# Nuclear response to weak interaction investigated by nuclear reactions


NUMEN

**Diana Carbone**

**for the NUMEN collaboration**

# Outline

- The problem of 0νββ-decay nuclear matrix elements
- The study of double charge exchange @ INFN-LNS
- The multichannel approach
- DCE experimental results
- Conclusions and perspectives

# 0νββ decay

**Open problem** in modern physics:

Neutrino absolute mass scale

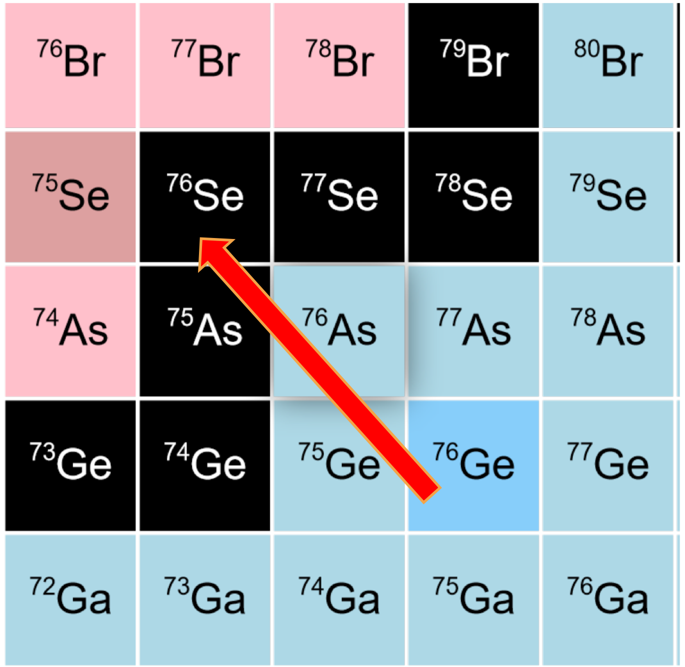
Neutrino nature

→ **0νββ** is considered the **most promising approach**

**Still not observed**

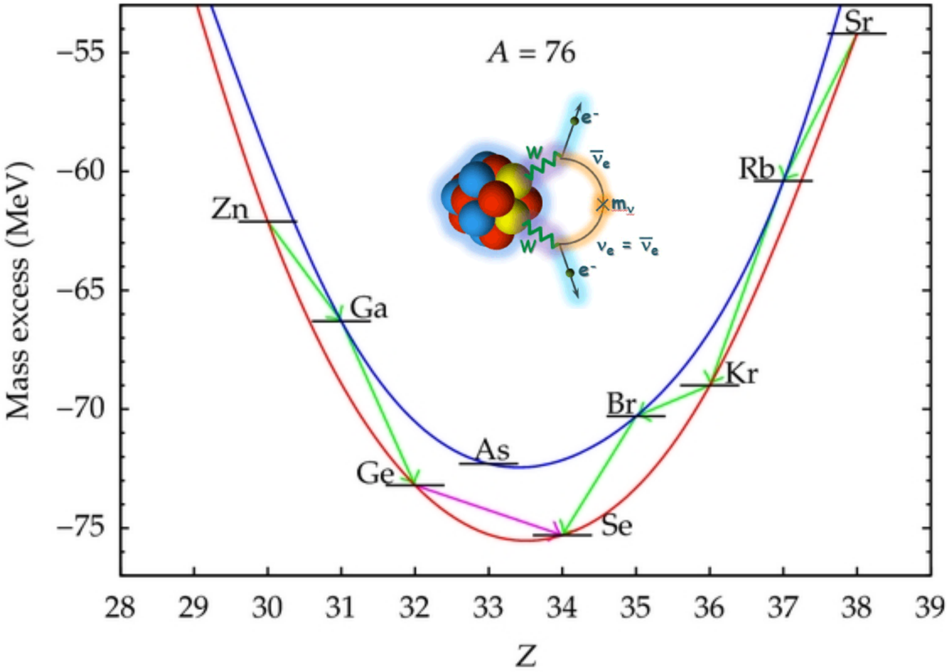
$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-}$$

E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184




**Beyond standard model:**

- Violation of lepton number conservation
- CP violation in lepton sector




- ✓ Process mediated by the **weak interaction**
- ✓ Observable in even-even nuclei where the **single β-decay** is energetically **forbidden**

# 0νββ decay

Intense activities in the searches for experimental evidence of this process

## A worldwide challenge

0νββ decay **half-life** — Phase space factor — contains the effective neutrino **mass**

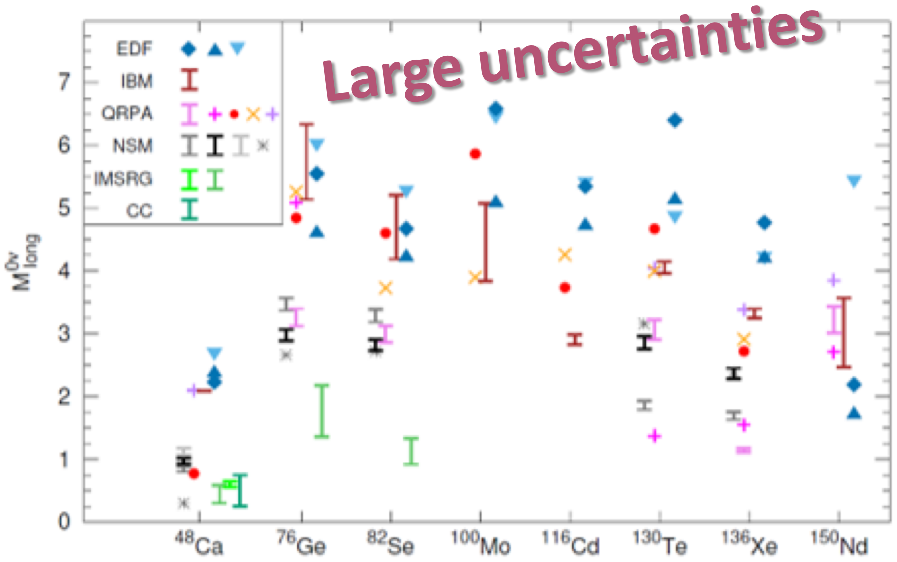
$$\left(T^{0\nu\beta\beta}_{1/2}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

### Nuclear Matrix Element (NME)

$$\left|M^{0\nu\beta\beta}_{\varepsilon}\right|^2 = \left|\left\langle \Psi_f \left| \hat{O}^{0\nu\beta\beta}_{\varepsilon} \right| \Psi_i \right\rangle\right|^2$$

Transition probability of a **nuclear** process

State of the art NME calculations




M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)
H. Ejiri et al., Phys. Rep. 797 (2019) 1–102

- ✓ NMEs are not physical observables
- ✓ The challenge is the description of the **nuclear many body states**
- ✓ **Calculations** (<u>still sizeable uncertainties</u>): QRPA, Large scale shell model, IBM, EDF, ab-initio …..

# Support from the experiments

Measurements (still not conclusive for 0νββ NME):

✓β-decay and 2νββ decay

1st order isospin probes

2nd order isospin probes

✓($\pi^+$, $\pi^-$), single charge exchange ($^3$He,t), (d,$^2$He), HI-SCE, electron capture, transfer reactions, μ-capture, γ-ray spectroscopy, γγ-decay etc.

✓A promising experimental tool: **Heavy-Ion Double Charge-Exchange (HI-DCE)**

NUMEN

(**NU**clear **M**atrix **E**lements for **N**eutrinoless double beta decay)

Extraction from measured cross-sections of *"data-driven"* information on NME for all the systems candidate for 0νββ

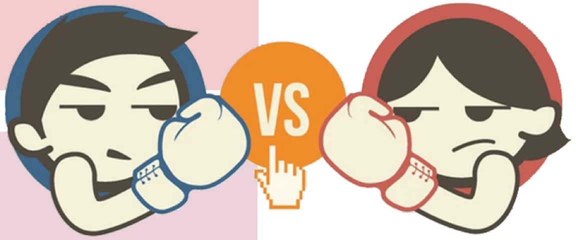
erc NURE

# Heavy-ion DCE reactions vs 0νββ

## To stimolate the same nuclear transition (g.s. to g.s.) occurring in 0νββ

### Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Reaction dynamics vs. decay
- DCE includes **sequential** multinucleon transfer **mechanism**
- **Projectile and target** contributions in the NME




### Similarities

- **Same initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ decay are the same as those of the target/residual nuclei in the DCE
- **Similar operator:** Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with tunable weight in DCE
- **Large linear momentum** (~100 MeV/c) available in the virtual intermediate channel
- **Non-local** processes: characterized by two vertices localized in a pair of nucleons
- **Same nuclear medium**
- **Off-shell propagation** through virtual intermediate channels

# Theory for DCE reactions

See H. Lenske, E. Santopinto and J. Bellone talks

## Heavy ion DCE can proceed:

**1)** Sequential **multi-nucleon transfer** (defined by mean-field dynamics, its contribution can be tuned by kinematics conditions)

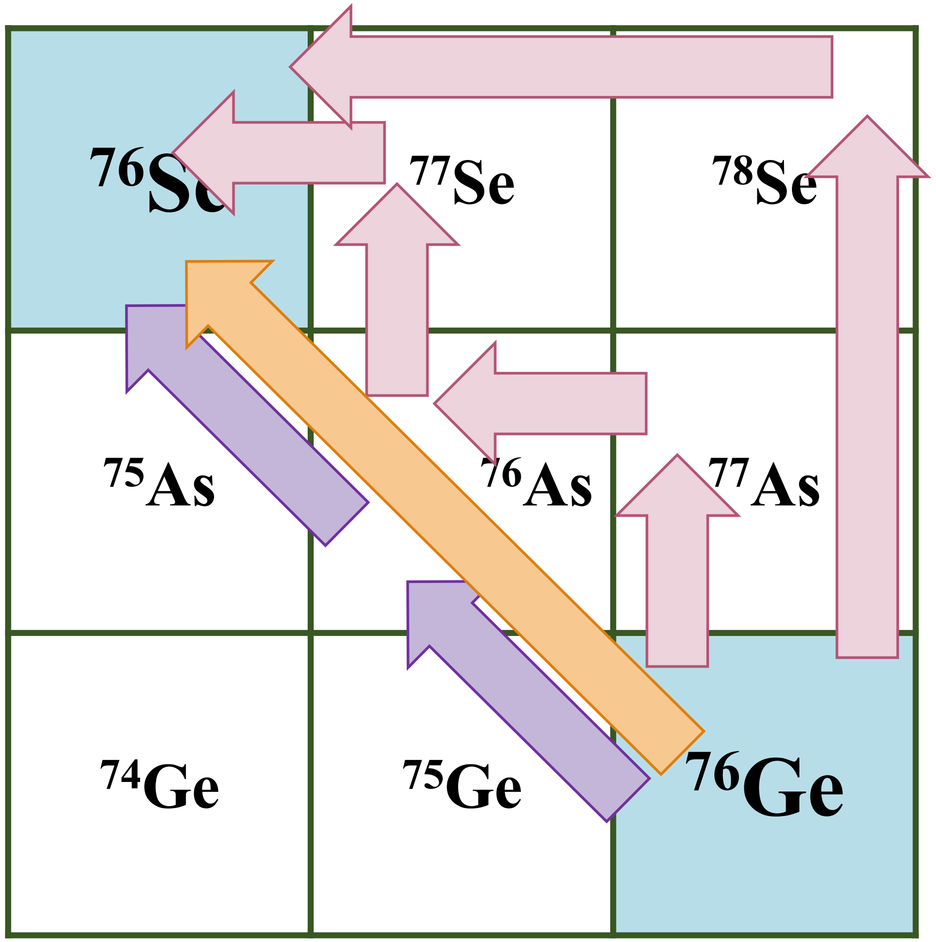
*J. Ferreira et al., PRC 105 (2022) 014630*

**2) Two-step DCE - Double single charge exchange (DSCE)**: two consecutive single charge exchange processes

*E. Santopinto et al., Phys. Rev. C 98 (2018) 061601*
*J.I.Bellone et al., PLB 807 (2020) 135528*
*H. Lenske et al., Universe 7 (2021) 98*

**3) One-step DCE - Two-nucleon mechanism (MDCE)**: relying on short range NN correlations, leading to the correlated exchange of two charged mesons between projectile and target

*H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716*
*H. Lenske, CERN Proceedings 2019-001 (2019)*




