Heavy-ion induced single and double charge exchange reactions in a multi-channel approach: new results from the NUMEN project

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Outline

- The problem of 0νββ-decay nuclear matrix elements (NMEs)
- The study of double charge exchange (DCE) @ INFN-LNS (NUMEN, NURE)
- The multichannel vision
- Recent results from SCE and DCE reactions
- Conclusions and perspectives

0νββ decay

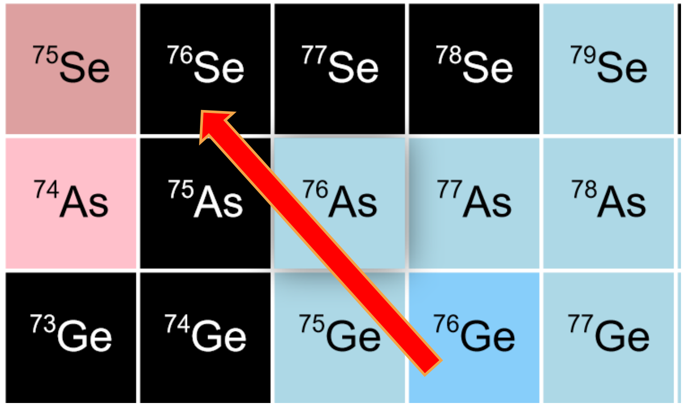
Open problem in modern physics:

Neutrino absolute mass scale

Neutrino nature

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

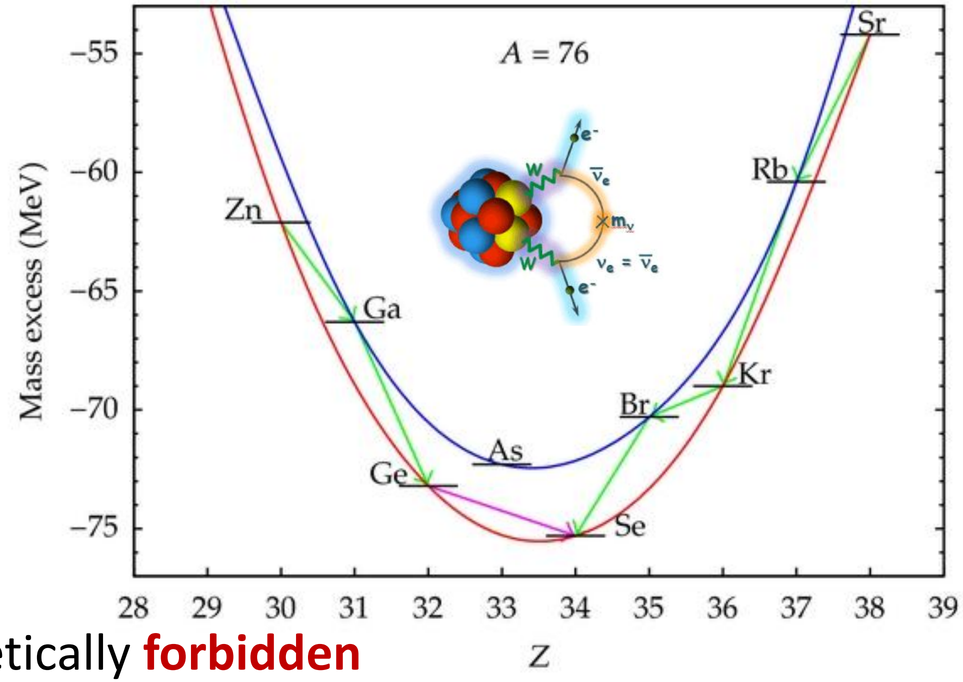
E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184



Still not observed

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

Isobaric nuclear transition where a parent nucleus spontaneously decays into a daughter nucleus changing by two units its charge and leaving the mass number unchanged



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

Beyond standard model:

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

Ejiri, H.; Suhonen, J.; Zuber, K. , Physics Reports **2019**, 1, 797
Agostini, M. ; Benato, G.; Detwiler J.A.; Menendez, J.; Vissani, F.; Reviews of Modern Physics **2023**, 95, 025002

0νββ decay

Intense activities in the searches for experimental evidence of this process

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

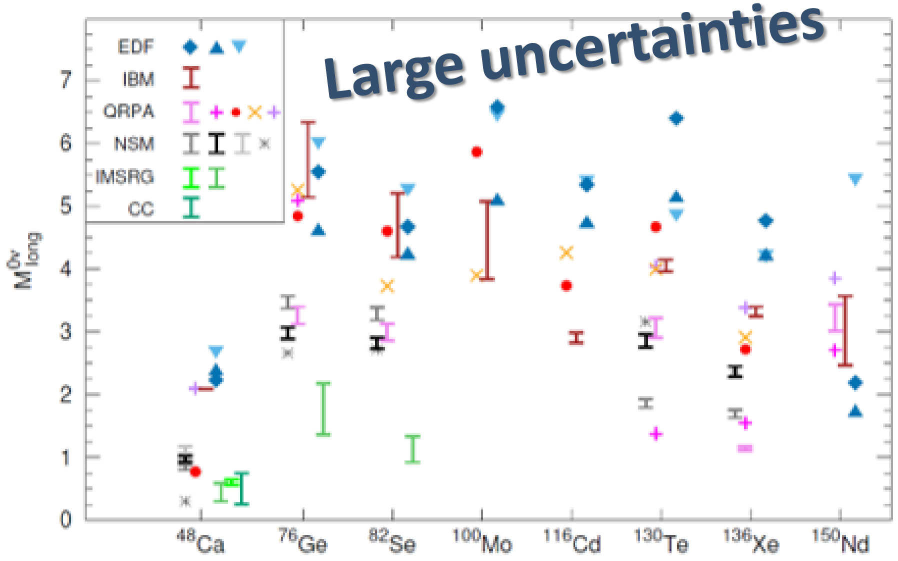
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

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

Transition probability of a **nuclear** process

State of the art NME calculations



M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

- ✓ NMEs are not physical observables
- ✓ The challenge is the description of the **nuclear many body states**
- ✓ Much work on the **transition operator**, now including all the known short-range weak interaction physics F.F. Deppisch et al., PRD 102, 095016 (2020)
- ✓ **Calculations** (<u>still sizeable uncertainties</u>): QRPA, Large scale shell model, IBM, EDF, ab-initio .....

Support from the experiments

Measurements (not very strong constraining the $0\nu\beta\beta$ NME):

1st order isospin probes

2nd order isospin probes

- ✓ β-decay and $2\nu\beta\beta$ decay
- ✓ (π^+, π^-), single charge exchange (SCE) $(^3He,t)$, $(d,^2He)$, HI-SCE, electron capture, transfer reactions, μ-capture, γ-ray spectroscopy, double γ-decay etc.
- ✓ A recent promising tool: **Heavy-Ion Double Charge-Exchange (HI-DCE)**

NUMEN

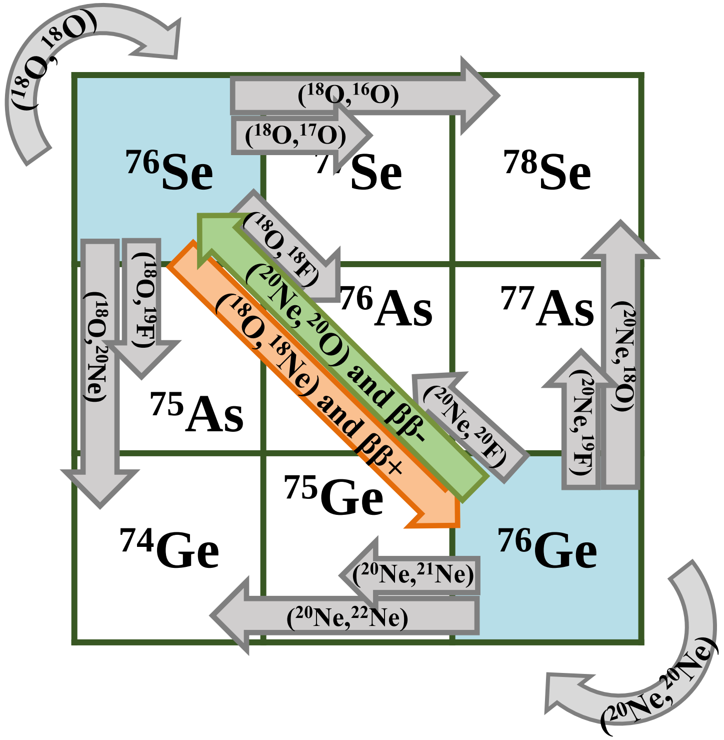
(**NU**clear **M**atrix **E**lements for **N**eutrinoless double beta decay)

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

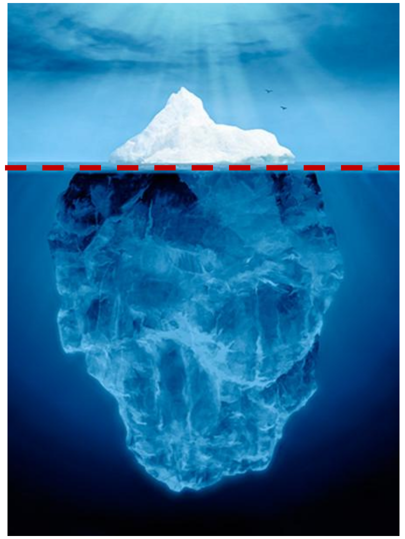
erc NURE

Heavy-ion DCE as surrogate processes of ββ-decay

- ✓ Induced by strong interaction
- ✓ Possibility to go in both directions
- ✓ Low but **measurable cross section in controlled laboratory conditions**



Tiny amount of DGT strenght for low lying states



NURE

Sum rule almost exhausted by DGT Giant Mode, still not firmly established. First indications in [*A. Sakaue et al. Prog. Theor. Exp. Phys. 123D03 (2024)*]

RIKEN

RCNP

Heavy-ion induced DCE

Heavy ion DCE can proceed via:

Mean field driven processes

1) 4th order sequential multi-nucleon transfer (TDCE) mediated by mean-field

J.L. Ferreira et al., PRC 105, 014630 (2022)
J.L. Ferreira et al., PRC 111, 014630 (2025)

