High resolution studies of multinucleon transfer reactions in the $^{206}Pb+^{118}Sn$ system from above to below the Coulomb barrier

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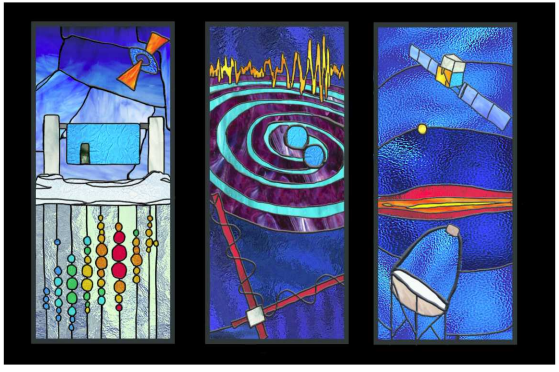
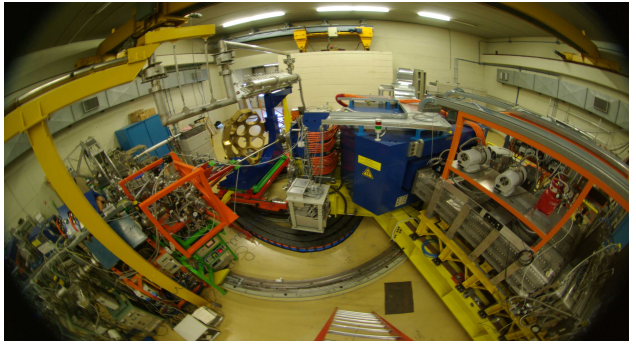
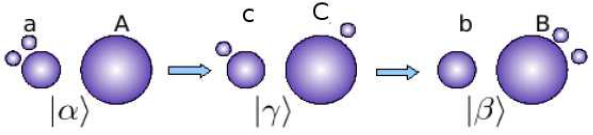


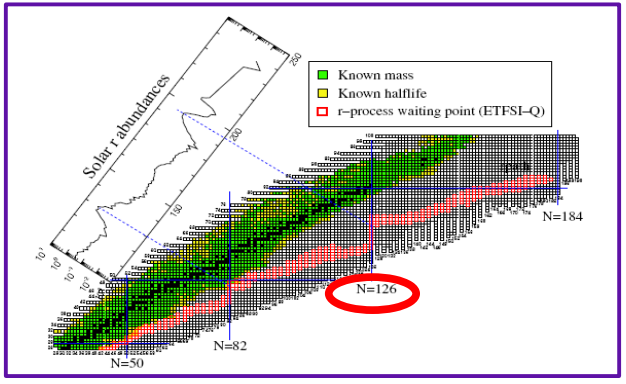




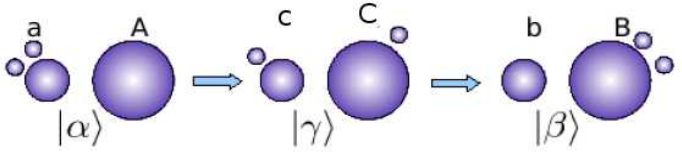
European Nuclear Physics Conference 2025, Caen, France

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.
→Data should cover a wide range of internuclear distances, from above to below the Coulomb barrier.
→The low energy region is characterized by low transfer cross sections (difficult to preserve the high resolution and detection efficiency).



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

THE EXPERIMENT:

→ $^{206}Pb+^{118}Sn$

→ inverse kinematics: "higher" kinetic energy of recoil (energy and mass resolution) and forward focused angular distribution (efficiency)

