Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11th-12th 2022

Transfer and particle spectroscopy

Leandro Gasques

University of Sao Paulo, Sao Paulo, Brazil

Franco Galtarossa

Università di Padova and INFN LNL, Italy

Conveners

- Leandro Gasques (University of Sao Paulo, Brazil)
- Franco Galtarossa (Università di Padova and INFN LNL, Italy)

Working group members

- Alinka Lépine-Szily (University of Sao Paulo, Brazil)
- Andres Arazi (Tandar Laboratory, Argentina)
- Ángel Miguel Sánchez Benitez (University of Huelva, Spain)
- Didier Beaumel (IJCLab, France)
- Juan Pablo Fernandez Garcia (University of Sevilla, Spain)
- Kazuyuki Sekizawa (Tokyo Institute of Technology, Japan)
- Laura Moschini (University of Surrey, UK)
- Marcos Aurélio Gonzalez Alvarez (University of Sevilla, Spain)
- Tea Mijatovic (Ruder Boskovic Institute, Croatia)

Study of the reaction mechanism

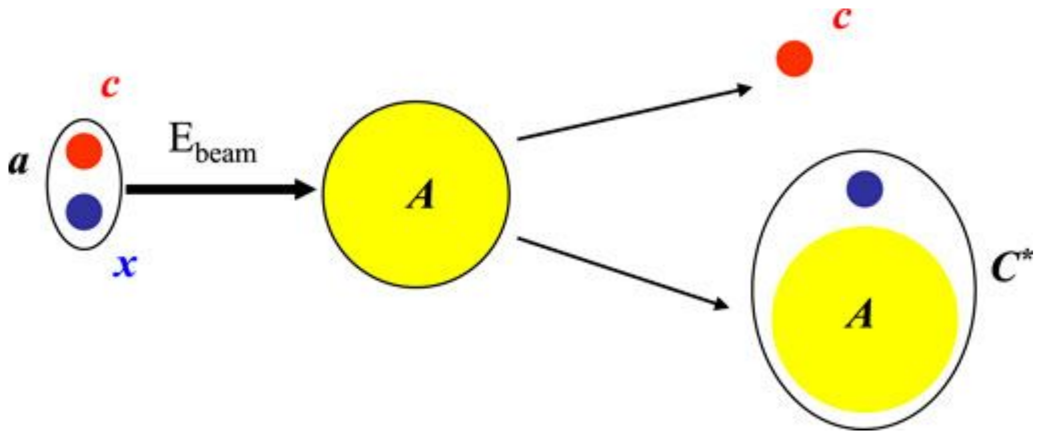
- ★ Multinucleon transfer reactions at near- ad sub-barrier energies
  - Production of neutron-rich heavy nuclei
  - Nucleon-nucleon correlations
- ★ Competition between transfer and near-barrier fusion

Applications of transfer to structure and astrophysical studies

- ★ Asymptotic Normalization Constant and its implications
- ★ The problem of ^{12}C and the ^{6}He elastic breakup

Tools to study transfer at LNL

- ★ Charged-particle detectors (PRISMA, GRIT, …)
- ★ Neutron detectors (NEDA, …)
- ★ Cryogenic targets (CTADIR, SUGAR, …)



Transfer reactions are an excellent spectroscopic probe. They are often used for:

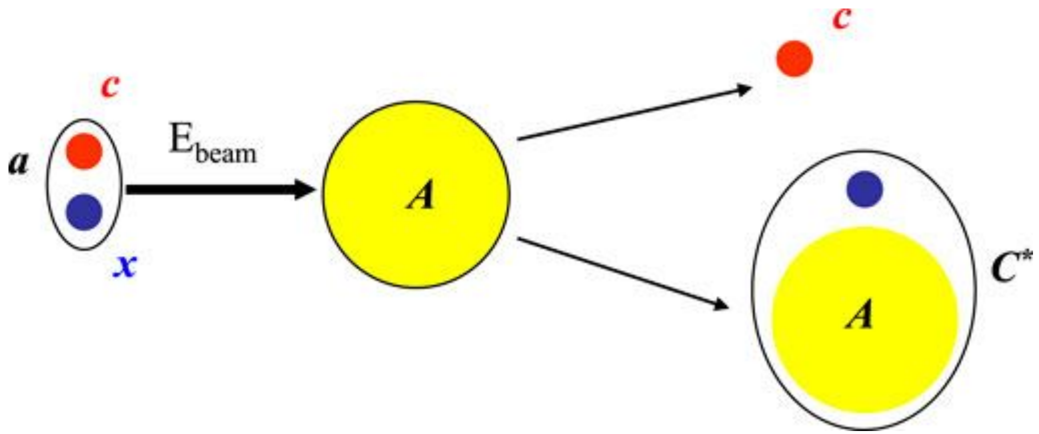
- unveil the nuclear structure of nuclei (single-particle states, pairing correlations, etc);

- probe the energies of shell model orbitals;

- study partial decay widths of states involved in resonant reactions (nuclear astrophysics);

- multinucleon transfer reactions are applied to produce neutron-rich isotopes.

The transfer process



The cluster of nucleons (x) can populate multiple states in the residual nucleus C* = A+x

The kinematics of the ejectile c gives information on the properties of these states

The angular distribution of c depends on the transferred angular momentum L

Therefore, knowledge about the bombarding energy and Q-value allows the determination of L (spin)

Absolute cross sections are linked with the spectroscopic strengths of the populated levels

The transfer process

frontiers in Physics | Nuclear Physics

REVIEW article

Front. Phys., 30 March 2021 | https://doi.org/10.3389/fphy.2020.602920

Check for updates

Transfer Reactions As a Tool in Nuclear Astrophysics

Faïrouz Hammache* and Nicolas de Séréville*

IJCLab, Université Paris-Saclay, CNRS/IN2P3, Orsay, France

Nuclear reaction rates are one of the most important ingredients in describing how stars evolve. The study of the nuclear reactions involved in different astrophysical sites is thus mandatory to address most questions in nuclear astrophysics. Direct measurements of the cross-sections at stellar energies are very challenging–if at all possible. This is essentially due to the very low cross-sections of the reactions of interest (especially when it involves charged particles), and/or to the radioactive nature of many key nuclei. In order to overcome these difficulties, various indirect methods such as the transfer reaction method at energies above or near the Coulomb barrier are used to measure the spectroscopic properties of the involved compound nucleus that are needed to calculate cross-sections or reaction rates of astrophysical interest. In this review, the basic features of the transfer reaction method and the theoretical concept behind are first discussed, then the method is illustrated with recent performed experimental studies of key reactions in nuclear astrophysics.

frontiers in Physics | Nuclear Physics

MINI REVIEW article

Front. Phys., 12 March 2019 | https://doi.org/10.3389/fphy.2019.00020

Check for updates

TDHF Theory and Its Extensions for the Multinucleon Transfer Reaction: A Mini Review

Kazuyuki Sekizawa*

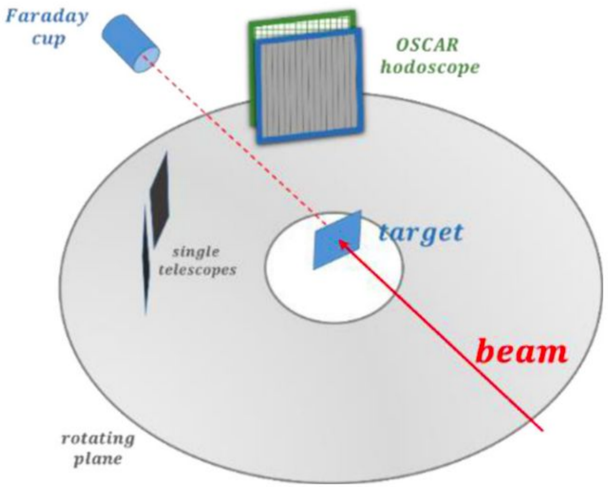
Center for Transdisciplinary Research, Institute for Research Promotion, Niigata University, Niigata, Japan

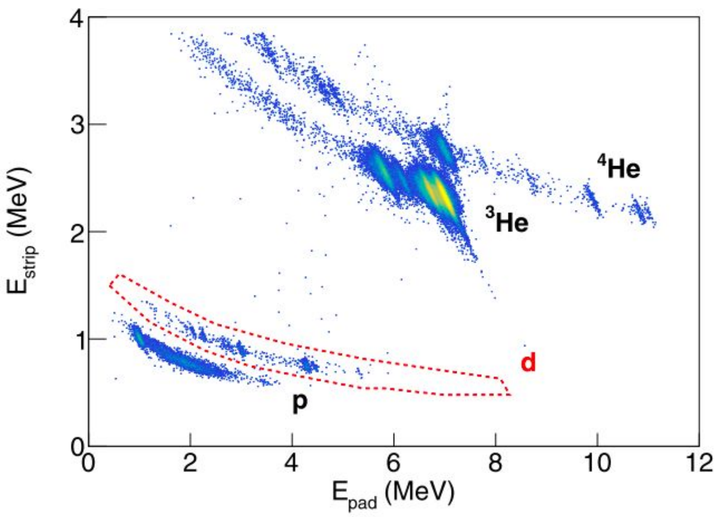
Time-dependent Hartree-Fock (TDHF) theory has been a powerful tool in describing a variety of complex nuclear dynamics microscopically without empirical parameters. In this contribution, recent advances in nuclear dynamics studies employing TDHF and its extensions are briefly reviewed, in line with the study of multinucleon transfer (MNT) reactions. The latter lies at the core of this Research Topic, whose application for the production of extremely neutron-rich nuclei has been extensively discussed in recent years. Having in mind the ongoing theoretical developments, it is envisaged how microscopic theories may contribute to the future MNT study.

