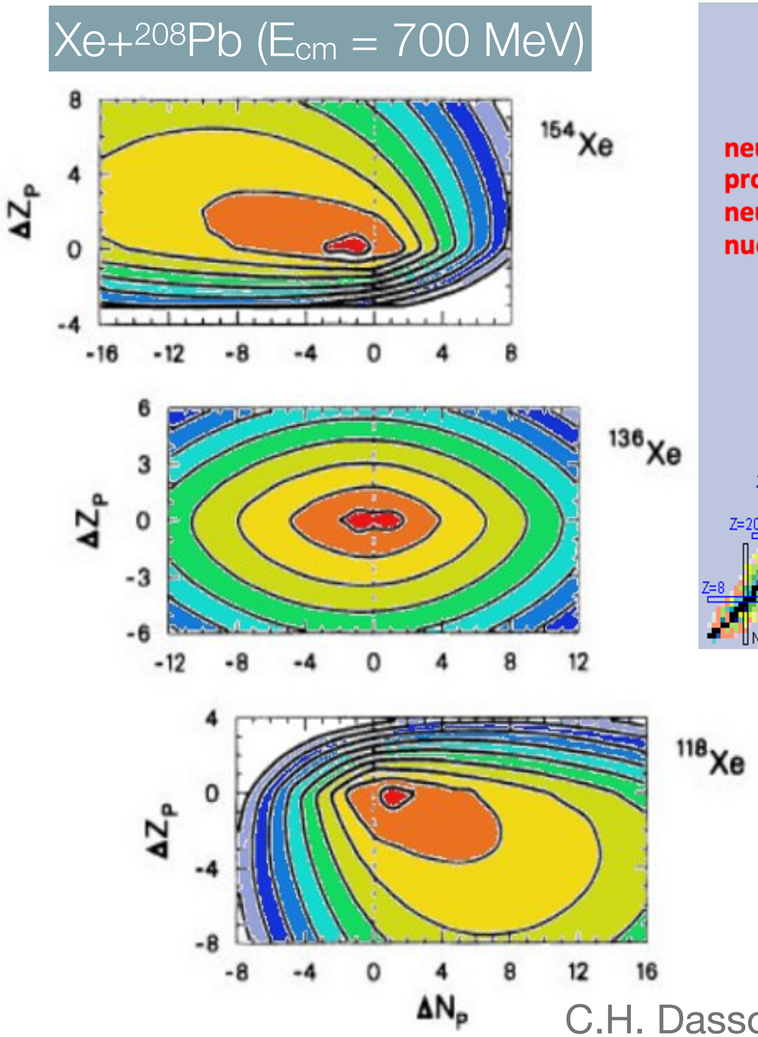
Advances in Heavy-Ion Transfer Reactions: Insights from Recent Experiments at LNL-INFN

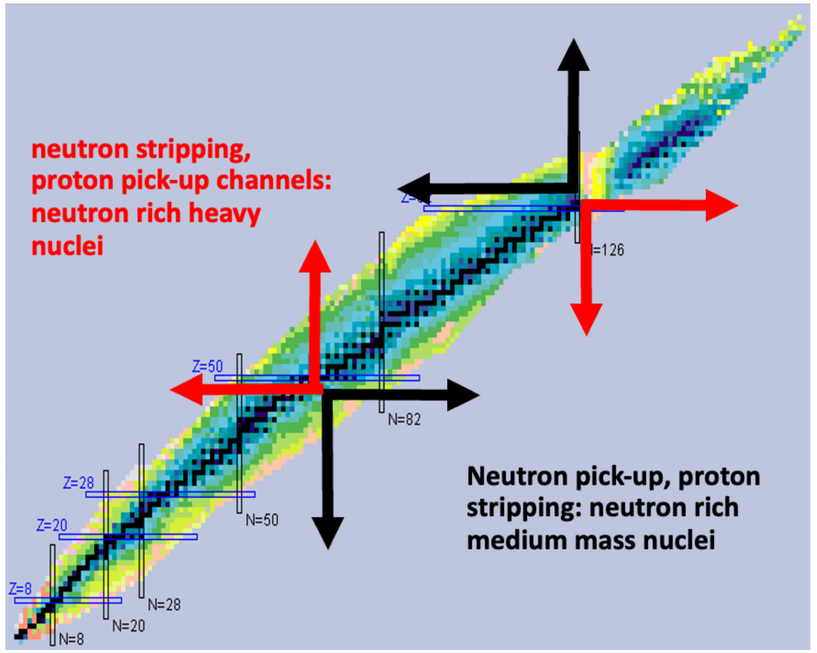
SSNET'24 Orsay, France, 4-8 Nov 2024

Tea Mijatović, RBI, Zagreb, Croatia

Multinucleon transfer reactions

- MNT above the barrier: many open transfer channels, governed by optimum Q-value and transfer form factors
- Interesting for the study of the structural properties of nuclei (single particle states, collective states, correlations between nuclei)
- Recent experimental highlights concerning reaction mechanism:
  - **Production of n-rich heavy isotopes:** important to understand proton pick-up channels
  - Simultaneous population of 1N and 2N channels: **study of nucleon-nucleon correlations**
- **PRISMA large solid angle magnetic spectrometer @ LNL-INFN, Italy**

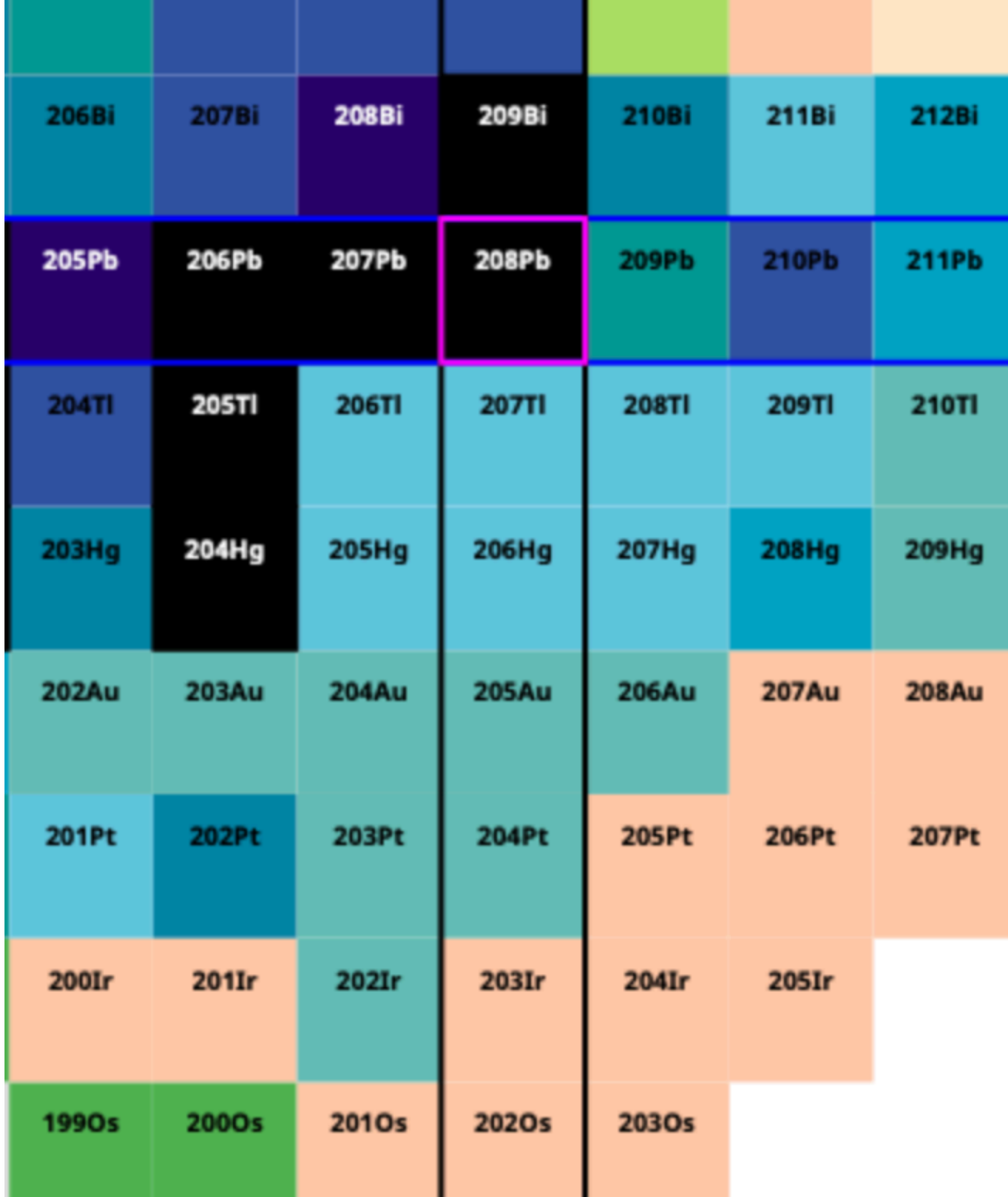




Other models predict large cross section for the production of n-rich nuclei with MNT: Langevin-type approach, TDHF, QMD, DNS…