**Cross section is a combination of the three different kinds of reaction dynamics**

*F. Cappuzzello et al., Progr. Part. and Nucl. Physics 128, 103999 (2023)*

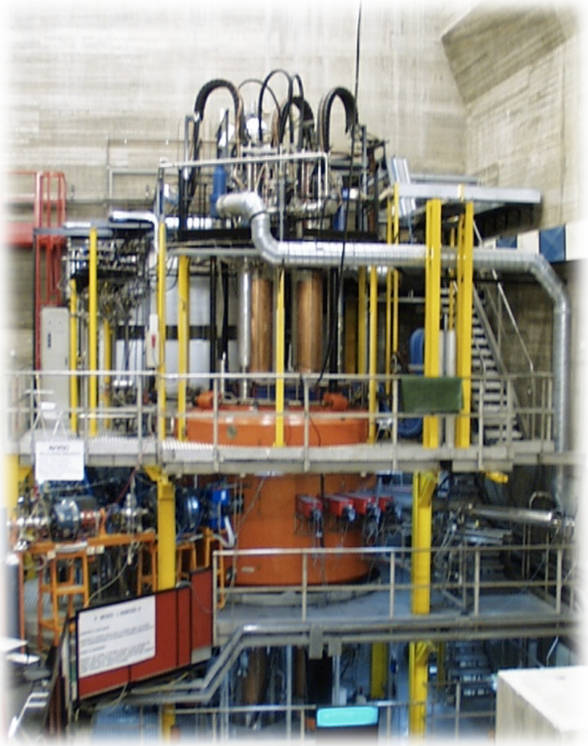
# DCE @ INFN - LNS

# The experiments @ INFN-LNS

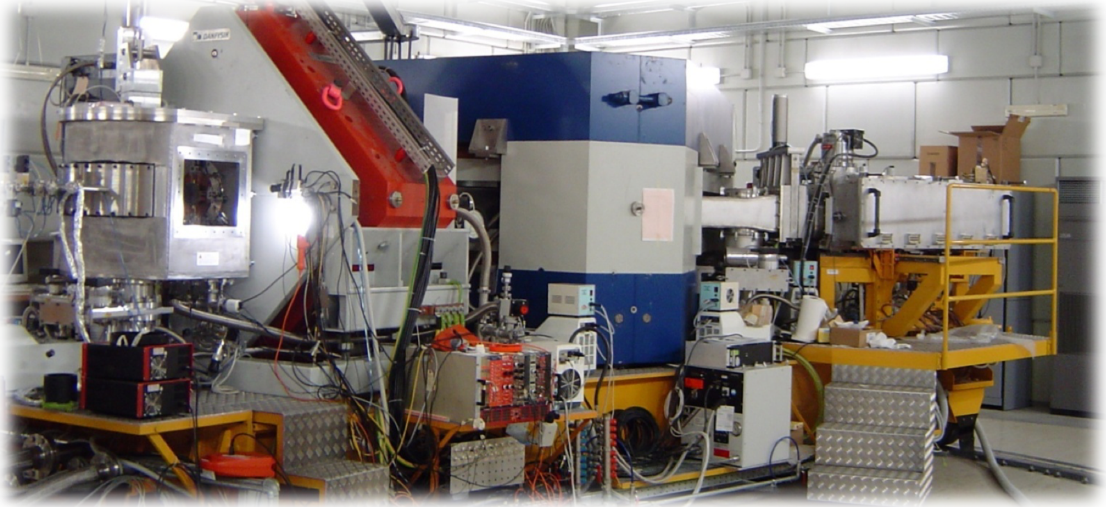
## Crucial for the experimental challenges

### K800 Superconducting Cyclotron

- **In operation since 1996.**
- **Accelerates from H to U ions**
- **Maximum energy 80 MeV/u.**



### MAGNEX magnetic spectrometer



| **Optical characteristics** | **Current values** |
|---|---|
| Maximum magnetic rigidity (Tm) | 1.8 |
| Solid angle (msr) | 50 |
| Momentum acceptance | -14%, +10% |
| Momentum dispersion (cm/%) | 3.68 |

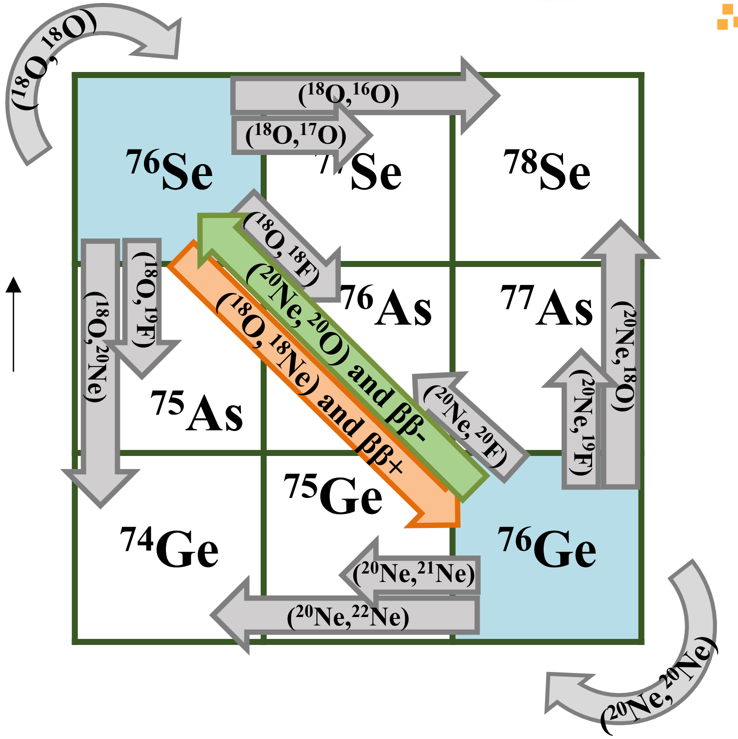
Measured resolutions:

- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/300$

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167
M. Cavallaro et al., NIM B 463 (2020) 334

# The multichannel strategy

- **Transitions of interest for 0νββ in two directions**
  $\beta\beta^-$ via ($^{20}$Ne,$^{20}$O) and $\beta\beta^+$ via ($^{18}$O,$^{18}$Ne)
- **Two (or more) incident energies**
  to study the reaction mechanism
- **Complete net** of reactions which provide important information




**Elastic** scattering → nucleus-nucleus optical potential

**Inelastic** scattering → coupling strenght to low-lying states

**One-nucleon** transfer reactions → single-particle spectroscopic amplitudes

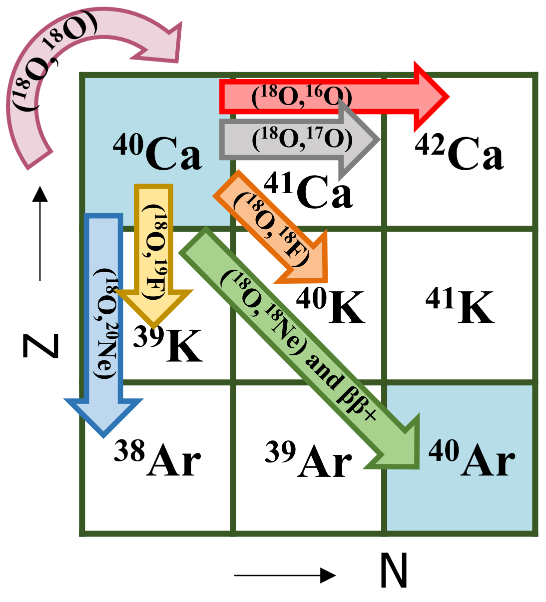
**Two-nucleon** transfer reactions → strenght of pairing correlations

Single charge exchange (**SCE**) → nuclear response to 1$^{st}$ order isospin operators (One-Body Transition Densities)

Double charge exchange (**DCE**) → nuclear response to 2$^{nd}$ order isospin operators (Two-Body Transition Densities)

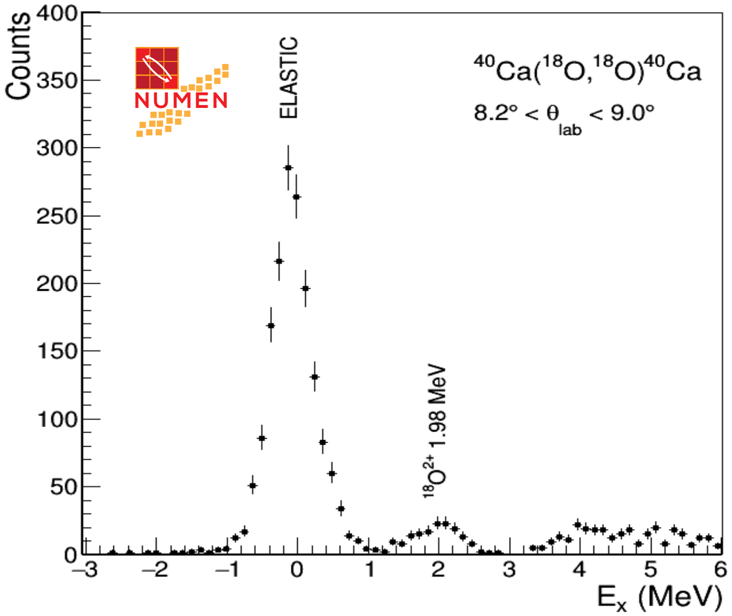
# The multichannel strategy

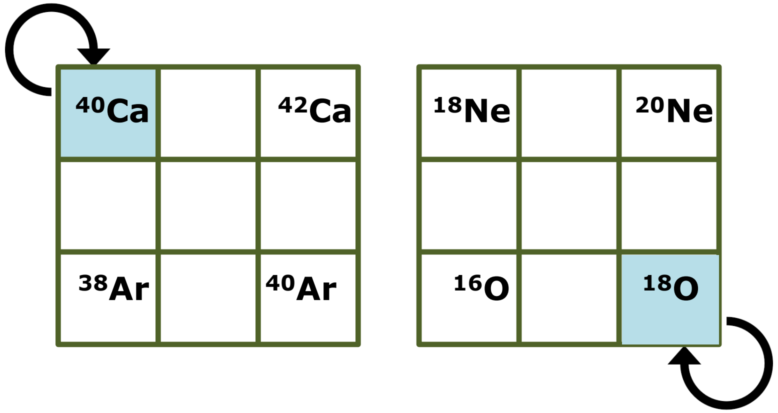
## The $^{18}O + ^{40}Ca$ @ 275 MeV case