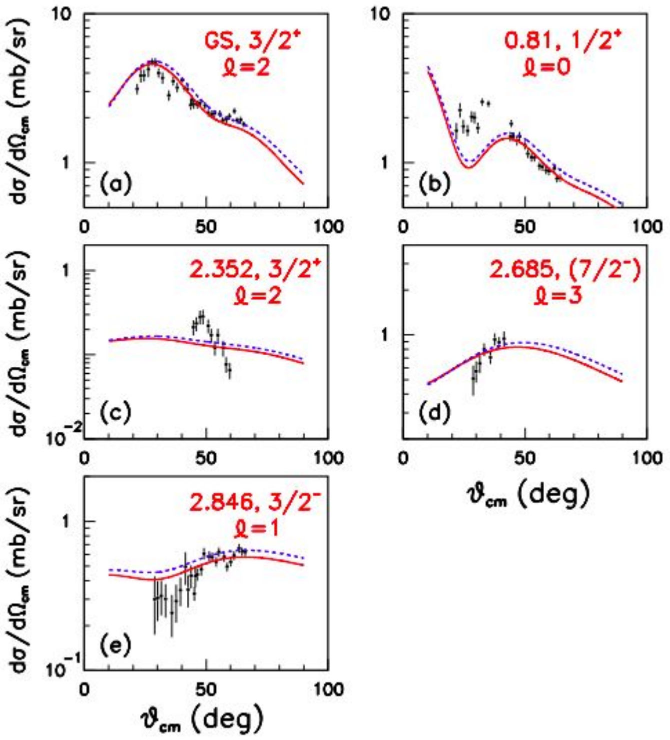
IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 48 (2021) 065101 (16pp) https://doi.org/10.1088/1361-6471/abdee4

Study of the ^{33}Cl spectroscopic factors via the ^{32}S(^{3}He, d)^{33}Cl one-proton transfer reaction

I Lombardo[1,*], D Dell'Aquila[2,3], M Cinausero[4], L R Gasques[5], M Vigilante[6,7], V A B Zagatto[8], S Barlini[9,10], R Bolzonella[11], M Bruno[12,13], A Buccola[9,10], A Camaiani[9,10], S M Carturan[4,11], G Casini[9], C Ciampi[9,10], M Cicerchia[4], M D'Andrea[1], M Degerlier[14], D Fabris[15], C Frosin[9,10], F Gramegna[4], A Lepine-Szily[5], G Maggioni[4,11], G Mantovani[4,11,16], T Marchi[4], A Ordine[7], P Ottanelli[9,10], G Pasquali[9,10], S Piantelli[9], V Rigato[4], M Russo[1,17], L Scomparin[11], S Valdrè[9] and G Verde[1]





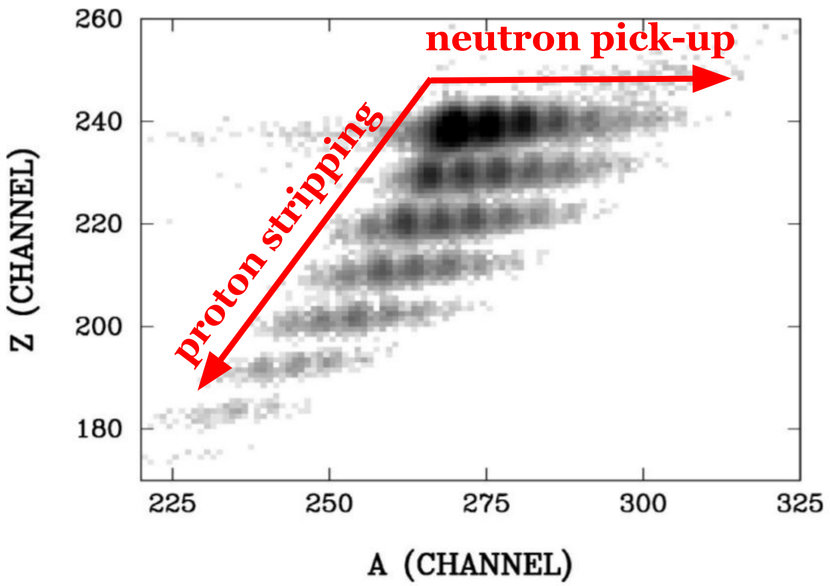


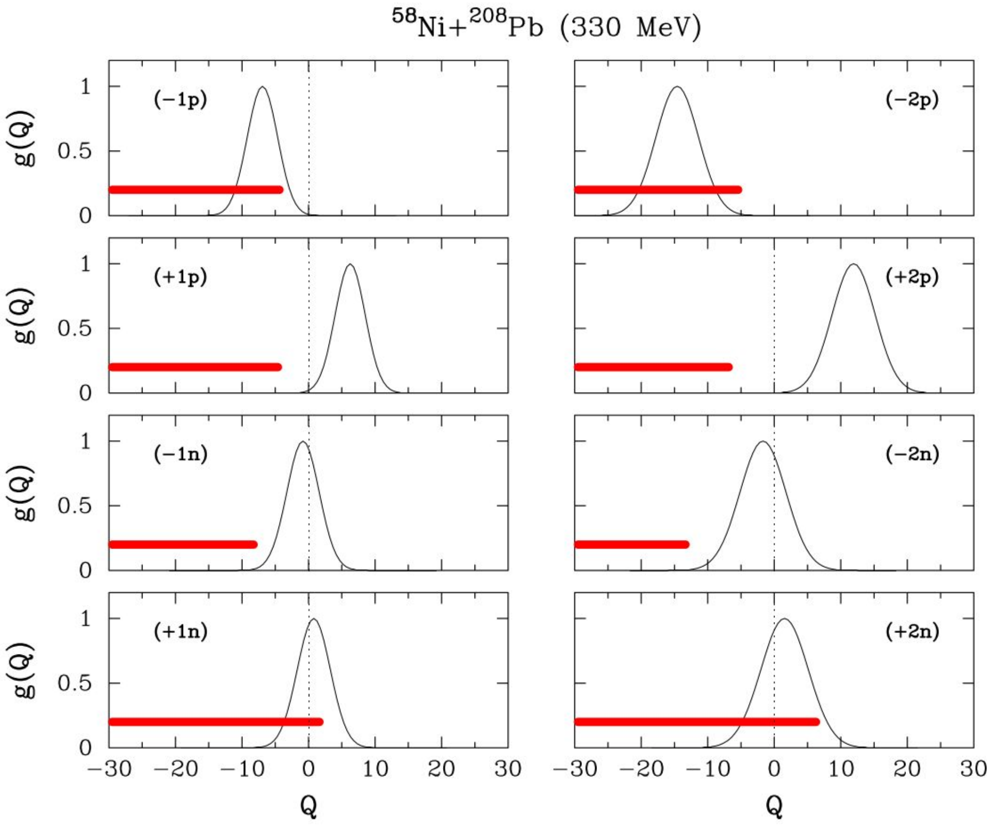
- Exchange of many nucleons around the Coulomb barrier (grazing reactions)
- Lighter stable beams on heavy target -> neutron pick-up and proton stripping channels are favored

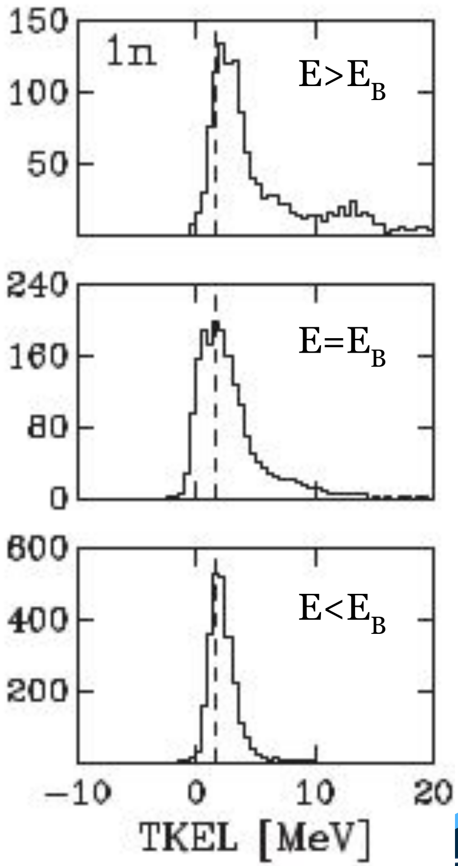
adiabatic cut-off function:

$$g(Q) = \exp\left(-\frac{(Q - Q_{opt})^2}{\hbar^2 \ddot{r}_0 \kappa_{a'_1}}\right)$$