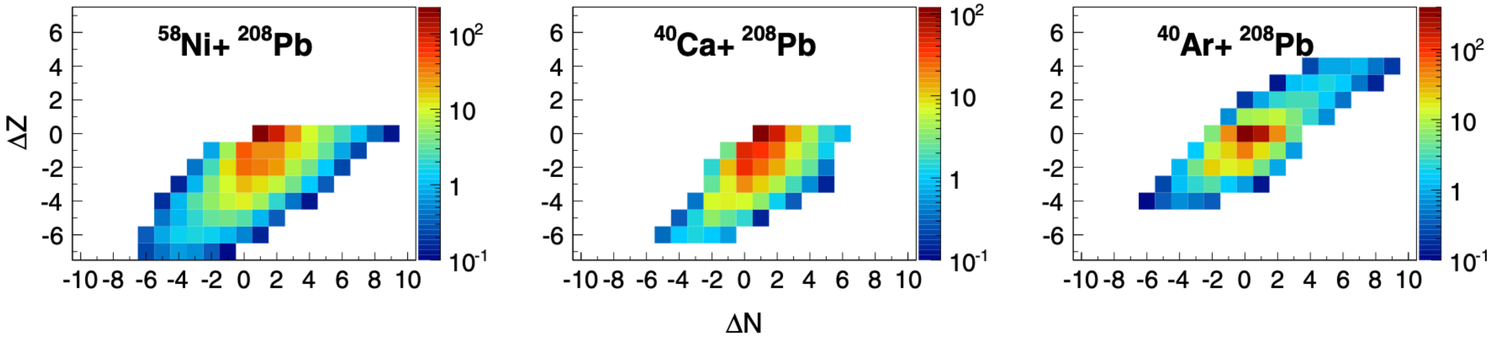
C.H. Dasso, G. Pollarolo and A. Winther, Phys. Rev. Lett. 73 (1994) 1907

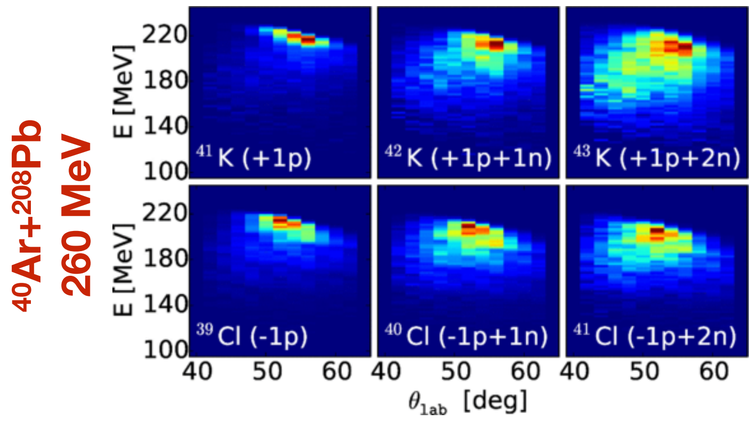
MNT and the production of heavy neutron-rich nuclei

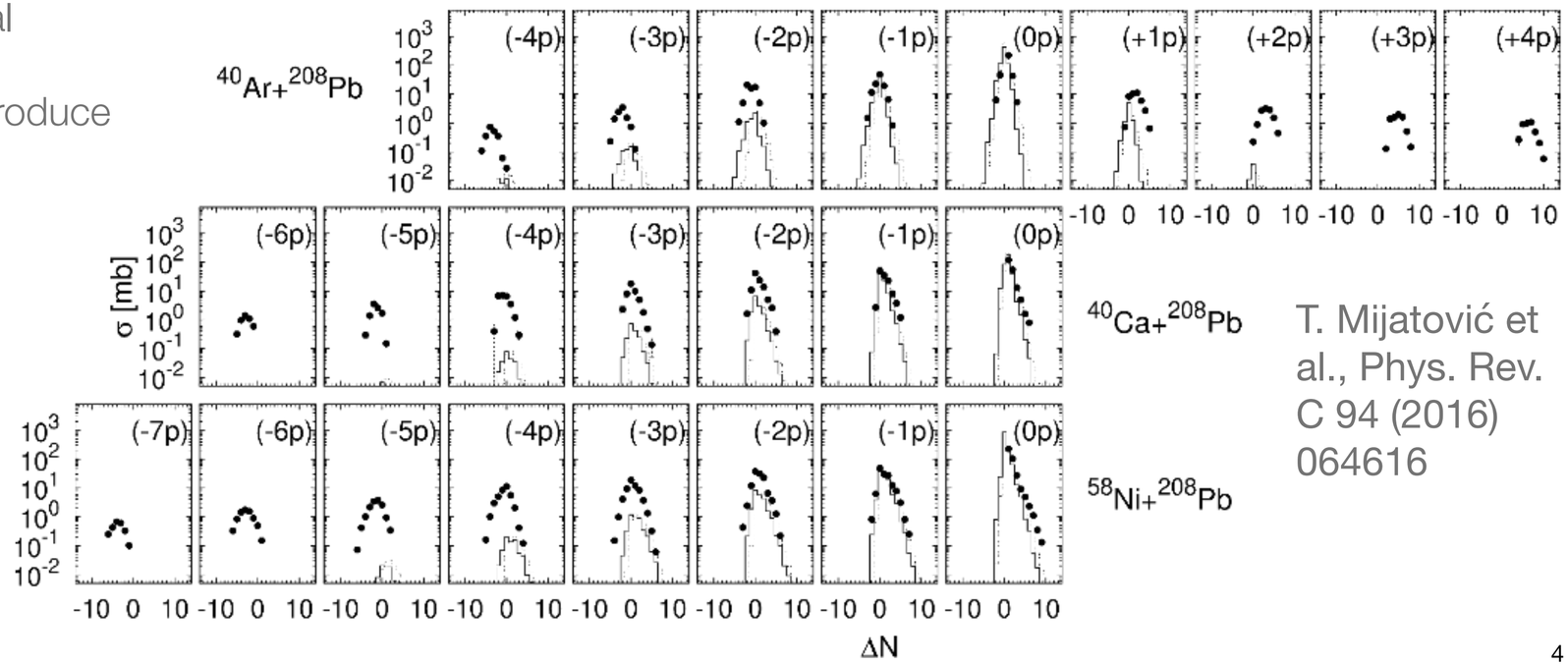


Change of population pattern from n-poor to n-rich projectiles

- Neutron-rich projectiles: both p stripping and pick-up channels observed in experiments
- Experimental cross section for multi-p transfer channels are much larger than GRAZING predictions, especially for the pick-up channels
- At energies above the barrier, DIC and secondary effects become increasingly more influential
- A lot of interest in the optimal method to produce heavy n-rich nuclei with MNT reactions





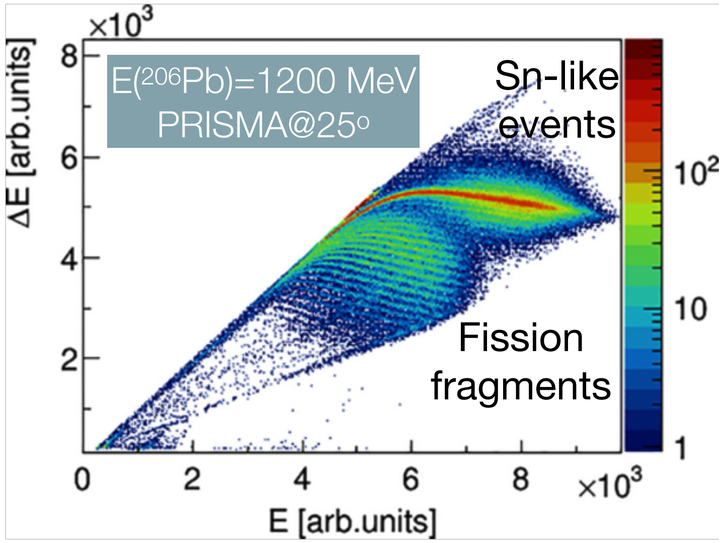


T. Mijatović et al., Phys. Rev. C 94 (2016) 064616

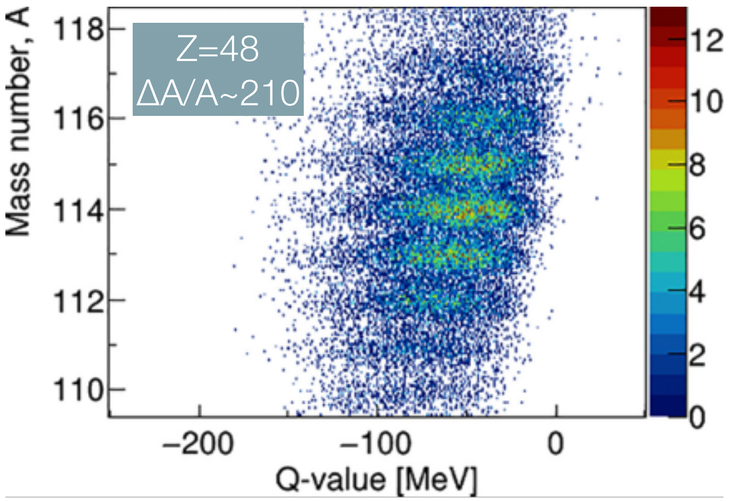
From quasi-elastic to deep-inelastic processes: the ^{206}Pb+^{118}Sn case