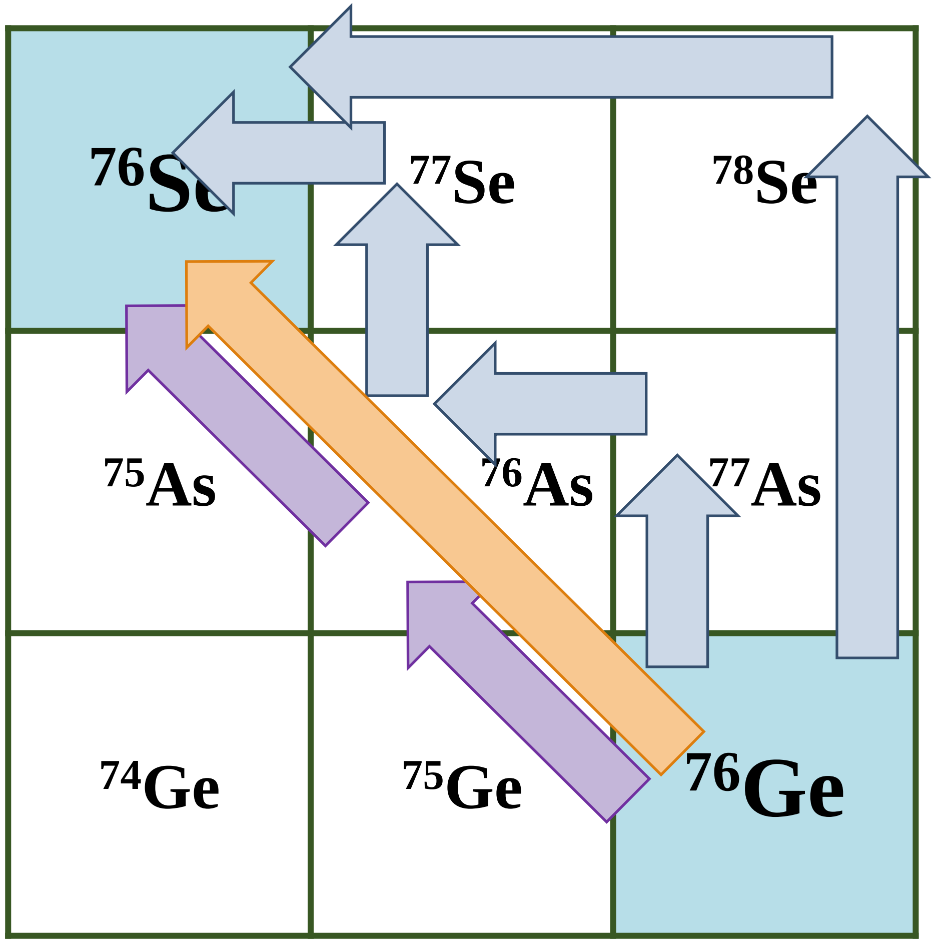
Collisional processes

2) Two-step DCE - Double single charge exchange (DSCE): two consecutive single charge exchange processes, <u>mediated by NN isovector interaction</u>

H.Lenske et al., Universe (2024), 10, 93

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

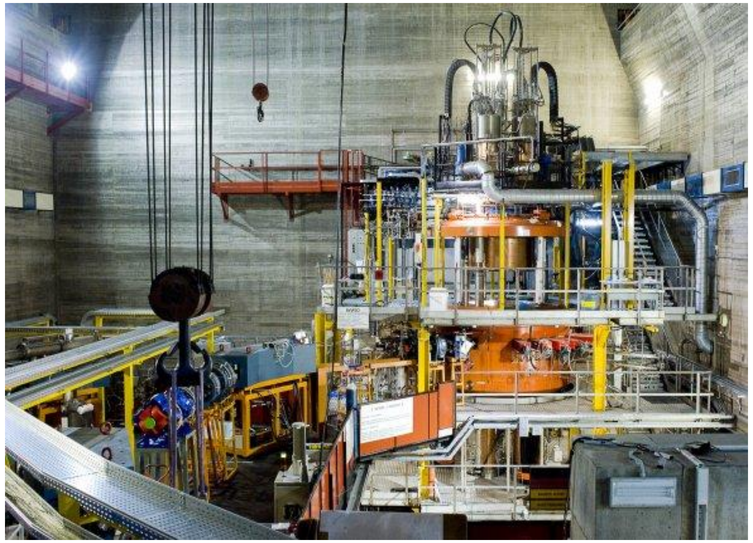
H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
H. Lenske, Universe (2024) 10, 202



The DCE cross section combines the three different classes of reaction dynamics

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

DCE @ INFN - LNS

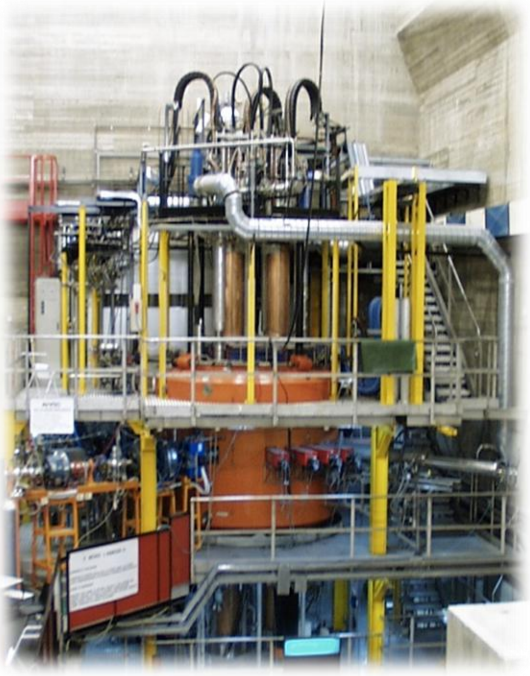


The experiments @ INFN-LNS

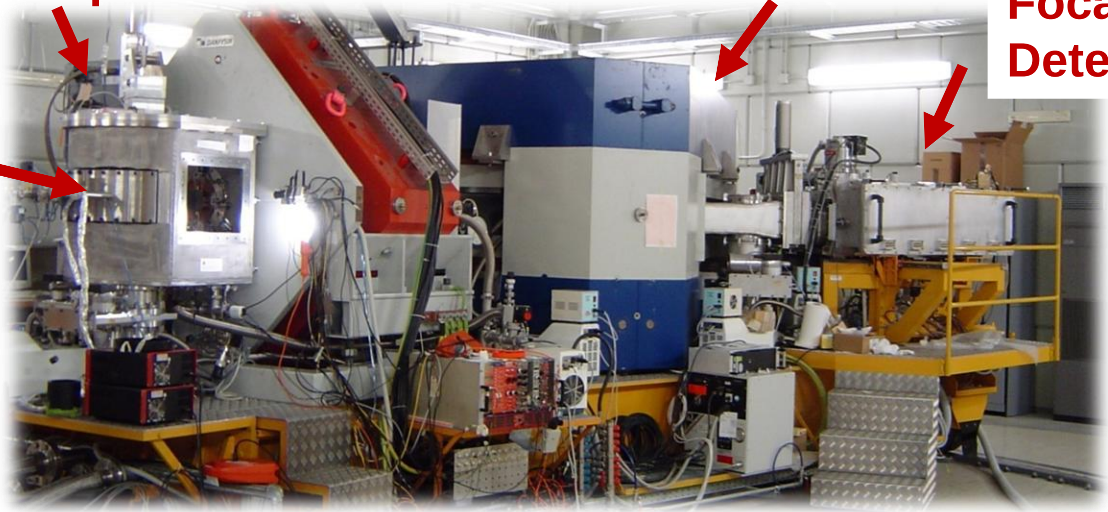
Crucial for the experimental challenges

K800 Superconducting Cyclotron

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



MAGNEX QD magnetic spectrometer



A **wide mass range** (from protons to medium-mass nuclei)

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

(*)presently being upgraded to 2.2 Tm

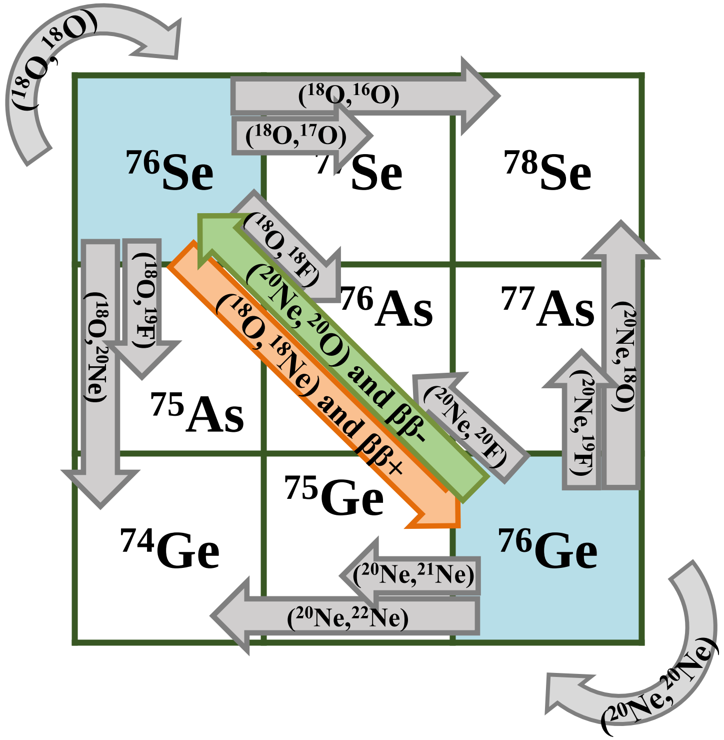
Measured resolutions:
- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/300$

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

The multichannel approach

Several scattering and reaction channels open in a heavy-ion collisions above Coulomb barrier

Although the main interest is for DCE reactions, all the other quasi-elastic processes are important sources of information, essential to **build a constrained analysis of the nuclear states of interest for DCE and 0νββ**



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 1st order isospin operators (One-Body Transition Densities)

