New results from the NUMEN project at the INFN LNS MAGNEX facility

F. Cappuzzello
University of Catania and INFN LNS

ISOLDE Superconducting Recoil Separator

ISRS Collaboration Meeting and Physics workshop

25–26 november 2024
CERN

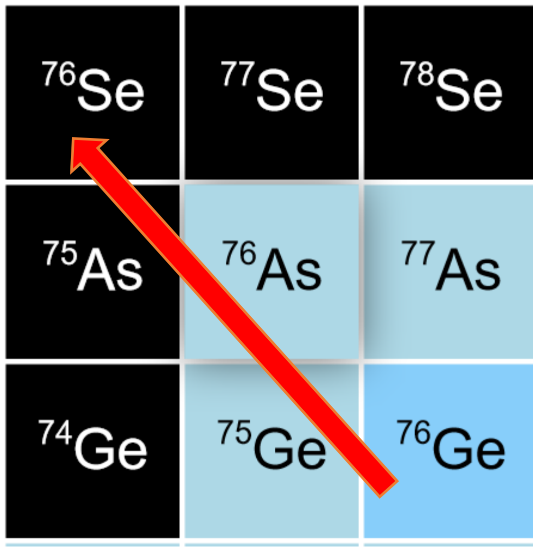
ββ decay

Open problems in modern physics:

Neutrino absolute mass scale

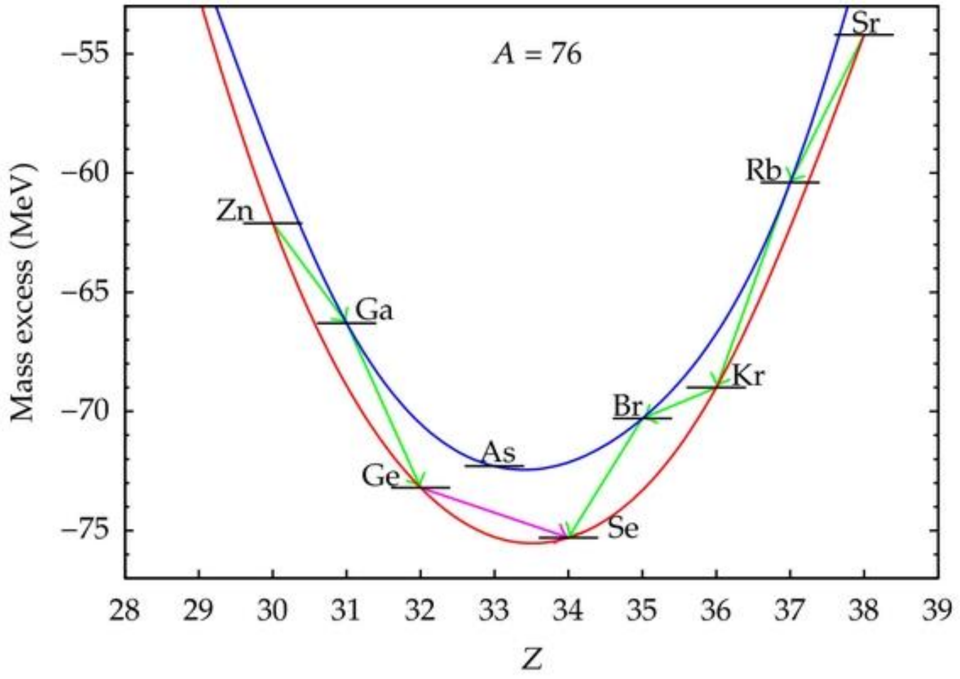
Neutrino nature

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



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

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 Physics **2023**, 95, 025002

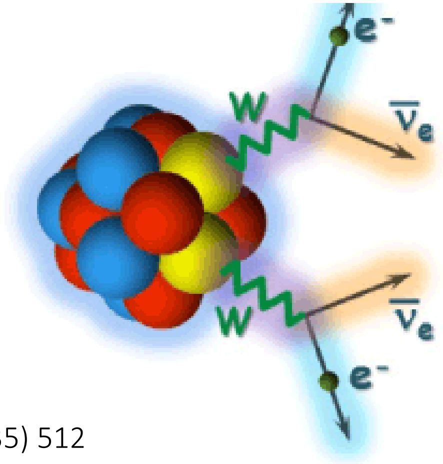
✓ Process mediated by the **weak interaction**

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

The double β-decay

Two-neutrino double beta decay

Observed in a dozen of nuclei since 1987



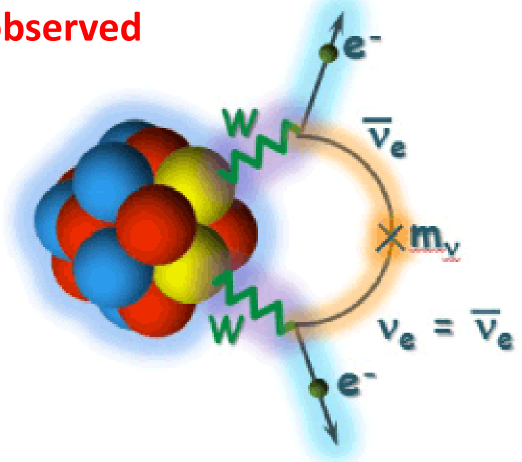
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

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 Grand Unification Theory**

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

The Nuclear Matrix Elements

New physics for the next decades

requiring

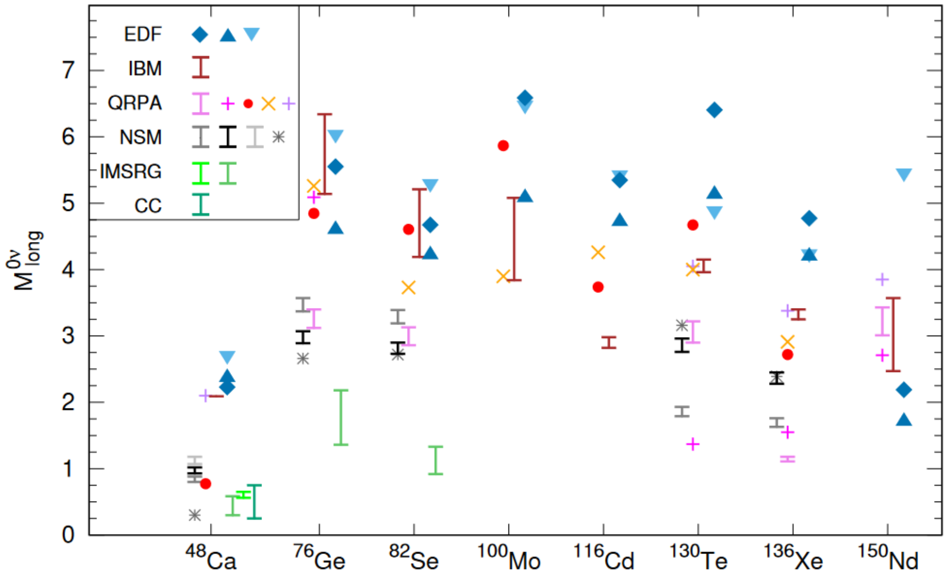
Nuclear Matrix Element (NME)!

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

- ✓ NMEs <u>are not</u> 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,** for which an exact solution is presently out of reach

- ✓ **State of the art calculations**: QRPA, Large scale shell model, IBM, EDF, ab-initio .....
- ✓ **Calculations** constrained mainly with known EM properties
- ✓ Still large uncertainties present

A recent review of NME calculations



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

Support from the experiments

Measurements (not yet strongly constraining the **0νββ** NME):

✓ **β**-decay and **2νββ**-decay

1st order isospin probes

2nd order isospin probes

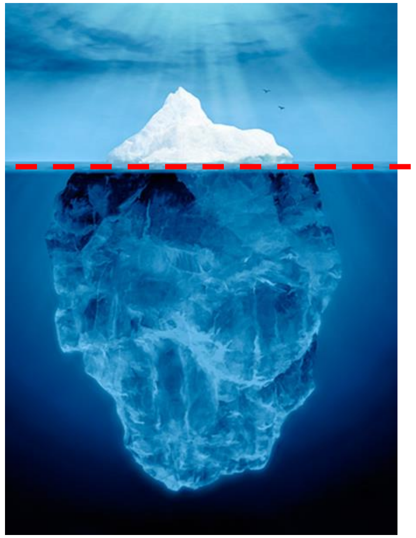
✓ **(π⁺,π⁻),** single charge exchange (SCE) **(^{3}He,t), (d,^{2}He), HI-SCE, electron capture,** transfer reactions, **μ-nucleus scattering**, **γ-ray spectroscopy, double γ-decay etc..**

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

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**

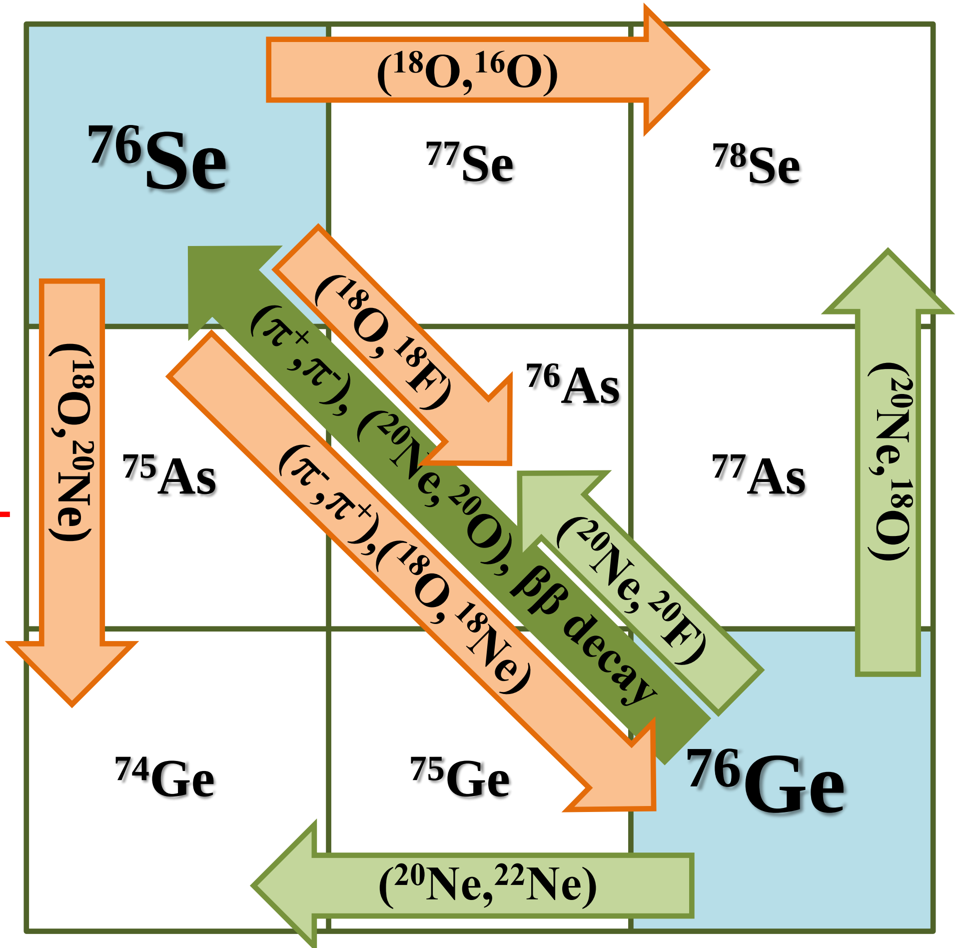
Tiny amount of DGT strenght for low lying states



Sum rule almost exhausted by DGT Giant Mode, still not observed

RIKEN

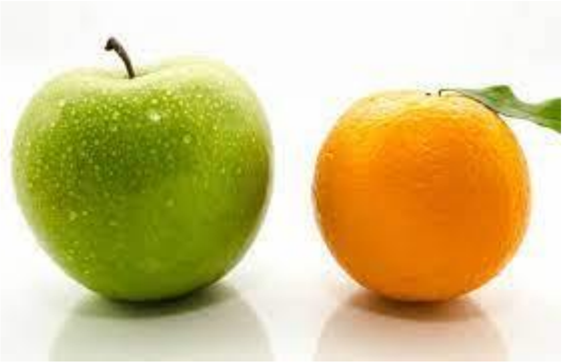
RCNP



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

Heavy-Ion induced Double Charge Exchange

Heavy-ion DCE can proceed via:

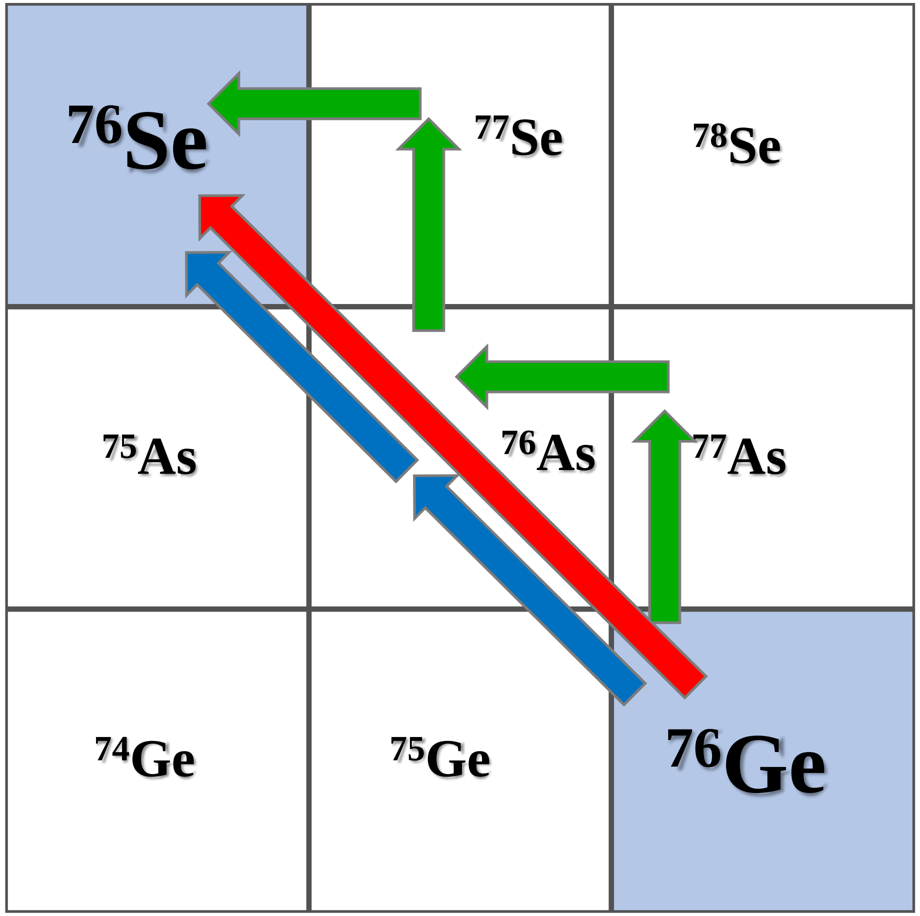
- Mean field driven processes

1) 4th-order sequential multi-nucleon transfer (TDCE) mediated by the nuclear mean-field J.L. Ferreira et al. PRC 105 (2022) 014630

- Collisional processes

2) Two-step DCE - Double single charge exchange (DSCE): two consecutive single charge exchange processes, mediated by NN isovector interaction. H.Lenske et al., Universe (2024), 10, 93

3) One-step DCE - Two-nucleon mechanism (MDCE): relying on short range NN correlations. H.Lenske et al., PPNP 109 (2019) 103716 and H.Lenske et al., Universe (2024), 10, 202



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

ELSEVIER

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

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,†]

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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

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† 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

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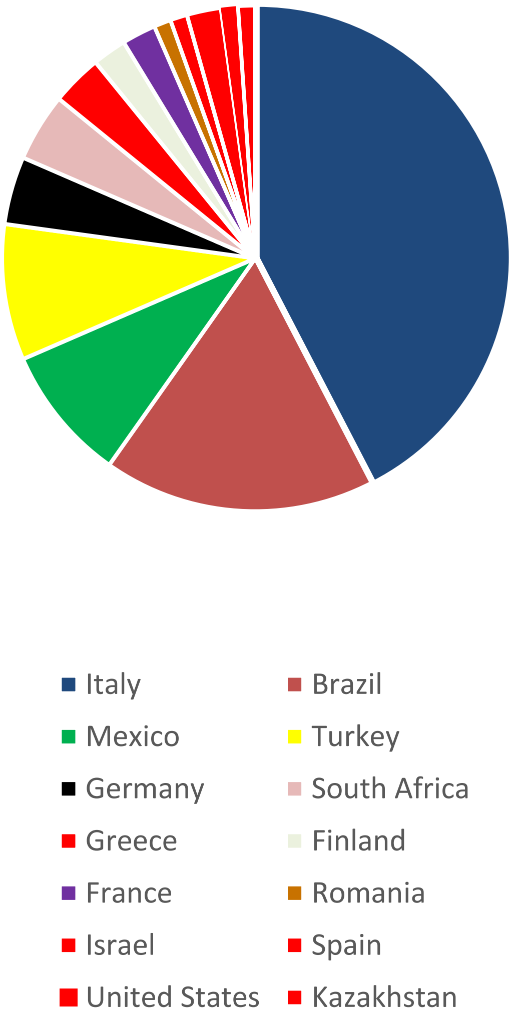
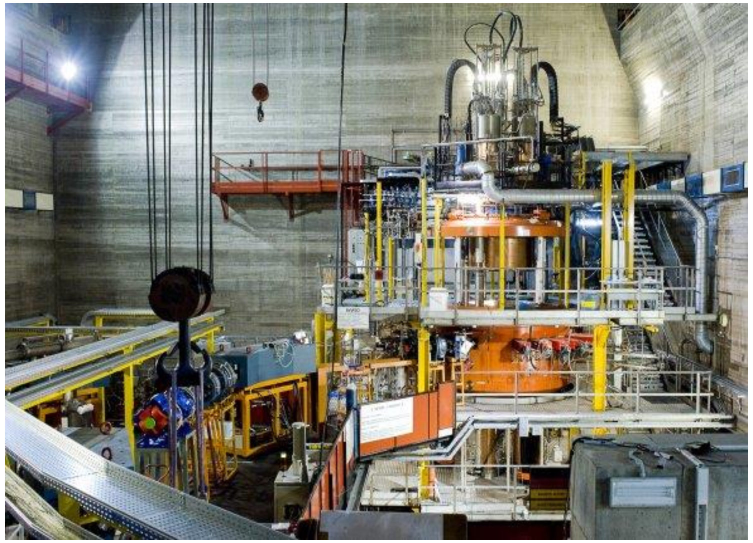
92 Researchers
36 Institutions
14 Countries

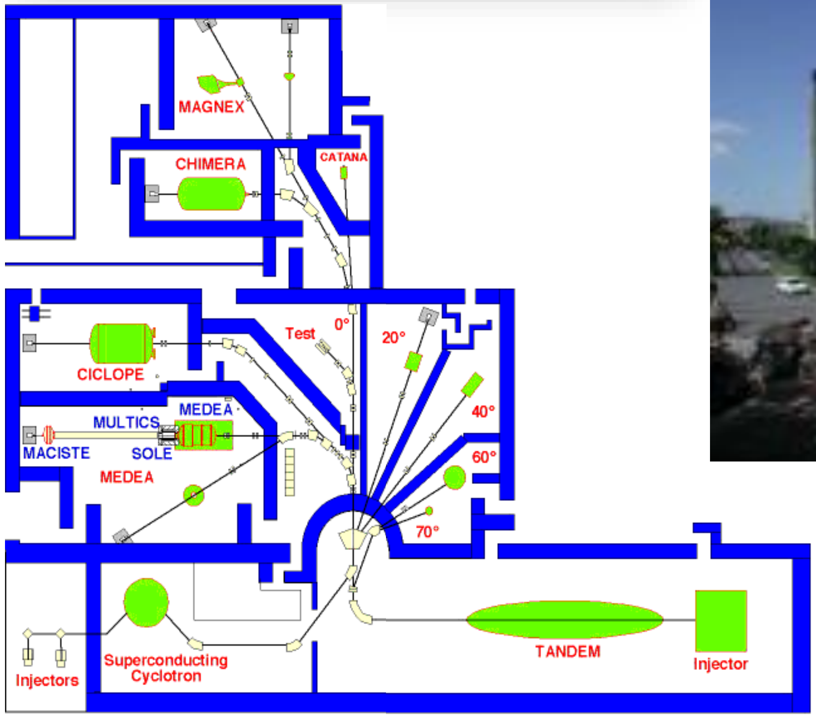


DCE @ INFN-LNS

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

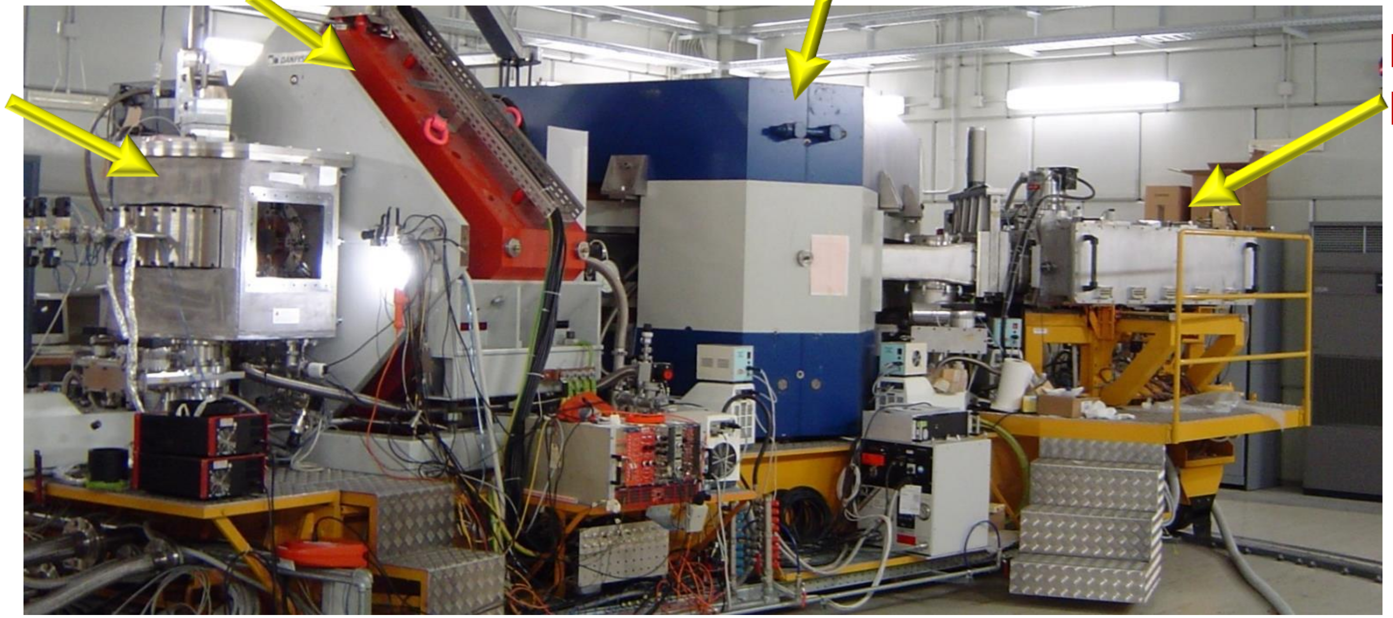
Optical characteristics	Measured values
Angular acceptance (Solid angle)	$50\ msr$
Angular range	$-20° \div +85°$
Momentum acceptance	$-14\% \div +10\%$
Momentum dispersion for $k = -0.104$	$3.68\ (cm/\%)$
Maximum magnetic rigidity	$1.8\ Tm$*

*presently being upgraded to 2.2 Tm

Quadrupole

Dipole

Scattering Chamber



Focal Plane Detector

Measured resolution:

Energy $\Delta E/E \sim 1/1000$

Angle $\Delta\theta \sim 0.3°$

Mass $\Delta m/m \sim 1/300$

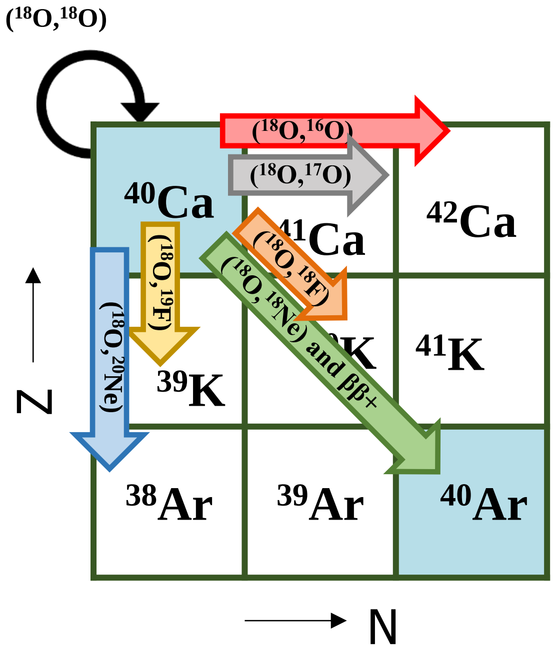
A **wide mass range** (from protons to medium-mass nuclei)