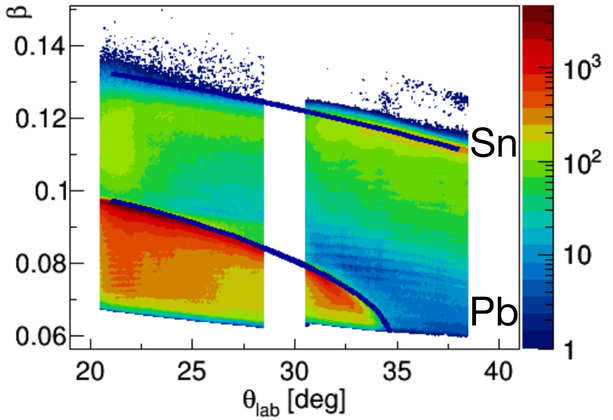
- The role of DIC was further studied in the heavy system with high Coulomb fields
- **^{206}Pb+^{118}Sn measured at 1200 MeV,** at 35° (grazing angle) and 25°
- Lighter fragment detected in PRISMA
- **MNT in inverse kinematics:**
  - Higher kinetic energy: energy and mass resolution
  - Forward focused angular distribution: efficiency
- A wealth of transfer channels identified in A, Z, and TKEL with high resolution

Excellent Z resolution



Excellent A resolution

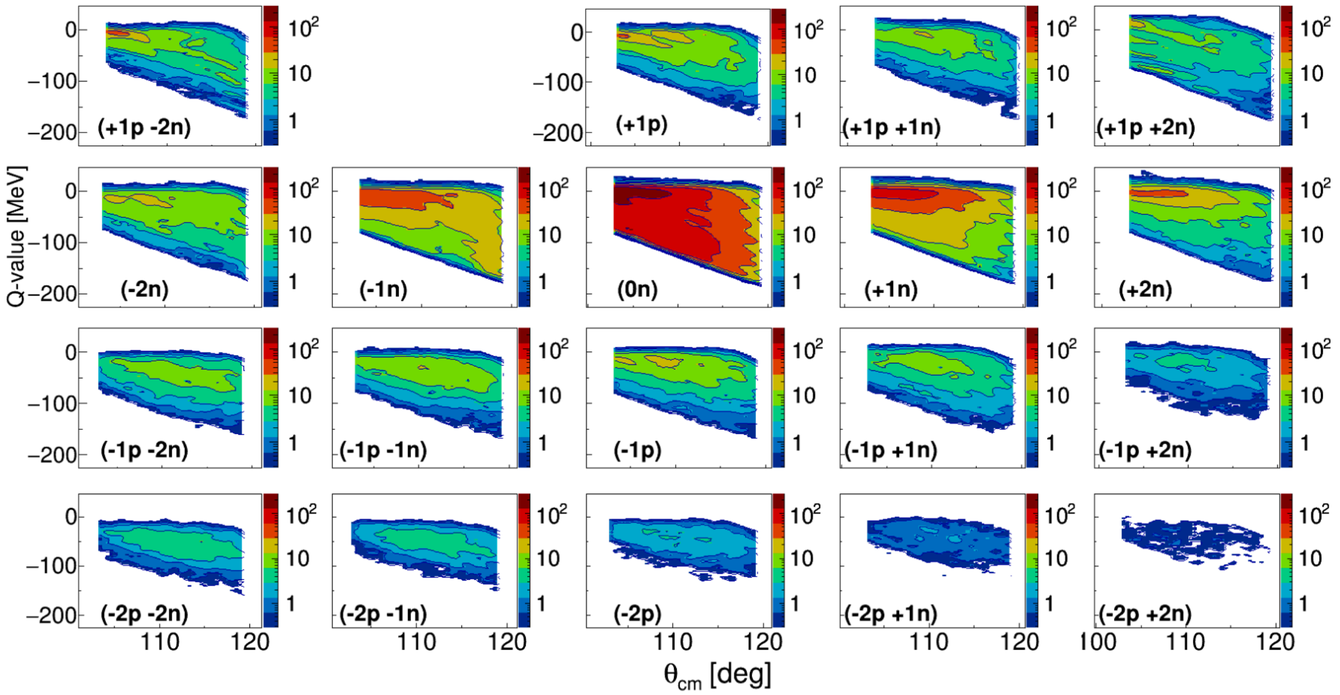




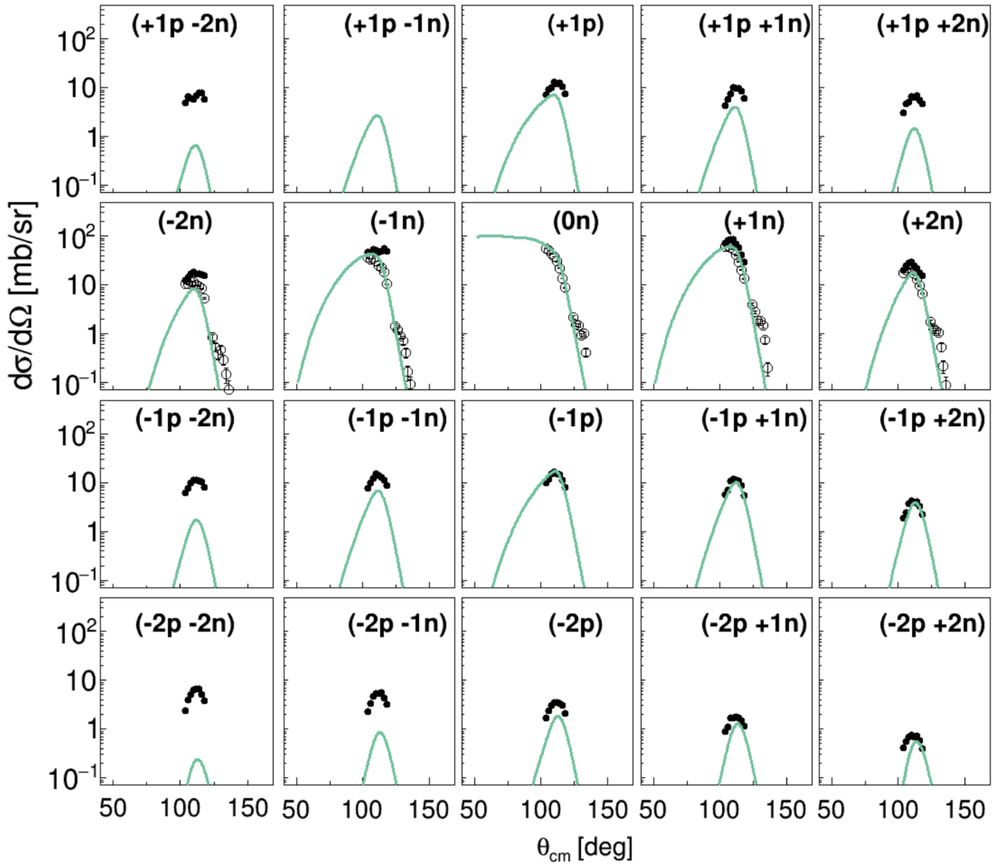
E(^{206}Pb)=1200 MeV
PRISMA@25° and 35°
35° is close to the limiting angle of Pb-like ions: Safe control of the correct geometry of the experiment

J. Diklić et al., Phys. Rev. C 107 (2023) 014619
S. Szilner et al., Phys. Rev. Lett., accepted

Q-value and angular distributions for the ^{206}Pb+^{118}Sn system



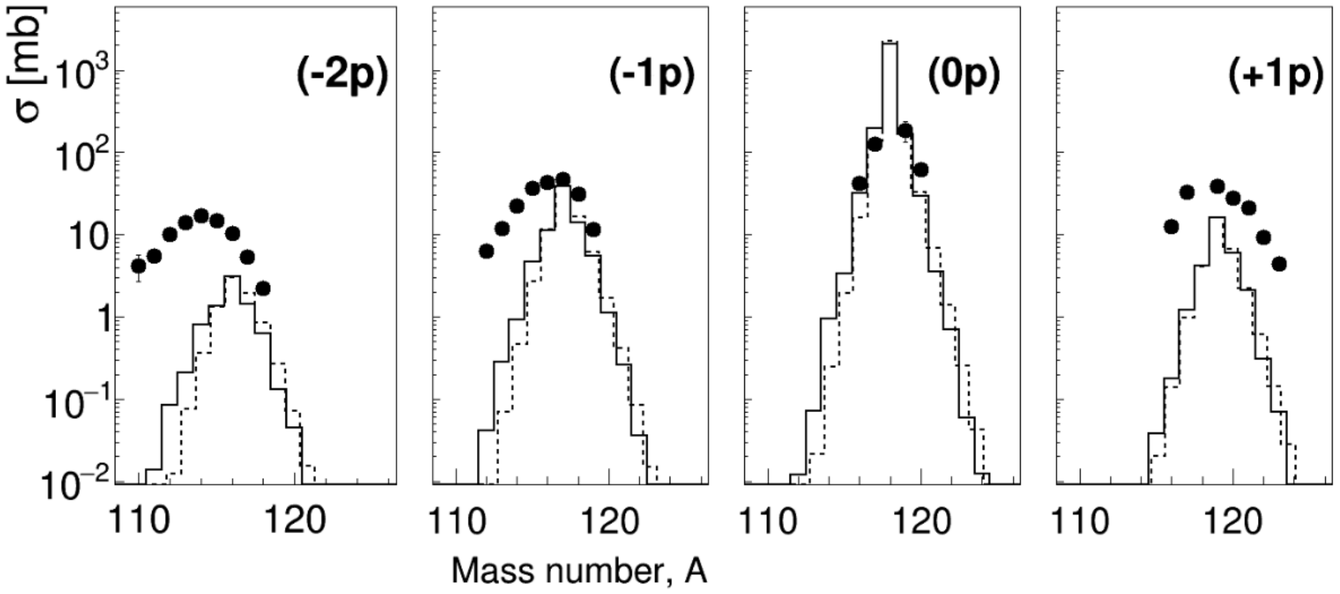
The yields of QE and DIC components depend on the angle.