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

→ $E_{lab}(^{206}Pb)$ = 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

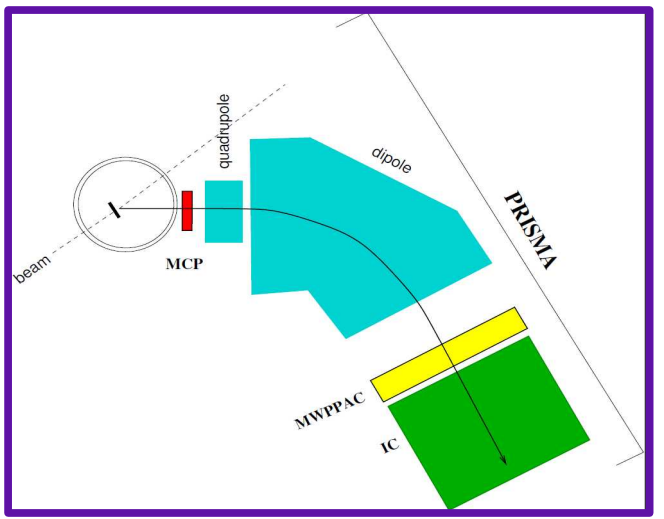
focal plane position: x_f,y_f

Time of Flight: ToF = t_f - t_i

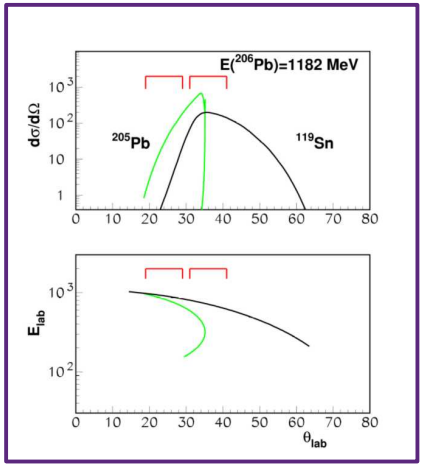
IC energy loss, total energy: ΔE, E

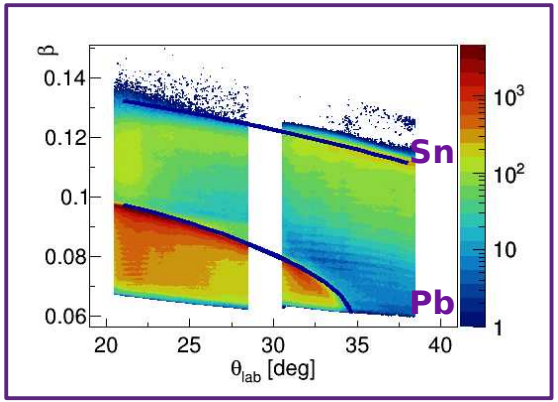
event-by-event trajectory reconstruction

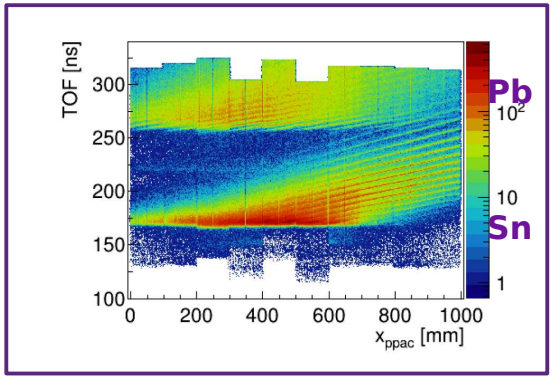
A, q, Z, E, v
mass, charge, atomic state, energy, velocity

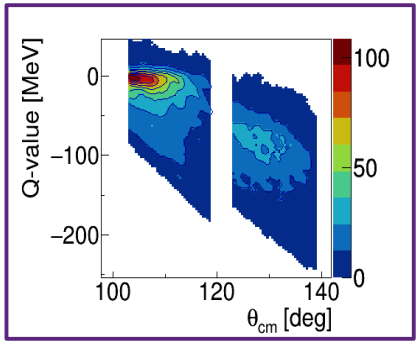


From quasi-elastic to deep inelastic collisions: ^{206}Pb+^{118}Sn

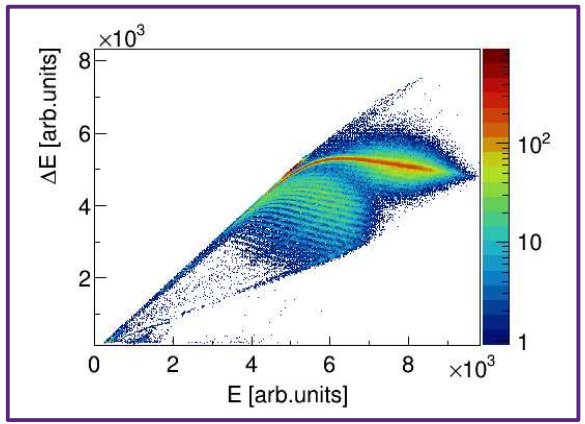


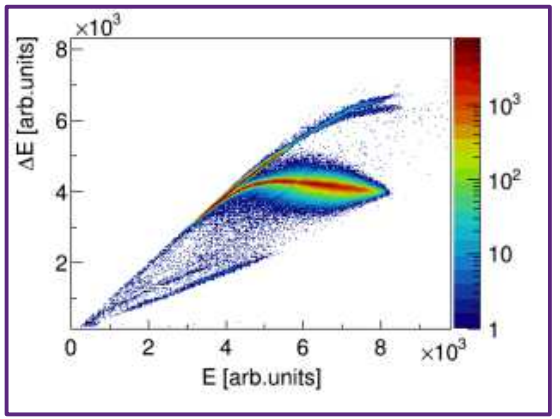




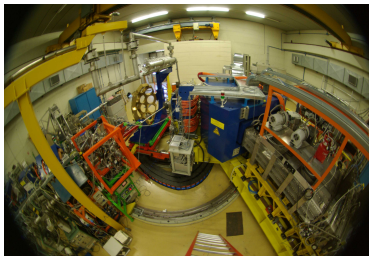


→ ^{205}Pb+^{119}Sn (+1n)



