# Population of heavy neutron-rich nuclei in multinucleon transfer reactions

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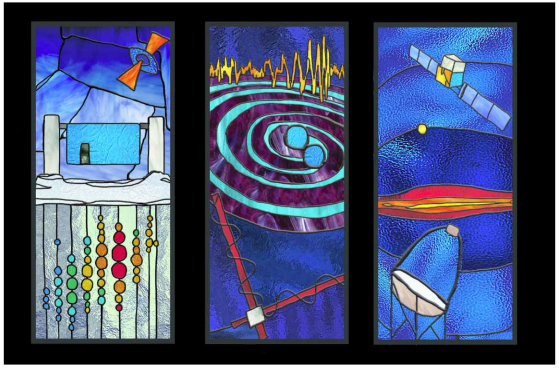
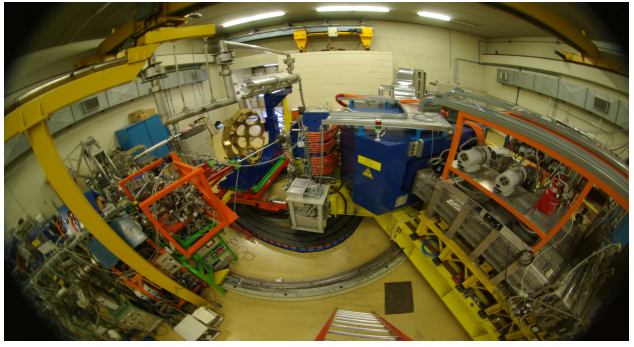
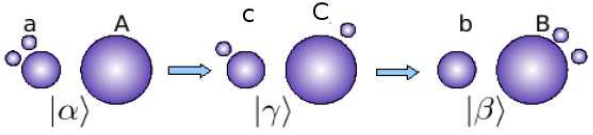
**Ruđer Bošković Institute, Zagreb**
**PRISMA collaboration**





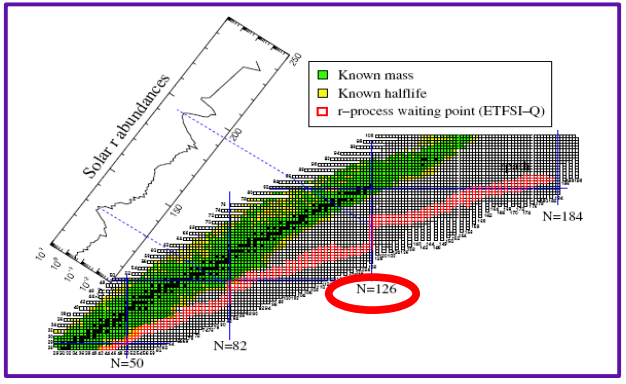


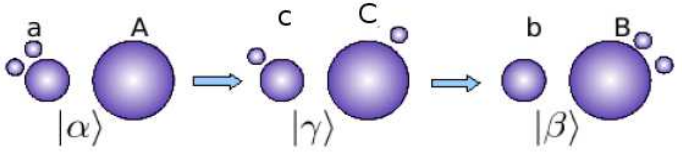

**ECT*, The Physics and Chemistry of the Heaviest Elements, Trento, 2026**

# Multinucleon transfer reactions

→A suitable tool for the production of neutron rich heavy nuclei, especially in the N=126 region.
→It is important to follow the evolution from the quasi-elastic to deep-inelastic regimes. These large energy losses may strongly influence the final yield distributions.
→It is important to measure the survival probability of neutron-rich isotopes.

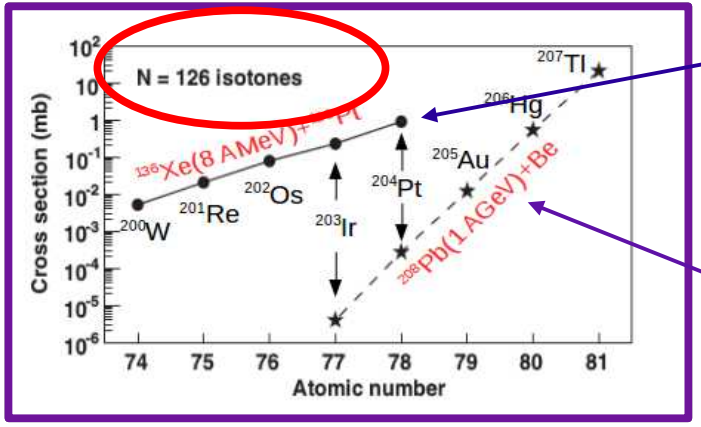
**NUCLEON-NUCLEON CORRELATIONS**
→Pairing leads to the modification of the level densities near the ground states, the odd-even staggering of nuclear masses...
→These structure properties may influence in a significant way the evolution of the collision of two nuclei.
→The low energy region is characterized by low transfer cross sections (difficult to preserve the high resolution and detection efficiency).



# Synthesis of heavy neutron rich nuclei

relativistic energies : fragmentation reactions
energies close to the Coulomb barrier : multinucleon transfer reactions
→ high primary cross sections ~ μb – nb range
→ secondary processes (evaporation and transfer induced fission)
→ the main contribution (heavy neutron-rich nuclei) → collisions with a small kinetic energy dissipation, where neutron evaporation is minimized
→ detection systems: large solid angle, large efficiency, large selectivity…

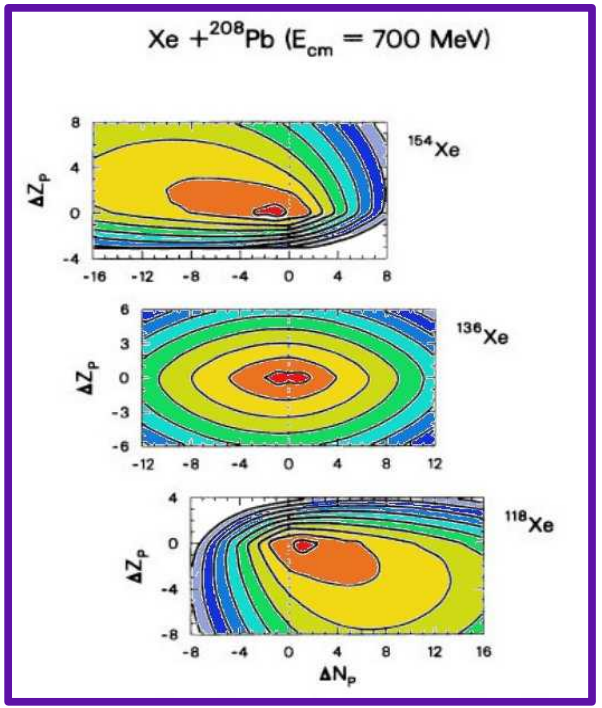



multinucleon transfer reactions: $^{136}$Xe + $^{198}$Pt @ $E_{lab}$ = 8 MeV/A

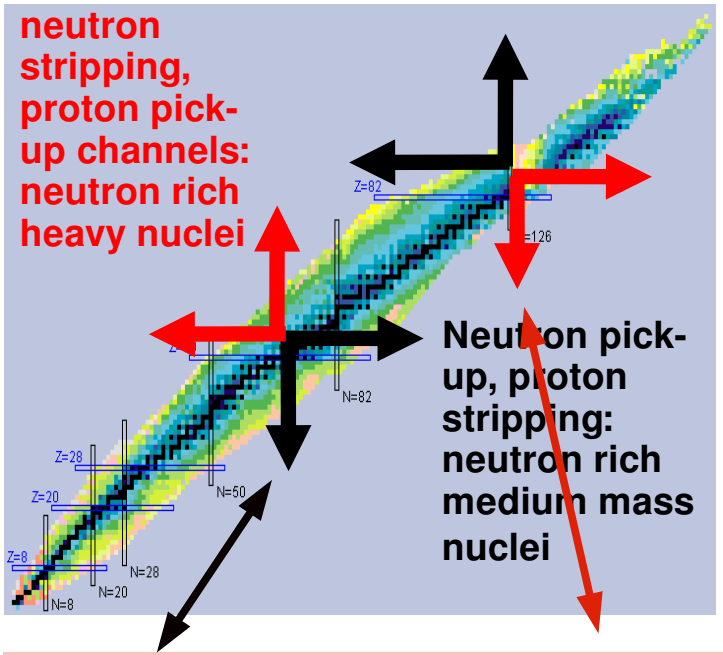
fragmentation reactions:
$^{208}$Pb + $^{9}$Be @ $E_{lab}$ = 1 GeV/A

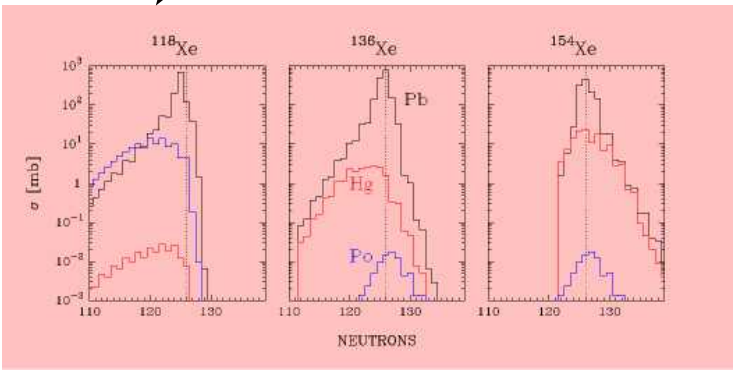
Y. Watanabe et al, Phys. Rev. Lett. 115 (2015) 172503, T. Kurtukian-Nieto et al., Phys. Rev. C 89 (2014) 024616.

