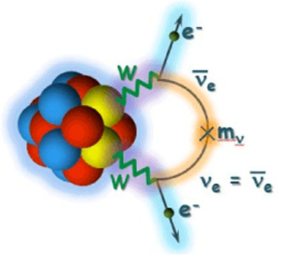
Heavy-ion induced direct reactions in a multi-channel approach: new results from the NUMEN project

F. Cappuzzello
University of Catania and INFN LNS

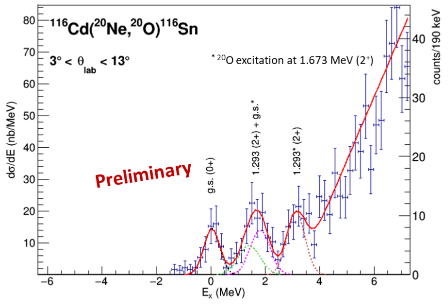
HINPw7

7^{th} Workshop of the Hellenic Institute of Nuclear Physics on Nuclear Structure, Astrophysics and Reaction Dynamics

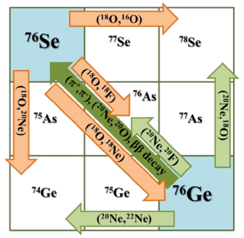
Outline



- ✓ The problem of $0\upsilon\beta\beta$-decay nuclear matrix elements



- ✓ The study of double charge exchange @ INFN-LNS (NUMEN, NURE)



- ✓ The multi-channel vision

- ✓ The NUMEN roadmap and its matching with POT-LNS and nuclear physics mid-term plans in Italy

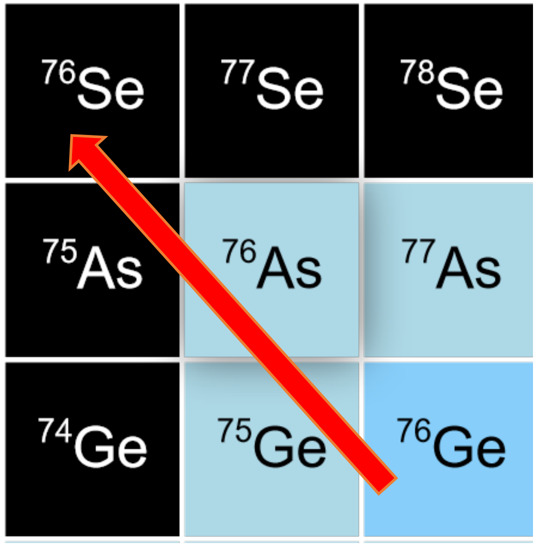
ββ decay

Open problems in modern physics:

Neutrino absolute mass scale

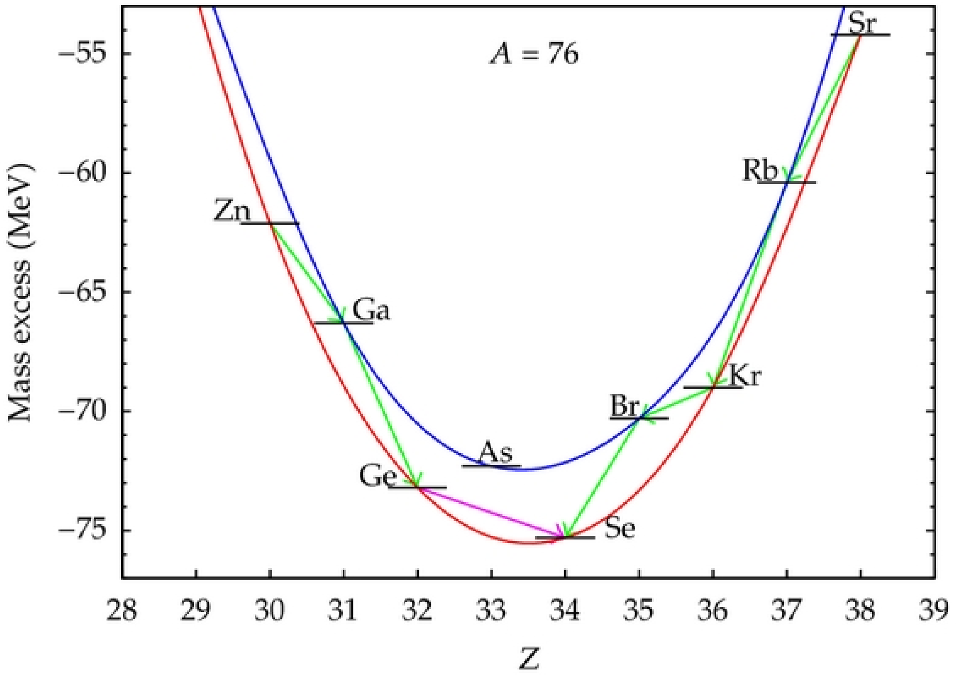
Neutrino nature

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



$$^{A}_{Z}X_{N} \rightarrow {}_{Z+2}^{\;\;A}Y_{N-2} + 2e^{-} + (2\bar{\nu})$$

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



- 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 Physycs **2023**, 95, 025002

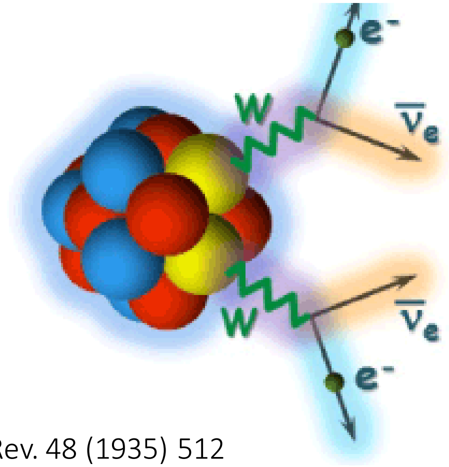
✓ Process mediated by the **weak interaction**

✓ Observable in even-even nuclei where the **single β-decay** is energetically **forbidden**

Double β-decay

Two-neutrino double beta decay

Observed in 12 nuclei since 1987



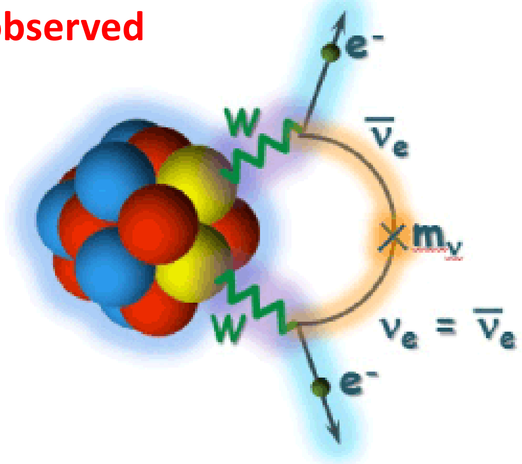
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. **Within standard model**
2. **$T_{1/2} \approx 7*10^{18}$ to $2*10^{21}$ yr**

$$1/T^{2\nu}_{1/2}(0^+ \to 0^+) = G_{2\nu}\left|M^{\beta\beta 2\nu}\right|^2$$

Neutrinoless double beta decay

Not yet observed



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

1. **Beyond standard model**
2. **Violation of lepton number conservation**
3. **Access to effective neutrino mass**
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**

$$1/T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{0\nu}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

The Nuclear Matrix Element

New physics for the next decades

requiring

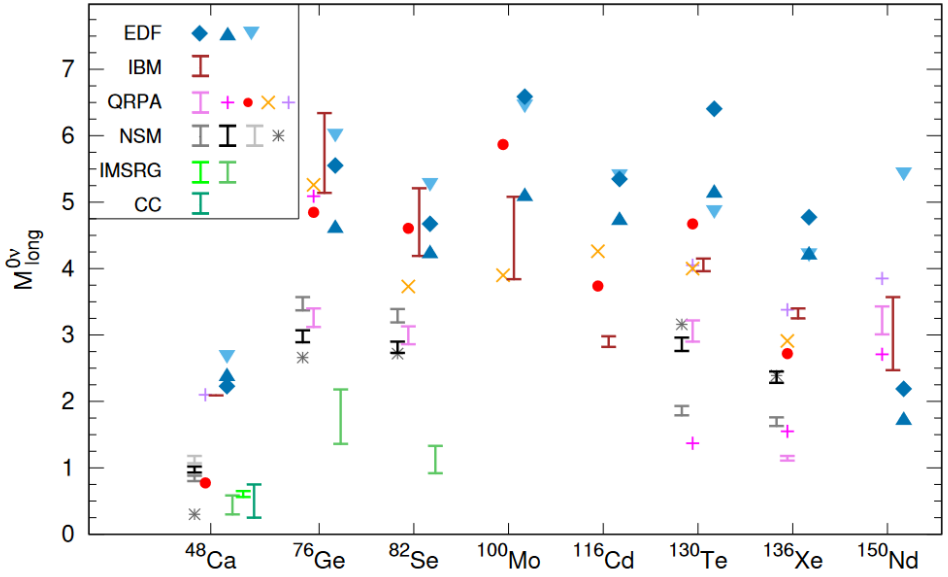
Nuclear Matrix Element (NME)!

$$\left|M_{\varepsilon}^{\beta\beta0\nu}\right|^{2} = \left|\left\langle \Psi_f \middle| \hat{O}_{\varepsilon}^{\beta\beta0\nu} \middle| \Psi_i \right\rangle\right|^{2}$$

- ✓ NMEs are not physical observables
- ✓ Much work on the **transition operator**, now including all the known short-range weak interaction physics (see F.F. Deppisch et al., PRD 102, 095016 (2020))
- ✓ The challenge is the description of the **nuclear many body states**

- ✓ **Calculations** (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF, ab-initio …..

State of the art NME calculations



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

Support from the experiments

Measurements (not yet strongly constraining the **$0\nu\beta\beta$** NME):

✓ β-decay and **$2\nu\beta\beta$**-decay

1st order isospin probes

2nd order isospin probes

✓ **(π^+, π^-)**, single charge exchange (SCE) **$(^3He,t)$, $(d,^2He)$, HI-SCE, electron capture,** transfer reactions, **μ-nucleus scattering**, **γ-ray spectroscopy, double γ-decay etc..**

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

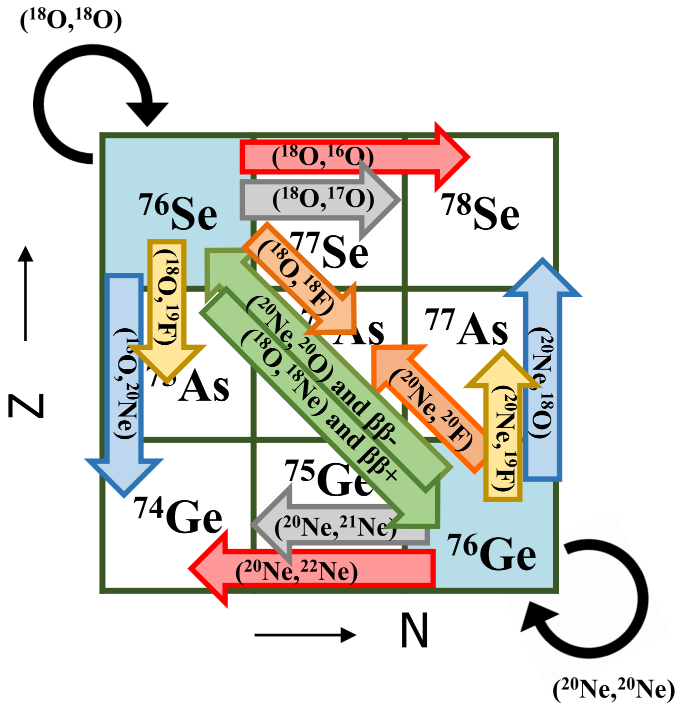
A new experimental tool

Heavy-Ion induced Double Charge Exchange reactions (DCE) as surrogate processes of 0νββ to stimulate in the laboratory the same nuclear transition (g.s. to g.s.)