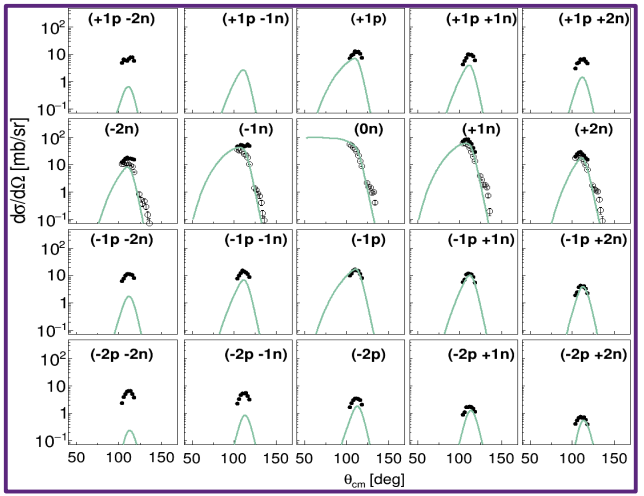


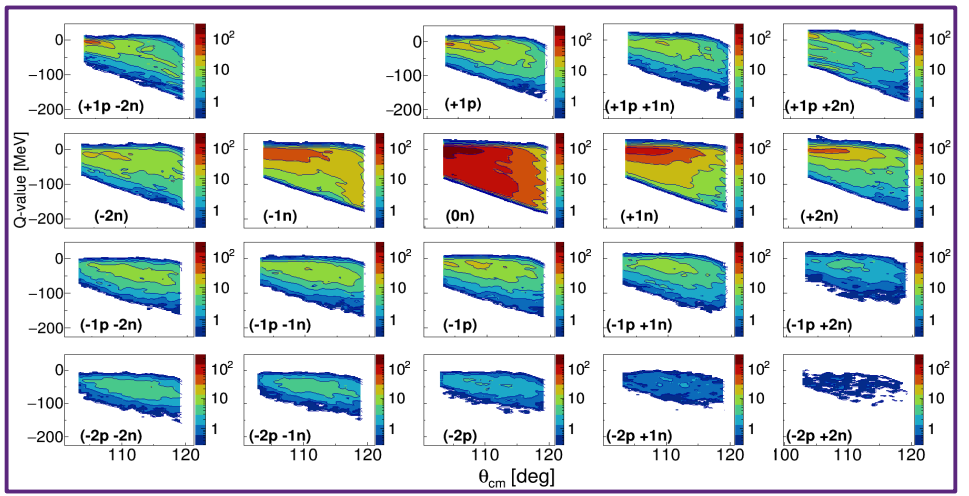
The yields of **QE** and **DIC** components (and fission fragments) strongly depend on (both) bombarding **energy** and **angles**.



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



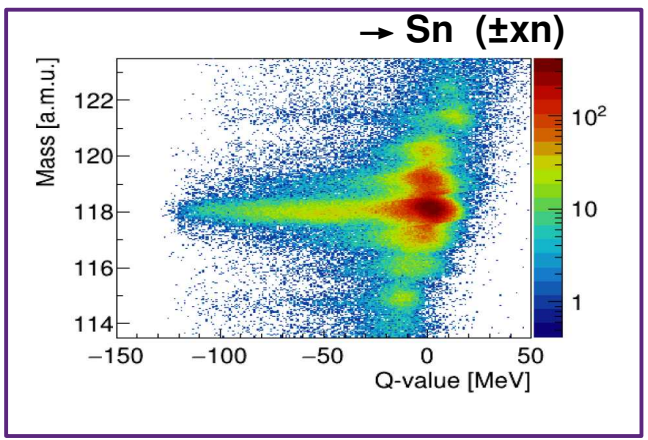


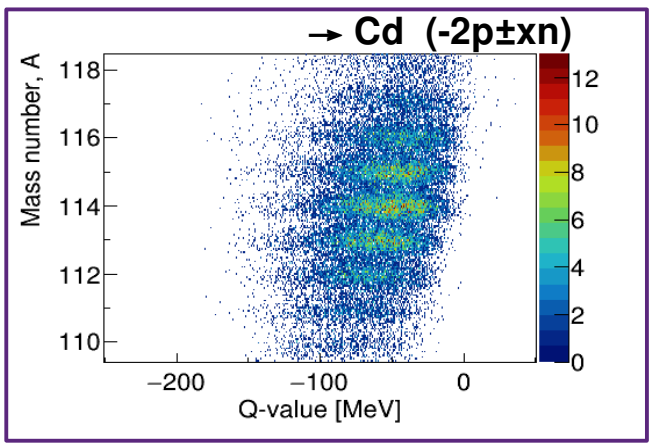
Sb (+1p±xn)

Sn (±xn)

In (-1p±xn)

Cd (-2p±xn)

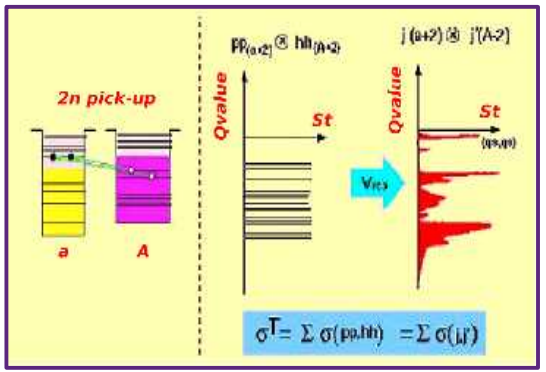


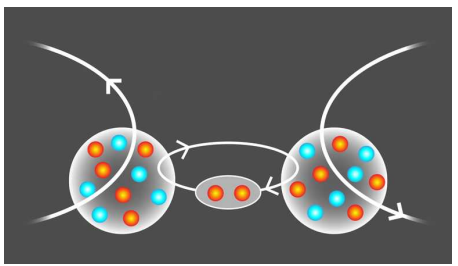


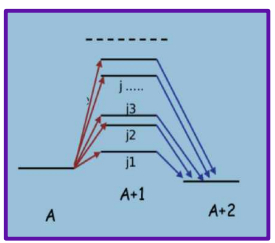
Few nucleon transfers → the main observables, Q values, and cross sections, retain the main characteristics of **direct processes** → well described with **GRAZING**