# Multinucleon transfer reactions



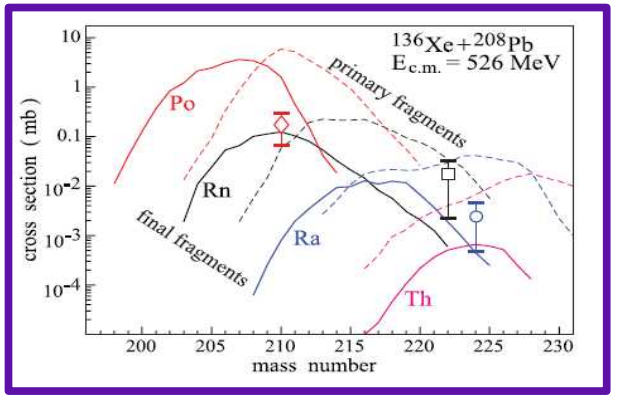

Xe (Z=54)
$^{118}$Xe ($T_{1/2}$ = 4 min)
$^{136}$Xe (“the last” stable)
$^{154}$Xe (no information)



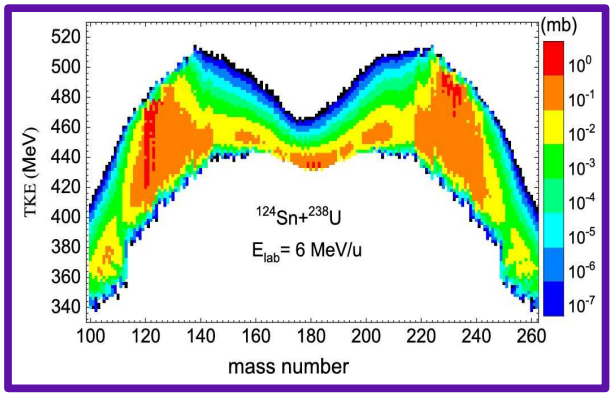




C.H. Dasso, G. Pollarolo and A. Winther, Phys. Rev. Lett. 73 (1994) 1907.

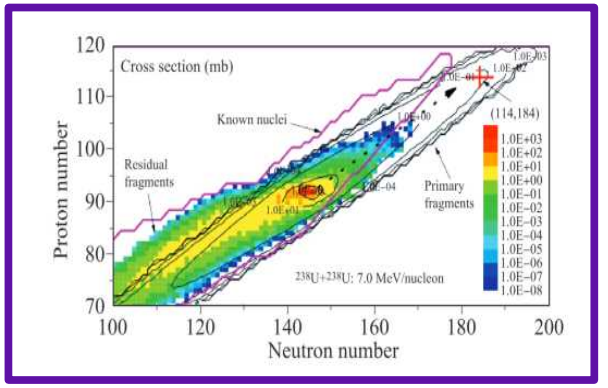
# Multinucleon transfer reactions : theory



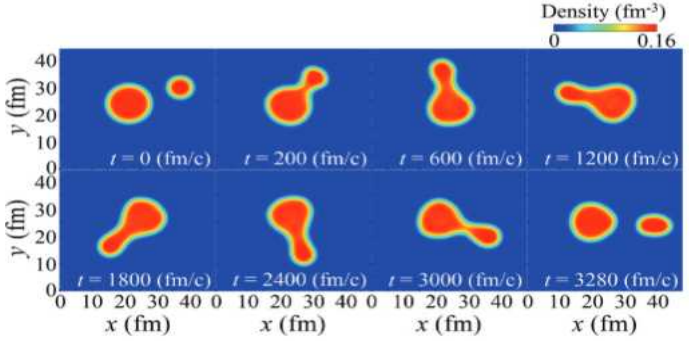

**Langevin-type approach:**V. Zagrebaev, W. Greiner, Phys. Rev. Lett. 101 (2008) 122701




**the dinuclear system model:** Peng-Hui Chen et al., Phys. Rev. C 101, 024610 (2020)




**the improved quantum molecular dynamics model (ImQMD):**Y.X. Zang et al., Front. Phys. 15 (2020) 54301




**TDFH based theory:** K.Sekizawa, K.Yabana, Pys. Rev. C 88 (2013) 014614; K. Sekizawa, Front. Phys. 7 (2019) 20
C. Simenel, A.S. Umar, Progress in Part. and Nucl. Phys. 103 (2018) 19
D.D. Zhang, D. Vretenar et al., Phys. Rev. C 109 (2024) 024614

→ see **Dandan Zhang talk**: Microscopic description of multinucleon transfer reactions

# Multinucleon transfer reactions: experiment

INSTRUMENTAL:
→ large solid angle spectrometer PRISMA
→ inverse kinematics: “higher” kinetic energy of recoil (energy and mass resolution) and forward focused angular distribution (efficiency)
→ coincident detection of the light and heavy binary partners
→ coincident detection of fragments and gammas

## $^{206}Pb+^{118}Sn$

→ PRISMA
→ lighter fragments
→ very heavy system (high Coulomb field)
→ evolution from the quasi-elastic to deep-inelastic regimes

J. Diklic, S. Szilner, L. Corradi et al., Phys. Rev. C 107 (2023) 014619;
S. Szilner, L. Corradi et al., Phys. Rev. Lett. 133 (2024) 202501

## $^{197}Au+^{130}Te$

→ PRISMA + NOSE
→ fragment – fragment
→ to study the final mass distribution of the heavy partner and the effect of secondary processes

F. Galtarossa, L. Corradi, S. Szilner et al., Phys. Rev. C 97 (2018) 054606

## $^{238}U+^{124}Sn$

→ PRISMA + NOSE + AGATA
→ fragment – fragment - gamma
→ to study the final mass distribution of the heavy partner

LNL, PRISMA+NOSE+AGATA measurement, 2026: L. Corradi et al., B. Sulignano et al.

# Multinucleon transfer reactions in $^{206}Pb+^{118}Sn$

**THE EXPERIMENT:**

→ $^{206}Pb+^{118}Sn$

→ inverse kinematics

→ lighter (target-like) fragments were detected in the large solid angle magnetic spectrometer **PRISMA** at INFN – LNL, Legnaro

→ $E_{lab}(^{206}Pb)$ = 1200, 1090 and 1035 MeV, $\theta_{lab}=35^0$ and $25^0$ ($\theta_{cm}=100^0$-$140^0$)

→ differential and total cross sections, total kinetic energy loss distributions, Wilczynski plots

position in MCP: $X_i$,$Y_i$

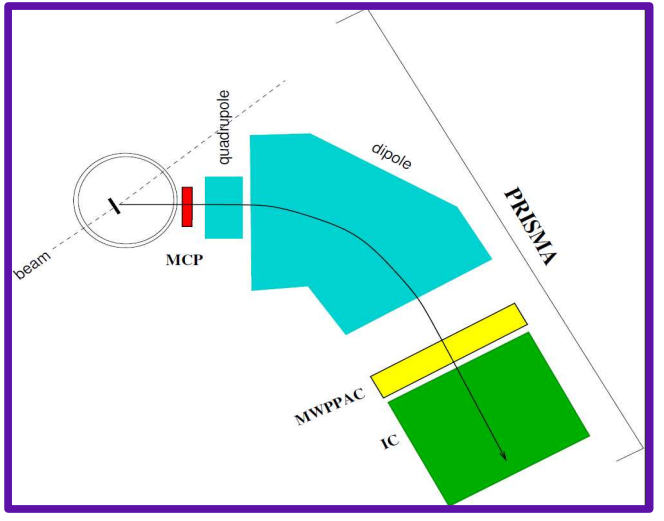
focal plane position: $x_f$,$y_f$

Time of Flight: ToF = $t_f$ - $t_i$

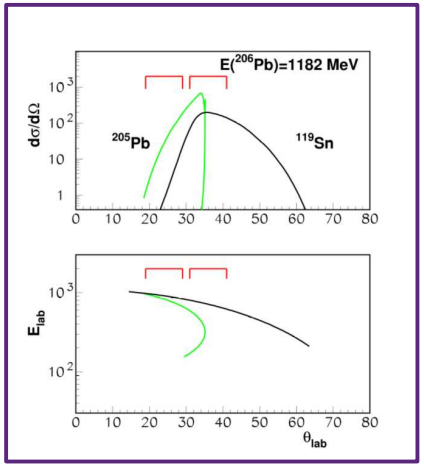
IC energy loss, total energy: ΔE, E

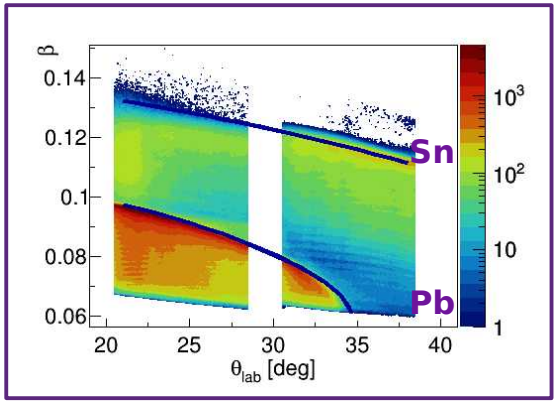
event-by-event trajectory reconstruction

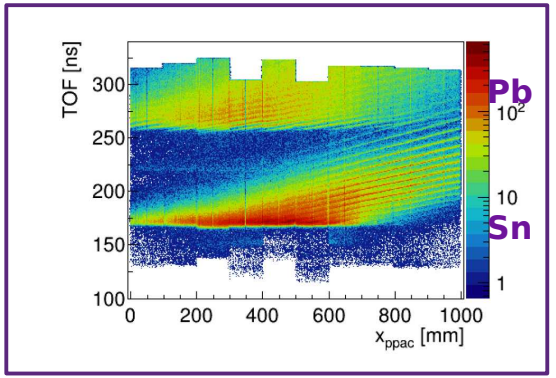
A, q, Z, E, v
mass, charge, atomic state, energy, velocity

