Heavy-ion induced transfer reactions and the role of pairing

NUSPRASEN Workshop on Nuclear Reactions (Theory and Experiment)

NuSPRASEN

Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

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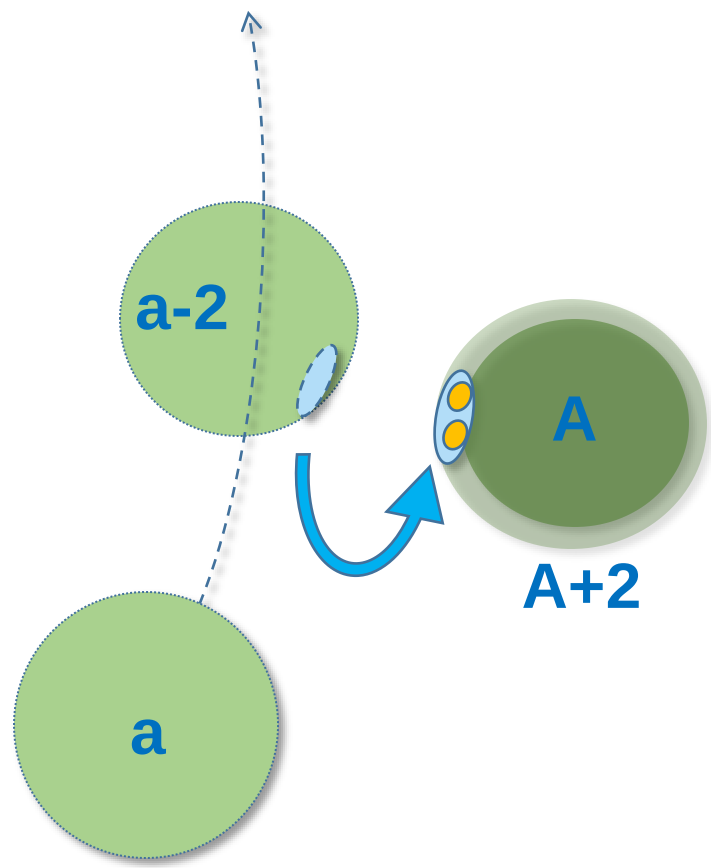
Direct transfer reactions

- Select specific degrees of freedom in the complex many-body nuclear system

- Exploration of the nuclear structure
  - Relation between 1n transfer cross sections and single-particle configurations
  - α transfer and clustering
  - Connection between 2n transfer probabilities and pairing correlations in nuclei



a + A → a-2 + A+2

The extraction of structure information from 2n transfer cross-sections is not straightforward

Heavy ions

Experimental difficulties

- Particle identification capability
- Resolution (energy and angle)
- Absolute cross-section measurement

Arbitrary scaling factors *"unhappiness"* (>>1) to reproduce the exp. angular distributions

The techniques to extract the optical potential from fits of elastic scattering data fail

- Coupling with inelastic excitations (CC corrections)
- Recoil effects
- Finite range f.f.
- Sequential transfer
- Only the product of projectile and target S.F. is accessible

Our study:
The (^{18}O,^{16}O) two-neutron transfer

The **(^{18}O,^{16}O)** reactions are good candidates to show the role of **pairing interaction** thanks to

- The presence of a **correlated pair** of neutrons in the $^{18}O_{g.s.}$ w.f.
- The very low polarizability of the **^{16}O core**

Different target systems explored

^{12}C(^{18}O,^{16}O)^{14}C
^{13}C(^{18}O,^{16}O)^{15}C
^{16}O(^{18}O,^{16}O)^{18}O
^{28}Si(^{18}O,^{16}O)^{30}Si
^{64}Ni(^{18}O,^{16}O)^{66}Ni
heavier…

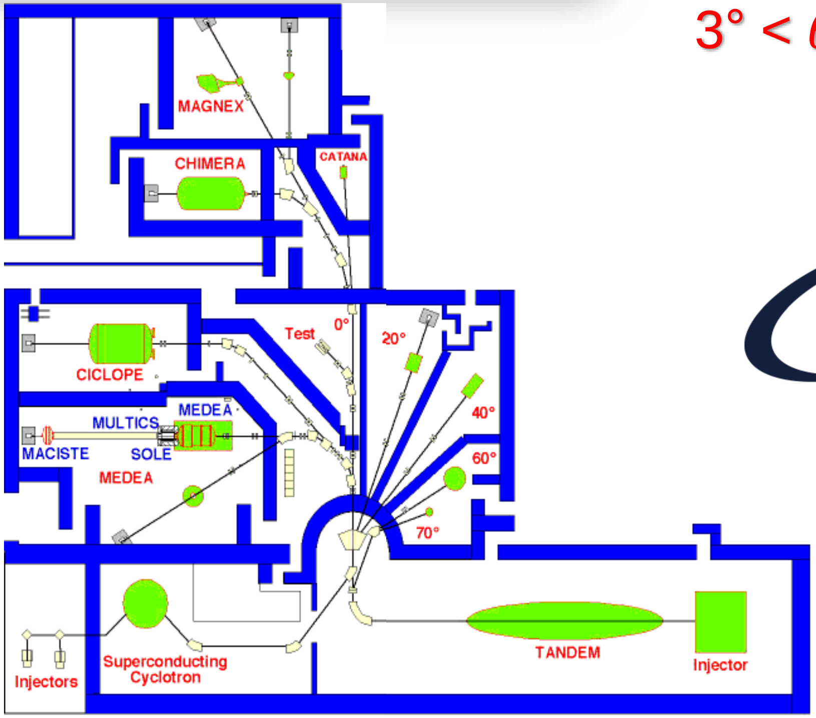
Studies on **one-neutron transfer** (^{18}O,^{17}O) to ascertain the selectivity of the two processes in exciting s.p. and two-particle configurations

One-proton and two-proton transfer channels measured, under analysis

The experiments

- ^{18}O beam from Tandem at 84 MeV (and Superconducting Cyclotron at 270 MeV)
- Several thin targets (50 -100 μg/cm^2)
- Ejectiles detected by the MAGNEX spectrometer
- Angular settings $\theta_{opt} = 6°, 12°, 18°, 24°$

$3° < \theta_{lab} < 31°$



MAGNEX

Large acceptance:

- Energy -28%, +20%
- Angle 50 msr

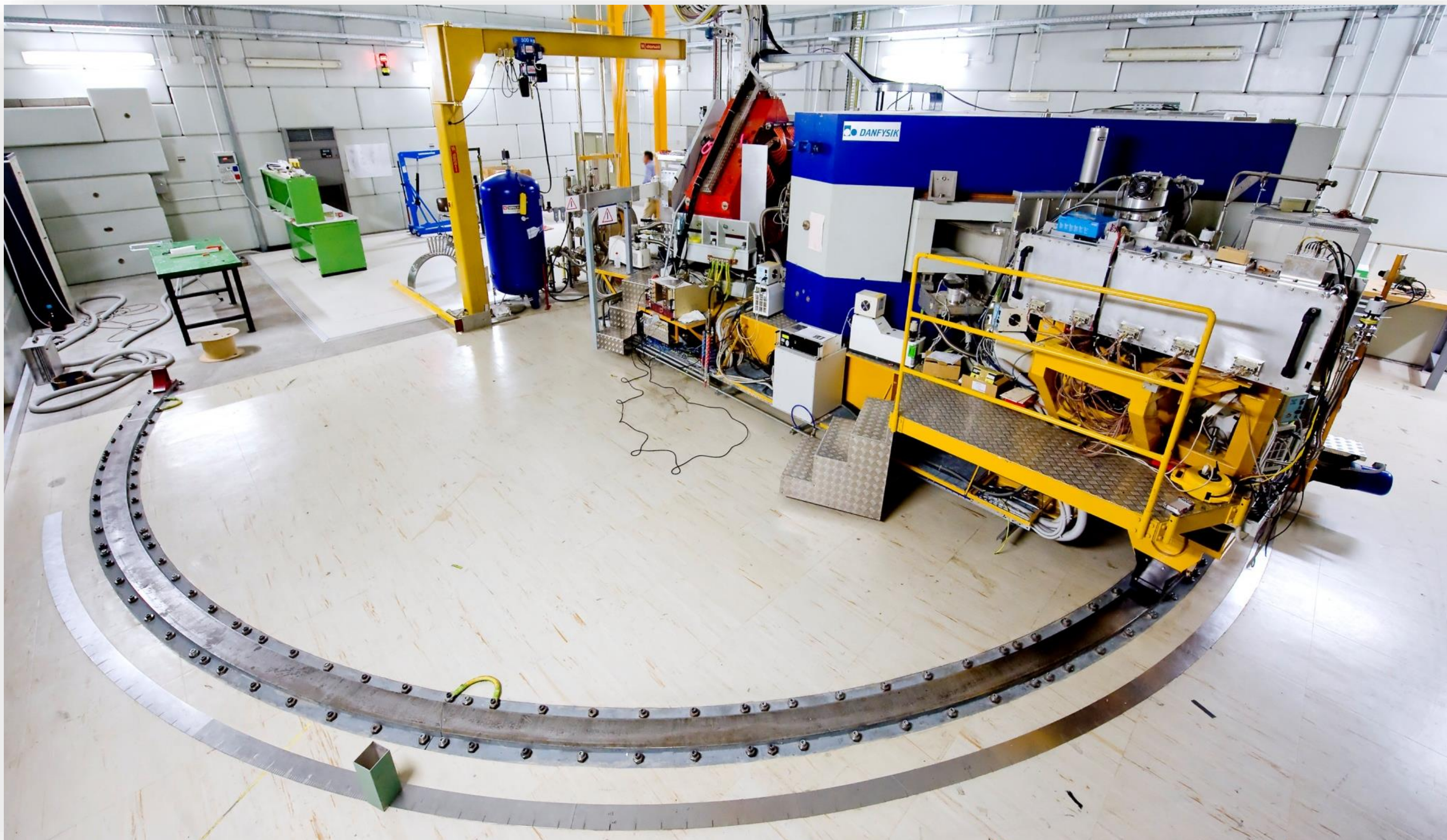
Good compensation of the aberrations

Trajectory reconstruction

Measured resolutions:

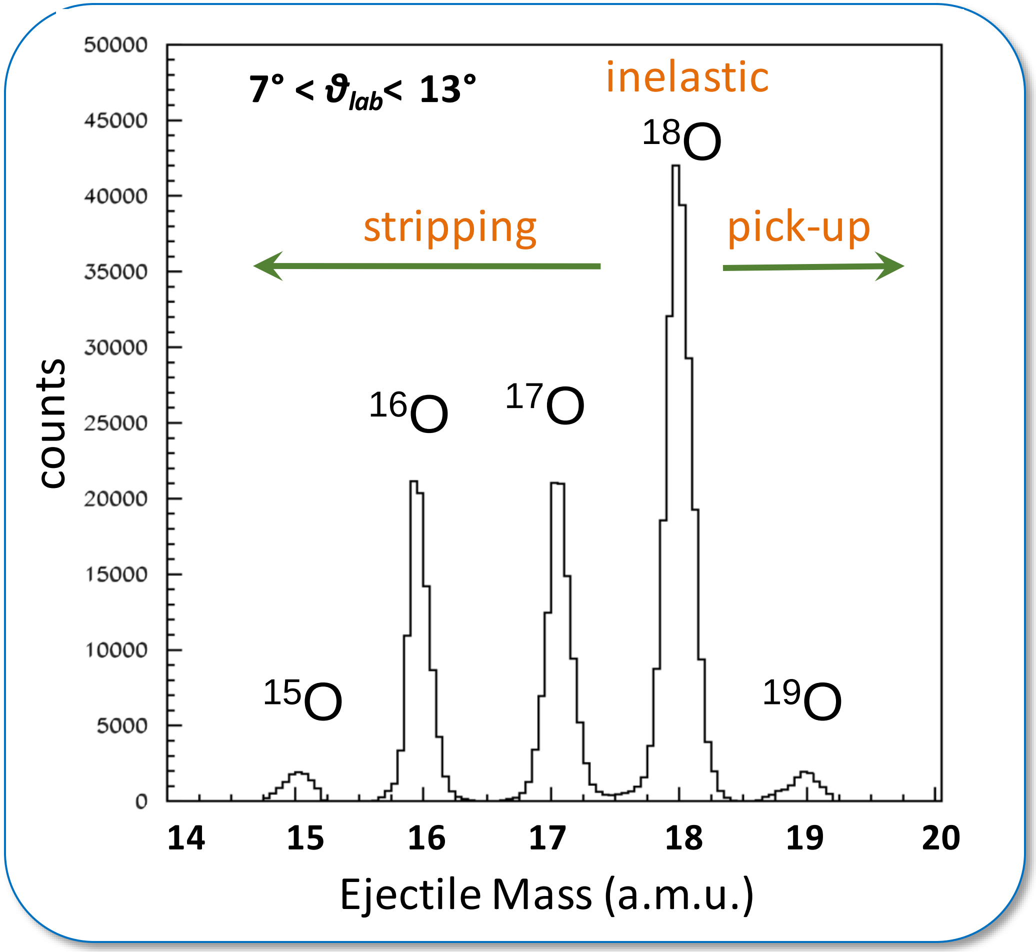
- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.3°$
- Mass $\Delta m/m \sim 1/160$