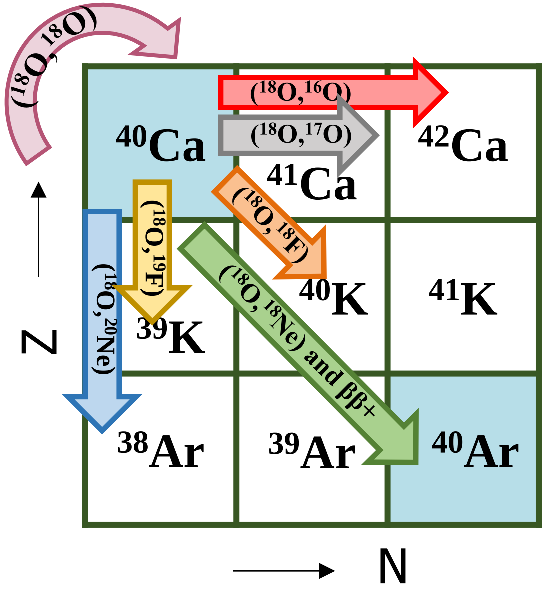
Double charge exchange (**DCE**) → nuclear response to 2nd order isospin operators (Two-Body Transition Densities)

The multichannel approach

- Measuring all the accessible quasi-elastic channels **<u>all at once</u>** gives a **high reliability of the measured observables**, since systematic errors are largely cancelled, thanks to the many available cross checks in the data

- From the theory side, **constrained data analyses can be performed**, such as CC approaches, largely reducing the need of free parameters in both nuclear structure and reaction models

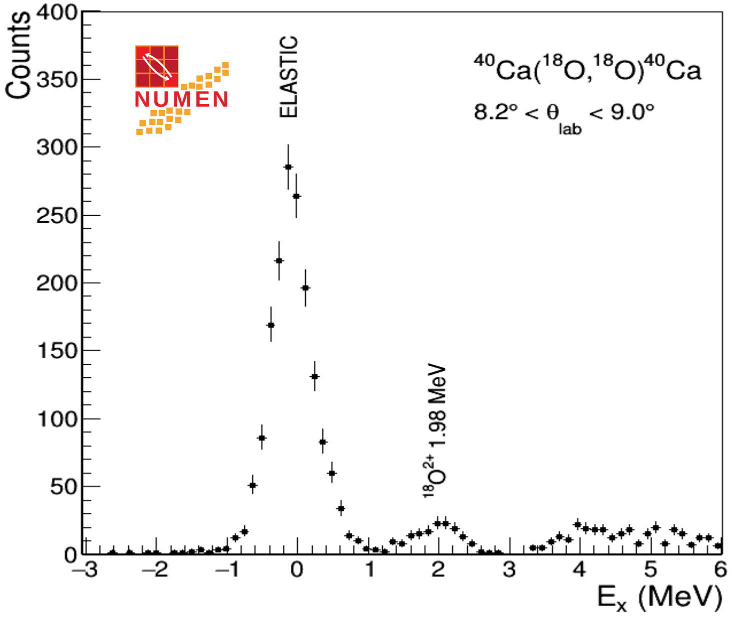
The ^{18}O + ^{40}Ca @ 275 MeV case

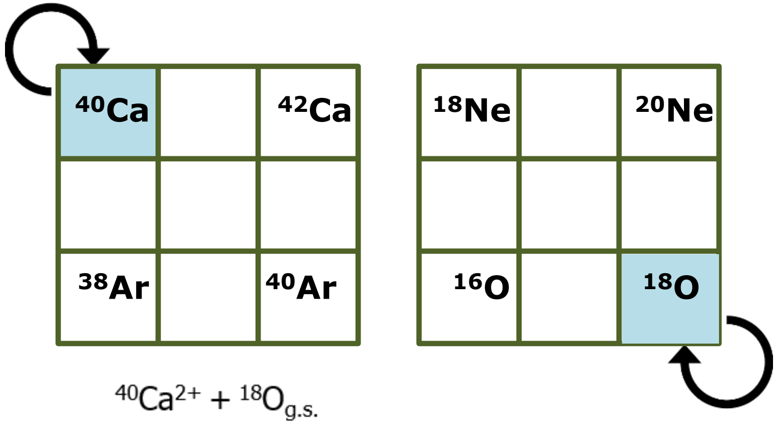


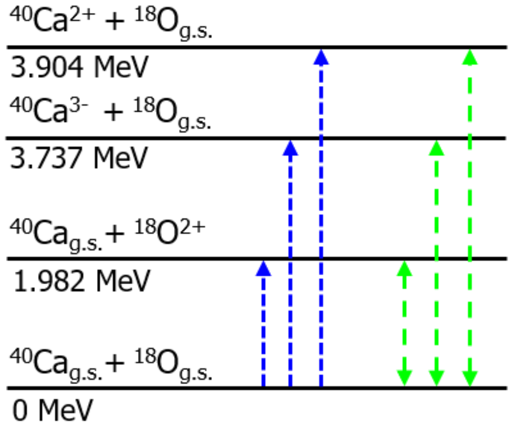
- ✓ F. Cappuzzello et al., EPJA 51, 145 (2015)
- ✓ M. Cavallaro et al., Front. Astr. Space Sci. (2021) 8:659815
- ✓ S. Calabrese et al., Phys. Rev. C (2021) 104, 064609
- ✓ J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604
- ✓ B.A. Urazbekov et al., PRC 108 (2023) 064609
- ✓ B.A. Urazbekov et al., PRC 111, 044603 (2025)
- ✓ J.L. Ferreira et al., PRC 111, 054609 (2025)

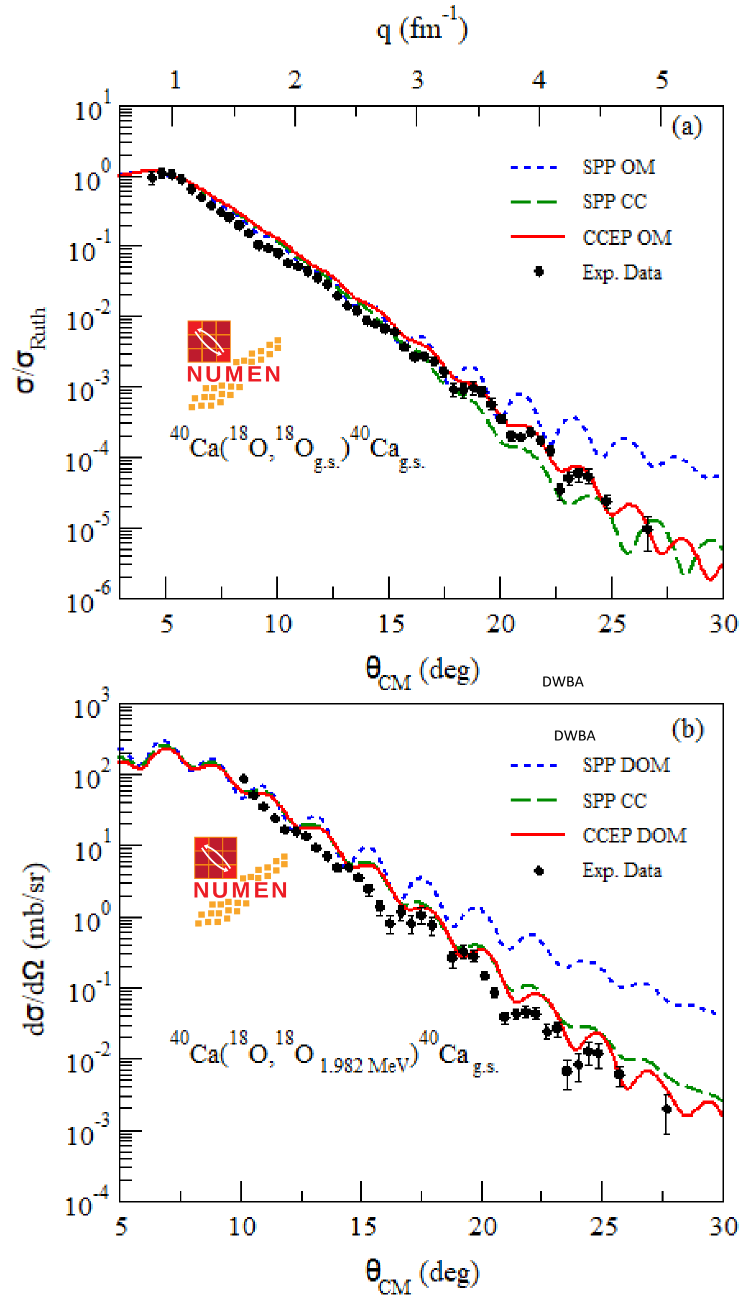
Elastic and inelastic scattering

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







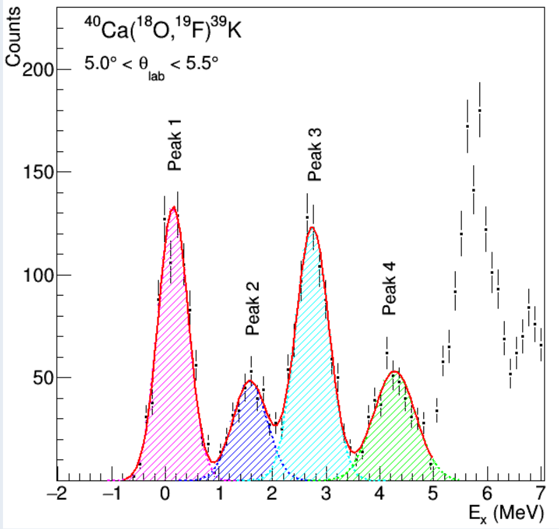


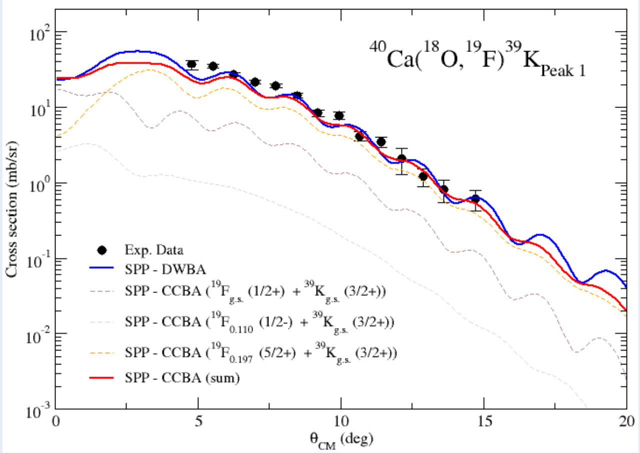
Key information from elastic and inelastic scattering data

- ✓ **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 Coupled Channel Equivalent Potential (**CCEP) approach**