^{58}Ni+^{208}Pb @ 330 MeV







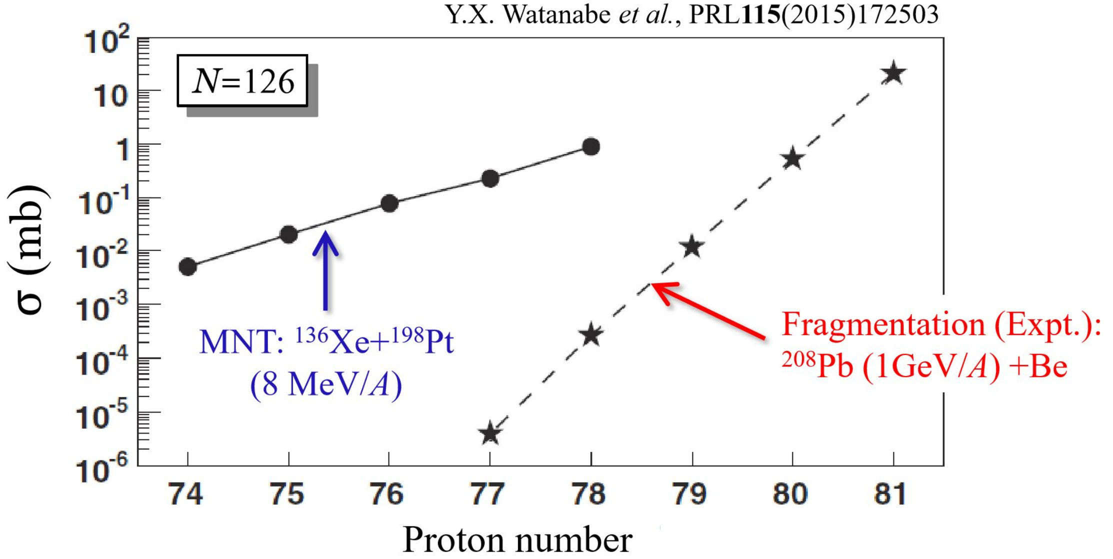
L. Corradi, G. Pollarolo, S. Szilner, J. of Phys. G:Nucl. Part. Phys. **36** (2009) 113101

- With (radioactive) n-rich beams neutron stripping and proton pick-up channels open!
- **MNT very promising way to populate n-rich heavy nuclei**
- Important implications for nuclear structure and astrophysical (*r process*) studies

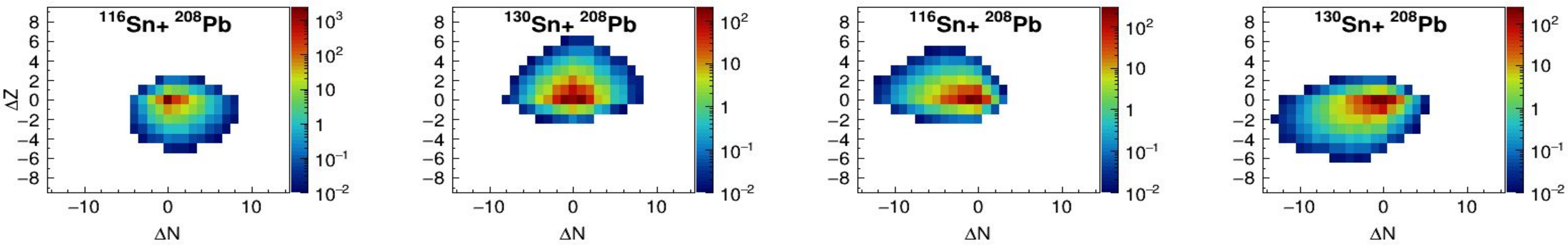
But:

- Proton transfer process is still poorly understood
- The effect of secondary processes is difficult to account for

Y.X. Watanabe *et al.*, PRL**115**(2015)172503



GRAZING CALCULATIONS



LIGHT **HEAVY**

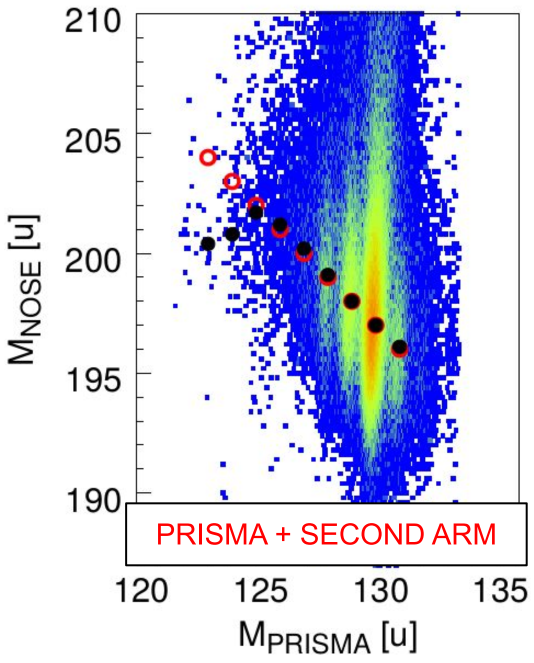
Multinucleon transfer - Secondary effects

- **Secondary effects** (evaporation, fission) significantly change the yield distribution of heavy primary nuclei
- Need to study the best experimental conditions for a large **survival probability** of n-rich heavy nuclei
- Studies performed with PRISMA coupled to second arm, DANTE, gamma-ray array
- Important to understand evolution of **QE** to **DIC** and **quasi-fission**

- Important **stable** beams: ^{48}Ca, ^{124}Sn, ^{136}Xe, ^{208}Pb, ^{238}U
- Important **SPES** beams: ^{90,92,94}Rb, ^{130,132}Sn, ^{140,144}Xe

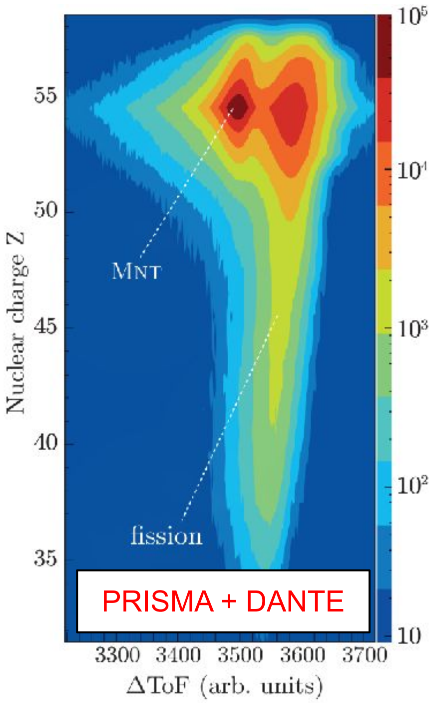
For the understanding of the reaction mechanism it is important to measure Z, A, angular distributions, total cross sections, Q-value distributions -> **PRISMA** (+ coincident γ and/or particle detectors)

^{197}Au+^{130}Te @ 1.07 GeV



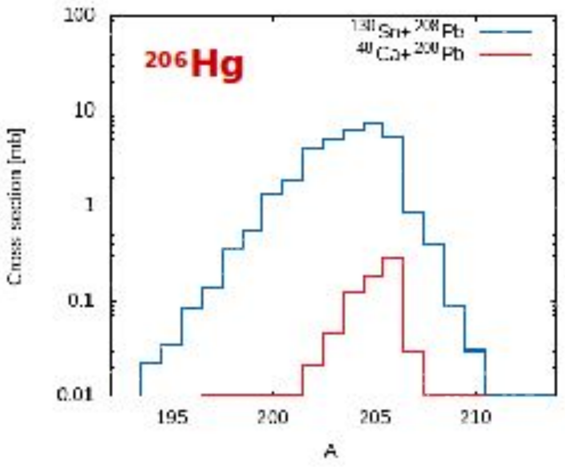
F. Galtarossa et al., PRC **97** (2018) 054606

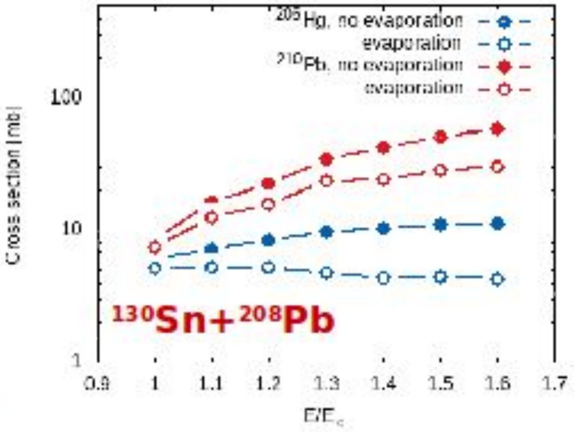
^{136}Xe+^{238}U @ 1 GeV



A. Vogt et al., PRC **92** (2015) 024619

Low bombarding energy, need of **inverse kinematics**!





