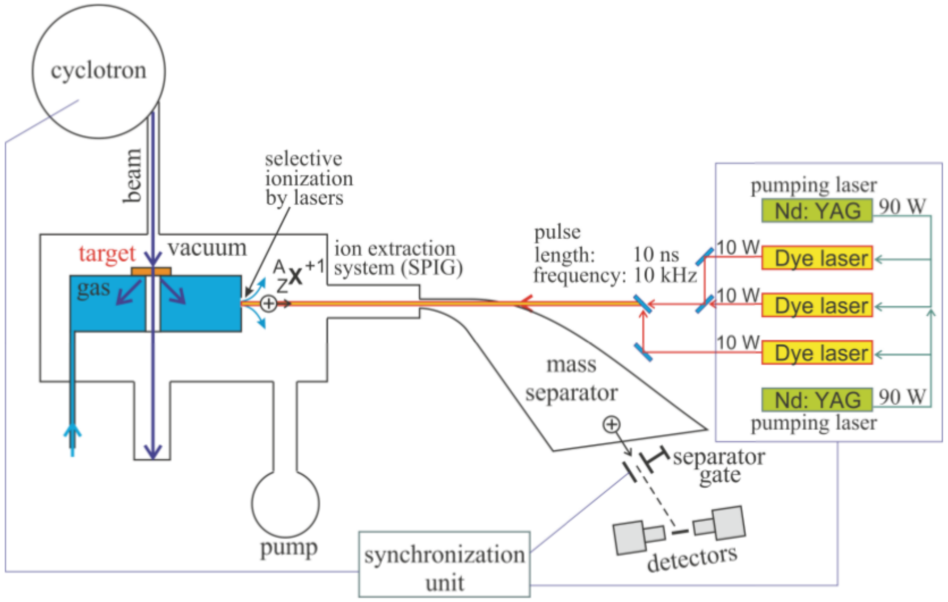


New set-ups for β and γ spectroscopy of heavy nuclei

KEK Isotope Separator System (KISS) for β-decay spectroscopy of neutron-rich nuclei with A~200 and N~126

Gas cell and Laser ion & Separation (GaLS) setup for β spectroscopy of neutron-rich nuclei at N~126





GRAZING

This is done in the semi-classical approximation where the relative motion is treated classically and the time evolution of the intrinsic states is described by the system of coupled equations.

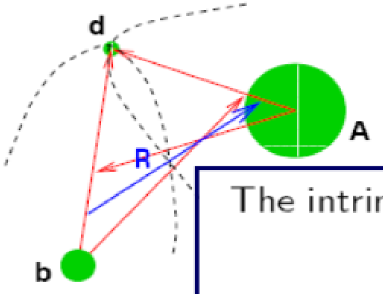
$$i\hbar\dot{c}_\beta(t) = \sum_\alpha < \beta|H_{int}|\alpha > c_\alpha(t)e^{\frac{i}{\hbar}(E_\beta - E_\alpha)t + i(\delta_\beta - \delta_\alpha)}$$

$$i\hbar\dot{\Psi}(t) = (H_0 + H_{int})\Psi(t)$$

$$\Psi(t) = \sum_\beta c_\beta(t)\psi_\beta e^{\frac{i}{\hbar}E_\beta t}$$

where ψ_α are the channels wave functions

$$\psi_\alpha(t) = \psi^a(t)\psi^A(t)e^{i\delta(\vec{R})}$$



It uses a microscopic approach.

Ingredients:

- **surface modes**

low and high lying states

- **transfer channels**

(form factor for transfer)

The intrinsic Hamiltonian and the interaction are:

$$\hat{H}_0 = \sum_i^{(a)} \epsilon_i a_i^\dagger a_i + \sum_{\lambda\mu}^{(a)} \hbar\omega_\lambda a_{\lambda\mu}^\dagger a_{\lambda\mu} + (A)$$

$$\hat{V}_{int}(t) = \hat{V}_{tr}(t) + \hat{V}_{in}(t) + \Delta U_{aA}(t)$$

V_{int} contains the well known **form-factors** for **inelastic excitation** and for **one-particle transfer** (both protons and neutrons).

