Searching for the nuclear Cooper pairs

@FlipPhysics Workshop

Josipa Diklić, March 2022.
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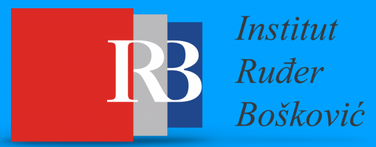
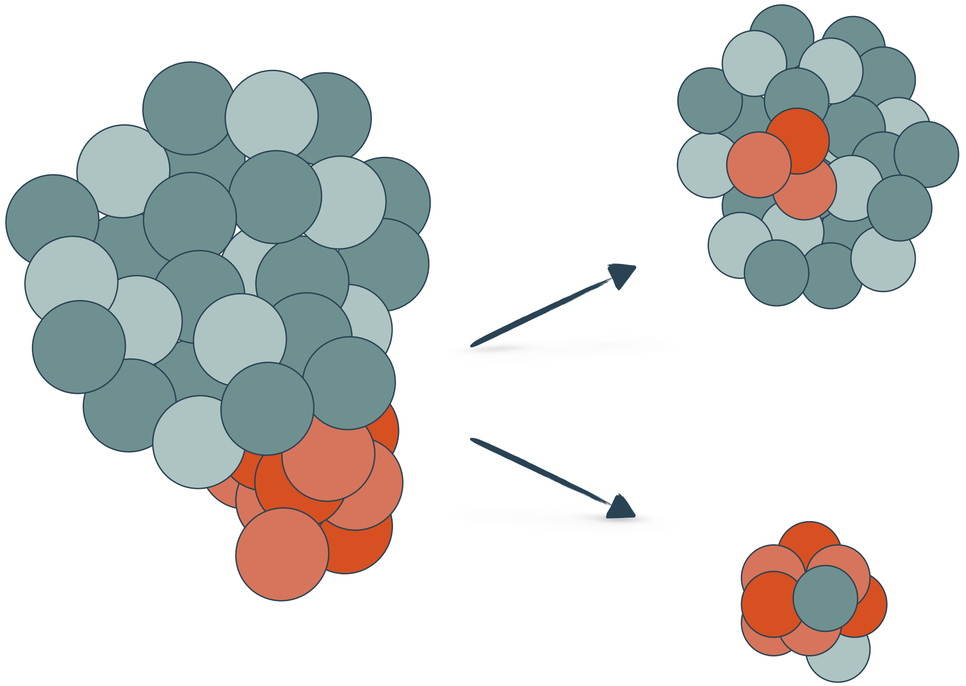


Introduction

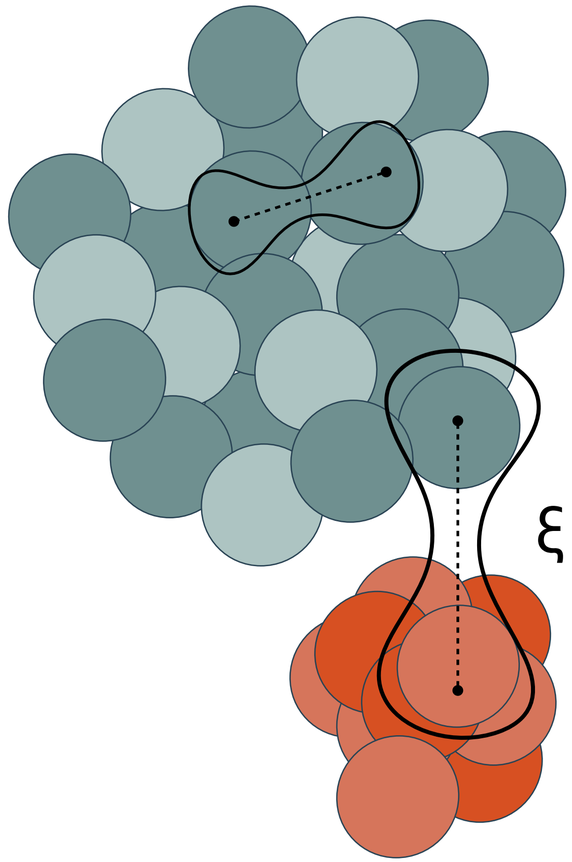
- The **two-nucleon transfer** reaction is a very specific probe of pairing component in the nuclear interactions, which ties up nucleons in a highly correlated state, the nuclear Cooper pairs
- Heavy-ion transfer reactions allow **simultaneous comparison** of different transfer channels
- We probe correlations in **heavy-ion transfer** reactions at energies close to the Coulomb barrier



Introduction

- **Nuclear Cooper pairs** are found to be correlated over a coherence distance ξ much larger than nuclear dimensions
  $\xi > R_1+R_2$

- The comparison of transfer probabilities with the **microscopic calculations** which incorporate nucleon-nucleon correlations will provide informations about pairing in nuclei



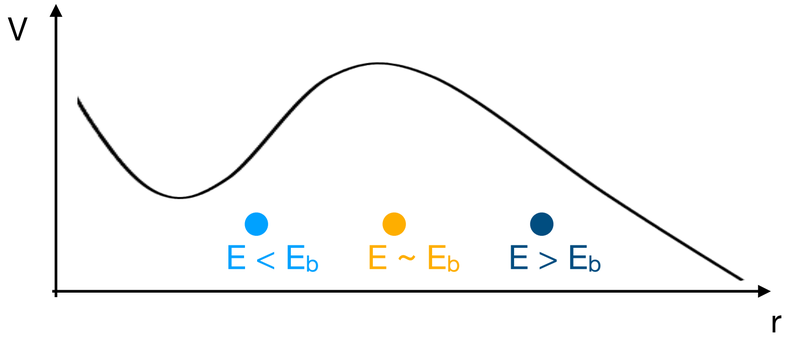
*G. Potel *et al.*, Phys. Rev. C. **103** (2021) L021601.