F. Cappuzzello et al. EPJA (2016) 52 :167



Some experimental evidence:
1) Transfer Yields

$^{18}O+^{13}C$ @84 MeV

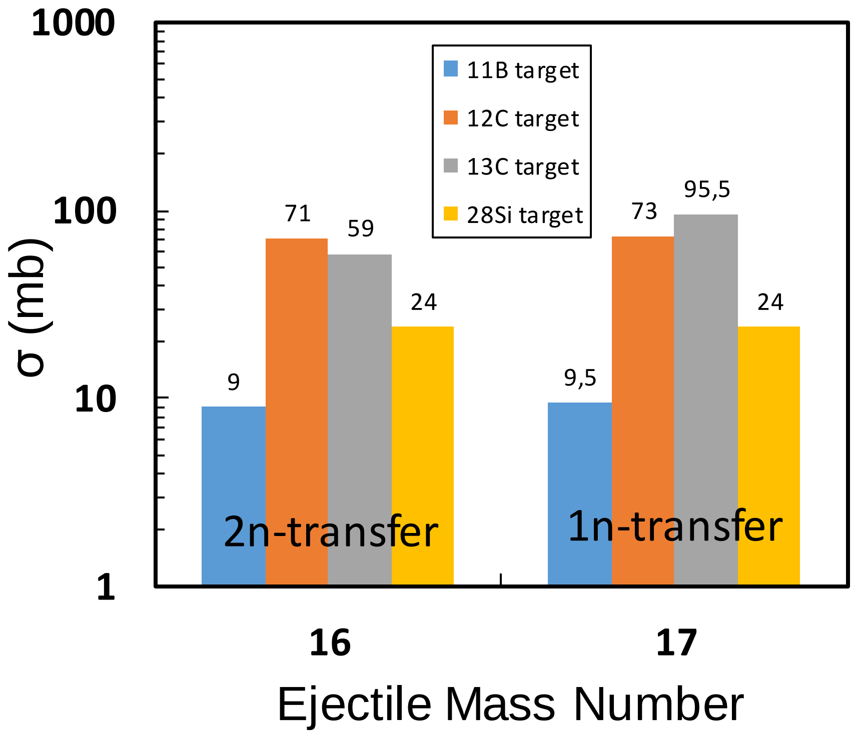


C. Agodi et al., Phys. Rev. C (2018) accepted

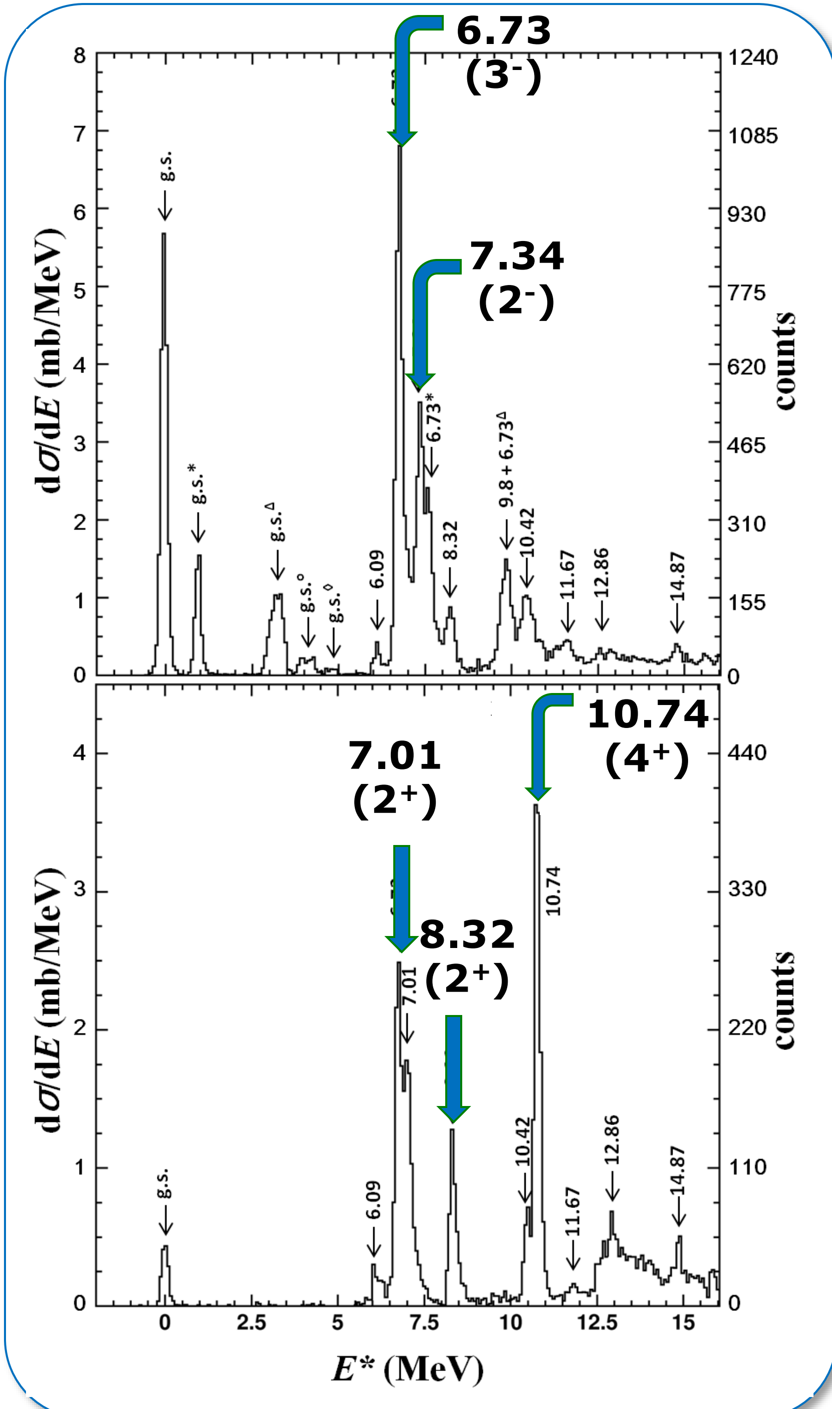
Enhancement of the two-neutron transfer channel

The 2n-transfer is not a 2^{nd} order process

TRANSFER OF A CORRELATED PAIR



Some experimental evidence: 2) Energy Spectra



$^{13}C(^{18}O,^{17}O)^{14}C$

$$\left|\left[\left(^{13}C_{gs}\right)^{1/2^-} \otimes \left(1d_{5/2}\right)^{5/2^+}\right]^{2^-,3^-}\right\rangle$$

In the (^{18}O,^{16}O), the **suppression of s.p. states**, which would require an uncorrelated transfer of 2n and the breaking of the initial pair in the $^{18}O_{g.s.}$, reveals the minor role of the **two-step dynamics**

$^{12}C(^{18}O,^{16}O)^{14}C$

$$\left|\left[\left(^{12}C_{gs}\right)^{0^+} \otimes \left(1d_{5/2},2s_{1/2}\right)^{2^+,4^+}\right]^{2^+,4^+}\right\rangle$$

