Int. Workshop on multi facets of
EOS and Clustering

Catania, Italy, May 6-9, 2014

Isospin effects in fragmentation reactions

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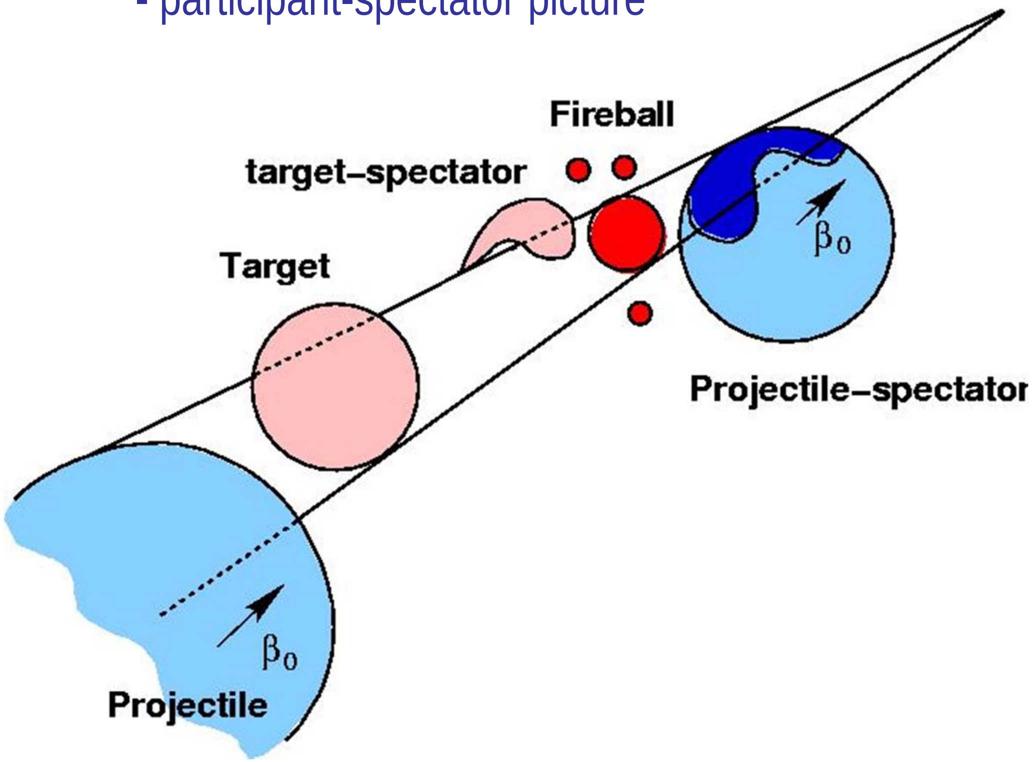
Spain

Fragmentation reactions

Heavy-ion induced reactions.

- kinetic energies above the Fermi energy up to few GeVs per nucleon
- peripheral or mid-peripheral collisions
- participant-spectator picture



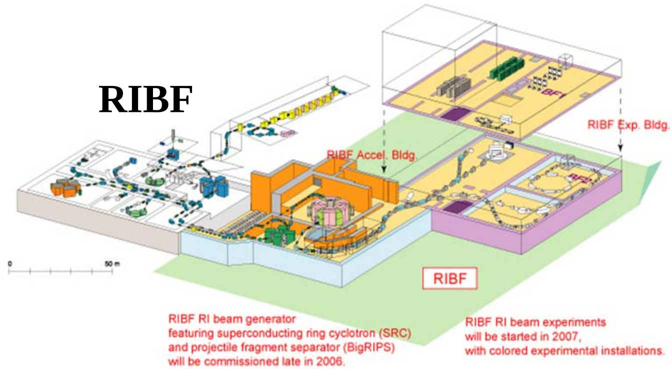
Two-stage reaction scheme:

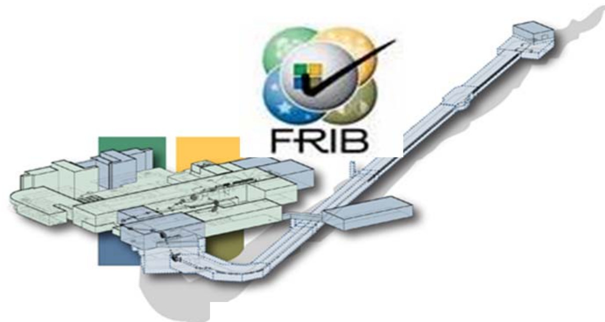
- abrasion
- ablation (evaporation, fission, multi-fragmentation)

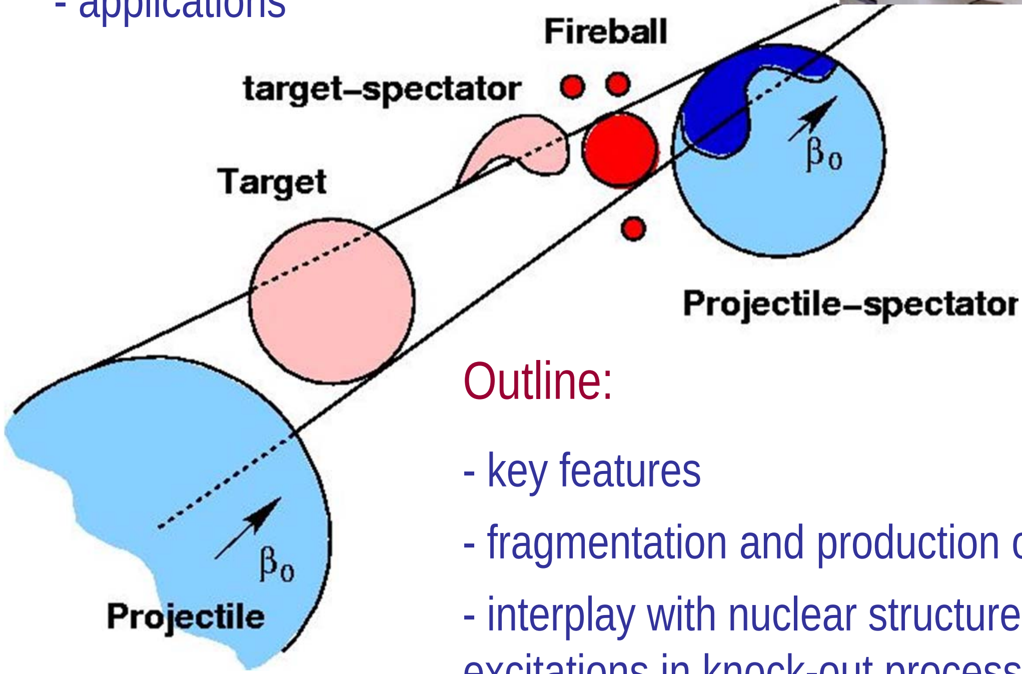
Fragmentation reactions

Main interest:

- large dynamical range
- large isospin range
- new RIB facilities and applications
- applications







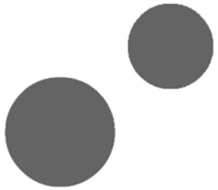
Outline:

- key features
- fragmentation and production of RIBs
- interplay with nuclear structure: nuclear excitations in knock-out processes

Key features

Large dynamical range

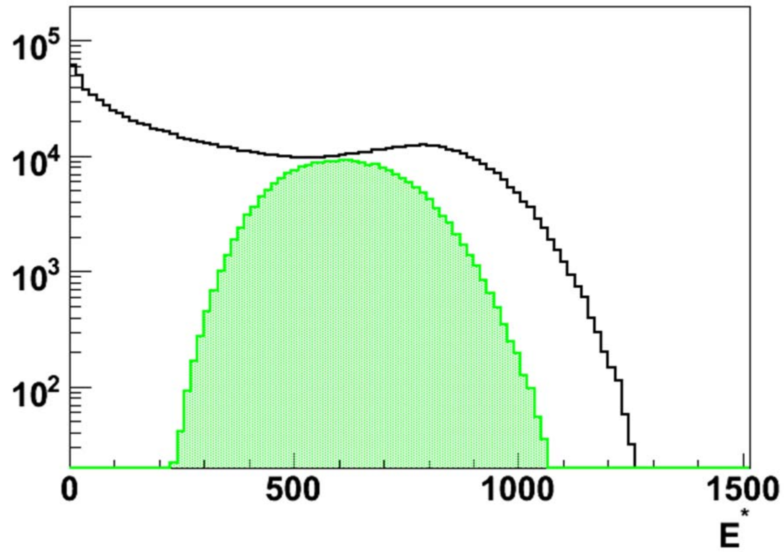
very peripheral



t ~10^{-16}-10^{-18} s
T ~ 1 MeV
$\rho < \rho_0$

peripheral

t ~10^{-18}-10^{-20} s
T ~ 2-4 MeV
$\rho \sim \rho_0$

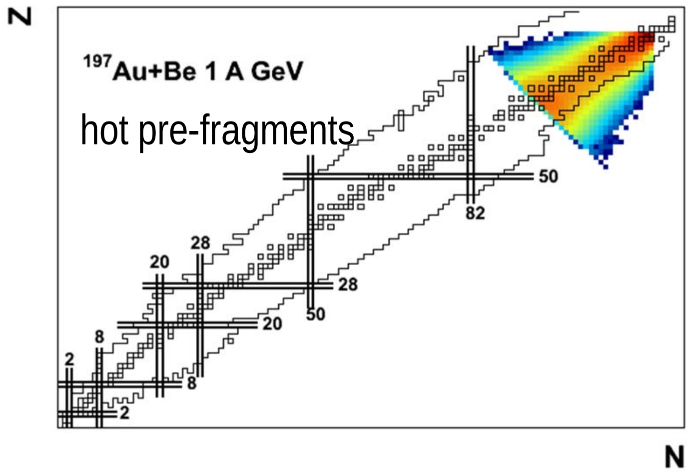


mid peripheral

t ~10^{-20}-10^{-22} s
T ~ 5-10 MeV
$\rho < \rho_0$

Key features of fragmentation reactions

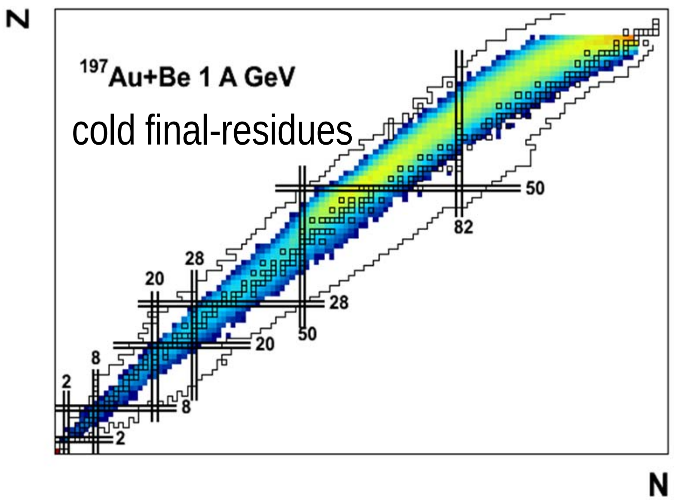
Isospin fluctuations



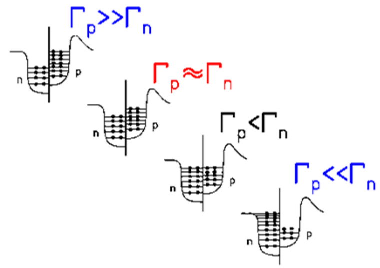
- the abrasion process is isospin independent:

$$P(N-n,Z-z)=\frac{\binom{Z}{z}\binom{N}{n}}{\binom{A}{a}} \qquad A=Z+N \qquad a=z+n$$

prefragments with large N/Z fluctuations

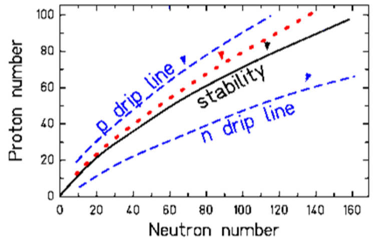


- nature of final fragments governed by neutron-proton evaporation:



$$\Gamma_n \approx \Gamma_p \quad \Rightarrow \quad B_n \approx B_p + E_C$$

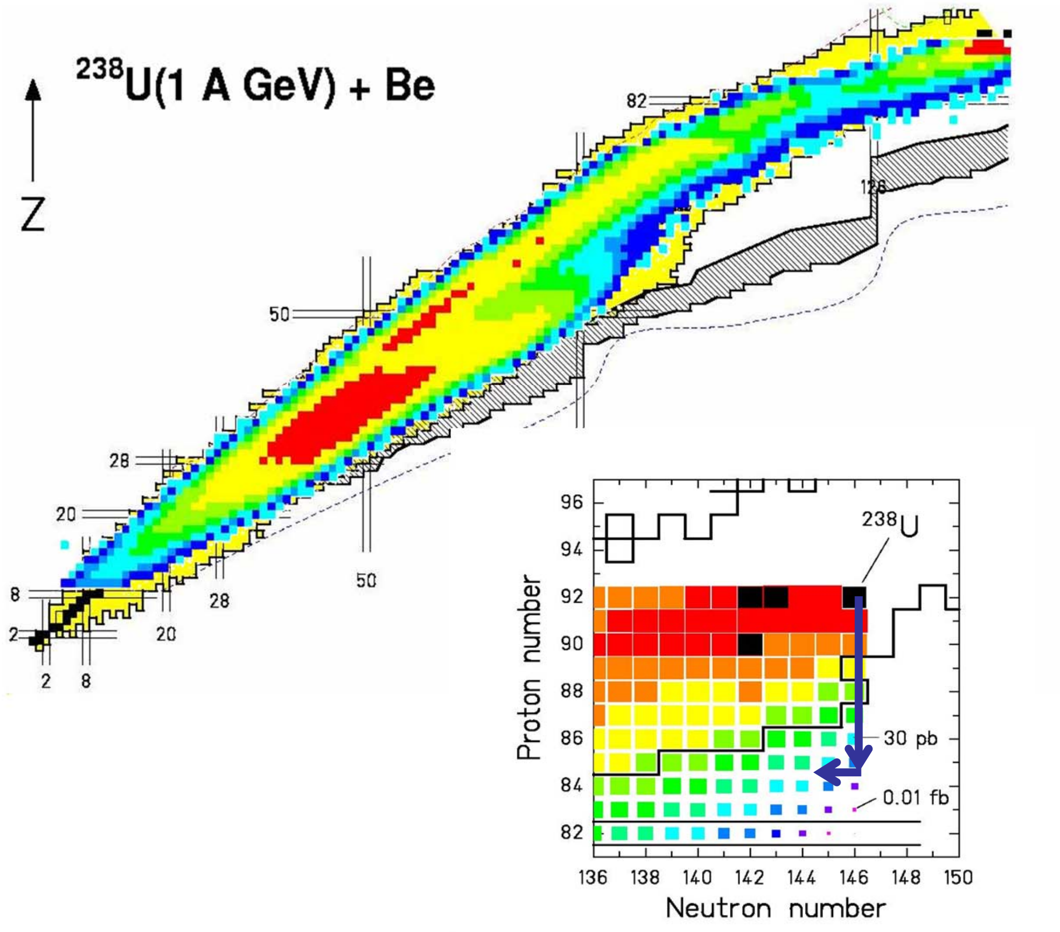
$$N \leq Z$$



N/Z fluctuations are reduced

Producing nuclei far from stability

Nuclei far from stability in fragmentation reactions

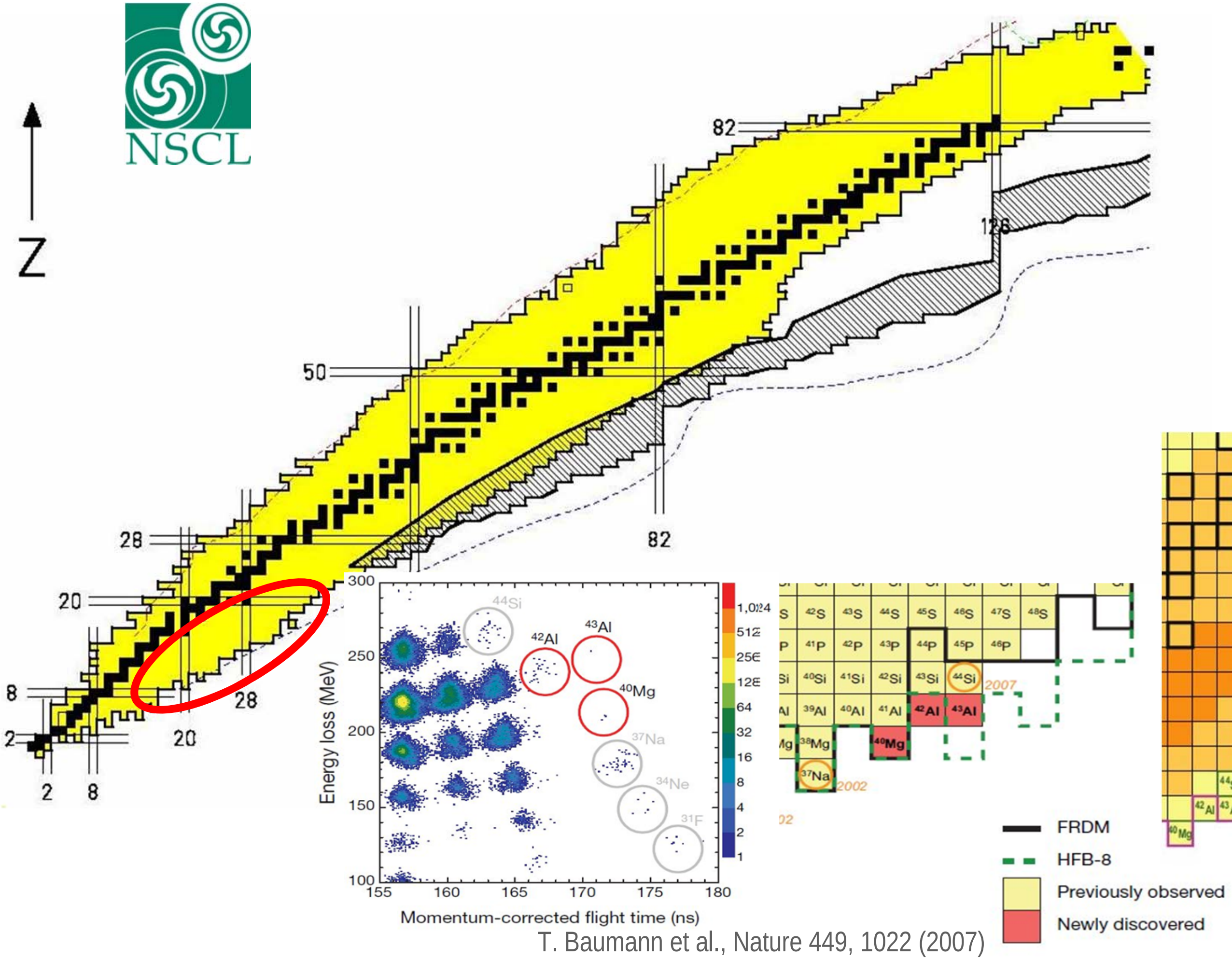


Fragmentation is an optimum reaction mechanism for exploring the nuclide chart:

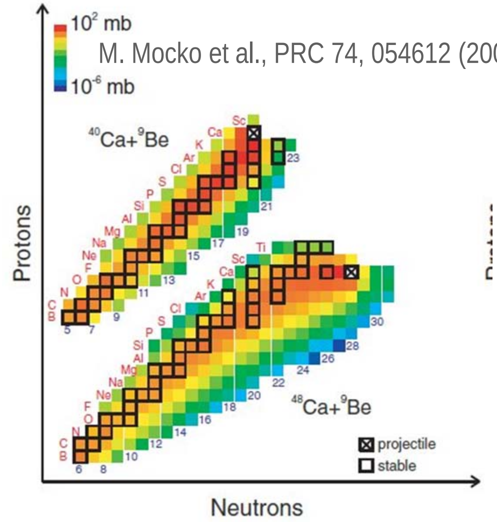
- neutron-deficient nuclei are highly populated up to the drip-line
- the in-flight fragmentation of heavy nuclei leading to fission produces medium-mass neutron-rich nuclei
- the large fluctuation in isospin (abrasion) and excitation energy (ablation) give access to **cold fragmentation** processes where neutron-rich nuclei are produced.

Producing nuclei far from stability

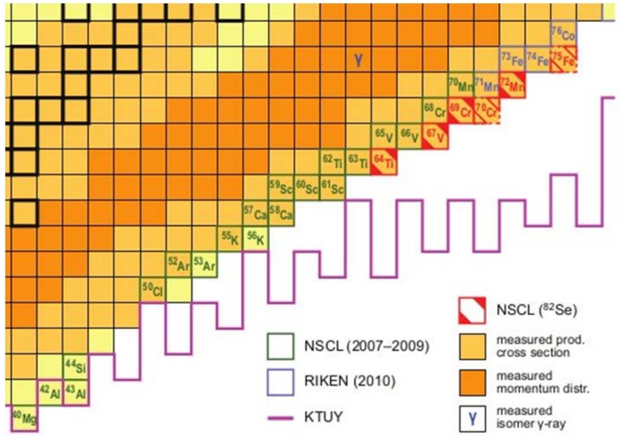
Light neutron-rich nuclei



T. Baumann et al., Nature 449, 1022 (2007)



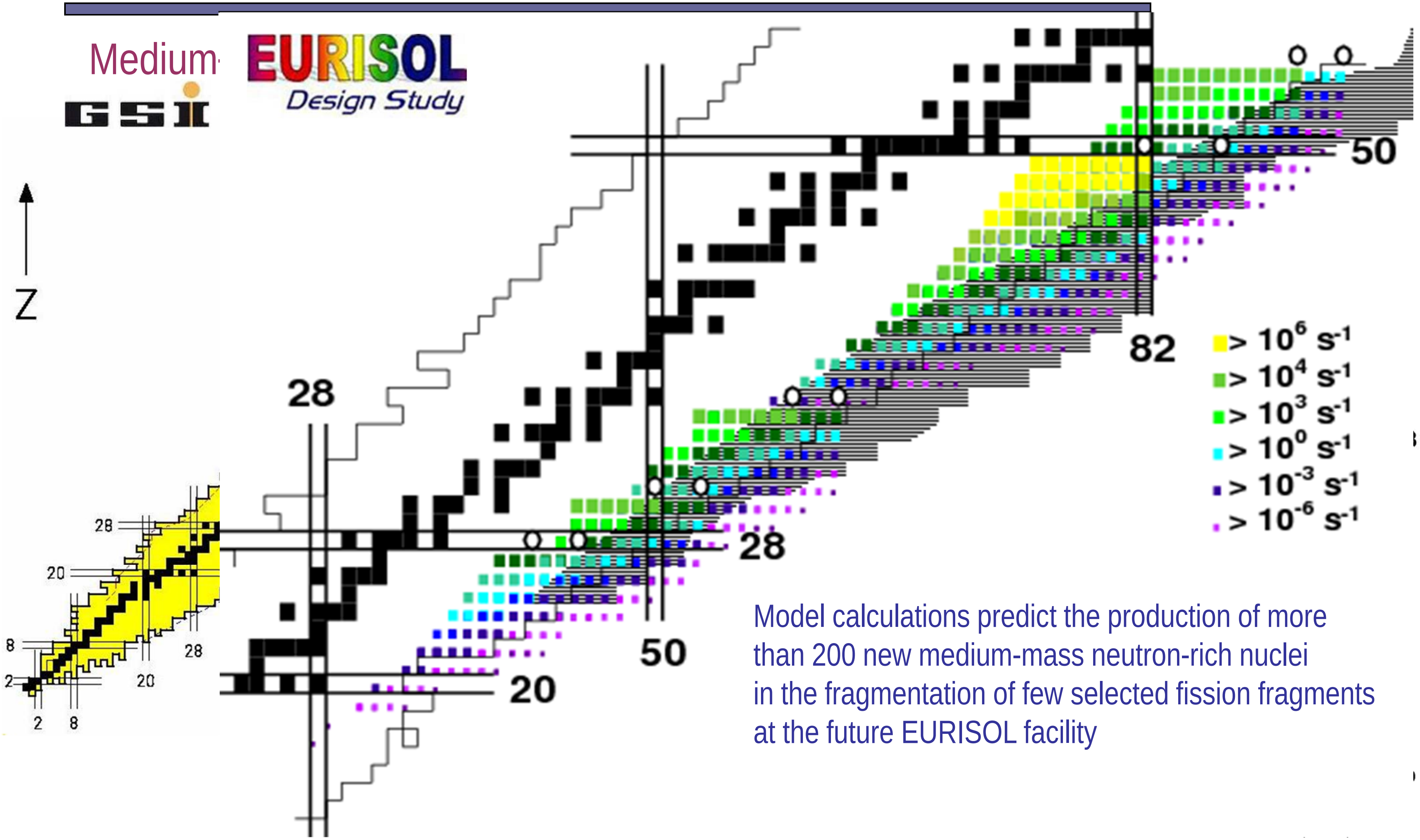
M. Mocko et al., PRC 74, 054612 (2006)