Nucleon-nucleon correlations

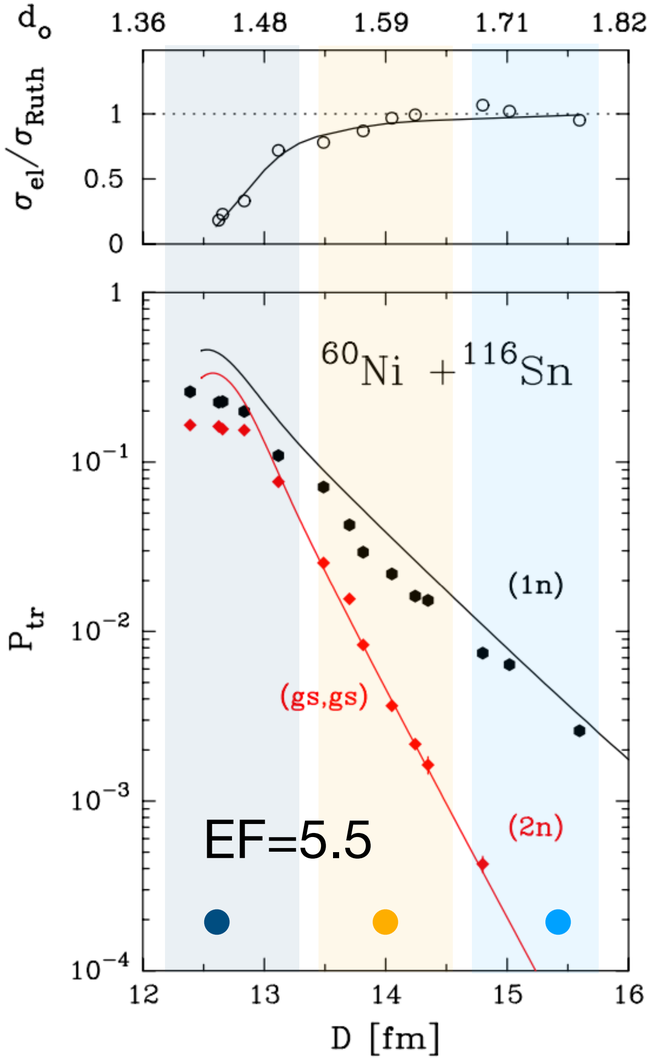
^{60}Ni+^{116}Sn

- **Heavy ion transfer reactions**: simultaneous comparison of (+1n) and (+2n) channels represented via the transfer probability ***(P_{tr})*** as a function of the distance of closest approach ***(D)***
- In approximation of **successive nucleon transfer** $P_{2n} = EF\, P_{1n}^2$, so if there are correlations enhancement factor $EF > 1$

- $D = \frac{Z_a Z_A e^2}{2E_{\text{c.m.}}}\left(1 + \frac{1}{\sin(\theta_{cm}/2)}\right)$
- $P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{el}}$



$d_0 = D/\left(A_1^{1/3} + A_2^{1/3}\right)$

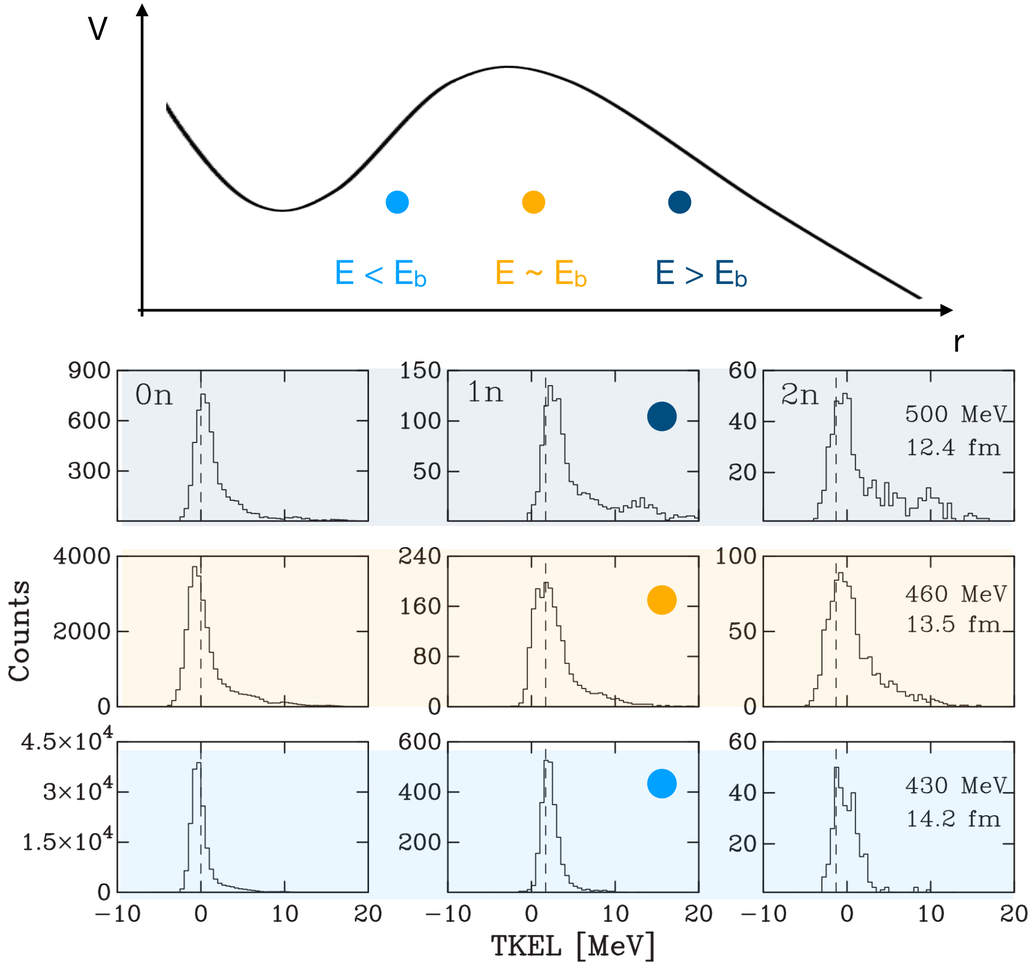


*D. Montanari *et al.*, Phys. Rev. Lett. **113** (2014) 052501.