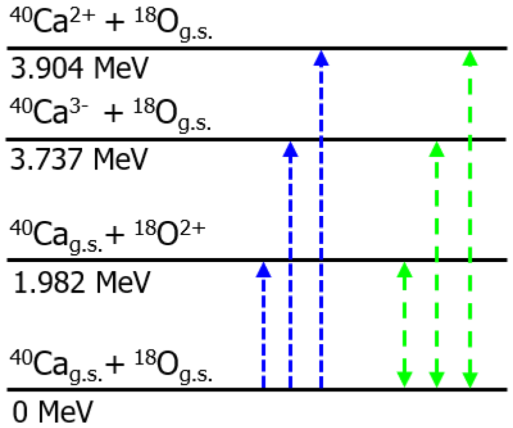


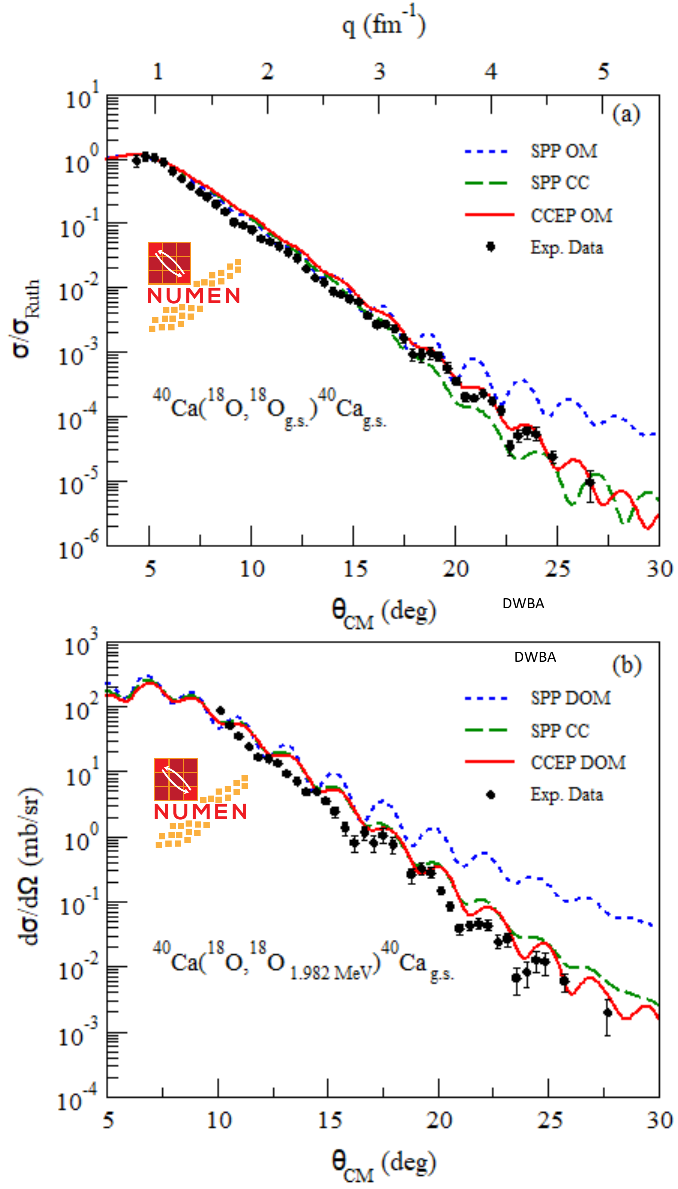
# Elastic and inelastic scattering

M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815



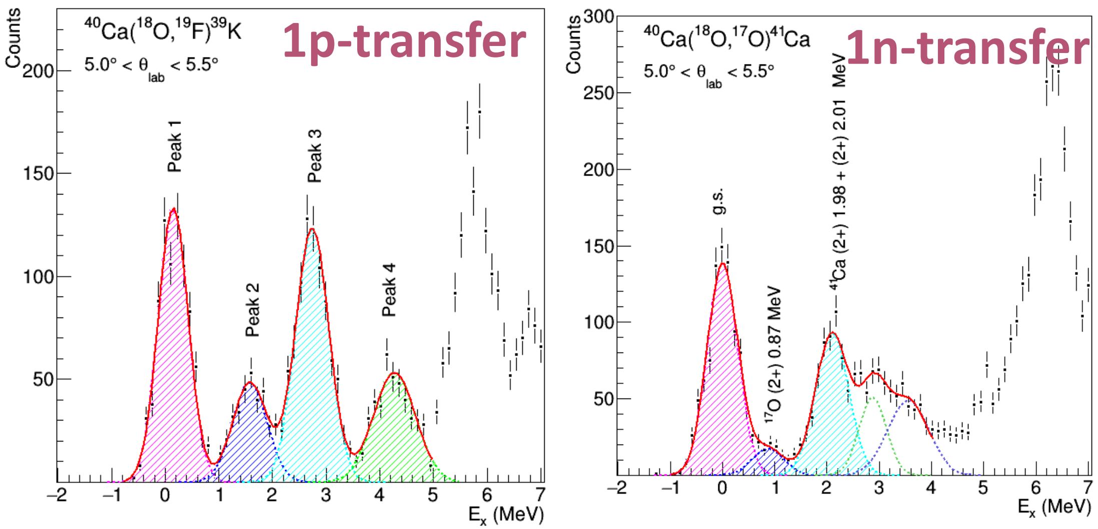



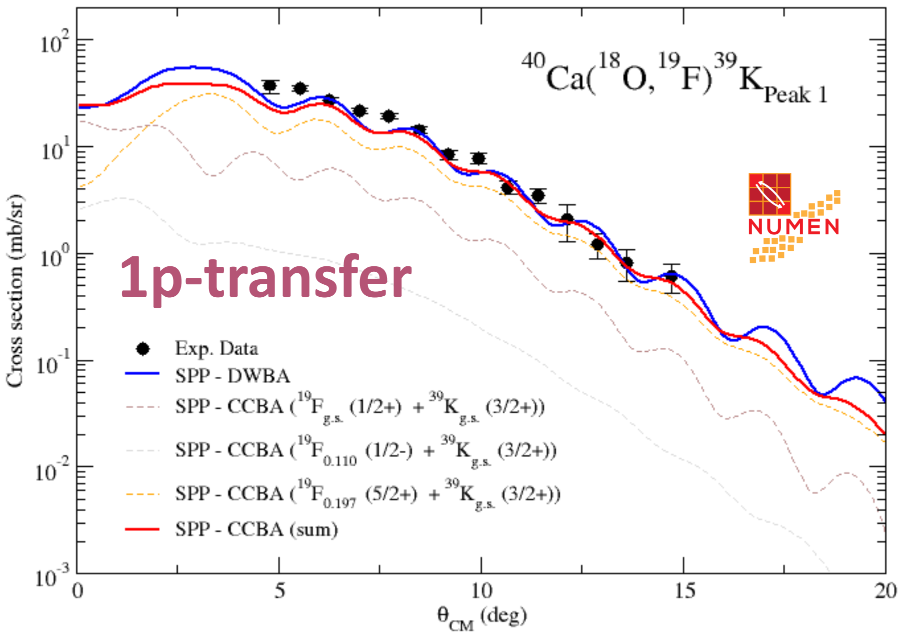

## Key information from elastic and inelastic scattering data

- ✓ **Double folding** Sao Paulo Potential works well
- ✓ **Coupling to** low-lying **$2^+$ and $3^-$ states** of $^{18}O$ and $^{40}Ca$ states is important
- ✓ Effects of coupling can be accounted for in average by **CCEP approach**

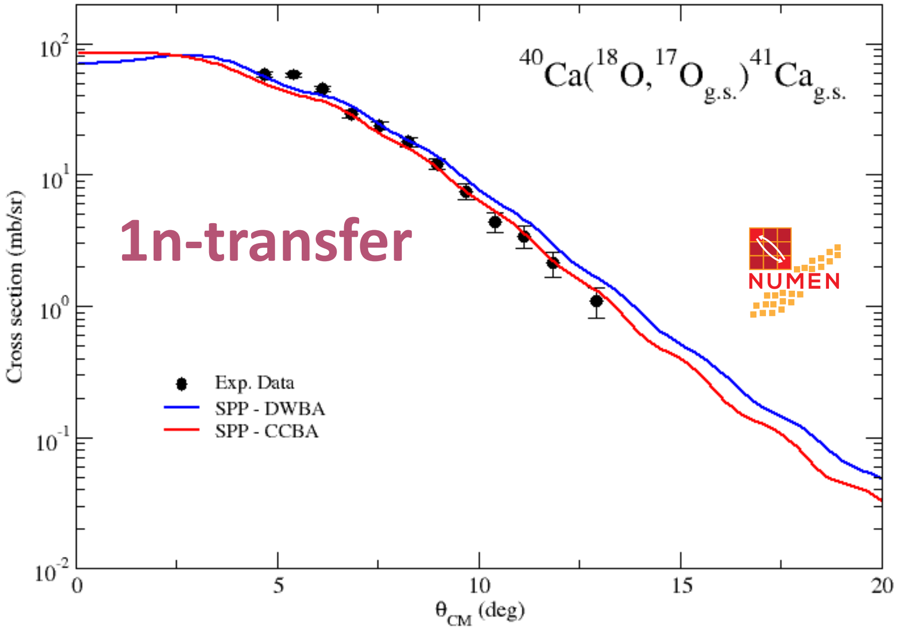
# 1p- and 1n-transfer reactions

S. Calabrese et al., Phys. Rev. C 104, 064609 (2021)




- OP extracted from elastic and inelastic scattering data
- **CCBA** analysis
- **Shell mode**l spectroscopic amplitudes

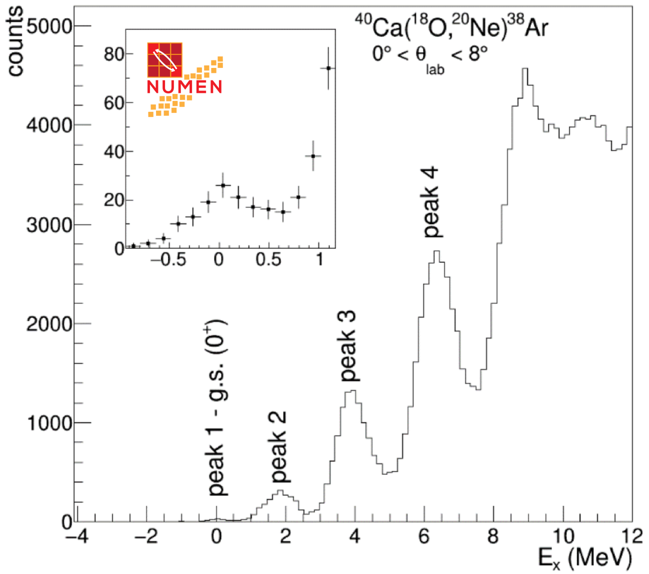


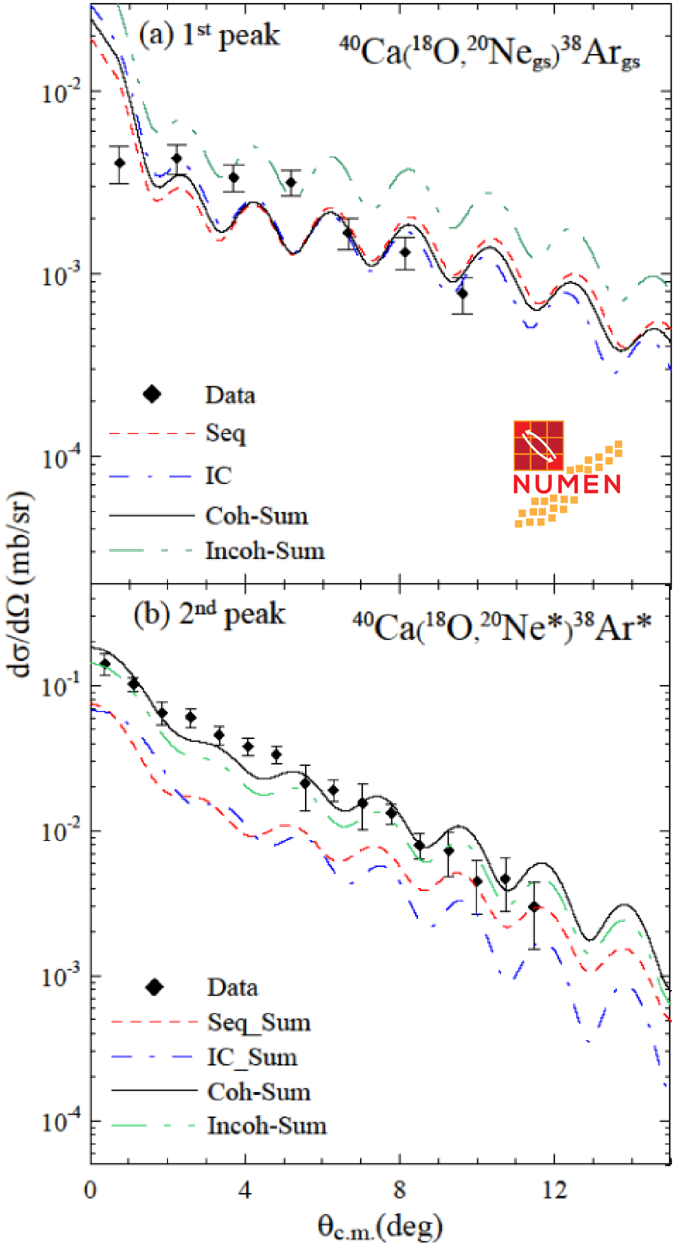

## Key information from one-nucleon transfer data

- ✓ Very good description of the data
- ✓ Mixing of single particle and core polarization configurations

# 2p-transfer reaction

J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604



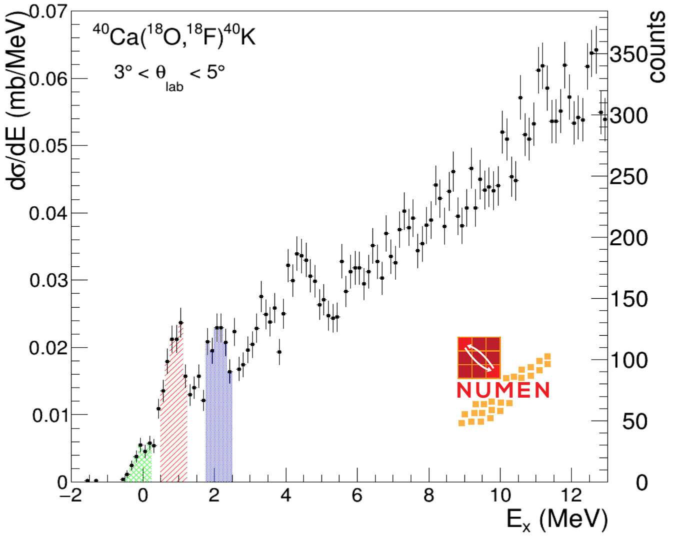

- OP extracted from elastic and inelastic scattering data
- **CCBA** analysis **direct** and **two-step transfer**
- **Shell model** spectroscopic amplitudes