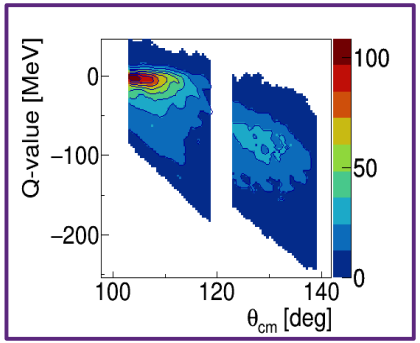


# From quasi-elastic to deep inelastic collisions: $^{206}$Pb+$^{118}$Sn

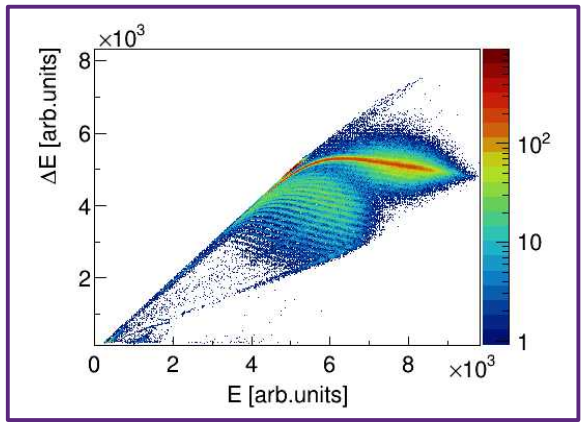


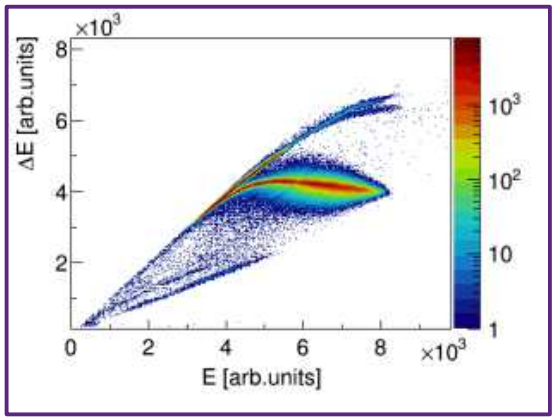



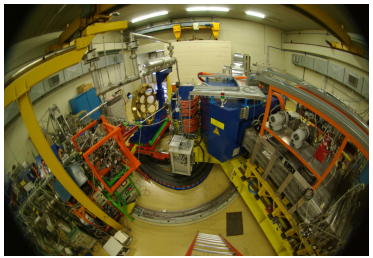




→ $^{205}$Pb+$^{119}$Sn (+1n)



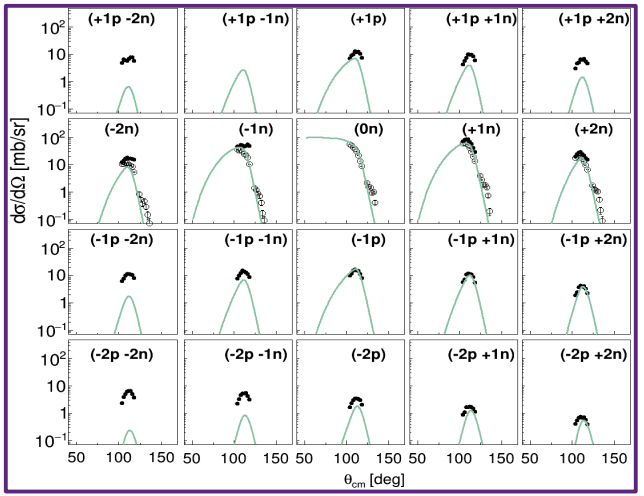



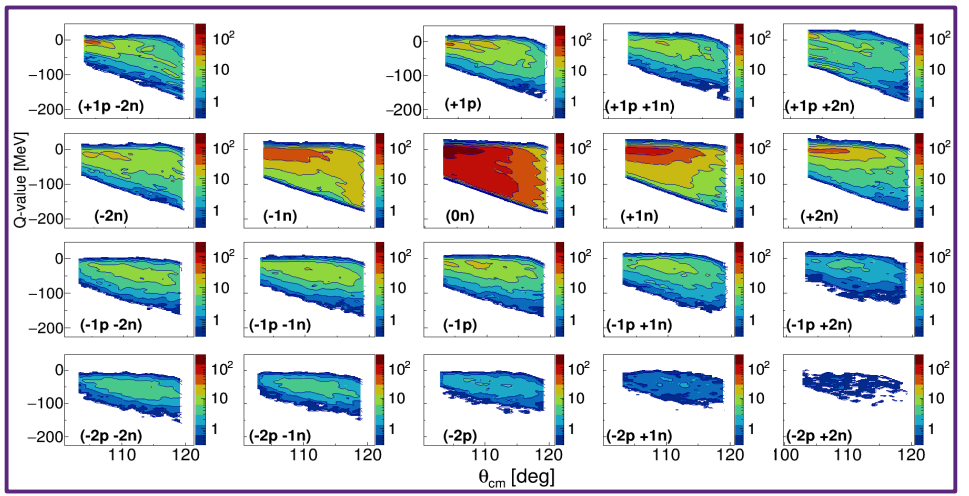

The yields of **QE** and **DIC** components (and fission fragments) strongly depend on (both) bombarding **energy** and **angles**.



J. Diklic, S. Szilner, L. Corradi et al., Phys. Rev. C 107 (2023) 014619

# From quasi-elastic to deep inelastic collisions: $^{206}$Pb+$^{118}$Sn



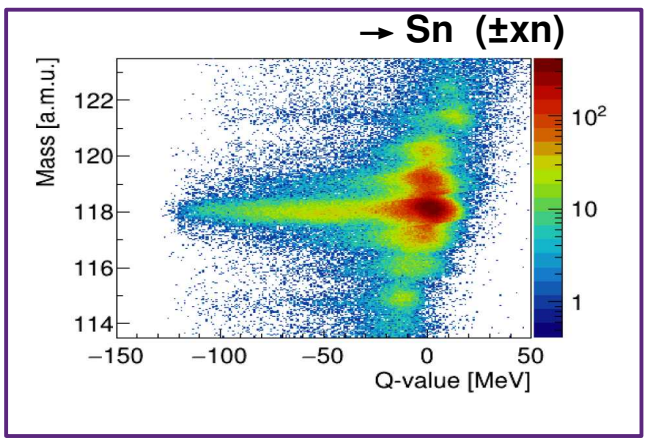



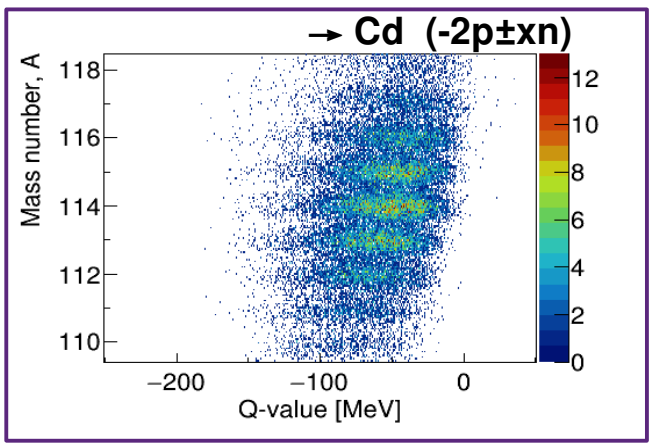

**Sb (+1p±xn)**

**Sn (±xn)**

**In (-1p±xn)**

**Cd (-2p±xn)**

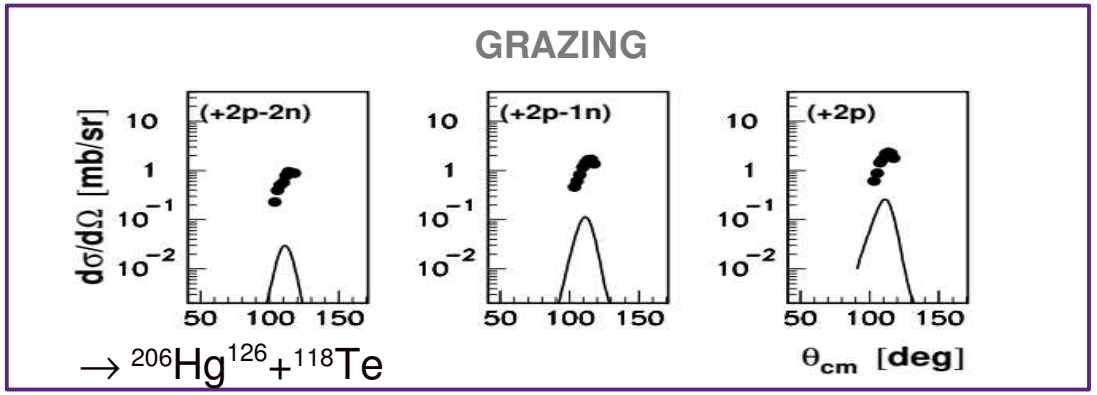



**Few nucleon transfers** → the main observables, Q values, and cross sections, retain the main characteristics of **direct processes** → well described with **GRAZING**

**GRAZING** progressively underestimates yields as more nucleons are transferred → more **complicated processes** than a direct transfer

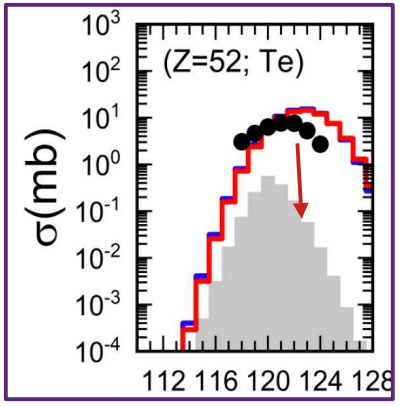
# Synthesis of heavy neutron-rich nuclei: $^{206}$Pb+$^{118}$Sn

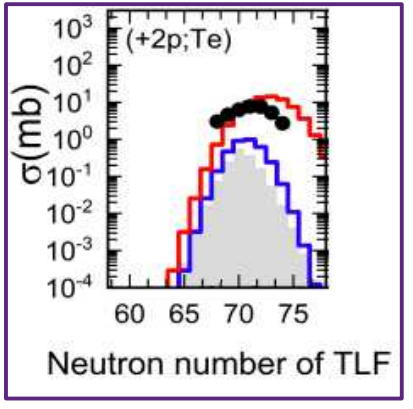



→ **GRAZING** vs. **TD-CDFT** (time-dependent covariant density functional theory) by D.D. Zhang et al. Phys. Rev. C 109 (2024) 024614