M. Cavallaro, et al., PRC 88 (2013) 054601
F. Cappuzzello et al., Nature Comm. 6 (2015) 6743

Microscopic quantum description of reaction mechanism and nuclear structure

Exact Finite Range CRC

- Sao Paulo Potential (**SPP**) used in the optical model
- **Wood-Saxon form factors** used to generate single particle and cluster wave functions. Depth adjusted to fit exp. separation energies
- **Deformation parameters** for collective excitations

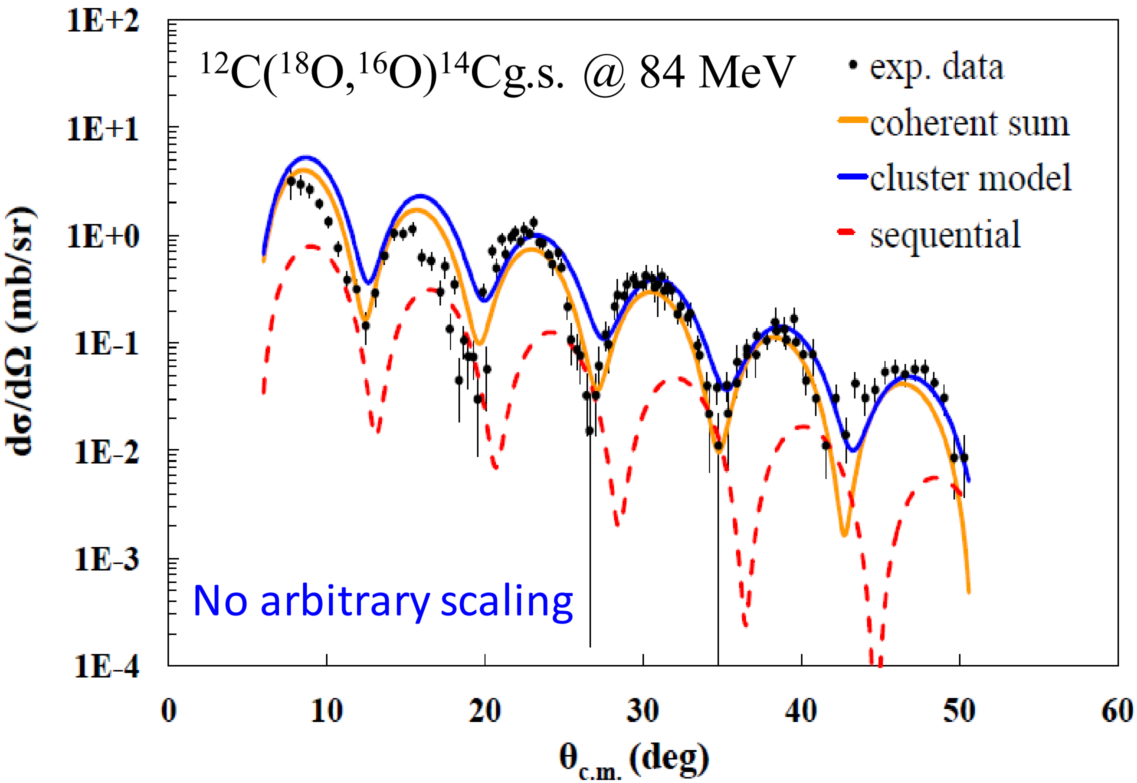
  Calculations by
  J. Lubian et al.– Niteroi (Brasil)

- **Spectroscopic Amplitudes** by shell-model, IBM-2, IFBM-2

  Calculations by
  A.Gargano – Napoli (Italy)
  S.M.Lenzi – Padova (Italy)
  E. Santopinto – Genova (Italy)

The $^{12}C(^{18}O,^{16}O)^{14}C$ reaction

M. Cavallaro, et al., PRC 88 (2013) 054601



A **0.89** amplitude is obtained by scaling to the experimental data (**0.91** S.A. predicted by shell model for the $(p_{1/2})^2$ configuration).

Extreme Cluster Model

(CRC)

- Relative motion of the 2n system frozen and separated by the c.m.
- Only the term with the 2n coupled to S = 0 participates to the transfer

Sequential transfer

(DWBA)

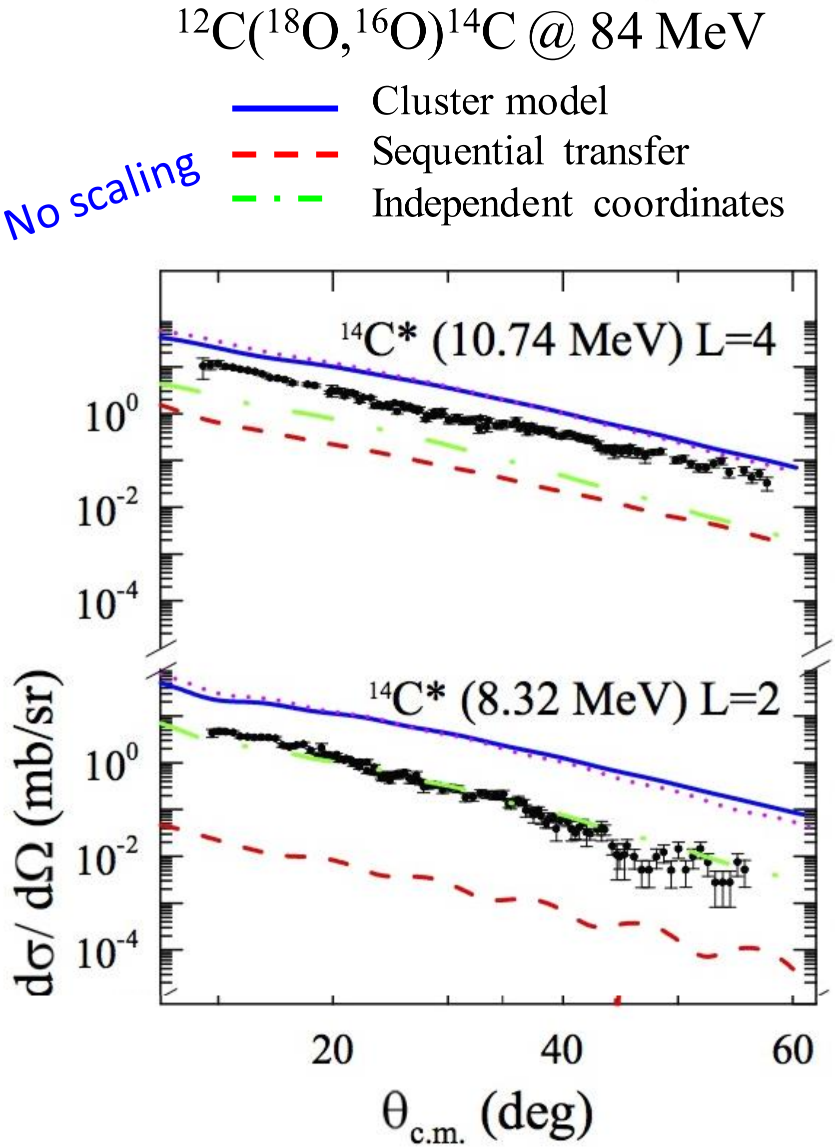
Introducing the $^{17}O + ^{13}C$ intermediate partition

Coherent sum

Presence of two-neutron pairing correlations in the ^{14}C ground state

The $^{12}C(^{18}O,^{16}O)^{14}C$ reaction

No scaling



Extreme cluster model largely overestimates the data. A larger model space for the cluster wave function is needed.