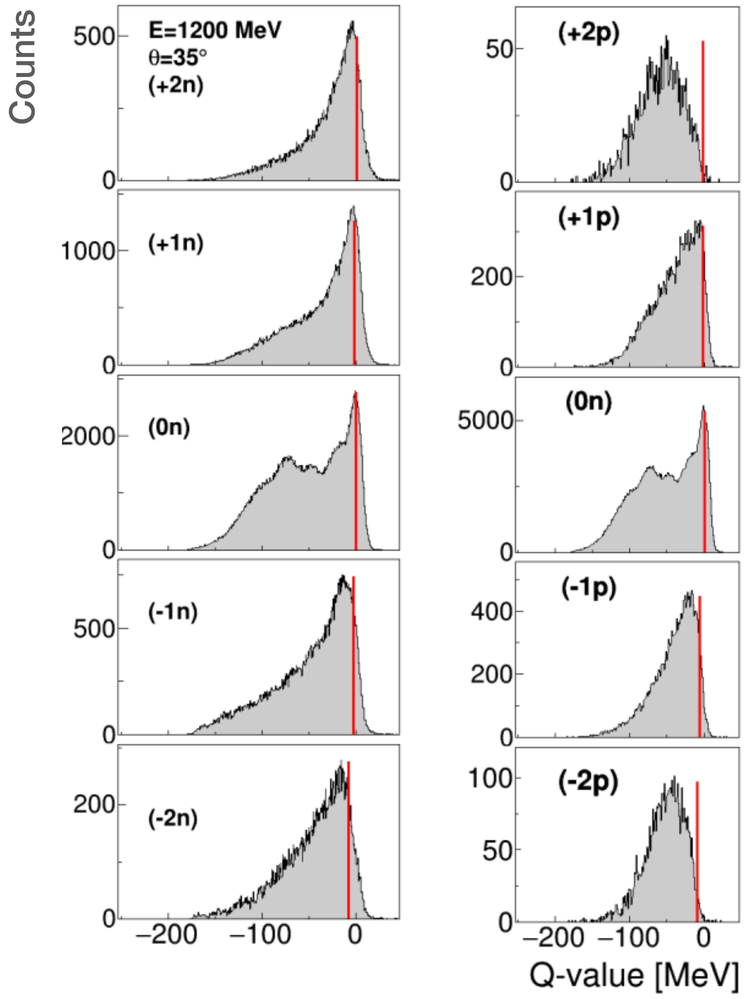


Experimental angular distributions compared with GRAZING. For few nucleon transfer channels, angular distributions retain the main characteristics of the direct process.

Cross section for the ^{206}Pb+^{118}Sn system

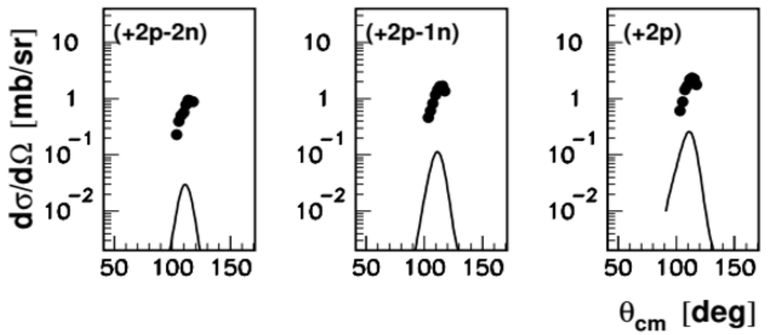
- Comparison with GRAZING:
  - An overall good agreement for most of few nucleon transfer channels
  - Proton stripping side: shift towards lower masses
  - Proton pick-up side: underestimation of the cross section

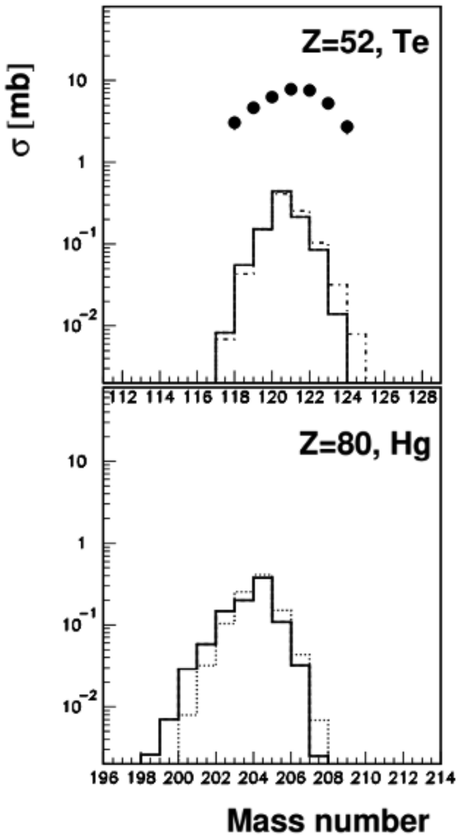


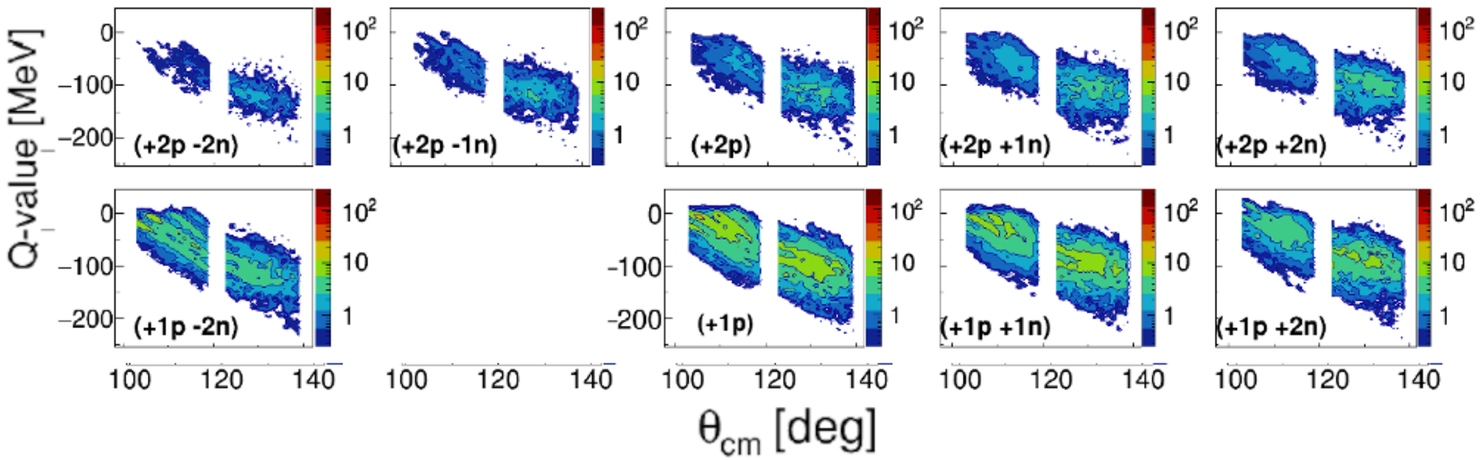


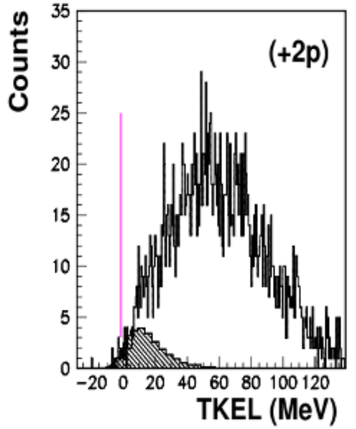
Synthesis of heavy neutron-rich nuclei

- GRAZING progressively underestimates yields as more nucleons are transferred - more complicated processes than a direct one
- Secondary processes may strongly modify the final cross section
- Important to study the survival probability of the heavy binary partner









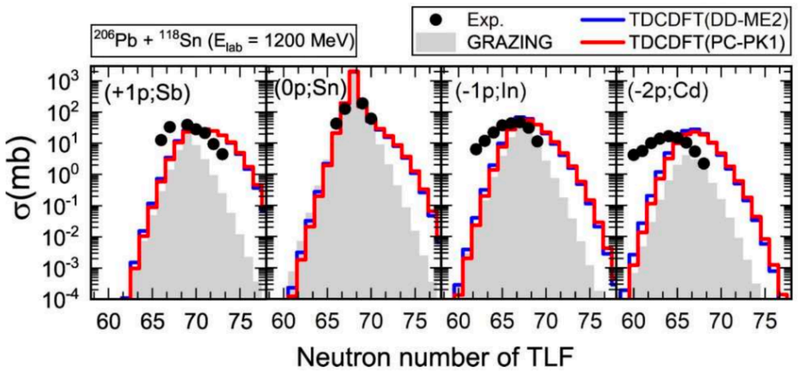
Theoretical interest for the ^{206}Pb+^{118}Sn system

- Recent cross section data quickly attracted theorist's interest
  - Time-dependent covariant density functional theory
  - Langevin dynamics
- Calculations have been done for the light partner: high-quality data about the heavy is still lacking
- In general, big interest in developing new models able to predict cross sections and effects of secondary process (coupled channel, semiclassical, TDHF, Langevin, QMD, DNS…)