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 0νββ**



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

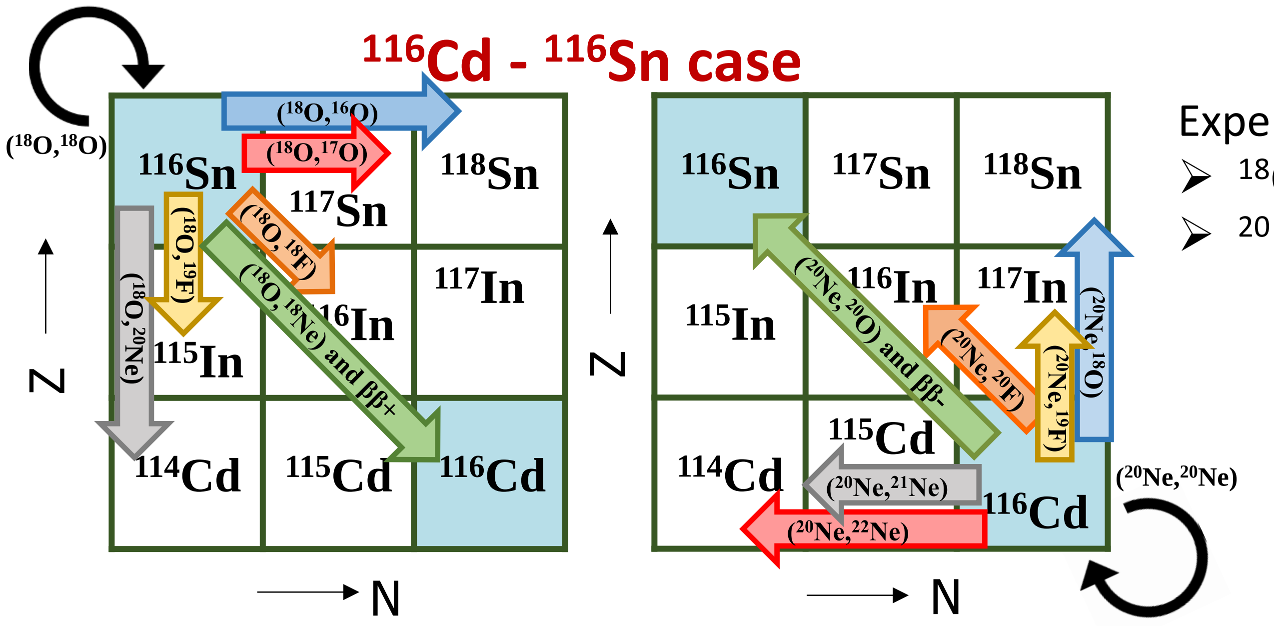
Double charge exchange (DCE) → nuclear response to 2nd order isospin operators (Two-Body Transition Densities)

The NUMEN multi-channel vision

- ✓ Measuring all the accessible quasi-elastic channels **all at once** 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



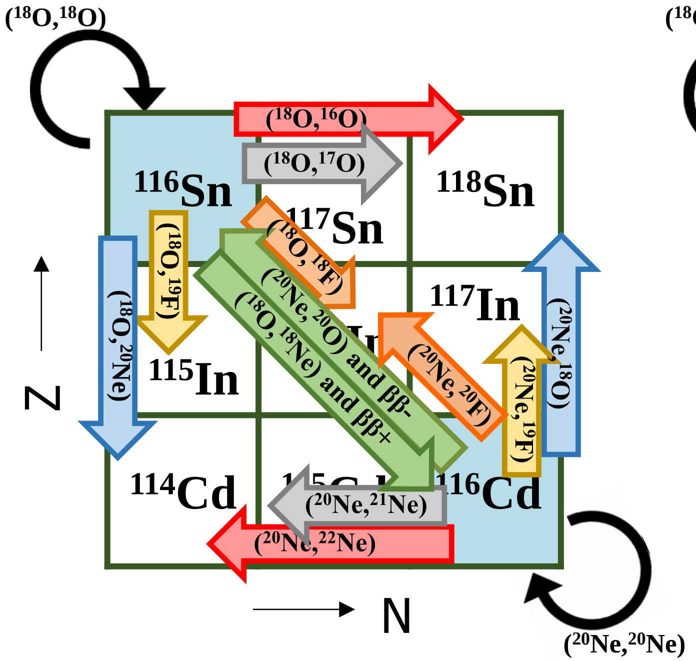
Experiments @ 15 MeV/A

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

Systems of interest for 0νββ already explored

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

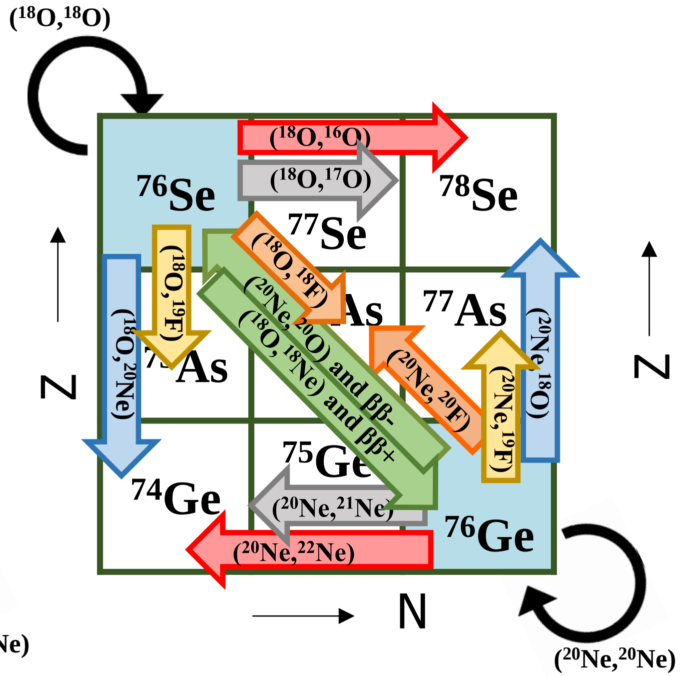
@ 15 AMeV
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



- 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
- I. Ciraldo et al. Res. In Phys. (2024) accepted

^{76}Ge – ^{76}Se case

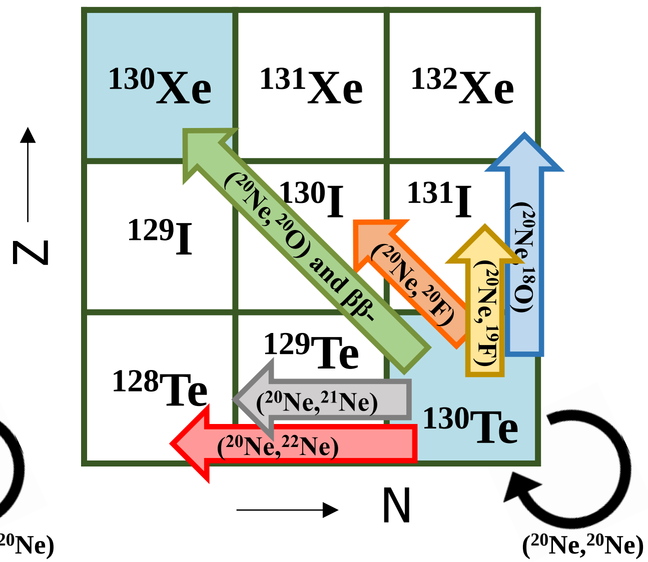
@ 15 AMeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



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

^{130}Te – ^{130}Xe case

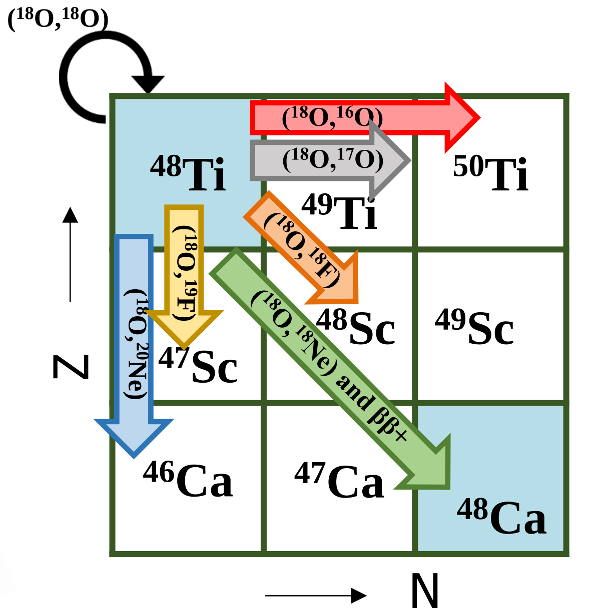
@ 15 AMeV
- ^{20}Ne + ^{130}Te



- 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



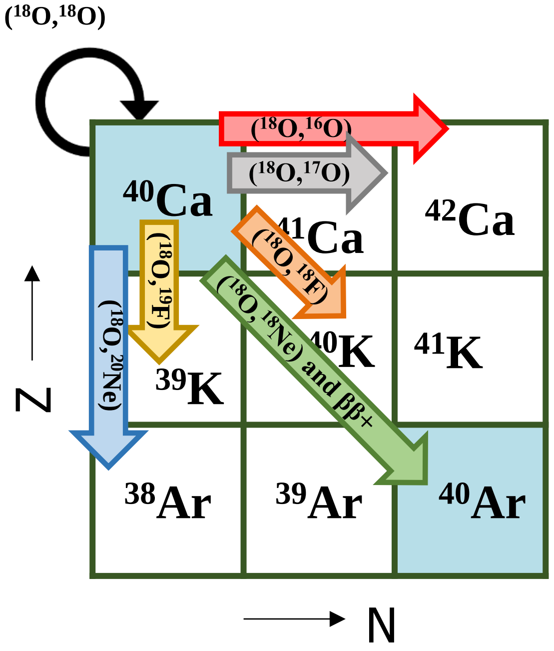
- O. Sgouros et al., PRC 104 (2021) 034617
- G. Brischetto et al., PRC 109 (2024) 014604
- O. Sgoursos et al. PRC 108 (2023) 044611

Other explored systems, relevant for the reaction mechanism

^{40}Ca – ^{40}Ar case

@ 15 AMeV

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

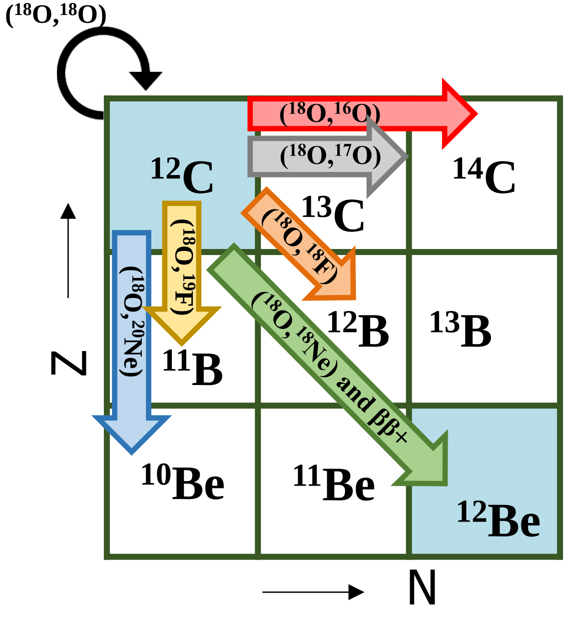


- ✓ M. Cavallaro et al., Front. Astr. Space Sci. (2021) 8:659815
- ✓ S. Calabrese et al., Phys. Rev. C (2021) 104, 064609
- ✓ J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604
- ✓ F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145
- ✓ B.A. Urazbekov, PRC 108 (2023) 064609
- ✓ B.A. Urazbekov, PRC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

