Heavy-ion induced direct reactions with the MAGNEX spectrometer at INFN-LNS: a multi-channel approach

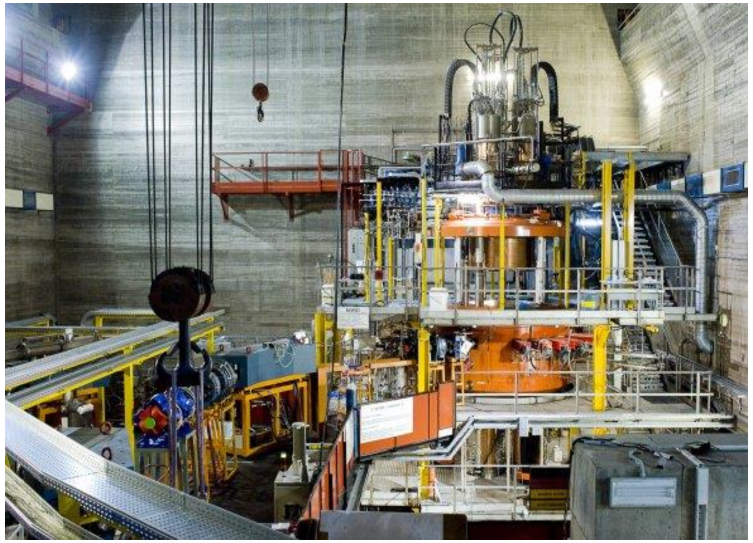
F. Cappuzzello
University of Catania and INFN LNS

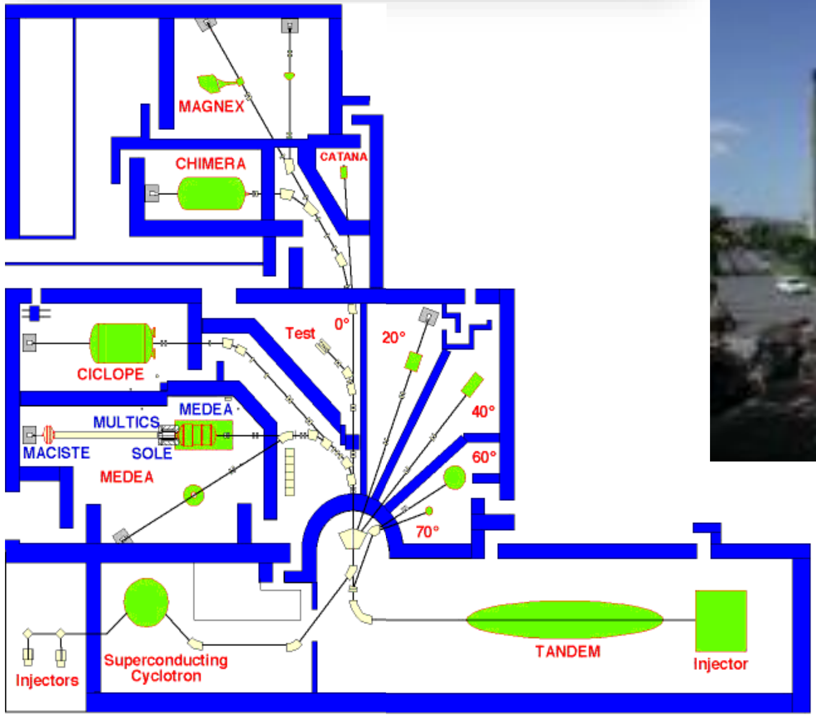
ISOLDE Superconducting Recoil Separator

ISRS meeting 2022

29 November 2022

The LNS laboratory in Catania





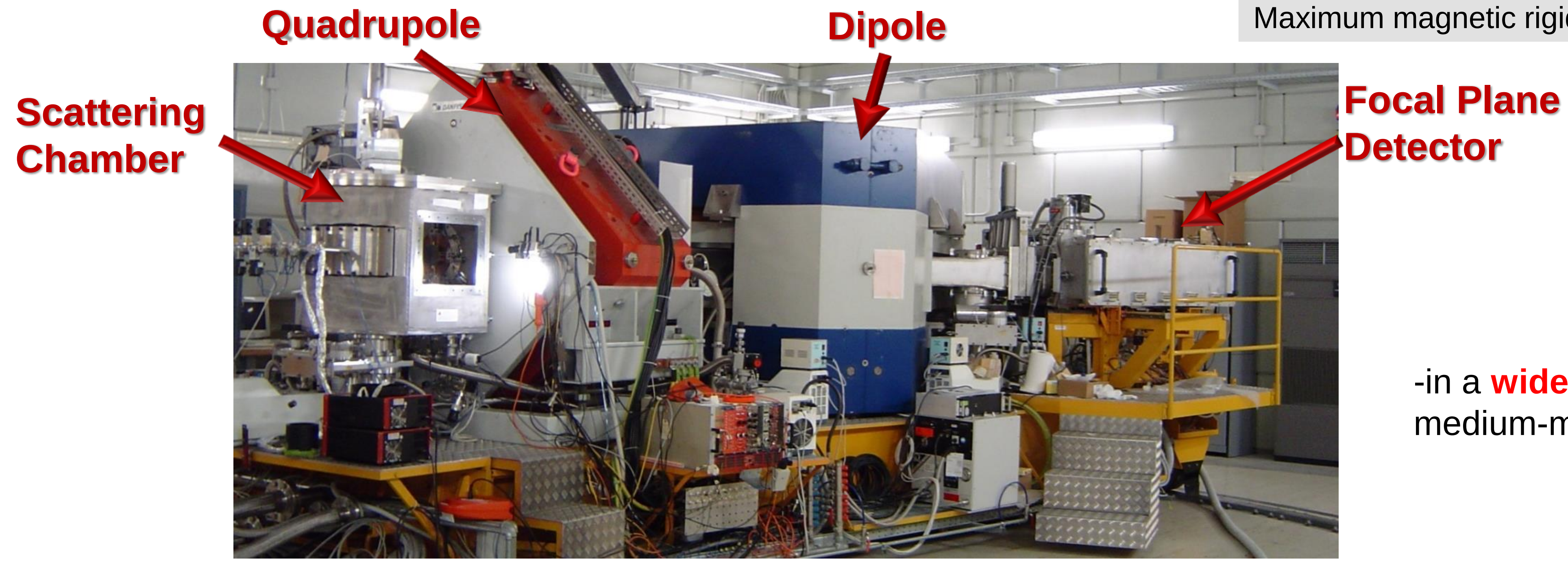
MAGNEX: a large acceptance QD spectrometer

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

- ❖ **The Quadrupole**: vertically focusing
  (Aperture radius 20 cm, effective length 58 cm. Maximum field strength 5 T/m)

- ❖ **The Dipole**: momentum dispersion (and horizontal focus)
  (Mean bend angle 55, radius 1.60 m. Maximum field ~ 1.15 T)

Optical characteristics	Measured values
Angular acceptance (Solid angle)	50 msr
Angular range	–20° - +85°
Momentum acceptance	-14%, +10%
Momentum dispersion for k= - 0.104 (cm/%)	3.68
Maximum magnetic rigidity	1.8 T m



Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.3^{\circ}$
Mass $\Delta m/m \sim 1/300$

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

Exploring nuclear phenomenology with MAGNEX

- ✓ Several experimental campaigns performed with MAGNEX since its installation in 2007
- ✓ Different classes of nuclear phenomena explored via direct nuclear reactions induced by light and heavy-ion beams

A review of main results from first years activity

Eur. Phys. J. A (2016) **52**: 167
DOI 10.1140/epja/i2016-16167-1
THE EUROPEAN PHYSICAL JOURNAL A

Review

The MAGNEX spectrometer: Results and perspectives

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An interesting discovery

nature COMMUNICATIONS
Nature Comm. 6 (2015) 6743

ARTICLE

Received 28 Dec 2014 | Accepted 24 Feb 2015 | Published 27 Mar 2015 DOI: 10.1038/ncomms7743 OPEN

Signatures of the Giant Pairing Vibration in the ^{14}C and ^{15}C atomic nuclei

F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondì[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]