PHYSICAL REVIEW C **109**, 024614 (2024)

Multinucleon transfer with time-dependent covariant density functional theory

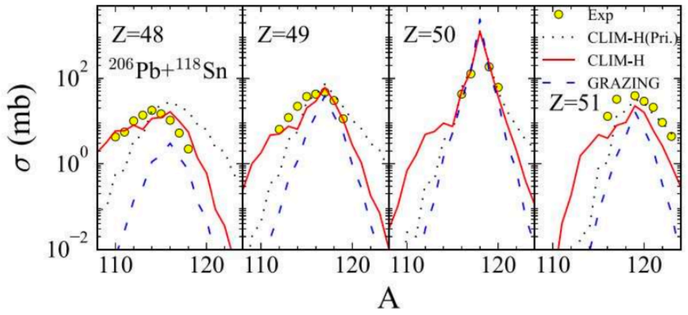
D. D. Zhang,[1] D. Vretenar,[2,1,*] T. Nikšić,[2,1] P. W. Zhao,[1,†] and J. Meng[1,‡]



PHYSICAL REVIEW C **109**, 024617 (2024)

Theoretical study of multinucleon transfer reactions by coupling the Langevin dynamics iteratively with the master equation

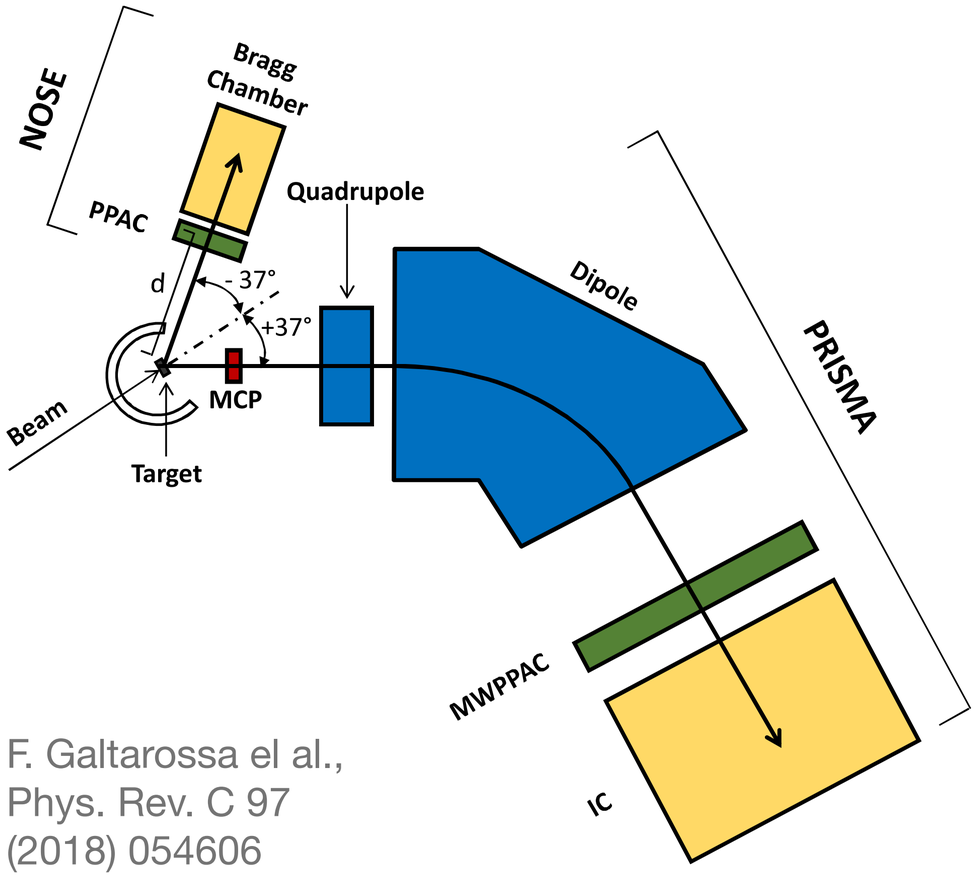
F. C. Dai,[1,2] P. W. Wen,[3,*] C. J. Lin,[3,4,†] J. J. Liu,[1] X. X. Xu,[1,2,5,‡] K. L. Wang,[1] H. M. Jia,[3] L. Yang,[3] N. R. Ma,[3] and F. Yang[3]



Study of the heavy partner: the ^{197}Au+^{130}Te case

- Important to understand the production mechanism for neutron-rich nuclei in the A=200 mass region and the effect of secondary processes on the final yields of fragments
- **^{197}Au+^{130}Te, 1070 GeV, inverse kinematics**
- PRISMA coupled to a second time-of-flight system NOSE, a gas detection system for fragment identification in low-energy heavy-ion collisions
  - Coincident detection of binary partners: PRISMA (Te-like) + NOSE (Au-like)
  - NOSE: solid angle ~1/3 PRISMA solid angle
- Study of the final mass distribution of the heavy partner and the effect of the secondary processes

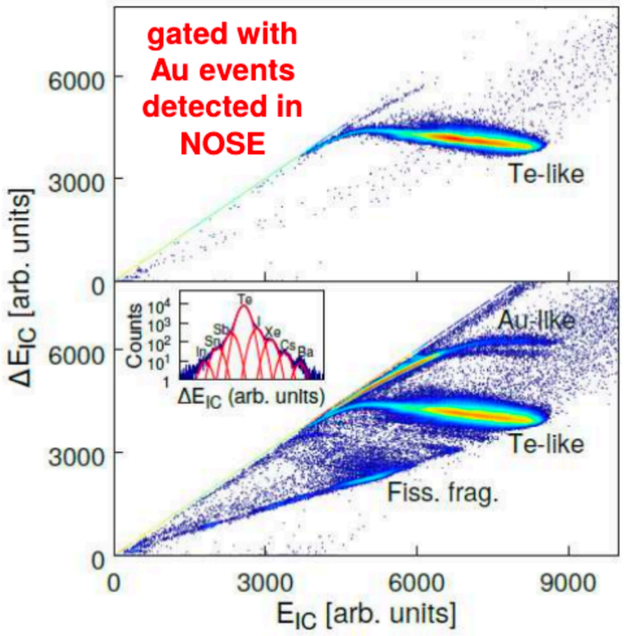
Before AGATA installation

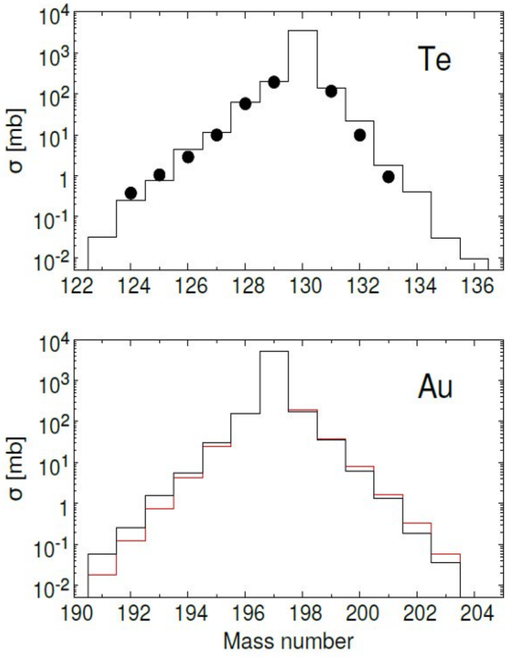


F. Galtarossa el al., Phys. Rev. C 97 (2018) 054606

Importance of secondary processes: ^{197}Au+^{130}Te

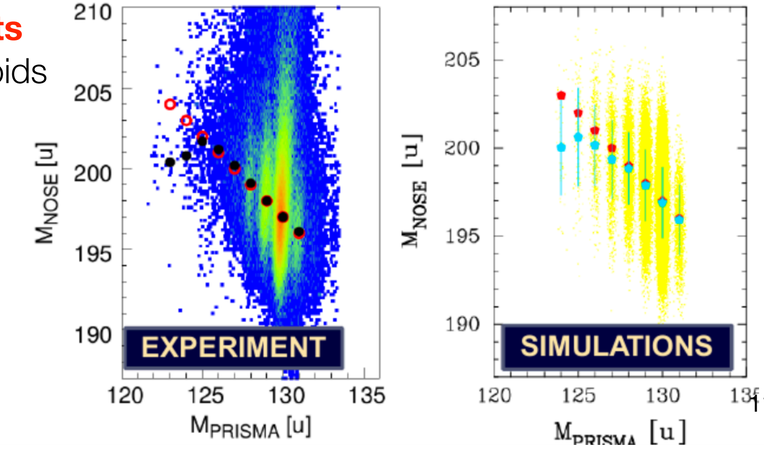
- Mass correlation between light and heavy reaction products
  - The mass distribution of the heavy partner separated in well defined bands, whose centroids and widths depend on secondary processes
  - The simulations incorporate a successive evaporation of neutrons taking into account the experimental TKEL distributions (to compute evaporation), the cross sections measured in PRISMA and the experimental resolution
  - Slight bend toward lower masses in comparison to those expected for the corresponding primary neutron transfer channels indicates that evaporation becomes relevant in defining the final yields
- MNT are suitable tool to populate heavy n-rich nuclei