The NUMEN project: NUclear **M**atrix **E**lements for **N**eutrinoless double beta decay

The NURE project: NUclear **RE**actions for for **n**eutrinoless double beta decay

- **DCE on isotopes of interest for 0νββ** via **(^{20}Ne,^{20}O)** ($\beta\beta^-$) and **(^{18}O,^{18}Ne)** $\beta\beta^+$ from 15 MeV/u to 60 MeV/u
- **Complete network** of reactions competing with the DCE and partly feeding DCE via multi-step processes: 1p-, 2p-, 1n-, 2n-transfer, SCE, (elastic and inelastic scattering)



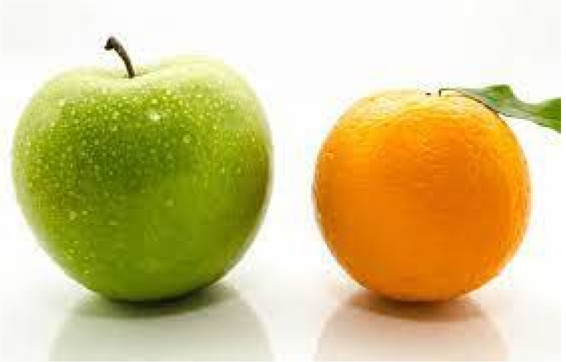
F. Cappuzzello et al., Eur. Phys. Jour. A (2018) 54:72

F. Cappuzzello et al., Prog. in Part. and Nucl. Phys. 128 (2023) 103999

Heavy-ion DCE vs 0νββ

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Decay vs reaction **dynamics**
- DCE includes **sequential** transfer **mechanism**



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:** Short-range 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**: Constraints on the theoretical determination of quenching phenomena on $0\nu\beta\beta$
- **Off-shell propagation** through virtual intermediate channels

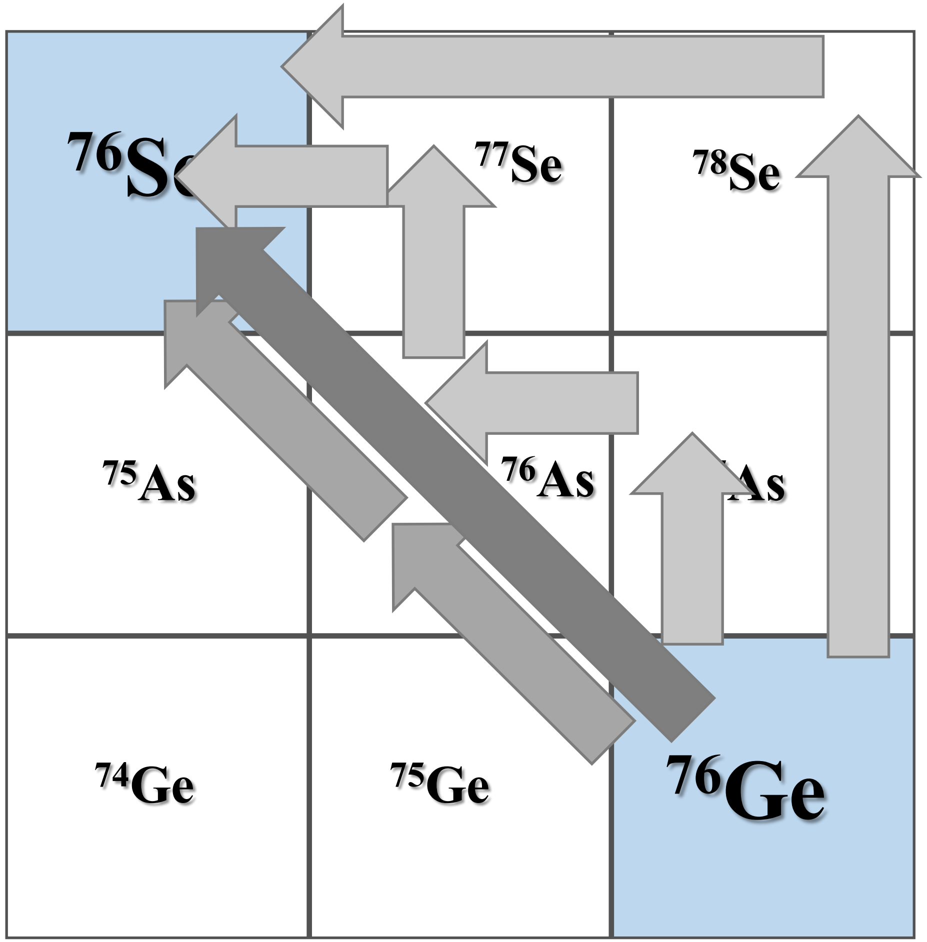
The DCE reaction mechanism

Heavy ion DCE can proceed:

1) **One-step DCE - Two-nucleon mechanism (MDCE)**: relying on short range NN correlations, leading to the correlated exchange of two charged isovector mesons between projectile and target.
H.Lenske et al., PPNP 109 (2019) 103716 and H.Lenske et al., Universe (2024), 10, 202

2) **Two-step DCE - Double single charge exchange (DSCE)**: two consecutive single charge exchange processes mediated by NN isovector interaction.
J.I.Bellone et al., PLB 807 (2020) 135528, H.Lenske et al., Universe 7 (2021) 98 and H.Lenske et al., Universe (2024), 10, 93

3) **High-order sequential multi-nucleon transfer** mediated by mean field.
J.L. Ferreira et al. PRC 105 (2022) 014630



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

F. Cappuzzello et al. Prog. Part. and Nucl. Phys., 128 (2023) 103999

Recent literature on HI-DCE

Progress in Particle and Nuclear Physics 109 (2019) 103716

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy ion charge exchange reactions as probes for nuclear β-decay

Horst Lenske [a,d,*], Francesco Cappuzzello [b,c,d], Manuela Cavallaro [b,d], Maria Colonna [b,d]

[a] Institut für Theoretische Physik, JLU Gießen, Gießen, Germany
[b] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy
[c] Dipartimento di Fisica e Astronomia "E. Majorana", Università di Catania, Catania, Italy
[d] The NUMEN Collaboration, LNS Catania, Catania, Italy

Progress in Particle and Nuclear Physics 128 (2023) 103999

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

Shedding light on nuclear aspects of neutrinoless double beta decay by heavy-ion double charge exchange reactions

F. Cappuzzello [a,b], H. Lenske [c], M. Cavallaro [b,*], C. Agodi [b], N. Auerbach [d], J.I. Bellone [a,b], R. Bijker [e], S. Burrello [f], S. Calabrese [b], D. Carbone [b], M. Colonna [b], G. De Gregorio [g,l], J.L. Ferreira [h], D. Gambacurta [b], H. García-Tecocoatzi [e], A. Gargano [g], J.A. Lay [i,j], R. Linares [h], J. Lubian [h], E. Santopinto [k], O. Sgouros [b], V. Soukeras [a,b], A. Spatafora [a,b], on behalf of the NUMEN collaboration

universe — *H.Lenske et al., Universe (2024), 10, 93* — MDPI

Article

Induced Isotensor Interactions in Heavy-Ion Double-Charge-Exchange Reactions and the Role of Initial and Final State Interactions

Horst Lenske [1,*,†], Jessica Bellone [2,†], Maria Colonna [2,†], Danilo Gambacurta [2,†] and José-Antonio Lay [3,4,†]

1 Institut für Theoretische Physik, Justus–Liebig–Universität Giessen, D-35392 Giessen, Germany
2 Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, I-95123 Catania, Italy; bellone@lns.infn.it (J.B.); colonna@lns.infn.it (M.C.); gambacurta@lns.infn.it (D.G.)
3 Departamento de FAMN, Facultad de Física, Universidad de Sevilla, Apartado 1065, E-41080 Sevilla, Spain; lay@us.es
4 Instituto Interuniversitario Carlos I de Física Teórica y Computacional (iC1), Apdo. 1065, E-41080 Sevilla, Spain
* Correspondence: horst.lenske@physik.uni-giessen.de; Tel.: +49-641-9933361
† Current address: The NUMEN Collaboration, LNS Catania, I-95123 Catania, Italy.

universe — *H.Lenske et al., Universe (2024), 10, 202* — MDPI

Article

Theory of Majorana-Type Heavy Ion Double Charge Exchange Reactions by Pion–Nucleon Isotensor Interactions

Horst Lenske [1,*,†], Jessica Bellone [2,†], Maria Colonna [2,†] and Danilo Gambacurta [2,†]

1 Institut für Theoretische Physik, Justus–Liebig–Universität Giessen, D-35392 Giessen, Germany
2 Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, I-95123 Catania, Italy; bellone@lns.infn.it (J.B.); colonna@lns.infn.it (M.C.); gambacurta@lns.infn.it (D.G.)
* Correspondence: horst.lenske@physik.uni-giessen.de; Tel.: +49-641-9933361
† The NUMEN Collaboration, LNS Catania, I-95123 Catania, Italy.

The NUMEN collaboration

https://web.infn.it/NUMEN/index.php/it/
F. Cappuzzello et al., Eur. Phys. J. A (2018) 54: 72

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

89 Researchers
33 Institutions
13 Countries

Proponents: C. Agodi, J. Bellone, S. Brasolin, S. Burrello, G.A. Brischetto, M.P. Bussa, D. Calvo, F. Cappuzzello, D. Carbone, G. Castro, M. Cavallaro, I. Ciraldo, M. Colonna, G. D'Agostino, C. De Benedictis, G. De Gregorio, C. Ferraresi, P. Finocchiaro, M. Fisichella, S. Gallian, D. Gambacurta, C. Garofalo, H. Garcia-Tecocoatzi, A. Gargano, L. La Fauci, G. Lanzalone, A. Lavagno, C. Lombardo, P. Mereu, L. Neri, L. Pandola, A. Pitronaci, A.D. Russo, E. Santopinto, D. Sartirana, O. Sgouros, V. Soukeras, A. Spatafora, D. Torresi, S. Tudisco

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud , Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
Dipartimento di Fisica e Astronomia, Università di Catania, Italy
Dipartimento di Fisica, Università di Torino, Italy
Dipartimento di Fisica, Università di Napoli Federico II, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Italy
DISAT, Politecnico di Torino, Italy
DIMEAS, Politecnico di Torino, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy
Università degli Studi di Enna "Kore", Italy

L.H. Avanzi, E.N. Cardozo, E.F. Chinaglia, K.M.Costa, J.L. Ferreira, R. Linares, J. Lubian, S.H. Masunaga, N.H. Medina, M. Moralles, J.R.B. Oliveira, T.M. Santarelli, R.B.B. Santos, M.A. Guazzelli, V.A.B. Zagatto

Centro Universitario FEI Sao Bernardo do Campo, Brazil
Universidade Federal Fluminense, Brazil
Universidade de Sao Paulo, Brazil
Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN, Brazil

L. Acosta, P. Amador-Valenzuela, R. Bijker, E.R. Chávez Lomelí, A. Huerta-Hernandez, D. Marín-Lámbarri, H. Vargas Hernandez, R.G. Villagràn

Instituto de Física, Universidad Nacional Autónoma de México, Mexico
Instituto Nacional de Investigaciones Nucleares, Mexico
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico

I. Boztosun, H. Djapo, C. Eke, S. Firat, A. Hacisalihoglu, Y. Kucuck, S.O. Solakcı, A. Yildirin

Department of Physics, Akdeniz University, Turkey
Ankara University of Physics, Institute of Accelerator Technologies, Turkey
Institute of Natural Sciences, Karadeniz Teknik University, Turkey

L.M. Donaldson, T. Khumalo, R. Neveling, L. Pellegri

School of Physics, University of the Witwatersrand, Johannesburg, South Africa
iThemba Laboratory for Accelerator Based Sciences, Faure, Cape Town, South Africa

H. Lenske, P. Ries, N. Pietralla, V. Werner

Department of Physics, University of Giessen, Germany
Institut fur Kernphysik, Technische Universitat Darmstadt, Germany

S. Koulouris, A. Pakou, G. Souliotis

Department of Physics, University of Ioannina, Greece
Department of Chemistry, National and Kapodistrian University of Athens, Greece

J. Ferretti, Z.J. Kotila,

University of Jyväskylä, Jyväskylä, Finland

F. Delaunay

LPC Caen, Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, France
IPN Orsay, CNRS/IN2P3, France

N. Auerbach

School of Physics and Astronomy Tel Aviv University, Israel

H. Petrascu,

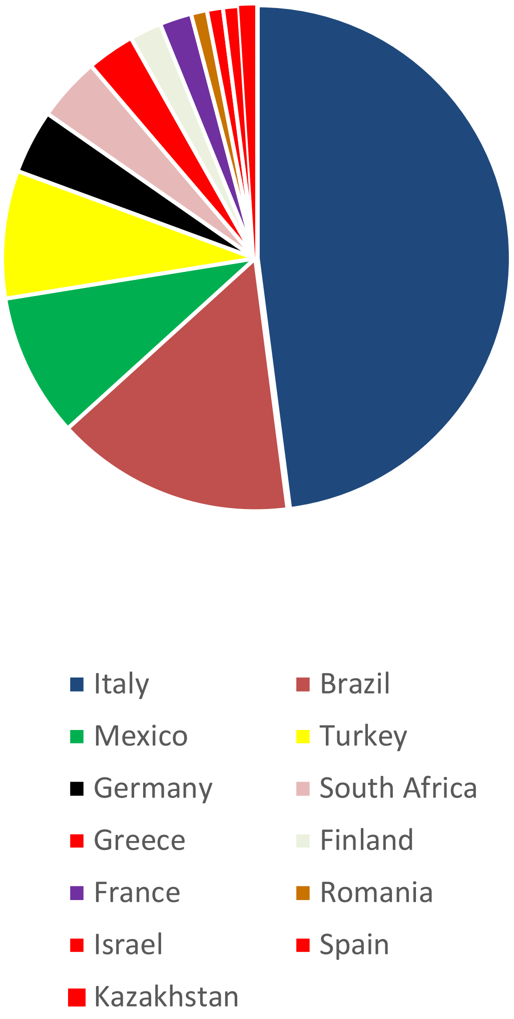
IFIN-HH, Bucarest, Romania

J.A. Lay

Departamento de FAMN, University of Seville, Spain

B. Urazbekov

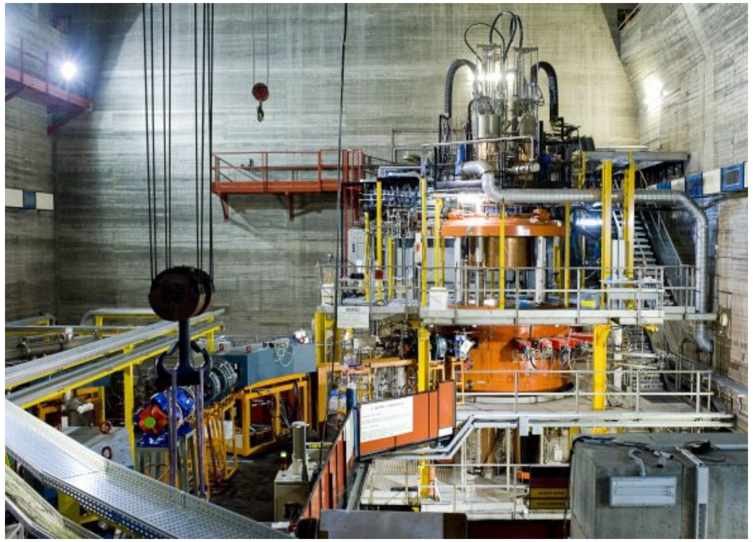
L.N. GUMILYOV EURASIAN NATIONAL UNIVERSITY,Kazakhstan