KS and K. Yabana, PRC**88**(2013)014614; KS, PRC**96**(2017)014615

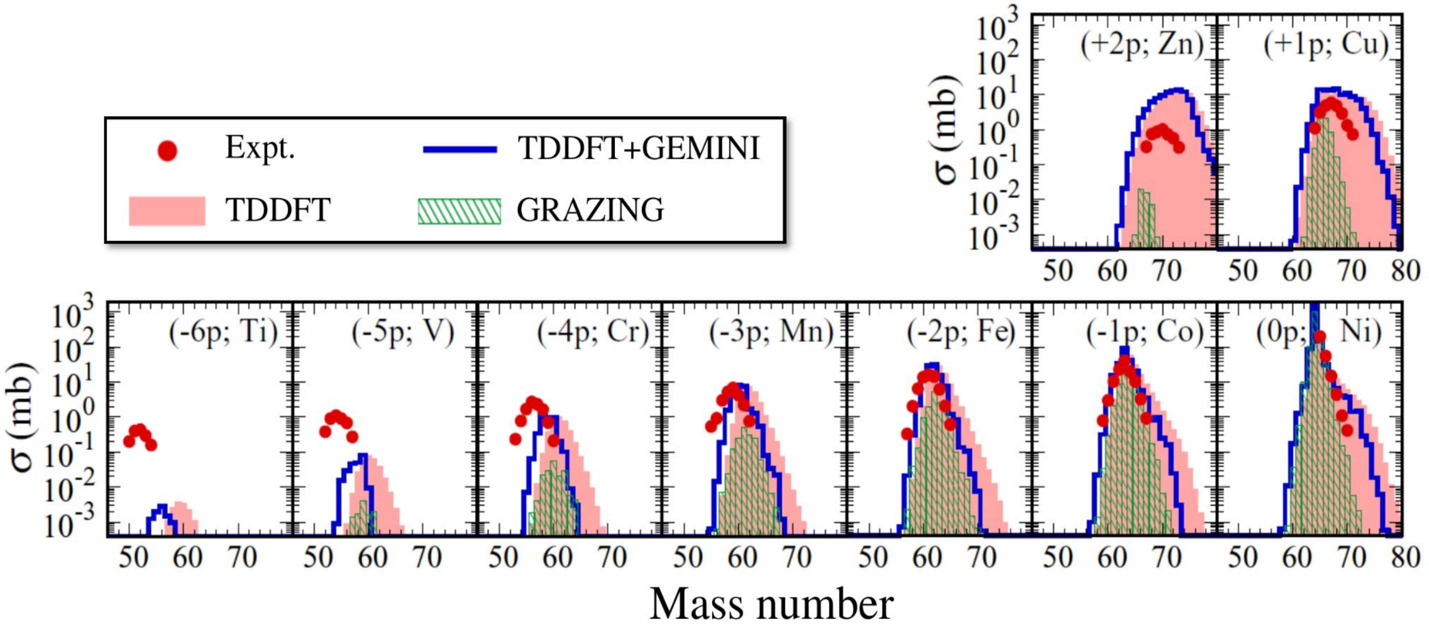
Production cross section for projectile-like fragments

- Validate different types of reaction models (GRAZING, DWBA, TDHF, Zagrebaev-Greiner model) and improve cross section prediction

- Microscopic theories have been developed with the use of supercomputers:
  - TDFH and extended approaches (TDRPA, SMF, TDHFB)

- Quantitative comparison with the experimental data: mean values and distributions

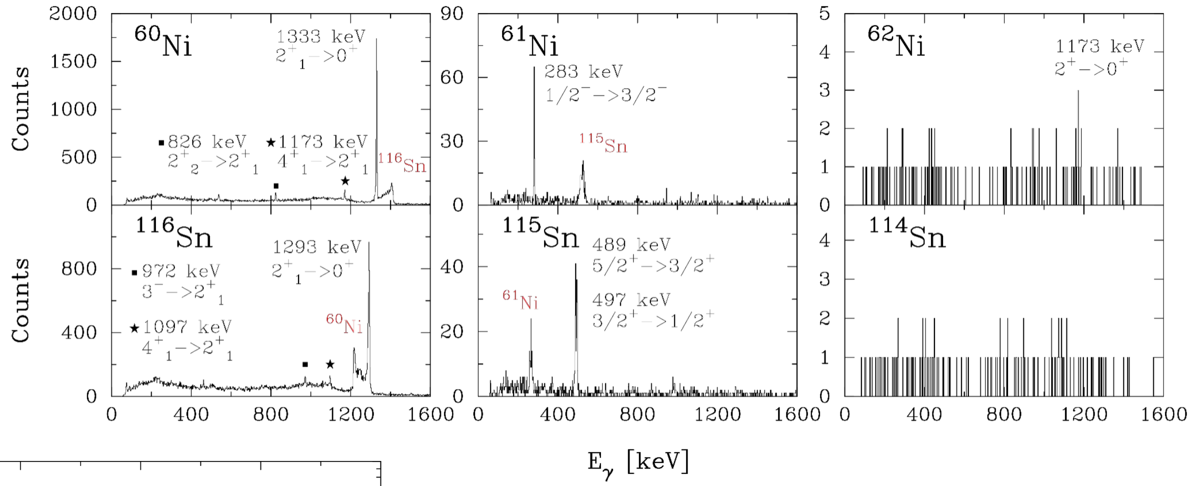
^{64}Ni+^{238}U ($E_{c.m.}$=307 MeV, E/V_B=1.27 [tip], 1.16 [side])



Expt.: L. Corradi et al., PRC**59**(1999)261

Two-nucleon transfer reactions are among the best tools to investigate correlations

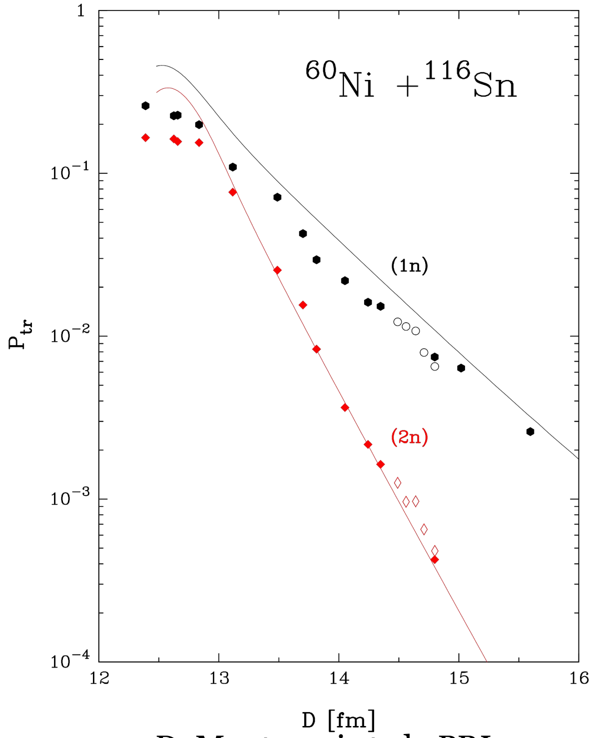
- ★ Heavy ions: simultaneous comparison of a single-nucleon transfer and a pair transfer (nn, pp and/or np)
- ★ Studies at energies near and below the Coulomb barrier by using **inverse kinematics**.
- ★ In the case of neutrons, an appropriate choice of the system (Q_{gs}~Q_{opt}~0) allows to transfer mainly to the gs (**Q-value matching**).



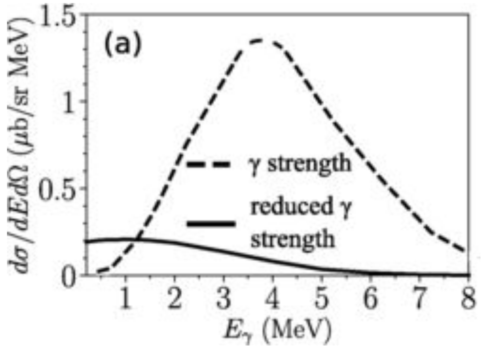
G. Potel et al, PRC **103** (2021) L021601

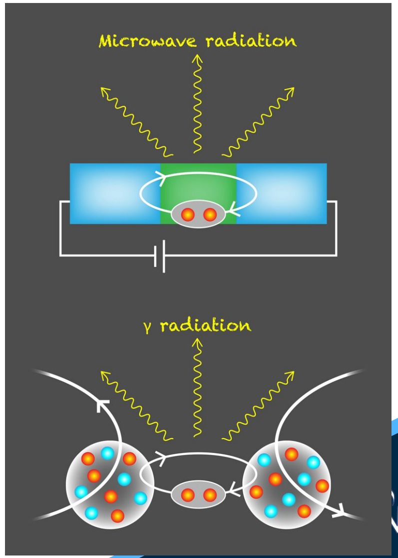
The ^{60}Ni+^{116}Sn case

- ❑ The experimental transfer probabilities have been well reproduced, for the first time with heavy ions, in **absolute value and slope**, by microscopic calculations
- ❑ Data have been interpreted as a manifestation of a **nuclear Josephson effect**, with Cooper pair tunneling between the superfluid nuclei
- ❑ A specific gamma ray associated with the oscillating motion of a neutron pair is predicted