^{12}C – ^{12}Be case

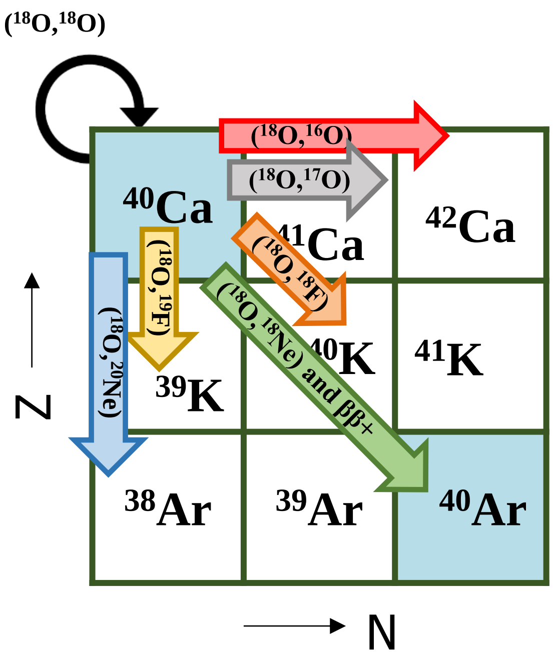
@ 15 AMeV and @ 22 AMeV

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

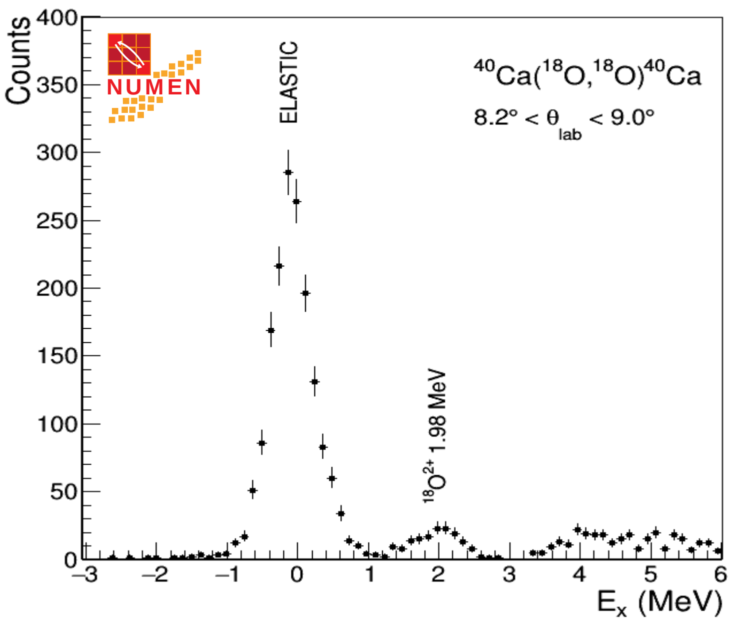


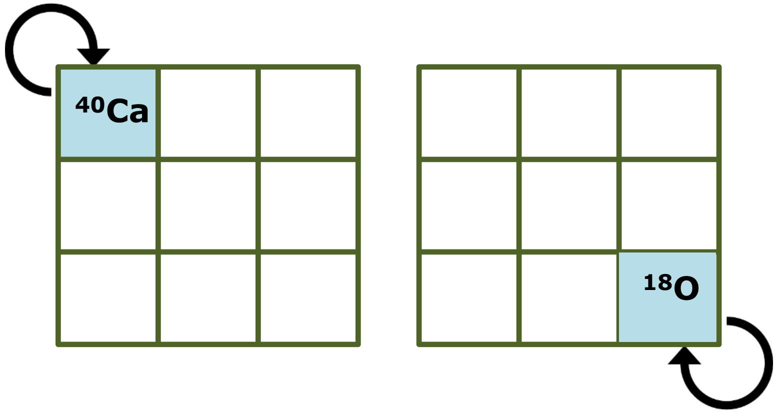
- ✓ A. Spatafora et al., Phys. Rev. C (2023) 107, 024605
- ✓ A. Spatafora et al., Phys. Rev. C accepted
- ✓ B. Urazbekov et al. Phys. Rev. C submitted

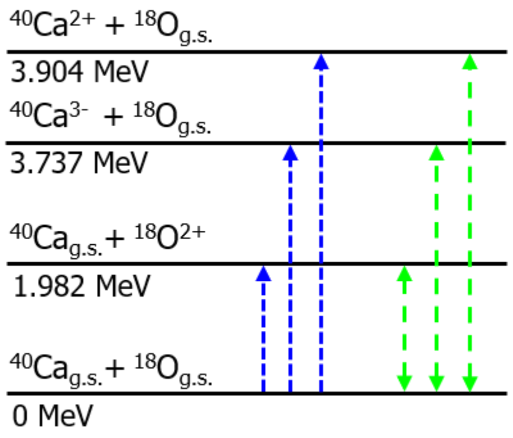
The multichannel approach at work: the ^{18}O + ^{40}Ca @ 270 MeV case

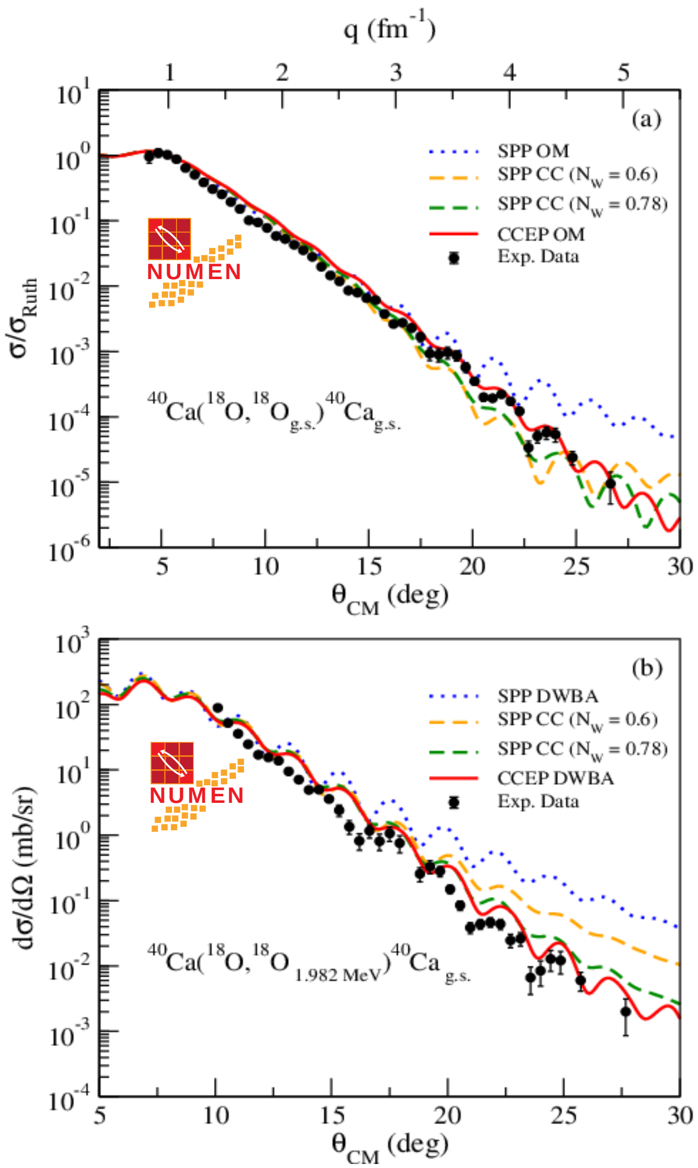


The $^{40}Ca(^{18}O,^{18}O)^{40}Ca$ elastic and inelastic scattering @ 270 MeV









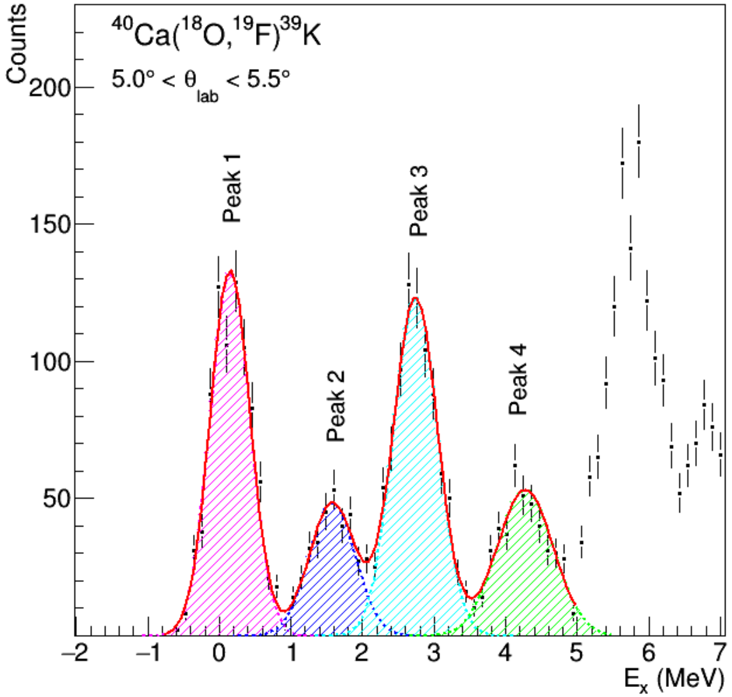
Key information from scattering data analysis:

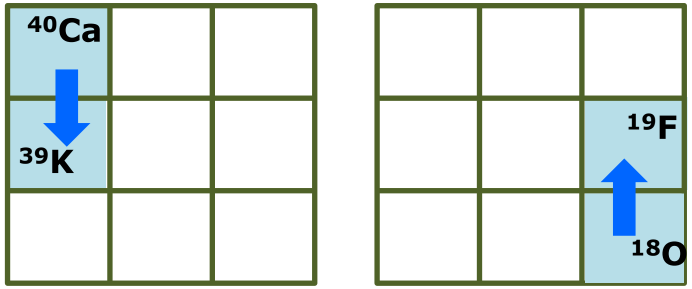
- Double folding Sao Paulo Potential works well
- **Coupling to low-lying 2^+ and 3^- states of ^{18}O and ^{40}Ca states is important**
- Effects of coupling can be accounted for in average by Coupled Channel Equivalent Potential (CCEP) approach

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

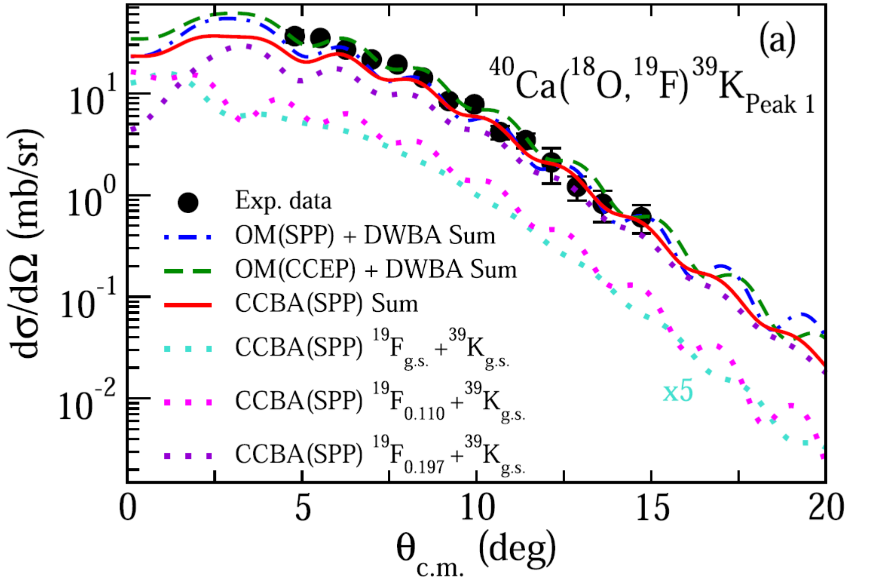
The ^{40}Ca(^{18}O,^{19}F)^{39}K 1p transfer @ 270 MeV

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)

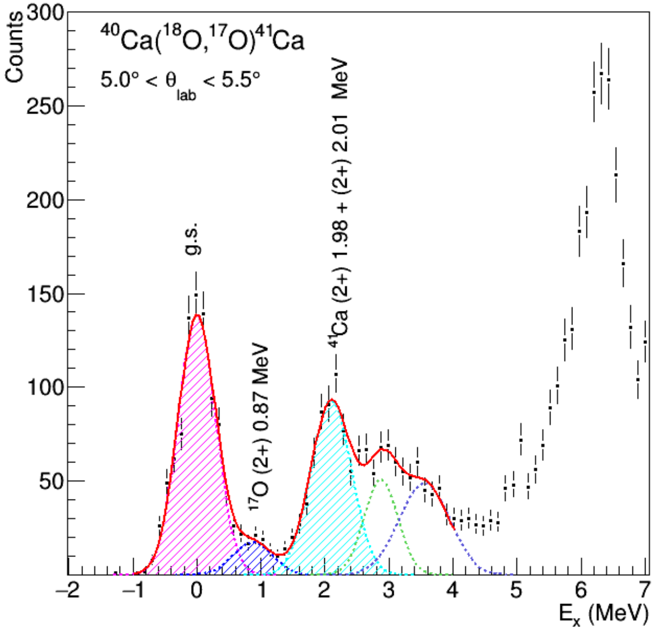
- ^{4}He as core, $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ $1d_{3/2}$ active orbitals with *p-sd-mod* interaction for projectile
- ^{28}Si as a core, $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$, $2p_{3/2}$ active orbitals with *ZBM2-modified* interaction for the target

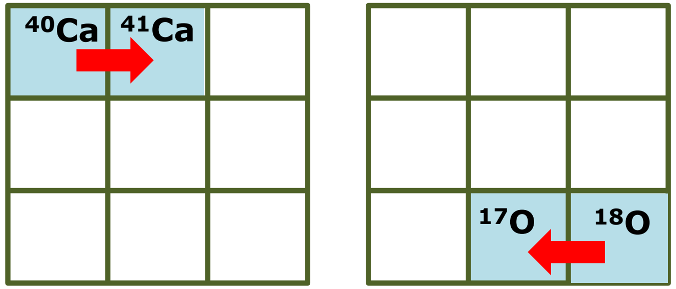
Key information from 1p transfer:

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

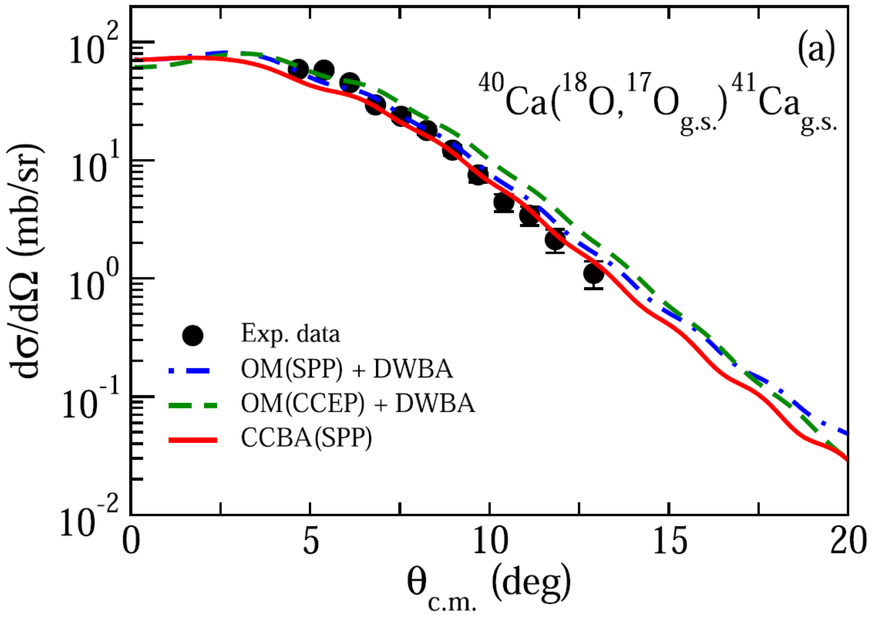
The $^{40}Ca(^{18}O,^{17}O)^{41}Ca$ 1n transfer @ 270 MeV

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



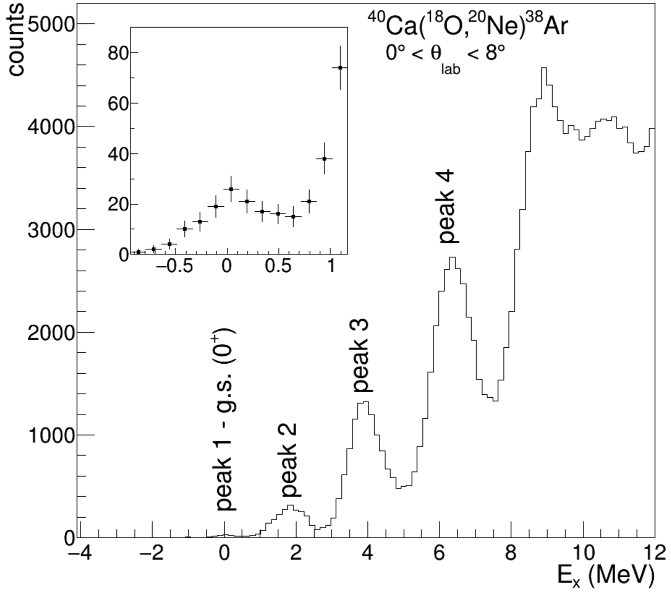
S. Calabrese et al., Phys. Rev. C 104, 064609 (2021)

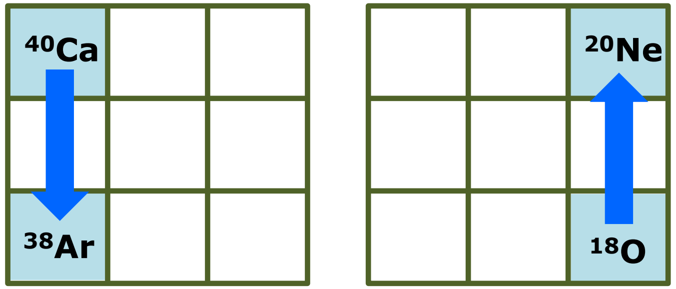
Key information from 1n transfer:

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

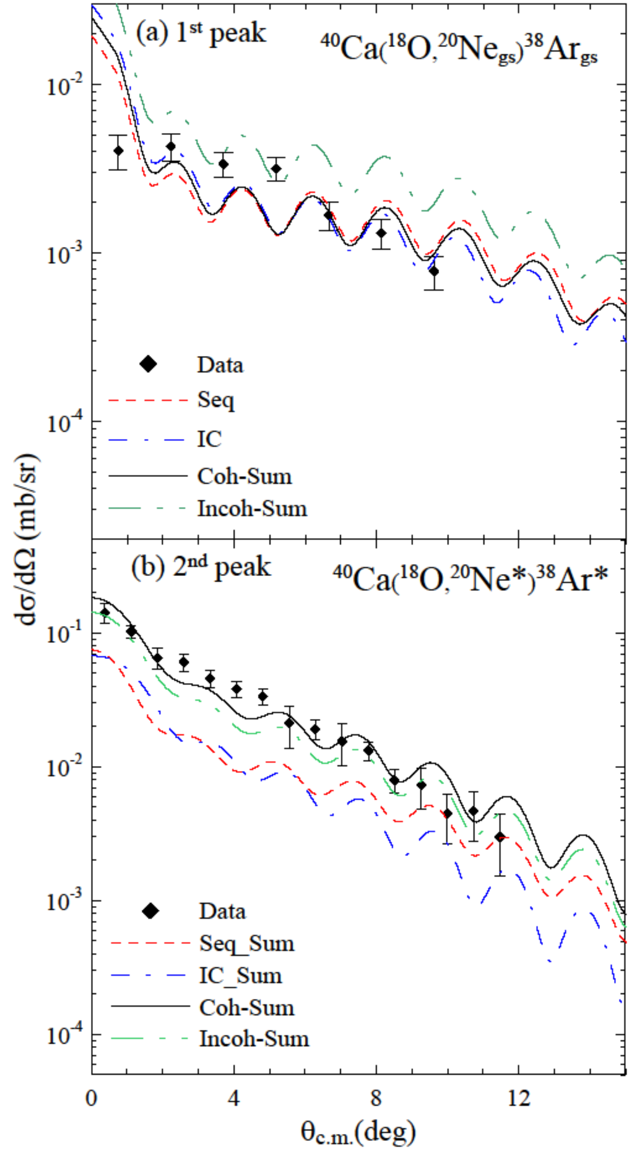
The $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ 2p transfer @ 270 MeV

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

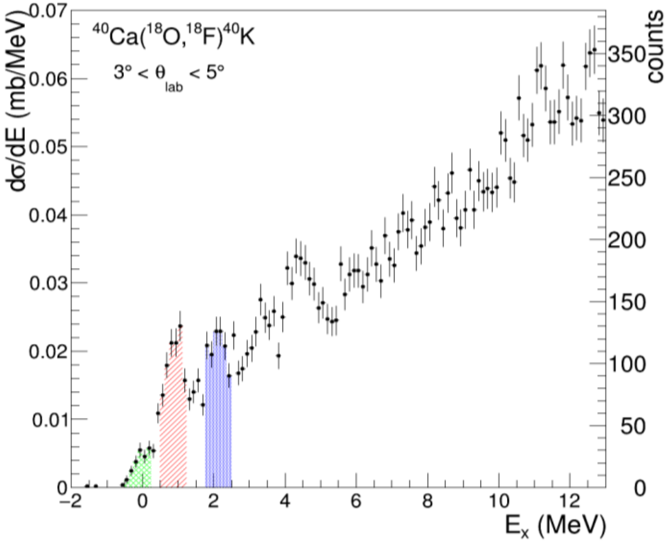


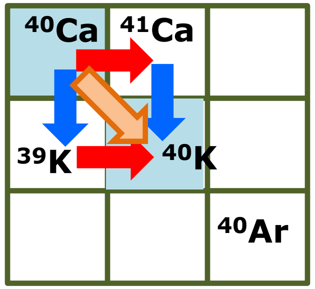
Key information from 2p transfer:

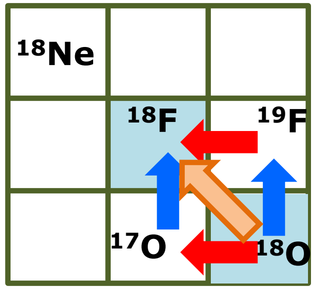
- **Very low cross section** (comparable with DCE) for low-lying states (poor kinematic matching)
- **Competition** between **one step** and sequential **two-step** mechanisms
- **Good description of the data from CCBA constrained approach**

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

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



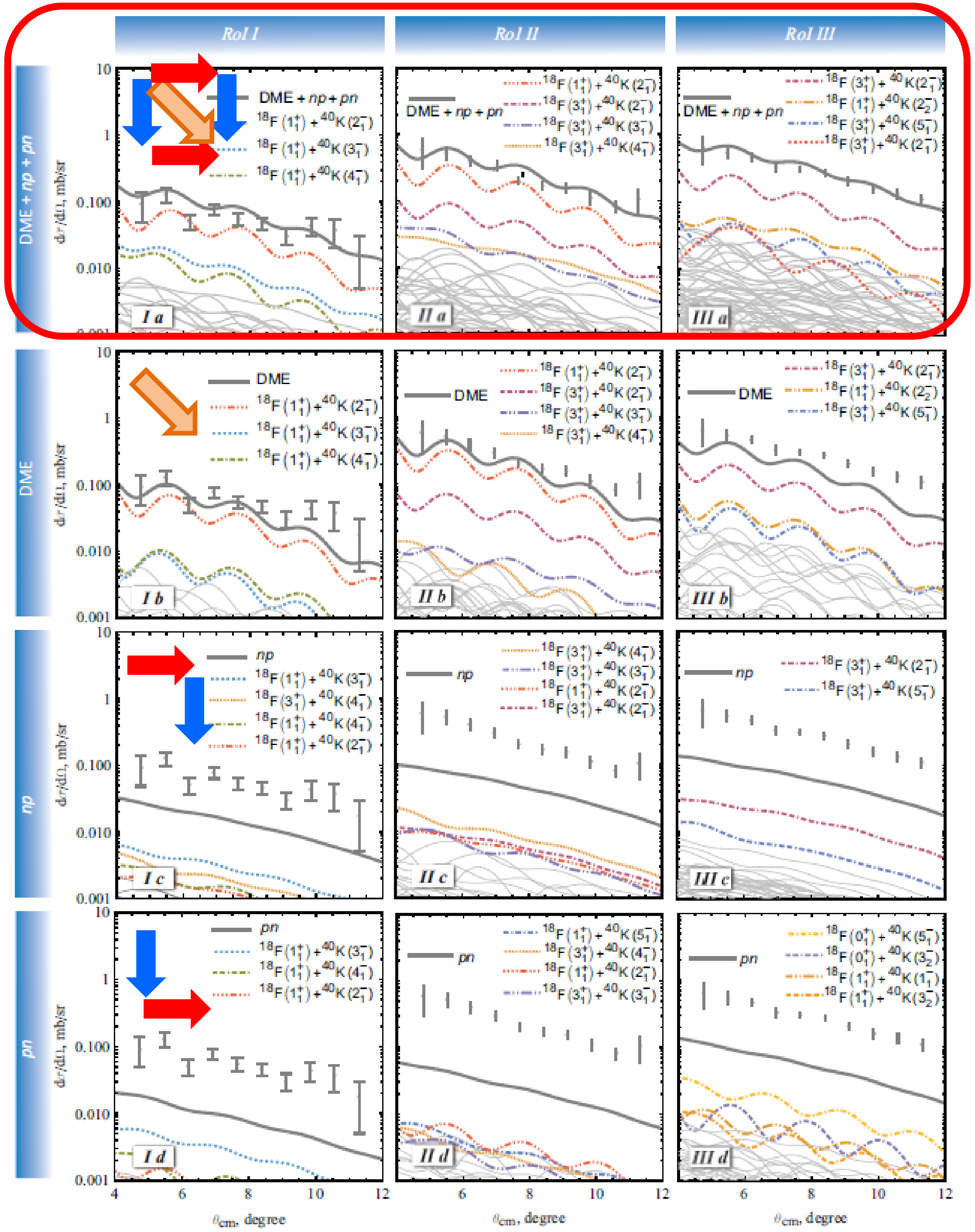




DWBA analysis based on the **coherent sum** of direct meson exchange and two-step nucleon transfer