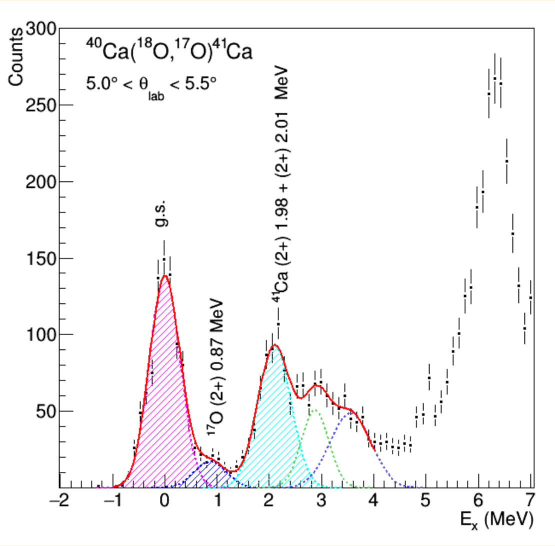
Transfer reactions

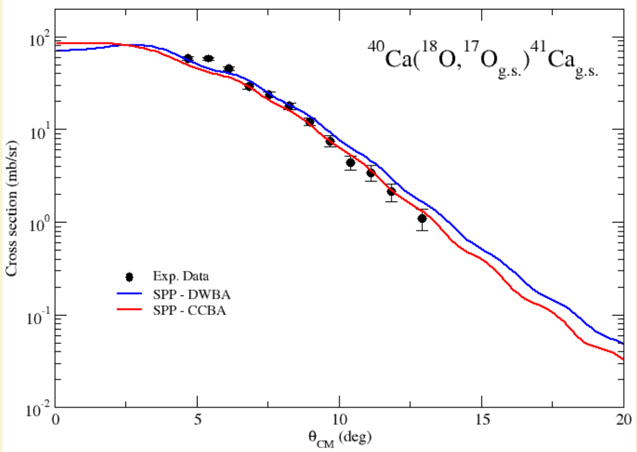
1p-transfer



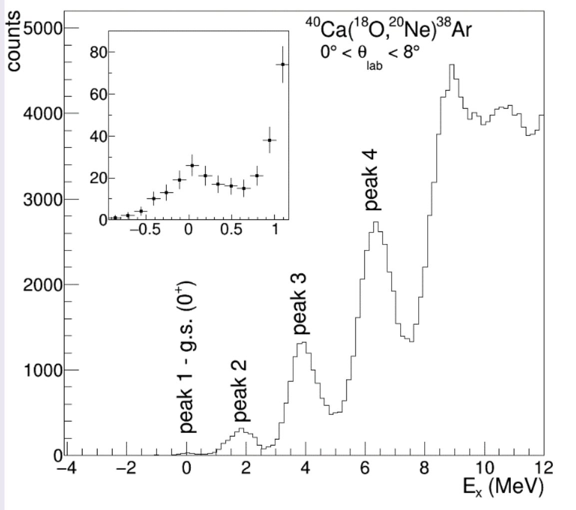


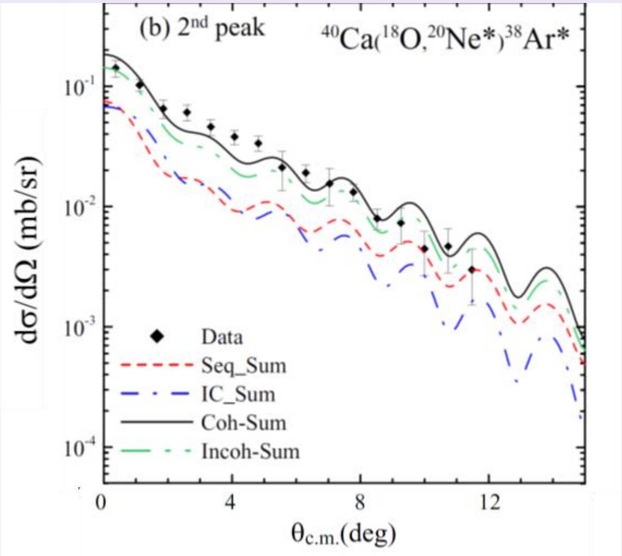
1n-transfer





2p-transfer



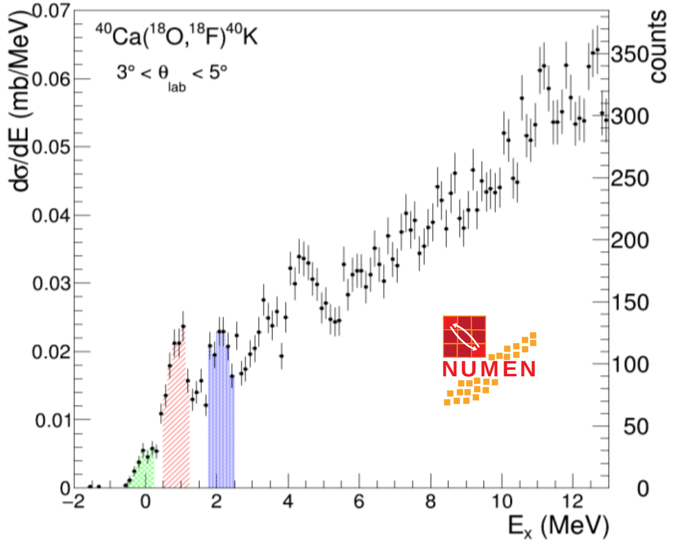


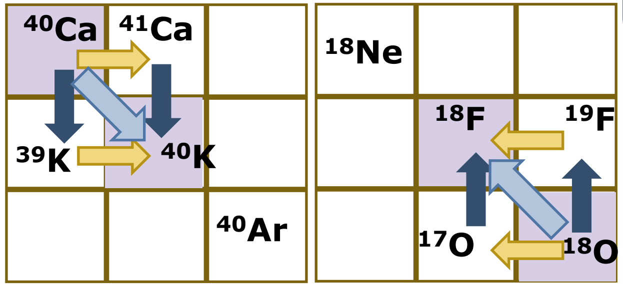
- OP extracted from elastic and inelastic scattering data
- **CCBA** analysis for direct and two-step transfer
- **Large scale shell mode**l spectroscopic amplitudes

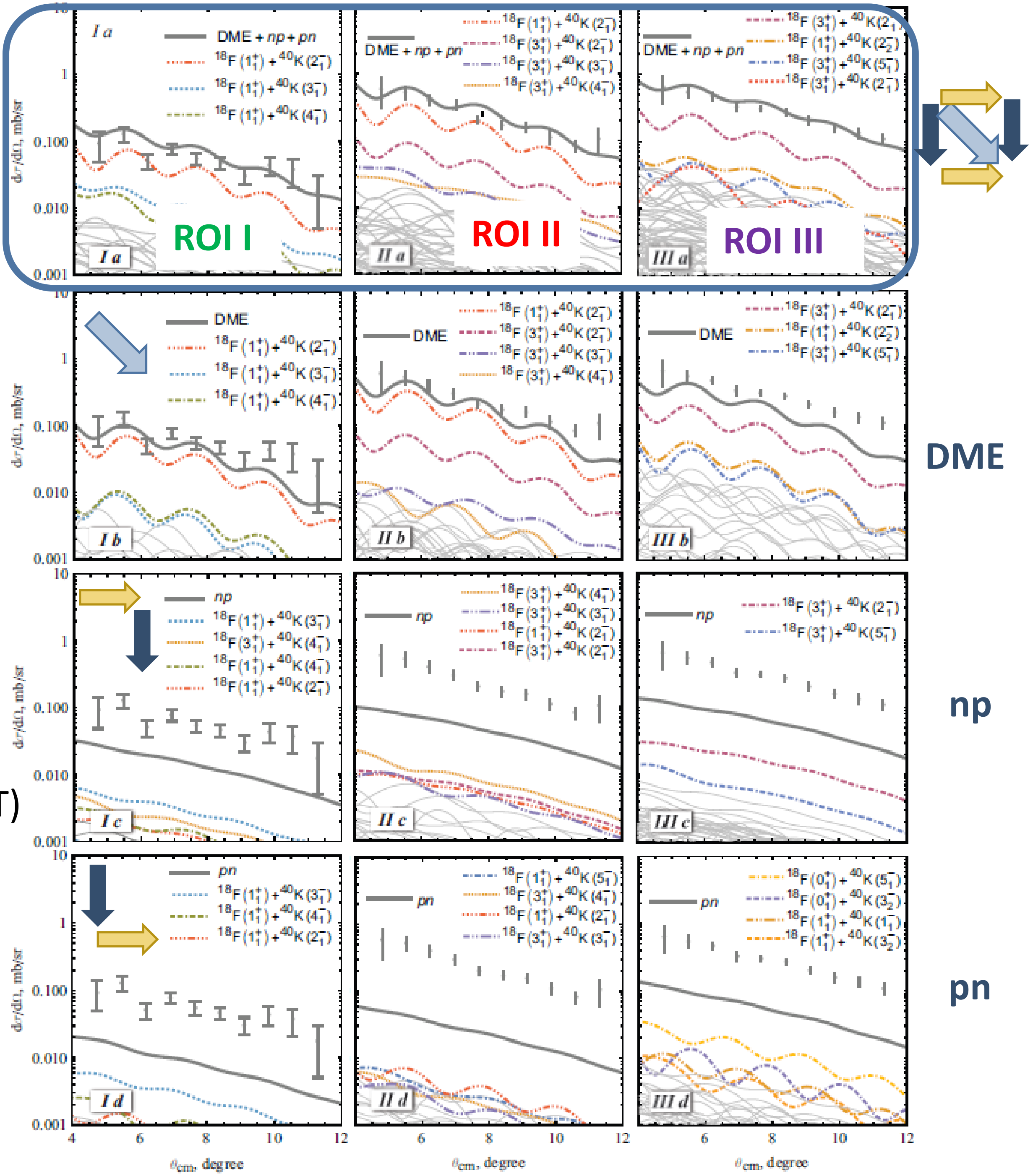
Key information from transfer data

- ✓ Very good description of the data from constrained CCBA
- ✓ Mixing of single particle and core polarization configurations
- ✓ Competition between one-step and two-step mechanisms

Single charge exchange reaction







- **DWBA** analysis based on the **coherent sum** of **direct meson exchange and two-step nucleon transfer**
- Nuclear structure input from large scale shell model (SA + OBDT)