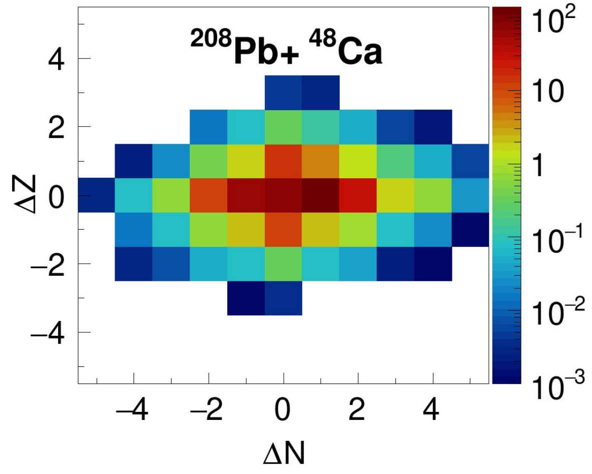


D. Montanari et al., PRL **113** 052501 (2014)





PRISMA+AGATA measurement to be performed in Autumn 2022



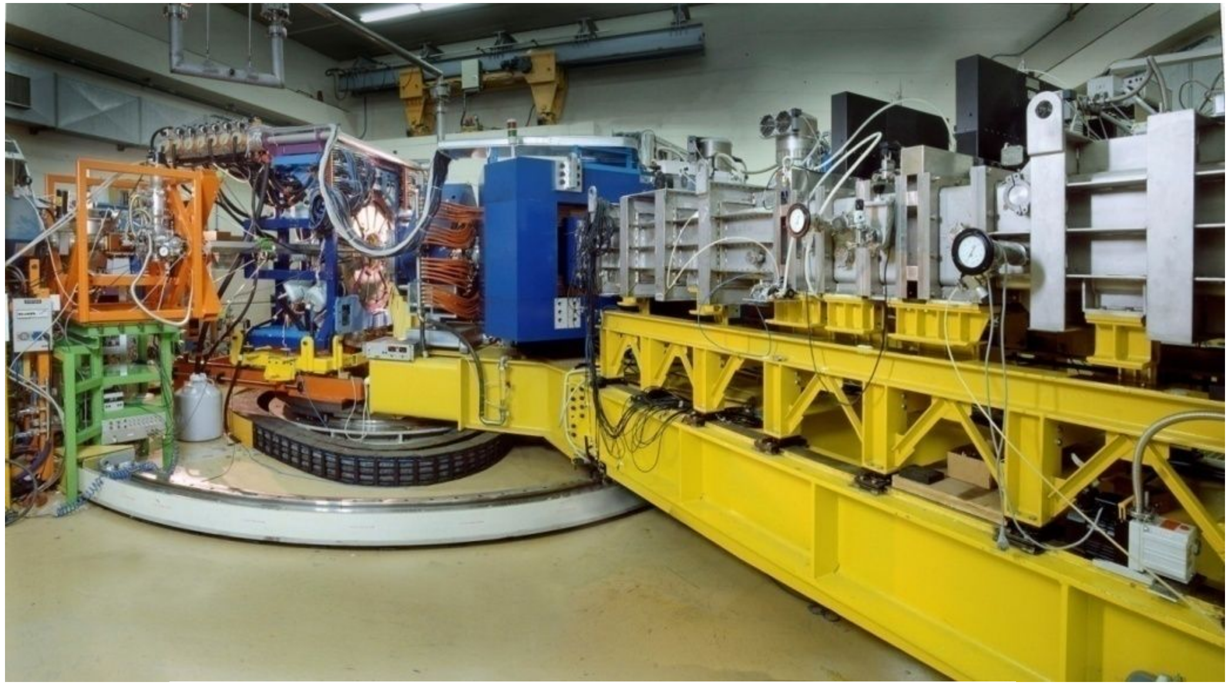
Stable beams:

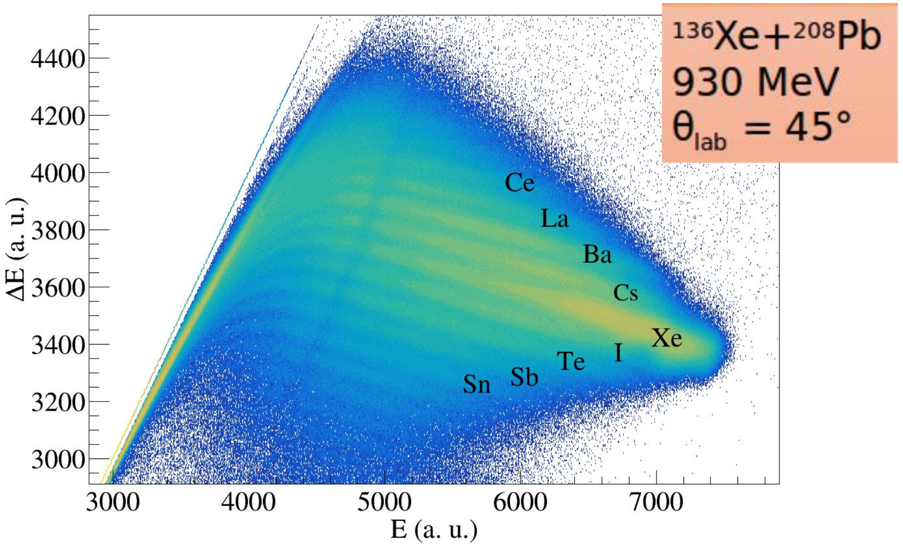
- $^{208}Pb+^{48}Ca$ double magic nuclei
- $^{206}Pb+^{62}Ni$ closed proton and open neutron shell
- $^{208}Pb+^{144}Sm$, $^{144}Sm+^{88}Sr$ superfluid proton system

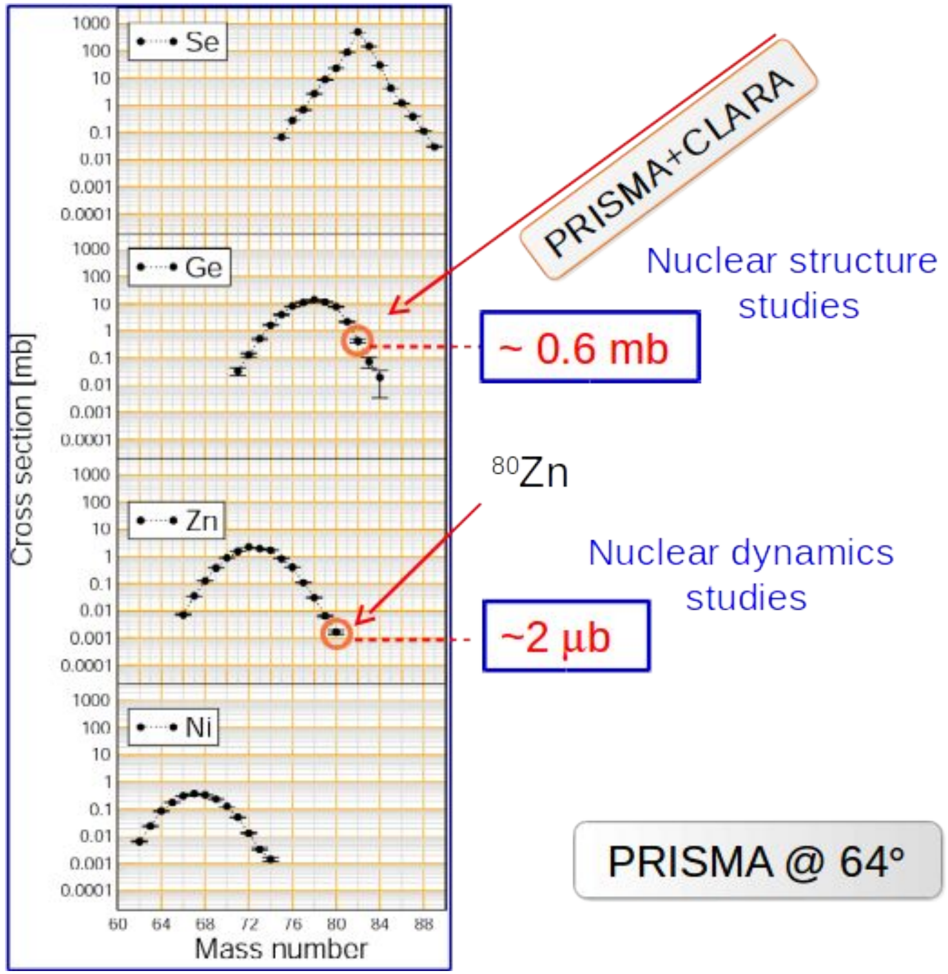
Radioactive beams:

- $^{132}Sn+^{40}Ca$
- $^{132}Sn+^{64}Ni$
- $^{132}Sn+^{208}Pb$

- Investigate nucleon-nucleon correlations **simultaneously** for a complete set of transfer channels, involving both addition and removal of neutron and proton pairs
  - To learn more about the influence of the pair mode in the proton channels, especially the pick-up one
  - The optimum Q value for proton transfer channels is not 0
- Nuclei with an extended n distribution: study the density dependence of the pairing force
- Comparison of results with theory and cross comparison between reactions performed with stable and radioactive beams will provide valuable insight into this topic







PRISMA @ 64°

PRISMA has been conceived to measure A, Z and Q-value distributions for heavy ions (30 <A<140) at energies in the range 3-10 MeV/u

The neutron transfer channel affect the near-barrier fusion of heavy-ions!

However ....

- the reaction mechanisms for fusion is still not yet fully understood

 * coupled reaction channel effects, sequential fusion, reaction dynamics (transfer/breakup), etc

- in general, coupled channel models can describe well collective excitation effects

 * the situation is more obscure concerning the neutron transfer process

- reactions with positive Q-values neutron transfer enhance the sub-barrier fusion probability

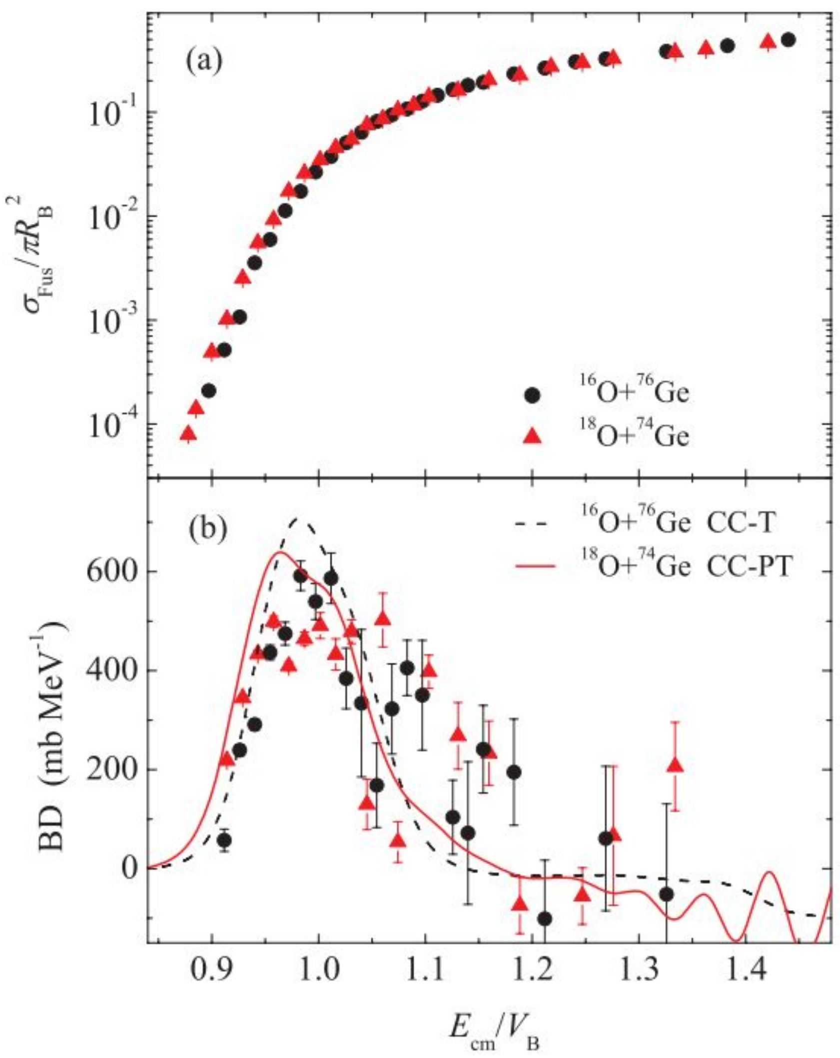
 * many examples in the literature: Ni+Ni, Ni+Ge, Ca+Ca, Ca+Zr, S+Sn, etc