Nucleon-nucleon correlations

$^{60}Ni+^{116}Sn$

- At **E>Eb** TKEL spectra have tails at large energy losses (onset of DIC), while for **E<Eb** the distribution becomes narrower and centred around 0

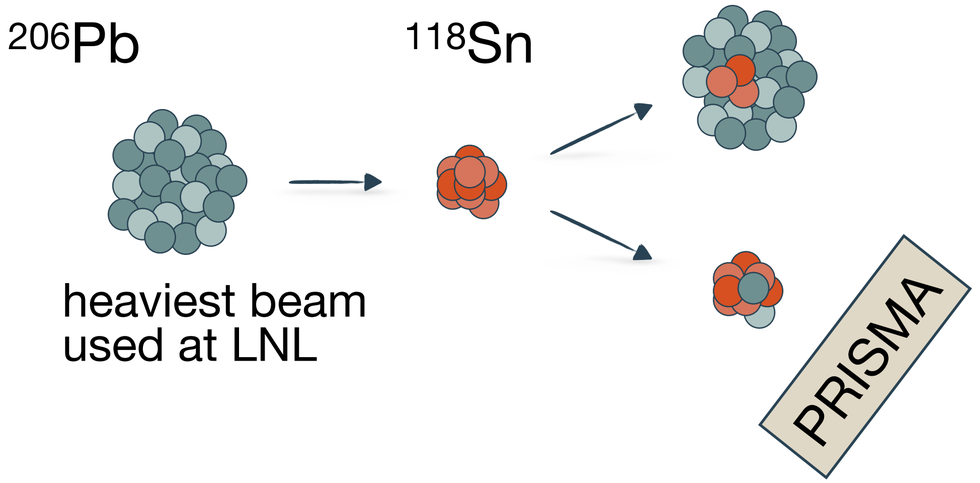


*D. Montanari *et al.*, Phys. Rev. Lett. **113** (2014) 052501.

Nucleon-nucleon correlations

^{206}Pb+^{118}Sn

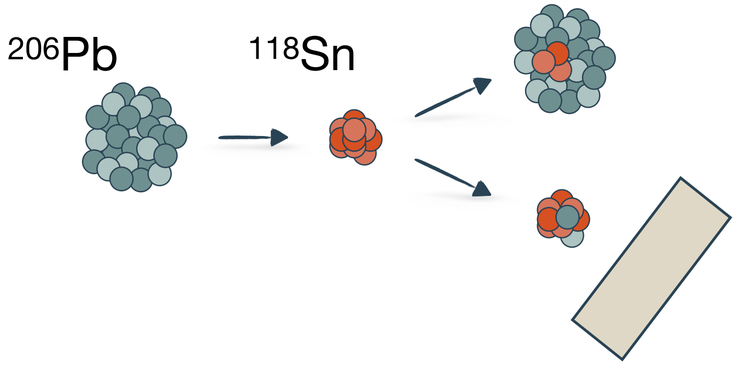
- Similar approach to ^{60}Ni+^{116}Sn, but with heavier system
- The experiment was performed with PRISMA at **Legnaro National Laboratories** (LNL, INFN)
- We measured an excitation function at three different bombarding energies ($E_{Coulomb}$ ≈1126 MeV) :
  - ***E* = 1200, 1090 and 1035 MeV**
- For the highest energy, PRISMA was initially placed close to the grazing angle at
  - ***Θ* = 35°** and then at **25°**
- We detect the target-like ions in the magnetic spectrometer **PRISMA**