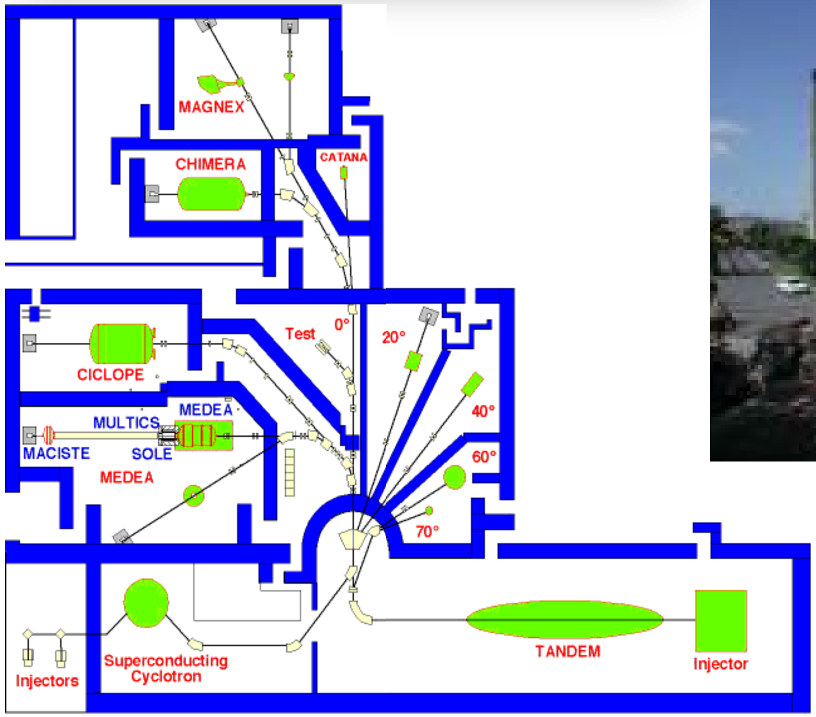


DCE @ INFN-LNS

The LNS laboratory in Catania

INFN
LNS





MAGNEX: a large acceptance QD magnetic spectrometer

- **The Quadrupole**: vertically focusing

(Aperture radius 20 cm, effective length 58 cm. Maximum field strength 5 T/m, *presently being upgraded to 6 T/m*)

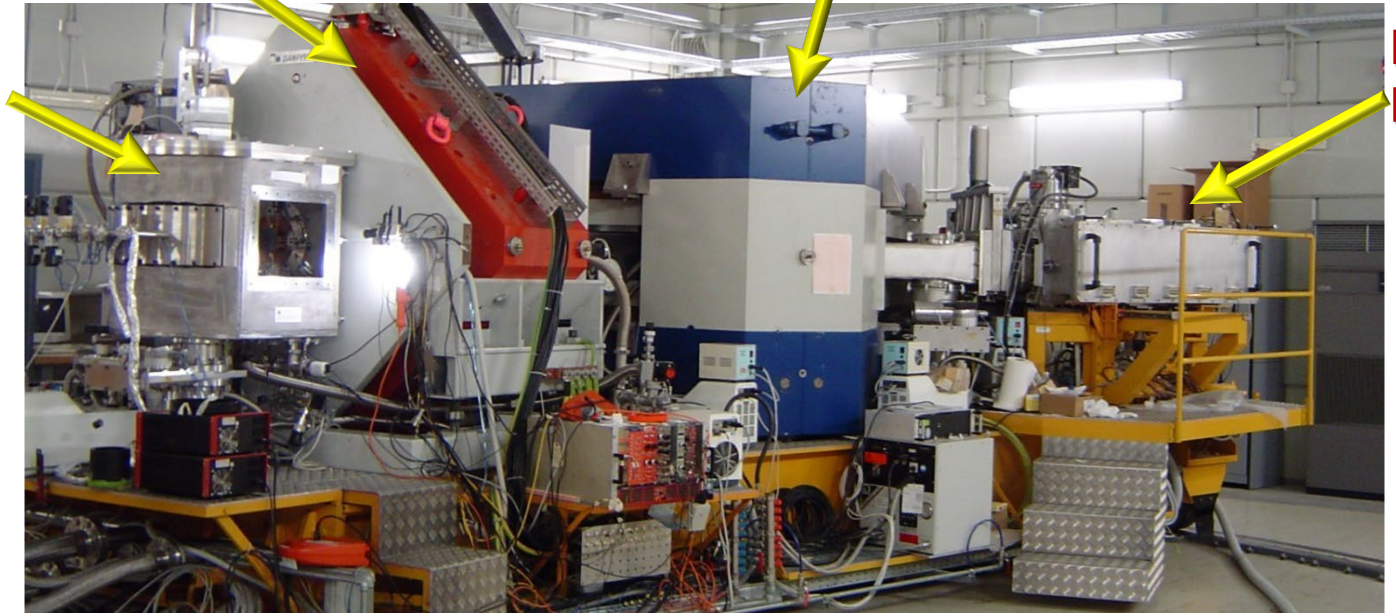
- **The Dipole**: momentum dispersion (and horizontal focus)

(Mean bending angle 55, radius 1.60 m. Maximum field ~ 1.15 T, *presently being upgraded to 1.38 T*)

F. Cappuzzello et al., Eur. Phys. Jour. A (2016) 52:167
M. Cavallaro et al., NIM B 463 (2020) 334–338

Optical characteristics	Measured values
Angular acceptance (Solid angle)	**$50\ msr$**
Angular range	**$-20° \div +85°$**
Momentum acceptance	**$-14\% \div +10\%$**
Momentum dispersion for $k = -0.104$	**$3.68\ (cm/\%)$**
Maximum magnetic rigidity	**$1.8\ Tm$***

*presently being upgraded to 2.2 Tm



Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.3°$
Mass $\Delta m/m \sim 1/300$

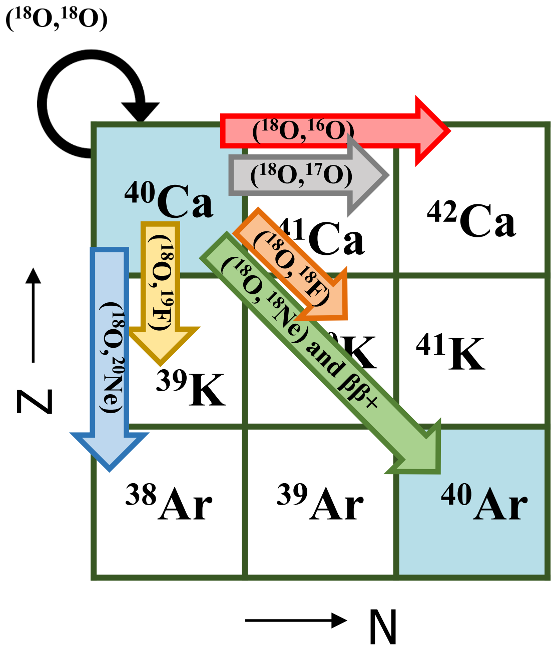
A **wide mass range** (from protons to medium-mass nuclei)

The multi-channel approach

The NUMEN multi-channel 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 $0\nu\beta\beta$**



Elastic scattering → nucleus-nucleus optical potential

Inelastic scattering → coupling strength to low-lying states

One-nucleon transfer reactions → single-particle spectroscopic amplitudes

Two-nucleon transfer reactions → strength 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)

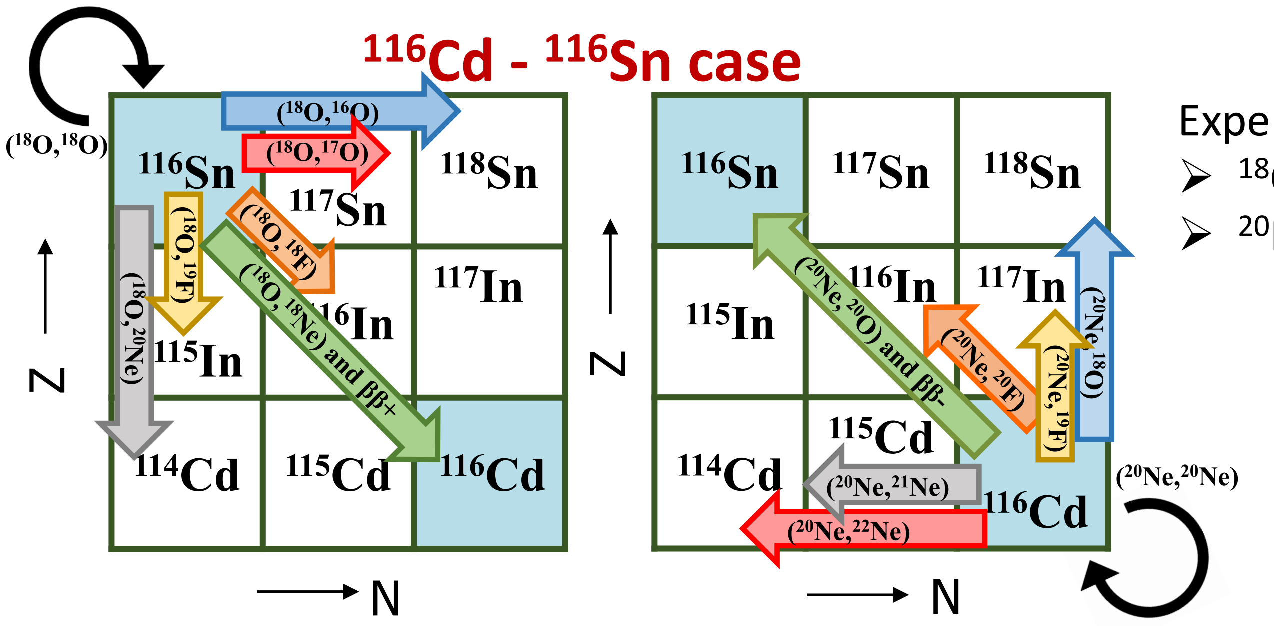
The NUMEN multi-channel vision

- ✓ 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 coupled channel approaches, largely reducing the need of free parameters in both nuclear structure and reaction models

