The NUMEN project: a new way to provide data-driven information on neutrino-less double-beta decay

Alessandro Spatafora for the NUMEN collaboration
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud

14th International Spring Seminar on Nuclear Physics:
"Cutting-edge developments in nuclear structure physics"
20th May 2025 - Ischia, Napoli, Italia

Background: **0νββ decay** and **DCE** reactions

Methods: the **multi-channel** strategy

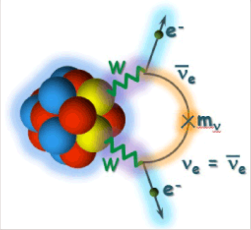
Results: DCE measured **cross-sections**

Conclusions and **perspectives**

0νββ decay: new physics beyond the Standard Model

Problems in modern physics:
1. Neutrinos absolute mass-scale
2. Neutrinos: Dirac o Majorana

0νββ is the most promising approach



Neutrinoless double beta decay**

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

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

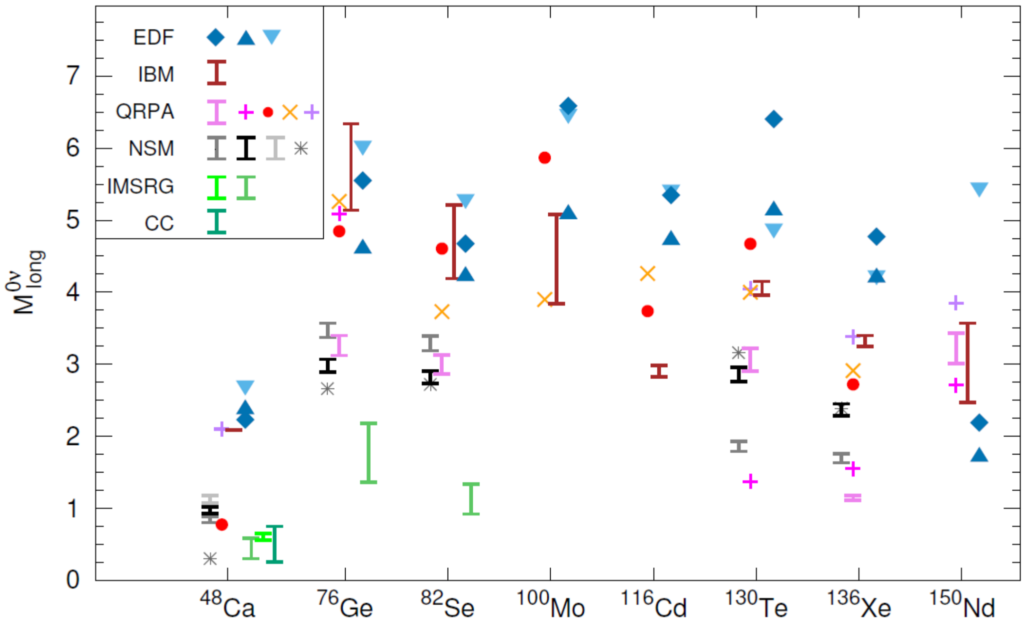
Still **not observed**!

- Beyond the **standard model**
  - Violation of **lepton number conservation**
  - **CP violation** in lepton sector
- Way to **leptogenesis** and **GUT**…
- Access to effective neutrino masses

$$\frac{1}{T^{0\nu}_{1/2}}(0^+ \rightarrow 0^+) = g_A^4 G_{0\nu} \left|M^{0\nu\beta\beta}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

Nuclear Matrix Elements (NMEs):

Nuclear transition probability $\left|M^{0\nu\beta\beta}\right|^2 = \left|\langle\Psi_f|\hat{O}^{0\nu\beta\beta}|\Psi_i\rangle\right|^2$?