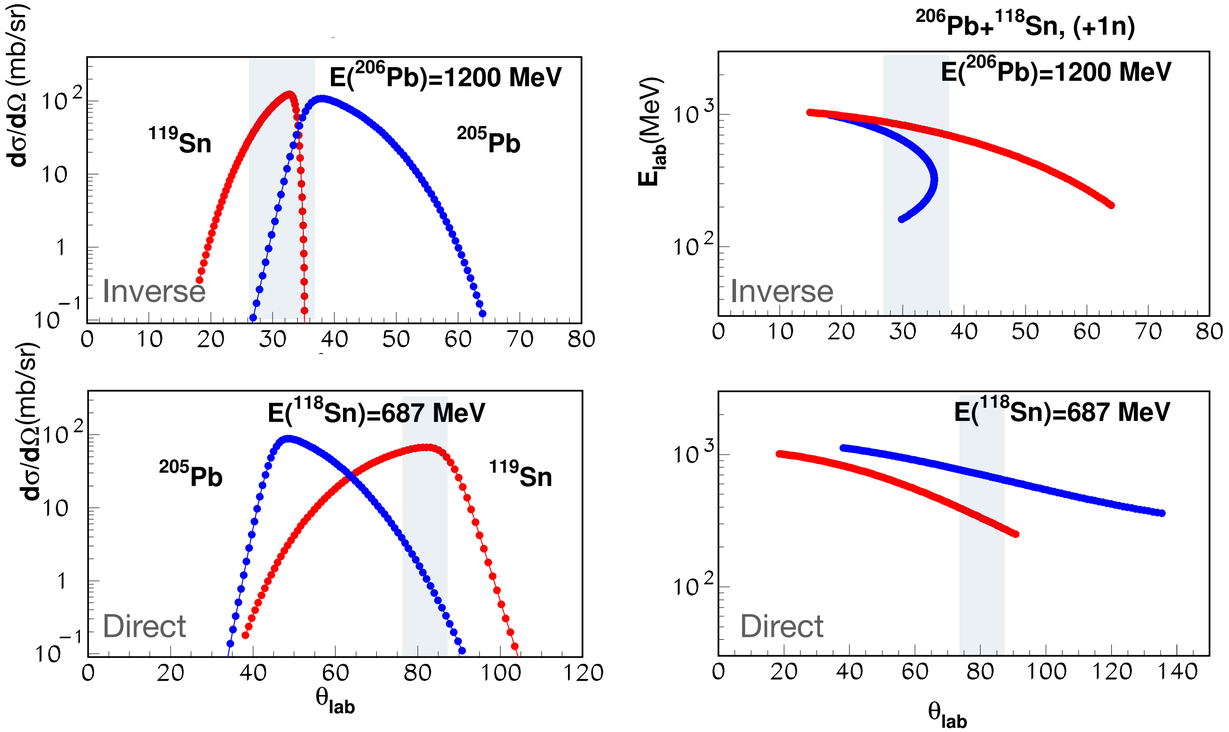


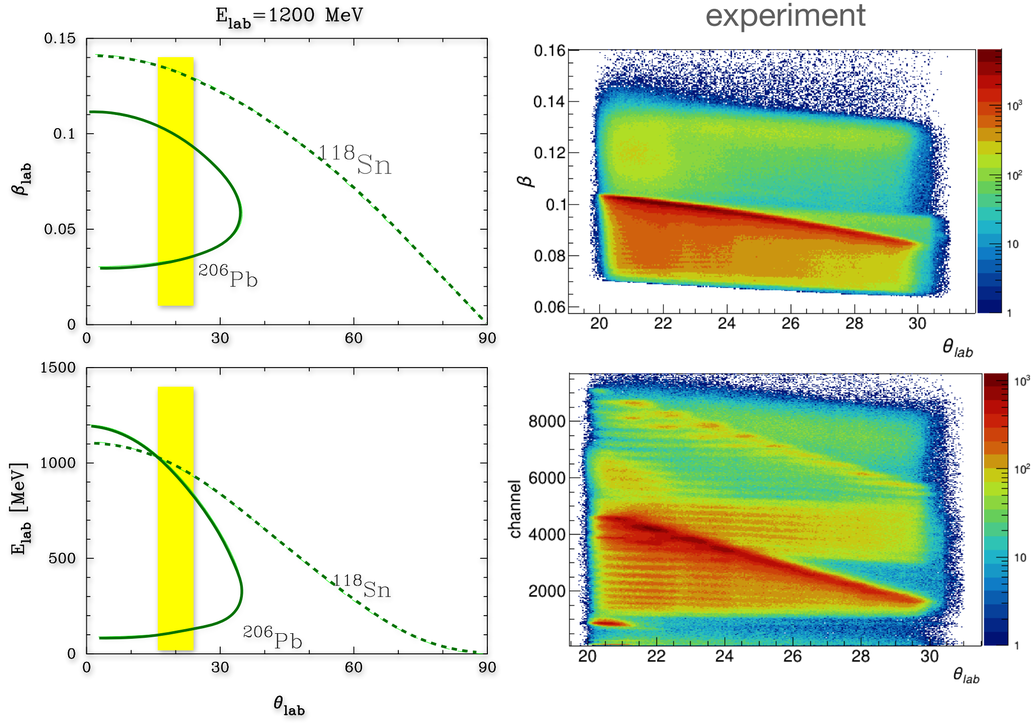
Legnaro National Laboratories (LNL, INFN)

Inverse kinematics

- Angular distribution focused at forward angles -> **higher efficiency**
- Around grazing angle kinetic energy per nucleon is around 2.5 times higher than with direct kinematics-> **better mass resolution**







PRISMA magnetic spectrometer

trajectory reconstruction

Measured:

(*x,y*) of MCP, and PPAC
time of flight ***TOF***
kinetic energy ***E***
energy loss ***ΔE***