## Key information from two-proton transfer data

- ✓ Very low cross section (comparable with DCE) for low-lying states
- ✓ Competition between one-step and two-step mechanisms
- ✓ Good description of the data

# Single charge exchange reaction

M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815

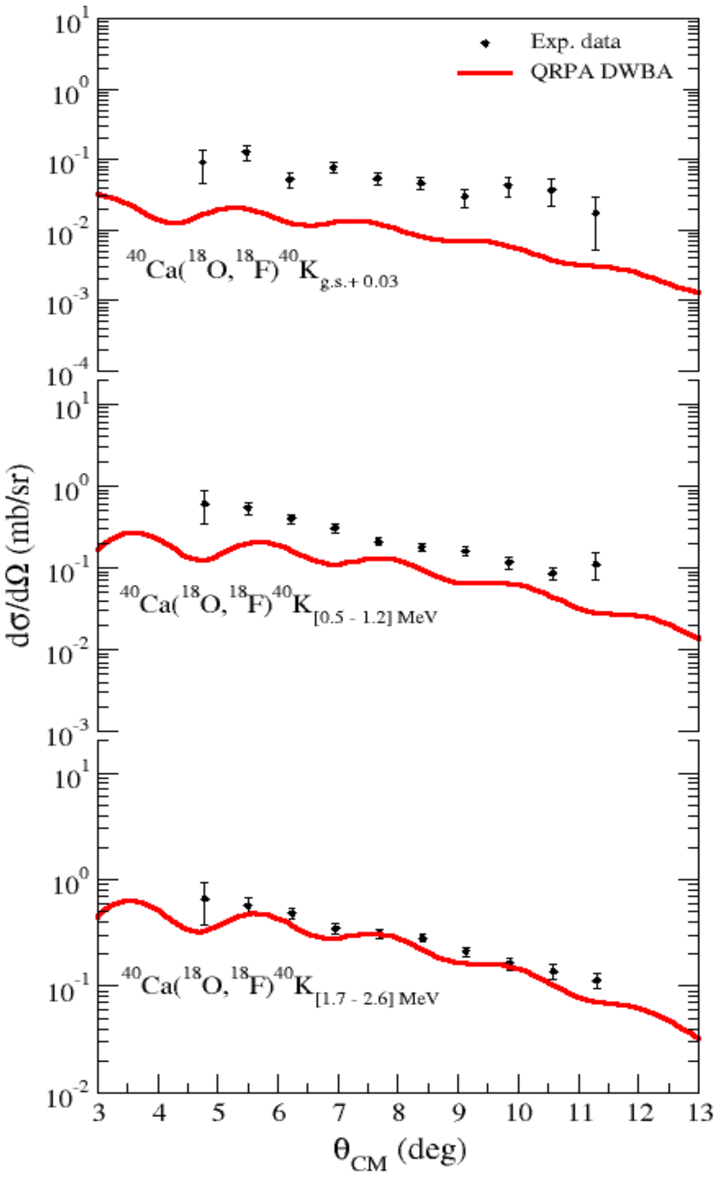


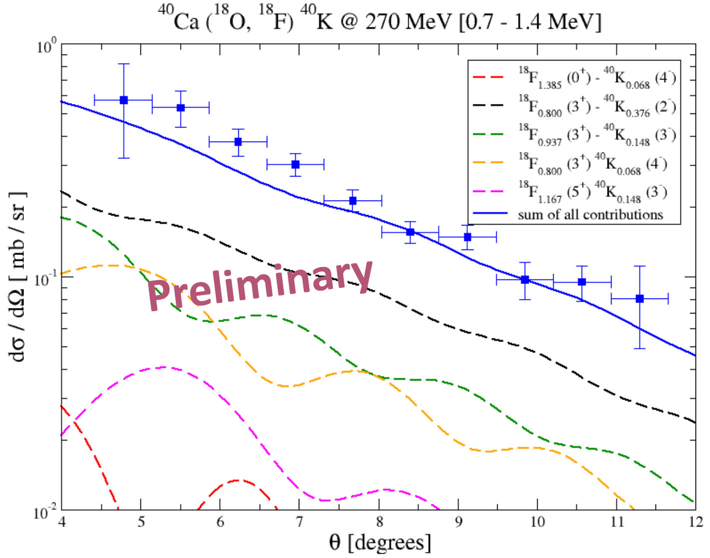

- OP extracted from elastic and inelastic scattering data
- **DWBA** analysis with double folding form factors for **direct**
- **QRPA** transition densities with NN isovector interaction
- **CCBA** approach for **two-step transfer**

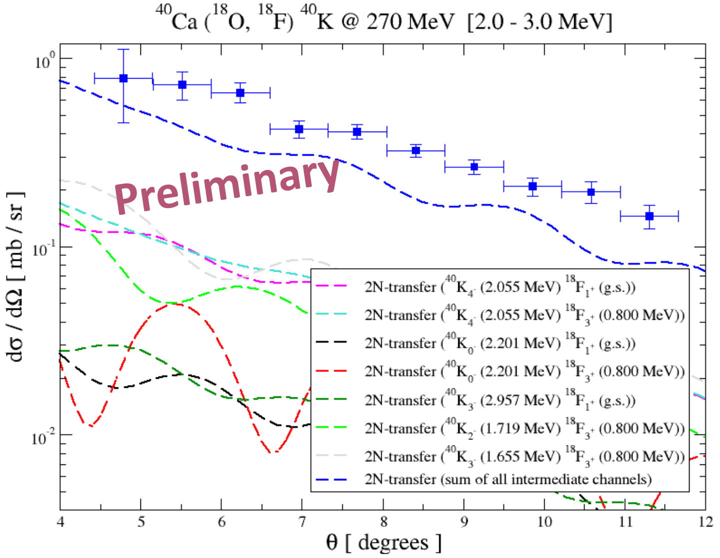
## Key information from SCE data

- ✓ Direct meson exchange mechanism important at low excitation energy
- ✓ Two-step nucleonic SCE plays a role, expected to contribute less at higher $E_x$

**Direct** vs **Two-step transfer**

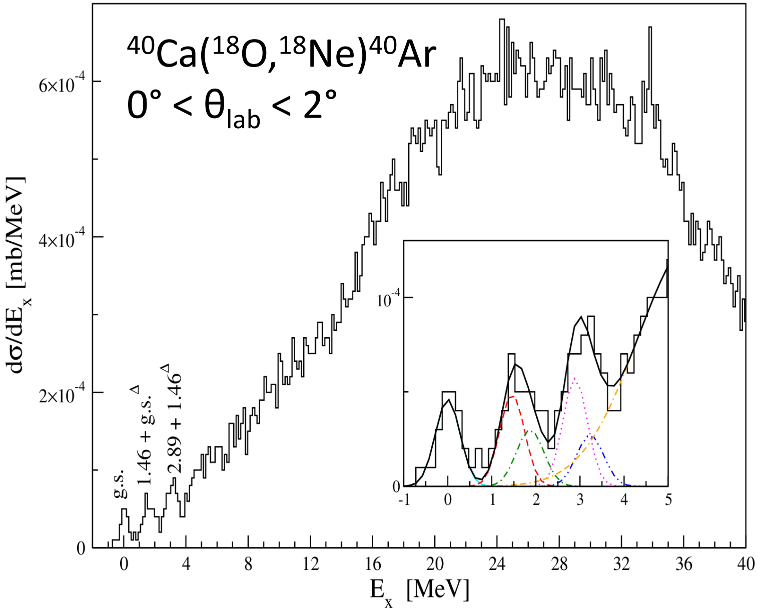


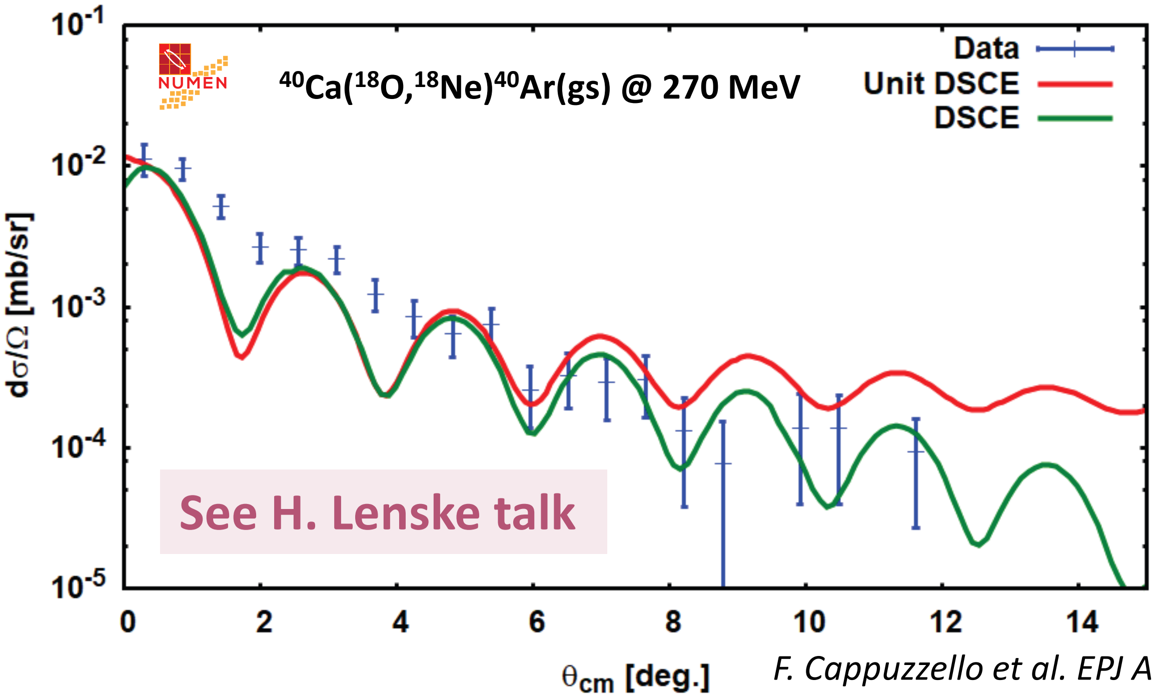



# Double charge exchange reaction

- ISI and FSI ion-ion interaction from double folding
- QRPA transition densities for microscopic form factors up to $J^\pi = 5^\pm$
- Two-step DWBA for the **DSCE** amplitudes




F. Cappuzzello et al. EPJ A (2015) 51:145
J. Bellone et al., PLB 807 (2020) 135528
H. Lenske et al., Universe 7 (2021) 98
F. Cappuzzello et al., PPNP 128, 103999 (2023)

## Key information from DCE data

- ✓ G.s. to g.s. transition isolated
- ✓ Spectroscopic factor extracted
- ✓ Good description of the data

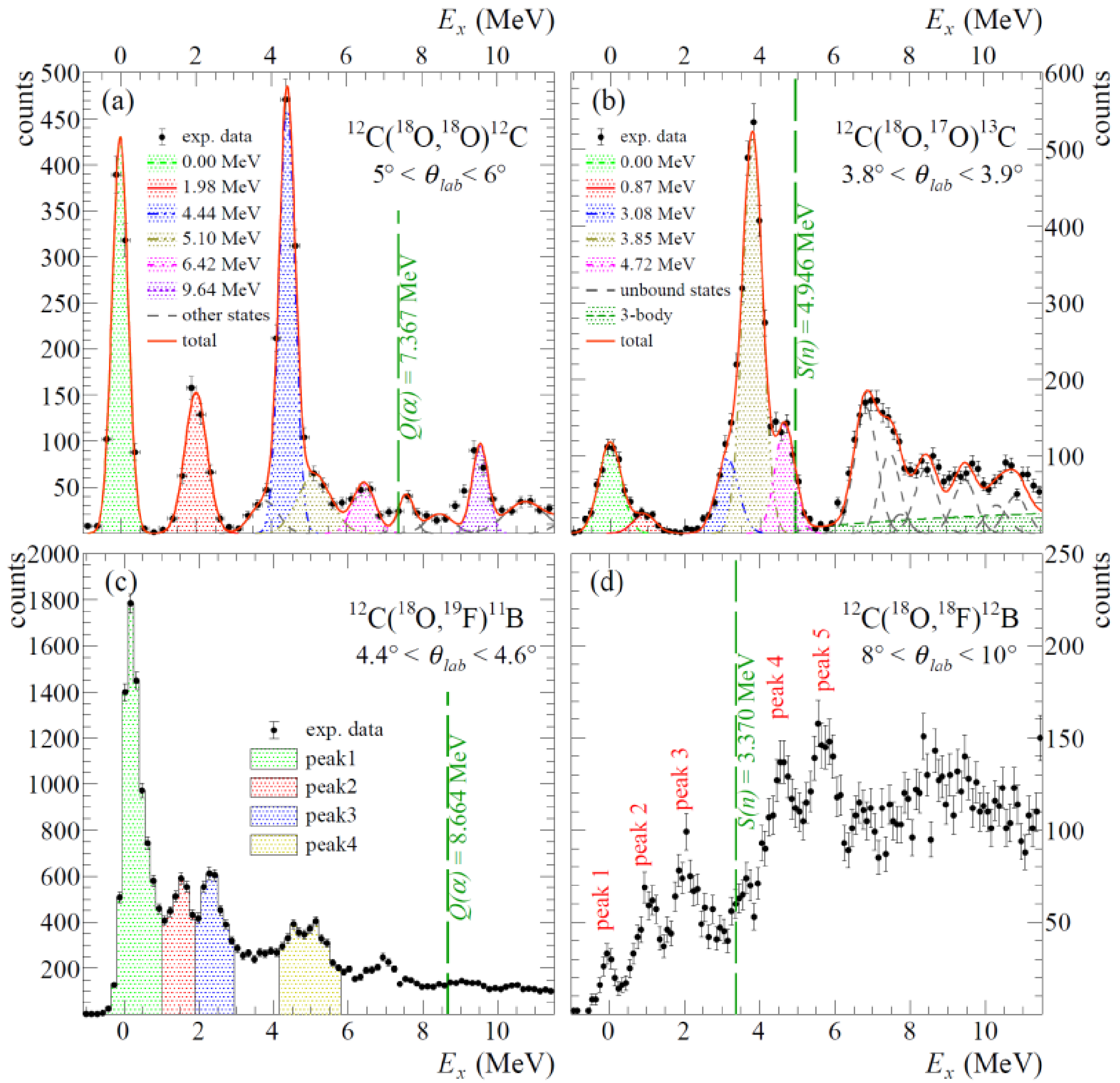
A spectroscopic factor of $\beta^2 = S^{I_A I_a S_1 S_2}_{J_A J_B j_a j_b} = 0.024$ is obtained, assuming closure approximation for $L_{13} = L_{24} = \lambda = 0$