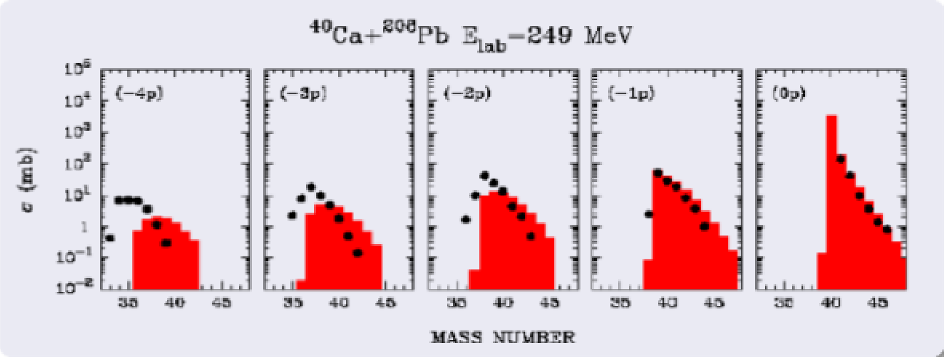
E. Vigezzi and A. Winther, Ann. Of Phys. 192, 432 (1989)

GRAZING code (www.to.infn.it/~nanni)

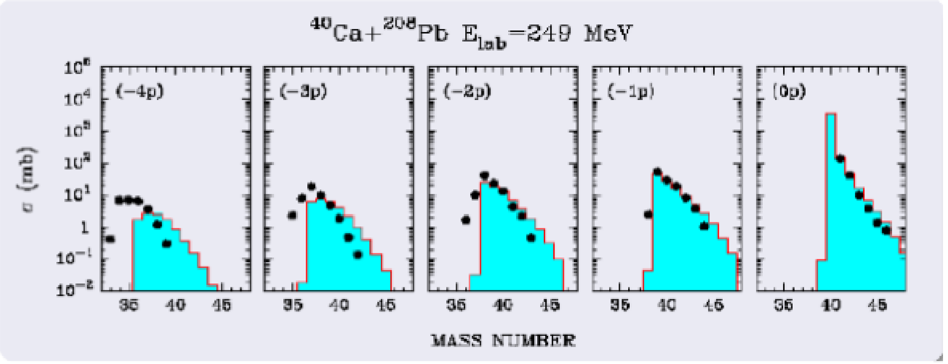
A. Winther, Nucl. Phys. A572,191(1994)
A. Winther, Nucl. Phys. A594, 203(1995)

The **time dependence** of the matrix elements is obtained by solving the Newtonian equations for the relative motion in the nuclear plus Coulomb field. For the nuclear potential we use the **Akyüz-Winther parametrization** that describes quite well elastic scattering data for several projectile and target combinations.