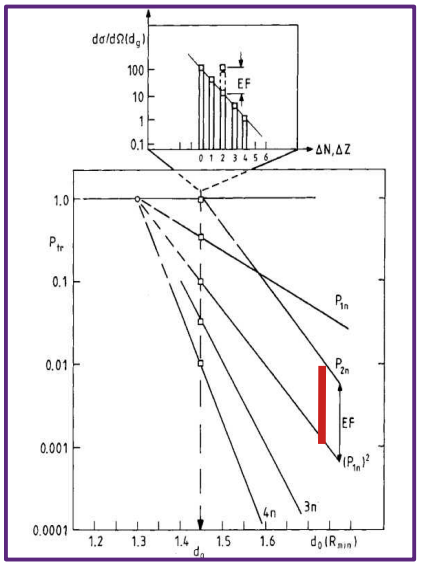
GRAZING progressively underestimates yields as more nucleons are transferred → more **complicated processes** than a direct transfer

Probing nucleon-nucleon correlations in transfer reactions









W. von Oertzen and A. Vitturi, Rep. Prog. Phys. 64 (2001) 1247–1337

Enhancement factors:
→ the ratio of the cross sections to predictions of models using uncorrelated states (a direct evaluation of the correlation of the populated states)
→ comparisons of the (1n) and (2n) transfer probabilities as a function of the distance of closest approach

Almost all previous studies involve inclusive cross sections at energies above the Coulomb barrier and at angles forward of the grazing (many open channels, complex reaction mechanism).

Data should cover a wide range of internuclear distances, from above to below the Coulomb barrier. The low energy region is characterized by low transfer cross sections (difficult to preserve the high resolution and detection efficiency).

Heavy-ion reactions: test of correlation properties in transfer processes via simultaneous comparison of ±n and ±p, and ±nn/±pp pairs

Nucleon-nucleon correlations studies with PRISMA

^{96}Zr+^{40}Ca, ^{116}Sn+^{60}Ni, ^{92}Mo+^{54}Fe, ^{206}Pb+^{116}Sn, ^{208}Pb+^{48}Ca
direct (angular distribution) + **inverse** (excitation function) kinematic, PRISMA and PRISMA + CLARA/AGATA/LaBr (10 experiments)

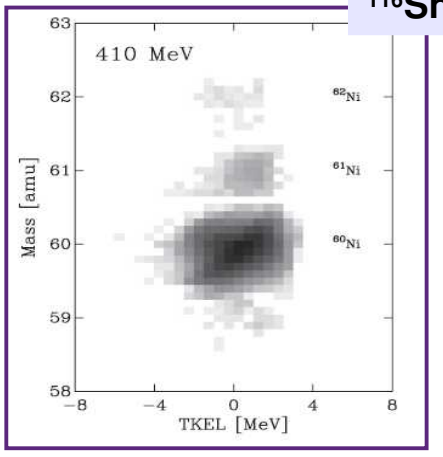
^{96}Zr+^{40}Ca:
S. Szilner et al., Phys. Rev. C 76 (2007) 024604
L. Corradi et al., Phys. Rev. C 84 (2011) 034603

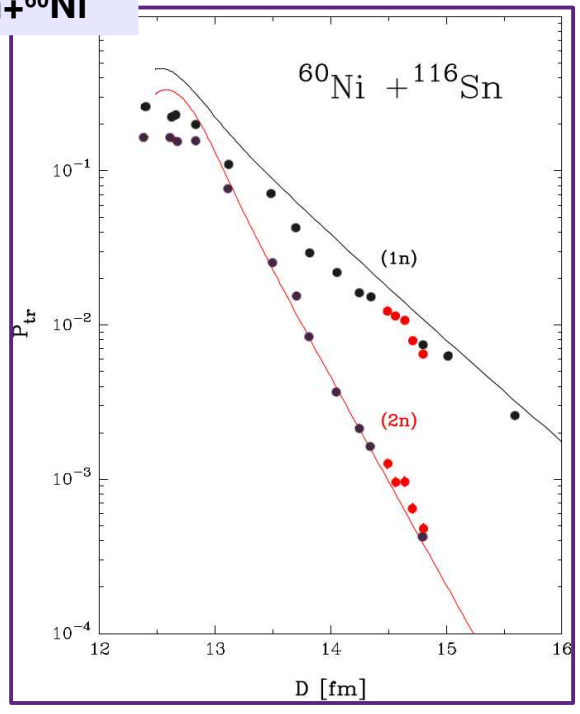
^{116}Sn+^{60}Ni:
D. Montanari et al., Phys. Rev. Lett. 113 (2014) 052501
D. Montanari et al., Phys. Rev. C 93 (2016) 054623
L. Corradi, S. Szilner et al., Phys. Lett. B 834 (2022) 137477
L. Corradi, S. Szilner: Search for a Josephson-like effect

^{92}Mo+^{54}Fe:
T. Mijatovic et al., Phys. Lett. B submitted

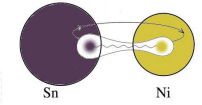
^{206}Pb+^{116}Sn:
S. Szilner et al., Phys. Rev. Lett. 133 (2024) 202501
J. Diklic et al., Phys. Rev. C 107 (2023) 014619