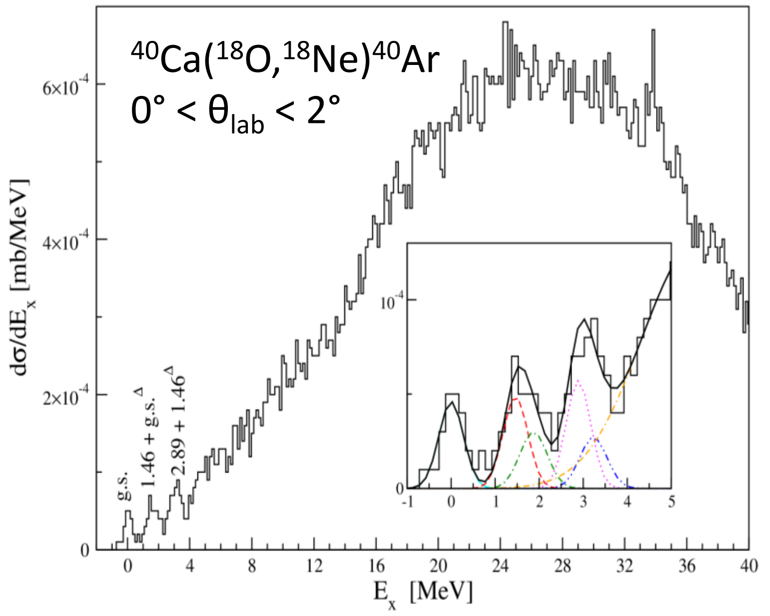
Key information from SCE data

- ✓ **A fair agreement with the data!**
- ✓ **Dominance of meson exchange mechanism**
- ✓ New avenues for precision SCE spectroscopy

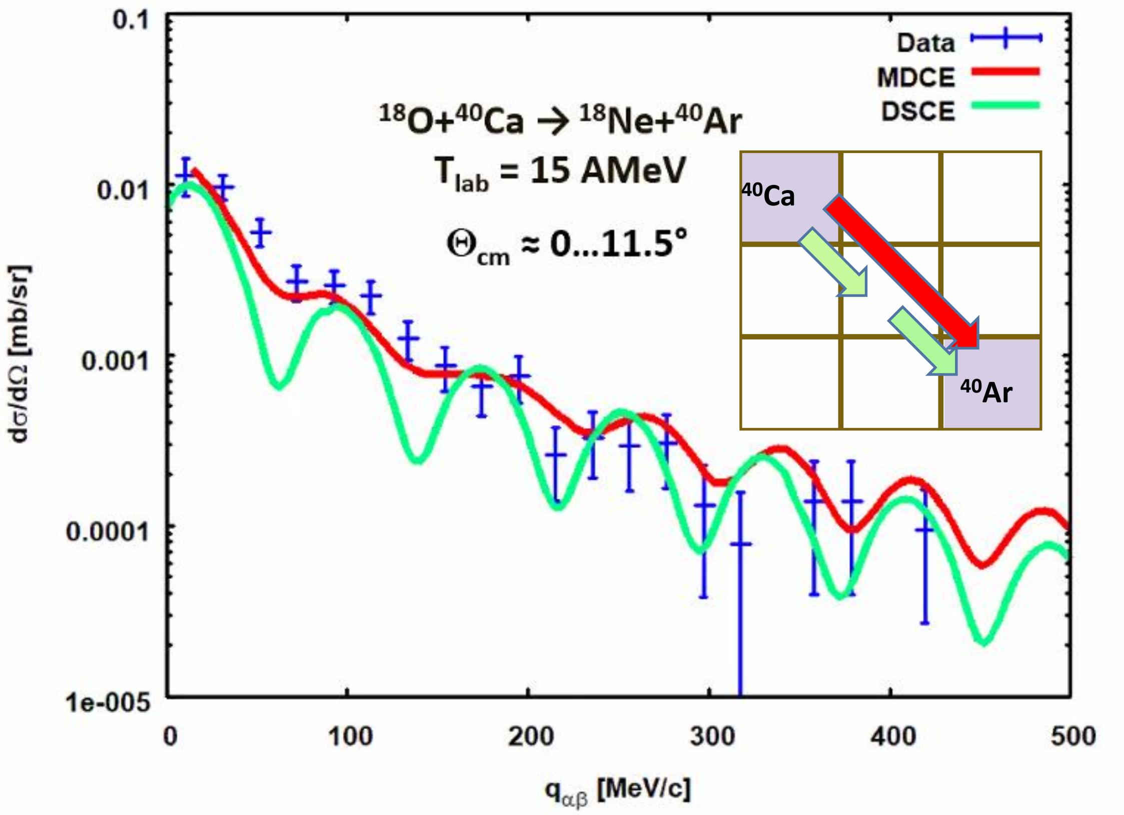
A. Spatafora et al. PRC 110, 064612 (2024)

B. Urazbekov et al. PRC 111, 044603 (2025)

Double charge exchange reaction



$\sigma_{g.s.\rightarrow g.s.}$ = 35 ± 2 nb



2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$

1-step MDCE: ^{40}Ca(0^+)→^{40}Ar([$n^{-2}p^2$]0^+) : J=0+ with L=S=0 & $[L=2 \times S=2]_{0+}$

➢ ISI and FSI ion-ion interaction from double folding (constrained by elastic and inleastic data)
➢ QRPA transition densities for microscopic form factors
➢ **One-step DWBA for MDCE** and **two-step DWBA for DSCE**

H. Lenske et al., Universe 10, 93 (2024)

Caveat:

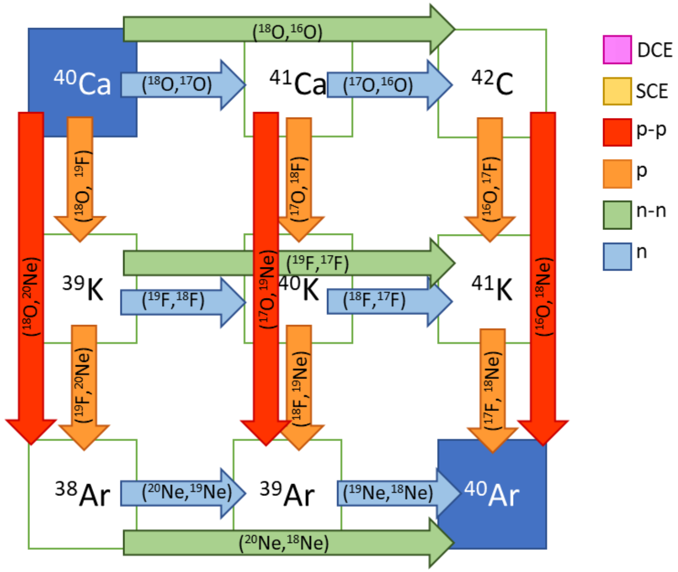
- Only Nπ-correlations included
- Off-shell momentum structure approximated with on-shell component (T-matrix instead of G-matrix)

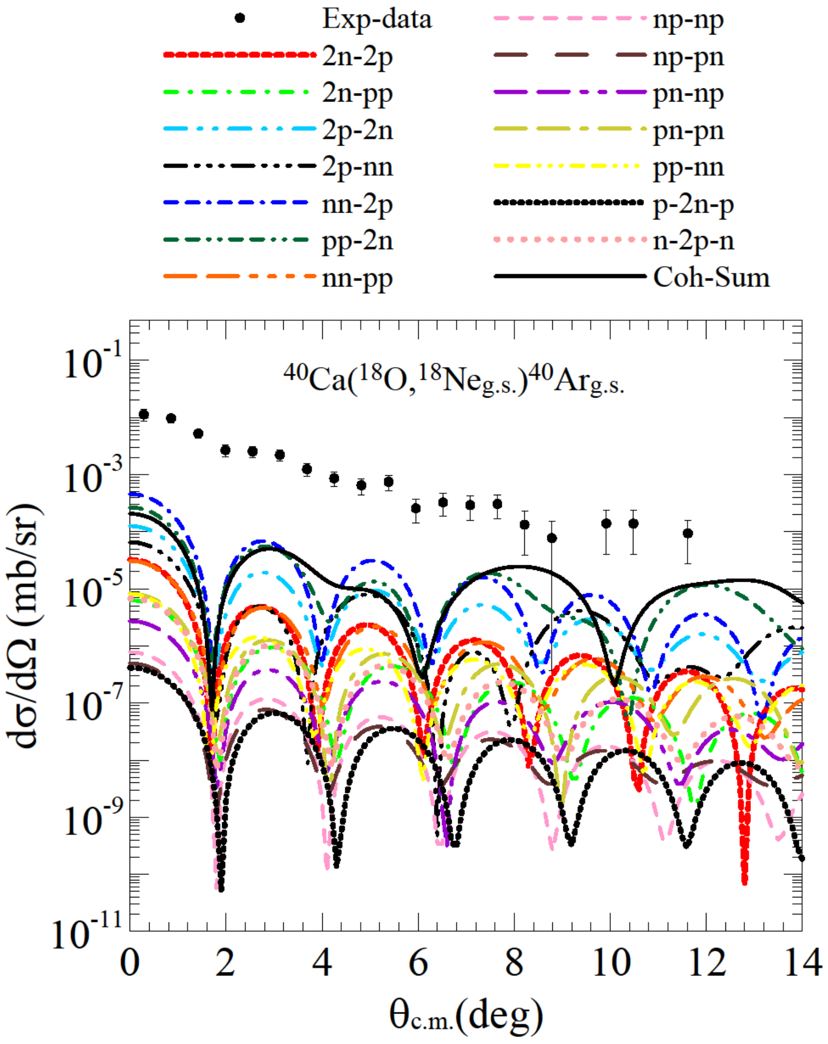
Key information from DCE data

✓ G.s. to g.s. transition isolated
✓ Good description of the data

Double charge exchange reaction

J.L. Ferreira et al., PRC 111, 014630 (2025)





The TDCE multi-nucleon transfer mechanisms

- ✓ **ISI and FSI** ion-ion interaction extracted **from elastic and inelastic data**
- ✓ **Shell model amplitudes** and deformations as for transfer calculations
- ✓ **Four-step DWBA and CCBA** calculations in large model spaces

TDCE contribution is negligible!