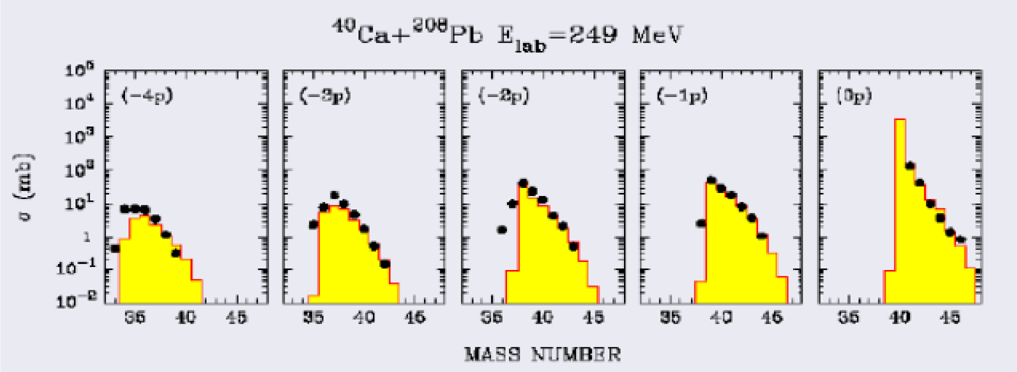
GRAZING



Independent particle transfer



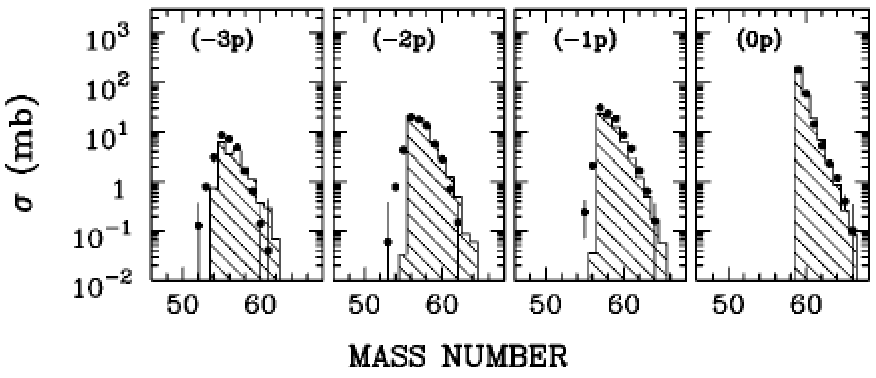
+ pair transfer modes



+ evap

L. Corradi, G. Pollarolo, S. Szilner, J. of Phys. G: Nucl. Part. Phys. ***36*** *(2009) 113101.*

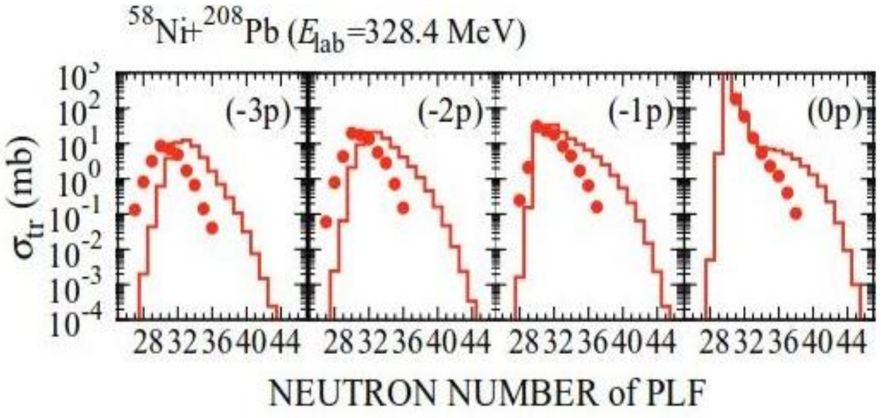
Theoretical models for MNT reactions



EXP: ^{58}Ni+^{208}Pb

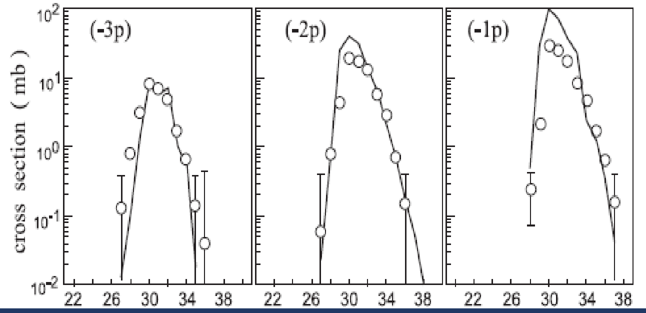
L. Corradi et al., PRC 66 (2002) 024606