O. Tarasov et al., PRC 874 054612 (2013)

Producing nuclei far from stability

Medium



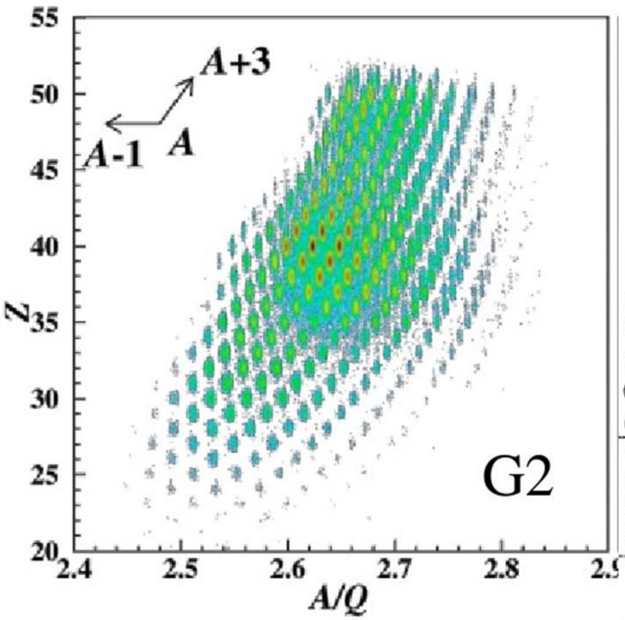
Model calculations predict the production of more than 200 new medium-mass neutron-rich nuclei in the fragmentation of few selected fission fragments at the future EURISOL facility

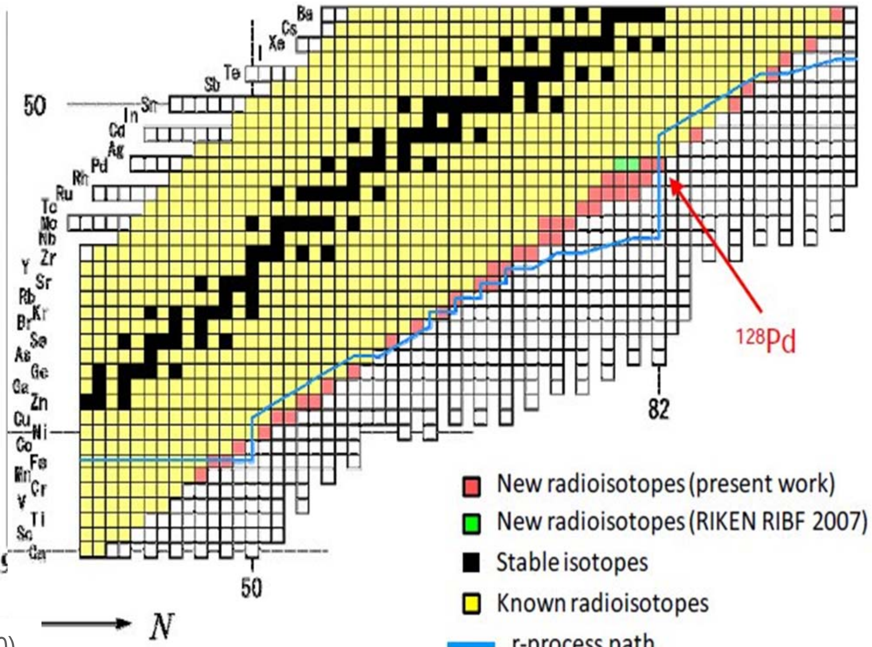
Producing nuclei far from stability

Medium-mass neutron-rich nuclei

RIBF/RIKEN

45 new medium-mass neutron-rich nuclei
in fission induced by in-flight fragmentation of ^{238}U

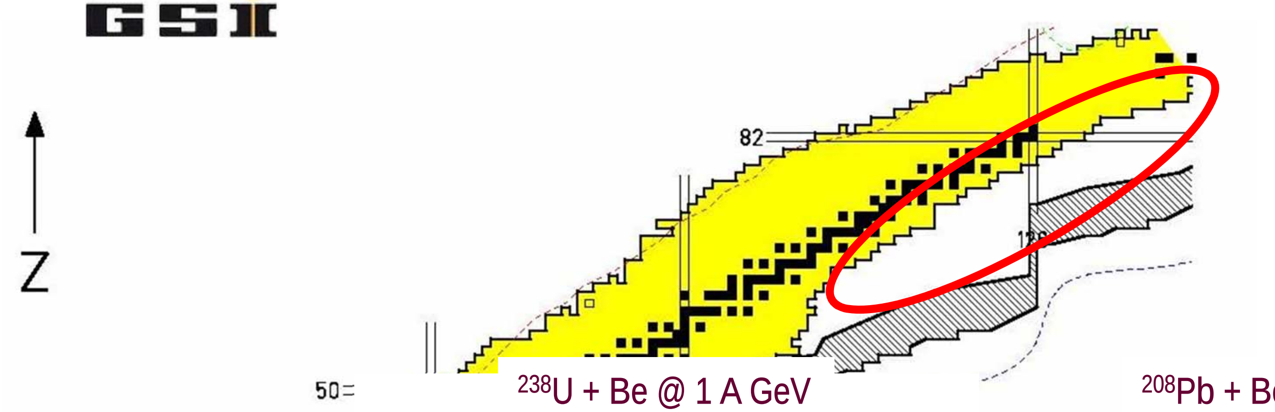


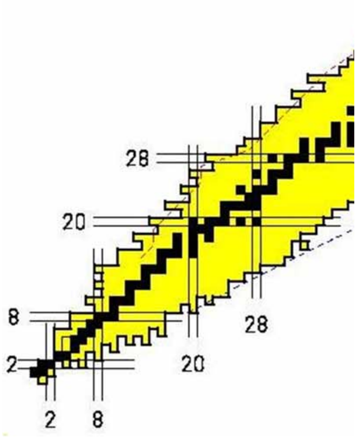


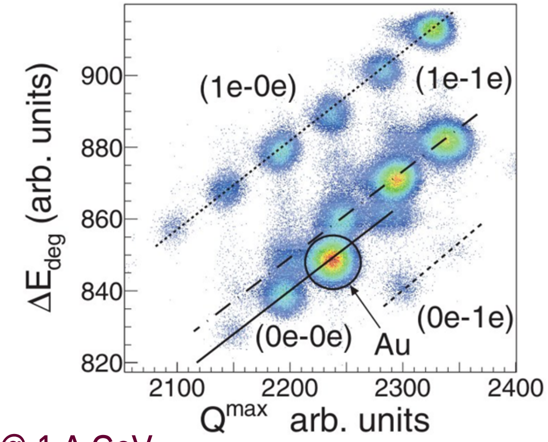
T. Ohnishi et al., J. Phys. Sc. Jpn. 79, 073201 (2010)