An example

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



Experiments @ 15 MeV/A

- ➢ ^{18}O + ^{116}Sn
- ➢ ^{20}Ne + ^{116}Cd

Systems of interest for 0νββ already explored

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

@ 15 AMeV

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

^{76}Ge – ^{76}Se case

@ 15 AMeV

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

^{130}Te – ^{130}Xe case

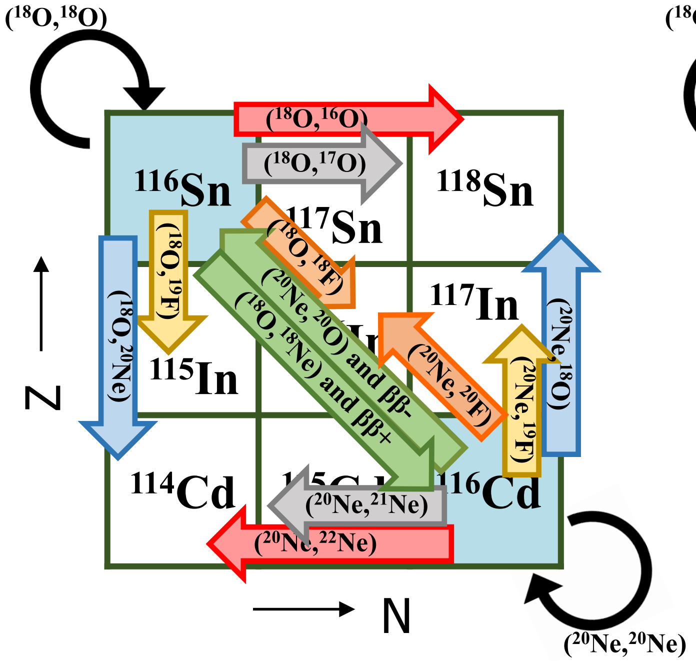
@ 15 AMeV

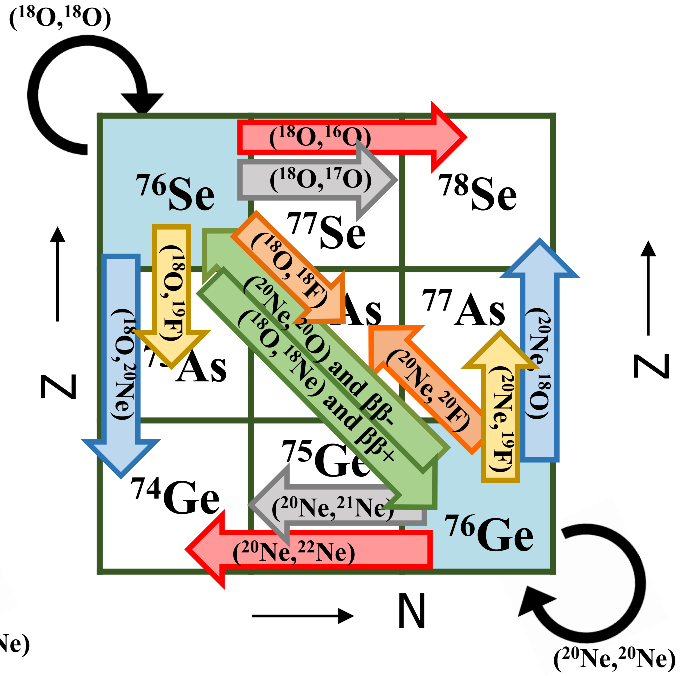
- ^{20}Ne + ^{130}Te

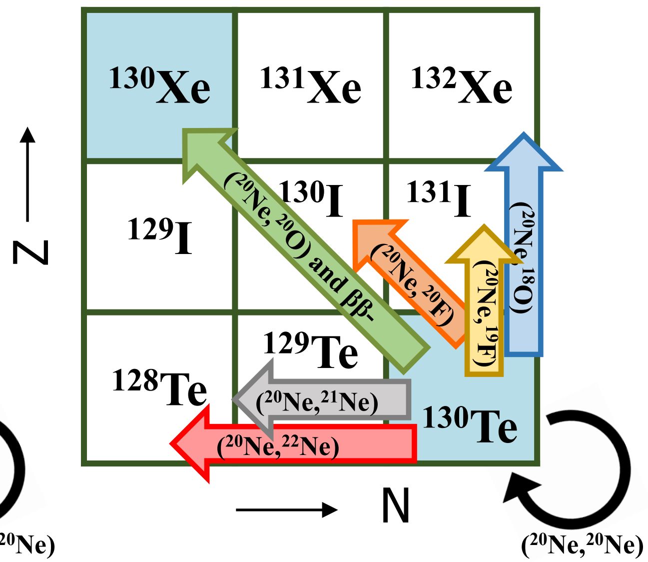
^{48}Ti – ^{48}Ca case

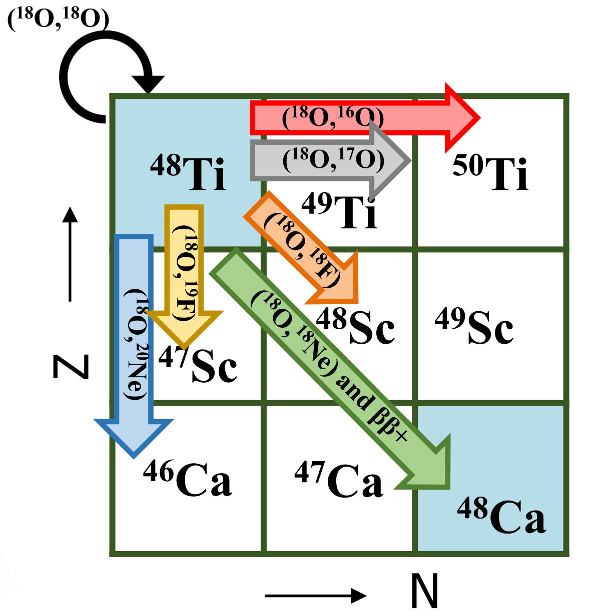
@ 15 AMeV

- ^{18}O + ^{48}Ti









- ✓ D. Carbone et al., PRC 102 (2020) 044606
- ✓ S. Calabrese et al., NIM A 980 (2020) 164500
- ✓ S. Burrello et al. PRC 105 (2022) 024616
- ✓ D. Carbone et al., Universe 7 (2021) 58
- ✓ J.L. Ferreira et al., PRC 105 (2022) 014630

- ✓ A.Spatafora et al., PRC 100 (2019) 034620
- ✓ L. La Fauci et al., PRC 104 (2021) 054610
- ✓ I. Ciraldo et al. PRC 105, (2022) 044607
- ✓ I. Ciraldo et al., PRC, 2024, 109(2), 024615

- ✓ V. Soukeras et al. Res. in Phys. 28 (2021) 104691
- ✓ D. Carbone et al., Universe 7 (2021) 58

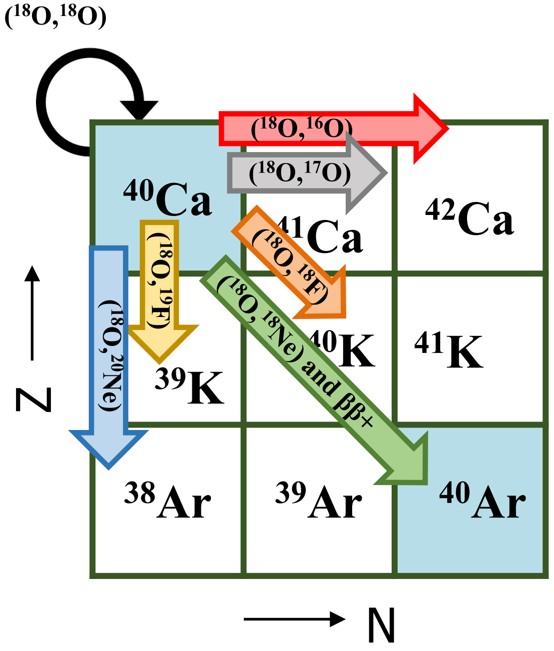
- ✓ O. Sgouros et al., PRC 104 (2021) 034617
- ✓ G. Brischetto et al., PRC 109 (2024) 014604
- ✓ O. Sgoursos et al. PRC 108 (2023) 044611

Other explored systems, relevant for the reaction mechanism

^{40}Ca – ^{40}Ar case

@ 15 AMeV

- ^{18}O + ^{40}Ca

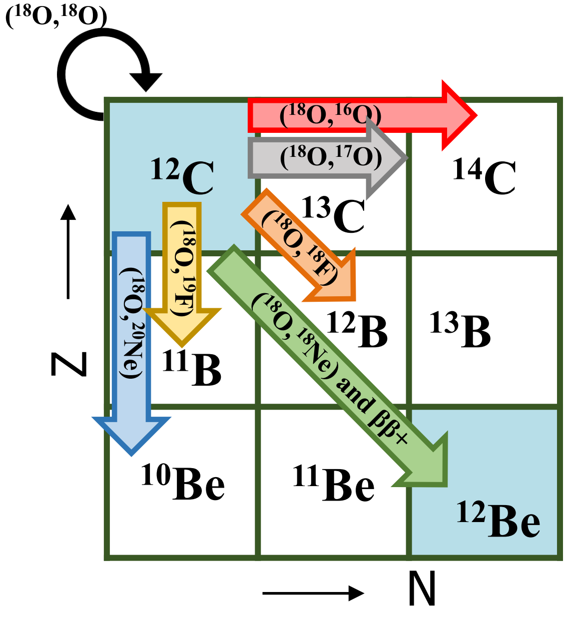


- ✓ M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815
- ✓ S. Calabrese et al., Phys. Rev. C (2021) 104, 064609
- ✓ J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604
- ✓ F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145
- ✓ B.A. Urazbekov, PRC 108 (2023) 064609

^{12}C – ^{12}Be case

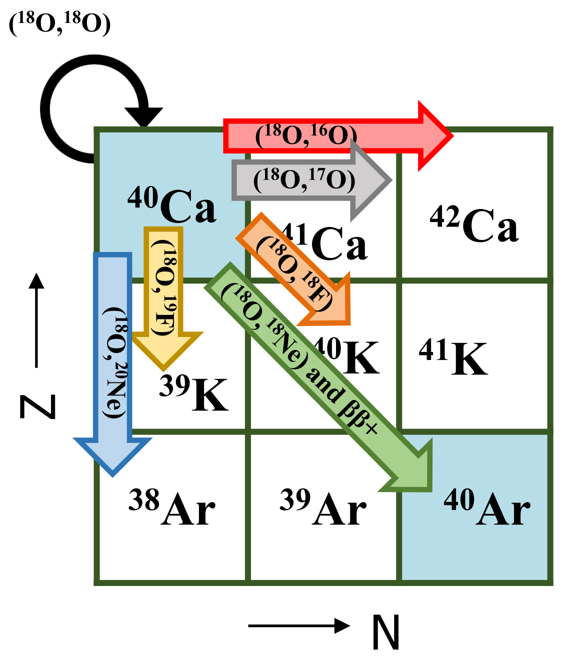
@ 15 AMeV and @ 22 AMeV

- ^{18}O + ^{12}C

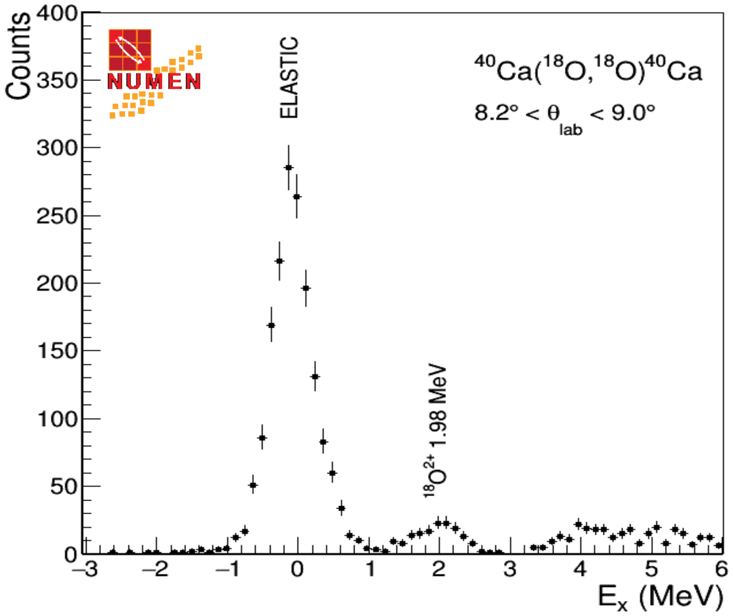


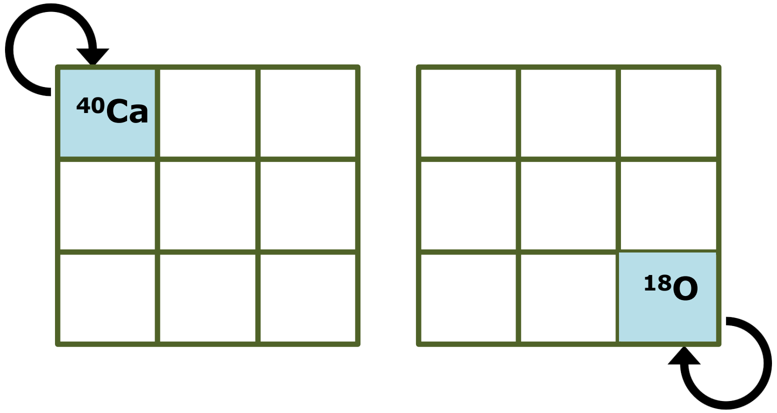
- ✓ A. Spatafora et al., Phys. Rev. C (2023) 107, 024605

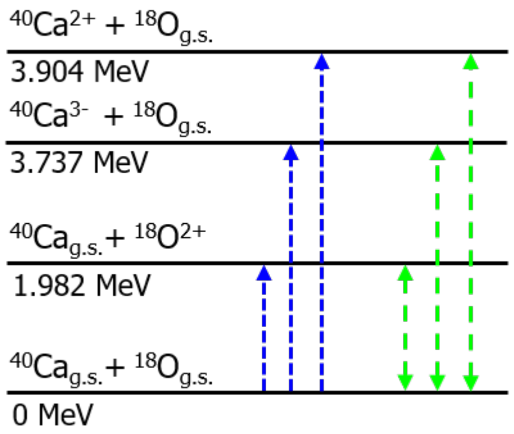
The multichannel approach at work: the $^{18}O + ^{40}Ca$ @ 270 MeV case