Eur. Phys. J. A (2021) 57:25
https://doi.org/10.1140/epja/s10050-020-00338-y
THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Review

Global descriptions and decay rates for continuum excitation of weakly bound nuclei

A. Pakou[1,a], O. Sgouros[2], V. Soukeras[2], F. Cappuzzello[2,3]

A review of light ion induced reactions on proton targets

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
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Review

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

Check for updates

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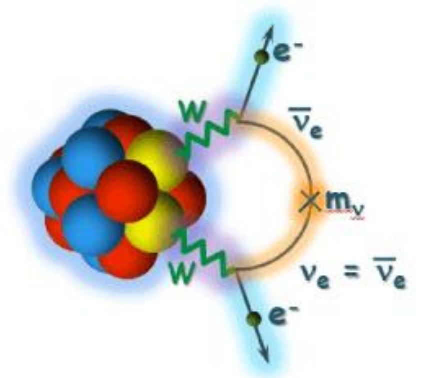
A review on heavy-ion induced charge exchange reactions

A new challenge for MAGNEX: studying $0\nu\beta\beta$ decay by nuclear reactions

0νββ decay



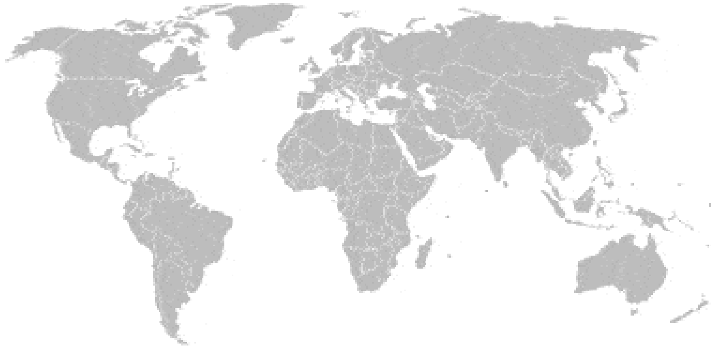
E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

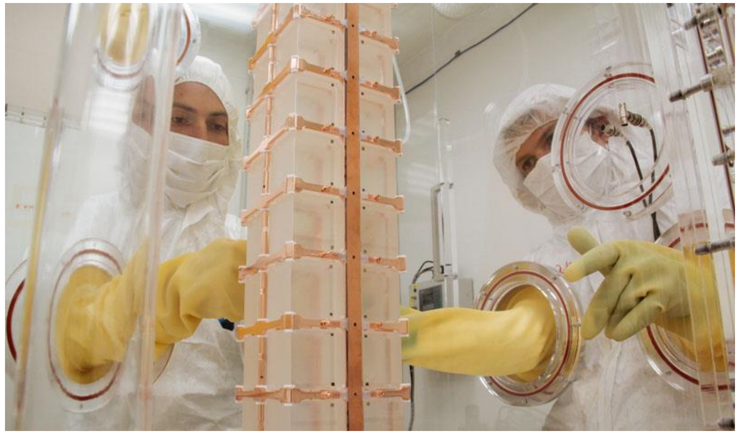
Still not observed

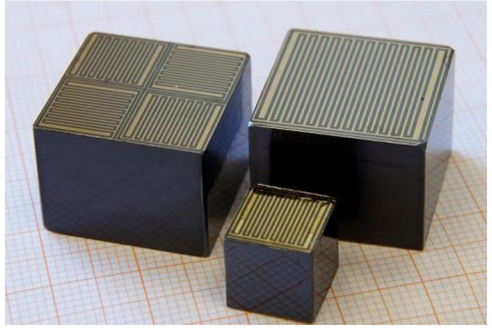
1. **Beyond standard model**
2. **Access to effective neutrino mass**
3. **Violation of lepton number conservation**
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**

The fundamental implications of 0νββ observation are the motivation for the prodigious activities in the searches for experimental evidence of this process

Search for 0νββ decay
A worldwide race







Nuclear Matrix Elements

0νββ decay **half-life**

Phase space factor

contains the average 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

Nuclear physics plays a key role!

The Nuclear Matrix Element

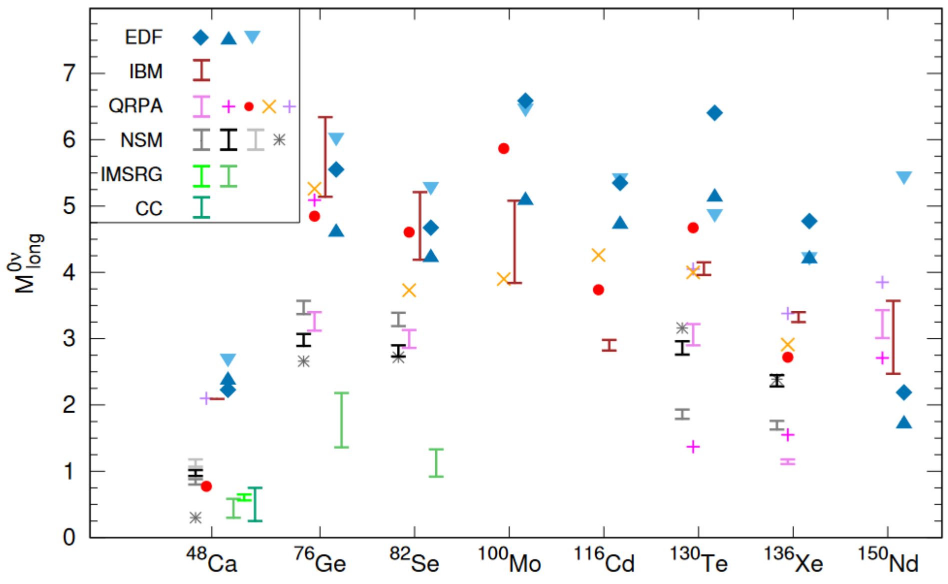
New physics for the next decades

requiring

Nuclear Matrix Element (NME)!

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

State of the art NME calculations



M.Agostini et al., (2022) arXiv:2202.01787v1

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

Engel, J.; Menendez, J. Rep. Progr. Phys. **2017**, 80, 046301

A new experimental tool

NUMEN

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

F. Cappuzzello et al., EPJ A (2018) 54:72

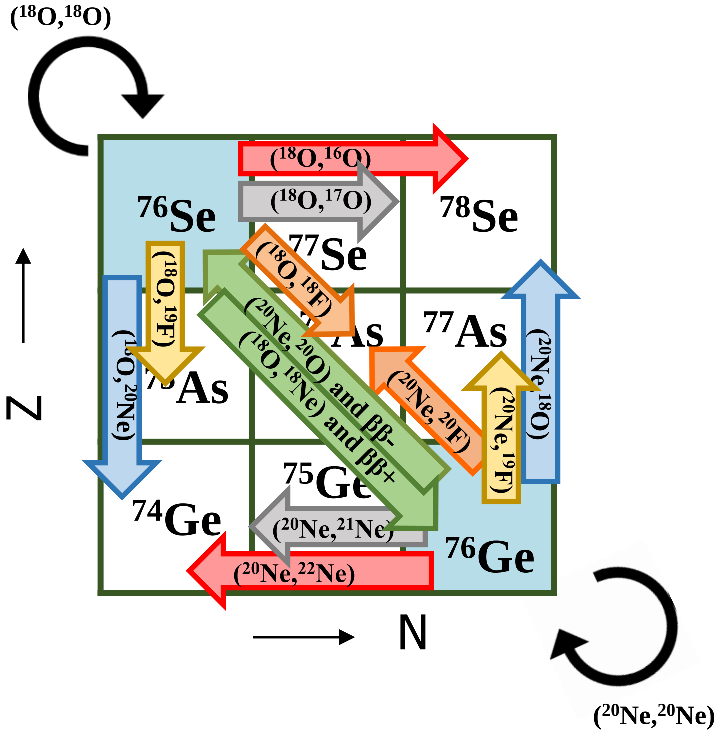
European Commission

erc NURE

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

- **DCE on isotopes of interest for 0νββ** via **(^{20}Ne,^{20}O)** (ββ^{-}) and **(^{18}O,^{18}Ne)** ββ^{+} from 15 MeV/u to 60 MeV/u