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

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

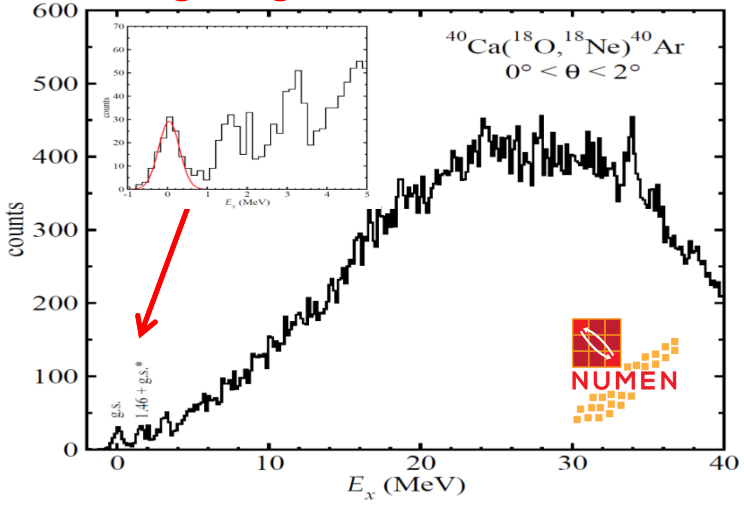


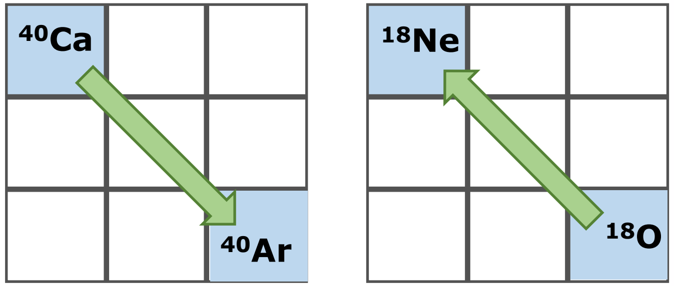
B. Urazbekov et al., Phys. Rev. C submitted

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

Access to ground-to-ground state transition

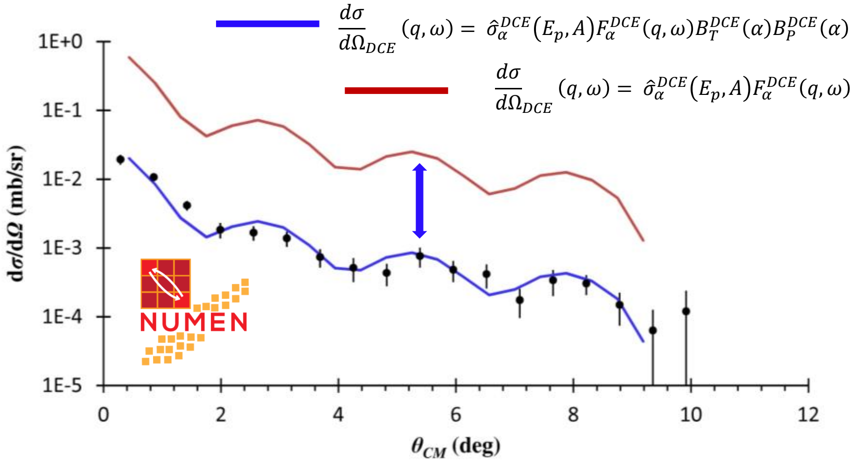
$\sigma_{g.s.\rightarrow g.s.} = 35 \pm 2$ nb

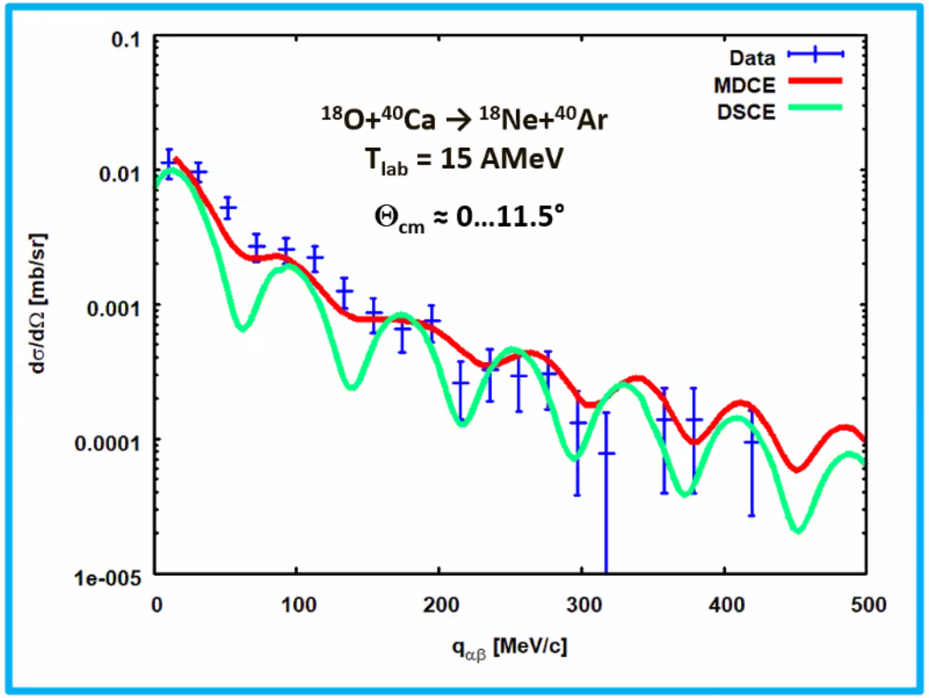




$$\left|M_{\sigma\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.2 \pm 0.6$$

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





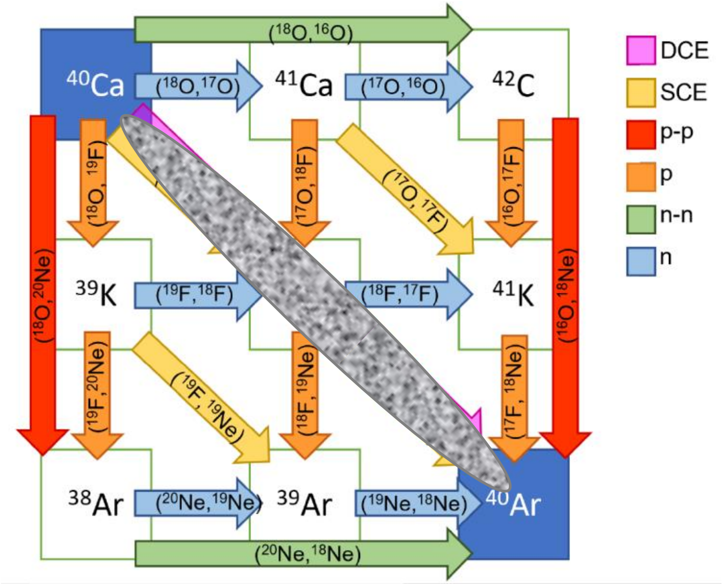
2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$

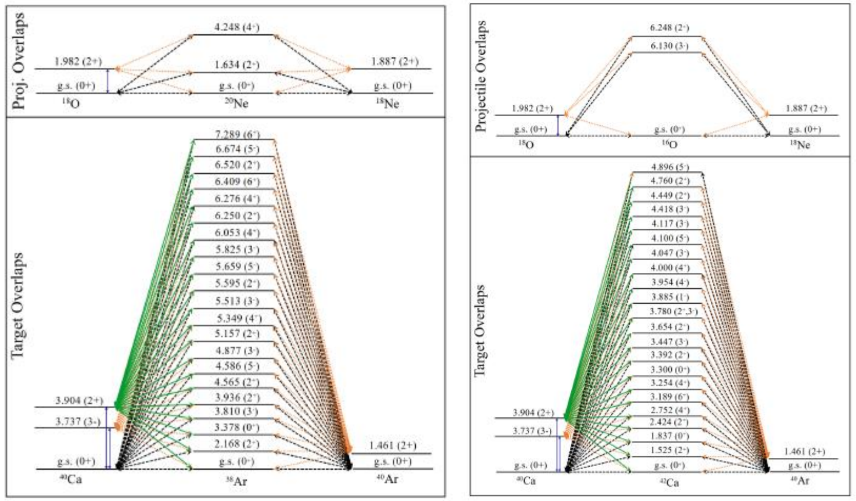
1-step MDCE: $^{40}Ca(0^+) \rightarrow ^{40}Ar([n^{-2}p^2]0^+)$: J=0+ with L=S=0 & $[L=2 \times S=2]_{0+}$

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

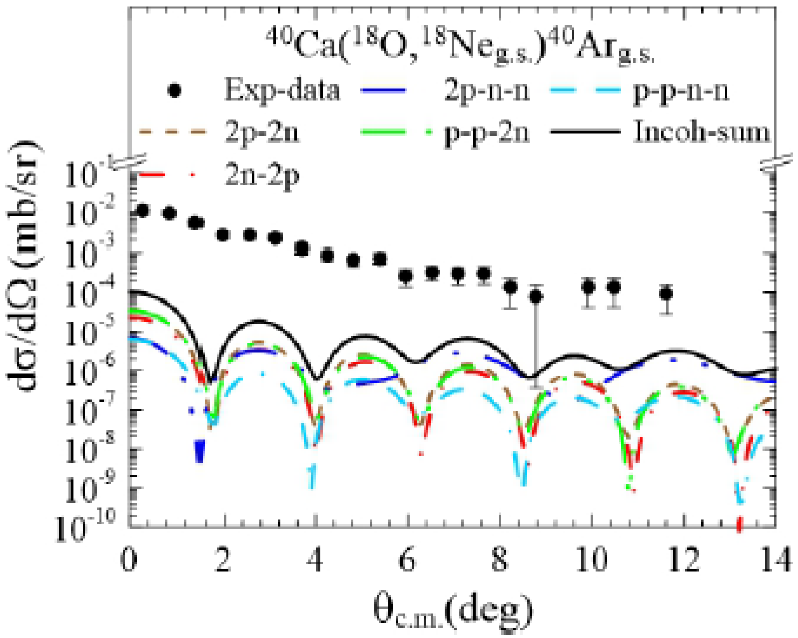
F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145

The TDCE multi-nucleon transfer mechanisms





- ✓ 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*

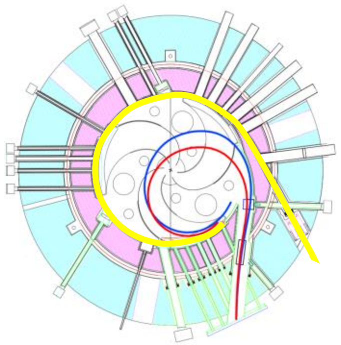
Present limitations and perspectives

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

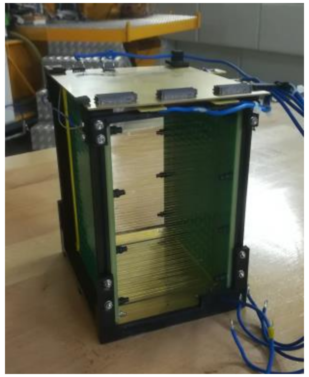
Systematic study of all the hot-cases

Much higher beam current is needed

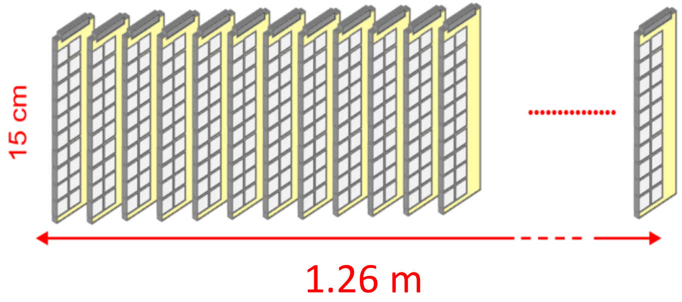
Physics case for the **upgrade of the LNS CS** and related infrastructures towards high intense beams (from the present 100 W to the foreseen 10 kW)



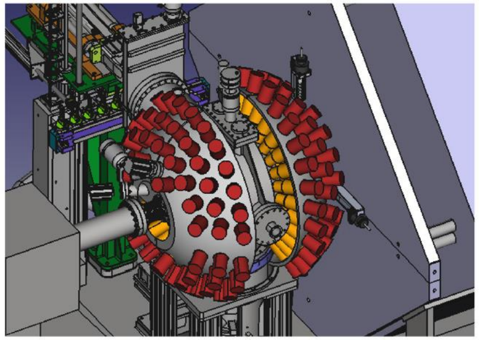
CS extraction by stripping



New tracker for the FPD
(THGEM technology)



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



New gamma-ray calorimeter
(110 LaBr3 scintillators)