GRAZING or CWKB, G. Pollarolo

$$P_{\beta\alpha}(\ell) = \left| \frac{i}{\hbar} \int_{-\infty}^{+\infty} dt\, e^{i\sigma_{\beta\alpha} t} f_{\beta\alpha}(0,\vec{r})\, e^{i[(E_\beta - E_\alpha)+(\delta_\beta-\delta_\alpha)]t/\hbar} \right|^2$$



Time Dependent Hartree-Fock theory
K.Sekizawa, K.Yabana, PRC 88 (2013) 014614

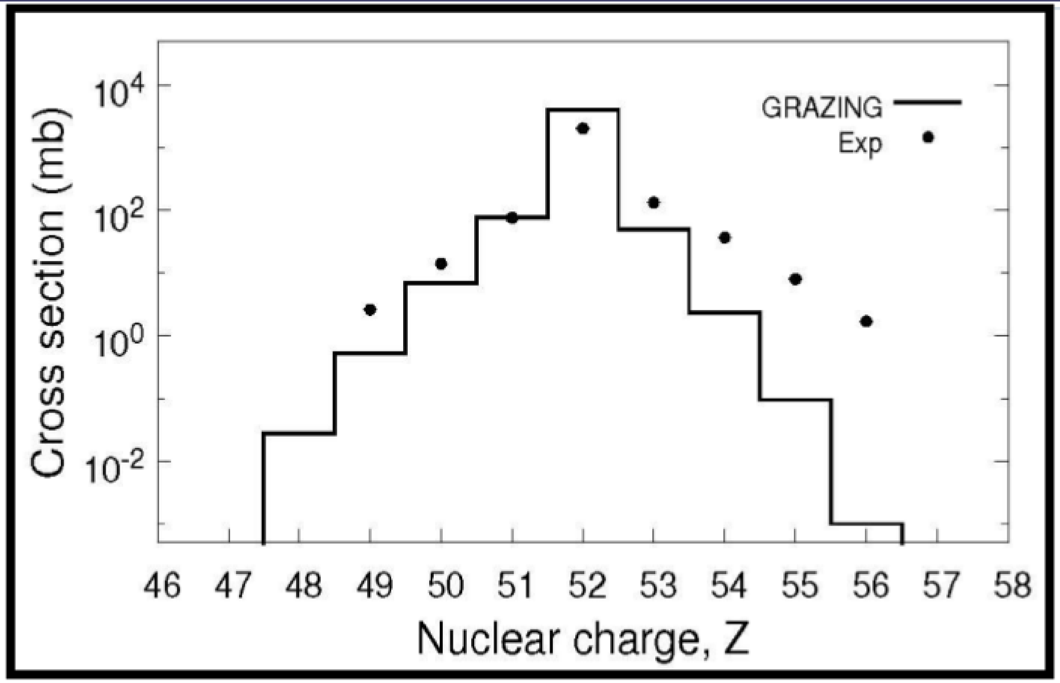
$$P_n = \int dx_1 \cdots \int dx_N\, \psi_1^*(x_1) \cdots \psi_N^*(x_N) \hat{P}_n \det\{\psi_i(x_j)\}$$