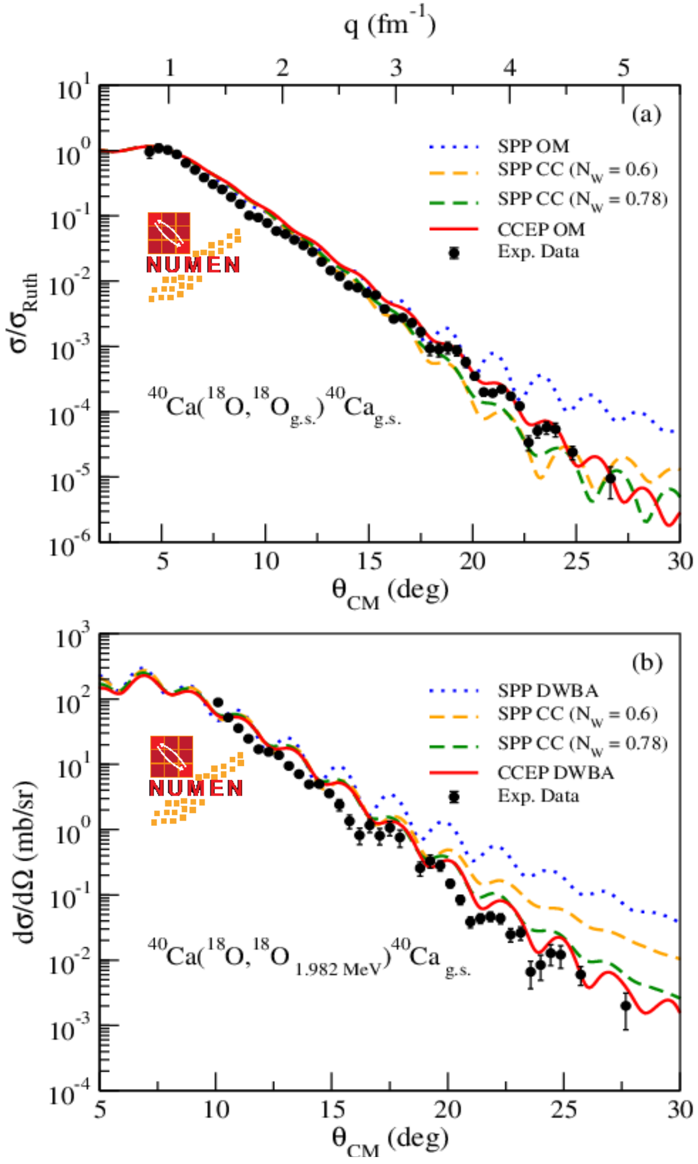


The $^{40}Ca(^{18}O,^{18}O)^{40}Ca$ elastic and inelastic scattering @ 270 MeV









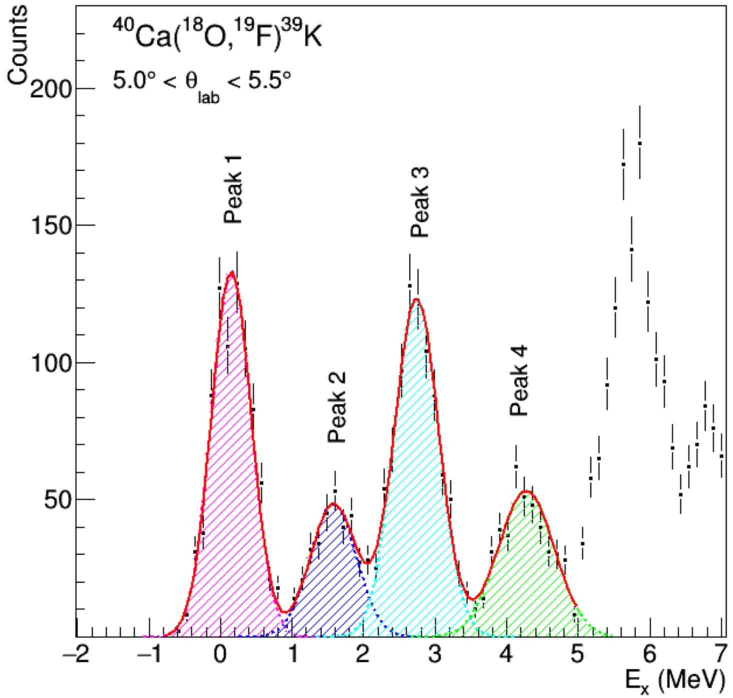
Key information from scattering data analysis:

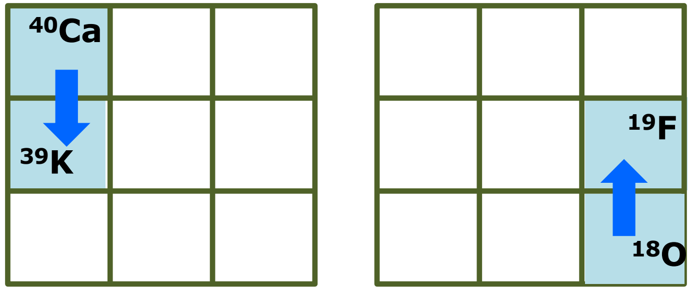
- Double folding Sao Paulo Potential works well
- **Coupling to low-lying 2^+ and 3^- states of ^{18}O and ^{40}Ca states is important**
- Effects of coupling can be accounted for in average by Coupled Channel Equivalent Potential approach

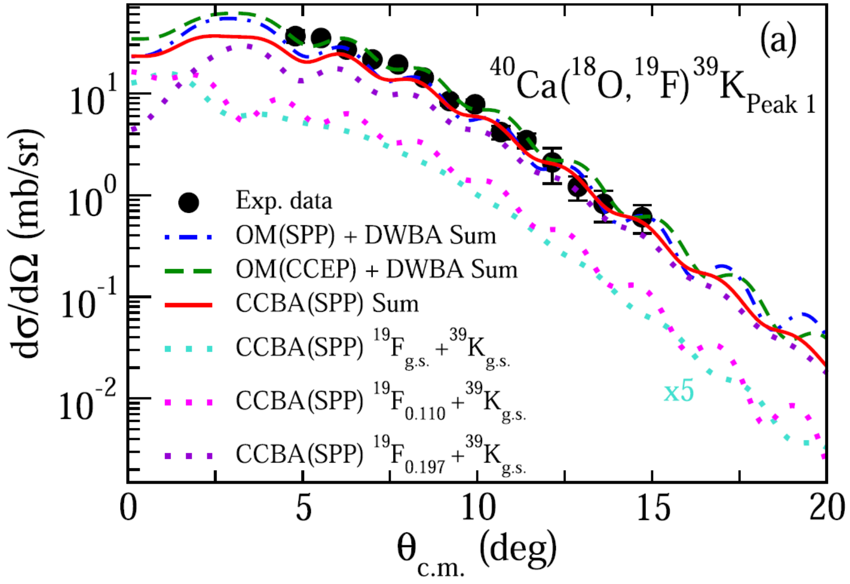
M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815

The $^{40}Ca(^{18}O,^{19}F)^{39}K$ 1p transfer @ 270 MeV

CCBA analysis based on shell model amplitudes







Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data

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

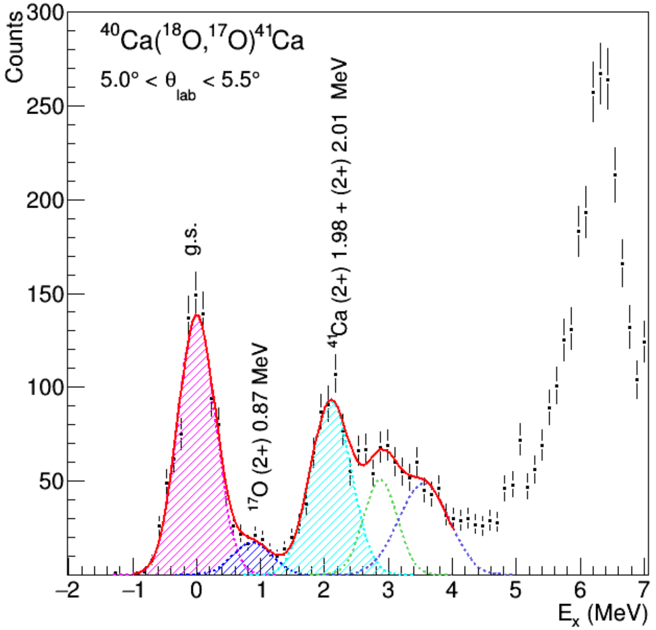
- ^{4}He as core, $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ $1d_{3/2}$ active orbitals with *p-sd-mod* interaction for projectile
- ^{28}Si as a core, $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, $2p_{3/2}$ active orbitals with *ZBM2-modified* interaction for the target

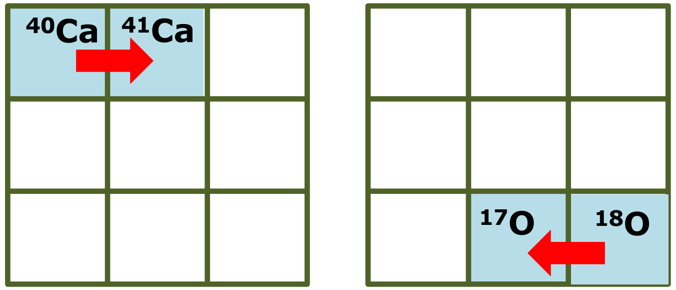
Key information from 1p transfer:

- **Very good description of the data from CCBA constrained approach**
- **Mixing of single particle and core polarization configurations**

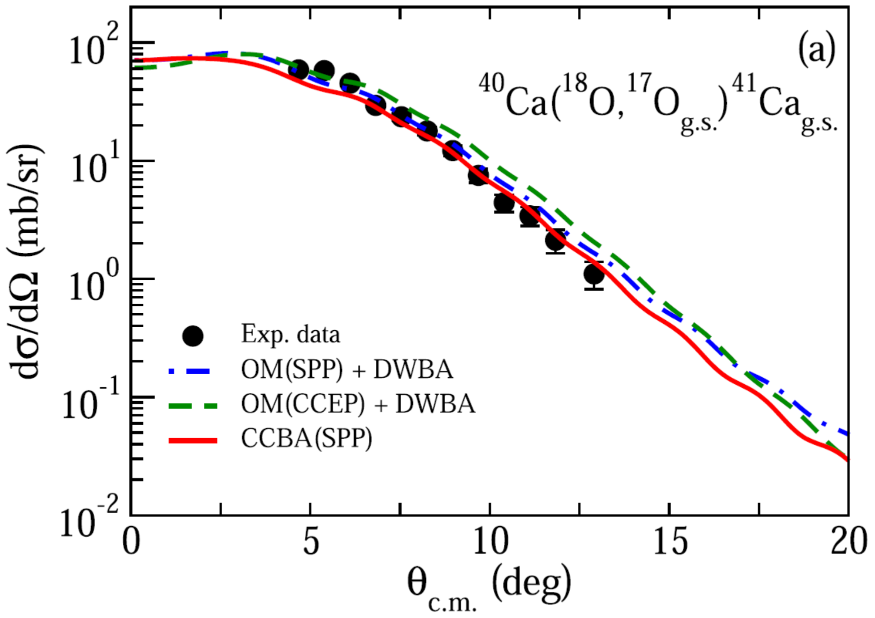
The $^{40}Ca(^{18}O,^{17}O)^{41}Ca$ 1n transfer @ 270 MeV

CCBA analysis based on shell model amplitudes using the same model space and interaction as for one-proton transfer reaction





Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data



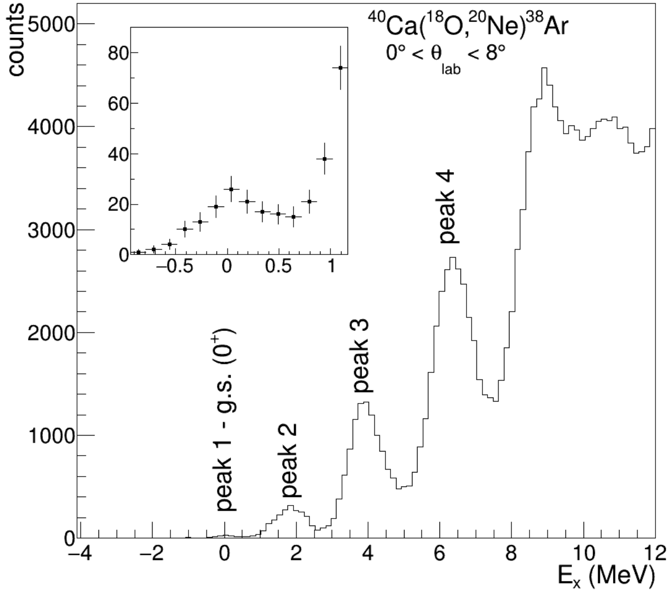
S. Calabrese et al., Phys. Rev. C 104, 064609 (2021)

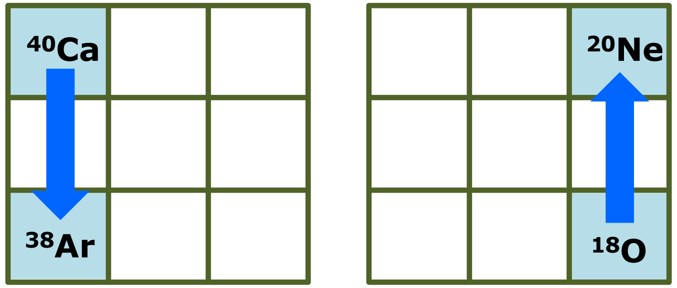
Key information from 1n transfer:

- **Very good description of the data from CCBA constrained approach**
- **Mixing of single particle and core polarization configurations**