- **Complete net** of reactions which can contribute to the DCE cross-section: 1p-, 2p-, 1n-, 2n-transfer, SCE, (elastic and inelastic)



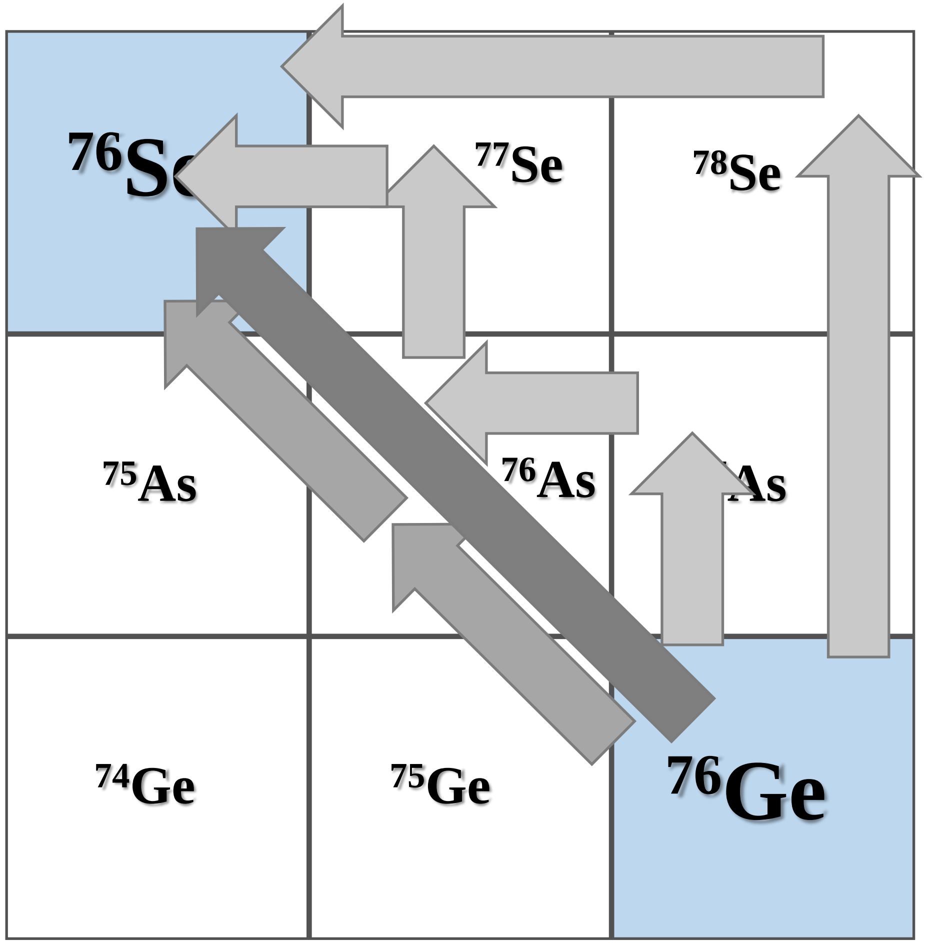
Study of competing channels

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*

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*

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



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

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

The NUMEN collaboration

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

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32 Institutions
12 Countries

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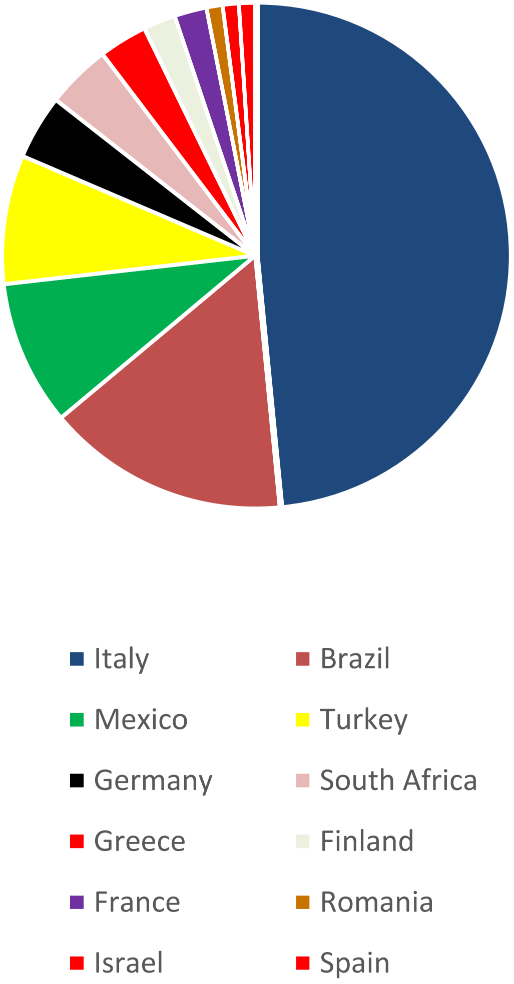
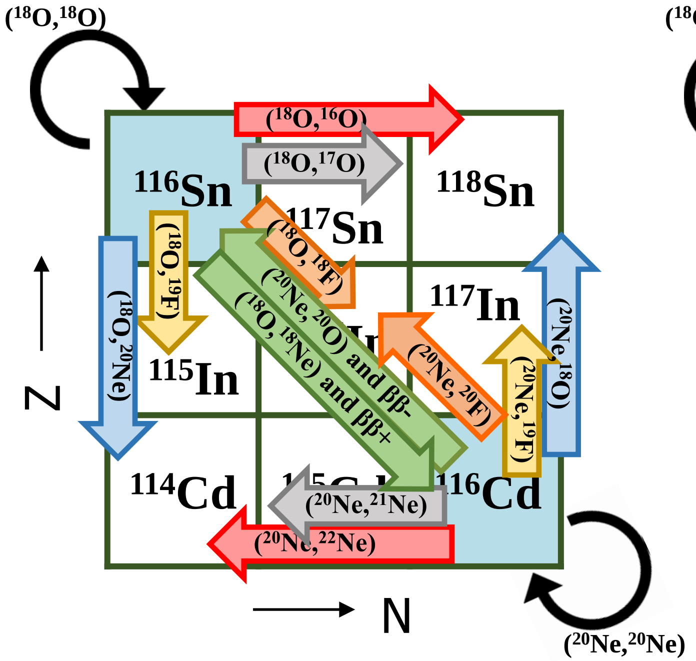


Systems of interest for 0νββ already explored

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

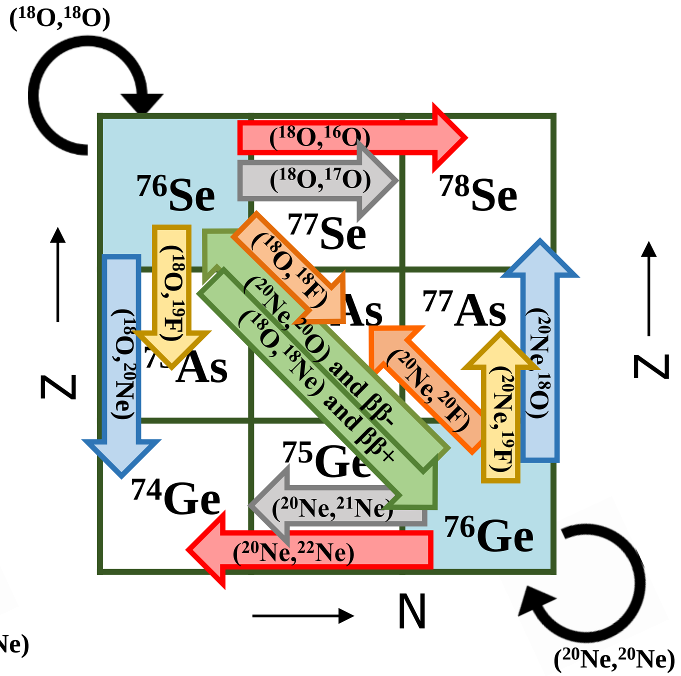
@ 15 AMeV
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