Independent coordinates scheme

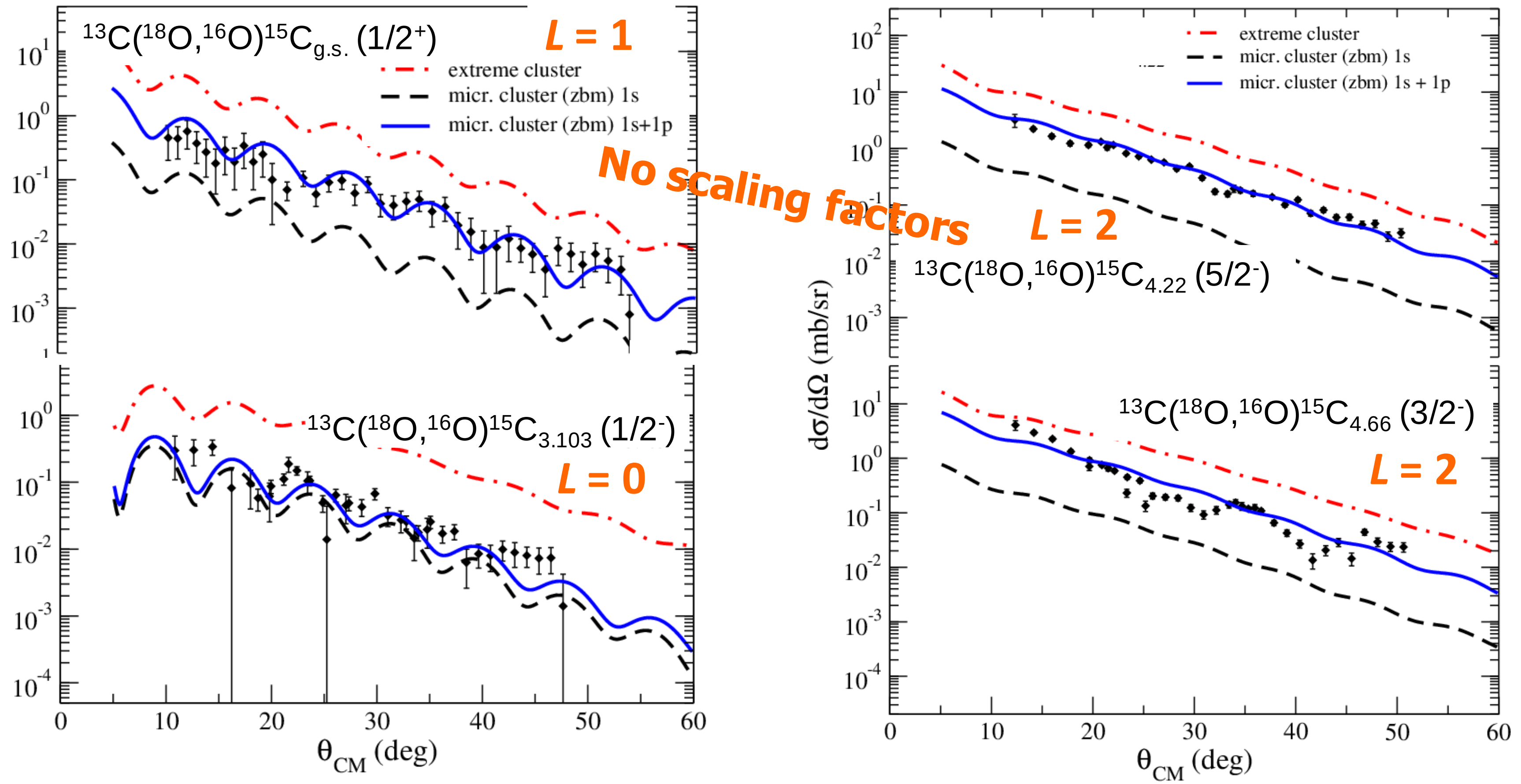
The transfer is described taking into account s.p. information obtained by shell model calculations ($p_{1/2}s_{1/2}d_{5/2}$)

- well reproduce L=2 data.
- underestimates the L=4 data. A larger space is required in the shell-model. Not surprising since one expects relevant ($d_{5/2}$ $d_{3/2}$) contributions in the 4^+ wave function, excluded in our model space

Sequential transfer small

M. Cavallaro, et al., PRC 88 (2013) 054601

The $^{13}C(^{18}O,^{16}O)^{15}C$ reaction



-·-·-·- **Extreme cluster model** overestimates data

The extreme cluster model assumes S = 0 coupling of the two neutrons with 100% of probability ⇒ **Overestimation of the cross-section**

D. Carbone et al., PRC 95 (2017) 034603

A «less extreme» cluster model: microscopic cluster model

- Introducing both parallel and antiparallel couplings (S=0 and S=1)
- Realistic spectroscopic amplitudes derived from shell-model calculations

Wave functions for two particles in terms of individual coordinates (*j-j* coupling)