Producing nuclei far from stability

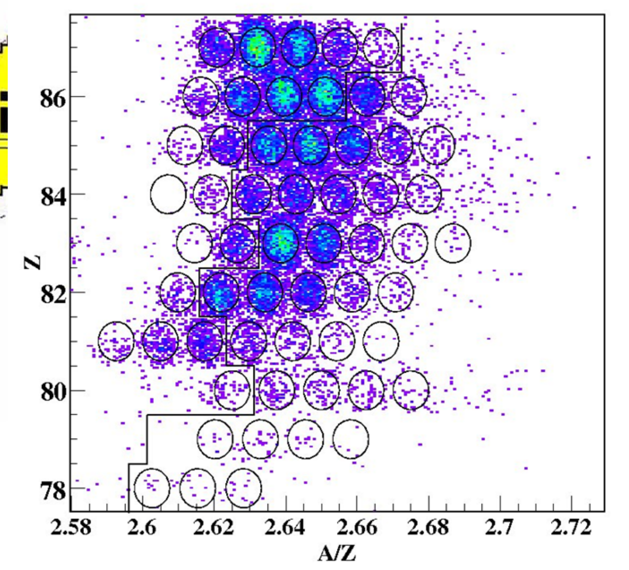
Heavy neutron-rich nuclei



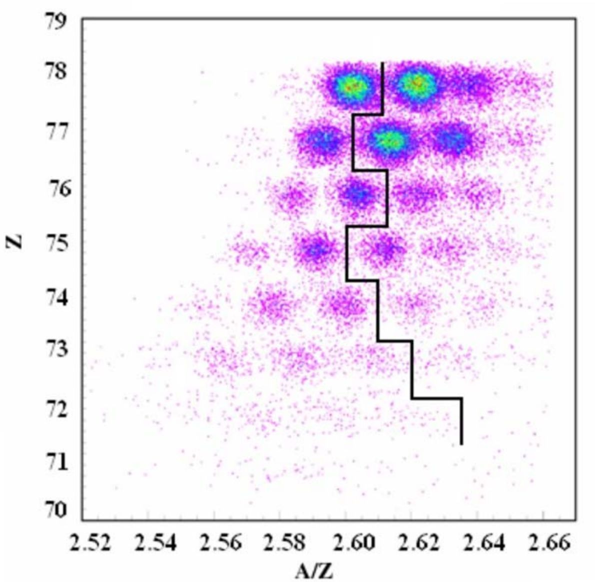




^{238}U + Be @ 1 A GeV

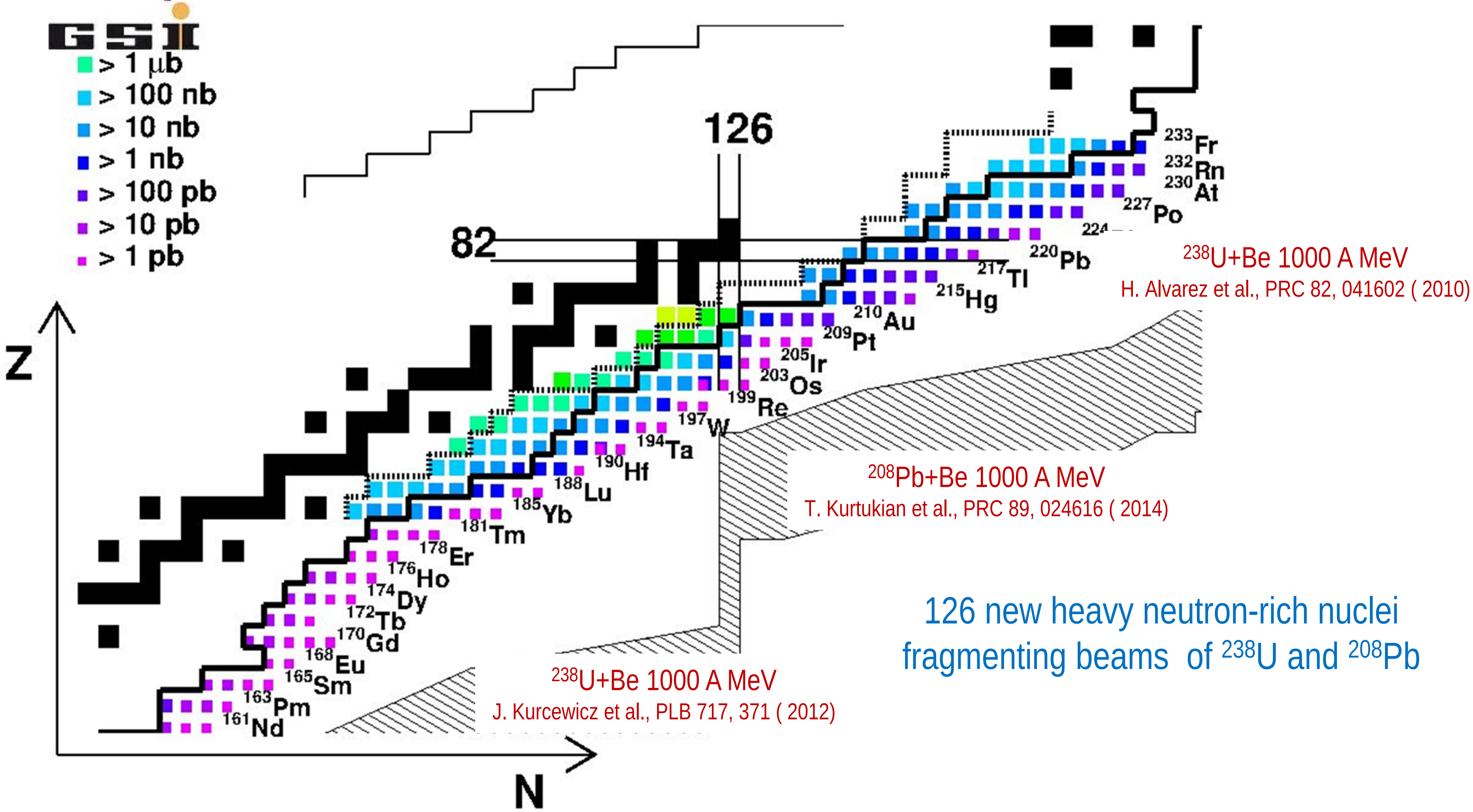


^{208}Pb + Be @ 1 A GeV



Producing nuclei far from stability

Heavy neutron-rich nuclei

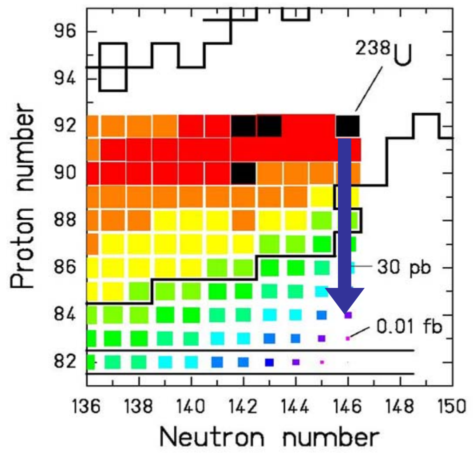


126 new heavy neutron-rich nuclei fragmenting beams of ^{238}U and ^{208}Pb

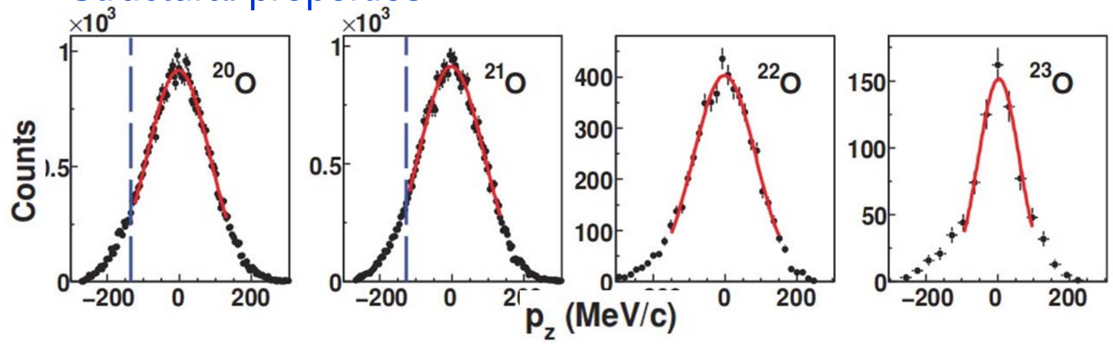
Proton knock-out in peripheral fragmentation

Interplay between fragmentation and nuclear structure

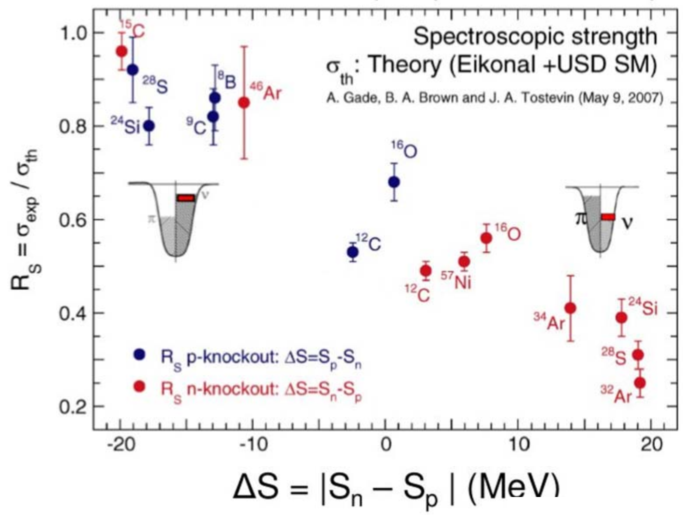
Production of neutron-rich nuclei



Structural properties



The puzzling quenching of deeply bound nucleons



Access to unbound systems

Nuclear excitations in proton knock-out

Model description: Glauber model

Adiabatic and inert-core approximations

core survival probability → $|S_C|^2$

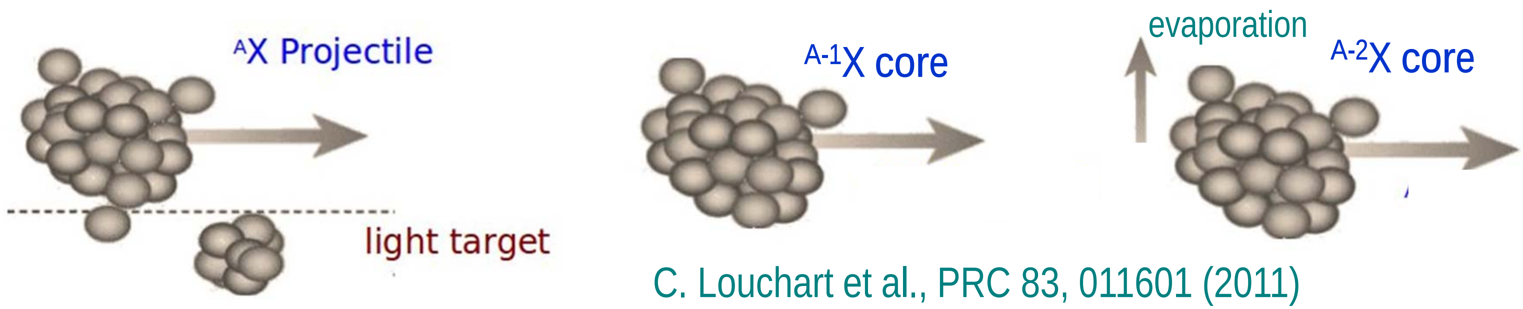
1-N removal probability → $|S_N|^2$

$$\sigma_{st} = 2\pi \int ddb |\phi_o|^2 |S_C|^2 (1 - |S_N|^2)$$

$$S_C(b) = exp(i\chi_C(b))$$

$$\chi_C(b) = -\sigma_{NN} \int d^2\overrightarrow{r_\perp} \rho_C(\overrightarrow{r_\perp}) \rho_T(|\vec{b} - \overrightarrow{r_\perp}|)$$

Explicit treatment of core excitations was suggested for the 1-N quenching puzzle

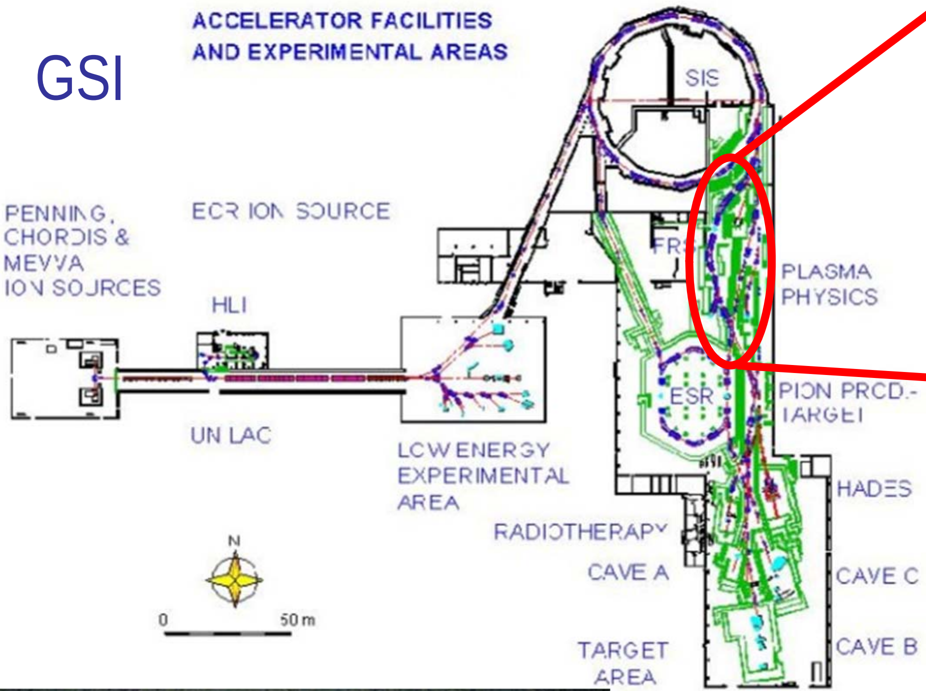


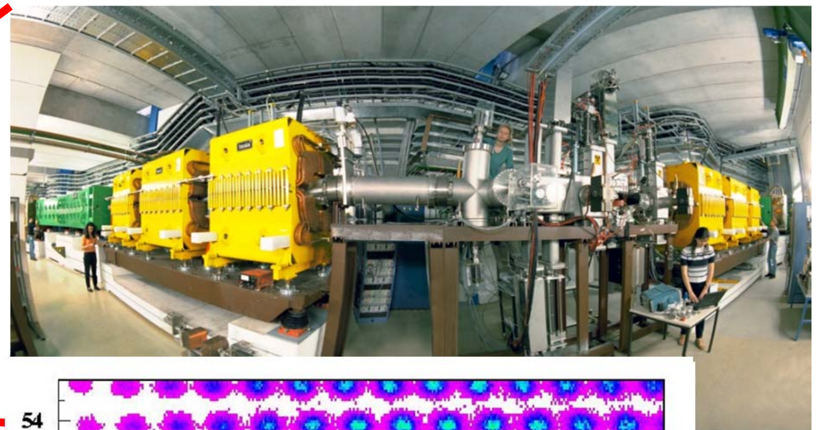
C. Louchart et al., PRC 83, 011601 (2011)

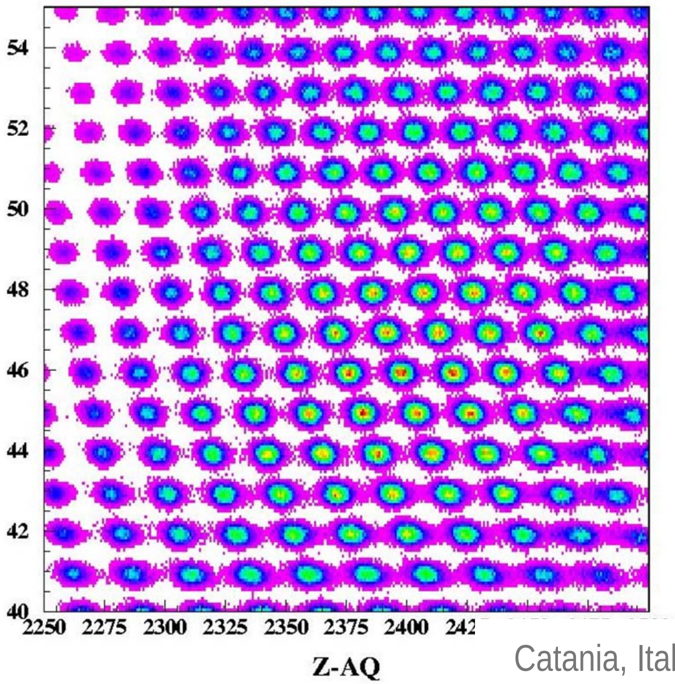
Investigating fragmentation/spallation reactions