- ✓ 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

^{76}Ge – ^{76}Se case

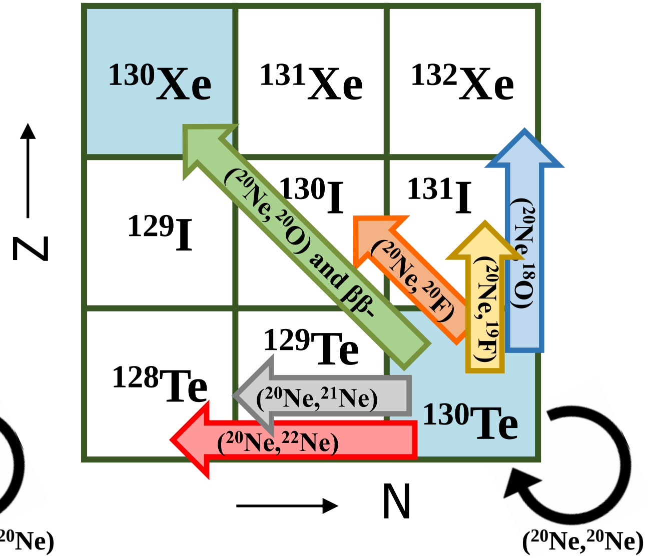
@ 15 AMeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



- ✓ A.Spatafora et al., PRC 100 (2019) 034620
- ✓ L. La Fauci et al., PRC 104 (2021) 054610
- ✓ I. Ciraldo et al., PRC, submitted

^{130}Te – ^{130}Xe case

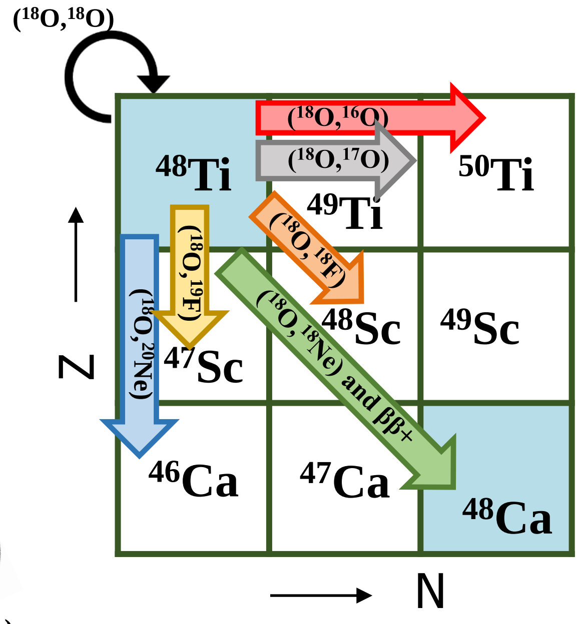
@ 15 AMeV
- ^{20}Ne + ^{130}Te



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

^{48}Ti – ^{48}Ca case

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



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

Recent literature on HI-DCE

Progress in Particle and Nuclear Physics 109 (2019) 103716

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Progress in Particle and Nuclear Physics

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

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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]

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Progress in Particle and Nuclear Physics 128 (2023) 103999

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ELSEVIER

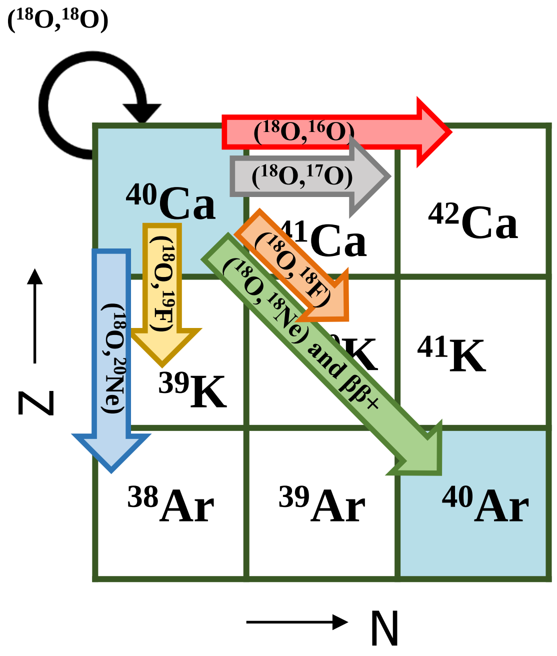
Review

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

The «multi-channel» approach

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



Even if the main interest is for DCE reactions, all the other quasi-elastic processes are important sources of information, essential to **build a contrained 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 → role of pairing correlations

Single charge exchange (SCE) → nuclear response to 1st order isospin operators

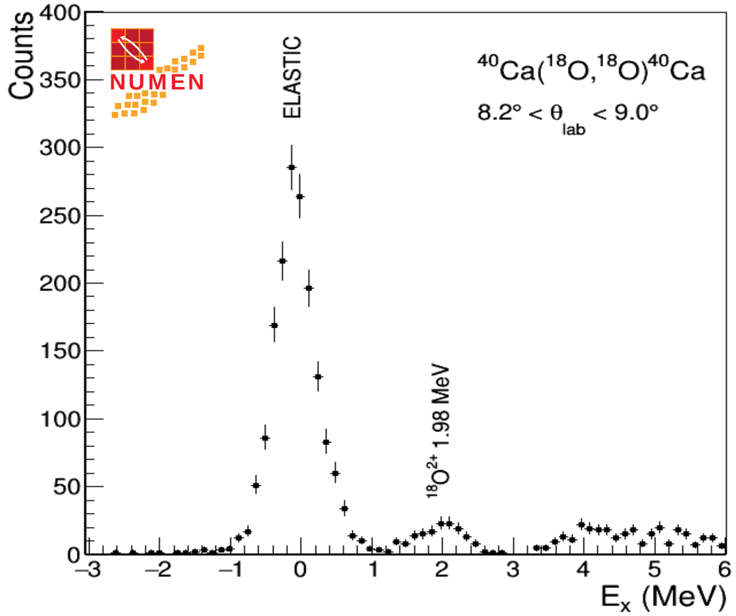
Double charge exchange (DCE) → nuclear response to 2nd order isospin operators

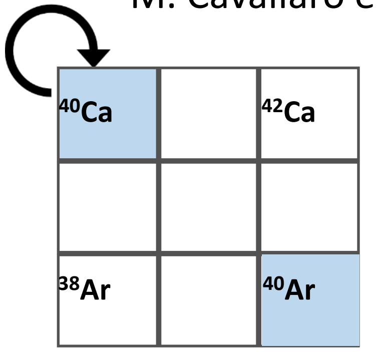
Constraints on experimental data and theoretical analysis

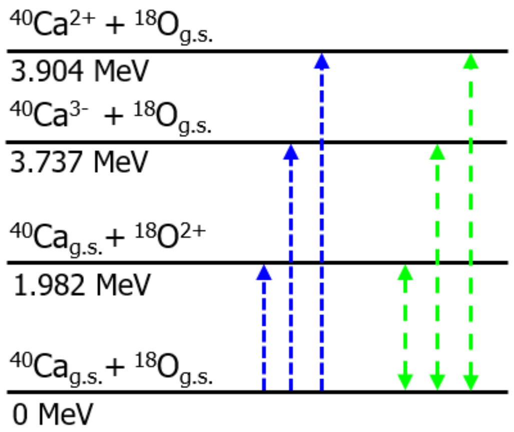
The multichannel approach at work: the ^{18}O + ^{40}Ca @ 270 MeV case