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

Conclusions

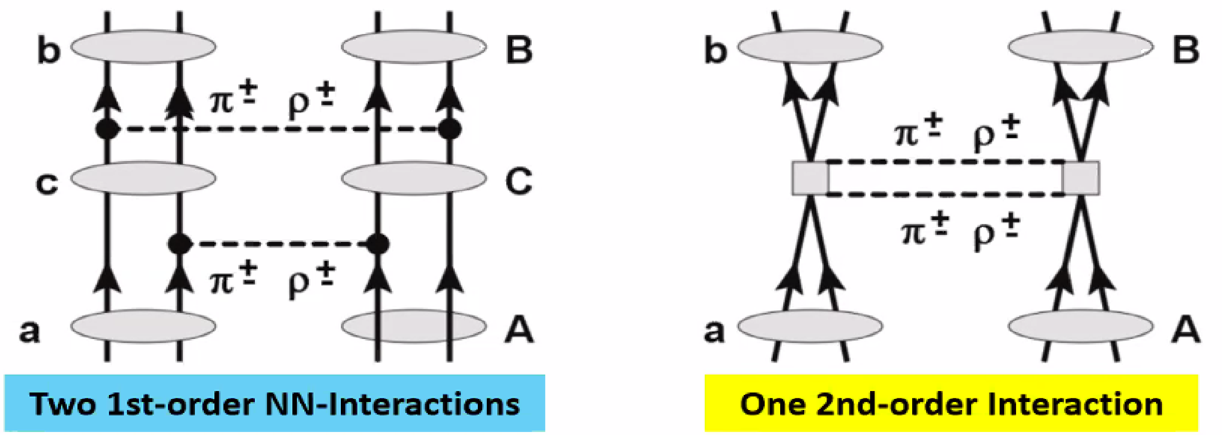
- **Second order isospin excitations** of nuclei **bridge the gap between nuclear and neutrino physics**
- **Heavy-ion DCE reactions can significantly contribute to this research field,** providing that nuclear structure and reaction aspects are accurately and consistently addressed
- **Multi-channel 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 0νββ decay **with the high intensity beams**

Thank you

The two competing hadron mechanisms for HI-DCE



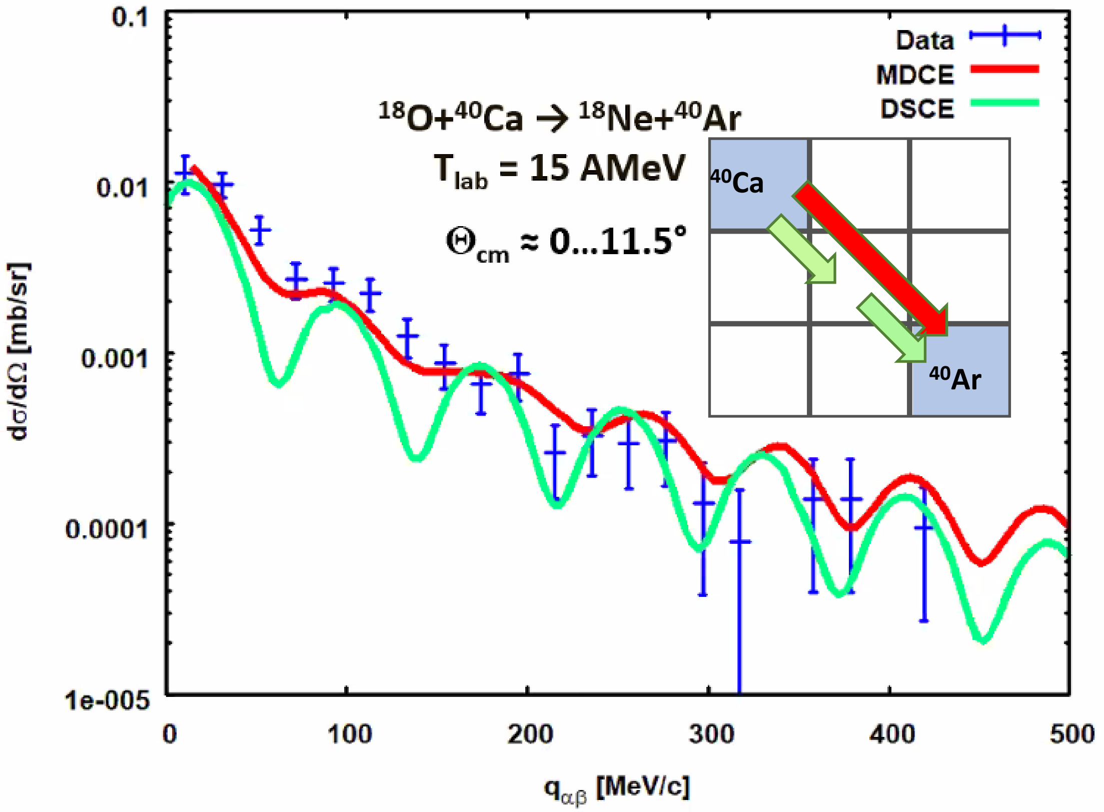
DSCE: Sequential single-meson exchange
H.Lenske et al., Universe (2024), 10, 93

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

Caveat:

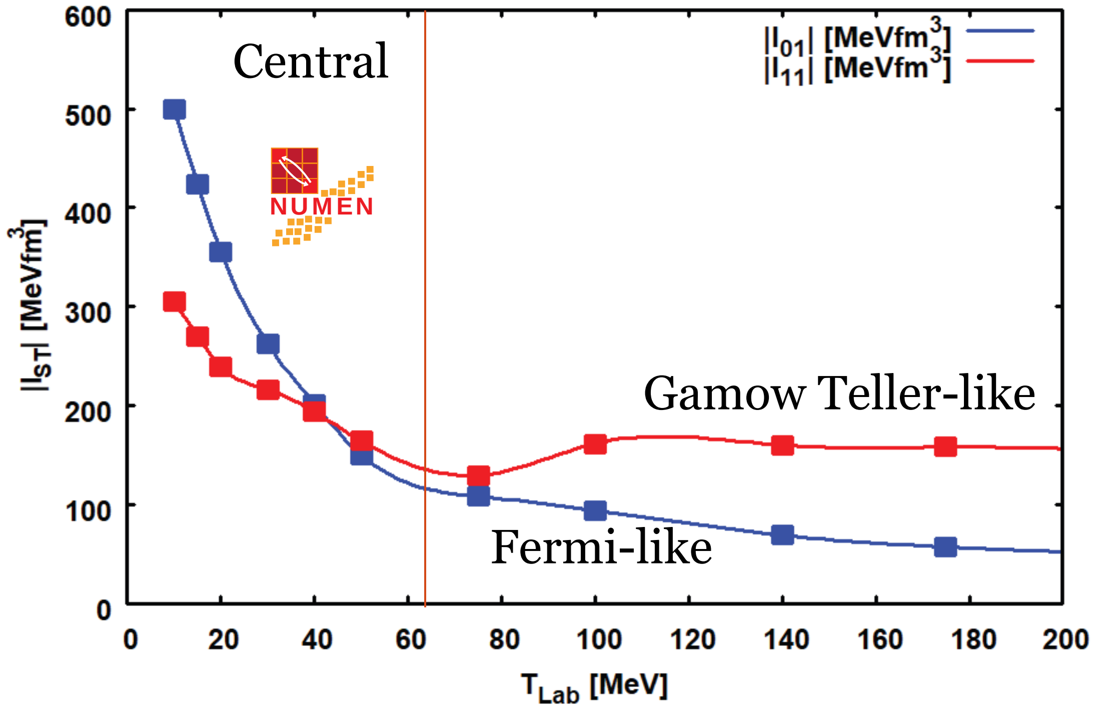
- ✓ Only Nπ-correlations included
- ✓ Off-shell momentum structure approximated with on-shell component (T-matrix instead of G-matrix)

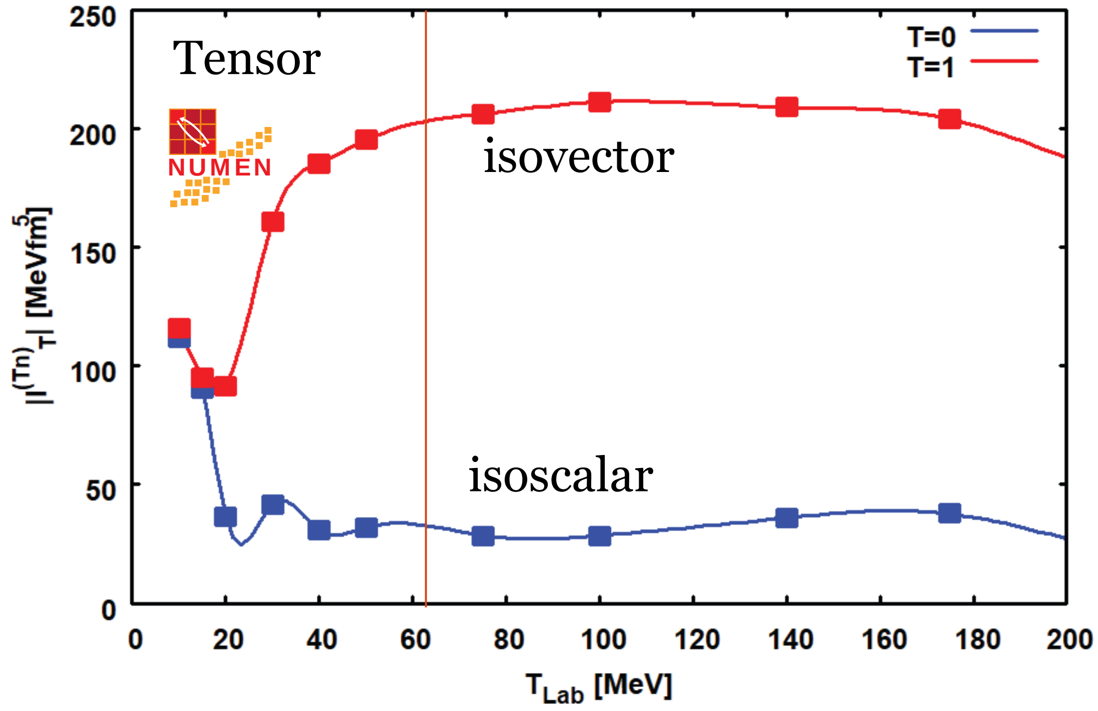
- ✓ ISI and FSI ion-ion interaction from double folding (constrained by elastic and inelastic data)
- ✓ QRPA transition densities for microscopic form factors
- ✓ One-step DWBA for MDCE and two-step DWBA for DSCE



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 & $[L=2 \times S=2]_{0+}$

… and NN T matrices



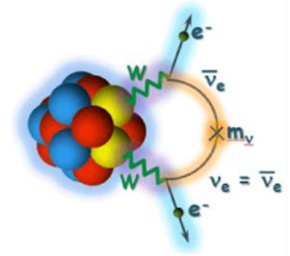


The T–matrices at T_{Lab} < 100 MeV have been **newly determined** while at higher energies the results of Franey and Love are used

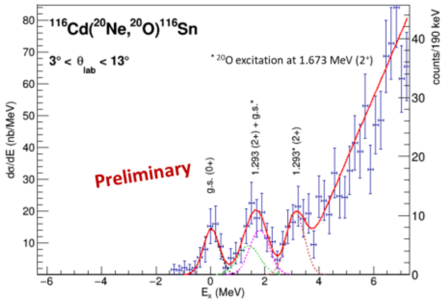
At the energy spanned by NUMEN the NN-T matrix changes significantly, making it easier to disentangle the individual components from experiments at different incident energy

Outline

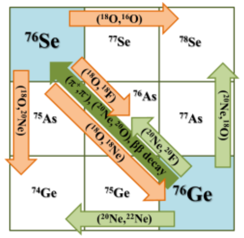
✓ The problem of $0\upsilon\beta\beta$-decay nuclear matrix elements (NMEs)



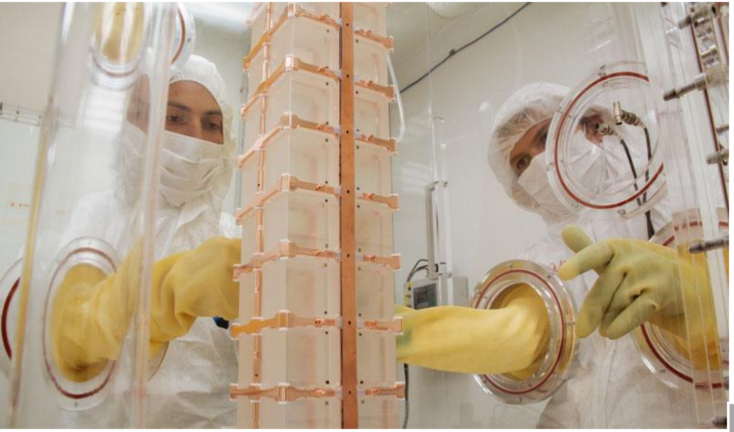
✓ The study of double charge exchange (DCE) @ INFN-LNS (NUMEN, NURE)