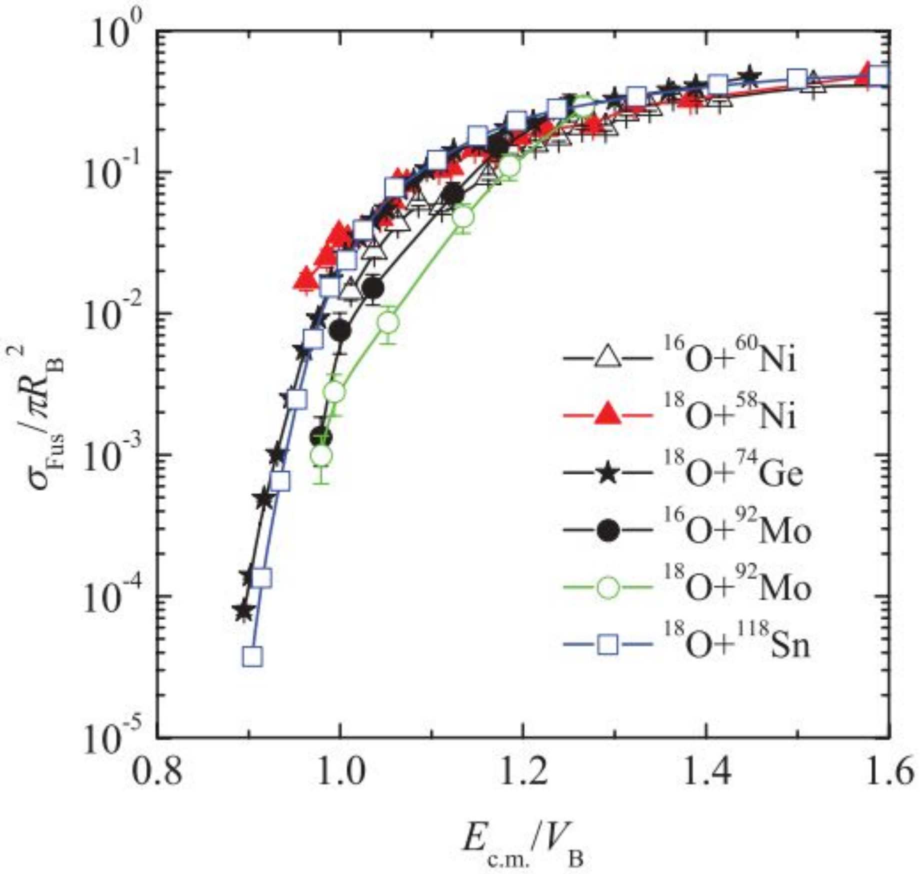
- both pickup and stripping transfer reactions affect the near barrier fusion cross sections?

 * pickup (yes) PRC 30, 1223 (1984); PRL 45, 1472 (1980); NPA 633, 421 (1998)

 stripping (no) PRC 30, 2088 (1984), PLB 175, 271 (1986), Nature 431, 823 (2004) - $^{18}O+^{58}Ni$ (2n stripping) shows large enhancements ???

H. M. Jia et al., Phys. Rev. C 86, 044621 (2012)





System	Q_{1n} (MeV)	Q_{2n} (MeV)
$^{18}O + ^{24}Mg$	−0.71	+6.24
$^{18}O + ^{50}Cr$	+0.84	+9.11
$^{16}O + ^{60}Ni$	−7.24	−8.20
→ $^{18}O + ^{58}Ni$	+0.96	+8.20
$^{18}O + ^{74}Ge$	−1.54	+3.75
$^{16}O + ^{92}Mo$	−8.53	−10.6
→ $^{18}O + ^{92}Mo$	+0.03	+5.56
→ $^{18}O + ^{118}Sn$	−1.56	+3.41
$^{40}Ca + ^{48}Ca$	−1.58	+2.62

How to investigate the transfer effect on fusion (experimentally)?

1) by comparing two or more nearby reactions (with positive and negative Q-values for the neutron transfer channel)

2) measuring "simultaneously" fusion, transfer/breakup and other peripheral processes (elastic, inelastic)

3) measuring fusion barrier distributions

Where to measure such reactions?

1) @ TANDEM - ALPI (regular and weakly bound projectiles)

2) @ SPES using radioactive projectiles

→ Pisolo beamline

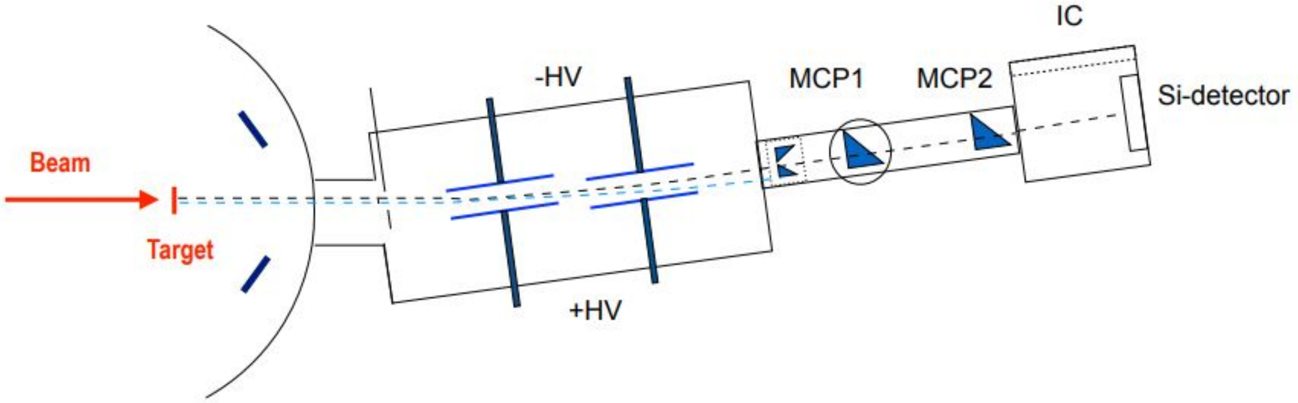
Few reactions recently investigated

1) $^{32,34}S+^{112,116,120,124}Sn$ @ CIAE, China

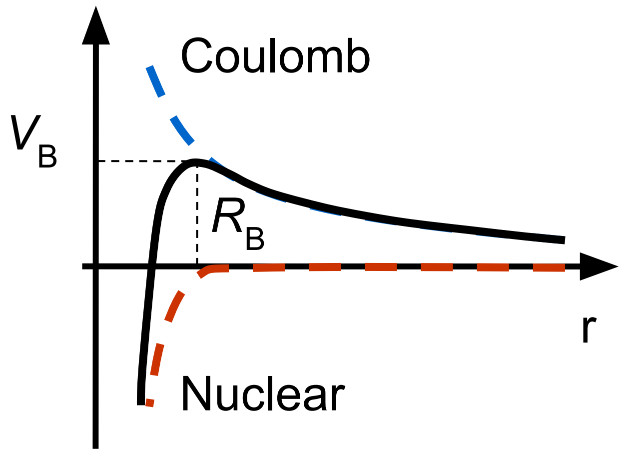
2) $^{32}S+^{130}Te$ @ IUAC, India

* First measurements are from 80's but some recent efforts demonstrate that there are still few important questions to be addressed

* It is a subject that presents a clear interplay with other key areas presented in the INFN MidTerm plan



$V_B \sim 240$ MeV



pickup

System	+1n	+2n	+3n
^{58}Ni+^{124}Sn	0.510	5.952	4.956
^{69}Ni+^{124}Sn	-1.183	-2.865	-4.789
^{70}Ni+^{124}Sn	-4.225	-3.280	-8.142

stripping

System	-1n	-2n	-3n
^{58}Ni+^{124}Sn	-6.483	-8.540	-19.656
^{69}Ni+^{124}Sn	1.147	1.545	1.265
^{70}Ni+^{124}Sn	-1.573	2.031	-0.234

The transfer cross section could be measured in PRISMA in a complementary experiment

SF's are very sensitive to the choice of the binding potential between the core and the transferred particle(s)

The Asymptotic Normalization Constant (ANC) was introduced to facilitate the comparison of structure information obtained from transfer direct reaction data