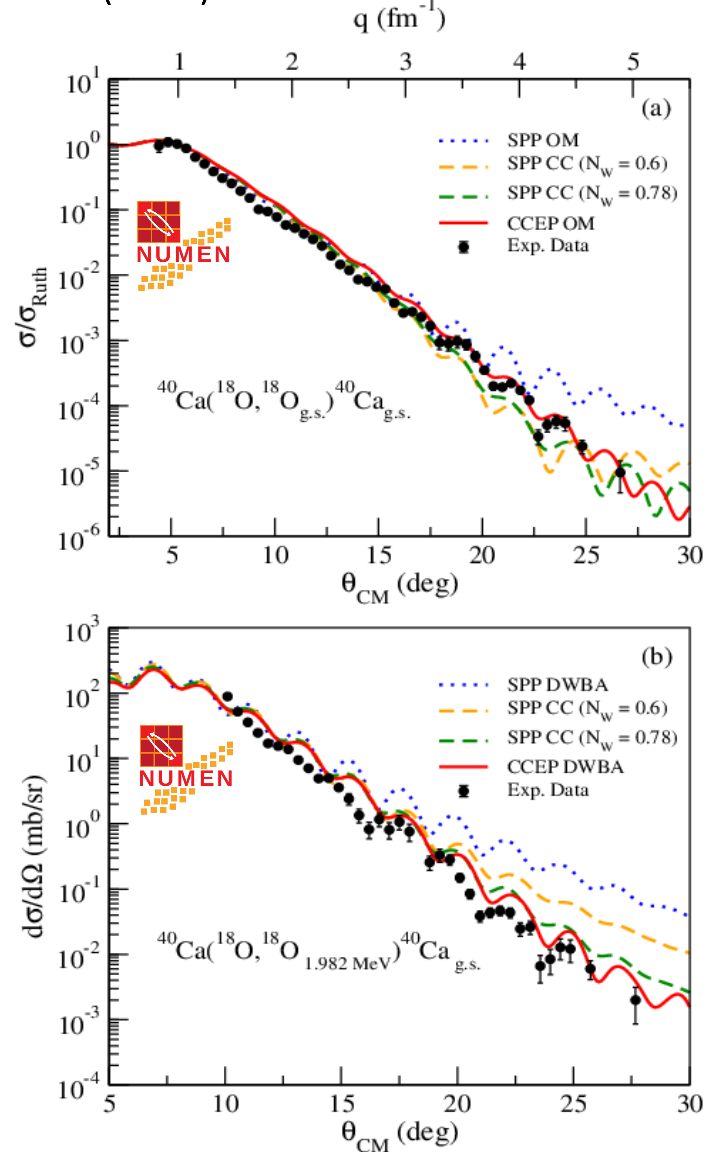
The $^{40}Ca(^{18}O,^{18}O)^{40}Ca$ elastic and inelastic scattering @ 15 MeV/u

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





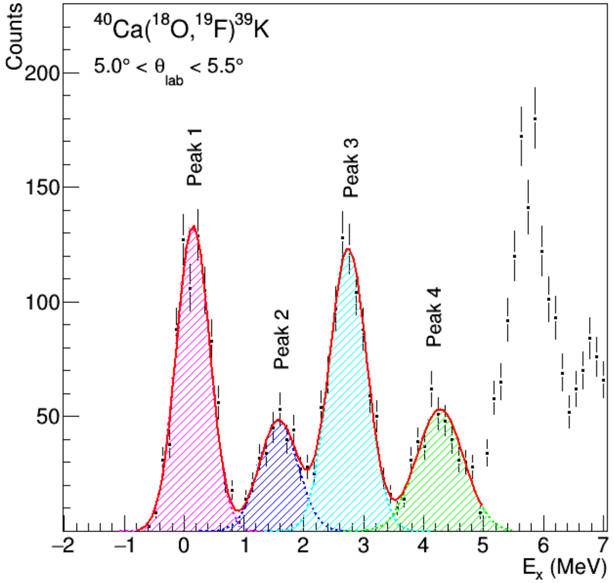


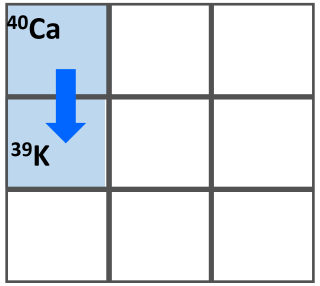


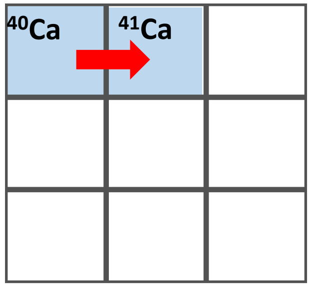
- Quantum-mechanics approach to nuclear reaction (double folding SPP) works well
- Coupling to low-lying 2^+ and 3^- states of ^{18}O and ^{40}Ca states is important
- Effects of coupling can be accounted for in average by Coupled Channel Equivalent Potential (CCEP) approach

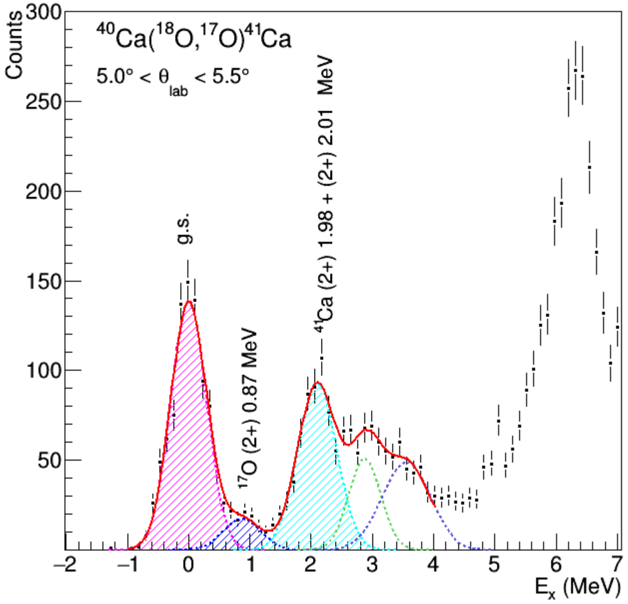
The $^{40}Ca(^{18}O,^{19}F)^{39}K$ 1p- and $^{40}Ca(^{18}O,^{17}O)^{41}Ca$ 1n-transfer @ 15 MeV/u