$$M^{J_A J_B I_A}_{J_a J_b I_a,\lambda\mu}(\boldsymbol{k}_\alpha, \boldsymbol{k}_\beta) \sim \sum_{S_1,S_2} \sum_{l_1,l_3,l_2,l_4} \sum_{L_{13},L_{24},} \left\langle \chi^{(-)}_\beta \middle| \left[ \bar{F}^{l_2,l_4,L_{24}}_{S_2 T} G_{opt}(\omega_\alpha - \bar{\omega}_\gamma) \otimes \bar{F}^{l_1,l_3,L_{13}}_{S_1 T} \right]_{\lambda\mu} \middle| \chi^{(+)}_\alpha \right\rangle \times S^{I_A I_a S_1 S_2}_{J_A J_B j_a j_b}(l_1, l_3, l_2, l_4, L_{13}, L_{24}, \lambda)$$

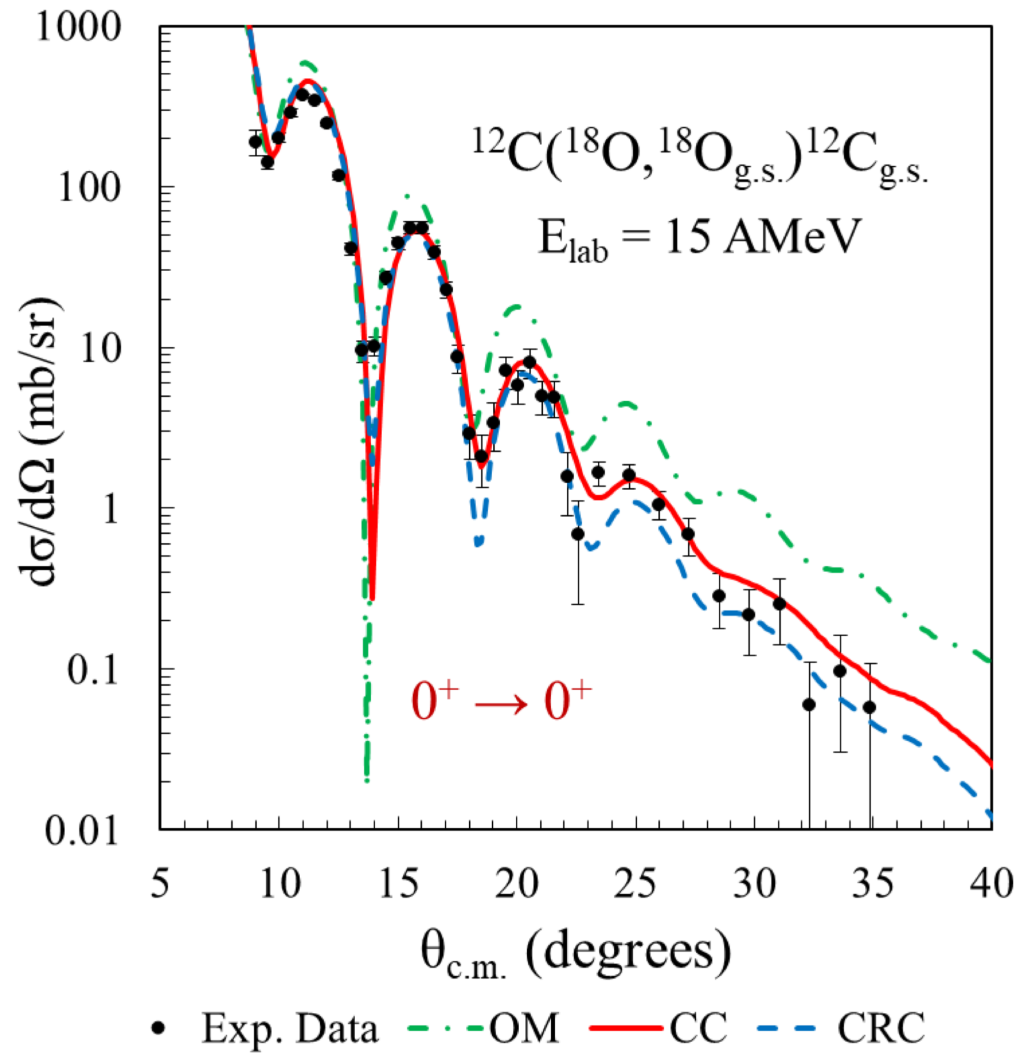
# The $^{18}O + ^{12}C$ @ 275 MeV case

# The multichannel approach

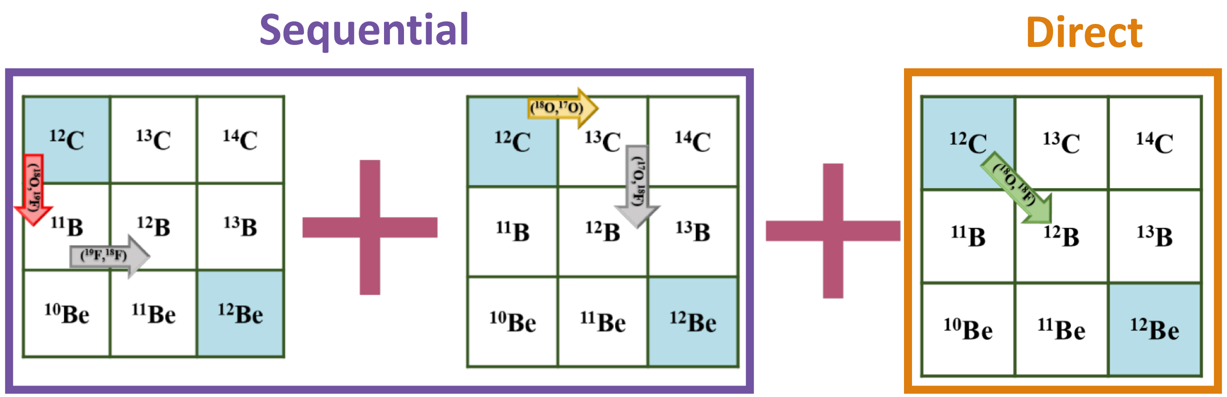
A. Spatafora et al. PRC 107, 024605 (2023)




**Initial state interaction**

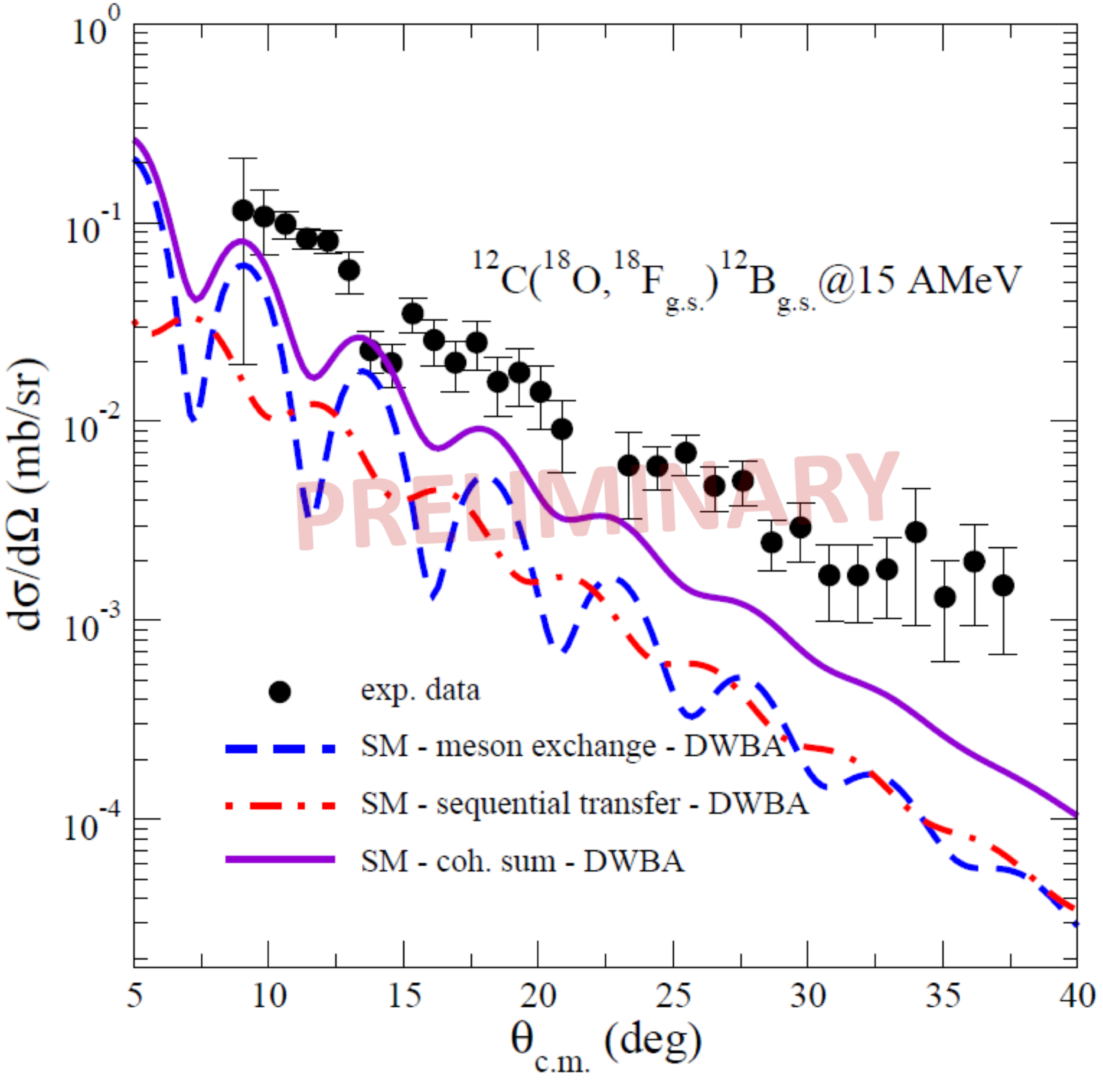


# Single charge exchange reaction




First **coherent calculation** with **direct and sequential SCE** reaction mechanism

*A. Spatafora et al., in preparation*




- OP extracted from elastic and inelastic scattering data
- **DWBA** analysis
- Large-scale shell-model **p-sd-mod interaction SA + OBTD**