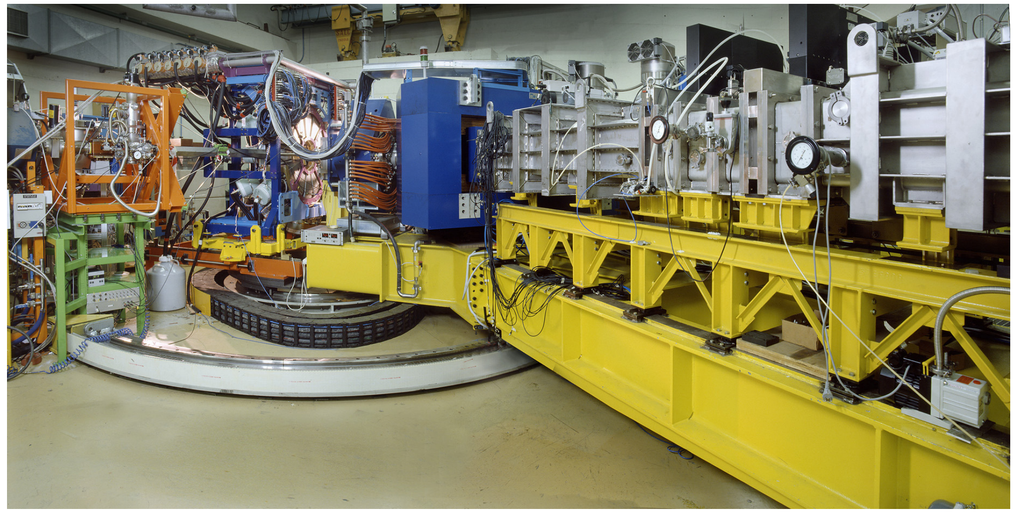
Known:
Magnetic fields
system geometry

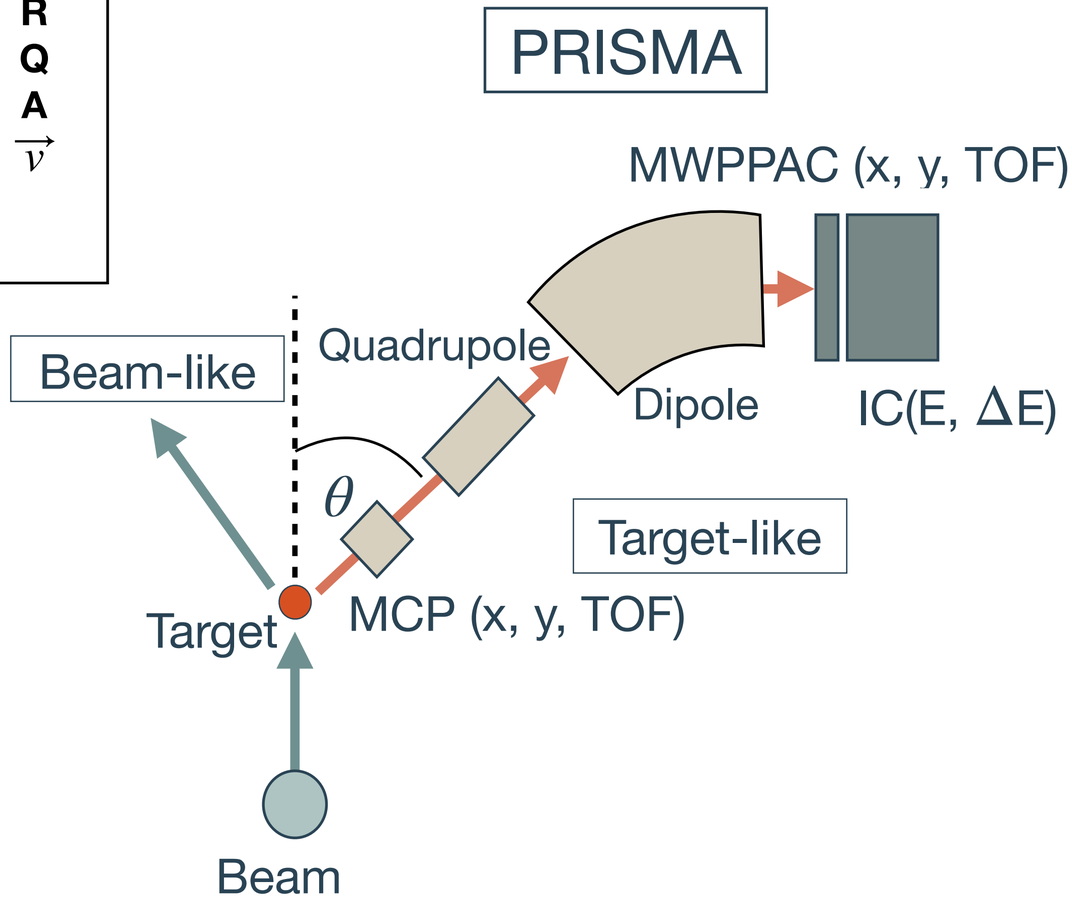
v, β
Z

"event-by-event"
reconstruction

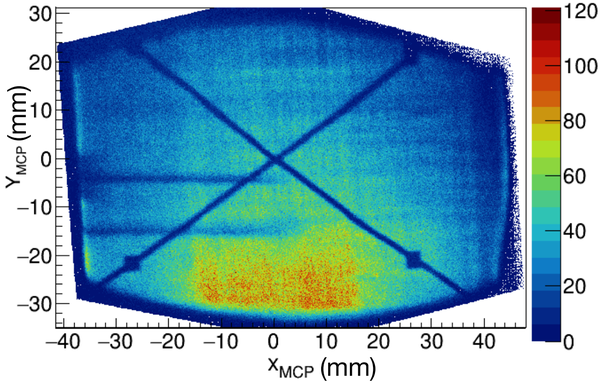
planar trajectory
approximation

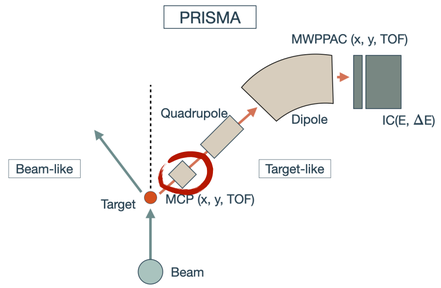
R
Q
A
$\vec{v}$





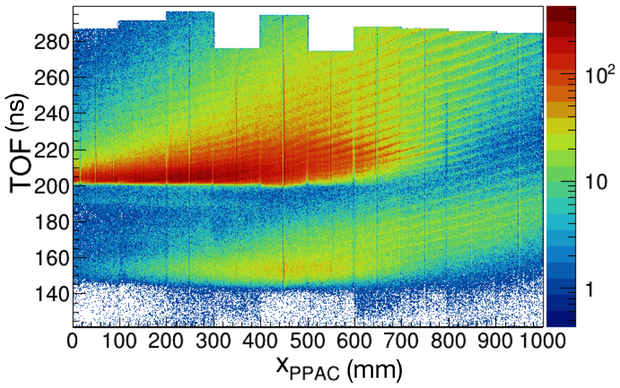
MCP-detector

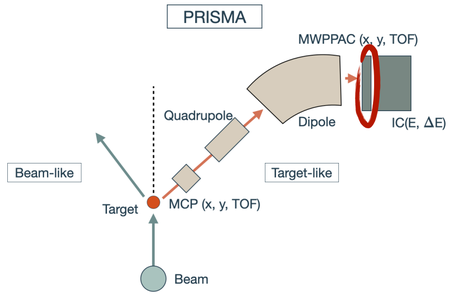




MCP(*x,y*)

MWPPAC-focal plane detector



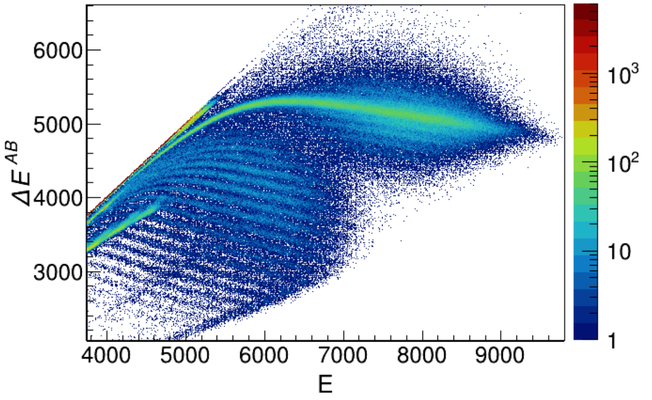


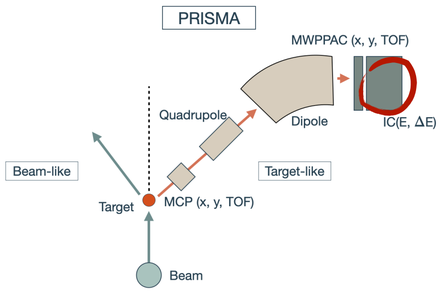
MWPPAC(*x,y*)