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



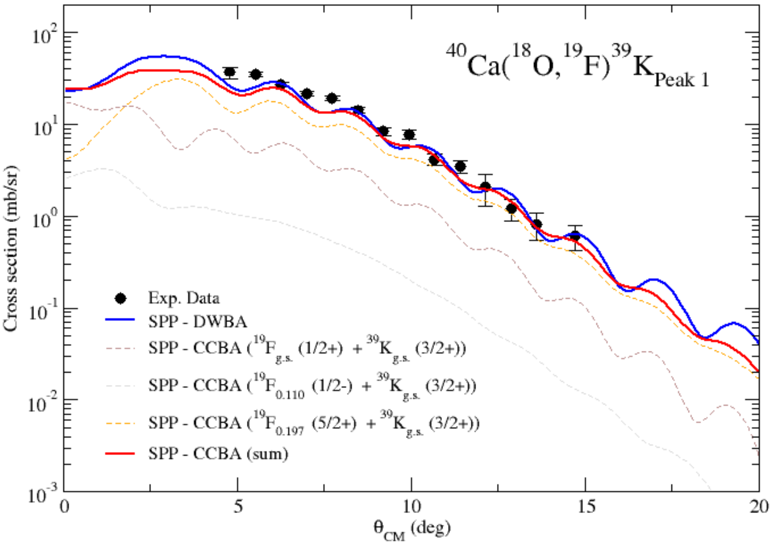




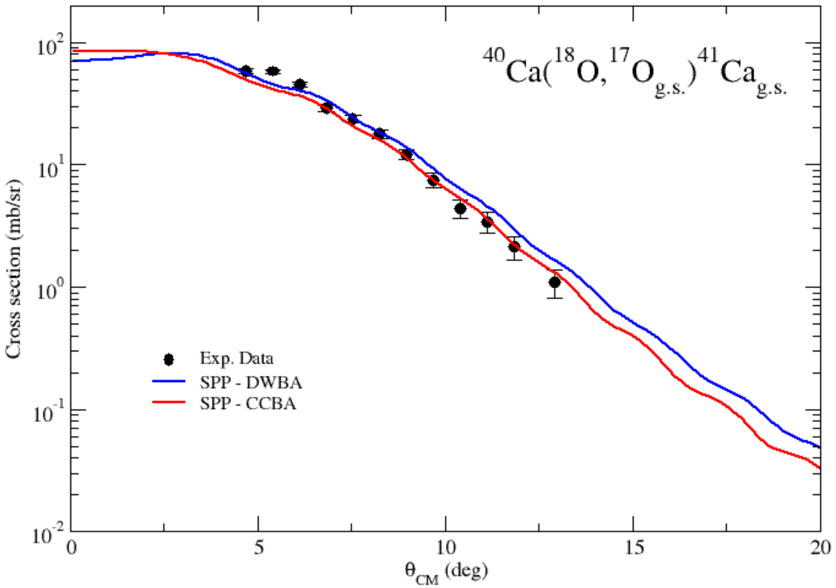


CCBA analysis with shell model amplitudes

- ^{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

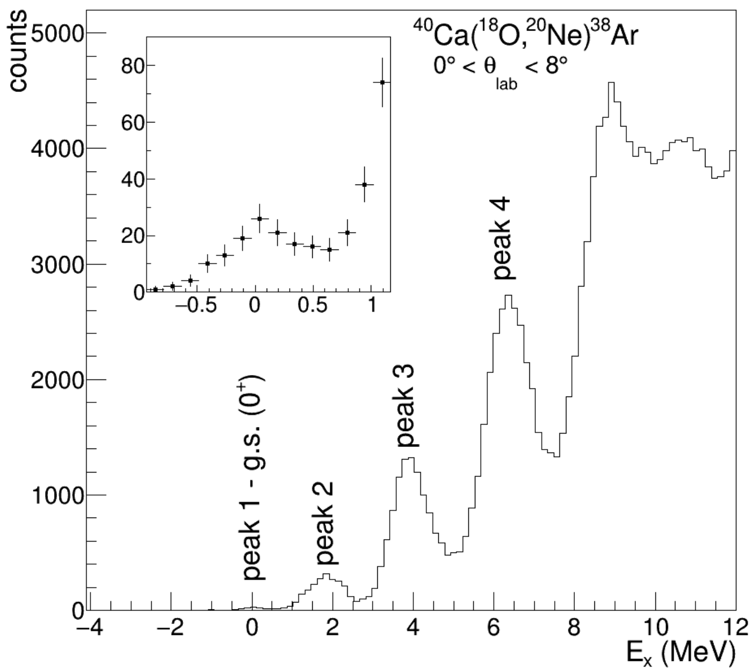


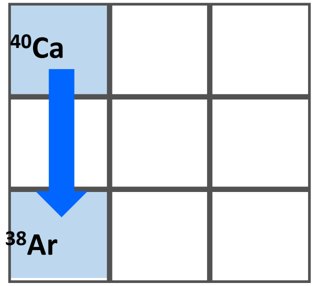
The optical potential is extracted from our analysis of elastic and inelastic scattering data with double folding potentials



The $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ 2p-transfer @ 15 MeV/u

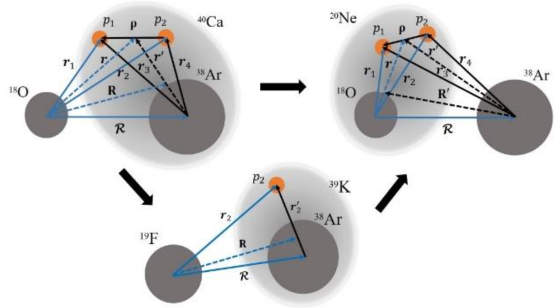
J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604

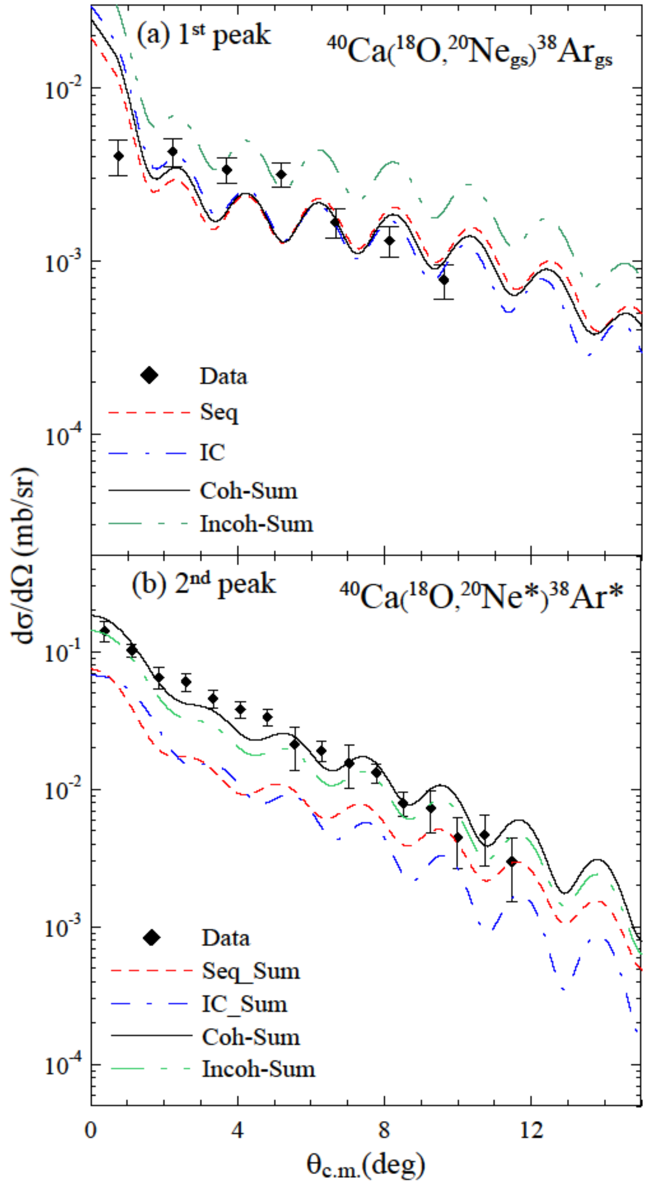




CCBA analysis based on **direct** and **sequential** transfer with shell model amplitudes

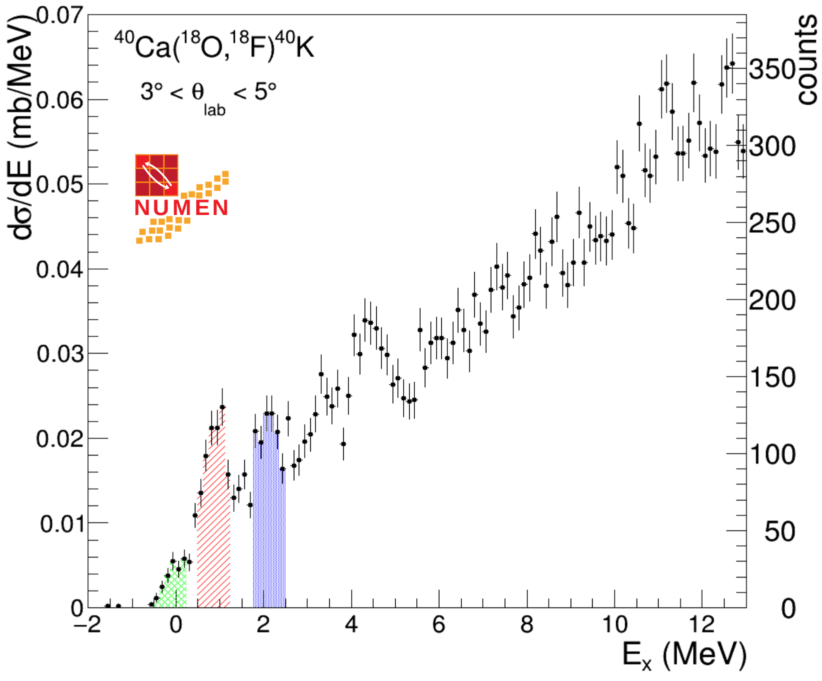
The optical potential is extracted from analysis of elastic and inelastic scattering data