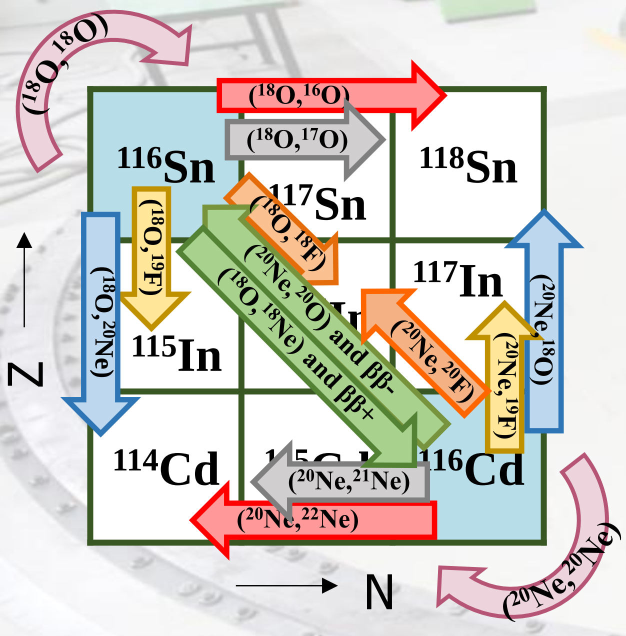
DCE on $0\nu\beta\beta$ candidates

NUMEN experimental runs

erc INFN LNS NUMEN

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

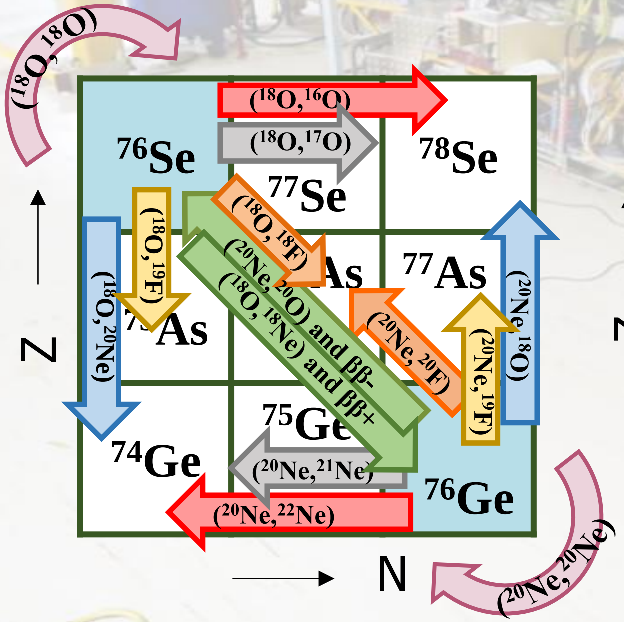
@ 15 AMeV
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



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)
C.Eke et al. Res. In Phys. 67, 108037 (2024)

^{76}Ge – ^{76}Se case

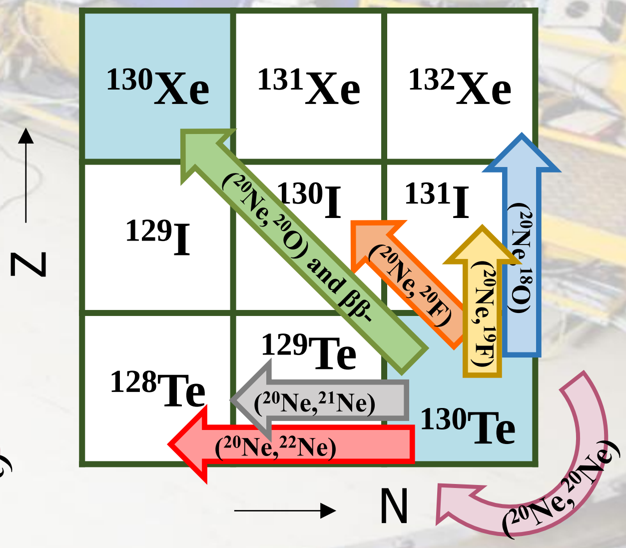
@ 15 AMeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



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
I. Ciraldo et al., PRC 109, 024615 (2024)

^{130}Te – ^{130}Xe case

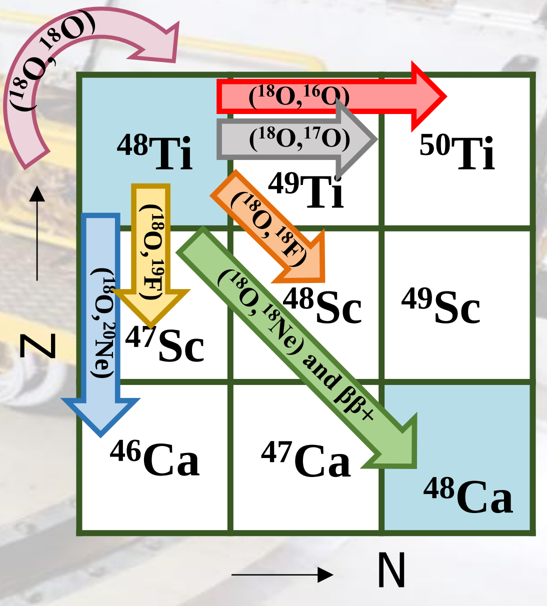
@ 15 AMeV
- ^{20}Ne + ^{130}Te



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)

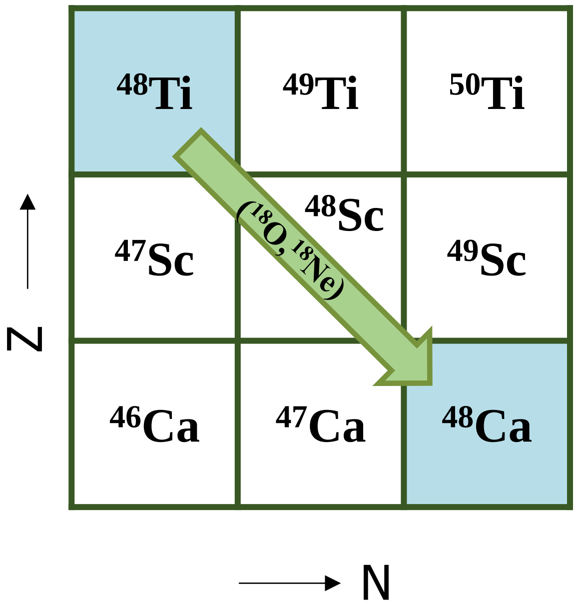
^{48}Ca - ^{48}Ti case

@ 15 AMeV
- ^{18}O + ^{48}Ti

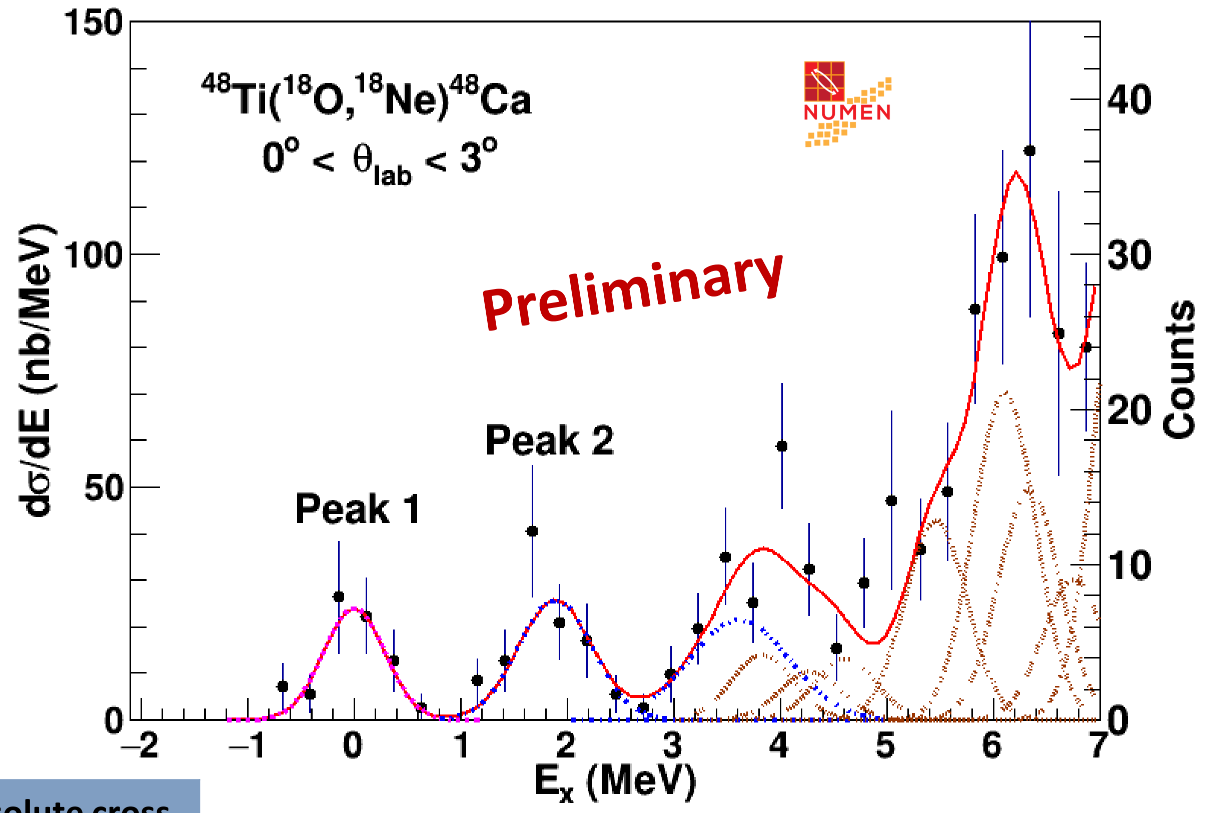


O. Sgouros et al., PRC 104, 034617 (2021)
O.- Sgouros et al., PRC 108, 044611 (2023)
G.A. Brischetto et al., PRC 109, 014604 (2024)