Langevin-type dynamical equations of motion
V. Zagrebaev, W. Greiner, PRL 101 (2008) 122701

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

Proton transfer channels



Experimental mass integrated cross sections - extracted via a multi-gaussian fit of the nuclear charge distribution - vs GRAZING calculations.

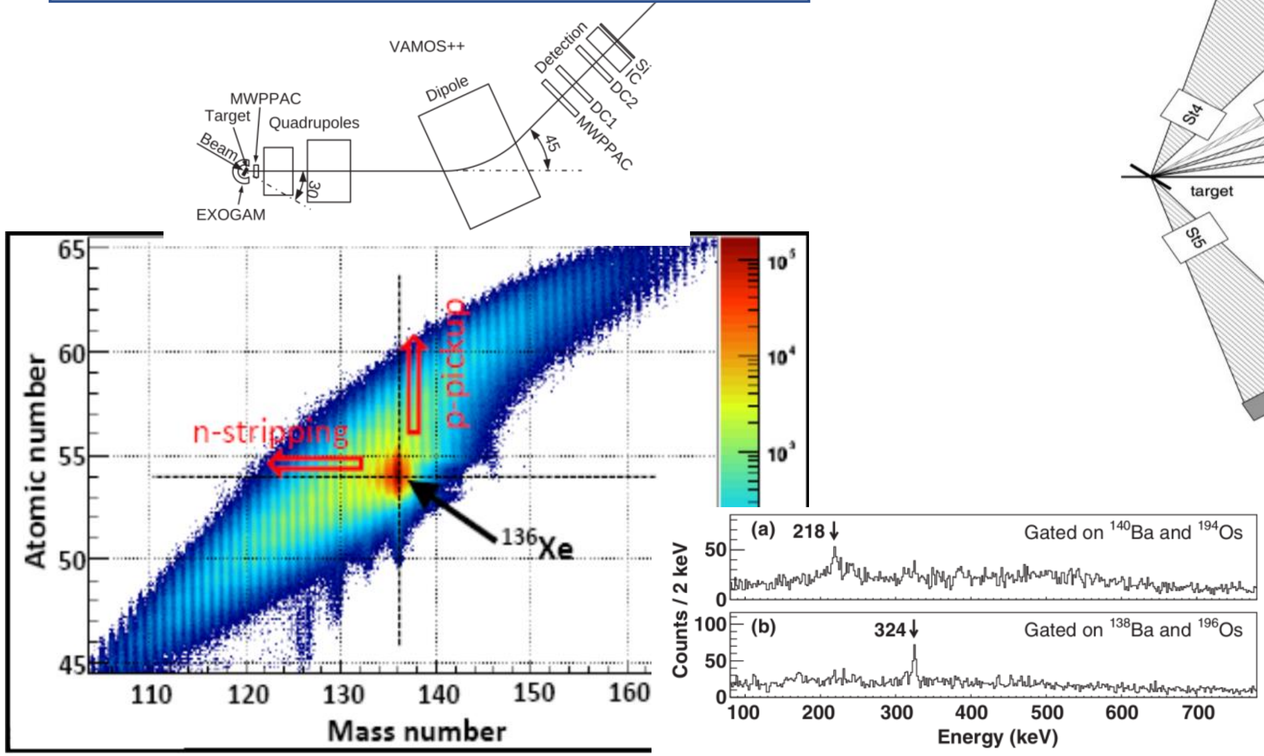
Same normalization constant as for the (-1n) transfer channel (129Te)

The (-1*p*) channel is very well reproduced by the calculations. A modest theoretical under prediction for the (-2*p*) channel with growing differences showing-up as more protons are stripped. On the proton pick-up side these differences become more pronounced as more protons are added.