Inverse kinematics

GSI

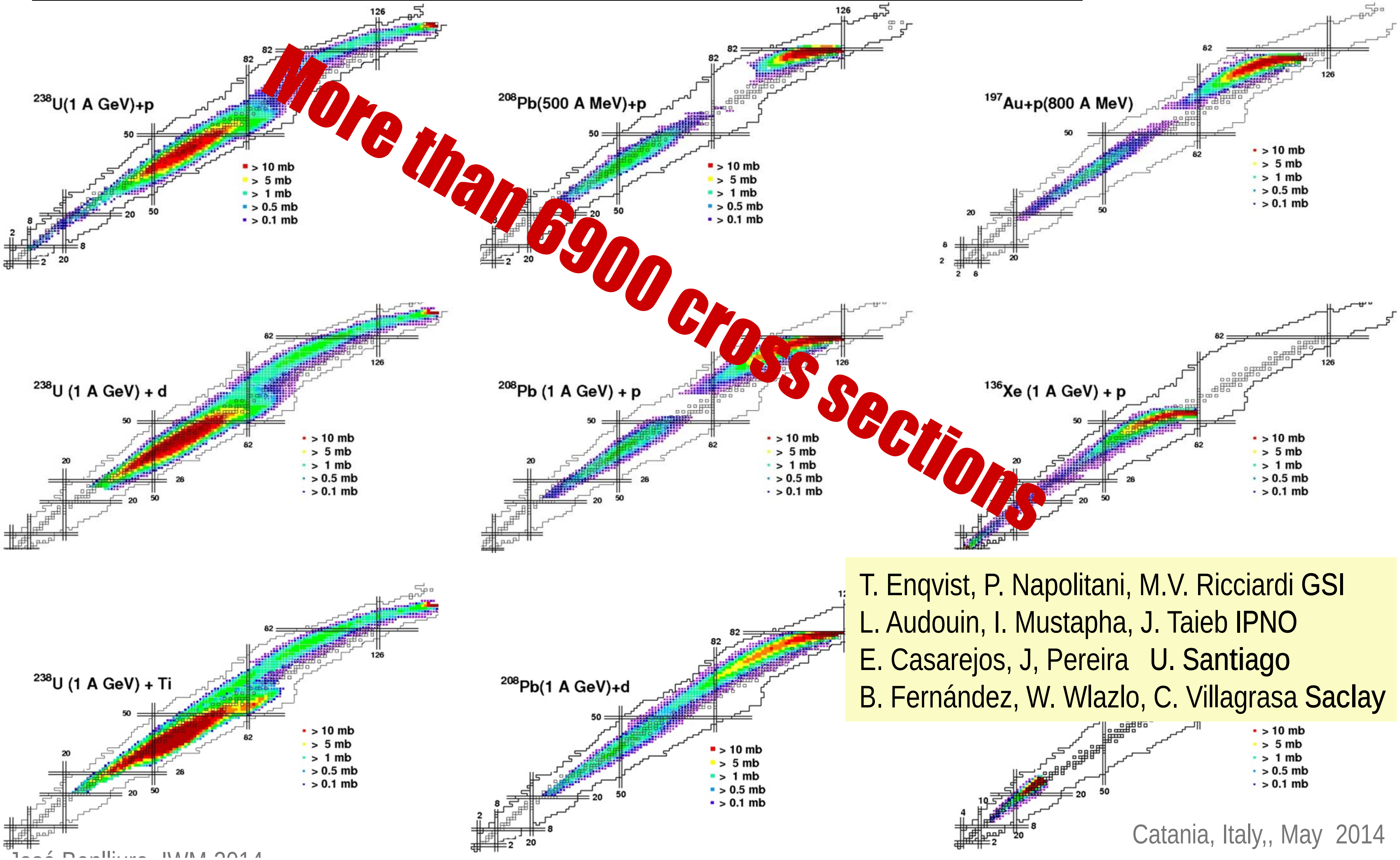






More than 1000 fission fragments identified in the reaction ^{238}U(1 A GeV)+d

Investigating fragmentation/spallation reactions

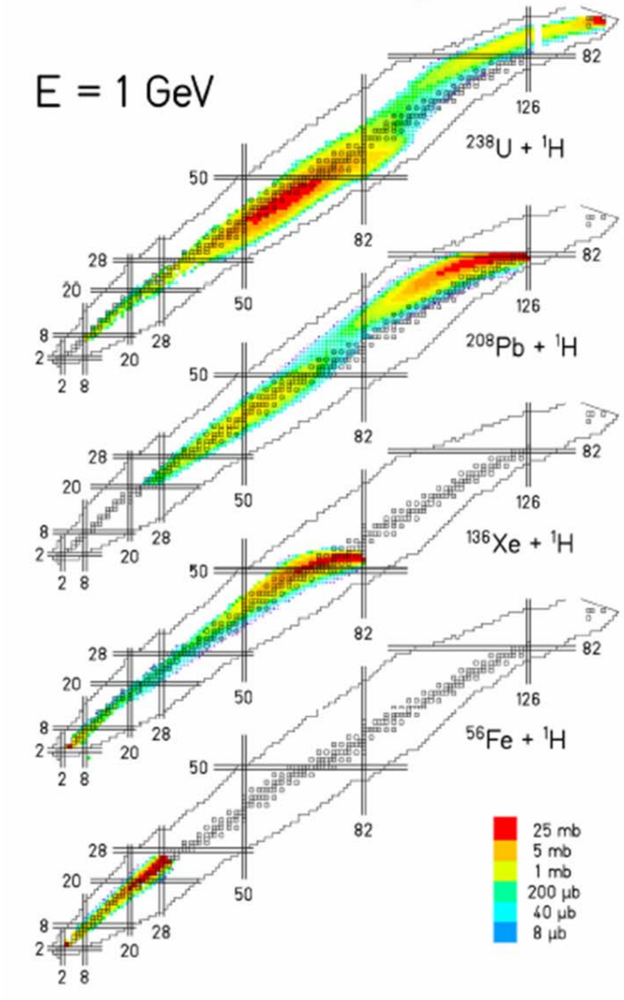


More than 6900 cross sections

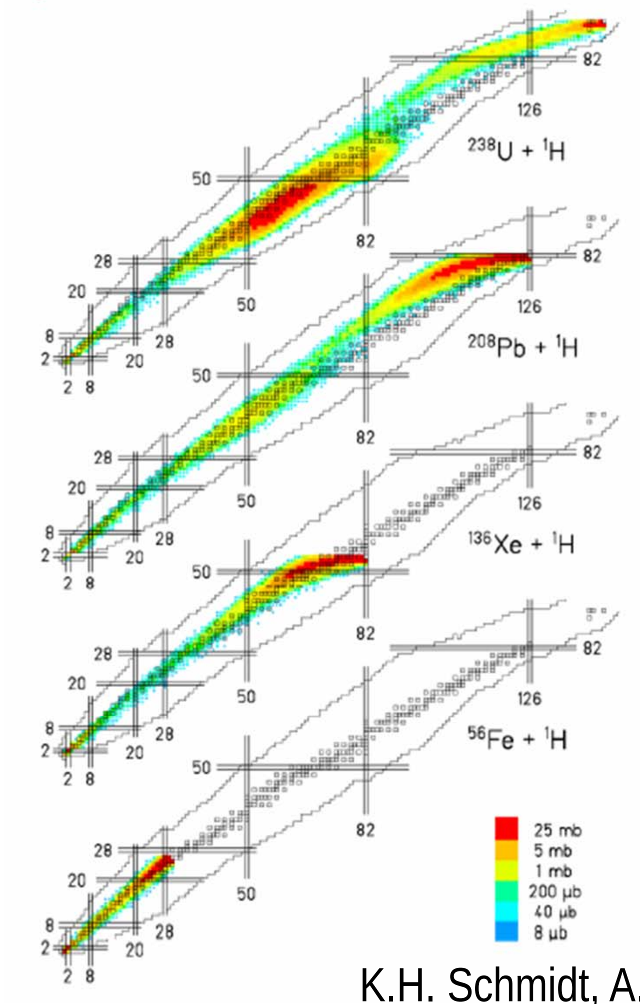
T. Enqvist, P. Napolitani, M.V. Ricciardi GSI
L. Audouin, I. Mustapha, J. Taieb IPNO
E. Casarejos, J, Pereira U. Santiago
B. Fernández, W. Wlazlo, C. Villagrasa Saclay

Investigating fragmentation/spallation reactions

New models with high predictive power: fragmentation/spallation



Experiment (FRS)