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

Measurements (still not conclusive for 0νββ)

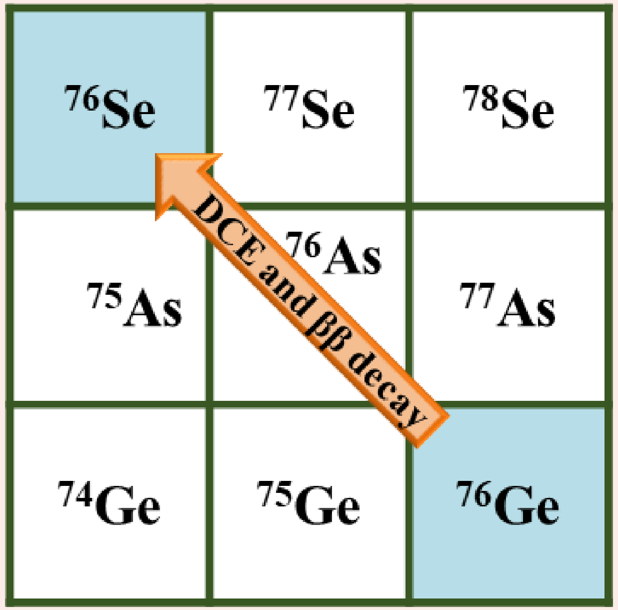
- ✓ β-decay and **2νββ** decay
- ✓ **(π$^+$, π$^-$)**, single charge exchange (^{3}He,t), (d,^{2}He), HI-SCE, electron capture, **transfer reactions**, μ-capture, γ-ray spectroscopy, **γγ-decay** etc.
- ✓ A promising experimental tool: **Heavy-Ion Double Charge-Exchange (HI-DCE)**

1st order isospin probes

2nd order isospin probes

Double Charge Exchange reactions (DCE)

$$ {}^{A}_{Z}x_{N} + {}^{A}_{Z}X_{N} \rightarrow {}_{Z\mp2}^{A}y_{N\pm2} + {}_{Z\pm2}^{A}Y_{N\mp2} $$



Why to study DCE?

- Population of exotic nuclei from stable target and projectile
- Nuclear response to second order isospin operator
- **Connection with second order weak processes**

Nuclear **Double Charge Exchange reactions (DCE)** to stimulate in the laboratory the same nuclear transition (**g.s. to g.s.**) occurring in 0νββ

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

Differences | Similarities

Theoretical aspects of Heavy-Ion Double-Charge Exchange

NUMEN

E. Santopinto, et al. Phys. Rev. C98 (2018)(R) 061601

Reaction part

$$\frac{d\sigma}{d\Omega} \rightarrow \frac{k}{k'}\left(\frac{\mu}{4\pi^2\hbar^2}\right)^2 \left| 2F(\theta) \left(\frac{\mathcal{M}^{\mathrm{DGT}}_{\mathrm{T}\to\mathrm{T}'}\mathcal{M}^{\mathrm{DGT}}_{\mathrm{P}\to\mathrm{P}'}}{\bar{E}^{\mathrm{GT}}_p + \bar{E}^{\mathrm{GT}}_t} + \frac{\mathcal{M}^{\mathrm{DF}}_{\mathrm{T}\to\mathrm{T}'}\mathcal{M}^{\mathrm{DF}}_{\mathrm{P}\to\mathrm{P}'}}{\bar{E}^{\mathrm{F}}_p + \bar{E}^{\mathrm{F}}_t} \right) \right|^2_{[q_1,q_2\approx 0]}$$

Structure part

$$\mathcal{M}^{\mathrm{DGT}}_{\mathrm{A}\to\mathrm{A}'} = c_{\mathrm{GT}} \left\langle \Phi^{(\mathrm{A}')}_{J'} \right| \sum_{n,n'} [\vec{\sigma}_n \times \vec{\sigma}_{n'}]^{(0)} \vec{\tau}_n \vec{\tau}_{n'} \left| \Phi^{(\mathrm{A})}_{J} \right\rangle$$

$$\mathcal{M}^{\mathrm{DF}}_{\mathrm{A}\to\mathrm{A}'} = c_{\mathrm{T}} \left\langle \Phi^{(\mathrm{A}')}_{J'} \right| \sum_{n,n'} \vec{\tau}_n \vec{\tau}_{n'} \left| \Phi^{(\mathrm{A})}_{J} \right\rangle$$