These results have been also emphasized in the very few systems studied so far where proton pick-up channels have been identified in high resolution measurements.

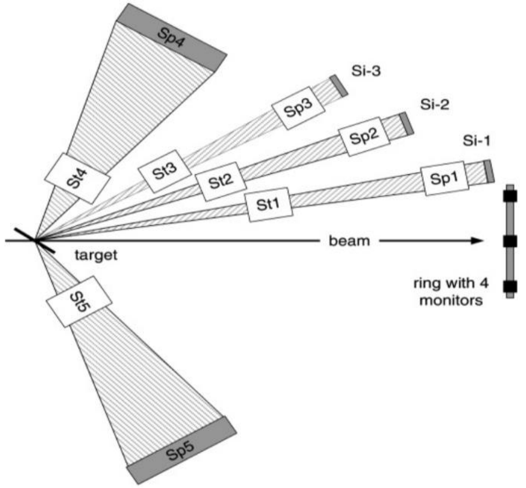
Exploring the neutron-rich heavy region via MNT

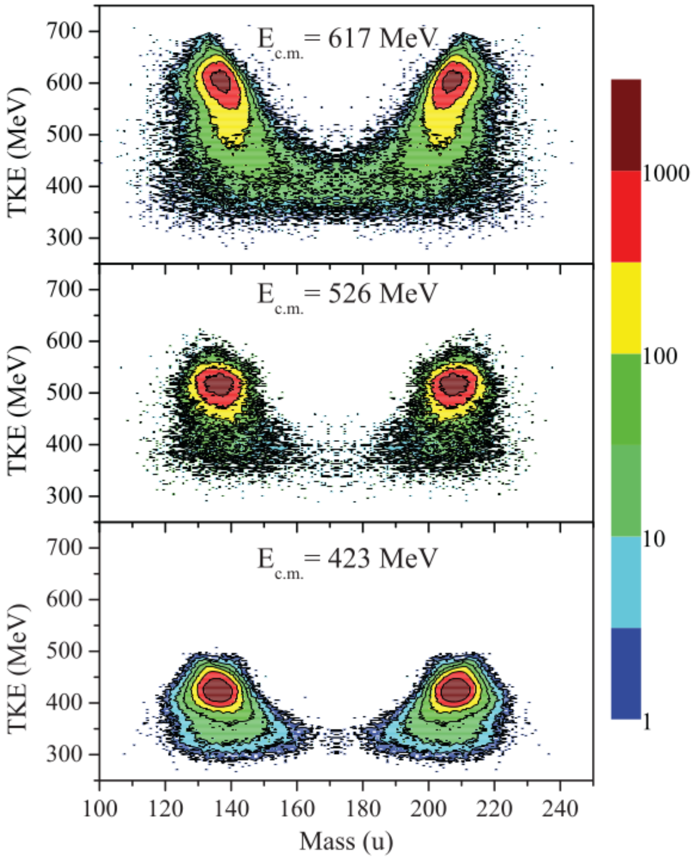
High-resolution but low-efficiency measurements, tagging the light partner with high-resolution spectrometers with the possibility to detect coincident Doppler-corrected γ rays of the heavy partner



Y. X. Watanabe et al., PRL **115** (2015) 172503

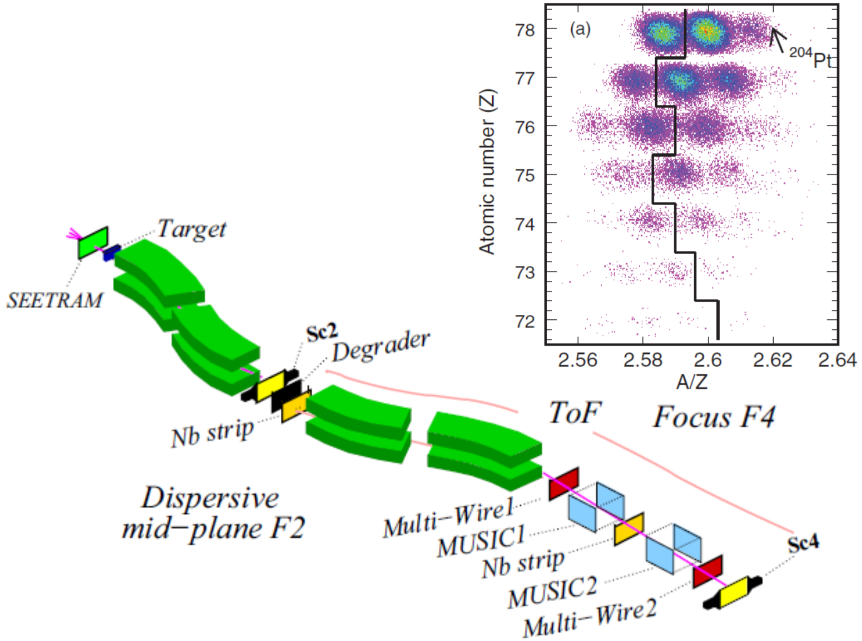
High-efficiency but low-resolution kinematic coincidences between binary partners (direct or inverse kinematics)