^{116}Sn+^{60}Ni





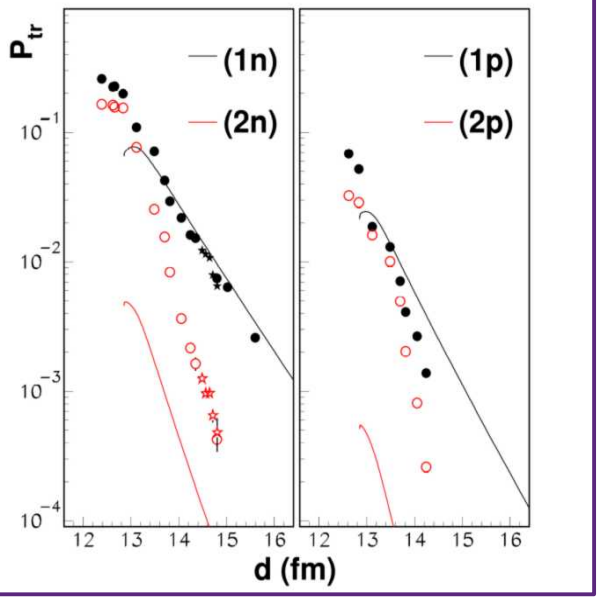
$$P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{\mathrm{Ruth}}}$$



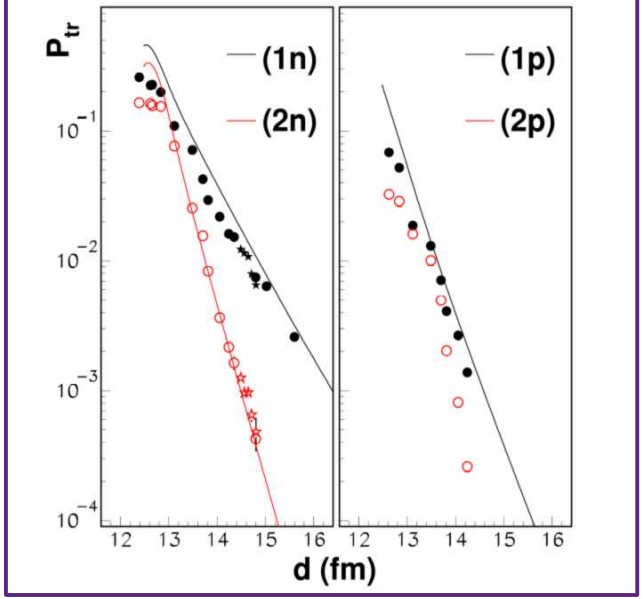
$$D = \frac{Z_a Z_A e^2}{2E_{\mathrm{c.m.}}}\left(1 + \frac{1}{\sin(\theta_{\mathrm{c.m.}}/2)}\right)$$

^{60}Ni+^{116}Sn: one- and two-particle transfers

The experimental transfer probabilities for the (1n) and (2n) channels (by detecting ^{61}Ni and ^{62}Ni) and for the (1p) and (2p) channels (by detecting ^{59}Co and ^{58}Fe)



comparison with the **GRAZING** code calculations (**independent** nucleon transfers)

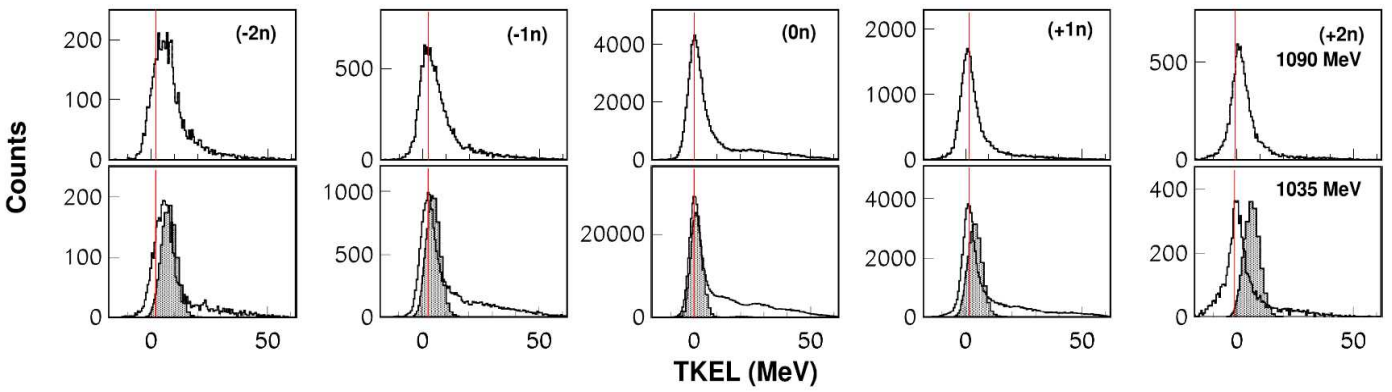


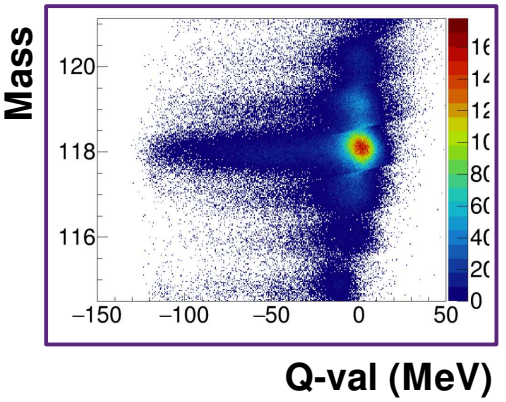
See also Lorenzo Corradi talk

comparison with the **microscopic calculations**: semiclassical theory (CWKB wave functions of relative motion), 2nd order Born app. The **inclusive cross section**: summing up all the contributions coming from the single particle transitions. Form-factors: the prior representation, SM single particle wave functions, by weighting each transition with experimental spectroscopic factor (**2n**): simultaneous + orthogonal + **successive** terms

D. Montanari et al., Phys. Rev. Lett. 113 (2014) 052501; D. Montanari et al., Phys. Rev. C 93 (2016) 054623; L. Corradi, S. Szilner et al., Phys. Lett. B 834 (2022) 137477.