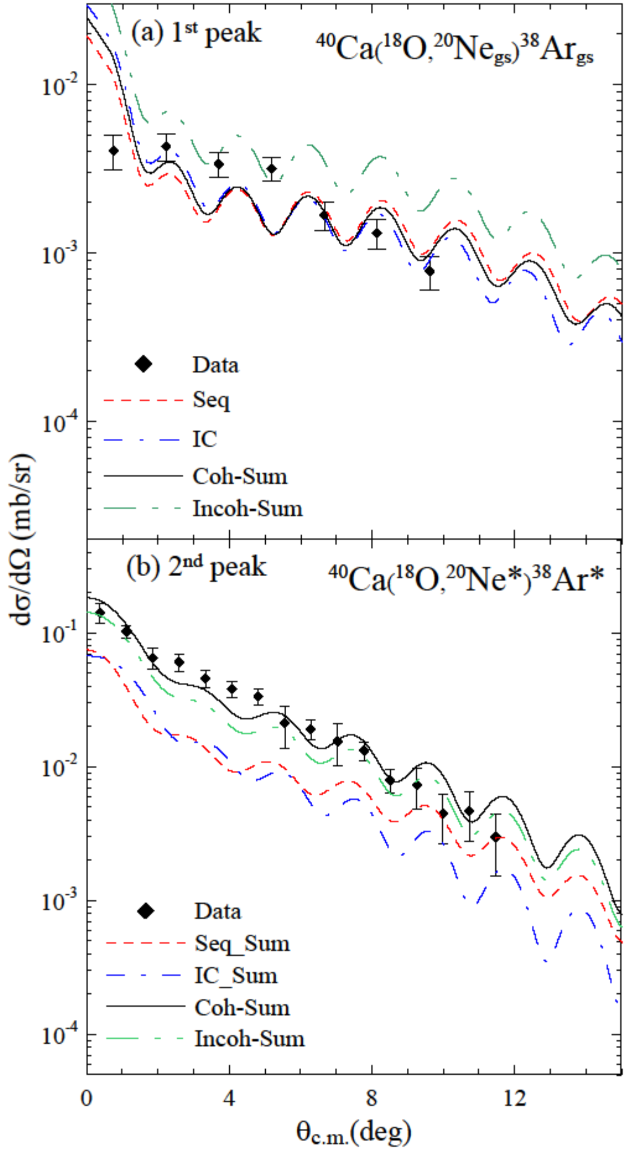
The $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ 2p transfer @ 270 MeV

CCBA analysis based on direct and two-step transfer with shell model amplitudes using the same model space and interaction as for one-nucleon transfer reactions





Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data



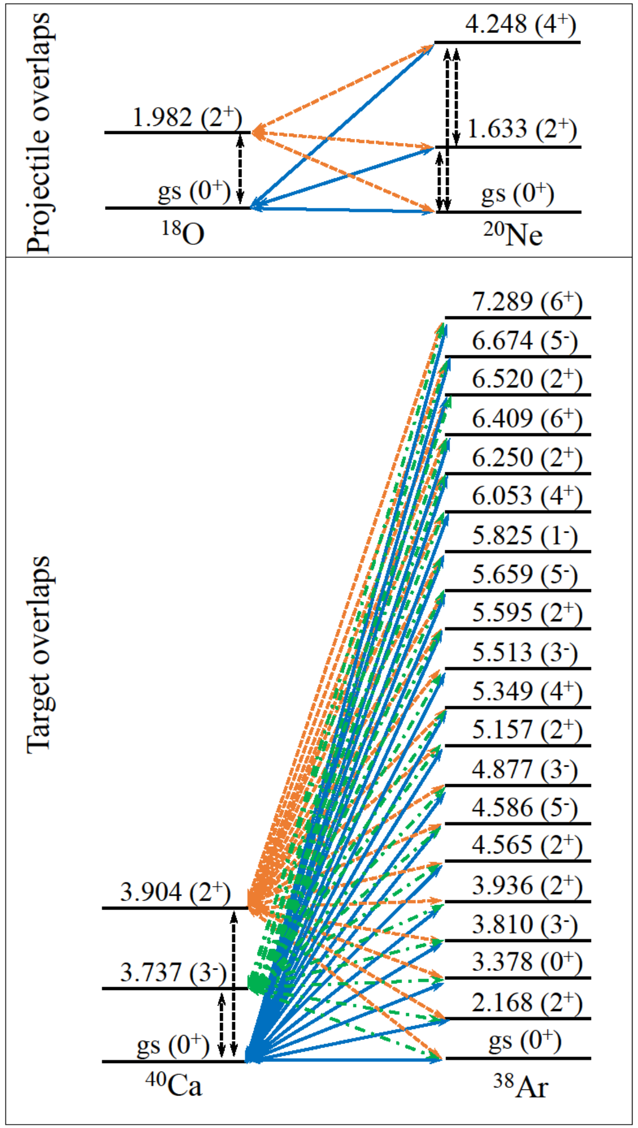
Key information from 2p transfer:

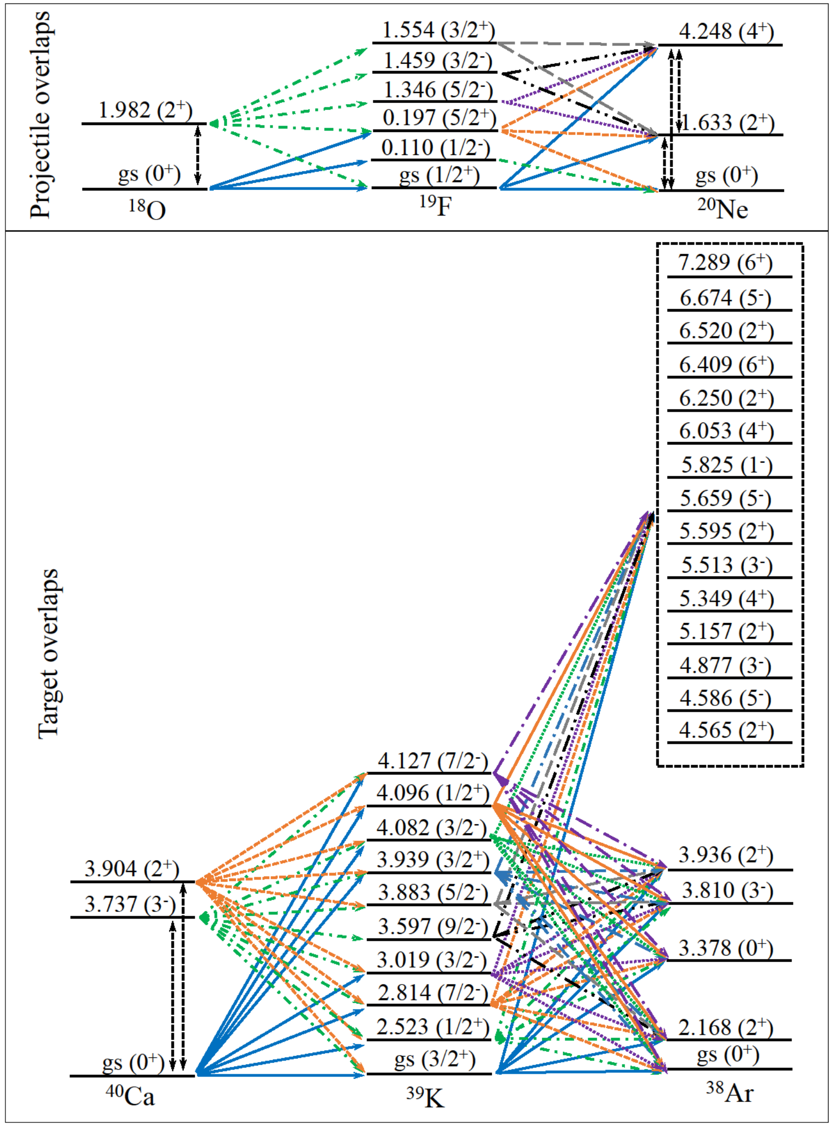
- **Very low cross section** (comparable with DCE) for low-lying states (poorly matched)
- **Competition** between **one step** and sequential **two-step** mechanisms
- **Good description of the data from CCBA constrained approach**

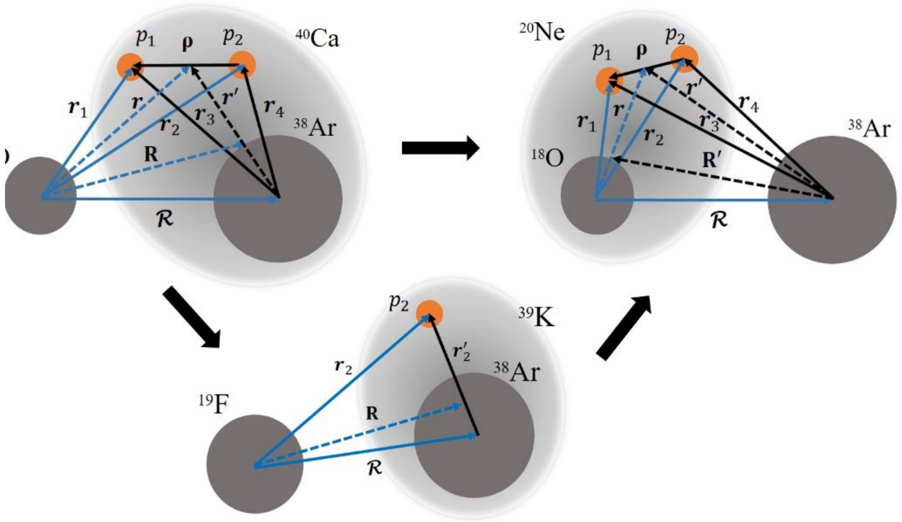
J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604

The $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ 2p transfer @ 270 MeV

CCBA analysis based on direct and two-step transfer with shell model amplitudes using the same model space and interaction as for one nucleon transfer reactions



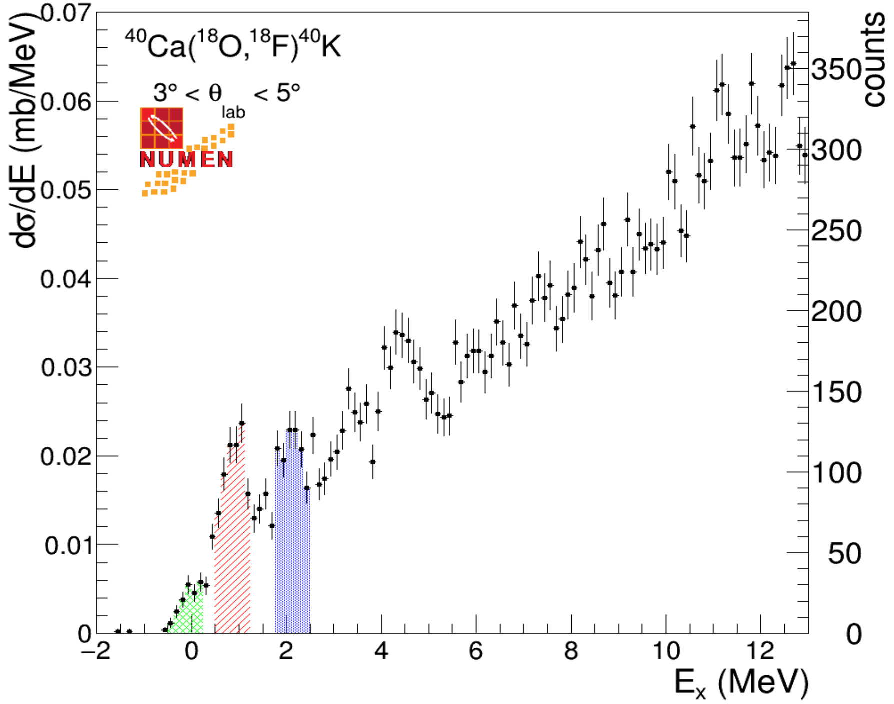


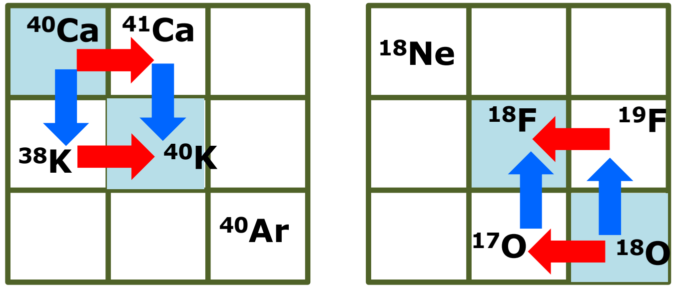


J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604

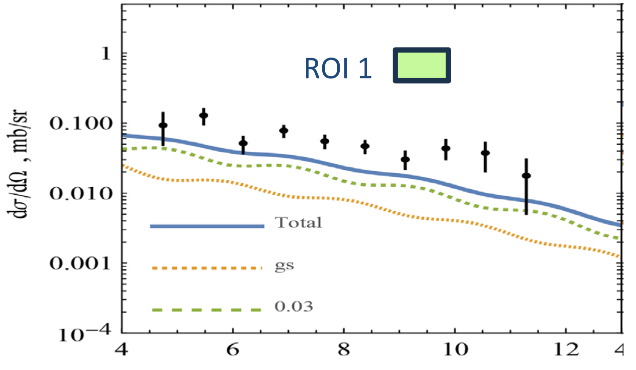
The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 270 MeV

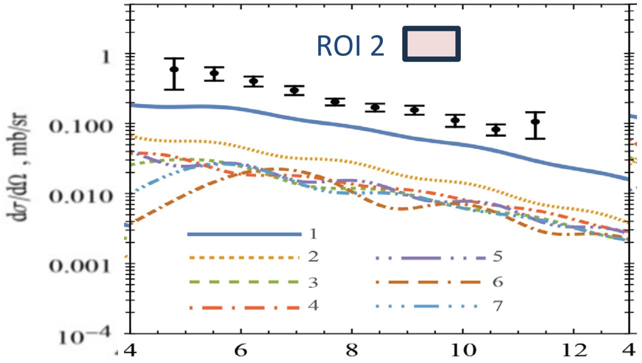
CCBA and CRC analyses based on direct and two-step transfer with shell model amplitudes using the same model space and interaction as for one nucleon transfer reactions