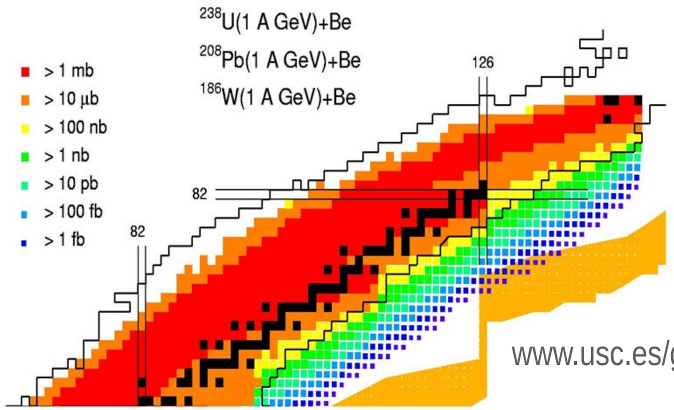
ABRABLA07

K.H. Schmidt, A. Kelic GSI

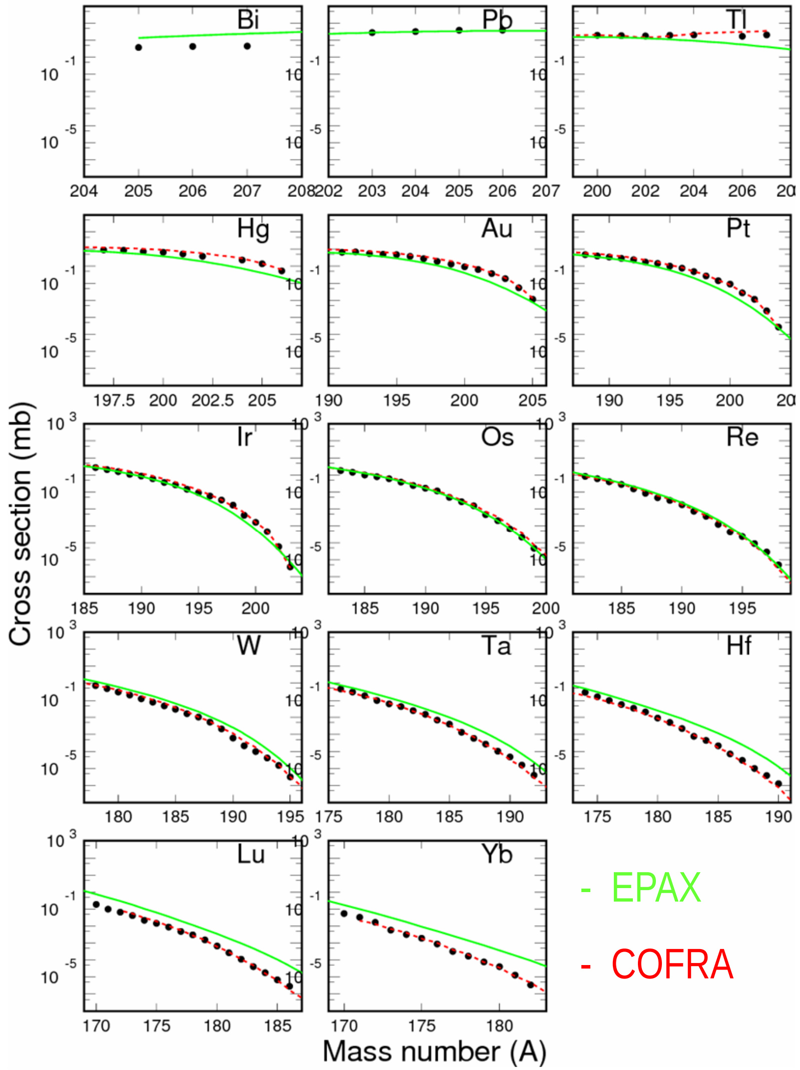
Production of heavy neutron-rich nuclei

Production of heavy neutron-rich nuclei

Predicted cross sections with COFRA

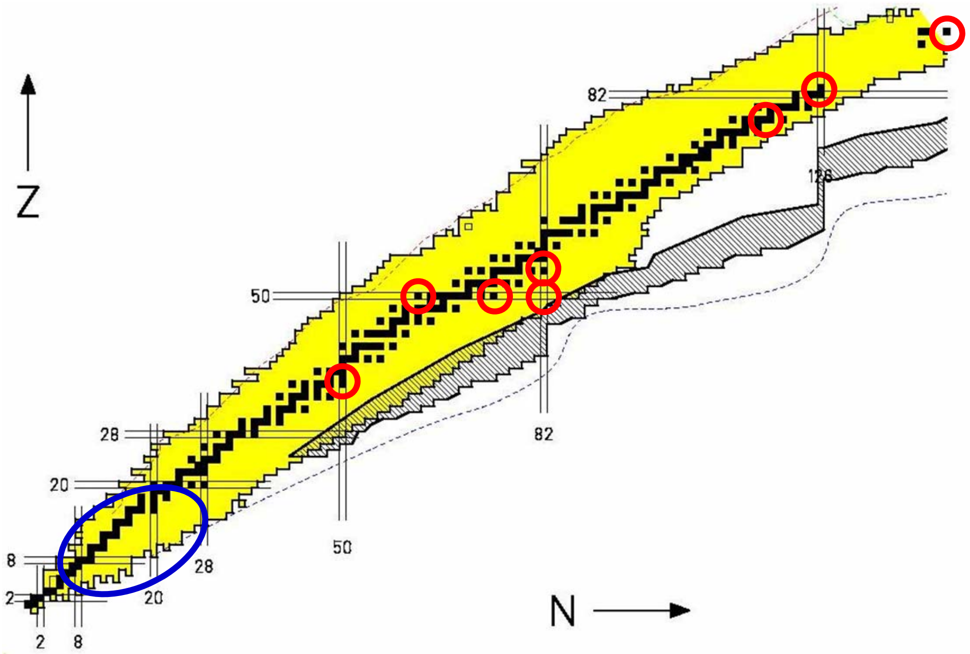


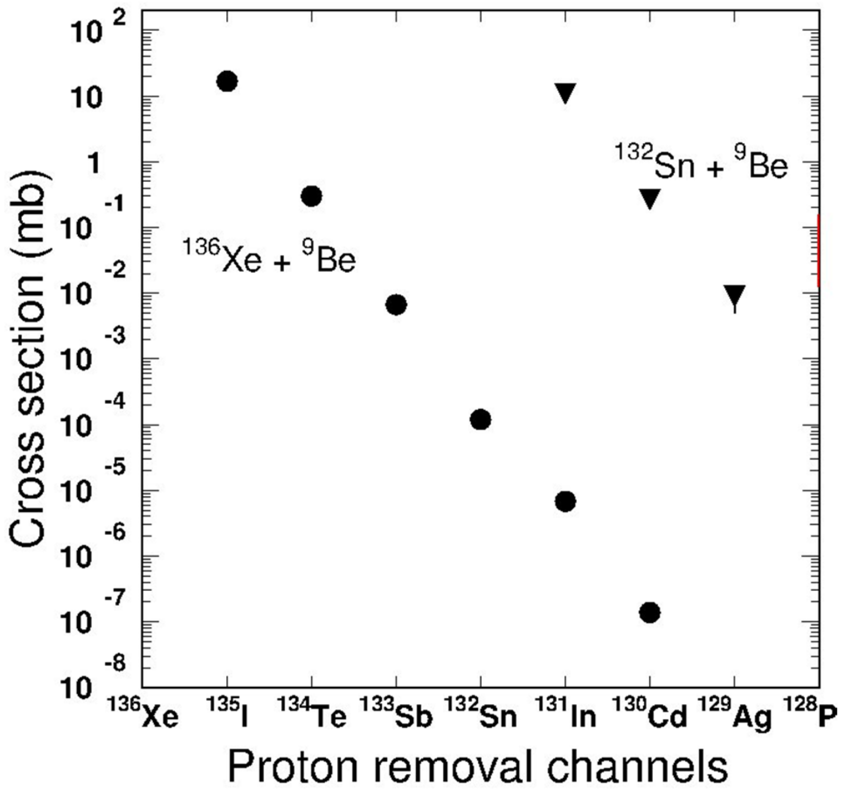
www.usc.es/genp/cofra



Nuclear excitations in proton knock-out

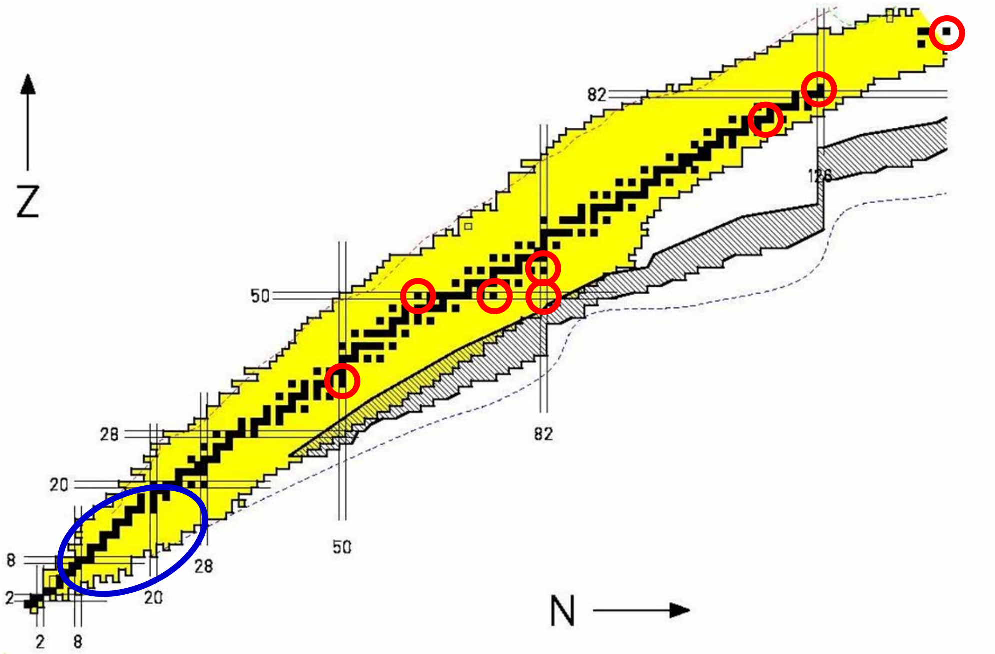
Proton knock-out at FRS/GSI

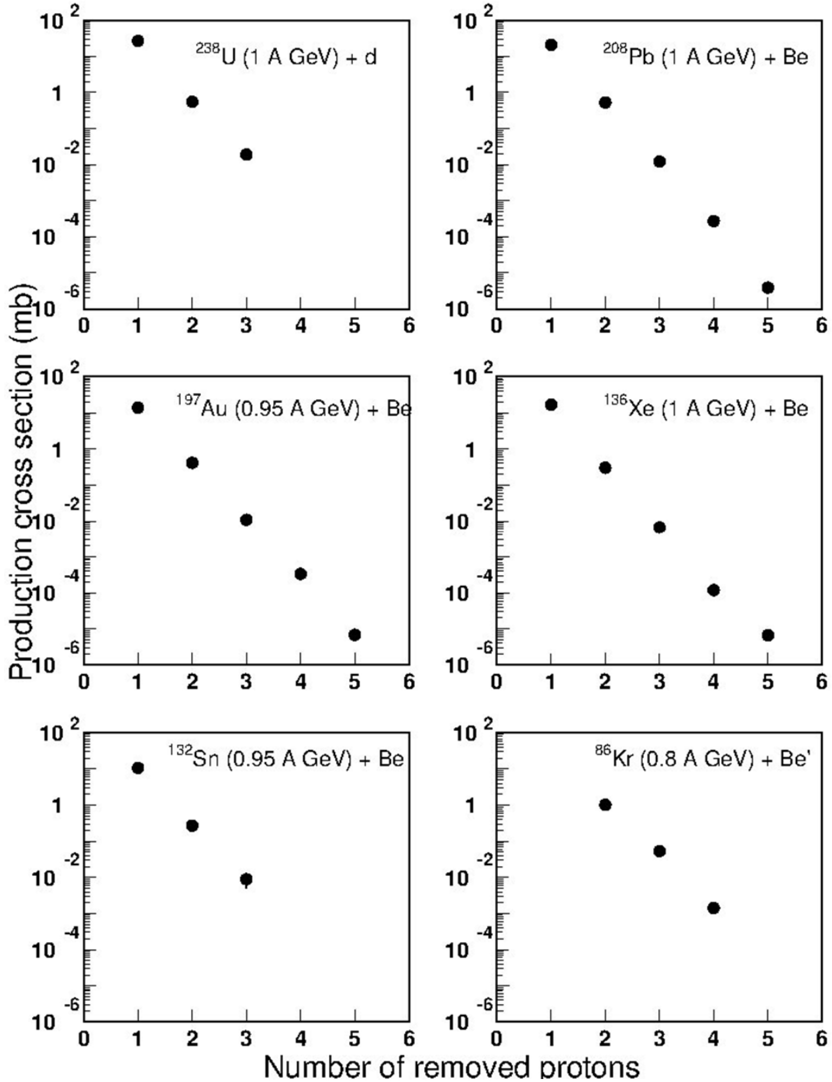




Nuclear excitations in proton knock-out

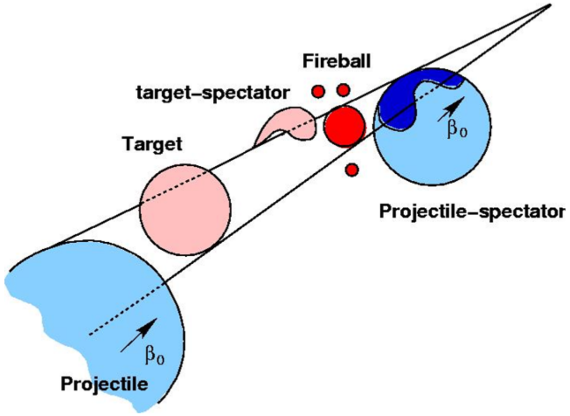
Measurements at FRS/GSI





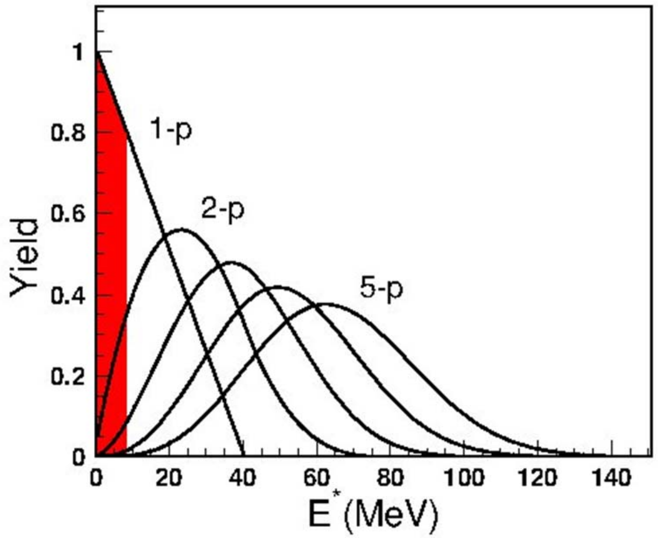
Nuclear excitations in proton knock-out

Model description: abrasion-ablation

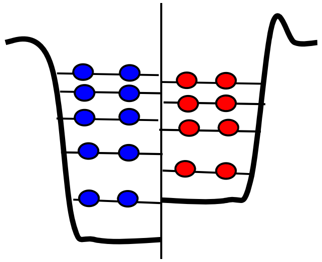


The probability for a one-proton removal is defined by the geometrical overlap between projectile and target nuclei

Remnants survive when excited below the neutron evaporation threshold (S_n).

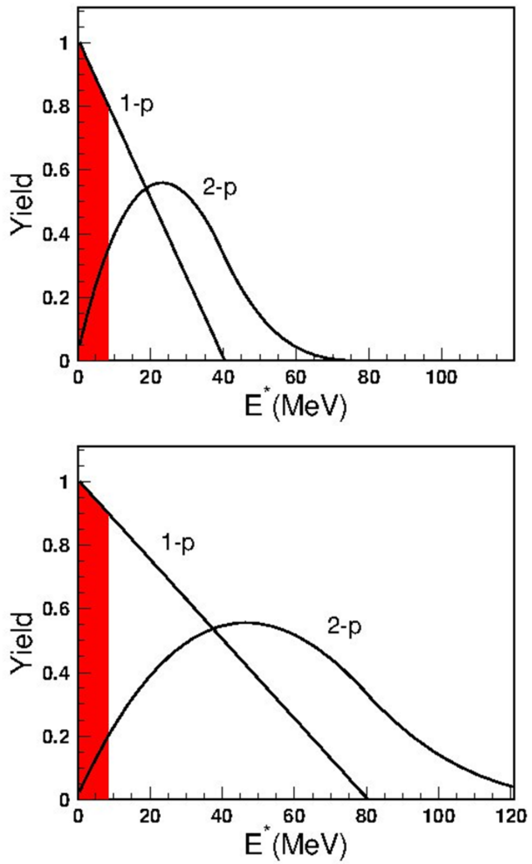


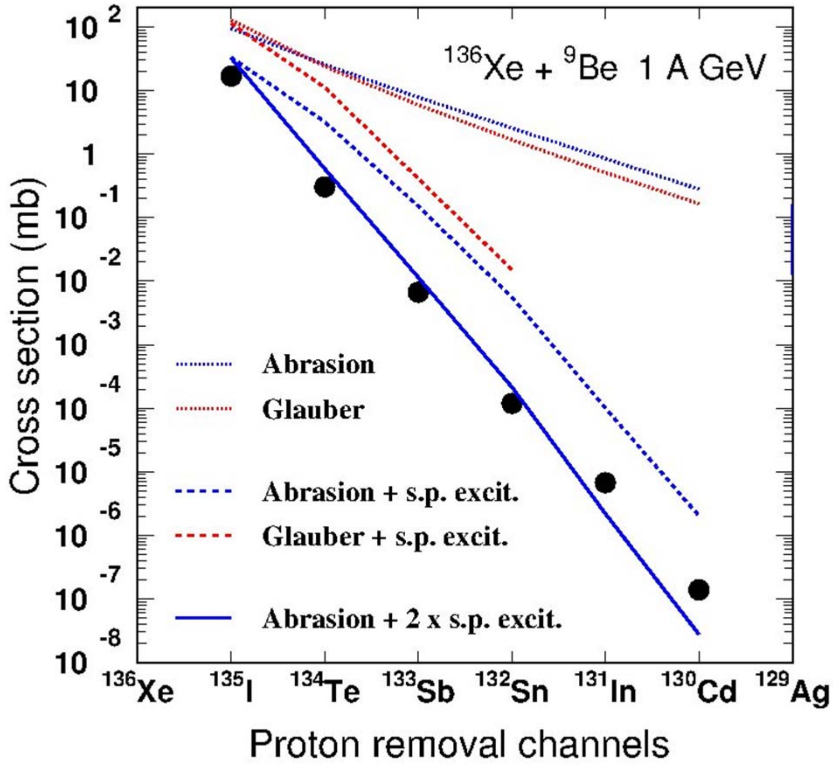
Excitations of the residual nuclei are considered from the holes created in the Fermi distribution of single-particle levels.