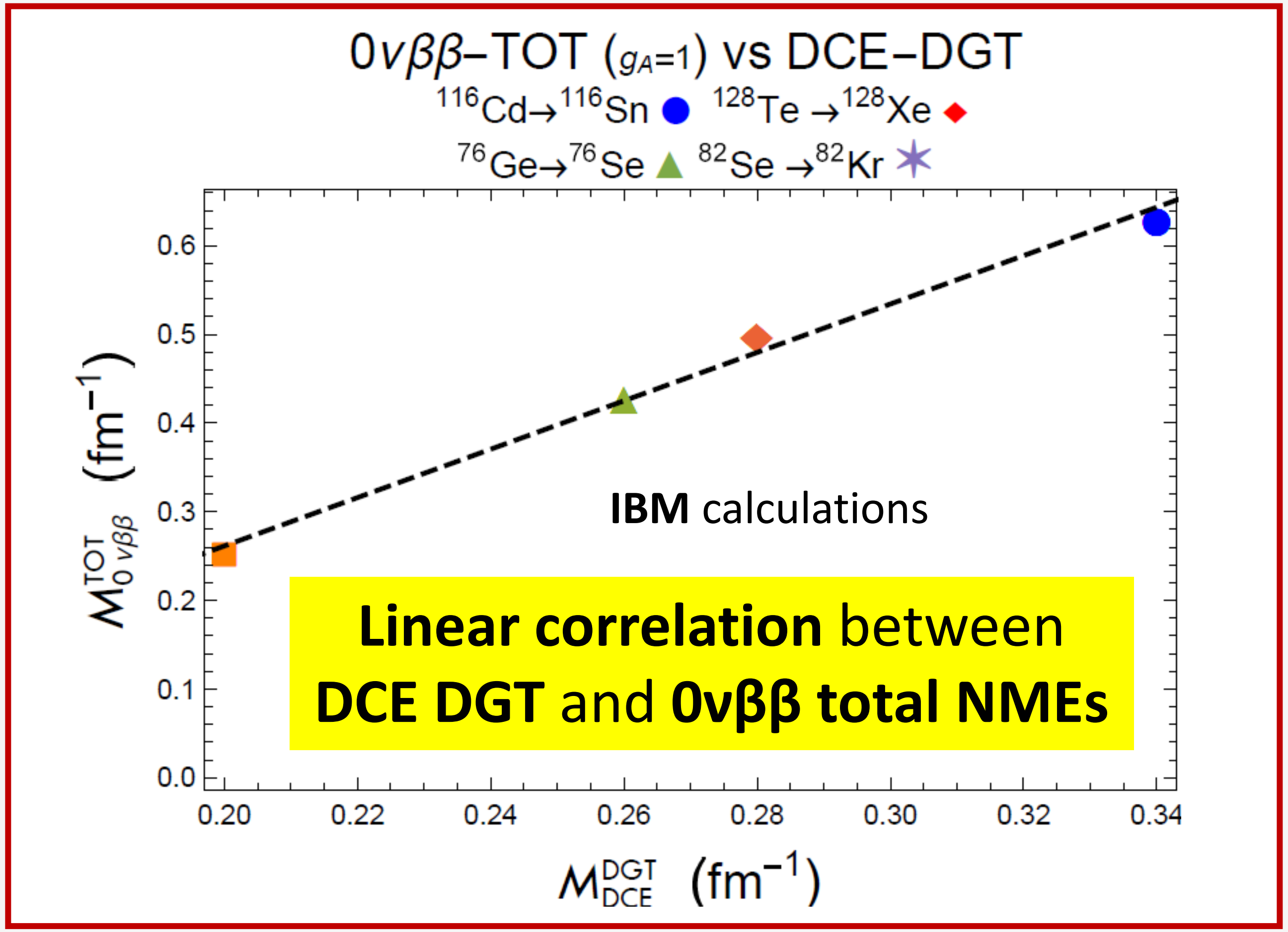
Milestones:
- o **DCE cross section** can be **factorized** in terms of reaction and nuclear structure parts
- o **Nuclear structure** part can be factorized in terms of **target** and **projectile matrix elements**