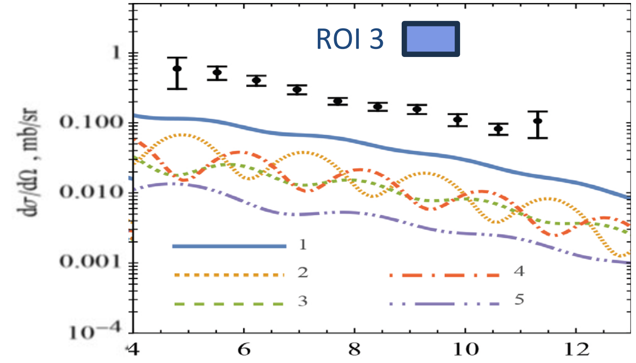




Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data







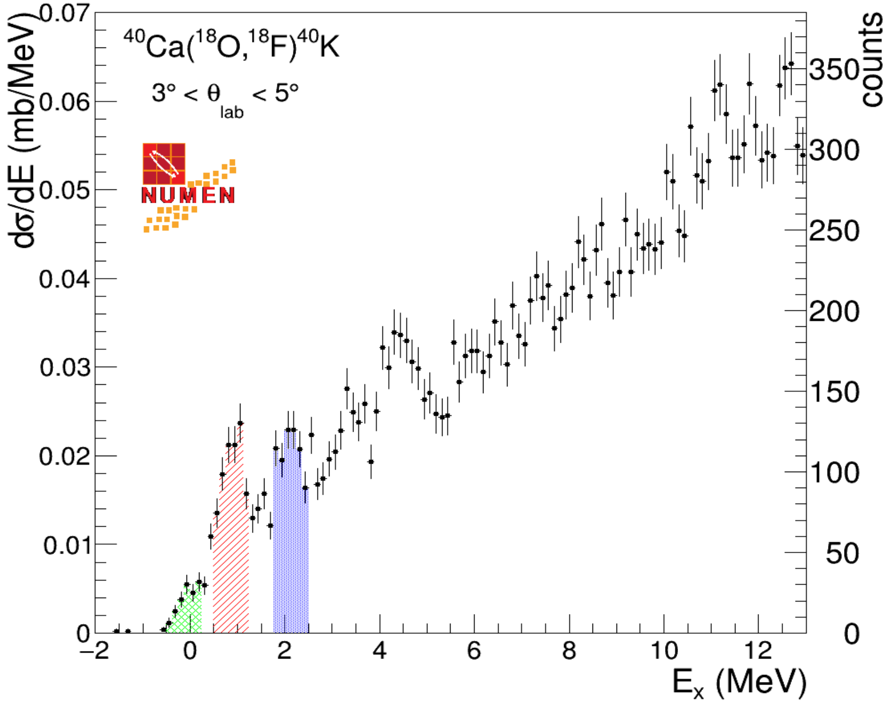
Key information from SCE data:

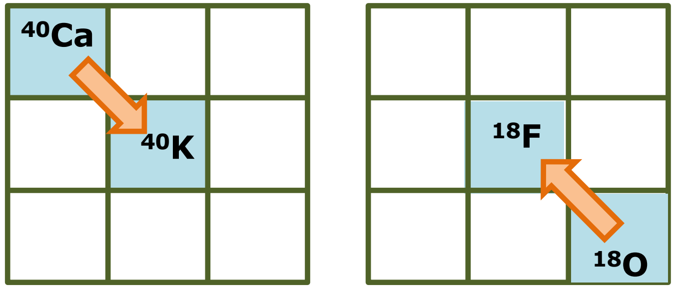
- **Two-step nucleonic SCE mechanism plays a significant role,** although it is expected to contribute less at higher excitation energy due to the progressively worse kinematical matching
- Room is left for alternative reaction mechanisms feeding the SCE channel, especially at high excitation energy

B.A. Urazbekov, PRC 108 (2023) 064609

The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 270 MeV

DWBA analysis based on double folding form factors of QRPA (or shell model) transition densities with NN isovector interaction



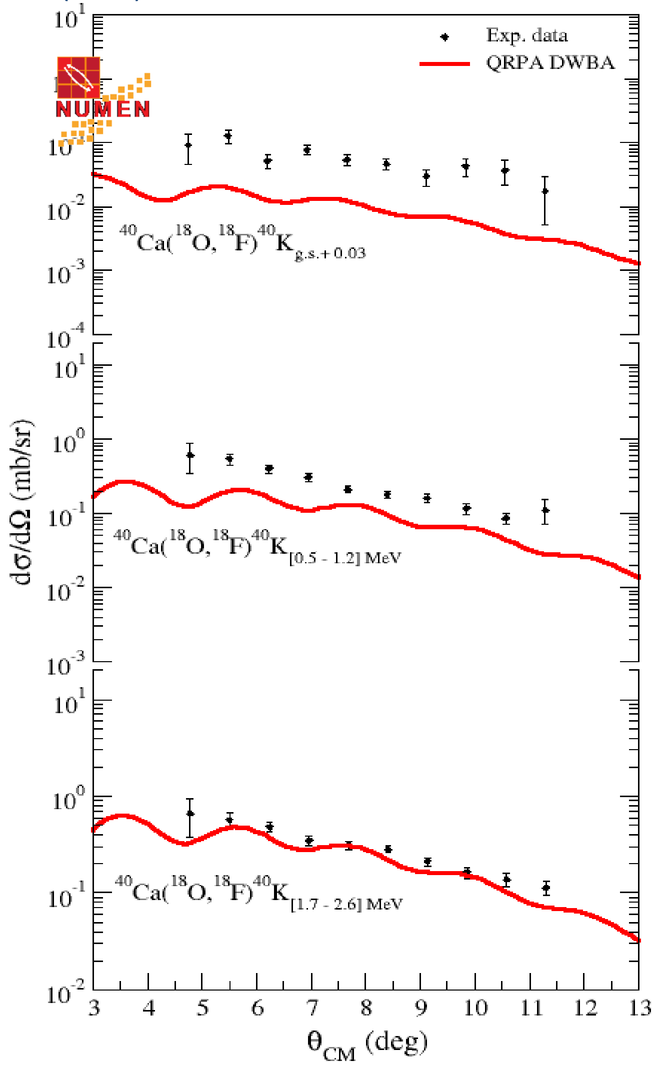


Note: the optical potential is extracted from our CCEP data analysis of elastic and inelastic scattering data

Key information from SCE data:

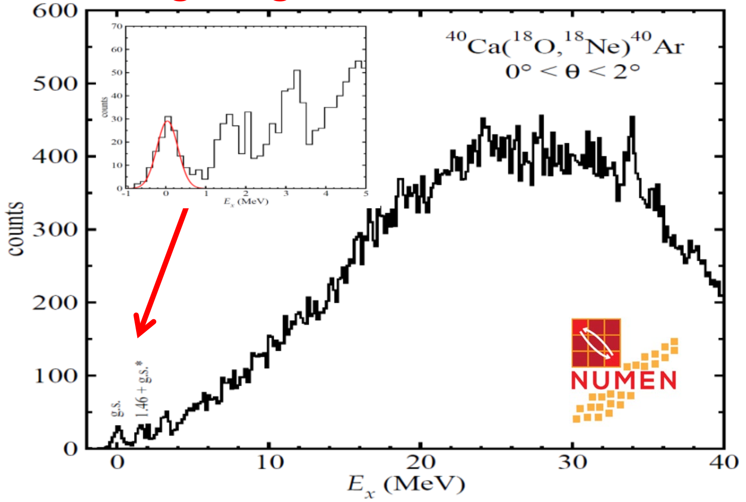
- **Direct meson exchange mechanism important at low excitation energy**
- **Access to** Fermi, Gamow-Teller as well as **to high-multipole isospin response, relevant for $0\nu\beta\beta$**
- **One needs** to accommodate both one- and two-step calculations in **the same DWBA or CC scheme with consistent nuclear structure input**

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

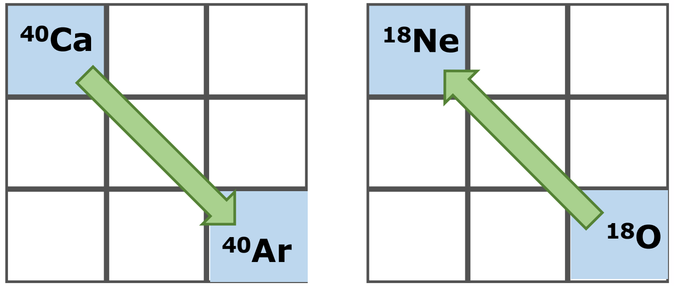


The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ double charge exchange @ 270 MeV

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

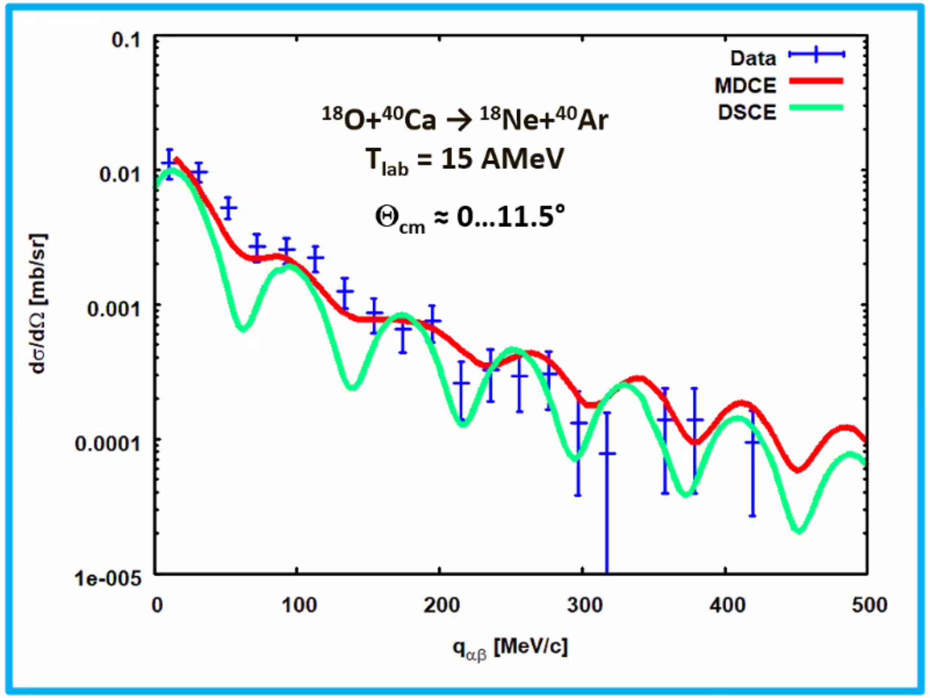


Access to ground-to-ground state transition



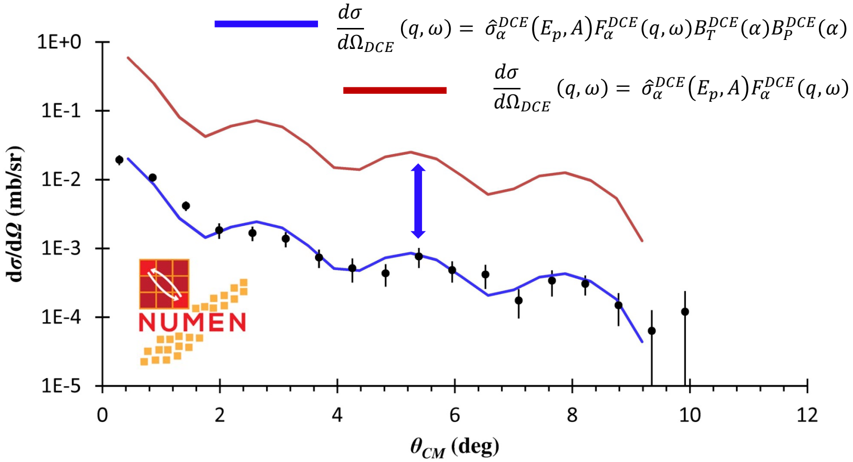
$$\left|M_{\sigma\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.2 \pm 0.6$$

$$\left|M_{\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.1 \pm 0.5$$



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

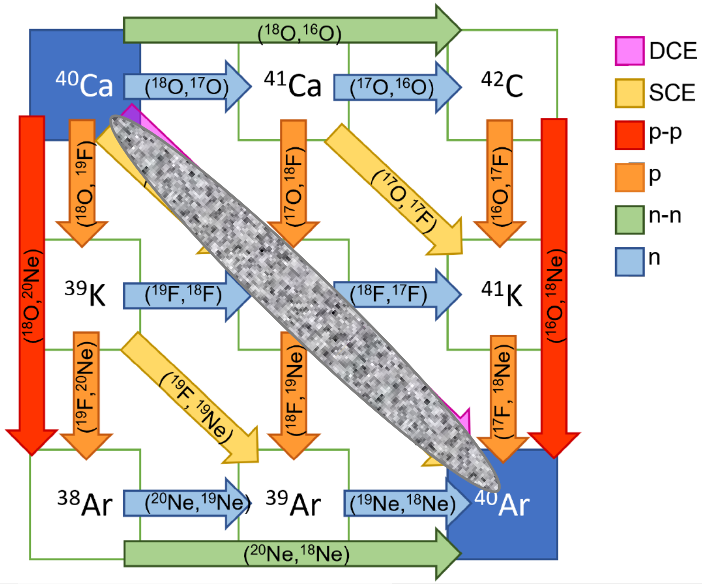
1-step MDCE: $^{40}Ca(0^+) \rightarrow ^{40}Ar([n^{-2}p^2]0^+)$: J=0+ with L=S=0 & $[L=2 \times S=2]_{0+}$