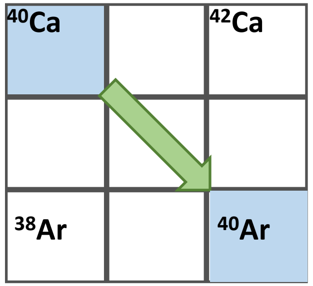


The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 15 MeV/u

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

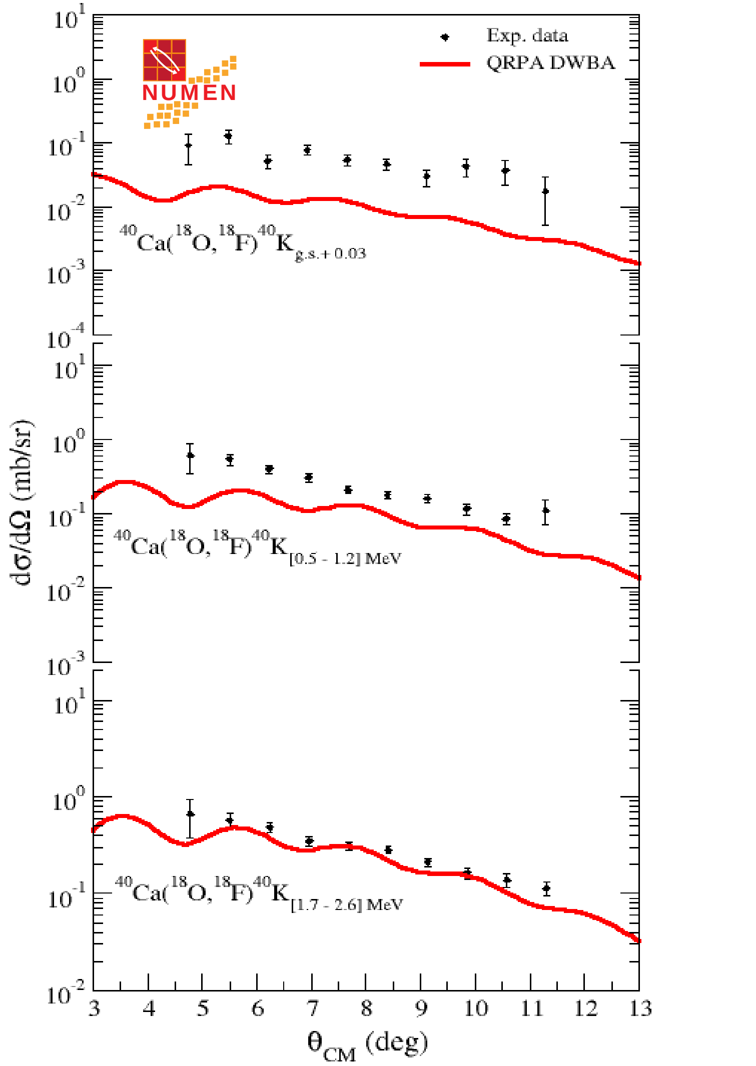


Direct meson exchange



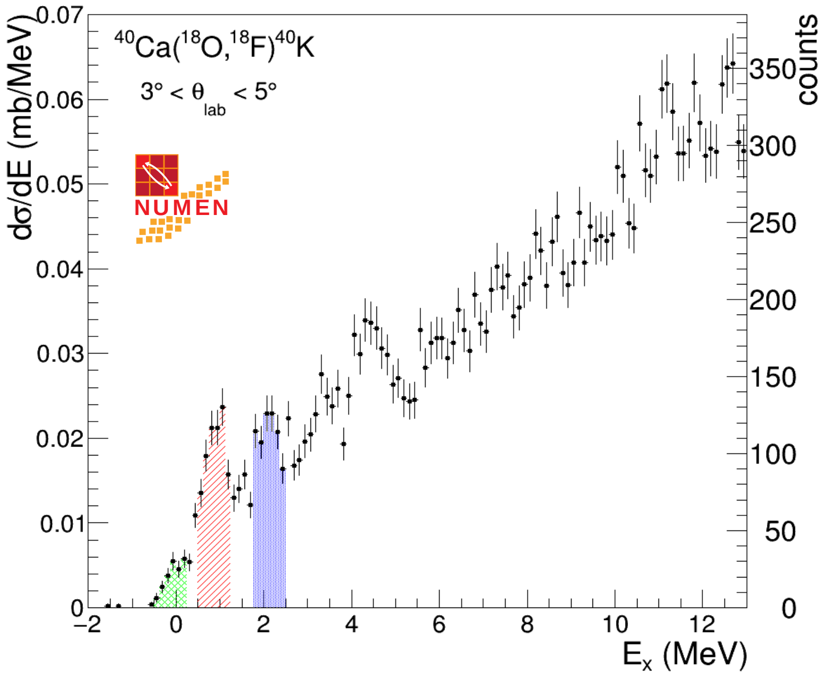
DWBA analysis based on double folding form factors of QRPA transition densities with NN isovector interaction

The optical potential is extracted from our CCEP data analysis of elastic and inelastic scattering data

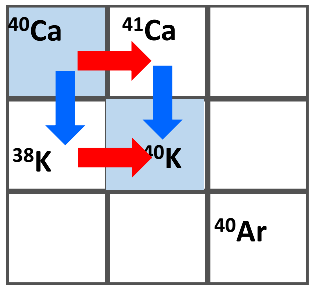


- Direct meson exchange mechanism important
- **Access to** Fermi, Gamow-Teller as well as **to high-multipole isospin response, relevant for $0\nu\beta\beta$**
- Two-step nucleonic SCE is expected to contribute more at lower excitation energy due to the best **kinematical matching**

The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 15 MeV/u

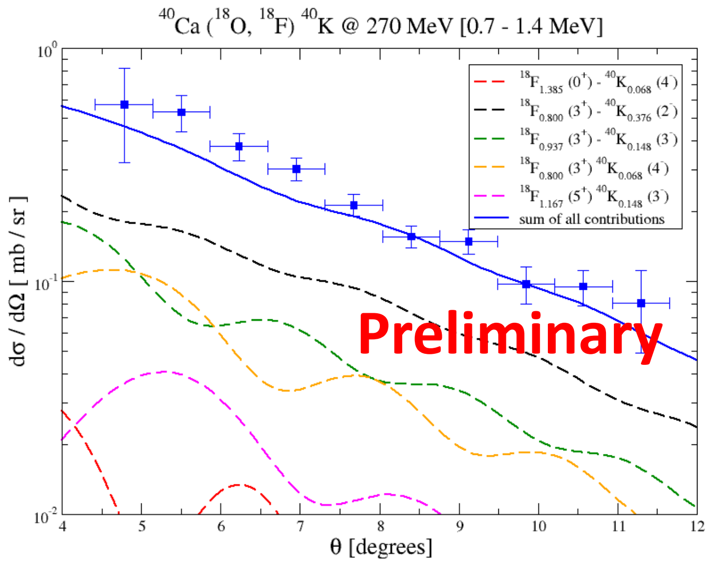


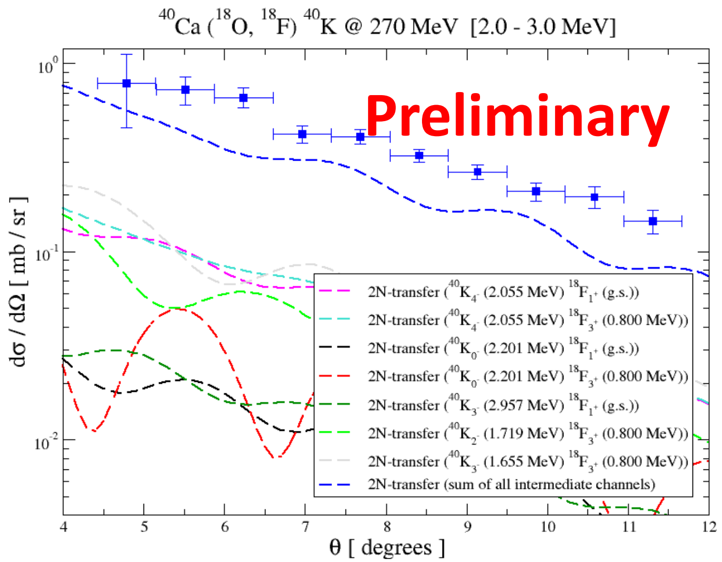
Two-step nucleonic transfer



The optical potential is extracted from analysis of elastic and inelastic scattering data