Nuclear excitations in proton knock-out

Data interpretation



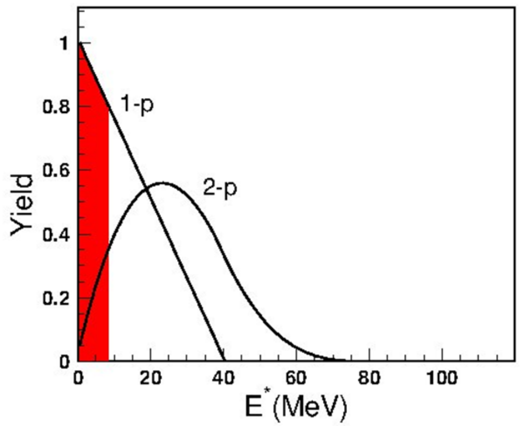


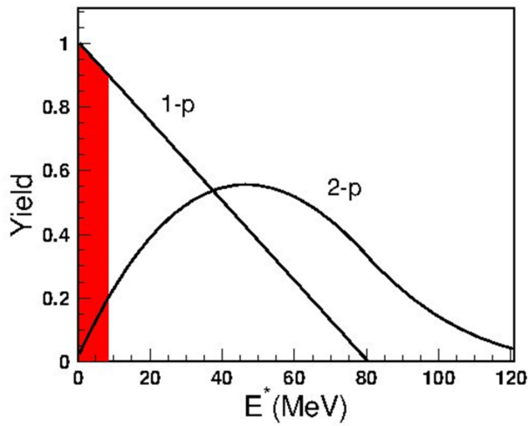
Excitation energy gained by the remnants seems to be larger than expected from particle-hole excitations

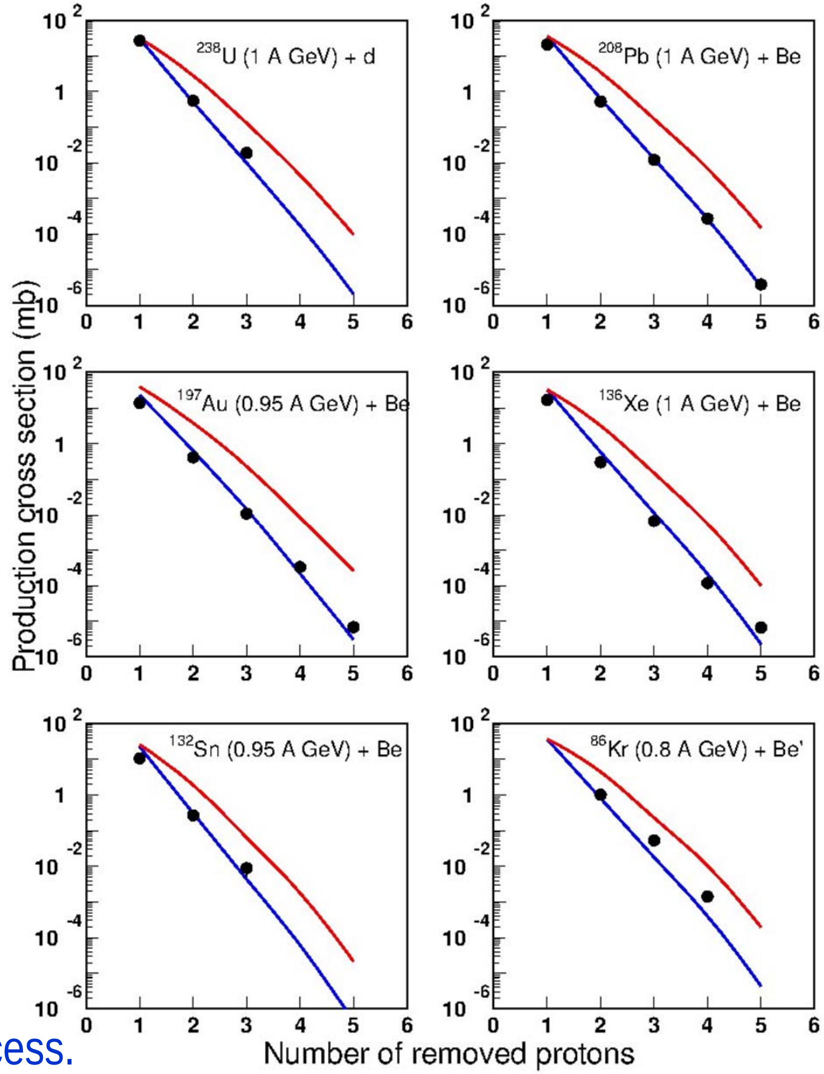
K.-H. Schmidt et al., PLB 300, 313 (1993)

Nuclear excitations in proton knock-out

Data interpretation



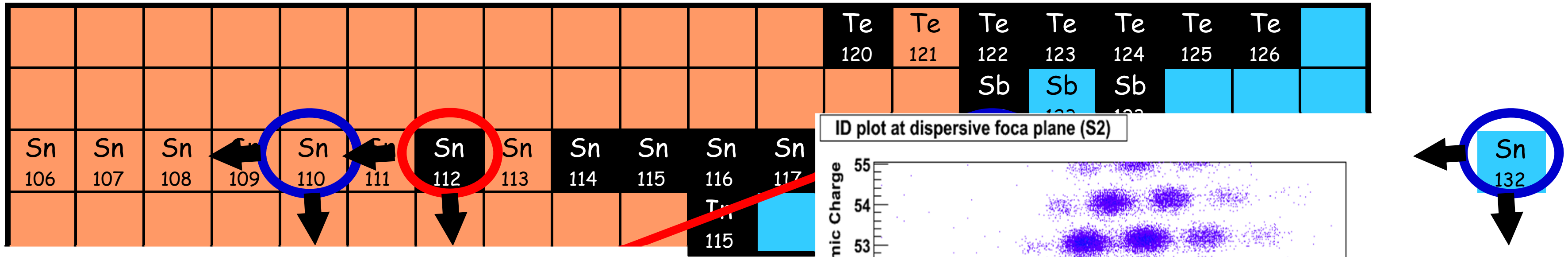


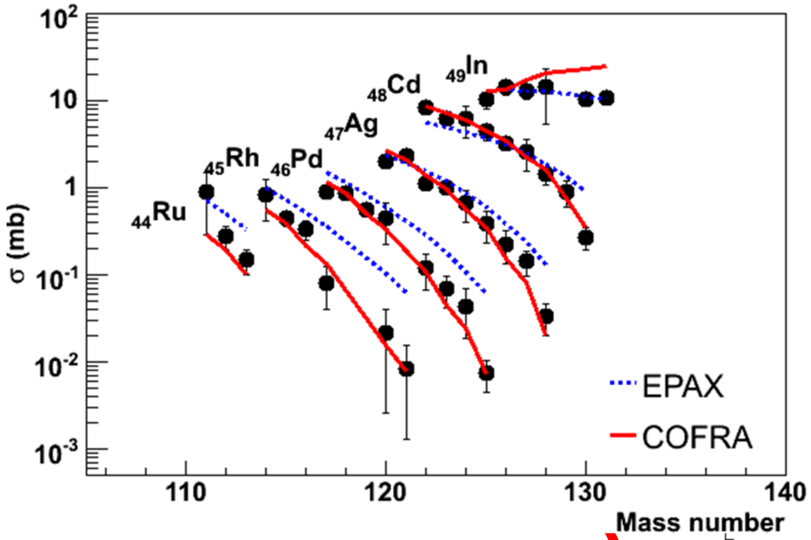


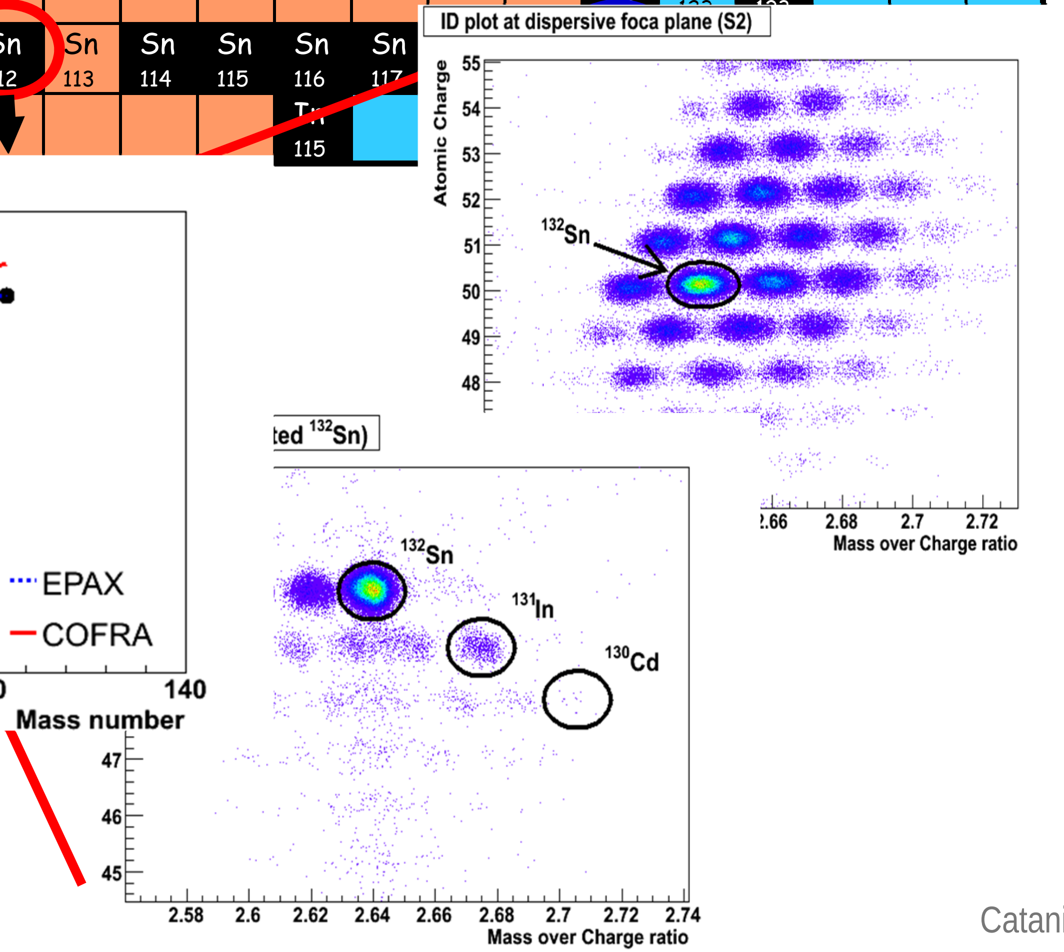
The persistence of this effect should be checked with lighter projectiles and as a function of the neutron excess.