L. D. Blokhintsev, I. Borbely, and E. I. Dolinskii, Fiz. Elem. Chastits At. Yadra 8, 1189 (1977); Sov. J. Part. Nuclei 8, 485 (1977)

SF's are very sensitive to the choice of the binding potential between the core and the transferred particle(s)

The Asymptotic Normalization Constant (ANC) was introduced to facilitate the comparison of structure information obtained from transfer direct reaction data

L. D. Blokhintsev, I. Borbely, and E. I. Dolinskii, Fiz. Elem. Chastits At. Yadra 8, 1189 (1977); Sov. J. Part. Nuclei 8, 485 (1977)

→ probes the strength of the tail of the exponential wave function (almost free from geometrical parameters - radius, diffuseness)

→ less sensitive to the entrance and exit channel potentials

SF's are very sensitive to the choice of the binding potential between the core and the transferred particle(s)

The Asymptotic Normalization Constant (ANC) was introduced to facilitate the comparison of structure information obtained from transfer direct reaction data
L. D. Blokhintsev, I. Borbely, and E. I. Dolinskii, Fiz. Elem. Chastits At. Yadra 8, 1189 (1977); Sov. J. Part. Nuclei 8, 485 (1977)

→ probes the strength of the tail of the exponential wave function (almost free from geometrical parameters - radius, diffuseness)

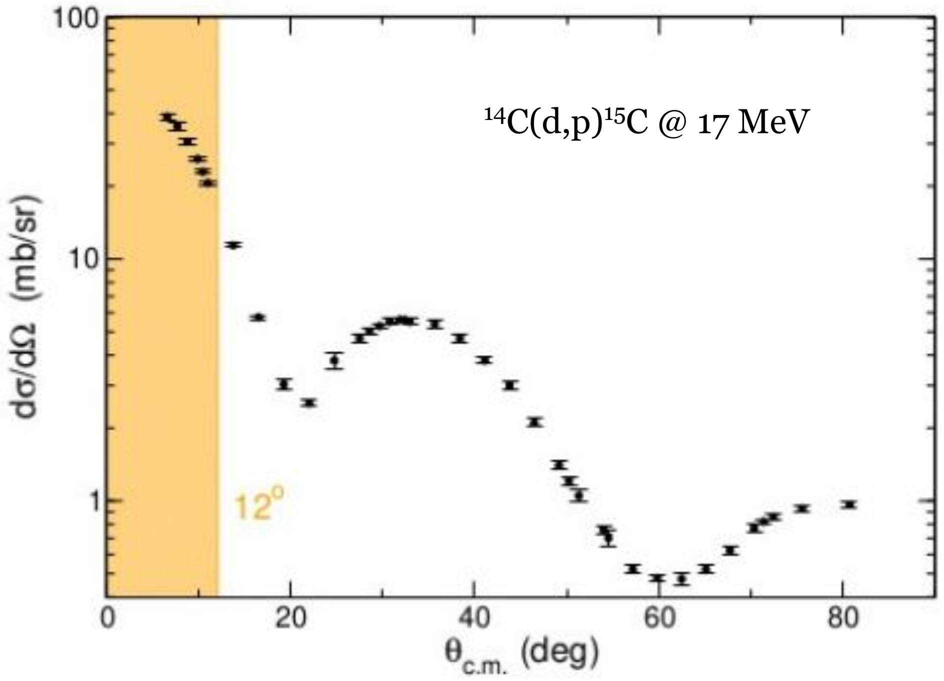
→ less sensitive to the entrance and exit channel potentials

The ANC plays an important role in low-energy elastic scattering, transfer nuclear and radiative capture reactions

- can provide information on the nuclear structure;
- helps to determine if the nucleus has an halo;
  $^{14}C(d,p)^{15}C$: *L. Moschini et al., Phys. Rev. C100, 044615 (2019)*
  $^{10}Be(d,p)^{11}Be$: *J. Yang and P. Capel, Phys. Rev. C98, 054602 (2018)*
- often used to constrain cross sections of astrophysical interest → radiative capture (n,g) and (a,g) reactions

Requirements from the experimental point of view:

- The reaction must be peripheral to provide precise ANC values;
- Low energy beam (E < 10 MeV/u) and forward angles < 12 degrees;



Moschini, Yang and Capel, PRC **100** (2019) 044615
Mukhamedzhanov et al., PRC **84** (2011) 024616

Requirements from the experimental point of view:

- The reaction must be peripheral to provide precise ANC values;
- Low energy beam (E < 10 MeV/u) and forward angles < 12 degrees;

Some interesting cases to be investigated:

- study of ^{8}Li and ^{8}B mirror nuclei;
  ^{8}B is supposed to be a proton halo nucleus
  both nuclei are involved in nucleosynthesis scenarios

Requirements from the experimental point of view:

- The reaction must be peripheral to provide precise ANC values;
- Low energy beam (E < 10 MeV/u) and forward angles < 12 degrees;

Some interesting cases to be investigated:

- study of ^{8}Li and ^{8}B mirror nuclei;
  ^{8}B is supposed to be a proton halo nucleus
  both nuclei are involved in nucleosynthesis scenarios

Proposal: measure the ^{7}Li(d,p)^{8}Li and ^{7}Be(d,n)^{8}B reactions at low beam energies and forward angles

- pin down the ANC associated with both transfer reactions
- good occasion to test the theory for mirror nuclei
  Timofeyuk et al., Phys. Rev. Lett. 96, 162501 (2006)

Requirements from the experimental point of view:

- The reaction must be peripheral to provide precise ANC values;
- Low energy beam (E < 10 MeV/u) and forward angles < 12 degrees;

Some interesting cases to be investigated:

- study of ^{8}Li and ^{8}B mirror nuclei;
  ^{8}B is supposed to be a proton halo nucleus
  both nuclei are involved in nucleosynthesis scenarios

neutrons might be difficult to measure

^{7}Be(^{3}He,d)^{8}B can be an alternatives

→ ^{3}He cryogenic targets?

benchmark for ANC calculations

Proposal: measure the ^{7}Li(d,p)^{8}Li and ^{7}Be(d,n)^{8}B reactions at low beam energies and forward angles

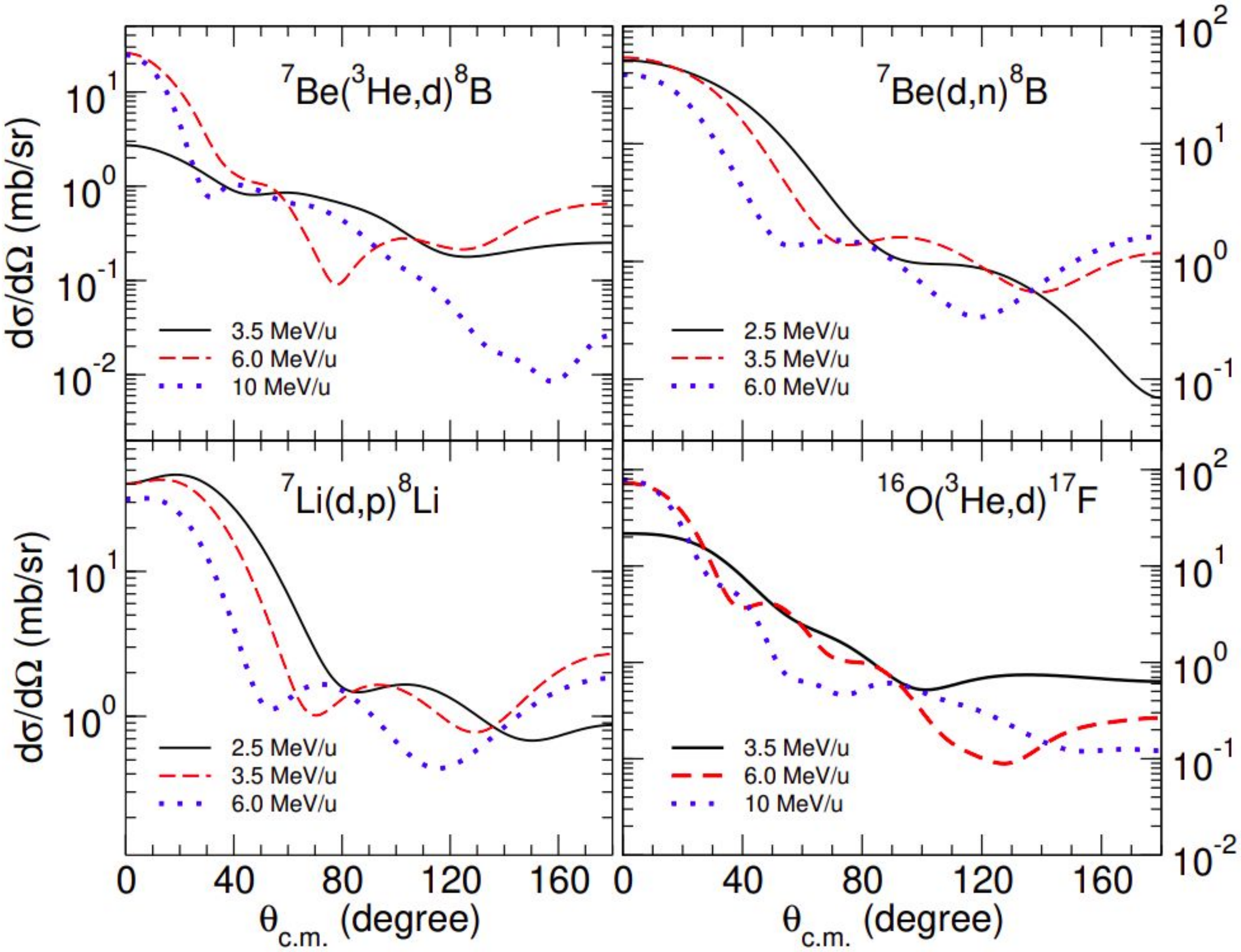
- pin down the ANC associated with both transfer reactions
- good occasion to test the theory for mirror nuclei
  Timofeyuk et al., Phys. Rev. Lett. 96, 162501 (2006)