CCBA analysis with shell model amplitudes



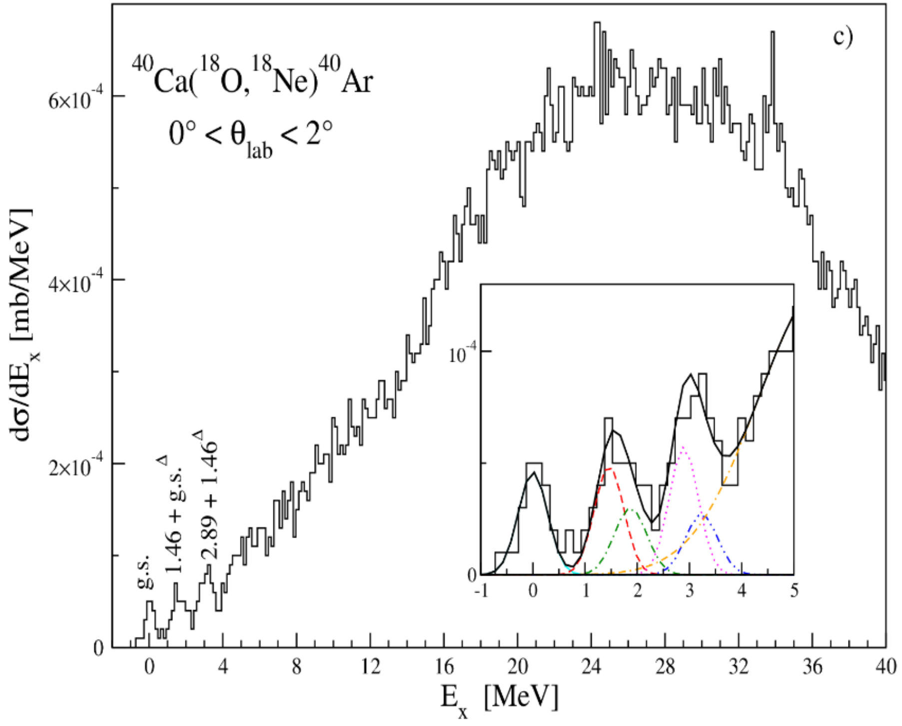


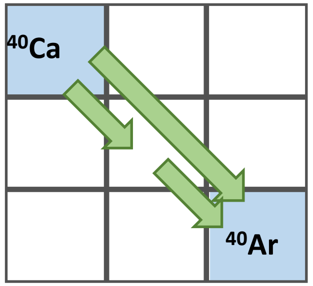
- **Two-step nucleonic SCE plays a role** and it is expected to contribute less at higher excitation energy due to the progressively worse kinematical matching

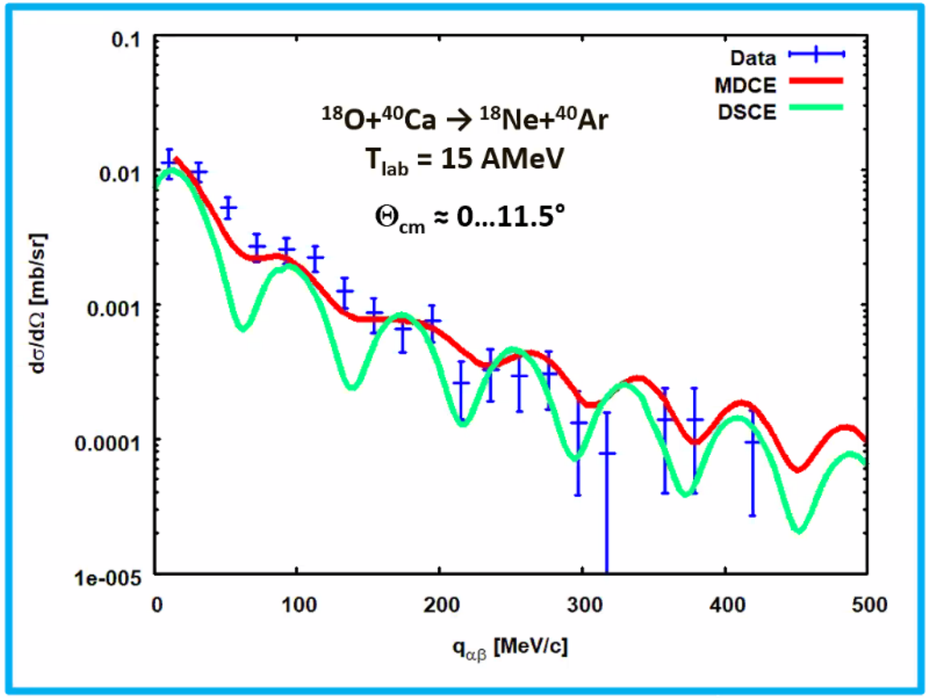
Calculations from S. Burrello

The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ double charge exchange @ 15 MeV/u

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







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

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

Access to g.s.-to- g.s transition for the first time

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

The sequential **multi-nucleon transfer** contribution has been demonstrated to be **negligible** for the $^{20}Ne+^{116}Cd$ DCE at 15 MeV/u

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

Present limitations and perspectives

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

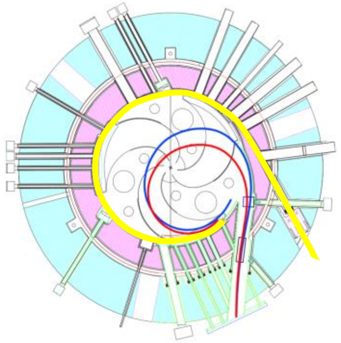
Systematic study of all the hot-cases

Much higher beam current is needed

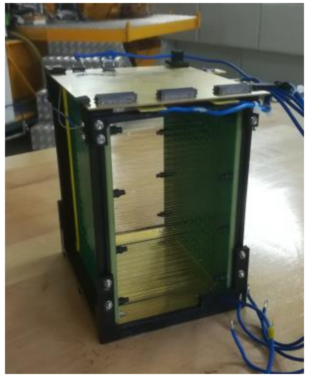
Scientific motivation for the **upgrade of the LNS superconducting cyclotron** and related infrastructures to deliver high intense beams (10kW)

POT lns

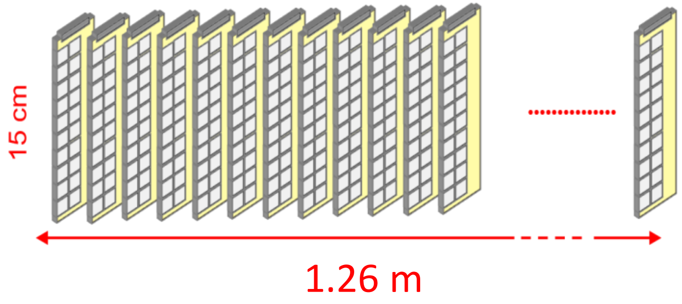
NUMEN TDR - F. Cappuzzello et al. Intern. Journ. of Mod. Phys. A 36, 30 (2021) 2130018



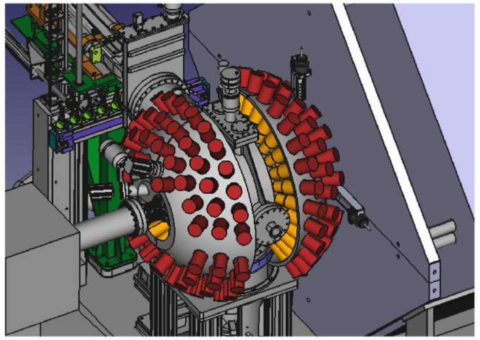
Superconducting cyclotron
Extraction by stripping (5-10 kW)



New tracker for the FPD
(THGEM technology)



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



New gamma-ray calorimeter
(LaBr3 scintillators)

Conclusions and Outlooks

- **Second order isospin excitations** of nuclei are key information **bridging the gap between nuclear and neutrino physics**
- **Magnetic spectrometry is a fundamental tool** for this challenging research program
- **Heavy-ion DCE reactions can significantly contribute in 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

Thank you