DCE experimental results



DCE reaction ^{48}Ti(^{18}O,^{18}Ne)^{48}Ca

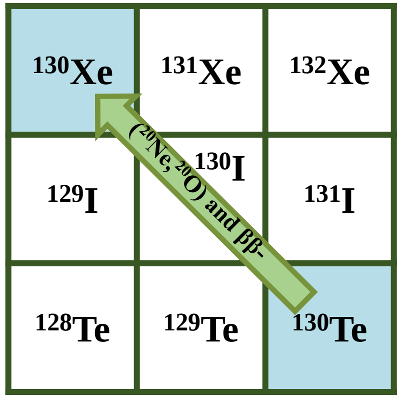


State (MeV)	Counts	Absolute cross section (nb)
$^{48}Ca_{gs}$ (0^+) + $^{18}Ne_{gs}$ (0^+)	24	**20 ± 4**
$^{48}Ca_{gs}$ (0^+) + $^{18}Ne_{1.89}$ (2^+)	33	28 ± 5

- g.s. → g.s. transition isolated (resolution ~ 680 keV FWHM)
- Absolute cross section measured
- Zero-degree measurement

O. Sgouros et al.

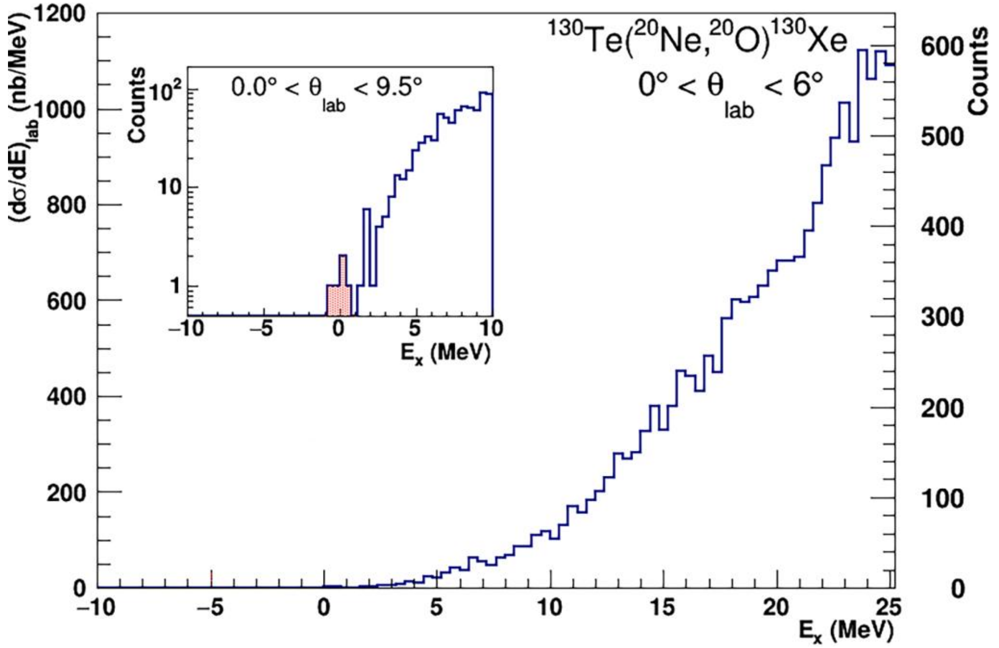
DCE experimental results



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

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

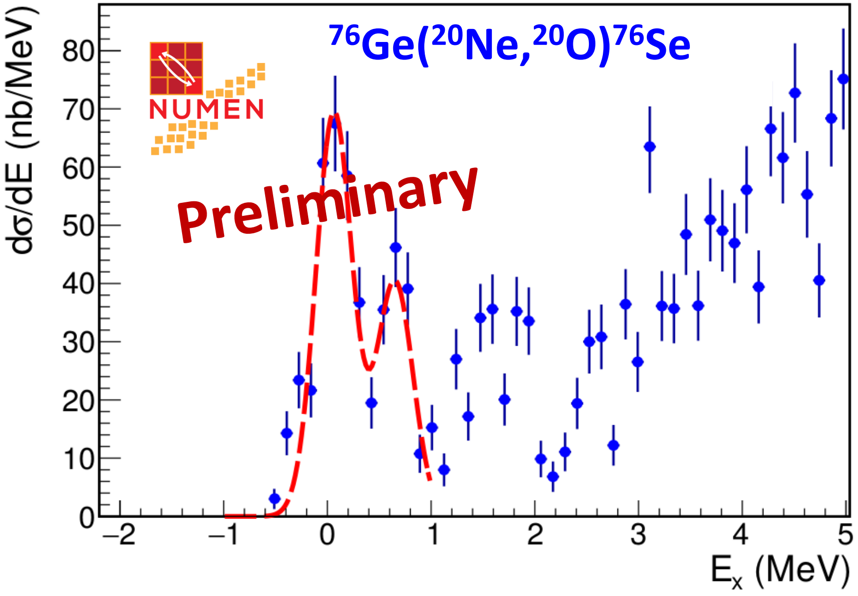
$\sigma_{-1\,MeV \rightarrow 1\,MeV}$ = **13 nb** ([3,18] nb at 95% CL)

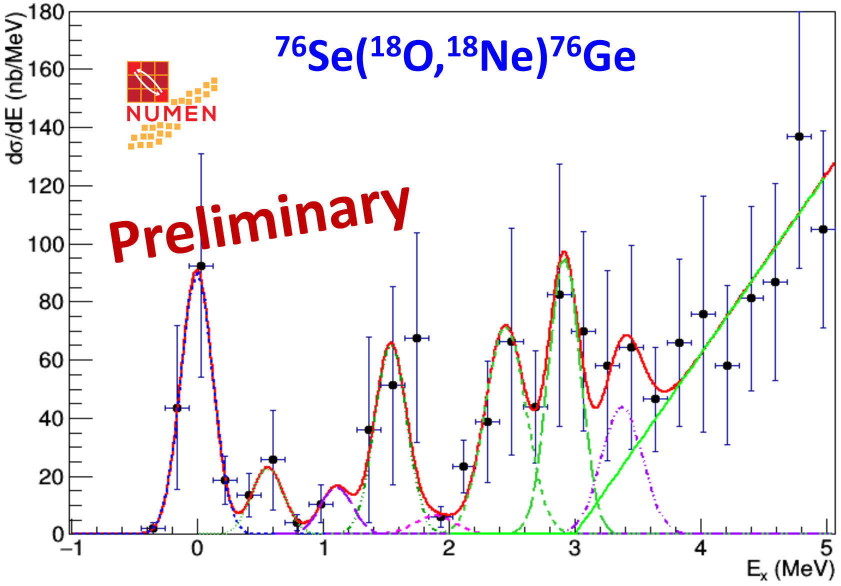


V. Soukeras et al., Results in Physics 28, 104691 (2021)

DCE experimental results

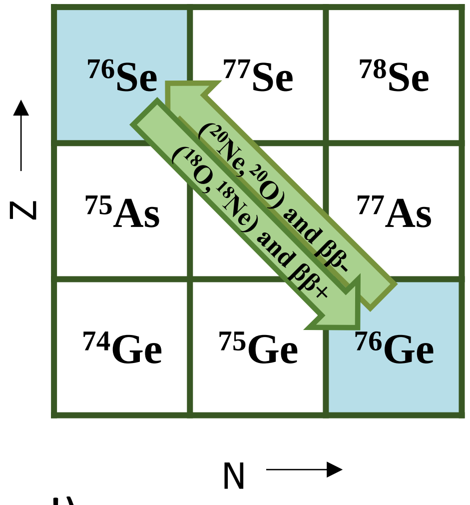
^{76}Ge – ^{76}Se case





$0° < \theta_{lab} < 8°$

$\sigma_{g.s.\rightarrow g.s.}$ **=30 ± 4 nb**



- Same cross sections for different directions
- Similar distorsion factors

→ Same NME (encouraging test of time invariance!)

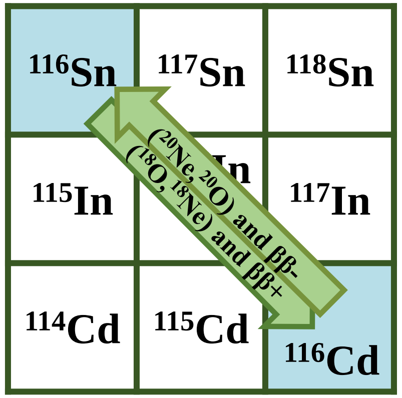
$\sigma_{g.s.\rightarrow g.s.}$ **=29 ± 6 nb**

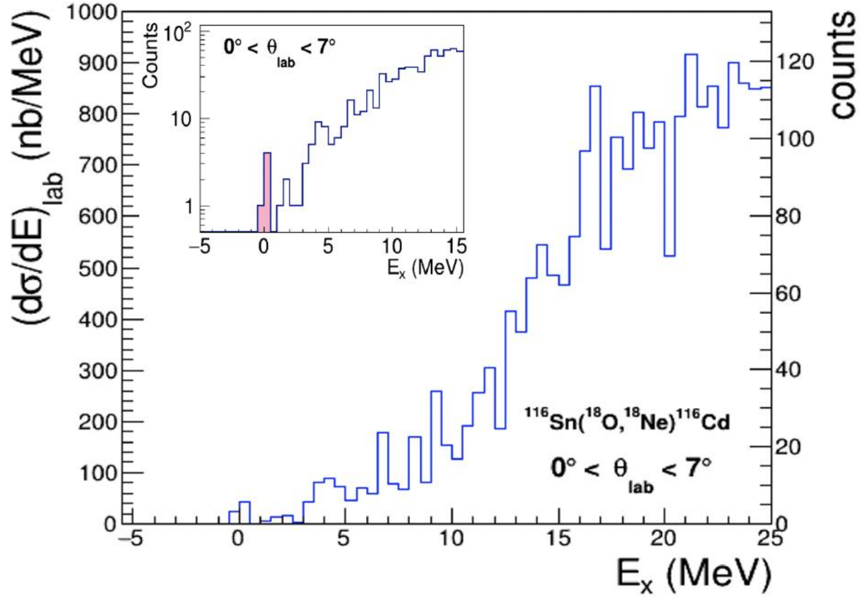
Warning:

- Only one case?
- Reaction calculations in progress

DCE experimental results

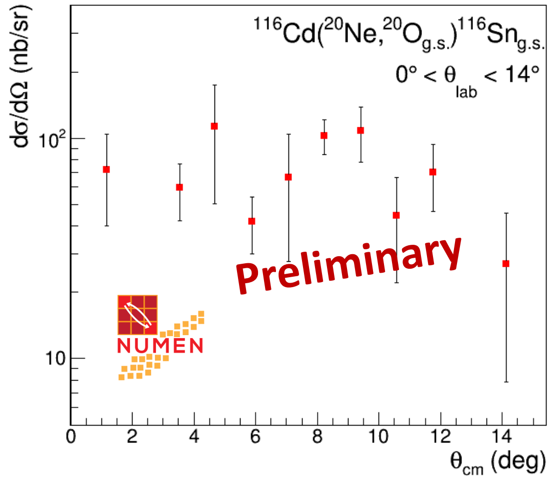
^{116}Cd – ^{116}Sn case

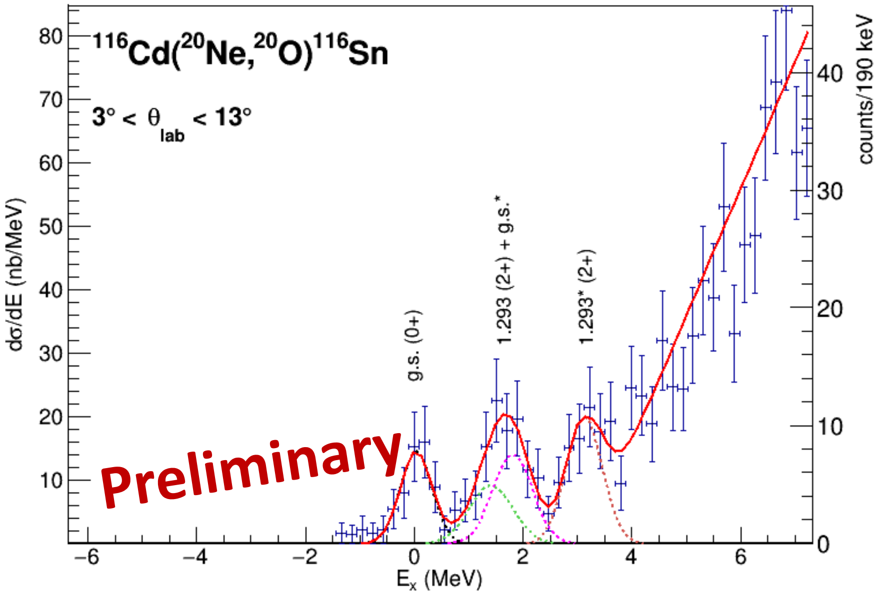




$\sigma_{-1\ MeV \rightarrow 1\ MeV}$ = **36 nb** ([4,46] nb at 95% CL)

C. Eke et al. Res. In Phys. 67, 108037 (2024)





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

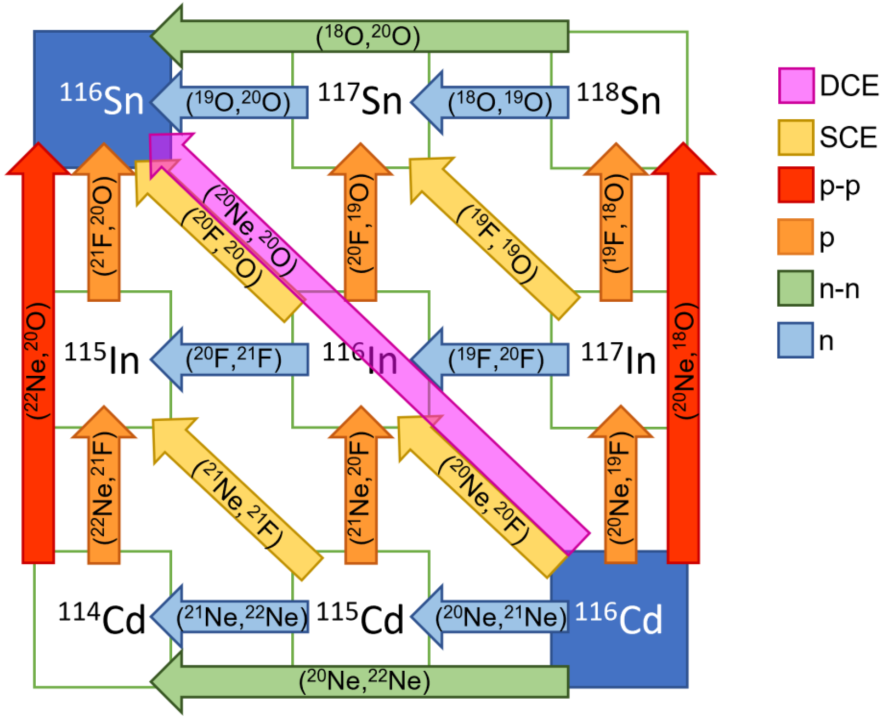
S. Calabrese et al., NIM A 980 (2020) 164500

Similar to the ^{76}Ge-^{76}Se case

TDCE mechanism

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

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



Mechanism	Int. cross section (nb) $^{20}O_{g.s.}(0^+) + ^{116}Sn_{g.s.}(0^+)$
$2p-2n$	$1,28 \times 10^{-4}$
$2n-2p$	$3,13 \times 10^{-4}$
$p-p-n-n$	$6,63 \times 10^{-5}$
$n-n-p-p$	$1,00 \times 10^{-5}$
$p-p-2n$	$4,15 \times 10^{-5}$
$n-n-2p$	$1,72 \times 10^{-6}$
$2p-n-n$	$9,26 \times 10^{-5}$
$2n-p-p$	$2,66 \times 10^{-4}$
$p-n-p-n$	$1,38 \times 10^{-7}$
$p-n-n-p$	$1,15 \times 10^{-6}$
$n-p-n-p$	$2,53 \times 10^{-7}$
$n-p-p-n$	$1,69 \times 10^{-7}$
$p-2n-p$	$2,51 \times 10^{-7}$
$n-2p-n$	$5,71 \times 10^{-6}$

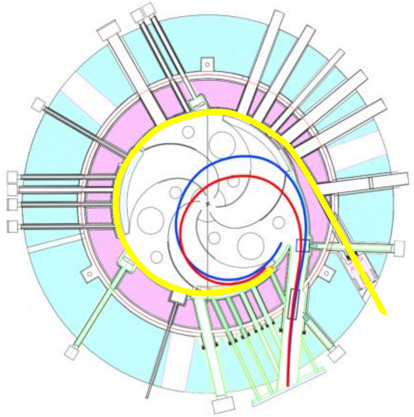
Incoh. Sum **9.60×10^{-4}**

Exp. DCE cross section 12 ± 2 nb

Negligible contribution of TDCE on the diagonal DCE process

Present limitations and perspectives

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



CS extraction by stripping

In the last years NUMEN studied only few systems

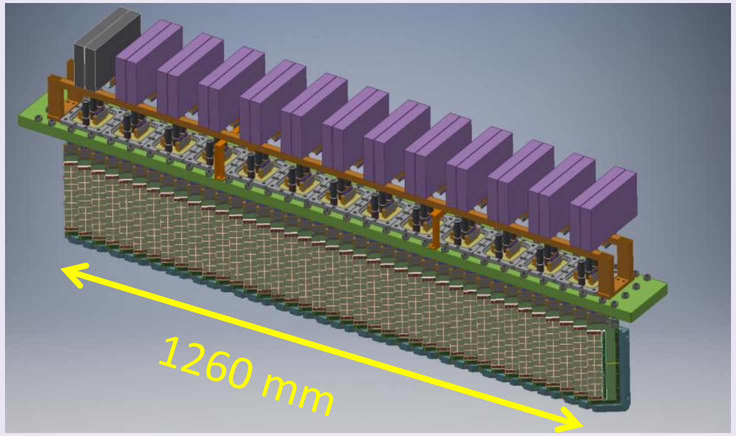
Much higher beam current is needed

POT lns

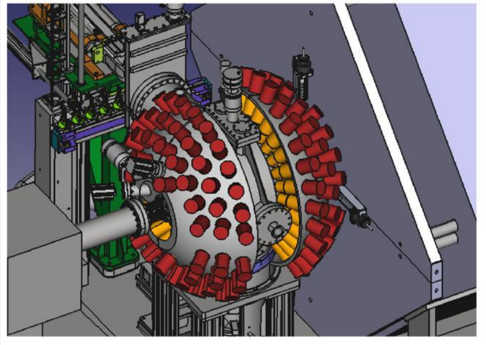
Project of **upgrade of the LNS Cyclotron (from 100 W to 5-10 kW) and infrastructures** (triggered by NUMEN physics case) funded by national grant (PON)

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

New tracker for the FPD (**THGEM** technology)



New PID-wall for the FPD (720 **SiC + CsI telescopes**)



New gamma-ray calorimeter (110 **LaBr3 scintillators**)

Conclusions and Outloooks

Use of HI-DCE reaction for 0νββ decay

- Second order isospin excitations of nuclei bridge the gap between nuclear and neutrino physics
- Heavy-ion DCE reactions can significantly contribute to this research field, providing that nuclear structure and reaction aspects are accurately and consistently addressed
- 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

Outlooks

- **MAGNEX** FPD @ iThemba LABS
- New measurements at iThemba LABS on ^{18}O + ^{76}Se

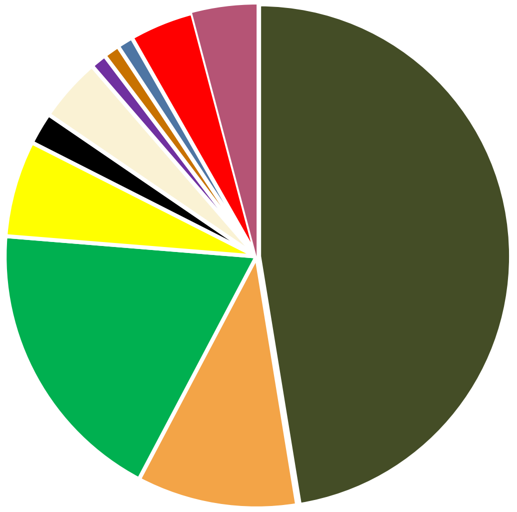
- CS and MAGNEX FPD **upgrade** ongoing for reaching high intensity
- Extensive exploration of all the nuclei candidate for 0νββ decay with the **high intensity beams**

The NUMEN collaboration

(NUclear Matrix Elements for Neutrinoless double beta decay)

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)

97 Researchers
34 Institutions
11 Countries



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Thank you