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





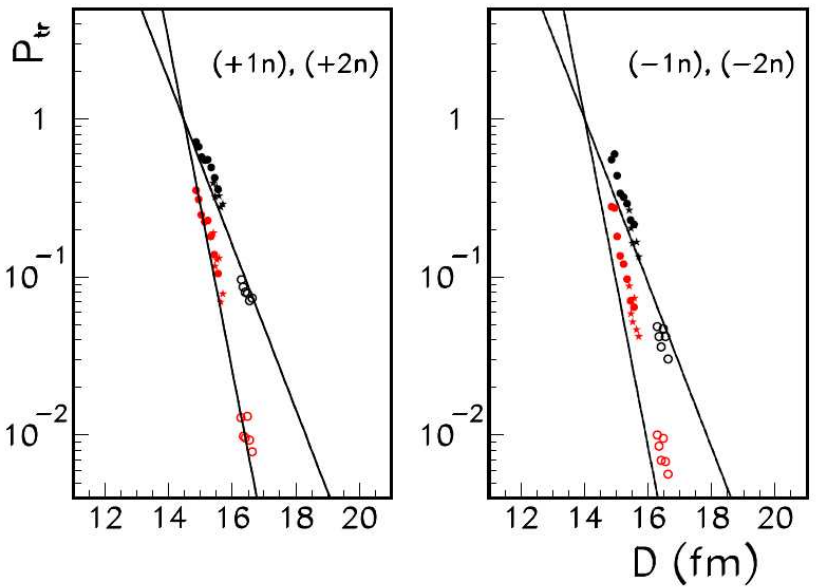
channel	reaction	Q_0 (MeV)
$(-2n)$	^{206}Pb+^{118}Sn $\rightarrow$ ^{116}Sn+^{208}Pb	-2.17
$(-1n)$	^{206}Pb+^{118}Sn $\rightarrow$ ^{117}Sn+^{207}Pb	-2.59
$(+1n)$	^{206}Pb+^{118}Sn $\rightarrow$ ^{119}Sn+^{205}Pb	-1.60
$(+2n)$	^{206}Pb+^{118}Sn $\rightarrow$ ^{120}Sn+^{204}Pb	0.77

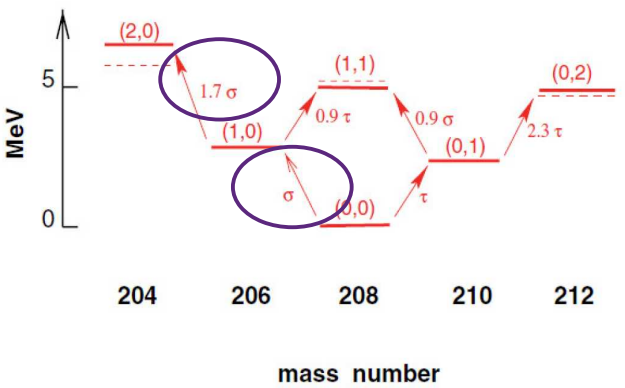
The TKEL distributions are very narrow, typical of scattering at sub-barrier energies, and with most of the events close to the ground-to-ground-state transitions. Tails reflecting large energy loss components are still visible in the spectra, though they did not affect significantly the evaluation of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

$\rightarrow$ to measure at the same time the addition and removal of pairs of neutrons from Pb and Sn