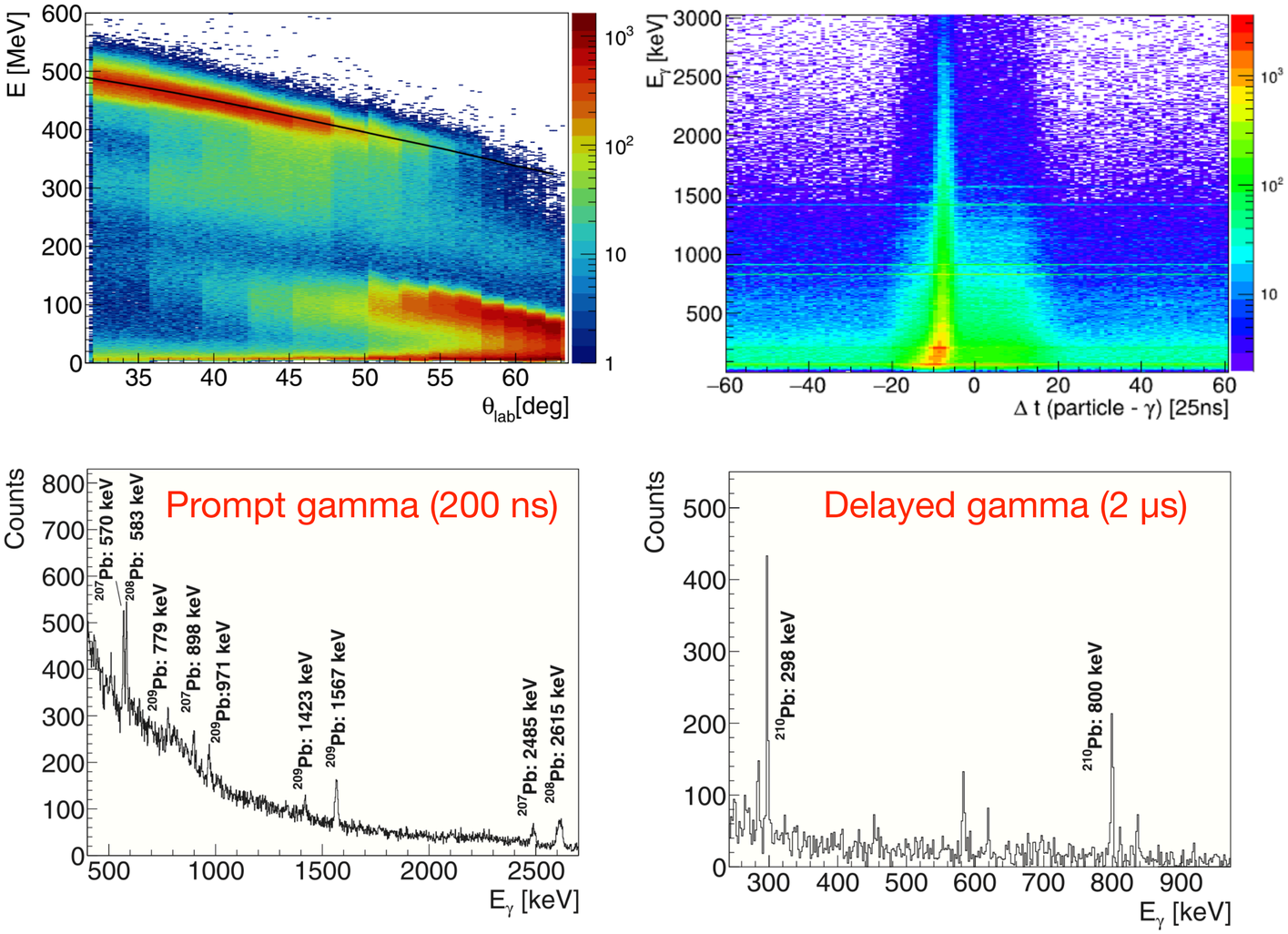
Red: primary fragments
Black: experimental centroids

F. Galtarossa el al., Phys. Rev. C 97 (2018) 054606



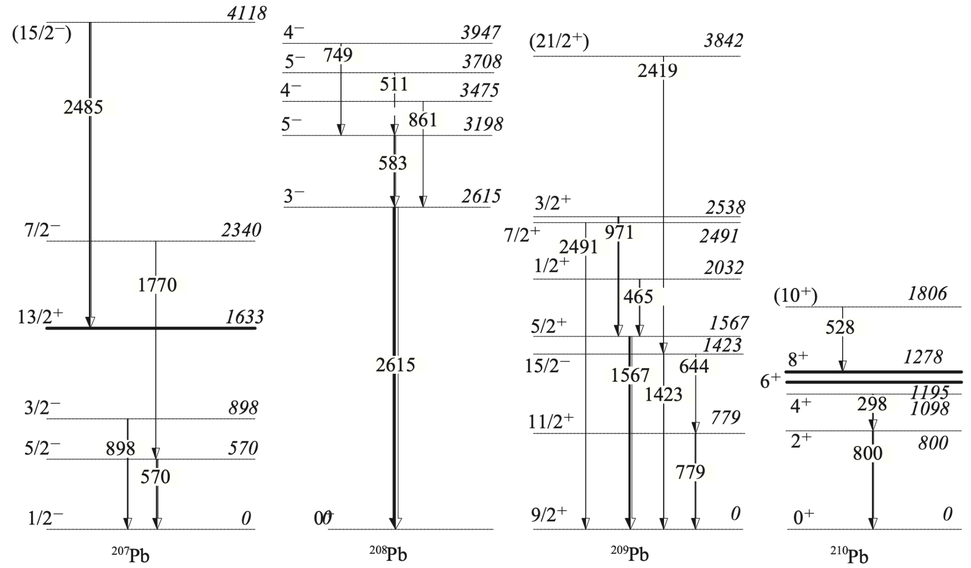
MNT with radioactive beams: the ^{94}Rb+^{208}Pb case

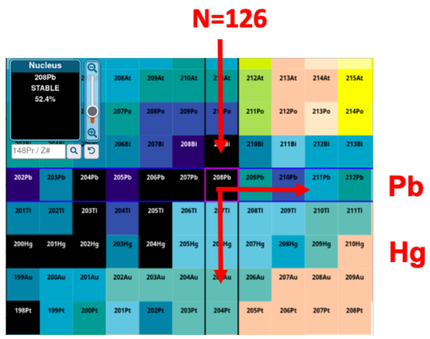
- Aim: To test multinucleon transfer (MNT) reactions for producing n-rich heavy nuclei
- **^{94}Rb+^{208}Pb, 6.2 MeV/u**
- ISOLDE - CERN: MINIBALL + CD particle detector
  - fragment-γ(-γ) coincidences
- Pb isotopes directly identified by the detection of their electromagnetic transitions
- Main γ-ray transitions for inelastic and neutron transfer channels
- Analysis of isomeric decay of ^{210}Pb



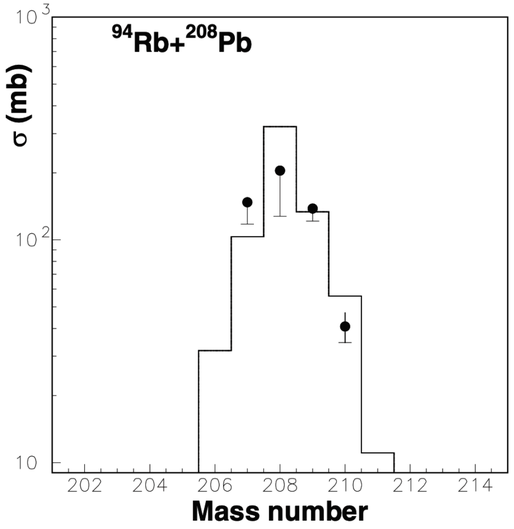
Cross sections with radioactive beam

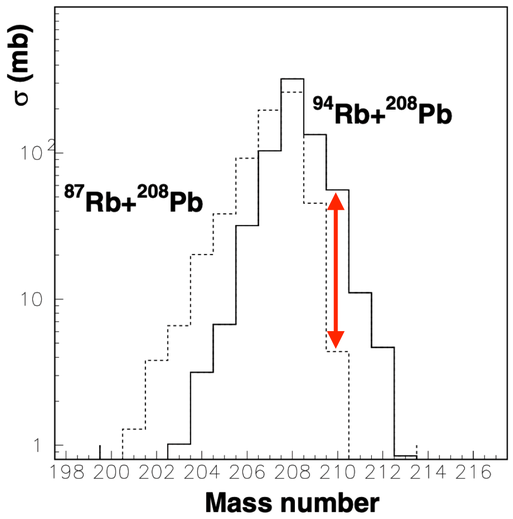
- The data show sizable cross sections for the n-rich mass region (in agreement with GRAZING)
  - Dominant cross section in the south-east region
- The calculated cross sections for Hg:
  - ^{87}Rb (the most neutron-rich stable) vs ^{94}Rb (RIB)
- Importance of increased beam intensities for further research