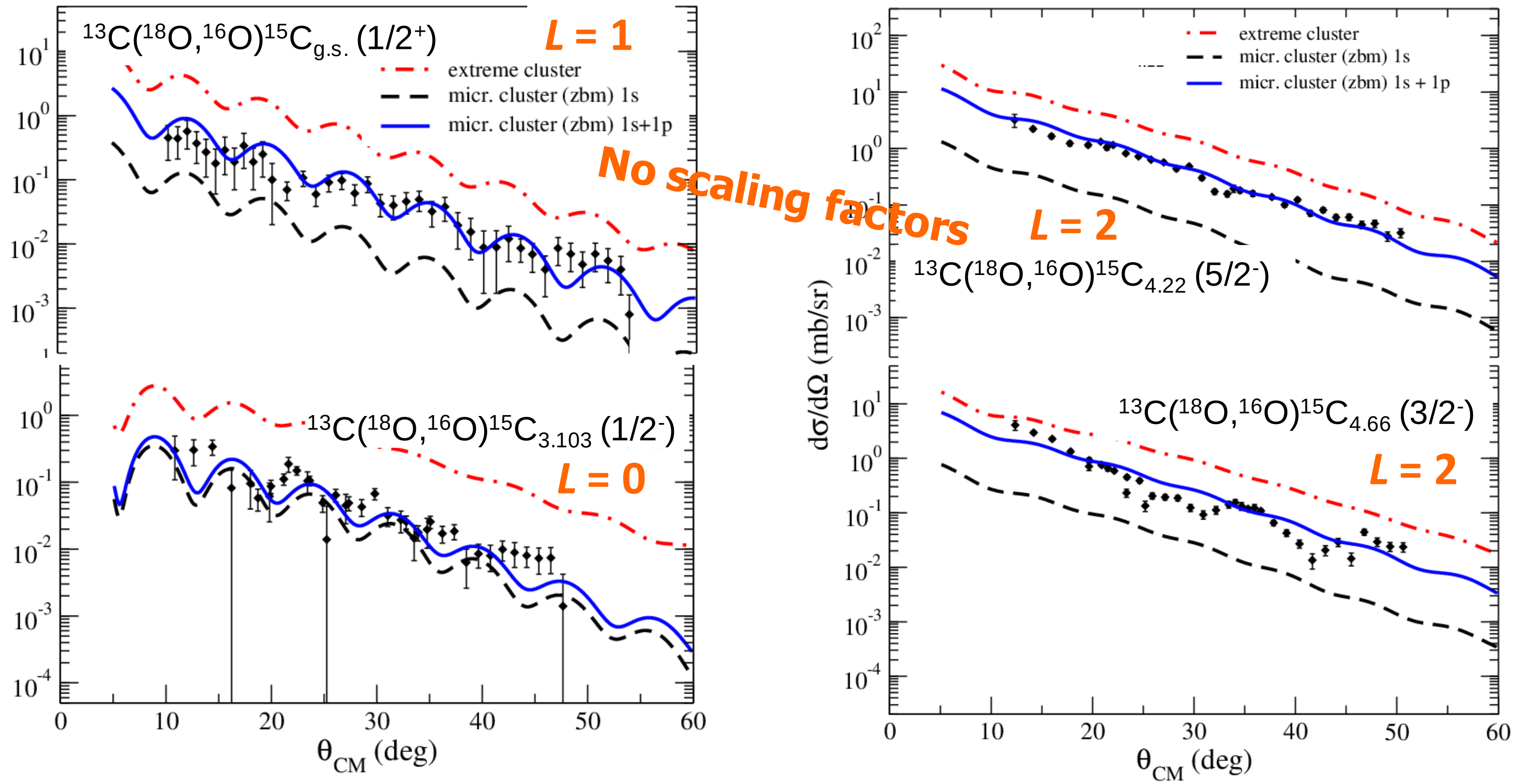
⇨ wave functions in terms of the relative and centre of mass coordinates of the two particles (*LS* coupling)

(n,l) cluster internal state
(N,L) cluster motion relative to the core

The use of this model can highlight the presence of cluster components in the involved wave functions

D. Carbone et al., PRC 95 (2017) 034603

The $^{13}C(^{18}O,^{16}O)^{15}C$ reaction



Extreme cluster model

Microscopic cluster 1s
Taking into account configurations with n = 1 l = 0

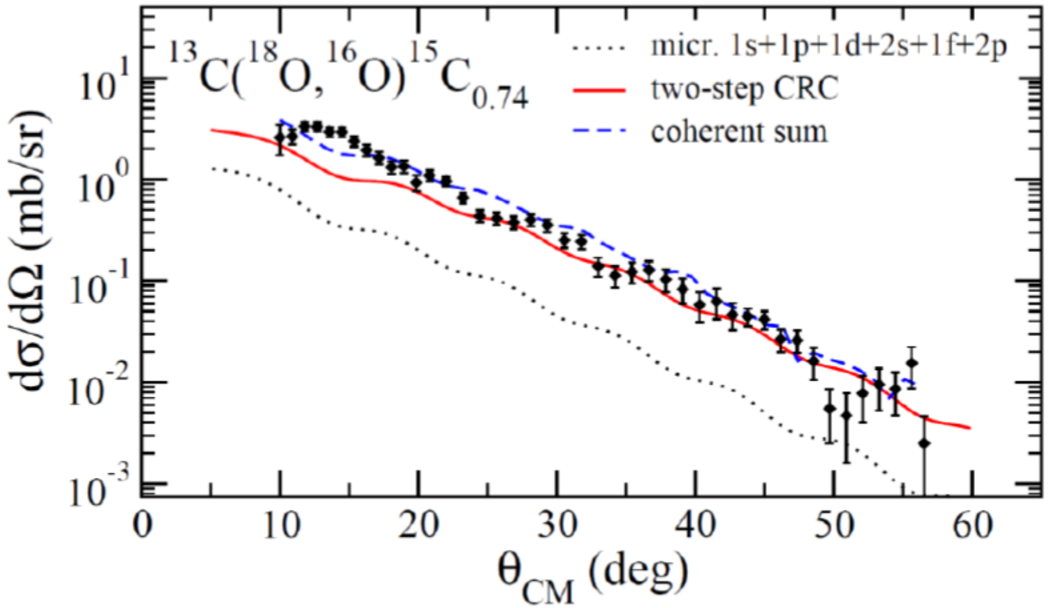
Microscopic cluster 1s + 1p
Taking into account configuration with n = 1 l = 0, 1

Cross sections **well reproduced by microscopic cluster** with 1s + 1p waves

D. Carbone et al., PRC 95 (2017) 034603

The $^{13}C(^{18}O,^{16}O)^{15}C$ reaction

The 0.74 MeV state has a different behaviour



Cross sections **underestimated by microscopic cluster** with 1s+1p+2d+2s+1f+2p waves

Two-step CRC gives the dominant contribution

Two-step CRC

Microscopic cluster 1s+1p+2d+2s+1f+2p

Coherent sum

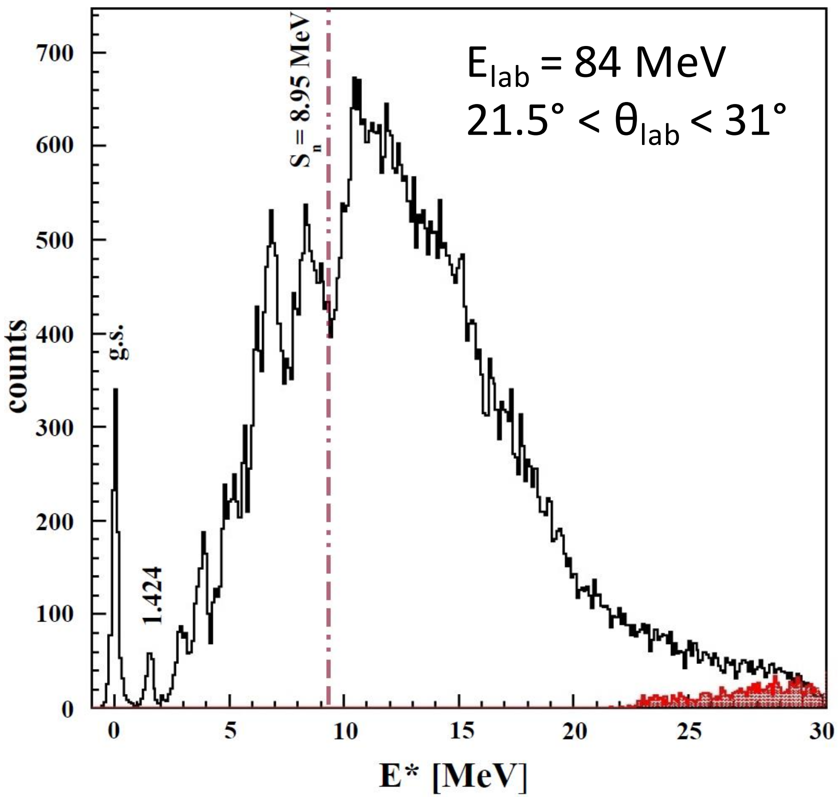
Single-particle state

$$\left| \left[\left(^{14}C_{gs} \right)^{0^+} \otimes \left(1d_{5/2} \right)^{5/2^+} \right]^{5/2^+} \right\rangle$$