TOF=t$_{MCP}$*-t*$_{PPAC}$

IC- ionization chamber

Z identification

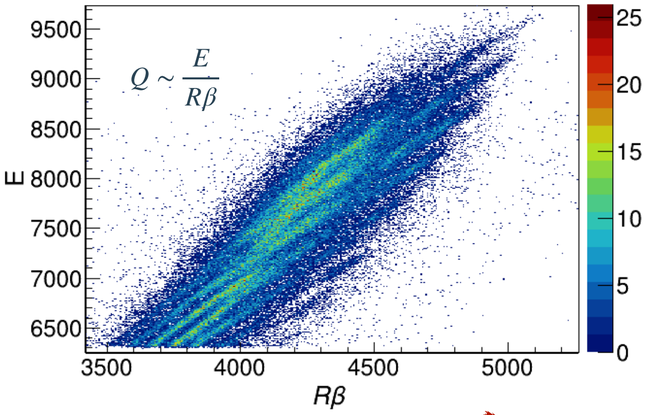


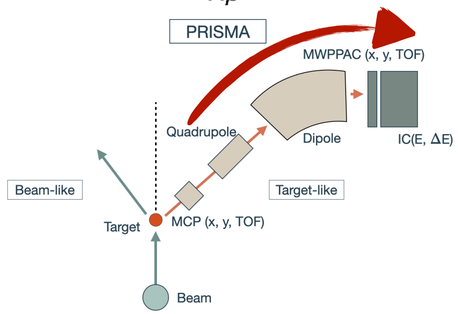


dE, E

Trajectory reconstruction

Q identification



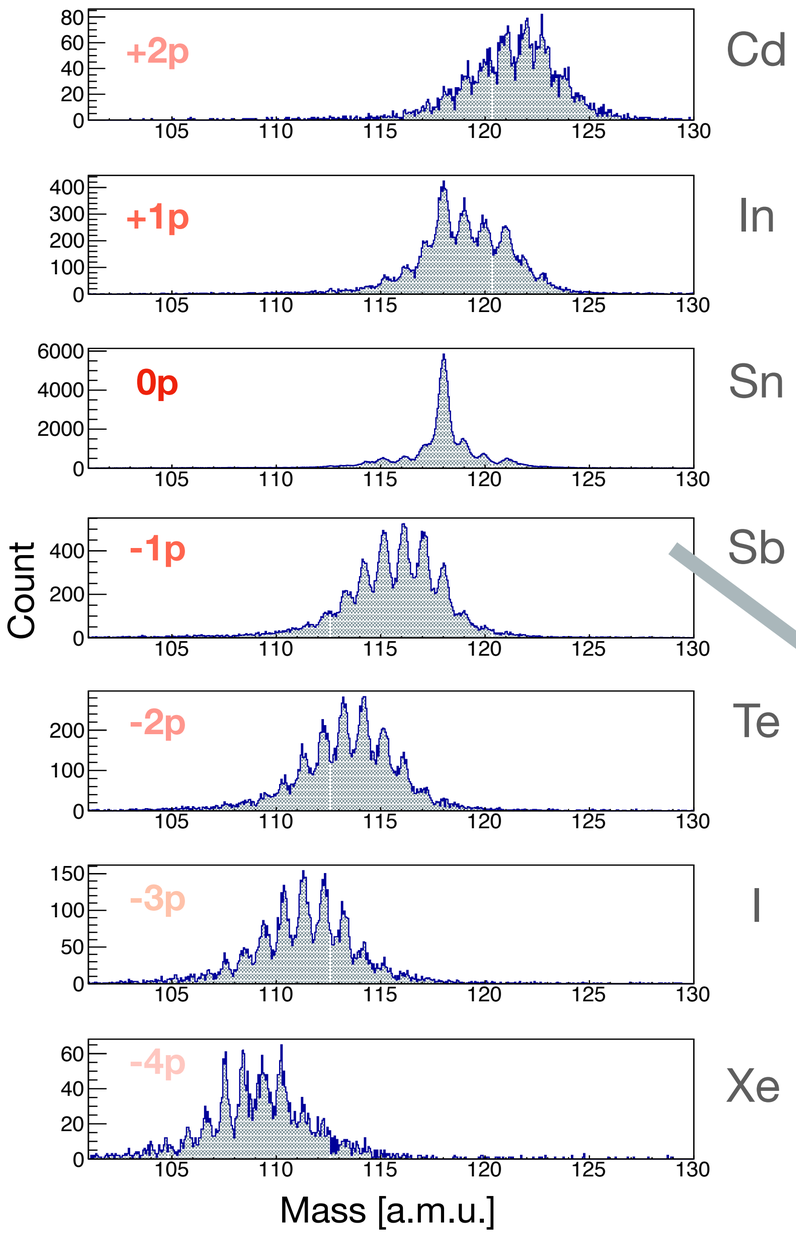


R

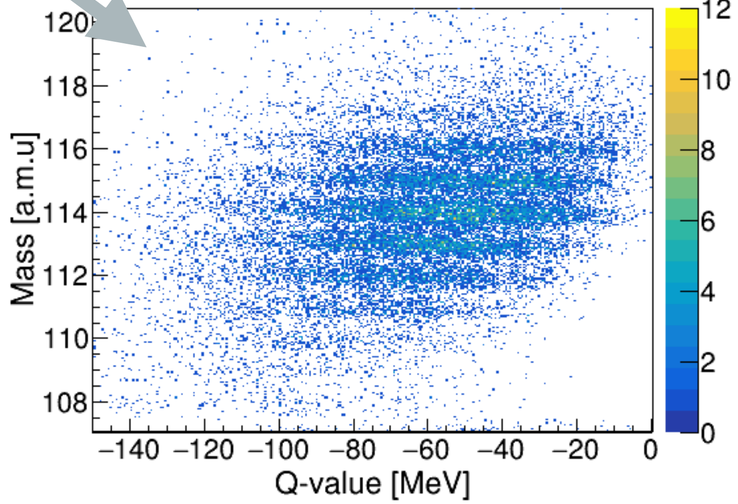
Analysis

^{206}Pb+^{118}Sn

- **Complete ion identification**: mass spectra were constructed for each atomic state (Z), with mass resolution $\Delta A/A \approx 1/190$
- It allows us to study ions from **Xe (Z=46) to Cd (Z=52)**