Useful approximations:
(to separate in terms of DGT and DF NMEs)
- Eikonal approximation
- Closure approximation
- Low momentum transfer ($\theta_{lab} \approx 0°$)

Separations confirmed in a fully quantum mechanical approach
H. Lenske et al., Universe (2024)

Theoretical aspects of Heavy-Ion Double-Charge Exchange

E. Santopinto, et al. Phys. Rev. C98 (2018)(R) 061601

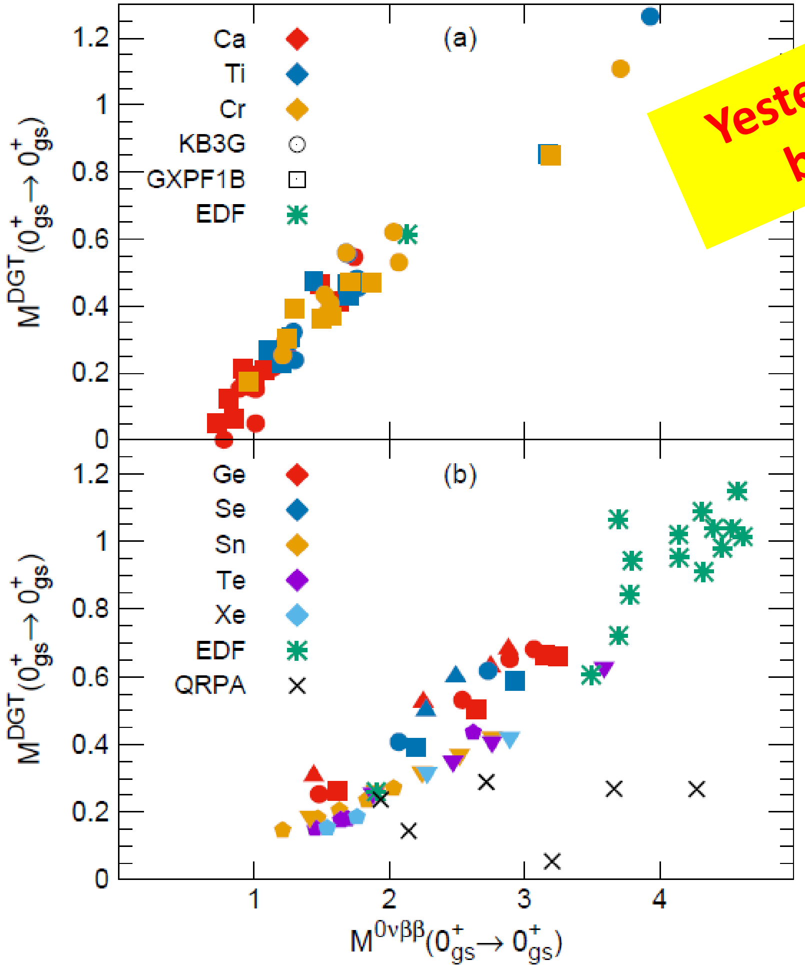


Useful approximations:
(to separate in terms of DGT and DF NMEs)

- Eikonal approximation
- Closure approximation
- Low momentum transfer ($\theta_{lab} \approx 0°$)

*"The possibility of a **two-step factorization** of the very forward differential DCE cross section [...], combined with a **linear correlation** between **DCE-DGT** and **0νββ** NMEs, opens the possibility of placing an upper limit on 0νββ NMEs in terms of the **DCE experimental data** at ϑ = 0°."*

Theoretical aspects of Double-Charge Exchange



Yesterday discussed by L. Jokiniemi

DGT vs 0νββ linearity SM and EDF nuclear structure calculations

J. M Shimizu, et al. Physics Review Letter 120 (2018) 142502

"Our findings suggest that DGT experiments can be a very valuable tool to obtain information on the value of ***0νββ*** *decay nuclear matrix elements."*

Ok, it is time for Nuclear reaction's **experiments**!