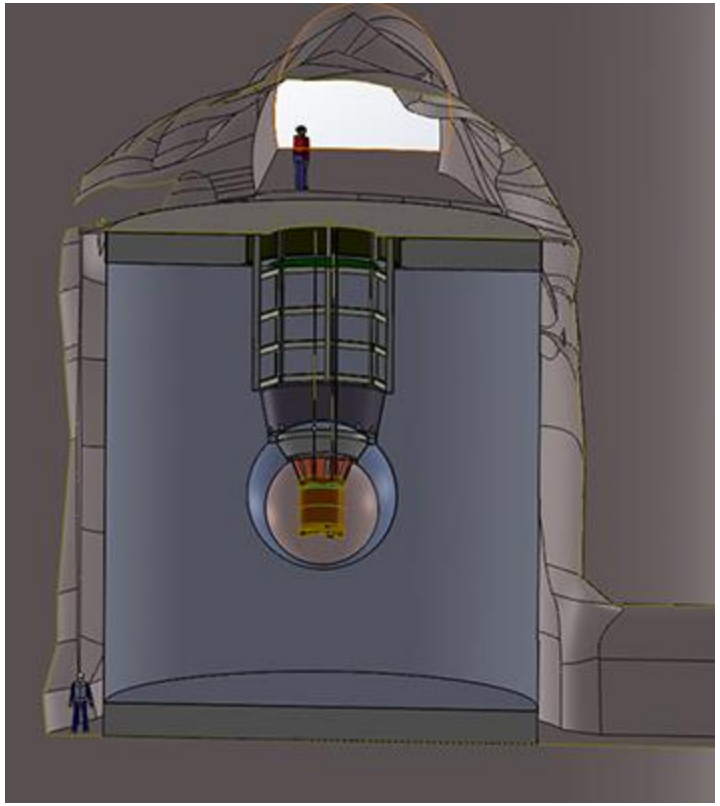
✓ The multi-channel vision



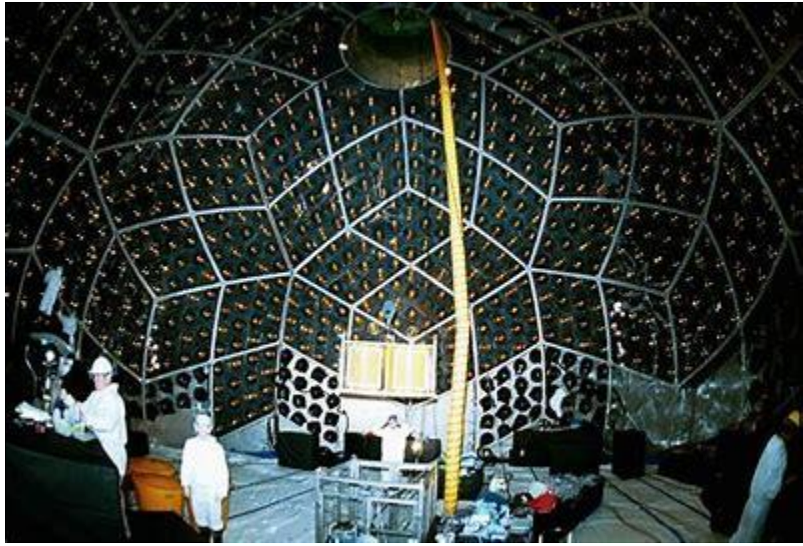
✓ The NUMEN roadmap and its matching with POT-LNS and nuclear physics mid-term plans in Italy



Search for 0νββ decay. A worldwide race



Experiment	Isotope	Lab
GERDA	^{76}Ge	LNGS [Italy]
CUORE	^{130}Te	LNGS [Italy]
Majorana	^{76}Ge	SURF [USA]
LEGEND	^{76}Ge	LNGS (Italy) -----
KamLAND-Zen	^{136}Xe	Kamioka [Japan]
EXO/nEXO	^{136}Xe	WIPP [USA]
CUPID - Lucifer	^{82}Se, ^{100}Mo	LNGS [Italy]
SNO+	^{130}Te	Sudbury [Canada]
SuperNEMO	^{82}Se	LSM [France]
CANDLES	^{48}Ca	Kamioka [Japan]
COBRA	^{116}Cd	LNGS [Italy]
DCBA	many	[Japan]
AMoRe	^{100}Mo	[Korea]
MOON	^{100}Mo	[Japan]
PandaX-III	^{136}Xe	CJPL [China]



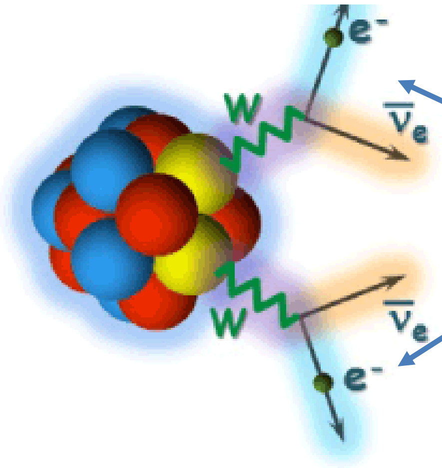
List not complete…

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

2νββ vs 0νββ decay

2νββ-decay

Two-step in weak interaction



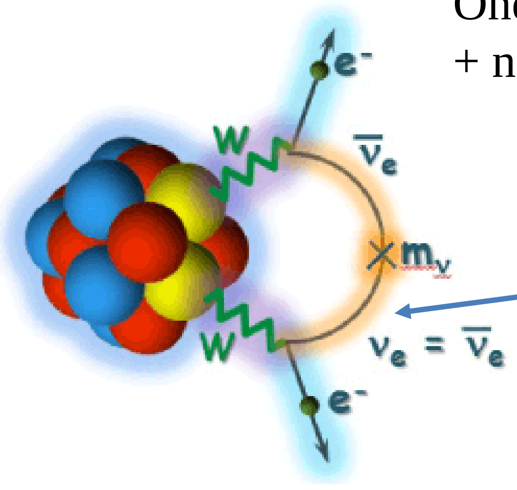
p ~ 1-2 MeV/c

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

Not very sensitive to high momentum components of Ψ

0νββ-decay

One-step in weak interaction + nn correlations



p ~ 100 MeV/c due to uncertainty principle

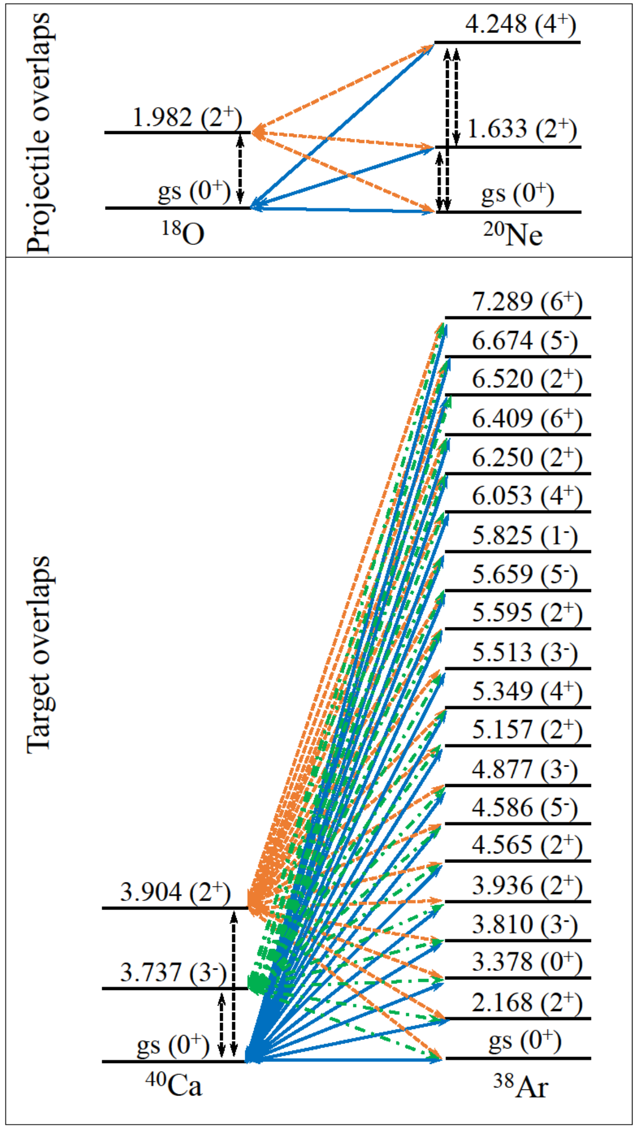
$$\left|M_\varepsilon^{\beta\beta 0\nu}\right|^2 = \left|\left\langle \Psi_f(p)\right|\hat{O}_\varepsilon^{\beta\beta 0\nu}(p)\left|\Psi_i(p)\right\rangle\right|^2$$

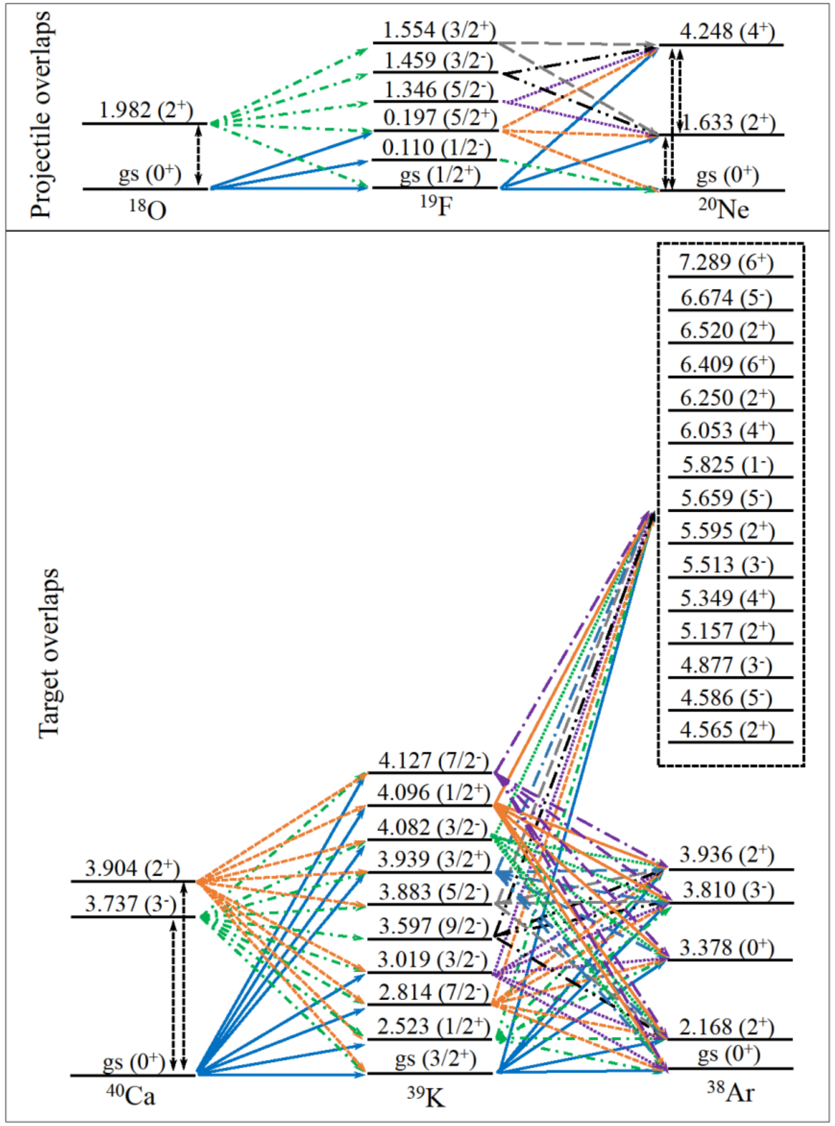
Crucial role of short range correlations

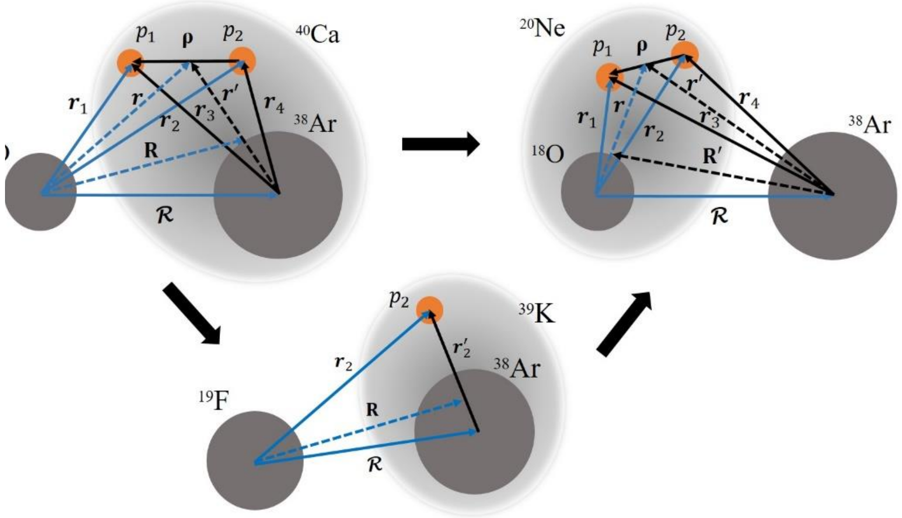
$$\left|M_\varepsilon^{\beta\beta 2\nu}\right|^2 \neq \left|M_\varepsilon^{\beta\beta 0\nu}\right|^2$$

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