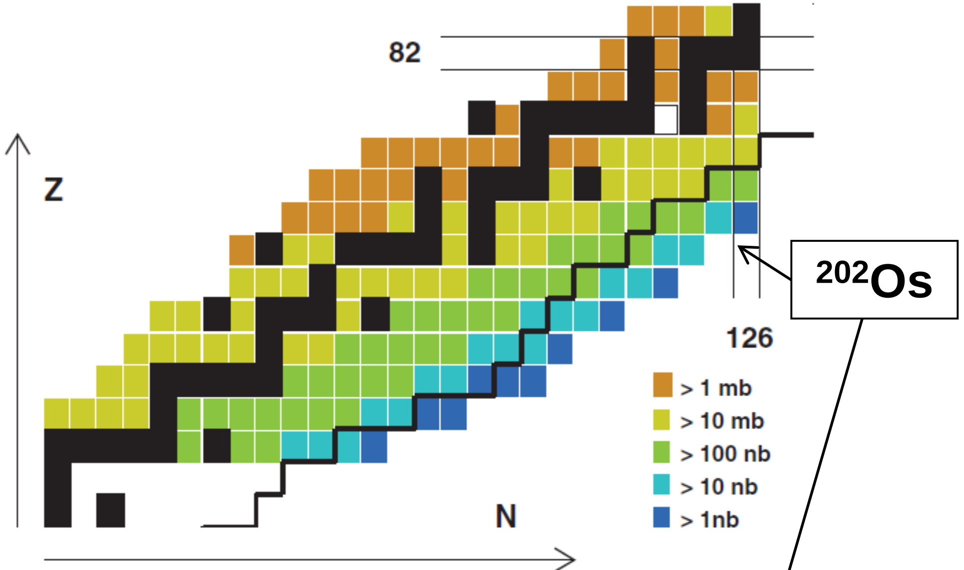


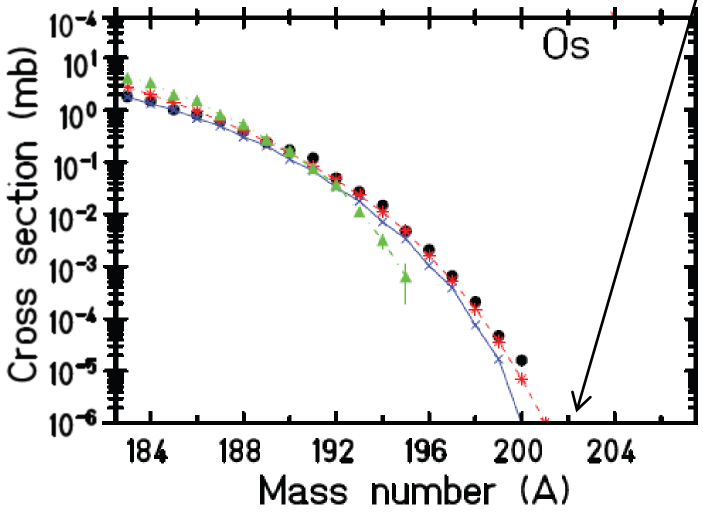


E. M. Kozulin et al., PRC **86** (2012) 044611

Fragmentation reactions of ^{208}Pb at 1 GeV/A on Be target





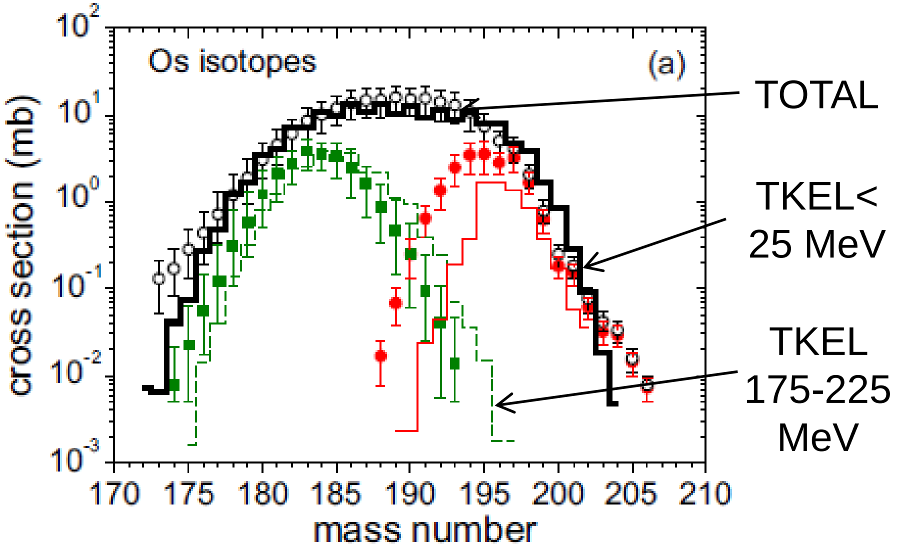


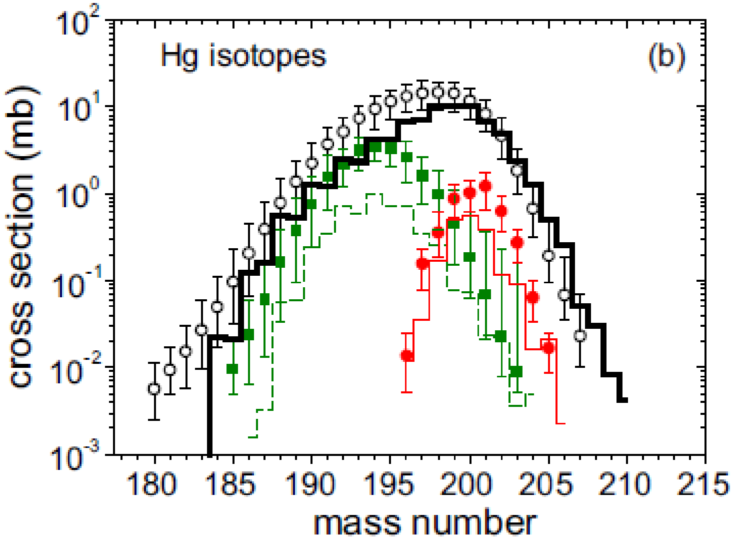
In fragmentation reactions on light targets one could produce neutron rich nuclei with measurable cross sections down to ~ nb level

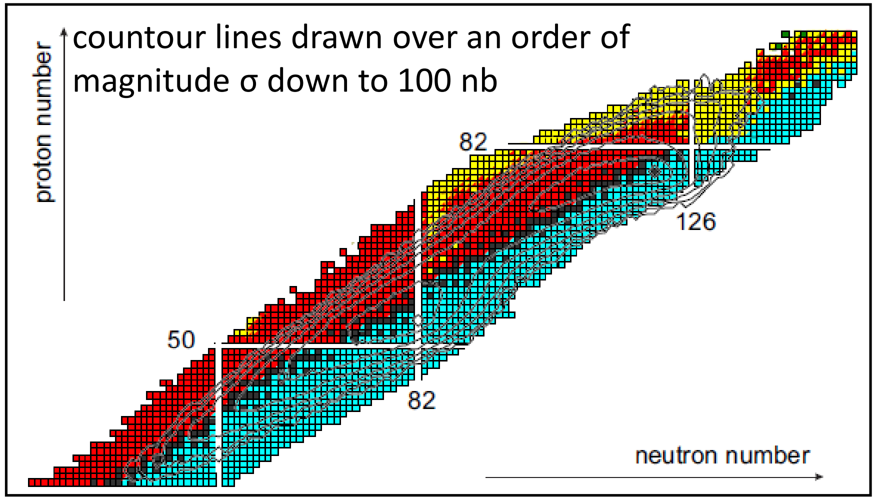
However σ drop off very quickly with neutron number