The NUMEN project

Neutrinoless double beta decay**

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

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

Nuclear **Double Charge Exchange reactions (DCE)** to stimulate in the laboratory the same nuclear transition (**g.s. to g.s.**) occurring in 0νββ

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

Why?

To extract **"data-driven" information** on NME for all the systems candidate for 0νββ:

- Constraints to the existing theories of NMEs (nuclear wave functions)
- Model-independent comparative information on the sensitivity of half-life experiments
- Complete study of the reaction mechanism

Where?

Catania, LNS-INFN

- **K800** Superconducting Cyclotron
- **MAGNEX** magnetic spectrometer
- Experience in **nuclear reactions**

F. Cappuzzello et al., EPJ A 52 (2016) 167

The NUMEN project

How?

Neutrinoless double beta decay**

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

**E. Maj... ...ovo Cimento 14 (1...
W. H. F... ...Rev. 56 (1939) 11...

Nuclear **Double Charge Exchange reactions (DCE)** to stimulate in the laboratory the same nuclear transition (**g.s. to g.s.**) occurring in 0νββ

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

W...

To extrac... ...a-driven... ...n on ... for all t... ...stems c... ...ate for 0νββ:

- ... ...e existin... ...s of NM... ...ear wa... ...tions)
- ... ...ent co... ...e informati... ...e sens... ...f half... ...ents
- Complete... ...of the ... mechanism

Wher...

...NS-INFN

- **K800** Superconducting Cyclotron
- **MAGNEX** magnetic spectrometer
- Experience in **nuclear reactions**

F. Ca... ...al., EPJ A 52 (2016) 167

Theoretical aspects of Heavy-Ion Double-Charge Exchange

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

Progress in Particle and Nuclear Physics 128 (2023) 103999

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Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

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

Check for updates

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

Theoretical aspects of Heavy-Ion Double-Charge Exchange

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

DCE cross section is a combination of three different reaction mechanisms

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

  H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
  H. Lenske, CERN Proceedings 2019-001 (2019)
  E. Santopinto et al., PRC 98, 061601 (2018)

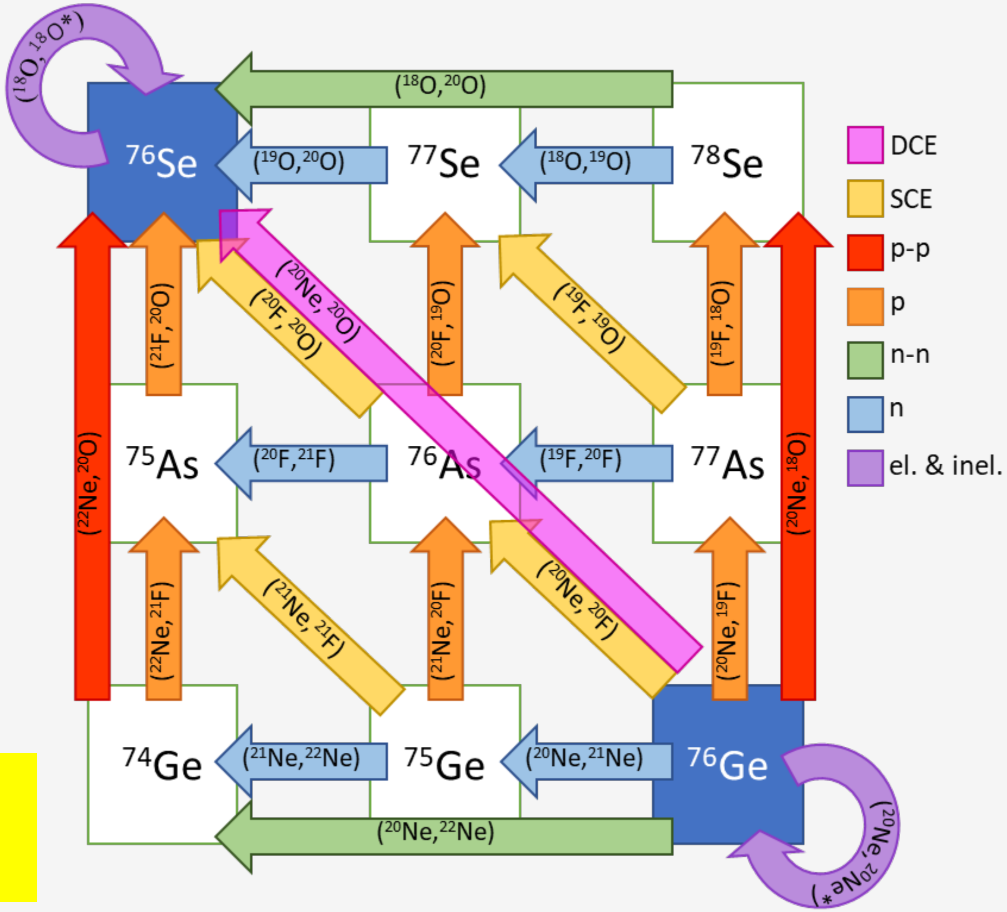
- **Two-step DCE - Double single charge exchange (DSCE):** two consecutive single charge exchange processes