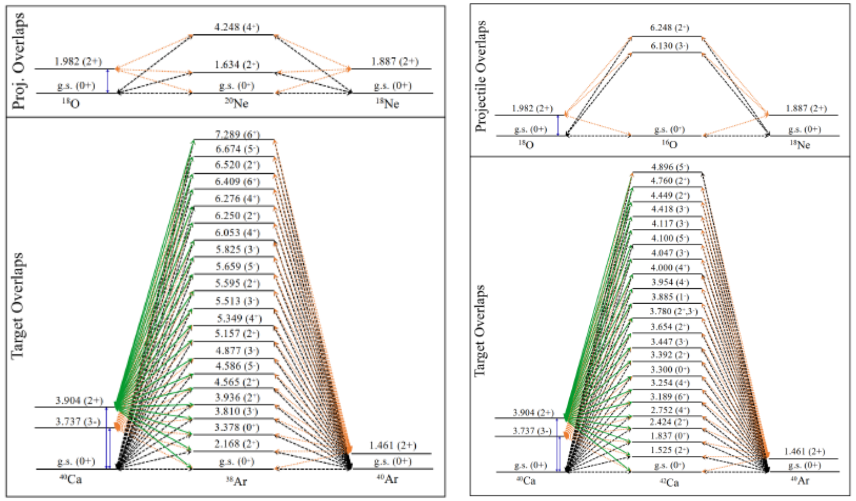


H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
J.I. Bellone et al., PLB 807 (2020) 135528
H. Lenske et al., Universe 7 (2021) 98
F. Cappuzzello et al. Prog. in Part. and Nucl. Phys. 128 (2023) 103999

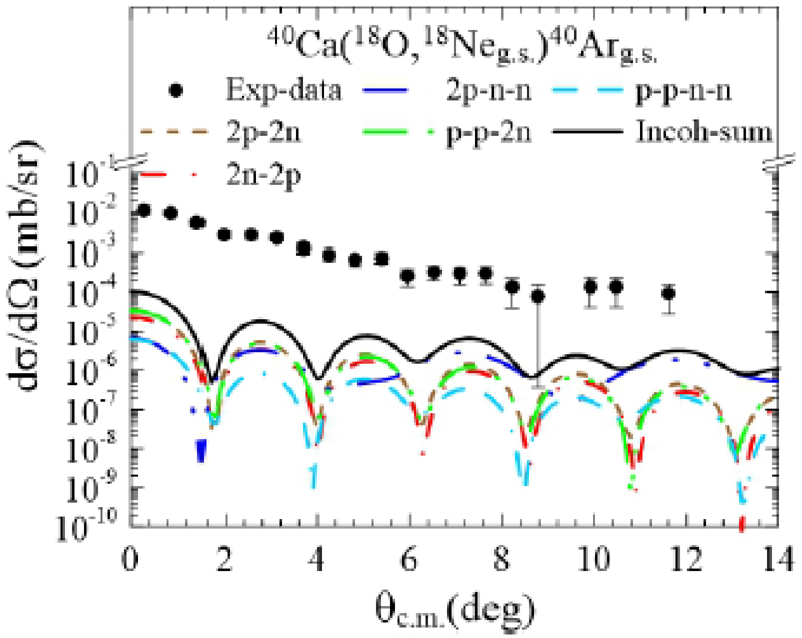
F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145

The multi-nucleon transfer mechanisms for HI-DCE





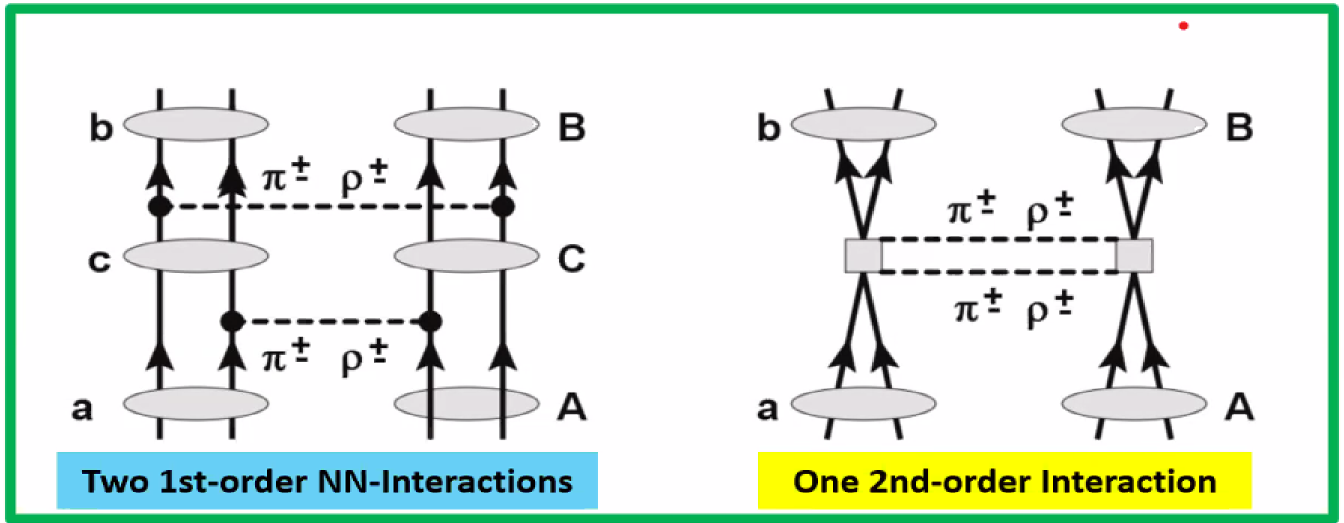
- ✓ ISI and FSI ion-ion interaction from double folding (available from elastic and inelastic data)
- ✓ Shell model amplitudes and deformations as for transfer calculations
- ✓ Four-step DWBA and CCBA calculations in large model spaces



TDCE contribution is negligible!

- *J.L. Ferreira et al., Phys. Rev. C 105, 014630 (2022)*
- *F. Cappuzzello et al. Prog. Part. and Nucl. Phys., 128 (2023) 103999*

The two competing hadron mechanisms for HI-DCE



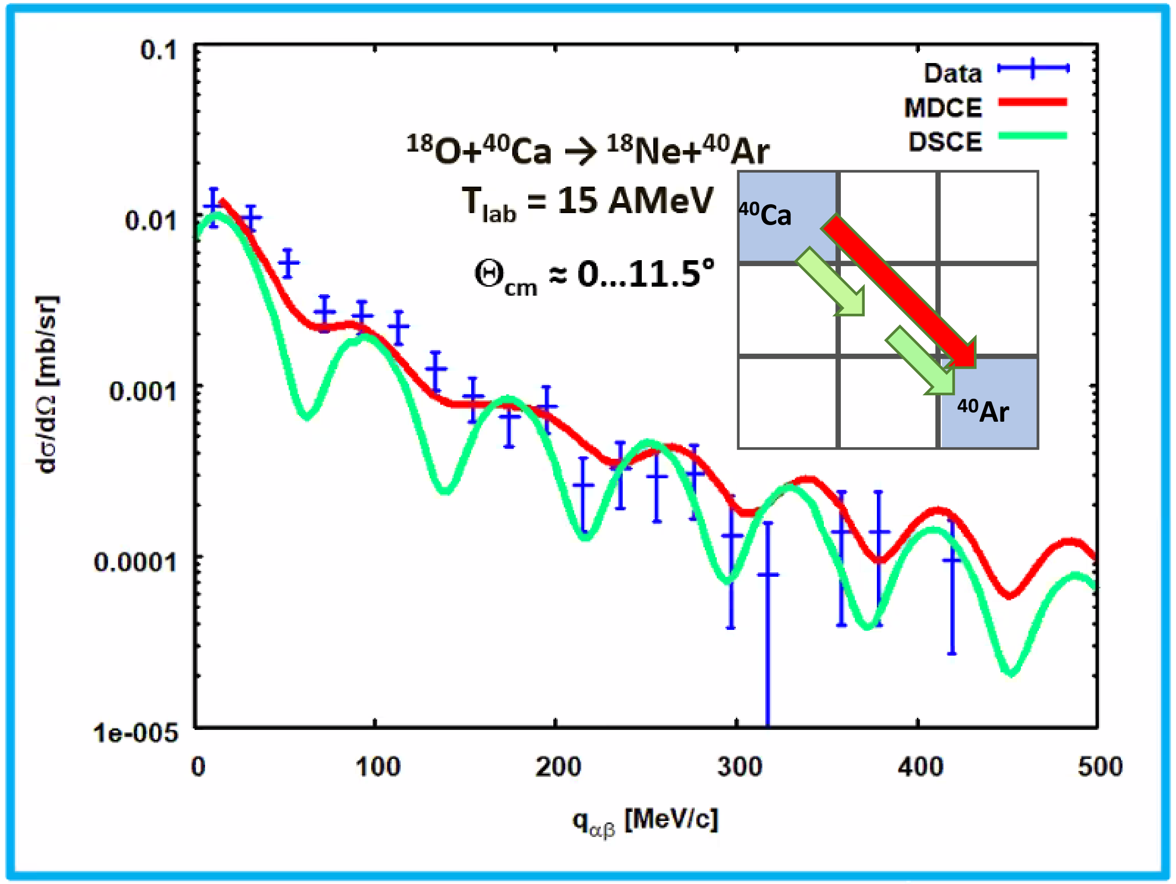
DSCE: Sequential single-meson exchange
H.Lenske et al., Universe (2024), 10, 93

MDCE: Coherent double-meson exchange
H.Lenske et al., Universe (2024), 10, 202

Caveat:

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

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



2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$
1-step MDCE: $^{40}Ca(0^+) \rightarrow ^{40}Ar([n^{-2}p^2]0^+)$: J=0+ with L=S=0 & $[L=2 \times S=2]_{0+}$

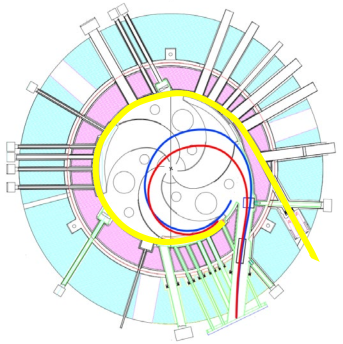
Present limitations and perspectives

- Only few systems have been studied in the present condition (due to the **low cross-sections**)

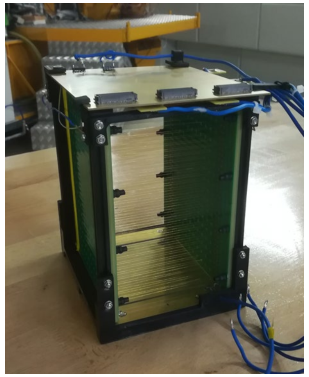
Systematic study of all the hot-cases

Much higher beam current is needed

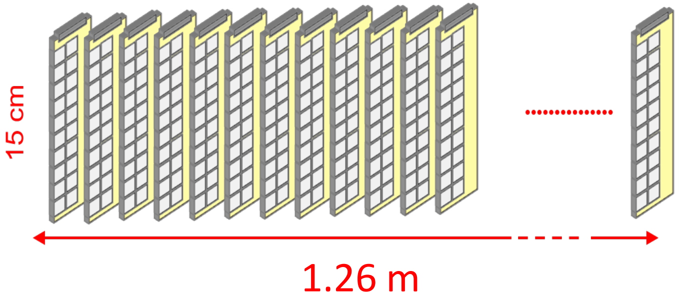
Physics case for the **upgrade of the LNS CS** and related infrastructures towards high intense beams (from the present 100 W to the foreseen 10 kW)



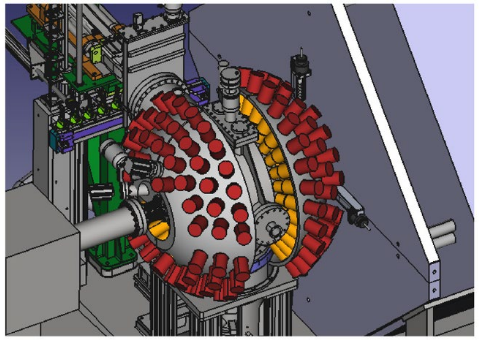
CS extraction by stripping



New tracker for the FPD (THGEM technology)



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



New gamma-ray calorimeter (LaBr3 scintillators)

NUMEN TDR - F. Cappuzzello et al. Intern. Journ. of Mod. Phys. A 36, 30 (2021) 2130018

Conclusions

- **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
- **Multi-channel reaction approach is mandatory and,** in my opinion, **should be generalized** to many other aspect of nuclear research

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 $0\nu\beta\beta$ decay **with the high intensity beams**

Thank you