T. Kurtukian-Nieto et al., PRC **89** (2014) 024616

Production of neutron-rich nuclei near N=126 via $^{136}Xe + ^{198}Pt$



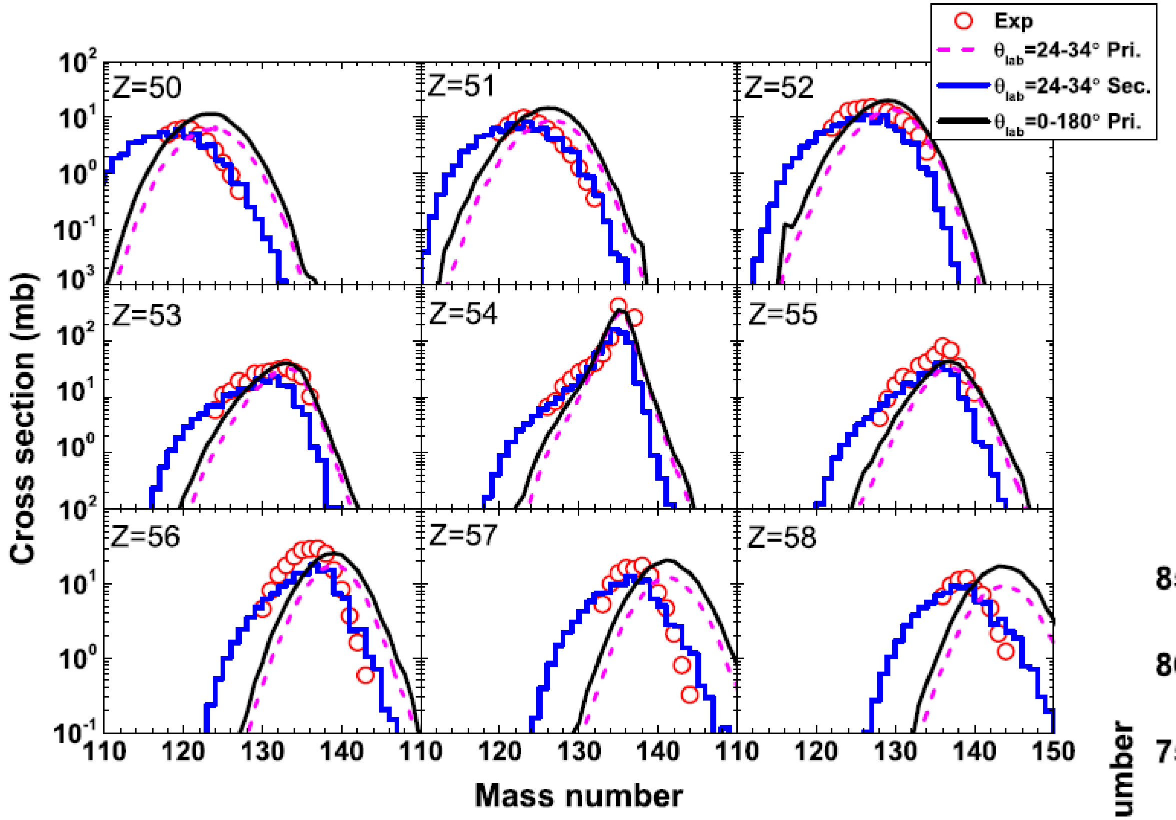




That very neutron-rich nuclei are populated only in transfer with low TKEL is confirmed in multidimensional dynamical model of nucleus-nucleus collisions based on Langevin equations

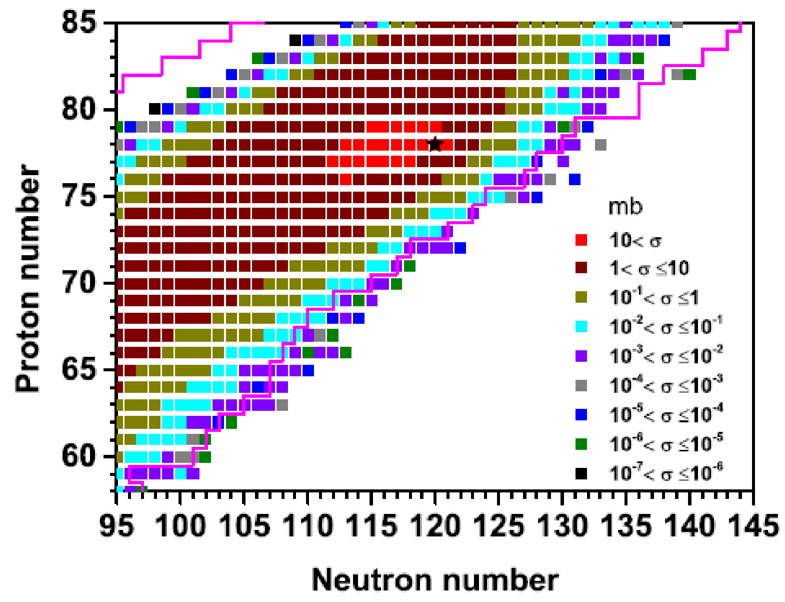
A. V. Karpov and V. V. Saiko, PRC **96** (2017) 024618

Production of neutron-rich nuclei near N=126 via $^{136}Xe + ^{198}Pt$



The effect of large TKEL is confirmed with calculations performed within the Improved Quantum Molecular Dynamics model ImQMD with GEMINI code for the treatment of secondary processes

new very neutron rich nuclei are predicted at the level of 10^{-3} - 10^{-6} mb



C. Li et al., PLB **776** (2018) 278