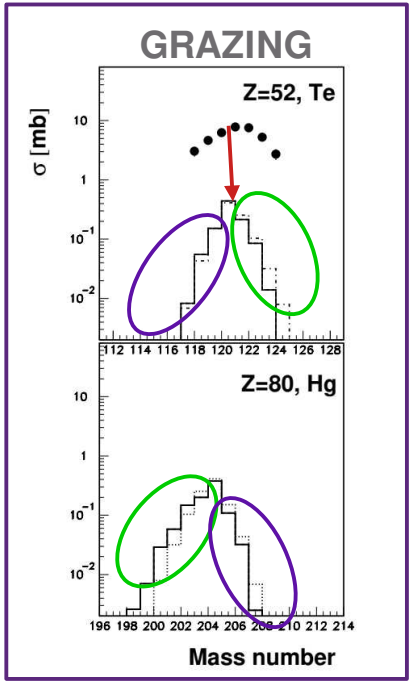
→ TD-CDFT well describes total cross sections for the (+2p), Te+Hg, channels

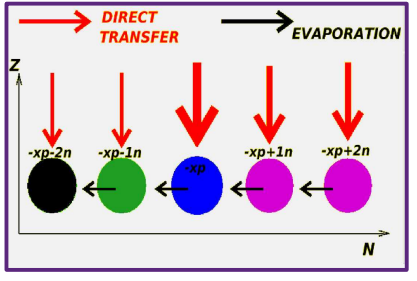
→ Large energy losses lead to a reshuffling in the final yield distributions → **secondary processes** may strongly modify the final cross sections → **survival probability** of the heavy binary partner



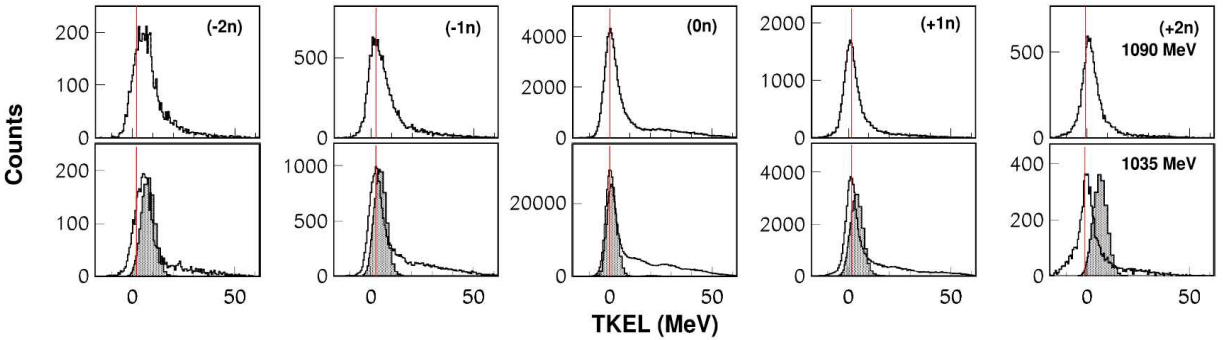




S. Szilner (data) and D.D. Zhang (TD-CDFT) et al, preliminary results for (+2p)



# Quest for Cooper Pair Transfer in Heavy-Ion Reactions: The $^{206}$Pb+$^{118}$Sn Case

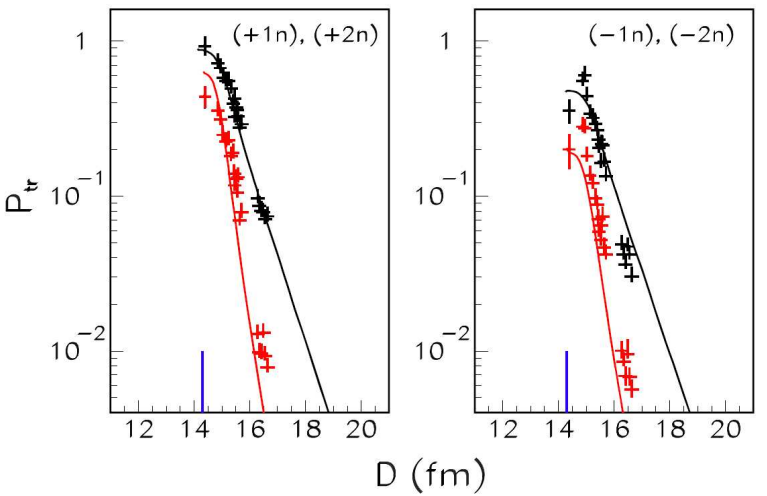



The TKEL distributions are very narrow, typical of scattering at sub-barrier energies, and with most of the events close to the ground-to-ground-state transitions. Tails reflecting large energy loss components are still visible, though they did not affect significantly the evaluation of the quasielastic components.

**$^{206}$Pb+$^{118}$Sn → QE and DIC** → a proper selection of the bombarding energies (the internuclear distances) is mandatory.

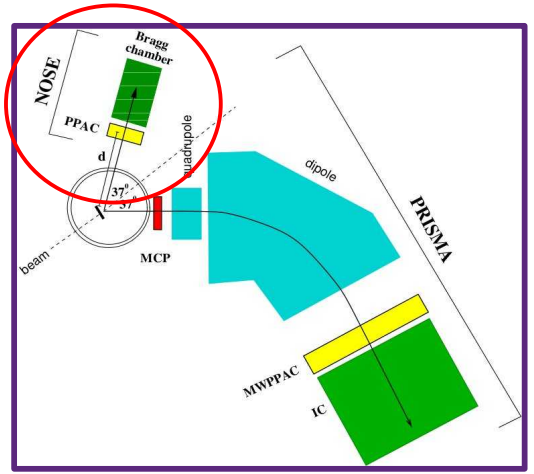
The experimental transfer probabilities for the one-neutron transfers are well reproduced by the theory – **GRAZING (independent particle transfer mechanism)**.

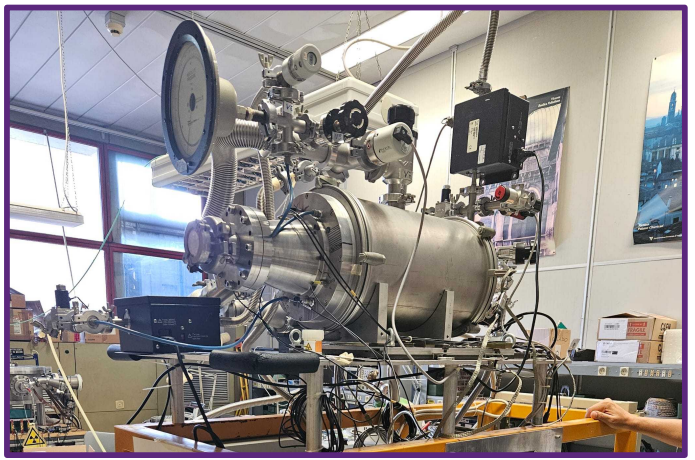
The experimental probabilities for the **two-neutron** transfers are slightly **underpredicted** (by a factor ≤ 2) → a measure of the effect of two-particle correlations

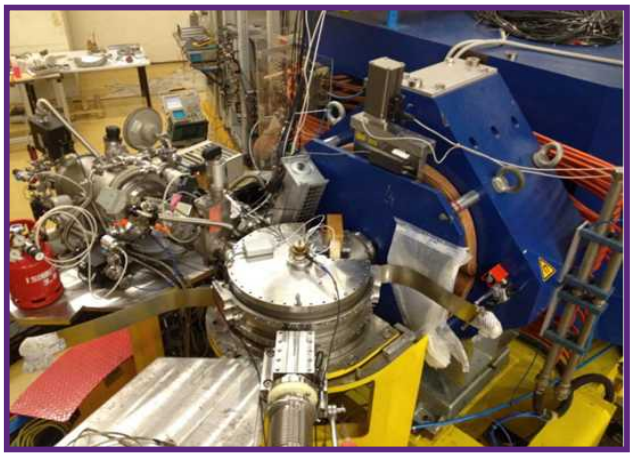


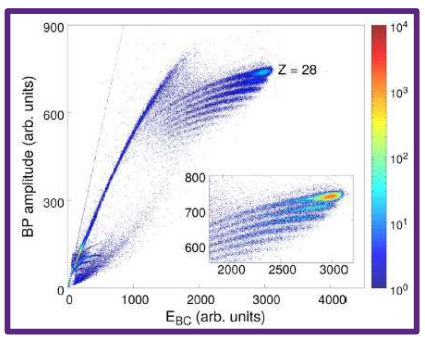

S. Szilner, L. Corradi et. al., Phys. Rev. Lett. 133 (2024) 202501

# Coincident detection of binary partners: $^{197}$Au+$^{130}$Te and $^{238}$U+$^{124}$Sn



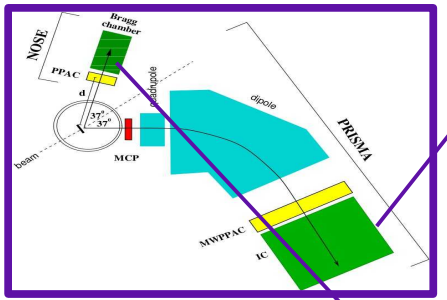


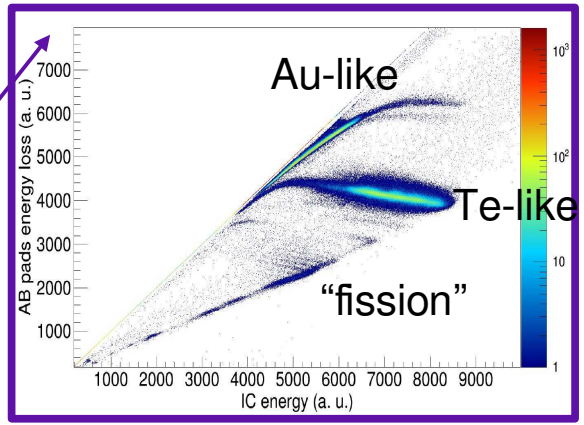


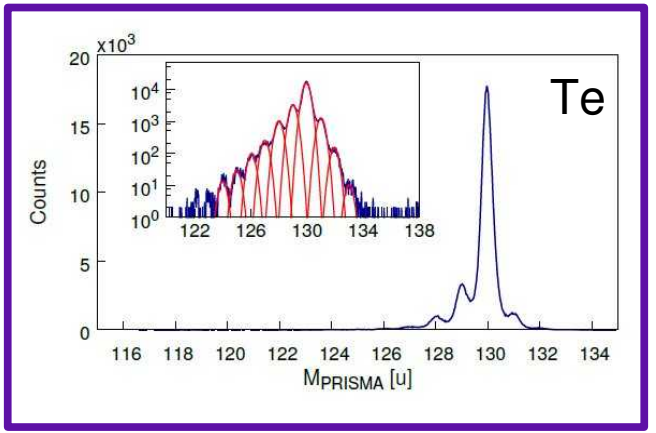

E. Fioretto et al. Nucl. Inst. and Meth. A 899 (2018) 73

Coincident detection of binary partners: PRISMA (target-like) + NOSE (beam-like)
NOSE: (solid angle ~1/3 of PRISMA): PPAC (multiwire parallel-plate avalanche counter) + ionization chamber (an axial-field ionization chamber, Bragg chamber)
→ time signal, 2-dim position signal (the time and position resolution similar as in PRISMA, ~1mm, ~350ps)
→ identification through the Bragg peak, total energy, and range