N. Shimizu et al., Comp. Phys. comm. 244, 372 (2019)

*A. Etchegoyen et al. Nuclear Physics A 397, 343 (1983)*

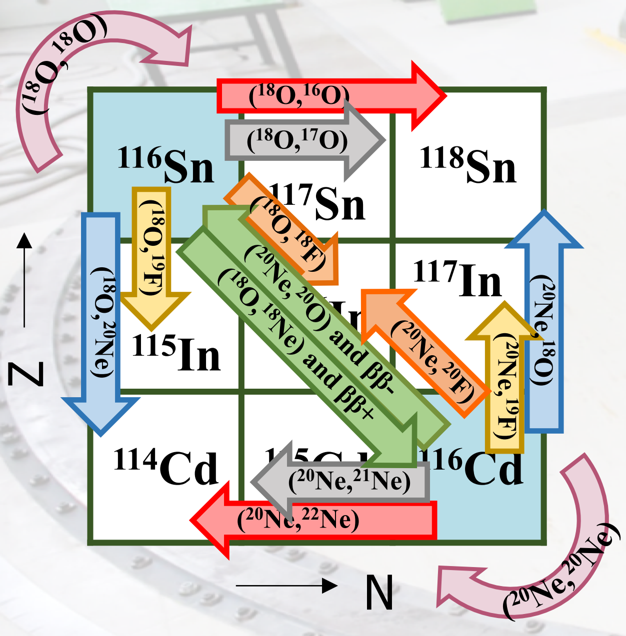
## Key information from SCE data

- ✓ **Interference** among direct and sequential mechanism is **constructive**
- ✓ Coherent sum of direct and sequential cross-sections is still small compared to the data
- ✓ **CCBA effects** need to be investigated

# NUMEN experimental runs

## $^{116}$Cd - $^{116}$Sn case

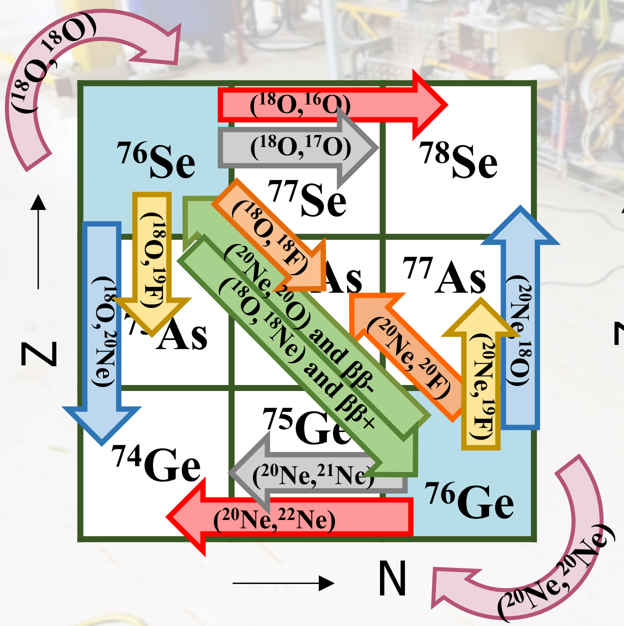
@ 15 AMeV
- ➢ $^{18}$O + $^{116}$Sn
- ➢ $^{20}$Ne + $^{116}$Cd




D. Carbone et al., PRC 102, 044606 (2020)
S. Calabrese et al., NIMA 980, 164500 (2020)
D. Carbone et al., Universe 07, 58 (2021)
S. Burrello et al. PRC 105, 024616 (2022)
J. Ferreira et al., PRC 105, 014630 (2022)

## $^{76}$Ge – $^{76}$Se case

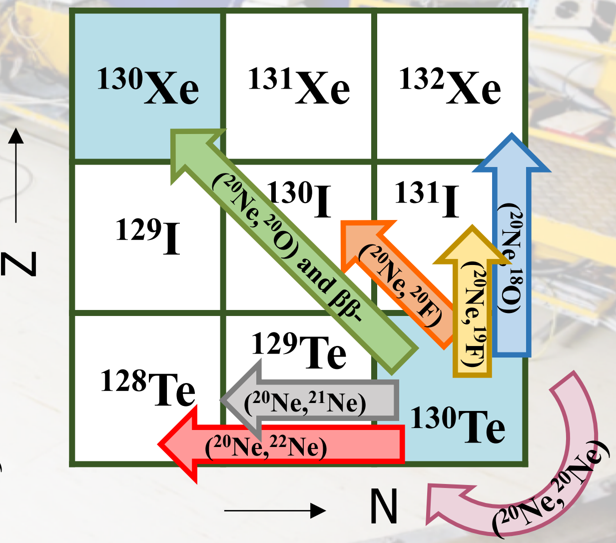
@ 15 AMeV
- ➢ $^{20}$Ne + $^{76}$Ge
- ➢ $^{18}$O + $^{76}$Se




A. Spatafora et al., PRC 100, 034620 (2019)
L. La Fauci et al., PRC 104, 054610 (2021)
I. Ciraldo et al., PRC 105 (2022) 044607

## $^{130}$Te – $^{130}$Xe case

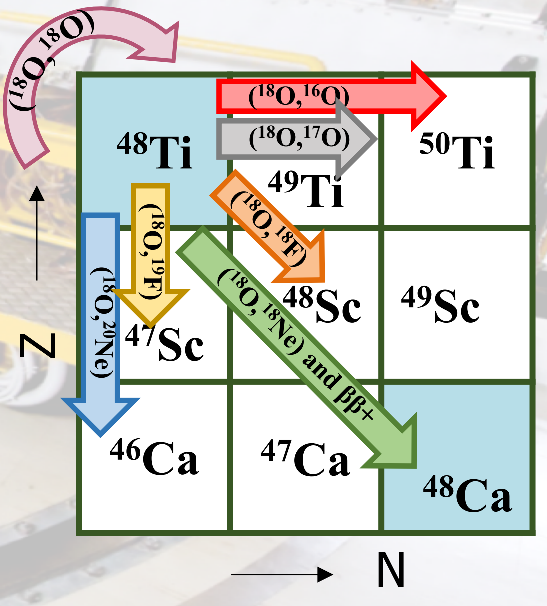
@ 15 AMeV
- ➢ $^{20}$Ne + $^{130}$Te




M. Cavallaro et al., Res. Phys. 13, 102191 (2019)
V. Soukeras et al., Res. Phys. 28, 104691 (2021)
D. Carbone et al., Universe 07, 58 (2021)

## $^{48}$Ca - $^{48}$Ti case

@ 15 AMeV
- ➢ $^{18}$O + $^{48}$Ti

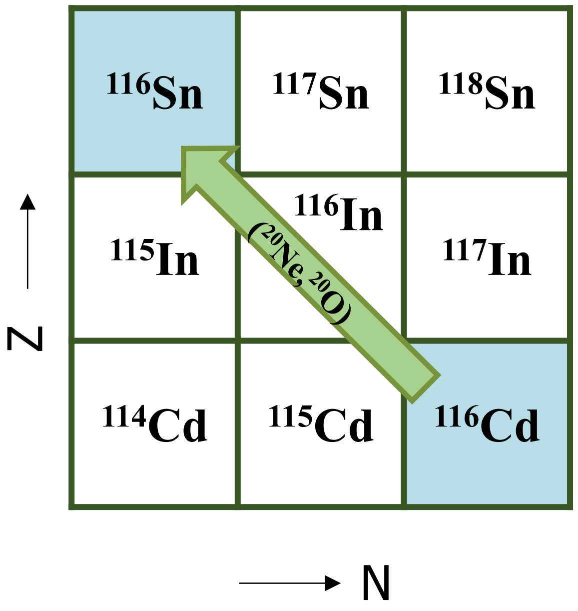


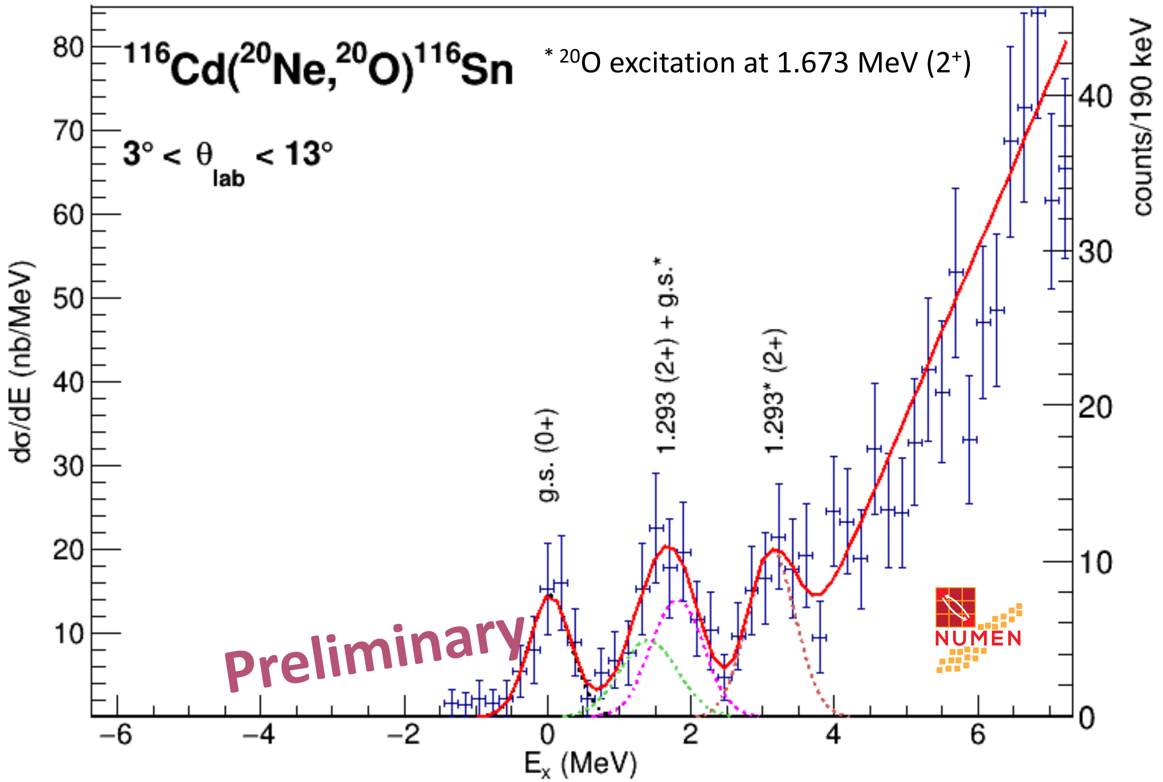

O. Sgouros et al., PRC 104, 034617 (2021)

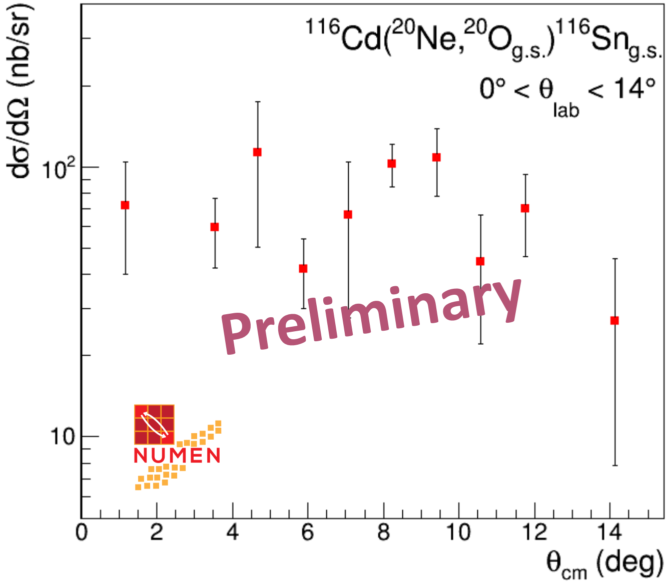
**See O. Sgouros and V. Soukeras talks**

# Experimental results

## DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$



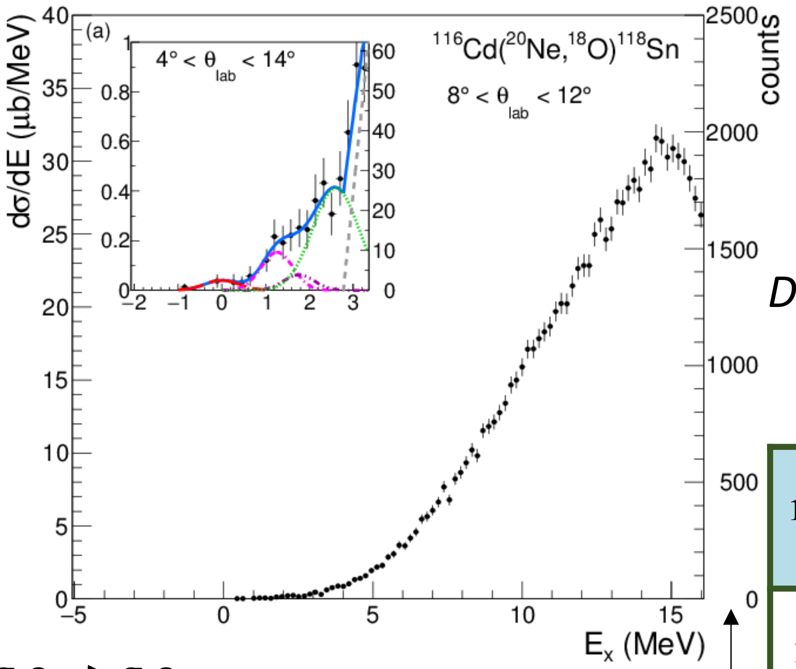




| State (MeV) | Counts | Absolute cross section (nb) |
| --- | --- | --- |
| $^{116}Sn_{gs}$ $(0^+)$ + $^{20}O_{gs}$ $(0^+)$ | 31 | 12 ± 2 |
| $^{116}Sn_{1.293}$ $(2^+)$ + $^{20}O_{gs}$ $(0^+)$<br>$^{116}Sn_{gs}$ $(0^+)$ + $^{20}O_{1.673}$ $(2^+)$ | 67 | 24 ± 3 |