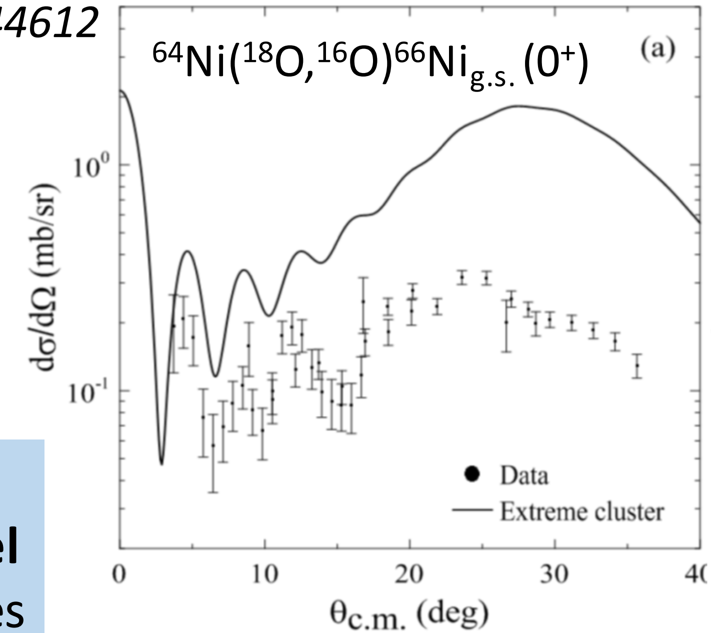
Breaking of the projectile pair in the transfer

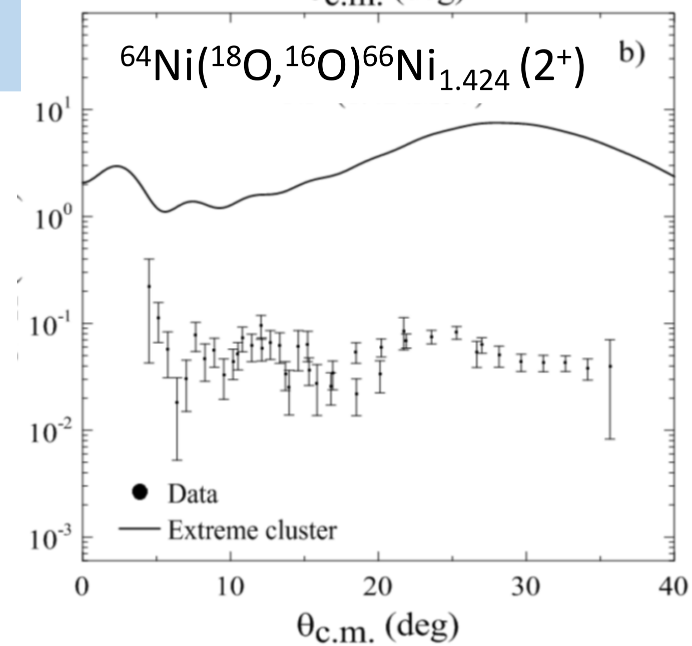
The $^{64}Ni(^{18}O,^{16}O)^{66}Ni$ reaction

B. Paes, et al., PRC 96 (2017) 044612



Extreme cluster model overestimates data





The $^{64}Ni(^{18}O,^{16}O)^{66}Ni$ reaction

B. Paes et al., PRC 96 (2017) 044612

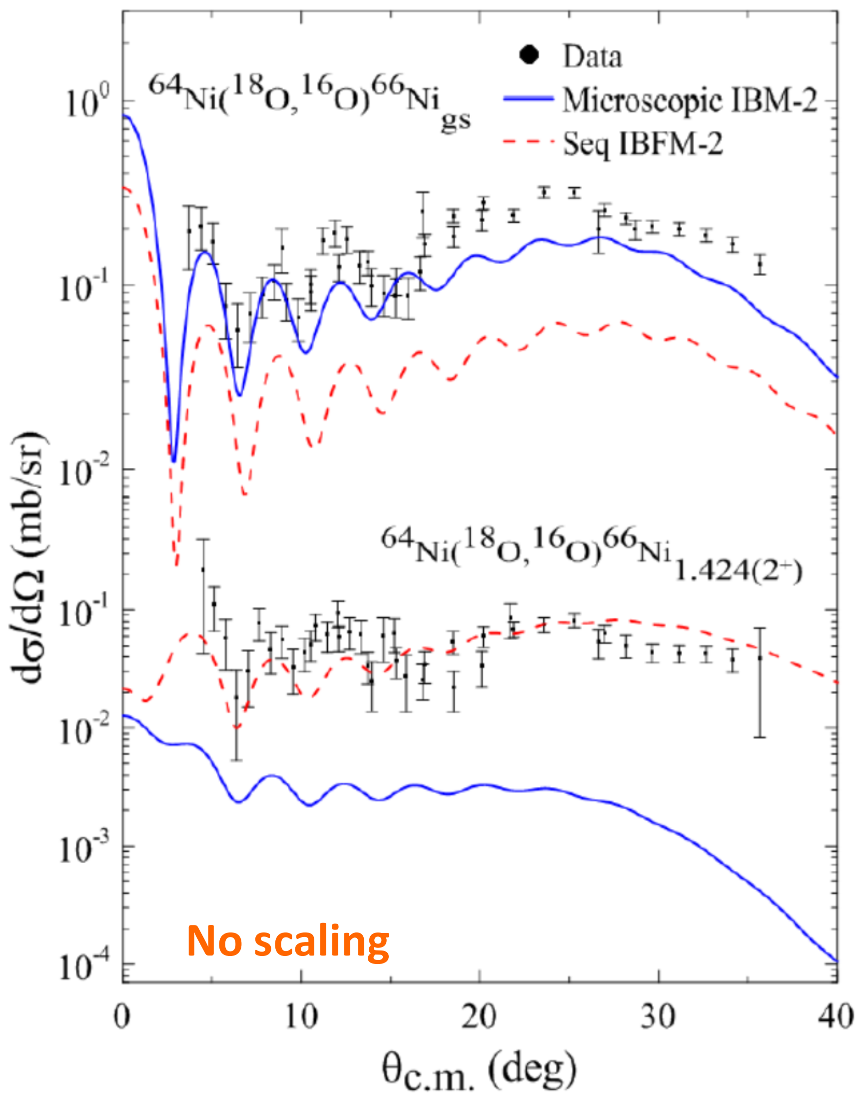
Microscopic Interacting Boson Model (IBM-2) applied for the first time to a 2n-transfer reaction (Ni isotopes upper limit of confident applicability of SM)