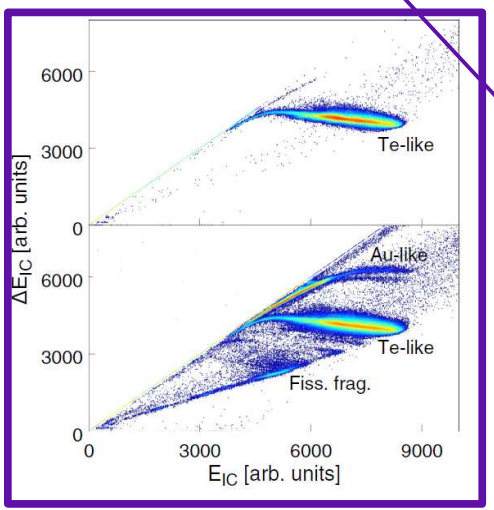
# $^{197}$Au+$^{130}$Te: coincident detection of binary partners

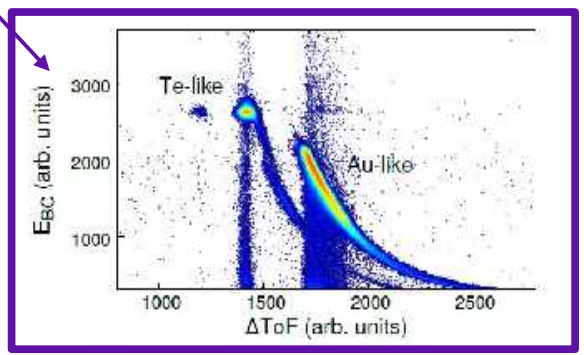


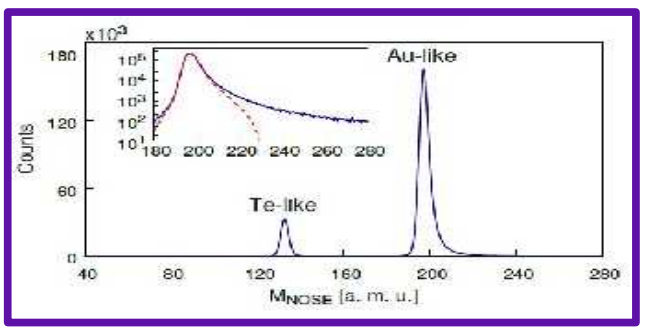




PRISMA



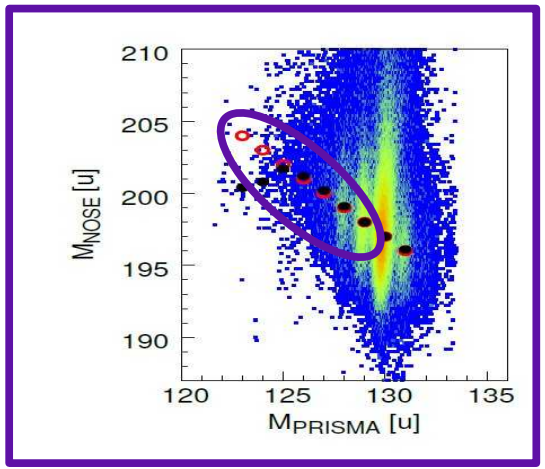



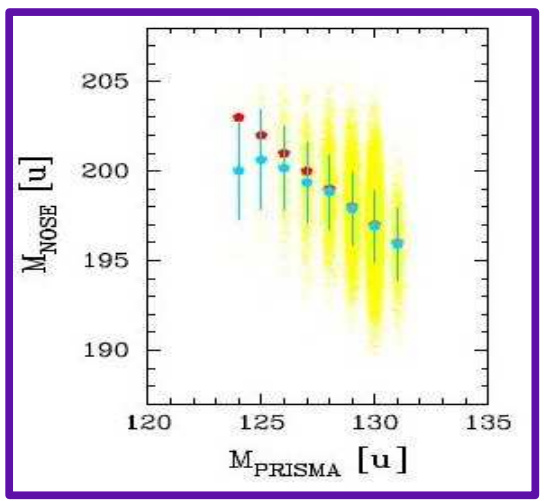

NOSE

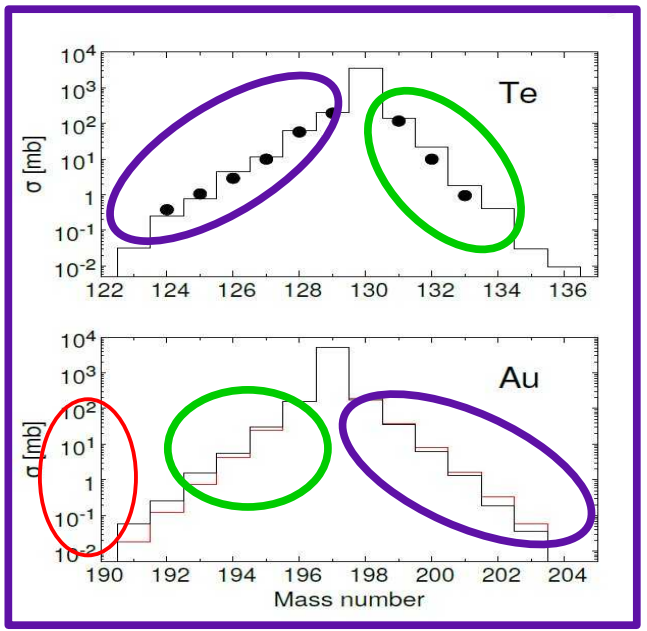
$^{197}$Au+$^{130}$Te
$E_{lab}$=1.07 GeV

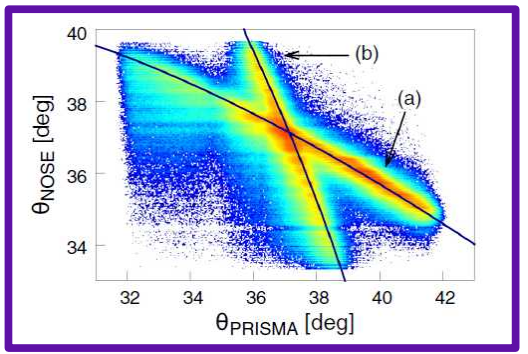
F. Galtarossa, L. Corradi, S. Szilner et al., Phys. Rev. C 97 (2018) 054606

# $^{197}$Au+$^{130}$Te: mass-mass correlations



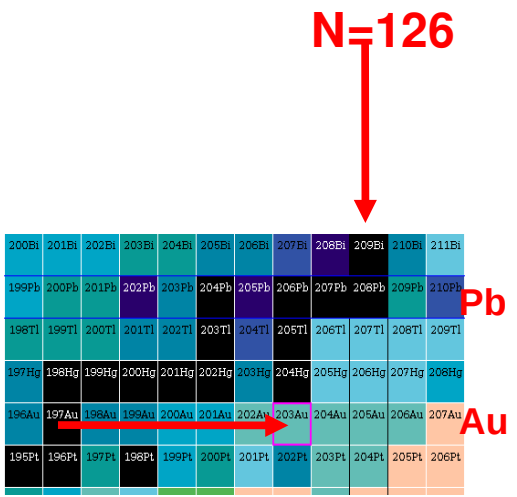



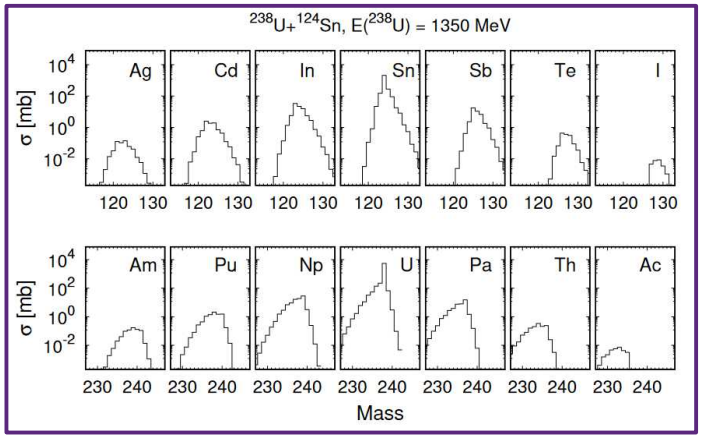

Multinucleon transfer reactions are a suitable tool for the production of heavy neutron-rich nuclei