  J.I. Bellone et al., PLB 807 (2020) 135528
  H. Lenske el al. Universe 7 (2020) 98

- **Multi-step nucleon transfer and SCE** (transfer defined by mean-field dynamics, its contribution can be tuned by kinematics conditions)

  J. A. Lay et al. JoP: Conf. Series 1056 (2018) 012029
  J. L. Ferreira et al., PRC 105 (2022) 014630

M. Colonna talk on Wednesday



The NUMEN Experiments

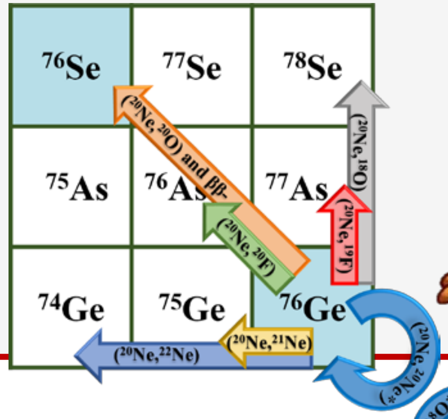
Two directions: $\beta\beta^-$ via (^{20}Ne,^{20}O) and $\beta\beta^+$ via (^{18}O,^{18}Ne)

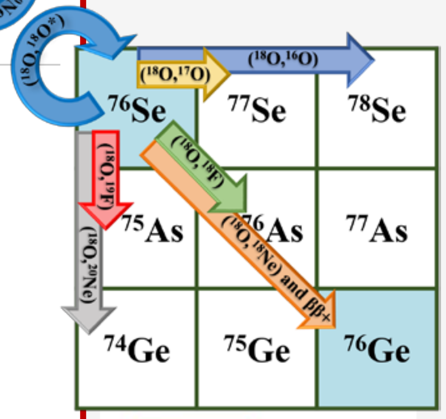
Complete net of reactions which can contribute to the DCE cross-section: 1p, 2p, 1n, 2n transfer, SCE, elastic and inelastic