Requirements from the experimental point of view:

- The reaction must be peripheral to provide precise ANC values;
- Low energy beam ($E < 10$ MeV/u) and forward angles < 12 degrees;

Some interesting cases to be investigated:

- extract the ^{17}F ANC values from the $^{16}O(d,n)^{17}F$ reaction;
  provides a precise estimate for the $^{16}O(p,g)^{17}F$ radiative capture cross sections;



^{7}Be(^{3}He,d)^{8}B
3.5 MeV/u
6.0 MeV/u
10 MeV/u
^{7}Be(d,n)^{8}B
2.5 MeV/u
3.5 MeV/u
6.0 MeV/u
^{7}Li(d,p)^{8}Li
2.5 MeV/u
3.5 MeV/u
6.0 MeV/u
^{16}O(^{3}He,d)^{17}F
3.5 MeV/u
6.0 MeV/u
10 MeV/u
dσ/dΩ (mb/sr)
θ$_{c.m.}$ (degree)

Another case: Using ^{16}O beam we could also test $^{12}C(alpha,gamma)^{16}O$

- when measured at low energy, it allows to extract the phase shift of the continuum state from which the alpha is captured;
- valuable info for ab initio theories and lattice QCD;
- there are previous data for the $^{12}C(^{6}Li, d)^{16}O$ and $^{12}C(^{7}Li, t)^{16}O$ reactions;
  Brune et al PRL83 4025 (1999)
- it might be a good opportunity to update the results.

The GRIT array

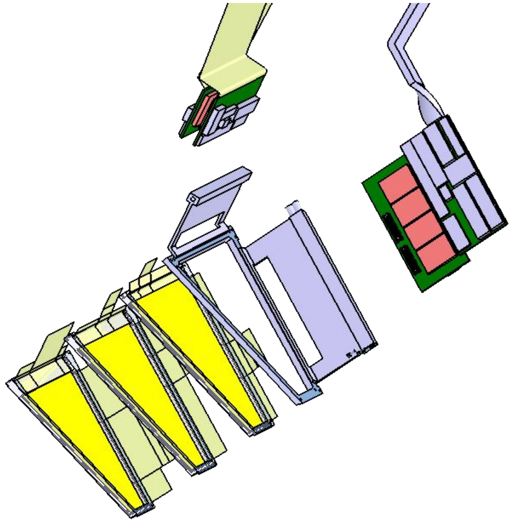
Granularity Resolution Identification Transparency

4π Silicon array fully integrable in AGATA & PARIS

Detectors

- High efficiency for particles
- High granularity (strip pitch < 0.8 mm)

Silicon layers	
	500 µm DSSD pitch < 0.8 mm
	1.5 mm DSSD pitch ~ 10mm

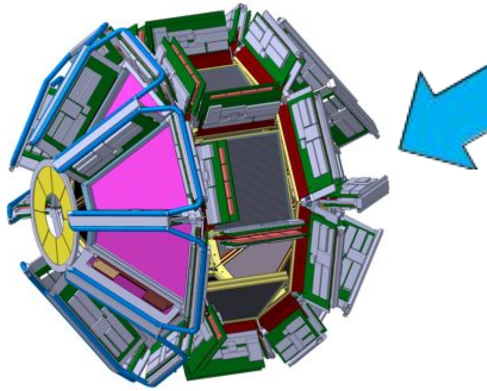


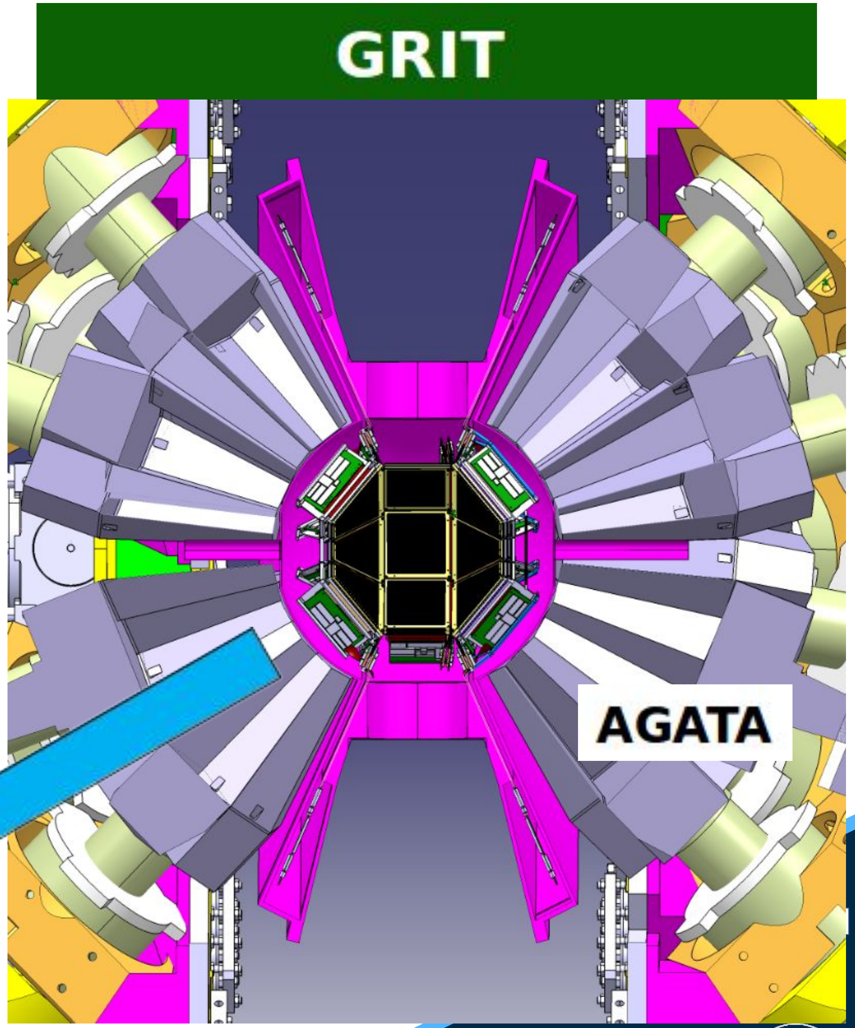
Electronics

- Large dynamical range
- PID using Pulse Shape Analysis techniques
- New Integrated Digital electronics

Mechanics

- Integration into AGATA (radius=23 cm)
- Transparency to γ rays
- High compactness
- Special targets : cryogenic, tritium, windowless





CTADIR

- ★ Havar windows (2 - 3.8 μm)
- ★ GM cryocooler for horizontal use
- ★ Temperature of 3K guaranteed in the head
- ★ Design and construction are completed
- ★ Gas filling system in 2022
- ★ Commissioning in Autumn 2022 at the CN accelerator

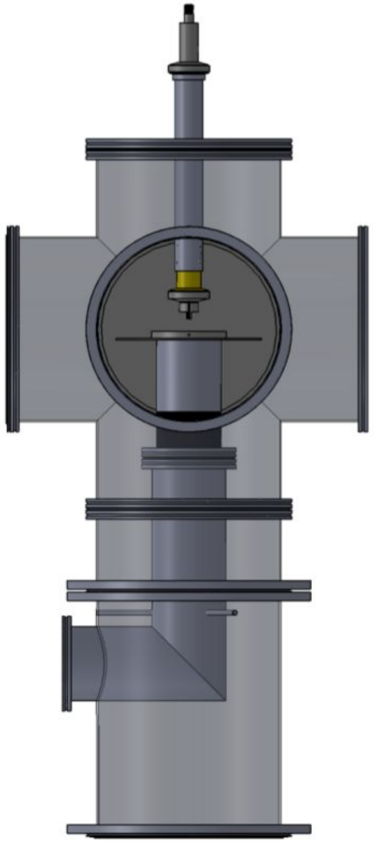
- ★ 1-2 mg/cm² of $^{3,4}He$

Courtesy of A. Gottardo

SUGAR

- ★ Windowless supersonic gas jet target
- ★ High pressure gas (1-5 atm) injected into the scattering chamber
- ★ Already commissioned (F. Favela at al., Accel. and Beams **18** (2015) 123502)

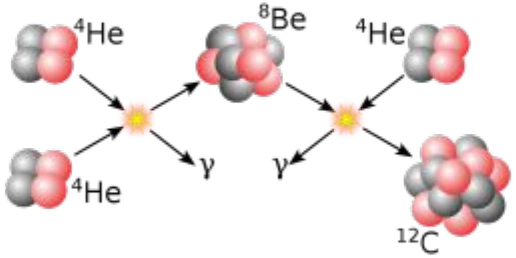
- ★ Density of scattering centers: 10^{17}-10^{18} atoms/cm²



The ^{12}C formation

^{12}C is the seed nucleus for the creation of heavier elements

- Triple alpha process



$^{4}He(an,g)^{9}Be$ → $^{9}Be(a,n)^{12}C$ (alternative path for the ^{12}C formation)

$^{4}He(nn,g)^{6}He(a,n)^{9}Be$

*** Already discussed yesterday by A. Caciolli and T. Kurtukian Nieto ***

Thanks for your attention !!!