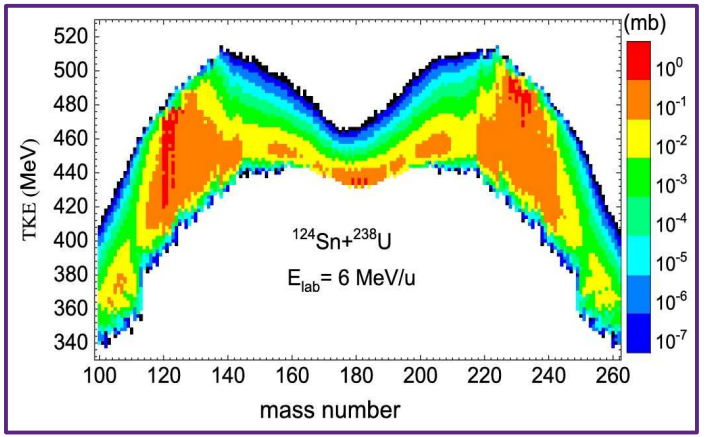
Te isotopes with "more" neutrons than $^{130}$Te

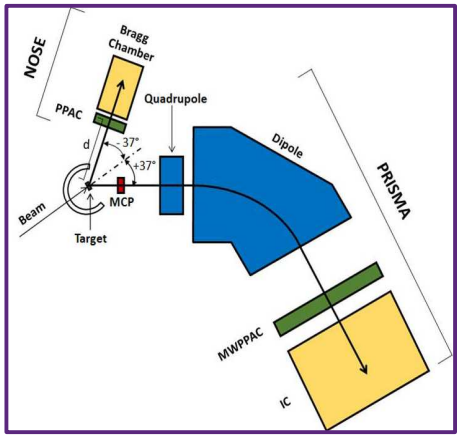
Au isotopes with "more" neutrons than $^{197}$Au



# $^{238}$U+$^{124}$Sn: fragment-fragment-gamma coincident detection




Primary cross sections - DNS model calculations, Peng-Hui Chen et al., Phys. Rev. C 101, 024610 (2020)

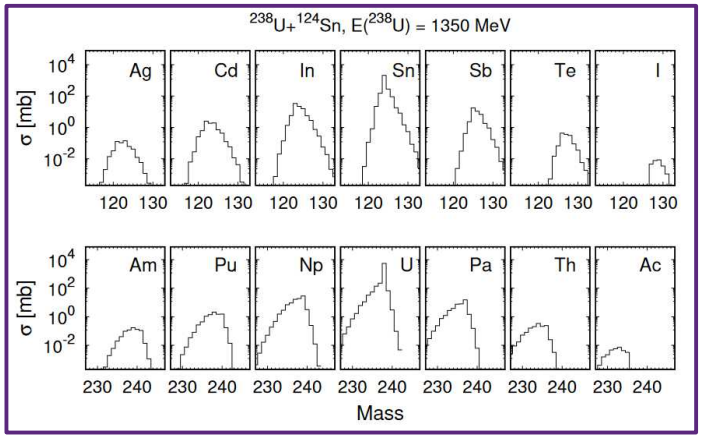
**$^{238}$U beam 1 pnA**
**$^{124}$Sn target 300 μg/cm$^2$**
**$E_{lab}$ = 1440 MeV**
**PRISMA $\theta_{lab} = 41^0$ and $29^0$**
**NOSE $\theta_{lab} = 29^0$**
**AGATA**

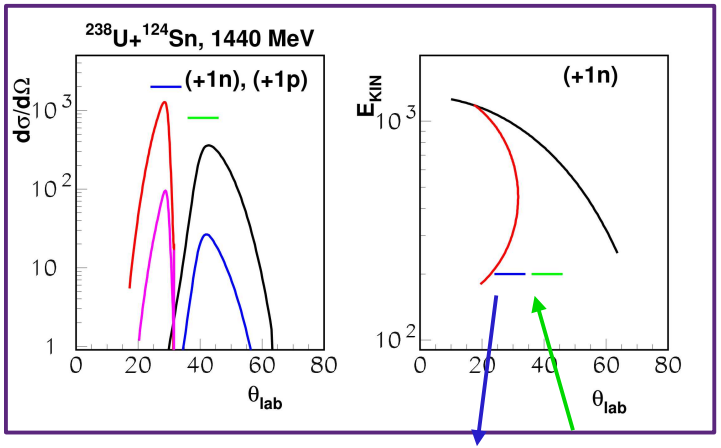
INFN – LNL **AGATA+PRISMA+NOSE** measurement July 2026, PRISMA (L. Corradi, F. Galtarossa, T. Mijatovic), Saclay-Orsay-GANIL (B. Sulignano, D. Ackermann, G. Iulian Stefan)

**Exp**: big interest in developing advanced techniques for high detection efficiency and high A,Z,Q resolution to get σ and associated nuclear structure information
**Theory**: big interest in developing theories able to predict cross sections and effects of secondary processes (Coupled channel, Semiclassical, TDHF, Langevin, QMD, DNS, EDF)

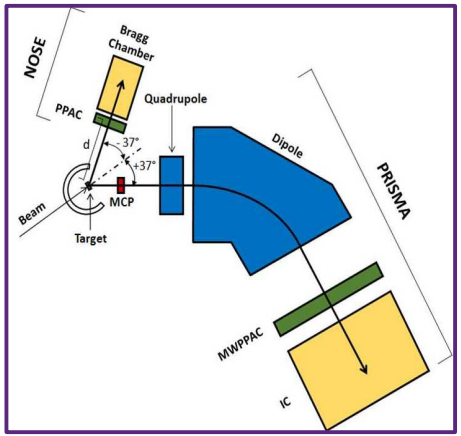
**GOAL**: measurement of the A, Z, Q-value distributions and associated σ for the population of nuclei around Z=92

# $^{238}$U+$^{124}$Sn: fragment-fragment-gamma coincident detection




NOSE PRISMA




**$^{238}$U beam 1 pnA**
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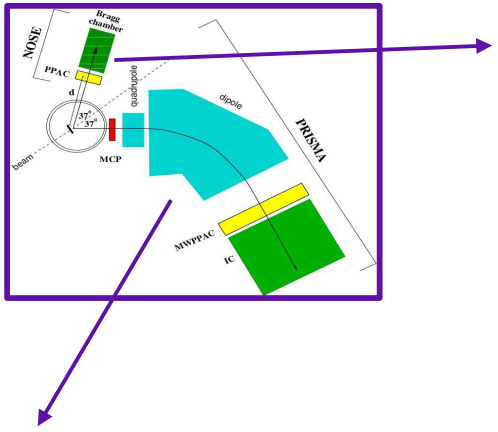
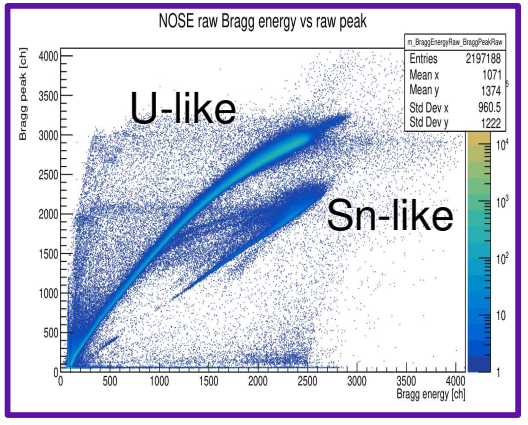
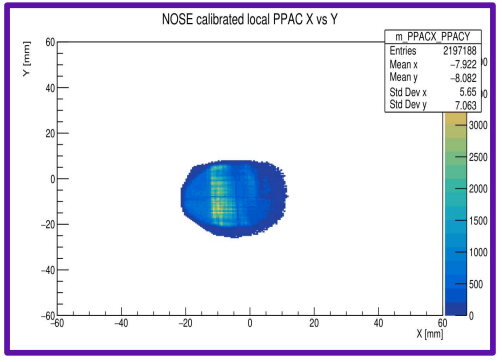
**GOAL**: measurement of the A, Z, Q-value distributions and associated σ for the population of nuclei around Z=92

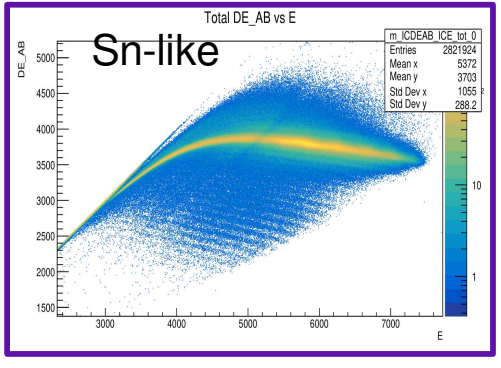
# $^{238}$U+$^{124}$Sn: coincident detection of binary partners