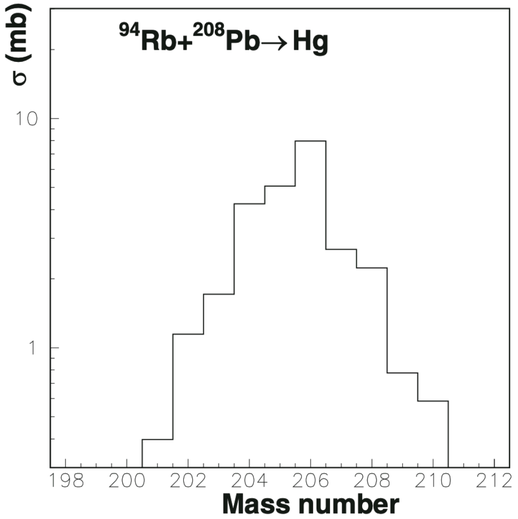




P. Čolović, et al.,
Phys. Rev. C 102 (2020) 054609

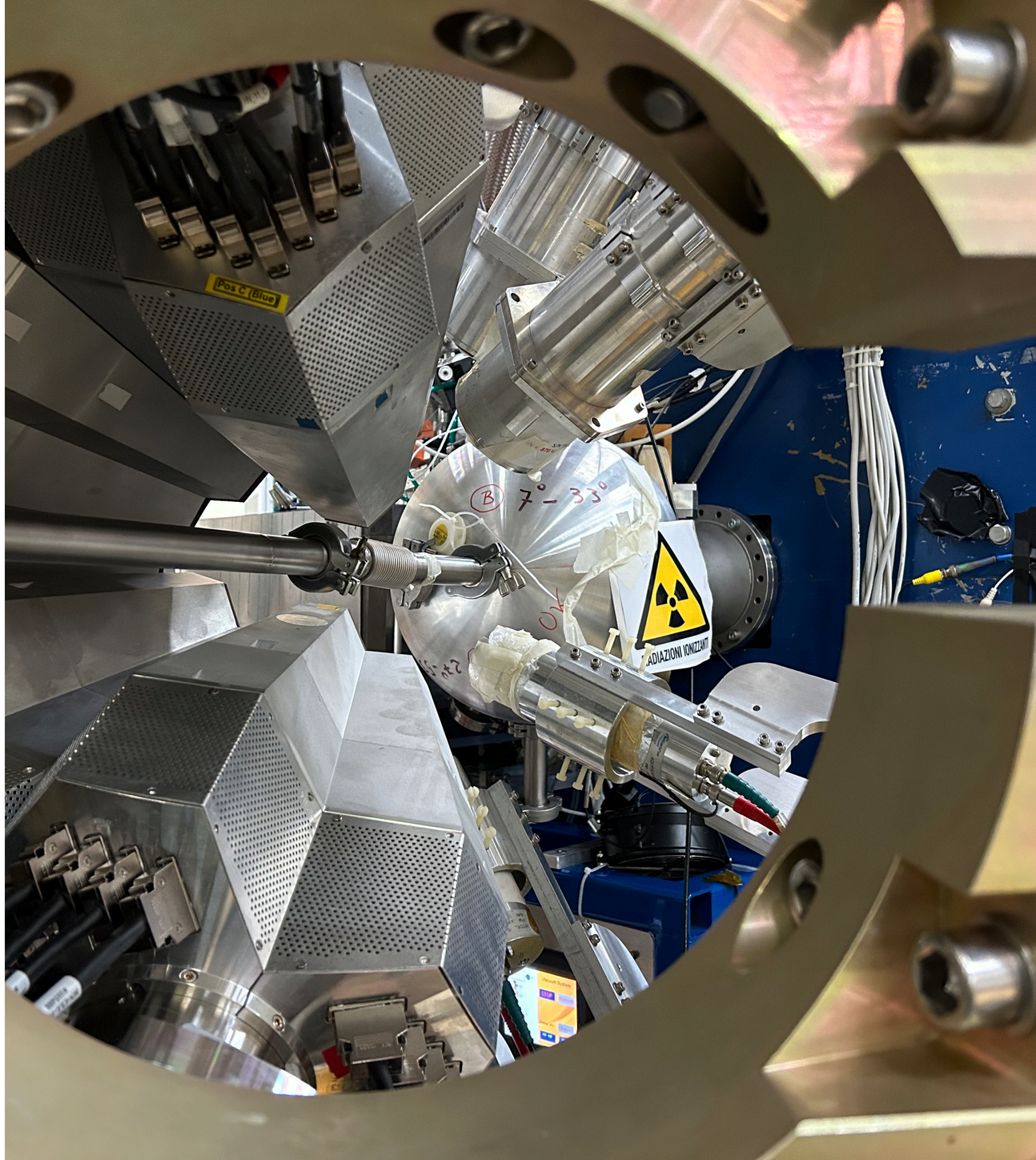






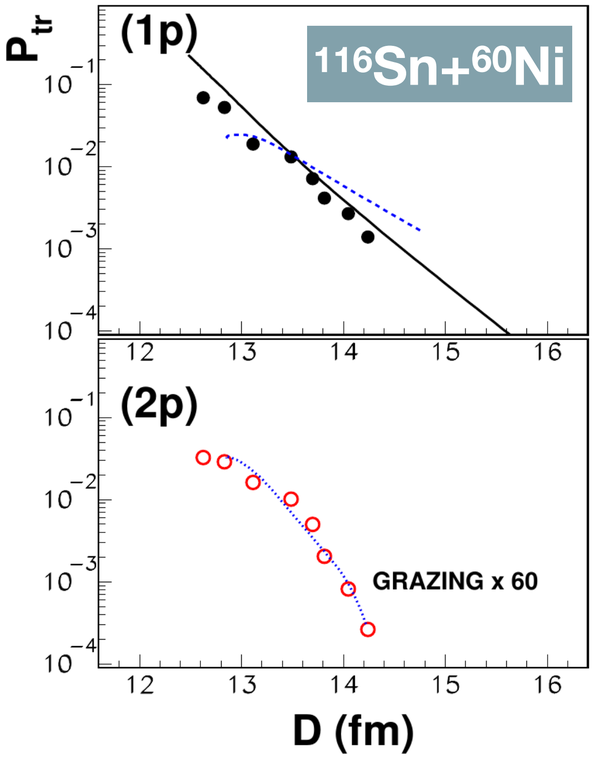
Proton transfer channels near and below the Coulomb barrier

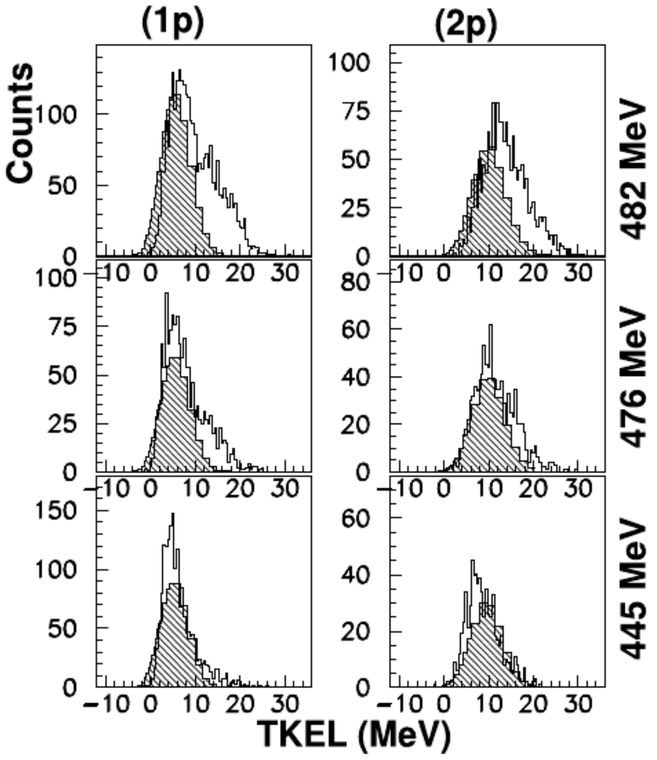
With some news from PRISMA-AGATA campaign



Nucleon-nucleon correlations with MNT reactions

- Two-particle transfer processes are an ideal tool to study the dynamical aspects of pairing correlations
- Heavy ions: in selected cases simultaneous comparison of ±nn, ±pp and ±np pairs
  - Proton pair transfer studies so far performed above the barrier: 2p cross section is enhanced
  - Below the barrier: experimental data very scarce
  - Large modification in the trajectories of entrance and exit channels due to the modification of the Coulomb field
  - Theoretically very challenging to reproduce