Nucleon excitations in proton knock-out

Isospin dependence of the proton-removal process



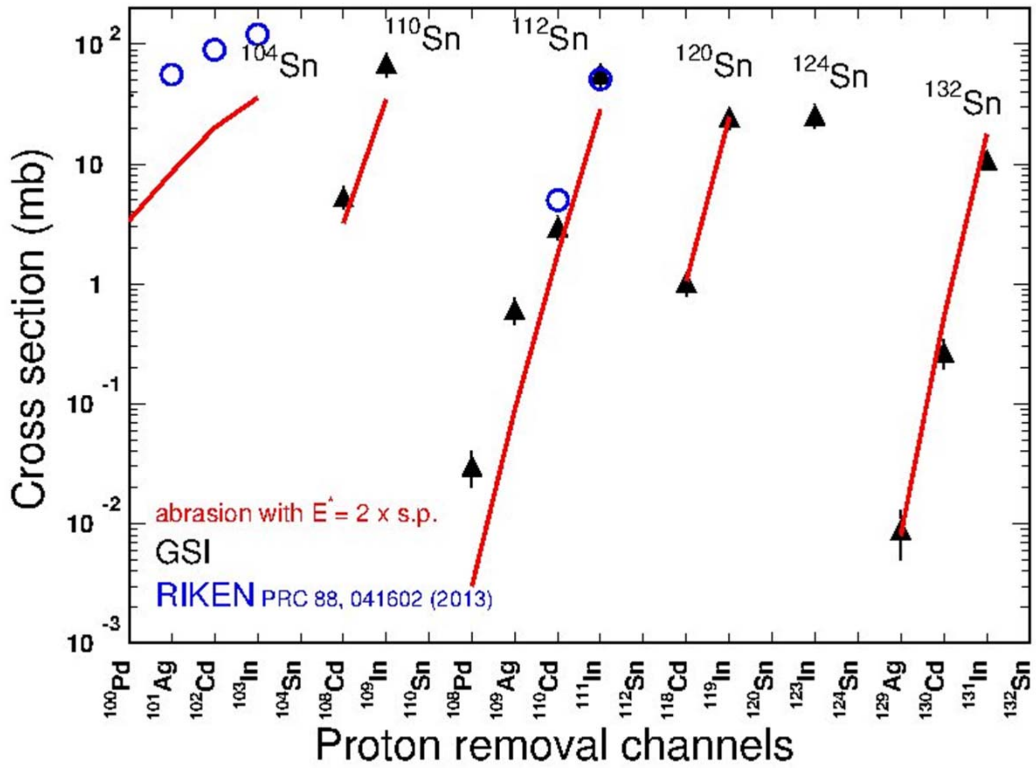




D. Pérez et al., PLB 703 (2011) 552

Nucleon excitations in proton knock-out

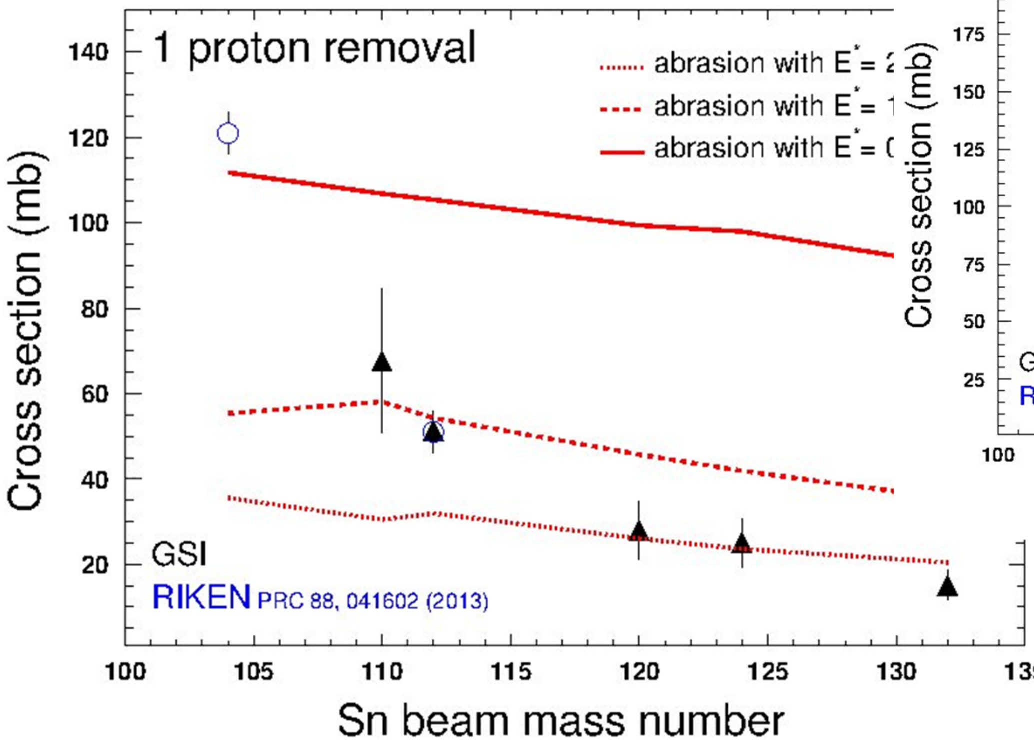
Isospin dependence of the proton-removal process

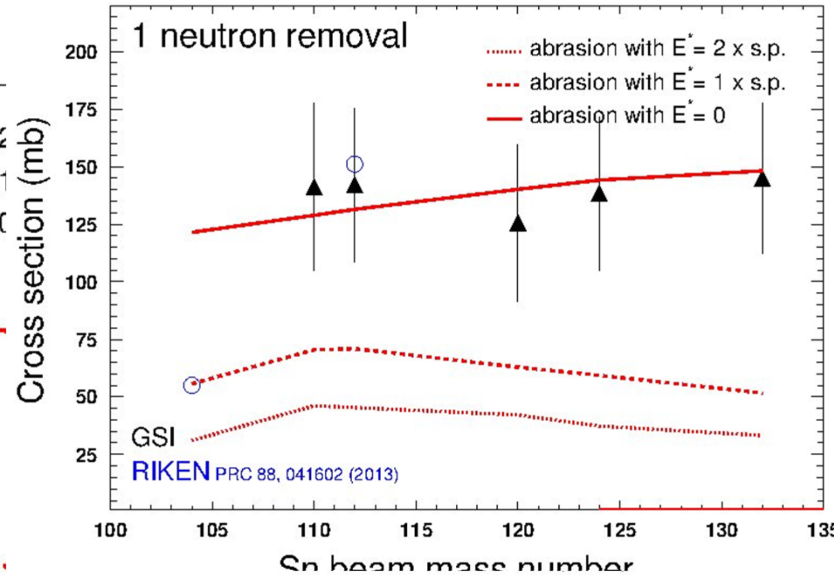


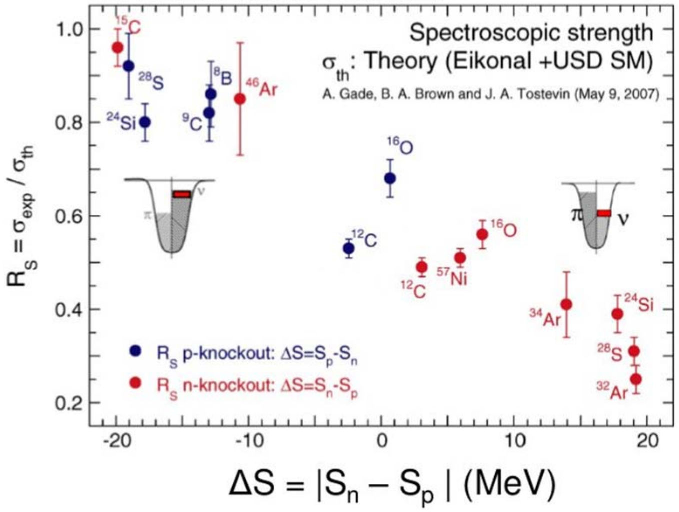
Calculations validated with stable beams underestimate the survival probability of proton knock-out residues obtained with neutron-deficient beams.

Nucleon excitations in proton knock-out

Isospin dependence of the proton-removal process



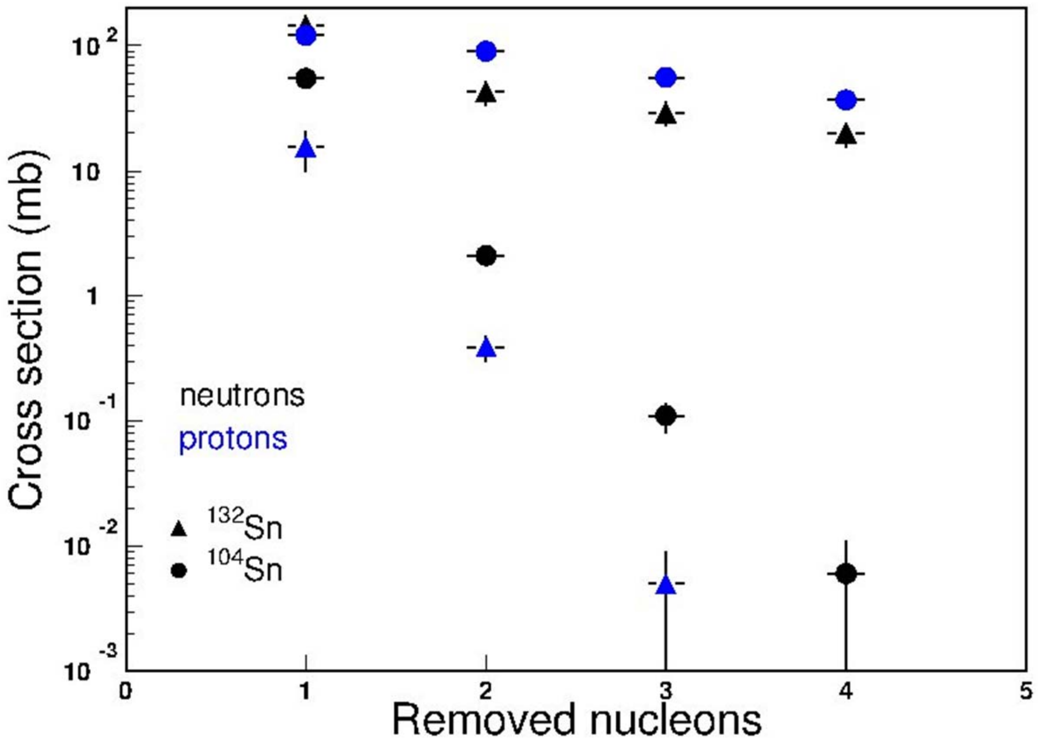




The excitation energy induced by nucleon removal seems to be enhanced for the deficient species in systems with large neutron-proton asymmetries.

Nucleon excitations in proton knock-out

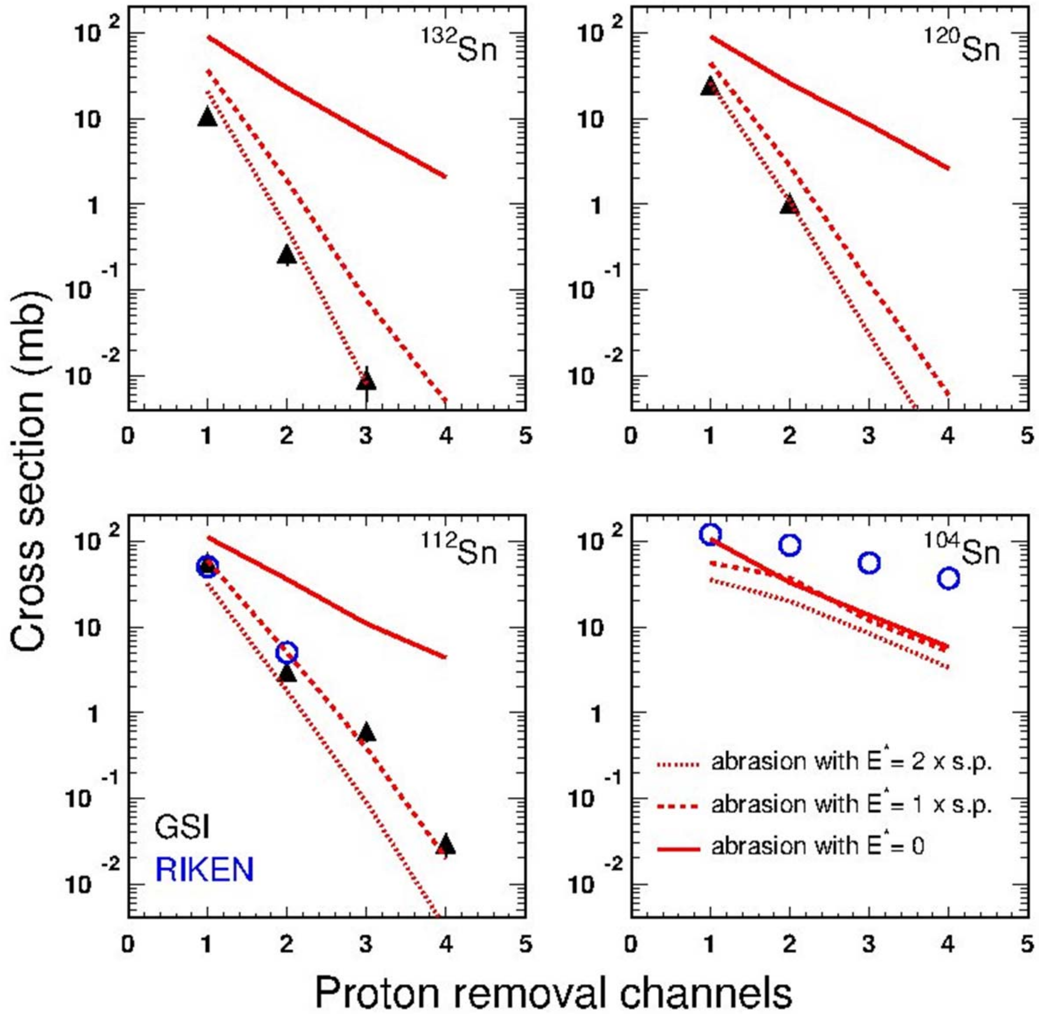
Isospin dependence of the proton-removal process



Protons and neutrons exchange their role in neutron-rich and proton-rich nuclei.

Nucleon excitations in proton knock-out

Isospin dependence of the proton-removal process



Conclusions

Peripheral fragmentation reactions play a key role in the production of nuclei far from stability because its large dynamical and isospin range

The investigation of proton-removal channels shows the existence of nuclear excitations beyond the single-particle picture.

These excitations are isospin dependent and could be related to the spectroscopic factors quenching. However, more realistic model calculations should be used for a final interpretation.

Collaborators:

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GSI: T. Aumann, J. Atkinson, K. Boretzky, A. Estrade, H. Geissel, A. Kelic, Y. Litvinov, S. Pietri, A. Prochazka, M. Takechi, J. Winfield

CEA/DAM: A. Chatillon, J. Taieb