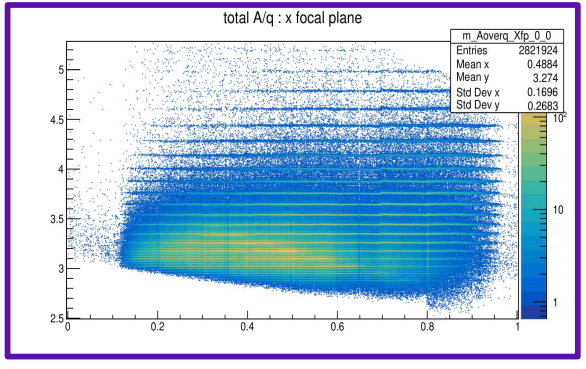


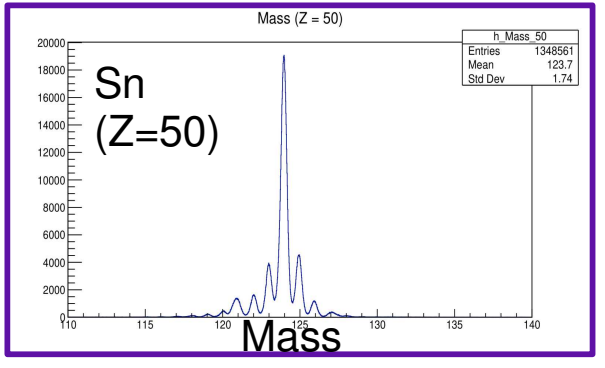




NOSE



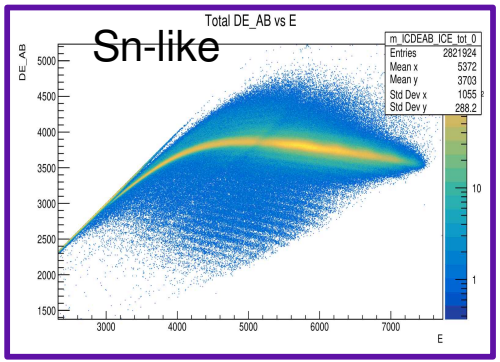




PRISMA

Pre-analysis: Laura Busak, Mirco del Fabbro, Matheo Coguic

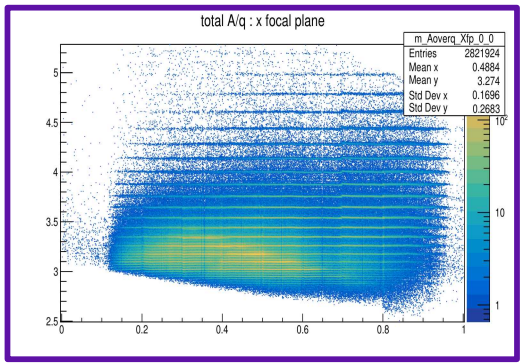
$^{238}$U+$^{123}$Sn $E_{lab}$=1.44 GeV

# $^{238}$U+$^{124}$Sn: Sn-like in PRISMA

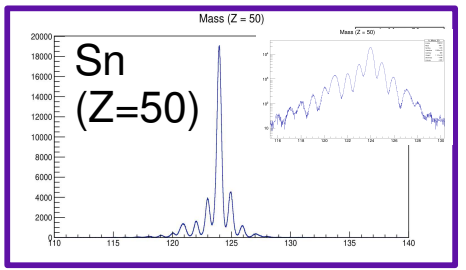



→ many open proton and neutron channels (energies close, but somewhat higher than Coloumb barrier)

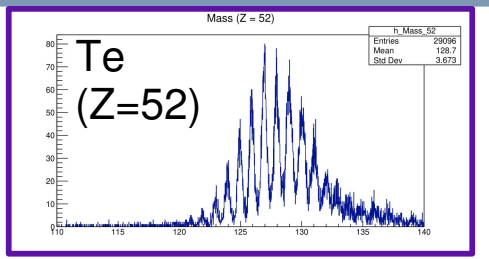
→ strong DIC components



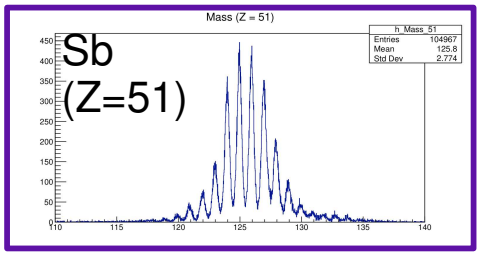

$^{238}$U+$^{123}$Sn



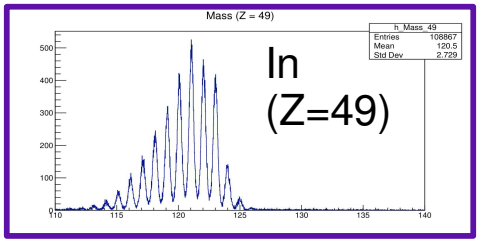

Mass



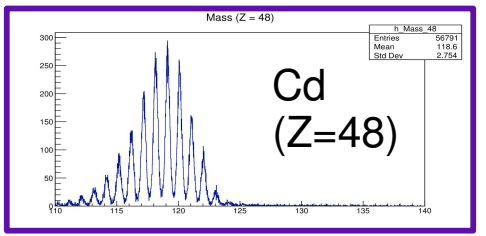

→ Te+Th




→ Sb+Pa

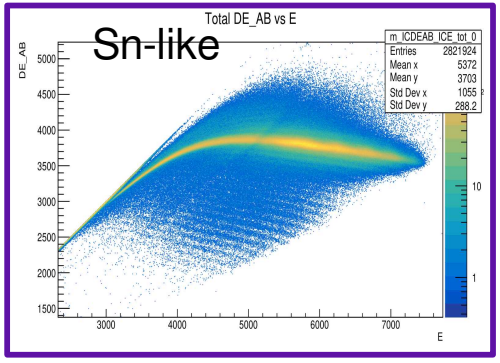


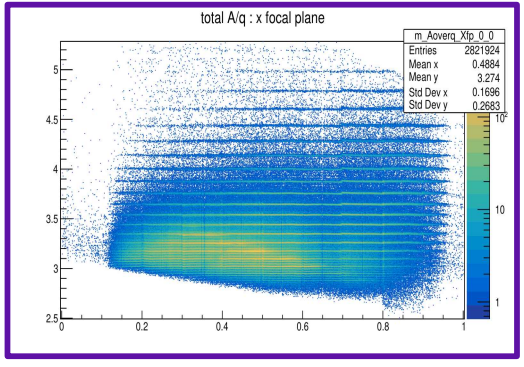

→ In+Np




→ Cd+Pu

# $^{238}U+^{124}Sn$: Sn-like in PRISMA



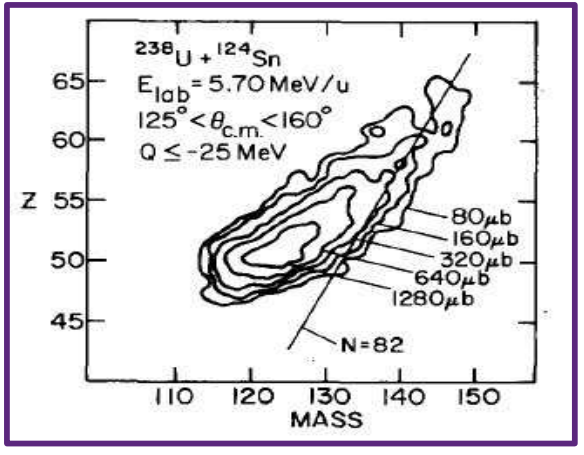




**$^{238}U+^{123}Sn$**

**W.Mayer et al., Phy. Lett. B 152, 162 (1985)**

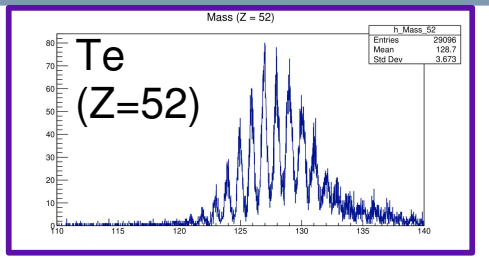
→ many open proton and neutron channels (energies close, but somewhat higher than Coloumb barrier)

→ strong DIC components

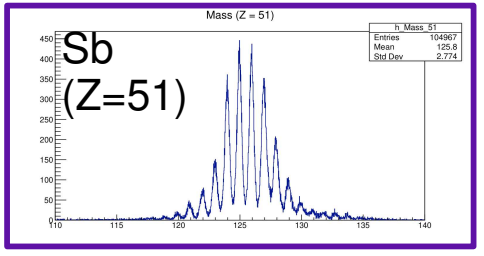



→ PRISMA+NOSE: to separate MNT from fission

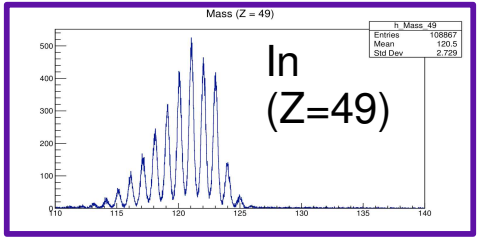
→ PRISMA+NOSE+AGATA: survivial probabilities of neutron-rich heavy nuclei