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

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





$$\alpha = \sqrt{\frac{2mB}{\hbar^2}}$$

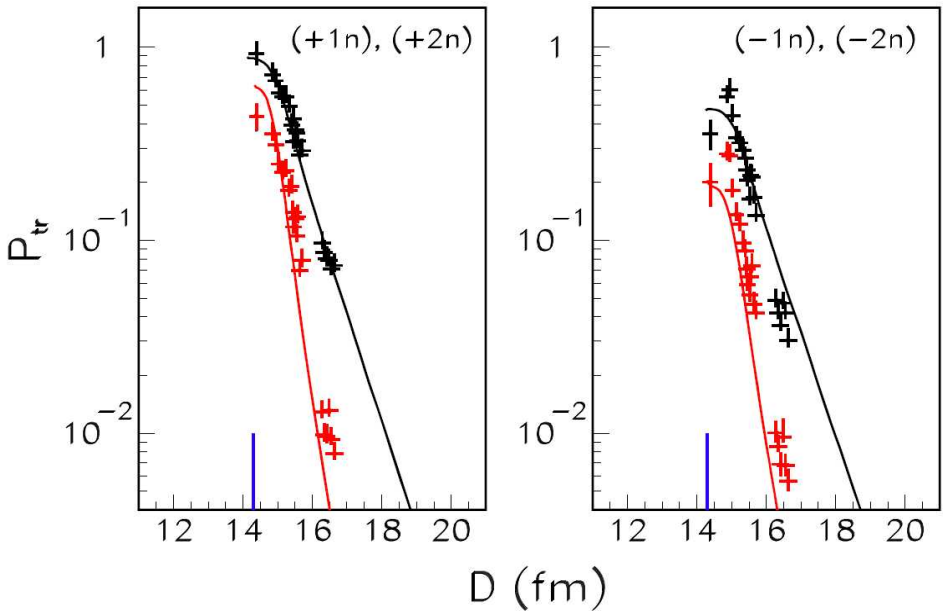
$$P_{tr} \approx e^{-2\alpha D}$$

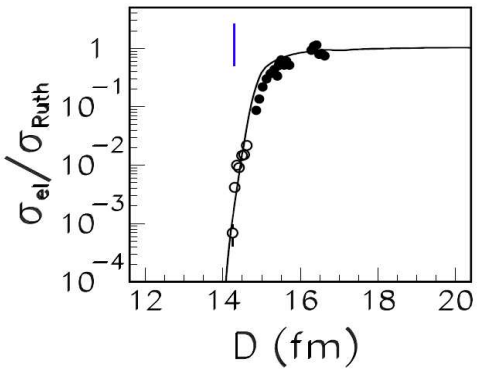
$$P_{tr}(2n) = P_{tr}(1n)^2$$

Since the form factor for transfer decays exponentially, the quasielastic transfer probabilities as a function of D follow, in a (semilogarithmic) plot, straight lines with **a slope** related to the **binding energy** of the transferred nucleon. The slope of the **two-neutron** transfer probability should then be **twice that of the one-neutron** one.

The **pairing vibration model** predicts that the ratio of the cross sections for the population of the different ground states is proper of an harmonic situation, with the strengths proportional to **the number of phonons in the final state**. The ratio turns out to mirror the one of the (p,t) and (t,p) reactions leading to ^{204}Pb and ^{208}Pb ground states, respectively (with the ratio of 1.7).

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



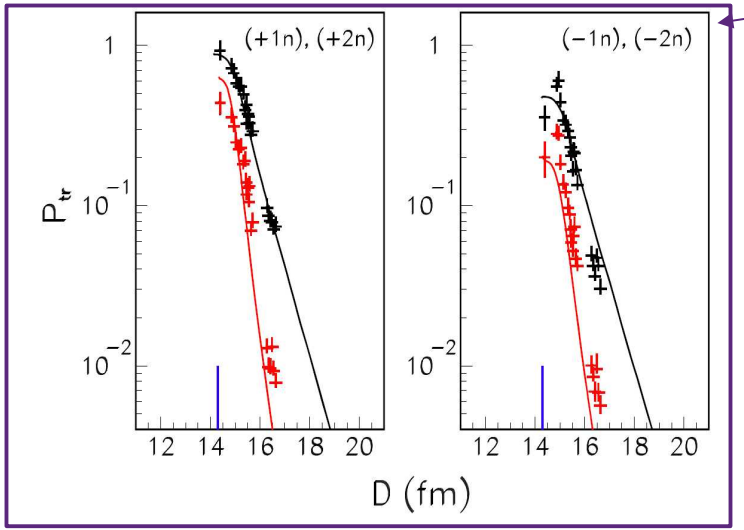


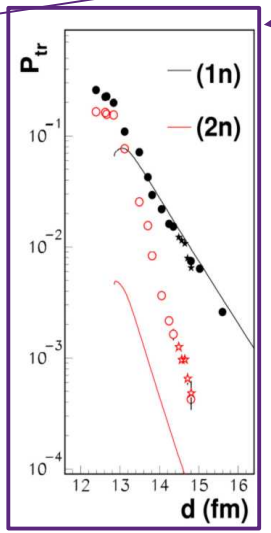
$$P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{el+in}}$$

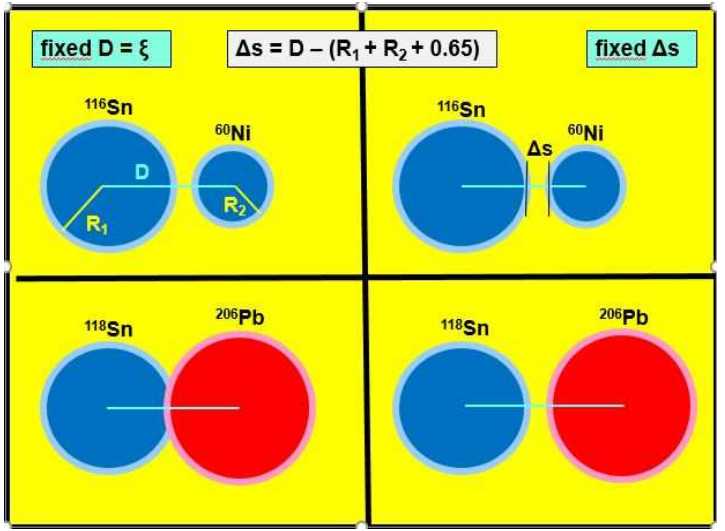
$$D = \frac{Z_P Z_T e^2}{2E_{cm}}\left(1 + \frac{1}{sin(\theta_{cm}/2)}\right)$$

The experimental transfer probabilities for the one-neutron transfers are well reproduced by the theory - **GRAZING**.
The model reproduces quite well **the ratio of elastic+inelastic over Rutherford** cross sections over several orders of magnitude.
The experimental probabilities for the **two-neutron** transfers are slightly **underpredicted** (by a factor ≤ 2). Since GRAZING incorporates an **independent particle transfer mechanism** only, this difference provides a measure of the effect of two-particle correlations in the presence of nuclei that are closed shells.