One-step (Ind. Coordinates) + IBM-2

- well describes the transition to 0^+ g.s.
- underestimates the transition to 2^+

Sequential + IBFM-2

- gives a very small contribution in the transition to 0^+
- well describes the transition to 2^+



The $^{64}Ni(^{18}O,^{16}O)^{66}Ni$ reaction

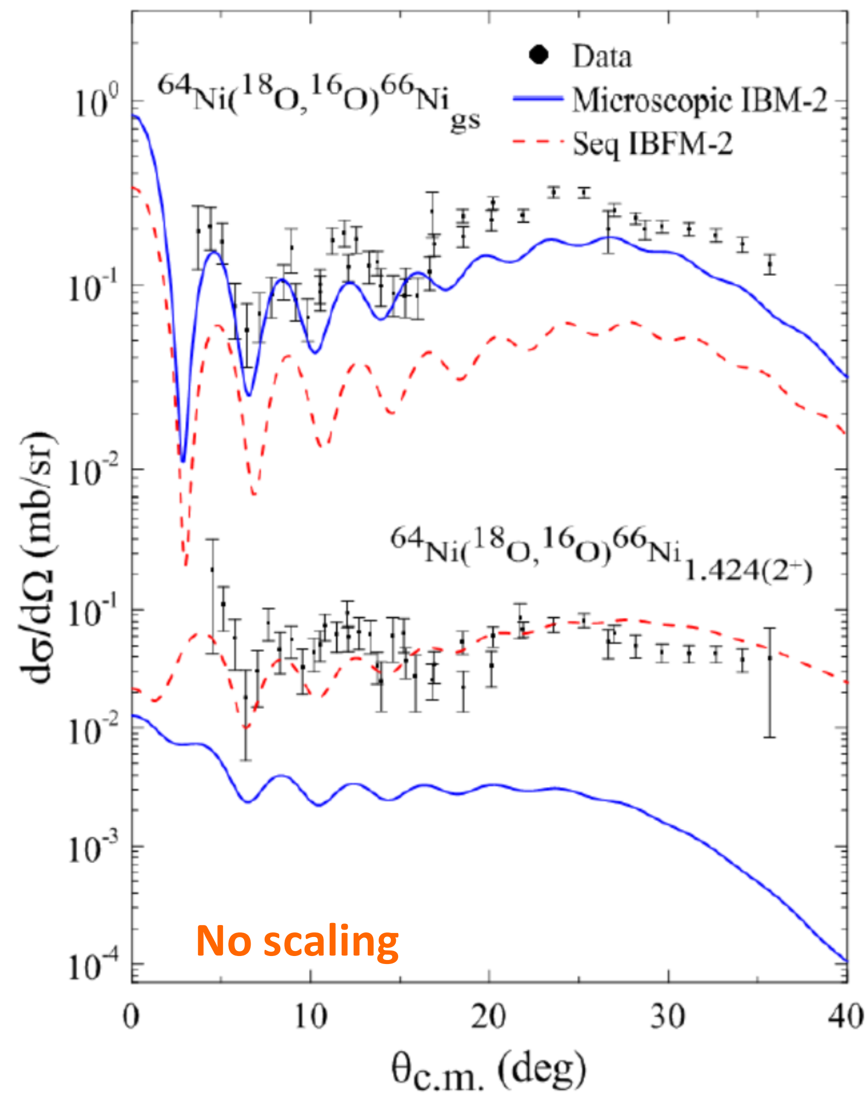
B. Paes et al., PRC 96 (2017) 044612

In the transfer to 0^+ g.s., **pairing correlations** play an important role (one-step mechanism is dominant)

In the 2^+ (collective) **other correlations** among nucleons are dominant over the pairing correlations (sequential mechanism is dominant)

Reduced electric quadrupole transition probabilities

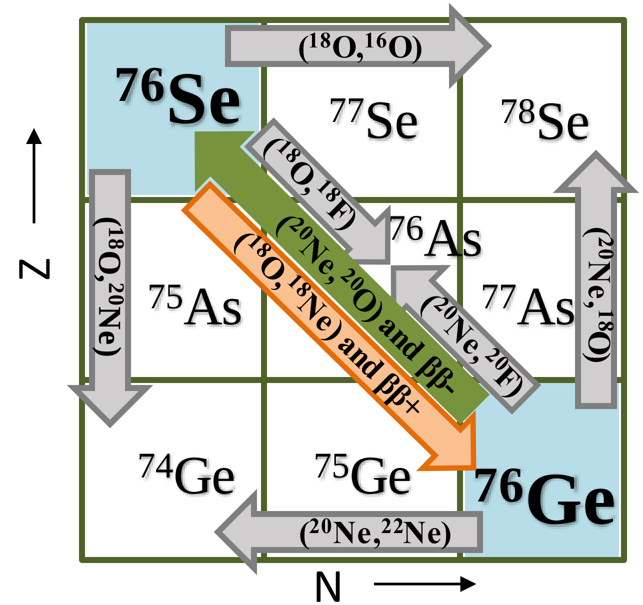
Nucleus	B(E2); $0^+ \rightarrow 2^+$ (e^2b^2)
^{14}C	0.0018
^{18}O	0.0045
^{28}Mg	0.035
^{30}Si	0.022
^{66}Ni	0.060 ←
^{76}Ge	0.270



The NUMEN program and the ERC project NURE

A **complete** and **reliable** description of HI induced transfer reactions is a crucial tool within the NUMEN project

Study **Double Charge Exchange (DCE) reactions** in systems candidate to 0νββ to stimulate in the laboratory the same nuclear transition occurring in 0νββ and get info on the NME



Two directions:
$\beta\beta^+$ via (^{18}O,^{18}Ne) and $\beta\beta^-$ via (^{20}Ne,^{20}O)

Contribution of all the **competing channels**
(We can measure most of them, while we need the prediction of theory for some other cases)

See poster by N. Nitin Deshmukh

Conclusion

❖ **High resolution measurements** of energy spectra and angular distribution for **HI reactions**

❖ **Enhancement of the 2n stripping** in the mass spectra and strong **selectivity** in the energy spectra

❖ Microscopic quantum description of the experimental cross-section for heavy-ion 2n transfer reactions **without unhappiness factors**

❖ Role of **pairing correlations**

❖ The possibility to achieve a **reliable** and **predictive description** of HI transfer channels on heavy targets is crucial for the research related to **$0\nu\beta\beta$ (NUMEN project)**

Working group

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Thank you!