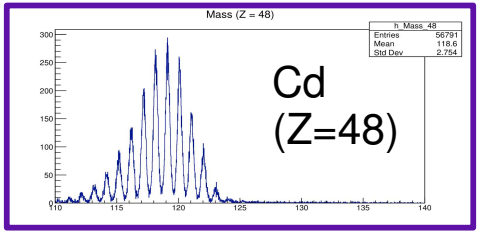

→ Te+Th




→ Sb+Pa

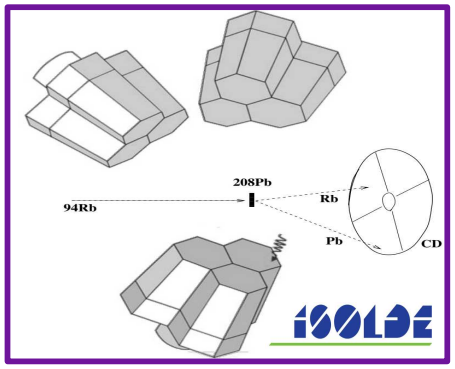


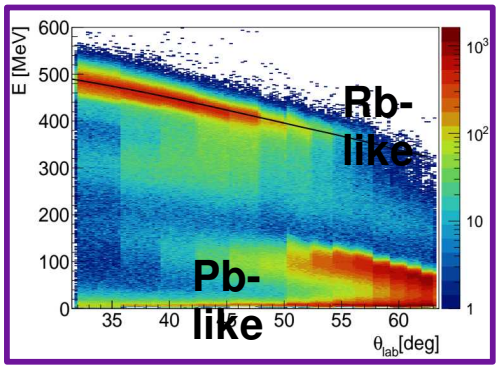

→ In+Np

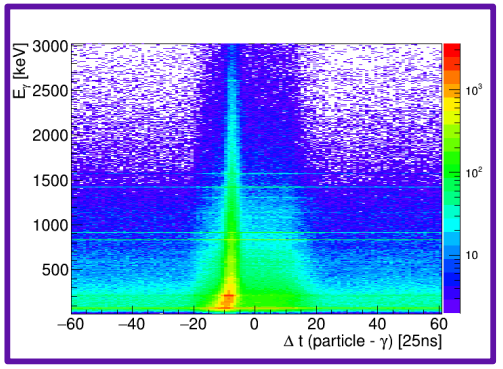


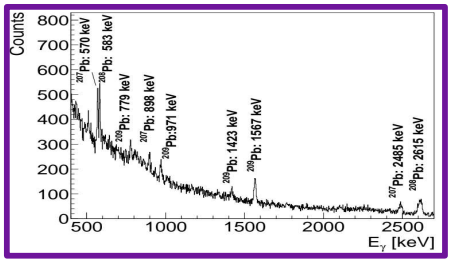

→ Cd+Pu

# $^{94}$Rb+$^{208}$Pb: MNT with neutron-rich beam

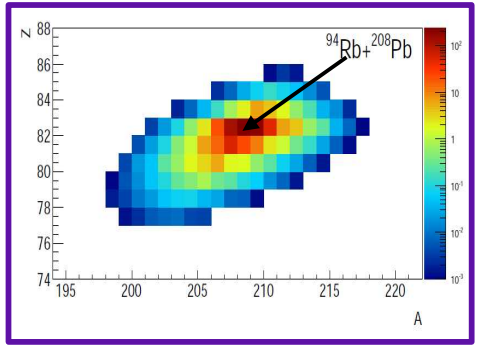


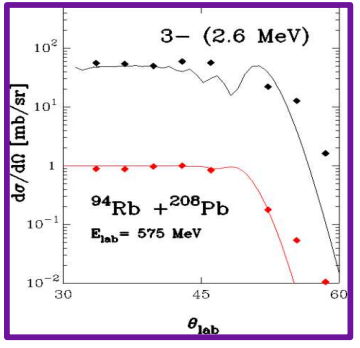




prompt gamma (200 ns)



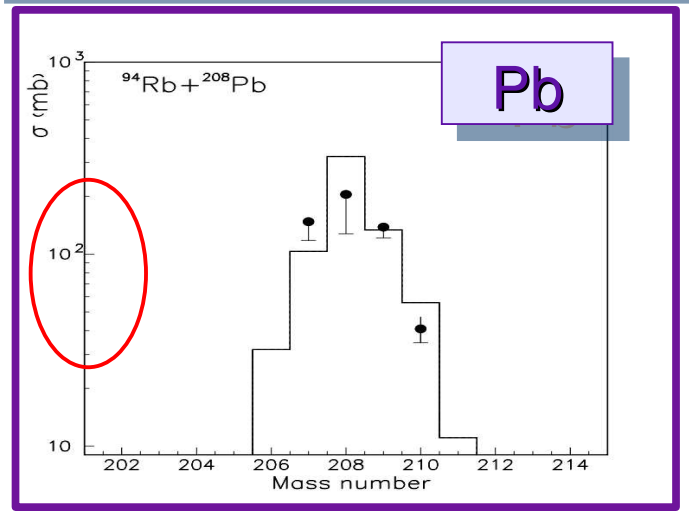

P. Colovic, S. Szilner et al., Phys. Rev. C 102 (2020) 054609

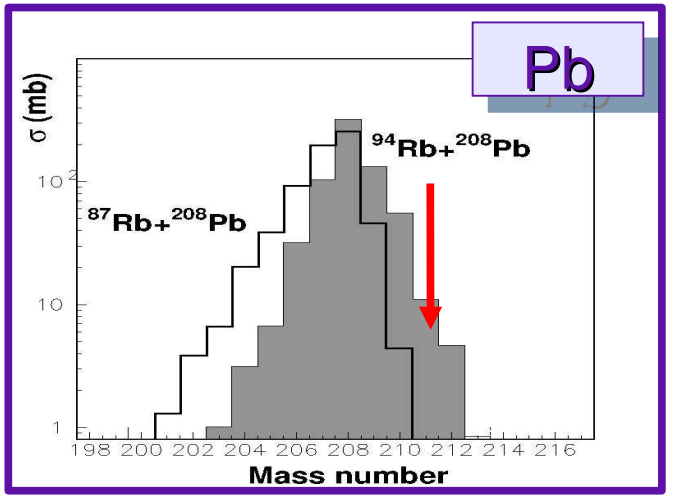
ISOLDE – CERN: MINIBALL + CD particle detector → fragment-gamma(-gamma) coincidencies

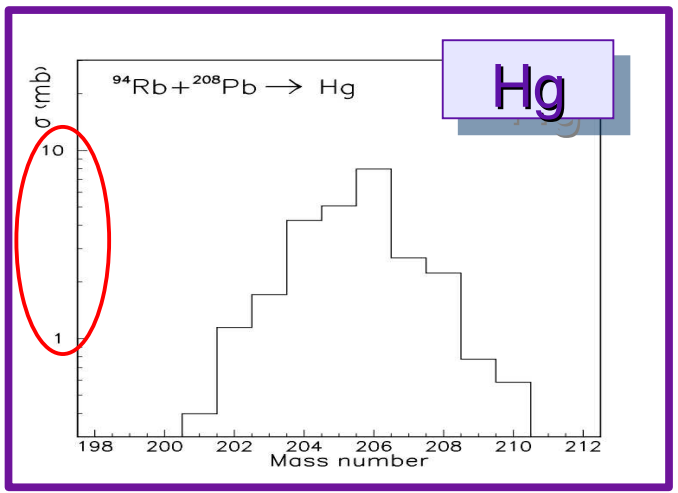
ISOLDE EXP IS572 (J.J. Valiente Dobon and S. Szilner)

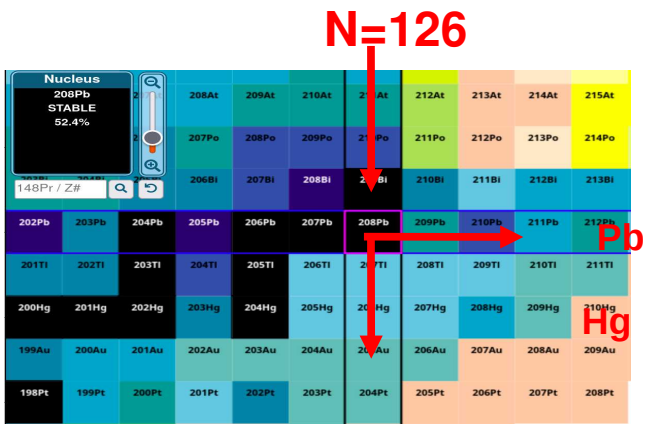
→ Data have been normalized at forward angles to the DWBA calculations (G. Pollarolo).
→ With this normalization we extracted a factor to convert the gamma yields into cross sections.The ground-state cross sections were evaluated.

# $^{94}$Rb+$^{208}$Pb: MNT with neutron-rich beam



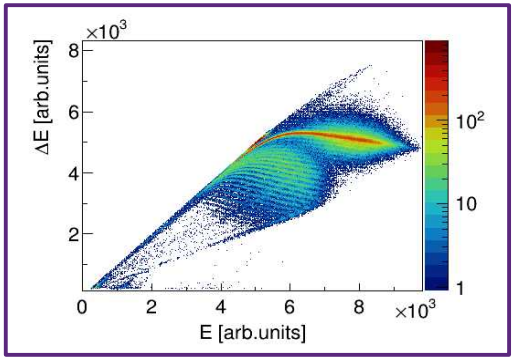




→The data show sizable cross sections for the neutron-rich mass region (in agreement with GRAZING)

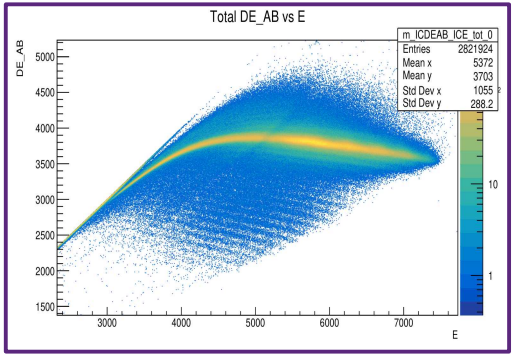
→ the calculated cross sections for Hg → could be reached in experiments with beam intensities an order of magnitude larger than the present one (already achievable at RIB facilities)

→ $^{87}$Rb (the most neutron-rich stable) vs $^{94}$Rb (RIB): much larger values for the neutron rich Pb, with $^{94}$Rb

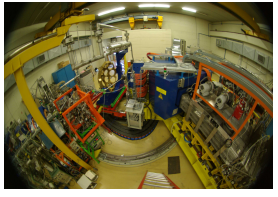
# MNT studies with PRISMA




→ Transfer channels have been successfully measured with high resolution in $^{206}Pb+^{118}Sn$ at $E_{lab}$=1200, 1090 and 1035 MeV, $^{197}Au+^{130}Te$ at $E_{lab}$=1035 MeV, $^{238}U+^{124}Sn$ at $E_{lab}$=1440 MeV with the large solid angle magnetic spectrometer PRISMA, PRISMA+NOSE, PRISMA+NOSE+AGATA.
→ Inverse kinematics (detection of (lighter) target-like fragment in PRISMA): enough kinetic energy of the outgoing recoils for energy and therefore mass resolution and forward-focused angular distribution for high efficiency.




MNT reactions around the Coulomb barrier → suitable tool to study the production of (heavy) neutron-rich nuclei
→ for few nucleon transfer channels, the reactions retain the main characteristics of direct processes
→ for channels involving many nucleons, the large energy loss leads to a reshuffling in the final yield distributions
→ more experimental studies for the best selection of mass asymmetry and collision energy for the largest survival probabilities of heavy partners → the direct detection of heavy (neutron rich) partners → further development of instrumentations for coincident detection of both partners (fragment-fragment, fragment-gamma), or direct detection of heavy partners.
→ MNT with RIB



L. Corradi, G. Pollarolo, T. Mijatović, F. Galtarossa, G. Andreetta, L. Busak, A. Goasduff, E. Fioretto, A.M. Stefanini, G. Montagnoli, J.J. Valiente-Dobon, A. Gottardo, D. Mengoni, P. Čolović, D. Jelavić Malenica, M. Milin, N. Soić, and PRISMA - AGATA collaboration

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INFN and Universita di Torino, Italy
INFN and Universita di Padova, Padova, Italy
University of Zagreb, Croatia












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