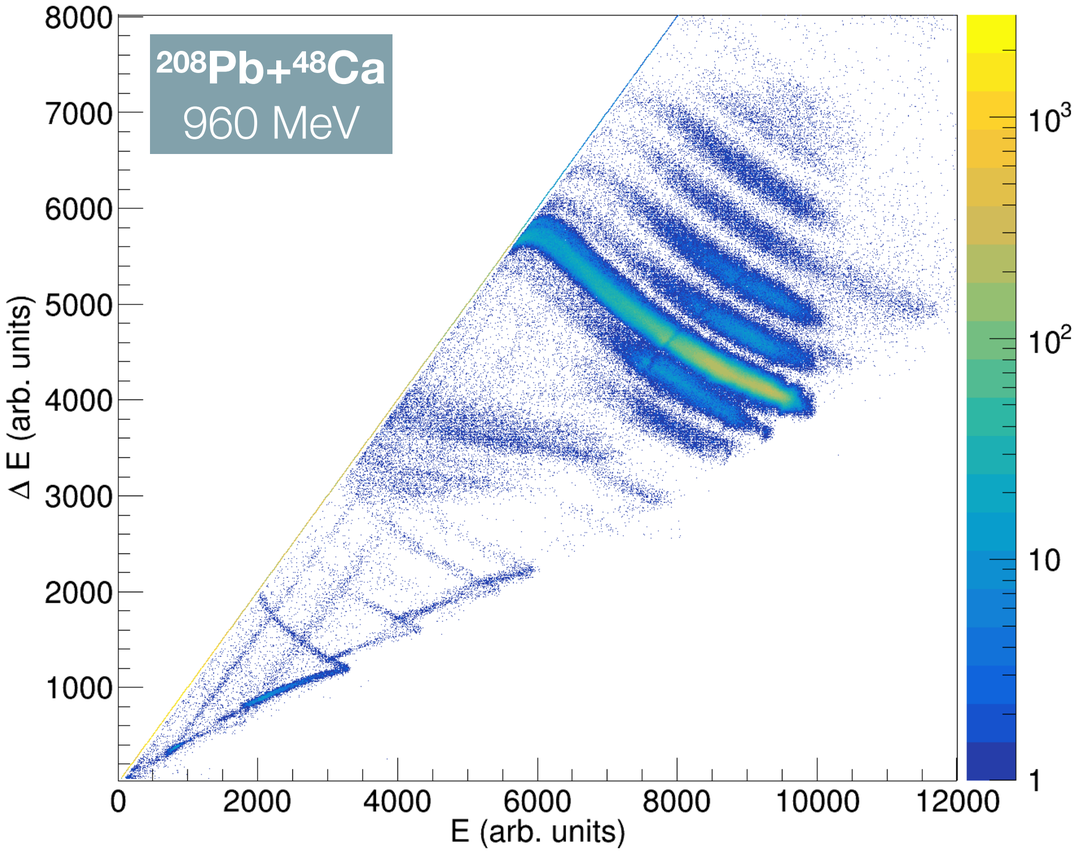
GRAZING calculation (independent nucleon transfer) is under-predicting Ptr (–2p) by a factor **60**

$$P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{el}};\ D = \frac{zZe^2}{2E}\left(1 + \frac{1}{\sin\frac{\theta}{2}}\right)$$

L. Corradi et al., PLB 834 (2022) 137477

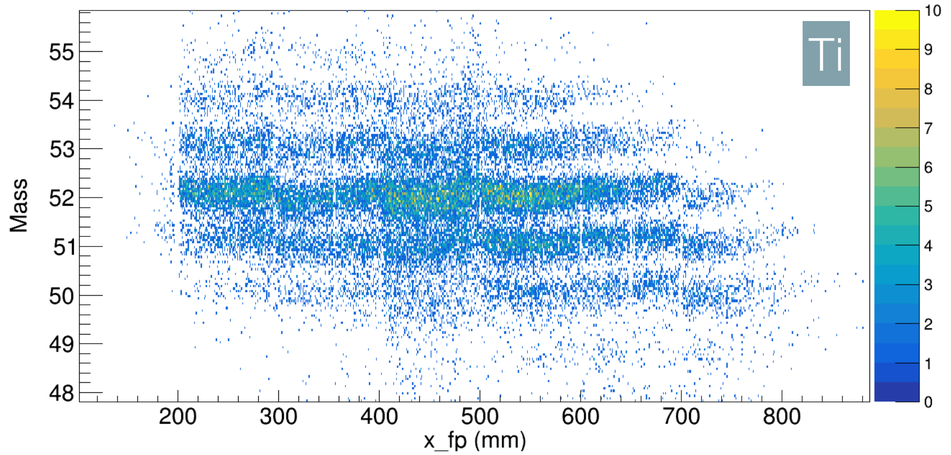
Probing nucleon-nucleon correlations: the $^{48}Ca+^{208}Pb$ case

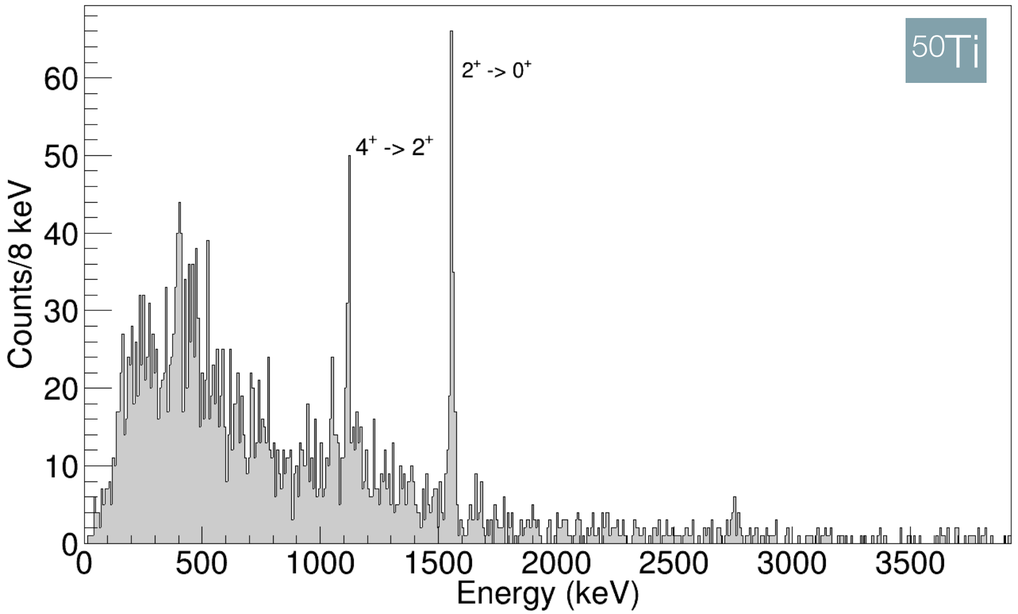
- Going towards more n-rich system, $^{48}Ca+^{208}Pb$:
  - Opportunity to investigate both addition and removal of n and p pairs, starting from doubly magic nuclei
  - Possibility to investigate correlations simultaneously for a complete set of transfer channels
- Exploring both pick-up and stripping channels should allow to better understand the relative contribution of pair transfer and DIC (below barrier DIC is much less)
- Measured at three bombarding energies with **PRISMA-AGATA**

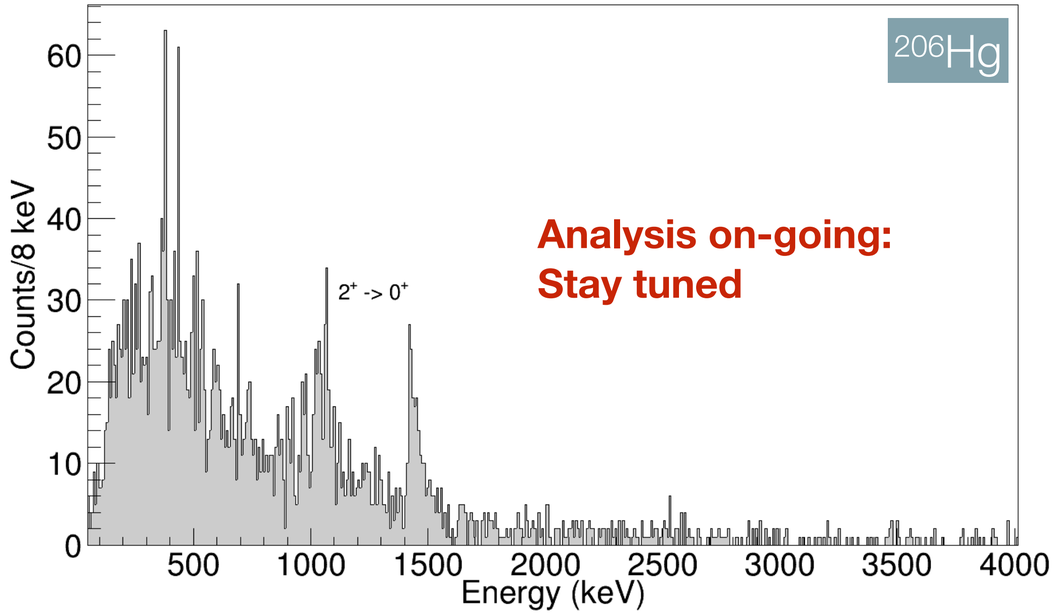


Preliminary results: the $^{48}Ca+^{208}Pb$ case

- Above the barrier: strong population of both +p and -p channels
- Below the barrier: p transfer channels diminished at a faster rate than predicted by theoretical models
- **Aim**: To get cross sections and other observables to test different reaction models, to study the production of n-rich heavy partner around the barrier







Analysis on-going: Stay tuned

Summary

- **Production of heavy neutron-rich with MNT reactions:**
  - the comparison between data and theory: elementary modes of the complex mechanism can be studied
  - still needed studies of the best selection of mass asymmetry and collision energy for the largest survival probabilities of heavy partners
  - new perspective: the use of neutron-rich projectiles (RIB)
- **Relative role of a transfer of one particle and pair of nucleons:**
  - sub-barrier transfer reaction measurement (nuclei interact at large distances)
  - the information about correlations are extracted when experimental absolute cross sections are compared with a microscopic theory which beside correlations includes the coupling between relative motion (reaction) and intrinsic motion (structure)

Thank you!

And a big thank you to all the AGATA-PRISMA collaboration!

S. Szilner, L. Corradi, G. Pollarolo, F. Galtarossa, P. Čolović, J. Diklić, A. Goasduff, D. Montanari, E. Fioretto, A.M. Stefanini, G. Montagnoli, G. Colluci, J.J. Valiente-Dobon, D. Mengoni, D. Jelavić Malenica, N. Soić, N. Vukman, M. Milin, A. Gottardo, T. Marchi, M. Siciliano…

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INFN and Universita di Padova, Padova, Italy University of Zagreb, Croatia
ISOLDE, CERN

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