- g.s. → g.s. transition isolated (resolution ~ 800 keV FWHM)
- Absolute cross section measured
- Angular distribution
- Zero-degree measurement

*S. Calabrese et al., NIM A 980 (2020) 164500*

# Multi-nucleon transfer



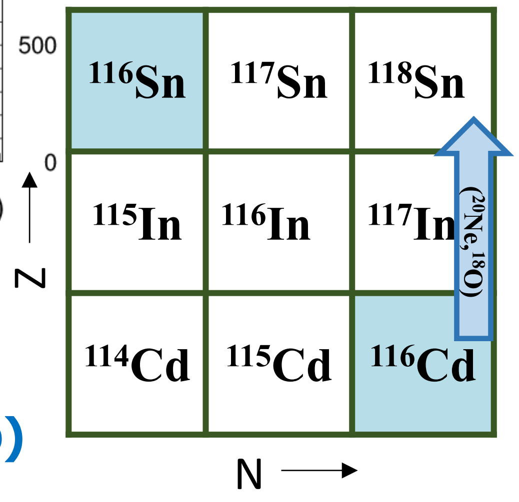

g.s. -> g.s.

**EXP. DATA** **40 ± 15 nb**

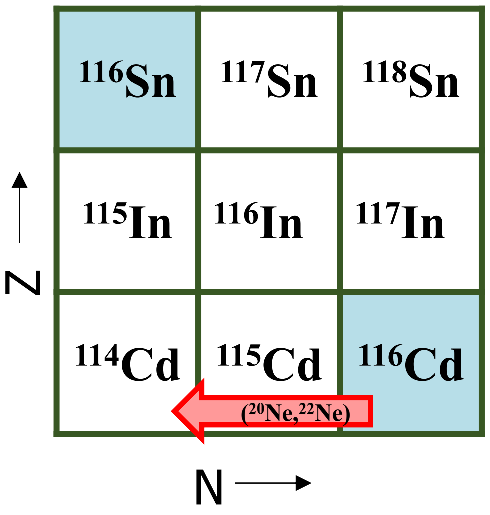
**CALCULATIONS: ~ 40 nb (1 step)**

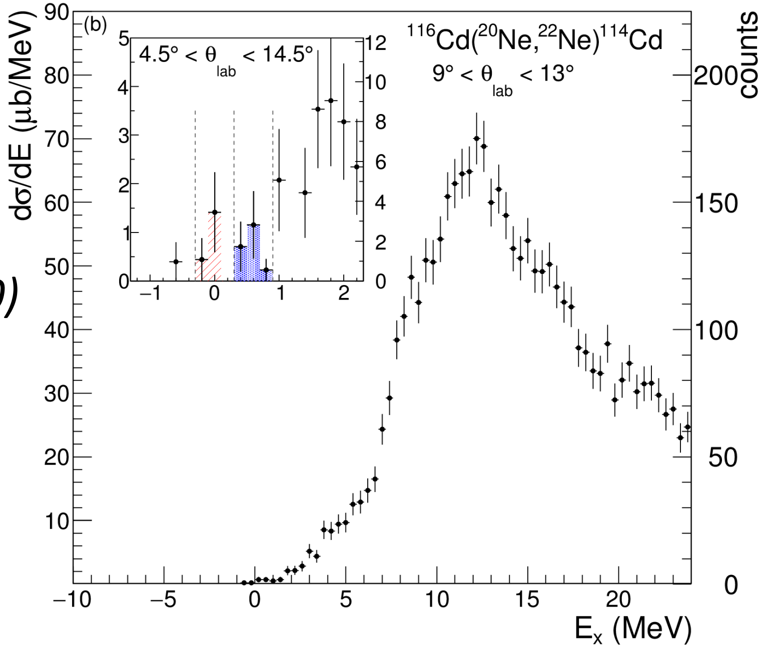
*D. Carbone et al., Phys. Rev. C 102, 044606 (2020)*

## 2p-transfer




## 2n-transfer




g.s. -> g.s.

**EXP. DATA** **370 ± 190 nb**

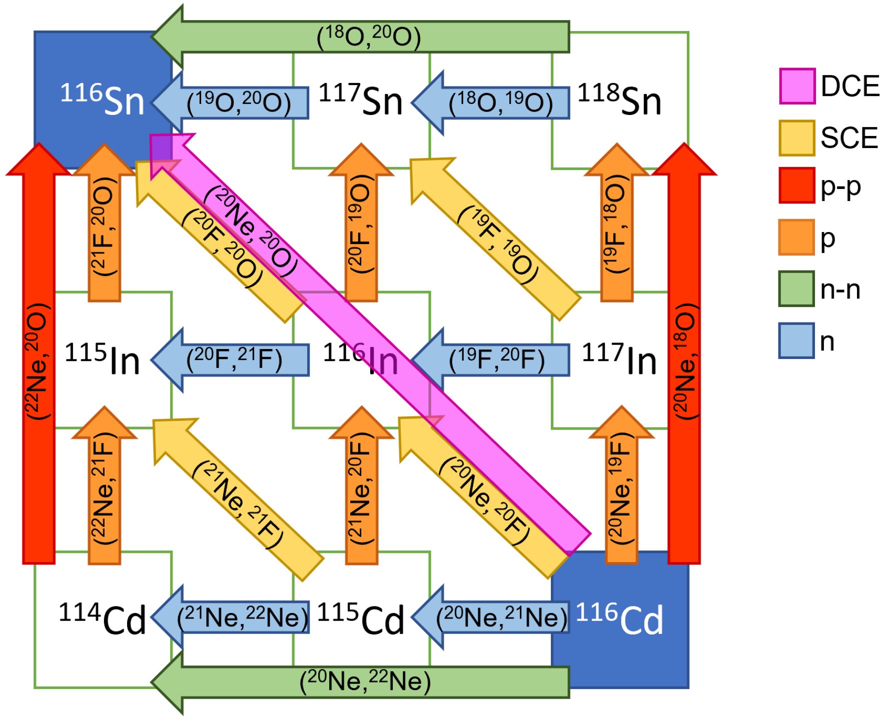
**CALCULATIONS: ~ 210 nb (1 step)**

**One-step and seq. cross section calculations (DWBA, CRC, CCBA)**
**ISI and FSI from double folding**
**SA from IBM, shell model, QRPA**

This framework is used to predict the multi-nucleon transfer cross section leading to the same DCE channels, for such steps where experimental information is missing

# Multi-nucleon transfer routes

- **DWBA** and **CRC calculations** of all the multi-nucleon transfer routes competing with meson-exchange processes.
- Coherent (and constrained) approach




J. Ferreira et al., Phys. Rev. C 105, 014630 (2022)

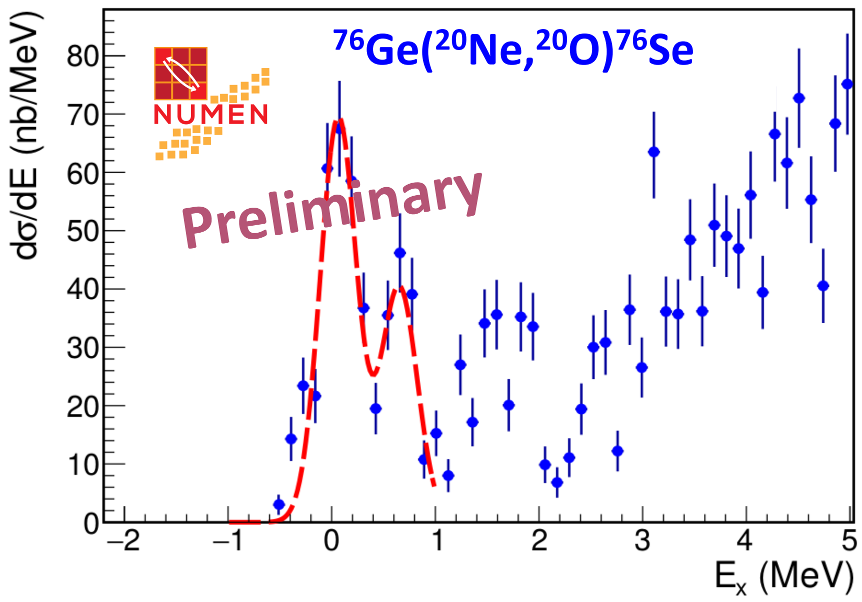
**(Exp. cross section DCE 12 ± 2 nb)**

| Mechanism | Int. cross section (nb) $^{20}O_{g.s.}(0^+) + ^{116}Sn_{g.s.}(0^+)$ |
|---|---|
| $2p-2n$ | $1,28\times10^{-4}$ |
| $2n-2p$ | $3,13\times10^{-4}$ |
| $p-p-n-n$ | $6,63\times10^{-5}$ |
| $n-n-p-p$ | $1,00\times10^{-5}$ |
| $p-p-2n$ | $4,15\times10^{-5}$ |
| $n-n-2p$ | $1,72\times10^{-6}$ |
| $2p-n-n$ | $9,26\times10^{-5}$ |
| $2n-p-p$ | $2,66\times10^{-4}$ |
| $p-n-p-n$ | $1,38\times10^{-7}$ |
| $p-n-n-p$ | $1,15\times10^{-6}$ |
| $n-p-n-p$ | $2,53\times10^{-7}$ |
| $n-p-p-n$ | $1,69\times10^{-7}$ |
| $p-2n-p$ | $2,51\times10^{-7}$ |
| $n-2p-n$ | $5,71\times10^{-6}$ |
| Incoh. Sum | $9,60\times10^{-4}$ |

**Negligible contribution of multi-nucleon transfer on the diagonal DCE process**

# DCE experimental results

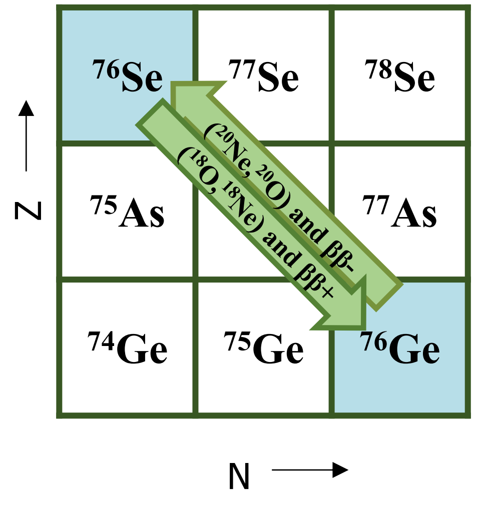
## $^{76}Ge$ – $^{76}Se$ case

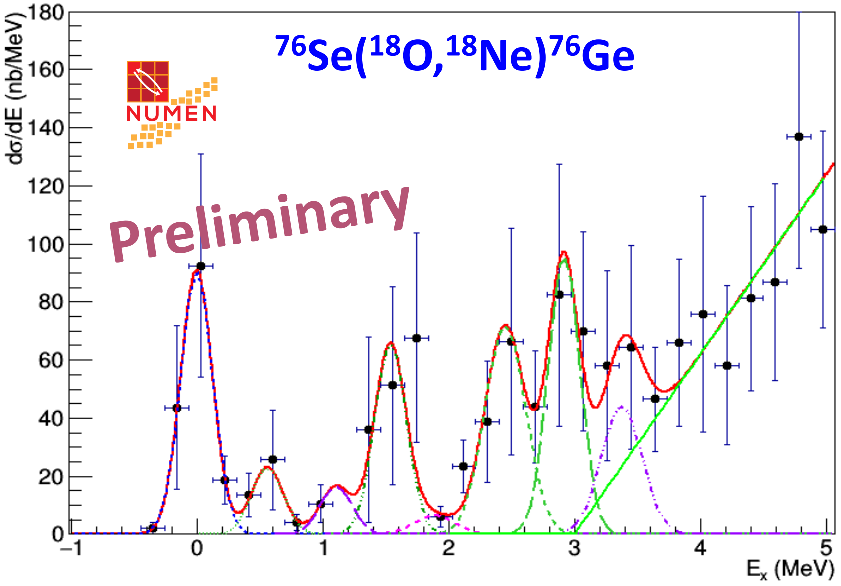



$0° < \theta_{lab} < 8°$

$\sigma_{g.s.\to g.s.}$ =30 ± 4 nb

*R. Linares et al.*




$\sigma_{g.s.\to g.s.}$ =29 ± 6 nb

*A. Spatafora et al.*

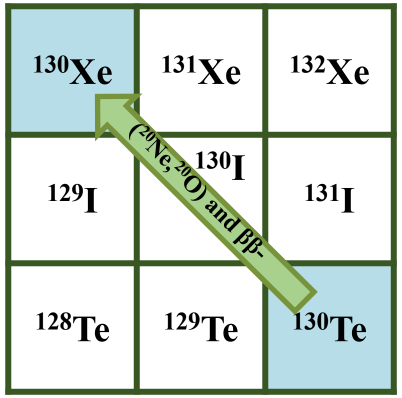
- Same cross sections for different directions
- Similar distorsion factors

→ Same NME (encouraging test of time invariance!)