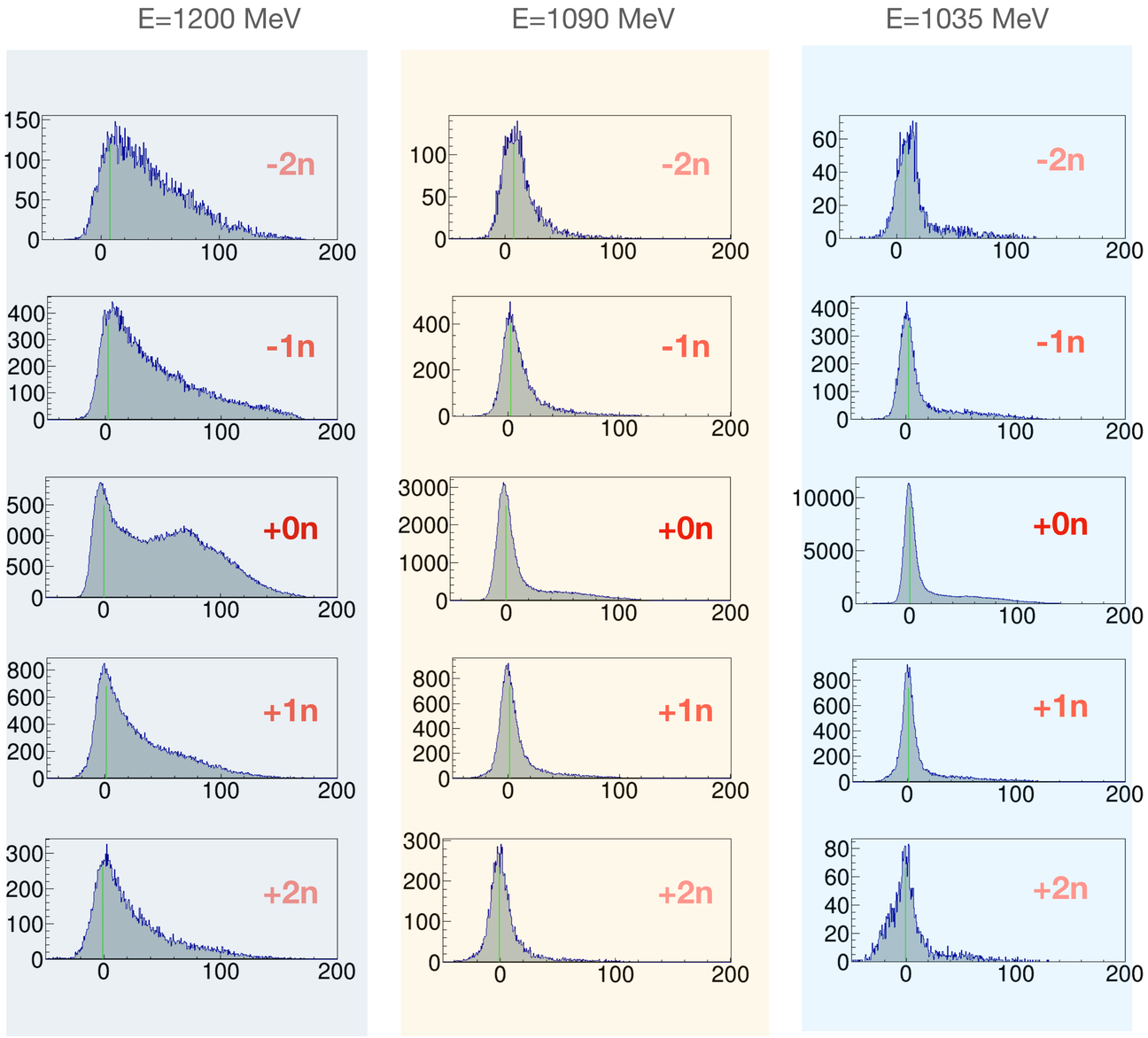
$\Delta A/A \approx 1/190$



Analysis

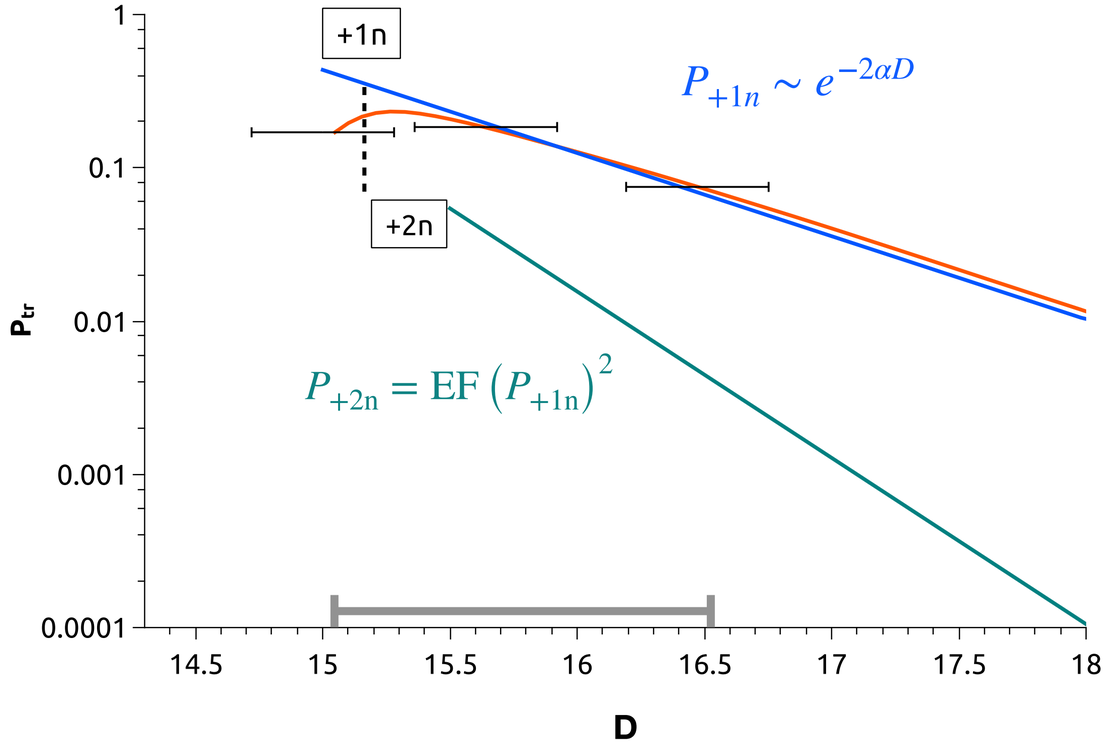
$^{206}Pb+^{118}Sn$

- Neutron striping and pick-up (Z=50, **Sn isotopes**)
- Due to the **optimum Q-value** considerations in the Pb+Sn system neutron stripping and pick-up channels are of similar strength
- Q-value = -TKEL



Conclusion

- Constructed **preliminary transfer probabilities** for (+1n,-1n) and (+2n,-2n) channels in the D range: 15 - 16.5 fm
- For neutron transfer channels, preliminary results give the value of the enhancement factor **EF>1**
- The comparison of experimental probabilities with the **microscopic calculations** which incorporate nucleon-nucleon correlations will provide informations about pairing in nuclei



Thank you!

J. Diklić[1], S. Szilner[1], L. Corradi[2], P. Čolović[1], G. Colucci[3], E. Fioretto[2], F. Galtarossa[2,4], A. Goasduff[3], A. Gottardo[2], J. Grebosz[5], A. Illana Sisón[2], G. Jaworski[2], M. Jurado Gomez[6], T. Marchi[2], T. Mijatović[1], G. Montagnoli[3], D. Nurkić[7], G. Pollarolo[8], F. Scarlassara[3], M. Siciliano[2], N. Soić[1], A. M. Stefanini[2], D. Testov[3], A. Utepov[2,9], J. J. Valiente-Dobón[2], N. Vukman[1]

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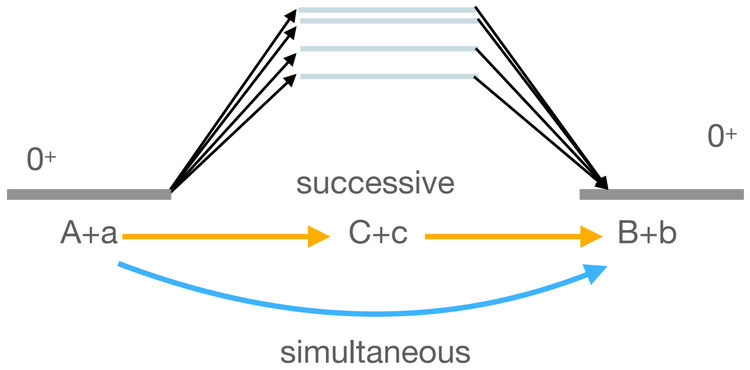
HRZZ

Institut Ruđer Bošković

^{60}Ni+^{116}Sn

Microscopic calculation

- For heavy-ion system Sommerfeld parameter $\eta \gg 1 \implies$ a condition necessary in order to describe the processes by **semi-classical methods** (Coulomb+ nuclear)