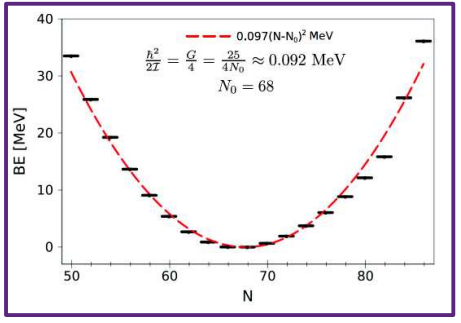
Quest for Cooper Pair Transfer in Heavy-Ion Reactions: ^{206}Pb+^{118}Sn and ^{116}Sn+^{60}Ni





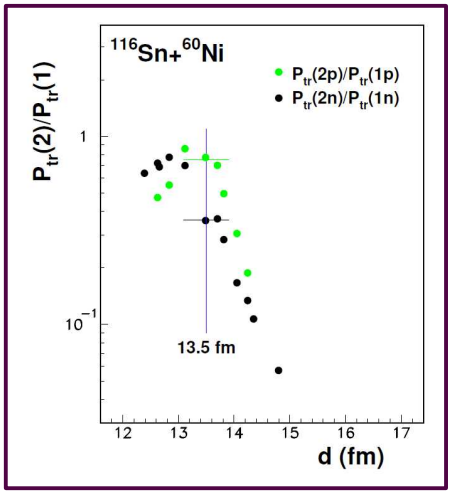


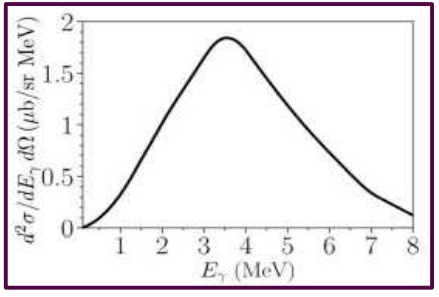
^{206}Pb+^{118}Sn → QE and DIC → a proper selection of the bombarding energies (the internuclear distances) is mandatory.
^{206}Pb+^{118}Sn: involves nuclei with open and closed neutron shells corresponding to **pair vibrations** (closed-shell nuclei like Pb) and **pair rotations** (nuclei with many particles outside closed shells like Sn); the Pb partner, which governs the size of the cross sections, manifests its vibrational structure and pair vibration character



Pairing rotational band associated with the ground state of the Sn-isotopes.

Correlation studies with PRISMA





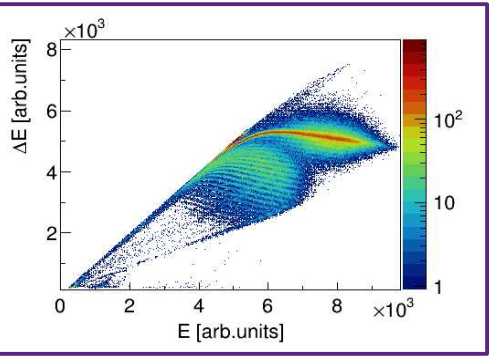
^{116}Sn+^{60}Ni→The emission of EM waves in the region of MeV gamma rays was predicted (G. Potel, F. Barranco, E. Vigezzi, R.A. Broglia, PRC 103 (2021) L021601, Quantum entanglement in nuclear Cooper-pair tunneling with gamma rays).
The physical origin is in the dipole oscillations generated by the oscillating motion of the Cooper pairs between the interacting binary partners.

INFN-LNL PRISMA+AGATA experiment: Search for a Josephson-like effect in ^{116}Sn+^{60}Ni (PhD thesis G. Andreetta) [see L. Corradi talk]

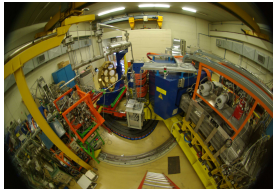
^{92}Mo+^{54}Fe→Revealing nucleon–nucleon correlation effects through sub-Coulomb transfer reactions **in ^{92}Mo+^{54}Fe,** T. Mijatovic et al.

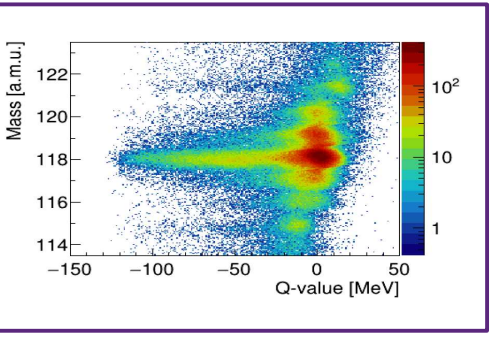
→ “large” spectrometers are powerful tools to study correlations
→ sub-barrier transfer reaction measurement (nuclei interact at large distances): good probe for pair correlations
→ Informations about correlations are extracted when experimental absolute cross sections are compared with theories which include the coupling between relative motion (reaction) and intrinsic motion (structure - correlations).

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 with the large solid angle magnetic spectrometer PRISMA.
→ 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) (see: Franco Galtarossa talk)

L. Corradi, G. Pollarolo, T. Mijatović, F. Galtarossa, G. Andreetta, A. Goasduff, D. Montanari, E. Fioretto, A.M. Stefanini, G. Montagnoli, J.J. Valiente-Dobon, A. Gottardo, D. Mengoni, T. Marchi, J. Diklić, P. Čolović, D. Jelavić Malenica, M. Milin, N. Soić, N. Vukman, G. Colucci, J. Grebosz, A. Illana, G. Jaworski, M. Siciliano and AGATA collaboration

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