Warning:

- Only one case
- Reaction calculations in progress

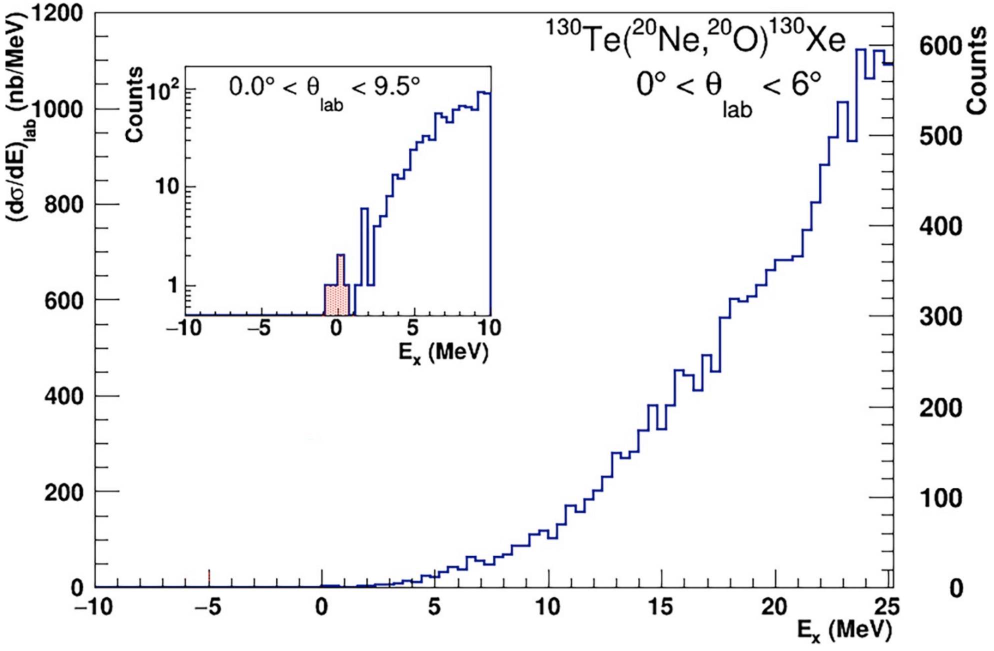
# DCE experimental results



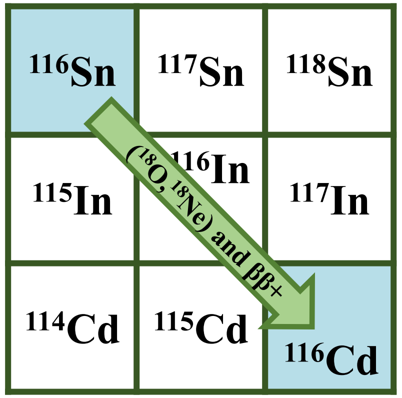

## $^{130}Te(^{20}Ne,^{20}O)^{130}Xe$

- Resolution ~ 500 keV FWHM
- No spurious counts at $-10 < E_x < -2$ MeV

$\sigma_{-1\ MeV \rightarrow 1\ MeV}$ = **13 nb** ([3,18] nb at 95% CL)

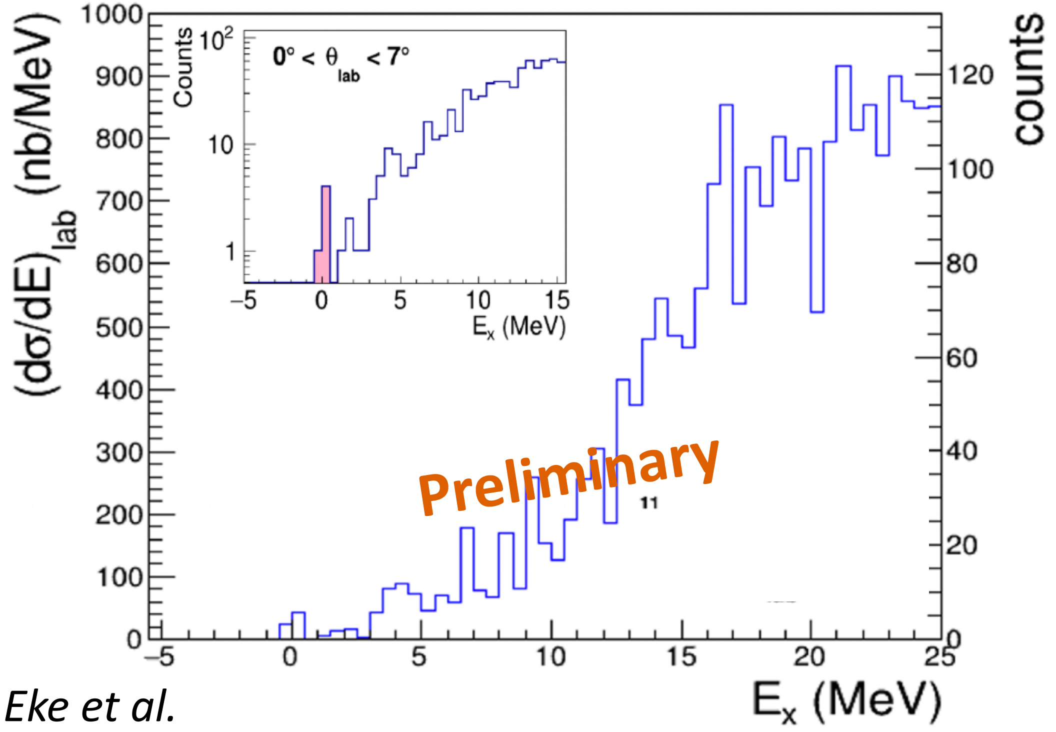



*V. Soukeras et al., Results in Physics 28, 104691 (2021)*




## $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$

$\sigma_{-1\ MeV \rightarrow 1\ MeV}$ = **36 nb** ([4,46] nb at 95% CL)




*C. Eke et al.*

# Present limitations

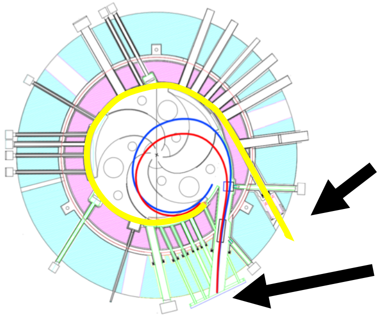
DCE reactions are characterized by very **low cross-sections**

In the last years NUMEN studied only few systems

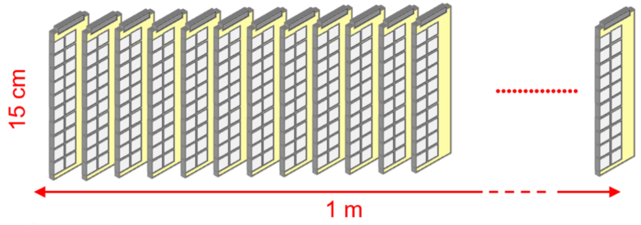
**Much higher beam current is needed**

Project of **upgrade of the LNS Cyclotron (from 100 W to 5-10 kW) and infrastructures** (triggered by NUMEN physics case) funded by national grant (PON)

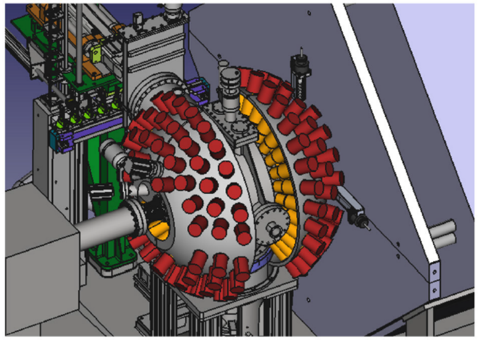
# Upgrade of LNS facilities



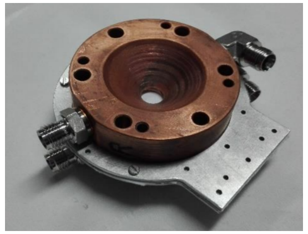

- **Upgrade of the LNS accelerator and beam lines**
  - CS accelerator **current** (from 100 W to 5-10 kW)
  - Beam transport line **trasmission efficiency** to nearly **100 %**




- **The MAGNEX Focal Plane Detector** (from 2 kHz to several MHz)
  - Gas tracker based on **multiple THGEM**
  - **SiC-CsI** telescopes for PID



- **Array of scintillators for $\gamma$-rays (G-NUMEN)**
  - LaBr3 scintillators
  - Measurement in coincidence with MAGNEX
- **Radiation tolerant targets**
  - Substrate of Highly Oriented Pyrolitic Graphite (HOPG)



- **New electronics**
  - CAEN VX2740 Digitizer module

See D. Torresi and M. Giovannini talks

**NUMEN TDR**

*F. Cappuzzello et al., Intern. Journ. of Mod. Phys. A 36 (2021) 2130018*

# Conclusions and Outloooks

## <u>Use of HI-DCE reaction for 0νββ decay</u>

- Promising results from the NUMEN experiments
- Multichannel approach for the data analysis
- **DCE reactions on $^{116}$Cd, $^{76}$Ge, $^{76}$Se, $^{130}$Te and $^{116}$Sn** measured for the first time
  - ✓ Good energy resolution to isolate the g.s. → g.s. transition
  - ✓ Absolute cross section measured
- Role of **multi-nucleon transfer** routes **negligible** with respect to the diagonal DCE in the case of $^{116}$Cd -$^{116}$Sn system

## <u>Outlooks</u>

- New measurements at iThemba labs on $^{18}$O + $^{76}$Se system
- CS and MAGNEX FPD **upgrade** ongoing for reaching high intensity
- Full experimental exploration of all the nuclei candidate for 0νββ decay with the **high intensity beams**

# The NUMEN collaboration

## (NUclear Matrix Elements for Neutrinoless double beta decay)

NUMEN

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86 Researchers
34 Institutions
12 Countries


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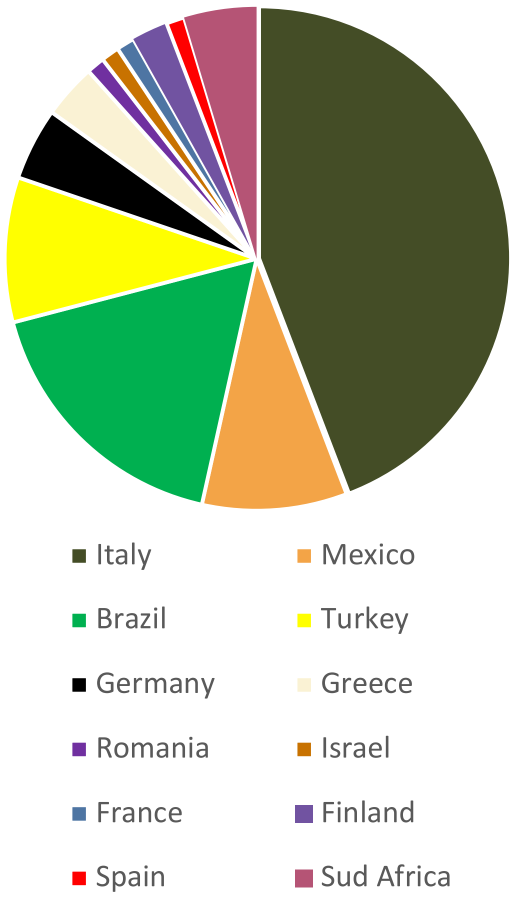

# Thank you