- The calculations are performed in a distorted wave Born approximation **(DWBA)**
- For the **one-neutron** transfer channel, the inclusive cross section is simply obtained by summing up all the contributions coming from the single particle transitions.
- To calculate the amplitude for the transfer of **two nucleons** one has to solve the well-known system of semiclassical coupled equations up to the second-order Born approximation
- For the **two-neutron** transfer channel, we included only the ground to ground state transition ($0^+ \rightarrow 0^+$) in the successive approximation (because simultaneous component is canceled out by the nonorthogonality correction).
- $c_\beta(\ell) = \left(c_\beta\right)_{(1)} + \left(c_\beta\right)_{\text{ort}} + \left(c_\beta\right)_{\text{succ}} \approx \left(c_\beta\right)_{\text{succ}}$



$$\left(c_\beta\right)_{\text{succ}} = \frac{1}{\hbar^2}\sum_{a_1,a_1'} B^{(A)}\left(a_1 a_1';0\right) B^{(a)}\left(a_1' a_1';0\right) 2\frac{(-1)^{j_1+j_1'}}{\sqrt{(2j_1+1)}\sqrt{(2j_1'+1)}} \sum_{m_1 m_1'} (-1)^{m_1+m_1'}$$
$$\times \int_{-\infty}^{+\infty} dt f_{m_1 m_1'}(\mathscr{R}) e^{i\left[\left(E_\beta - E_\gamma\right)t + \delta_{\beta\gamma}(t) + \hbar\left(m_1' - m_1\right)\Phi(t)\right]/\hbar}$$
$$\times \int_{-\infty}^{t} dt f_{-m_1 -m_1'}(\mathscr{R}) e^{i\left[\left(E_\gamma - E_\alpha\right)t + \delta_{\gamma\alpha}(t) - \hbar\left(m_1' - m_1\right)\Phi(t)\right]/\hbar}$$

* D. Montanari *et al.*, Phys. Rev. Lett. **113** (2014) 052501.
* L. Corradi *et al.*, Phys. Rev. C **84** (2011) 034603.