Two (or more) incident energies to study the reaction mechanism

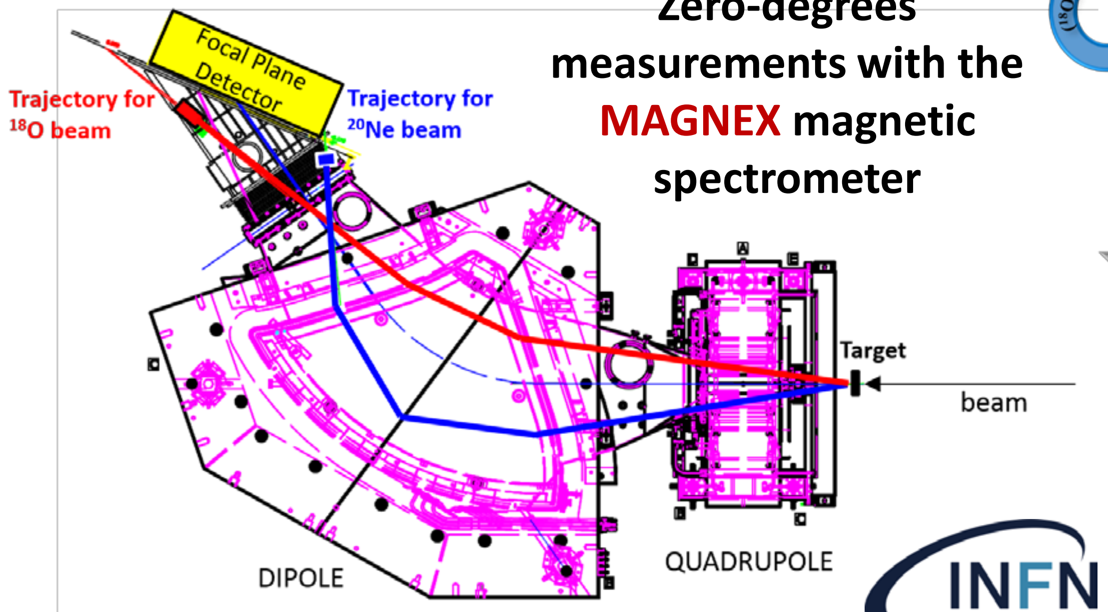
Transitions of interest for 0νββ: Limited number of targets so far, systematic exploration of all the candidates

Limitations of the past HI-DCE experiments are overcome!





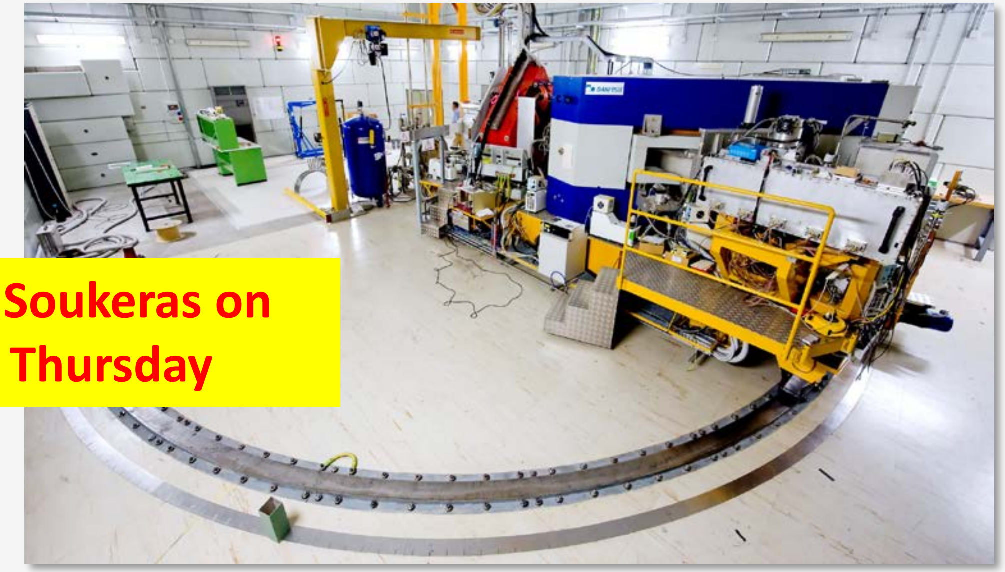
Zero-degrees measurements with the MAGNEX magnetic spectrometer



Heavy-Ion Double-Charge Exchange **Experiments @ LNS**

MAGNEX magnetic spectrometer

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



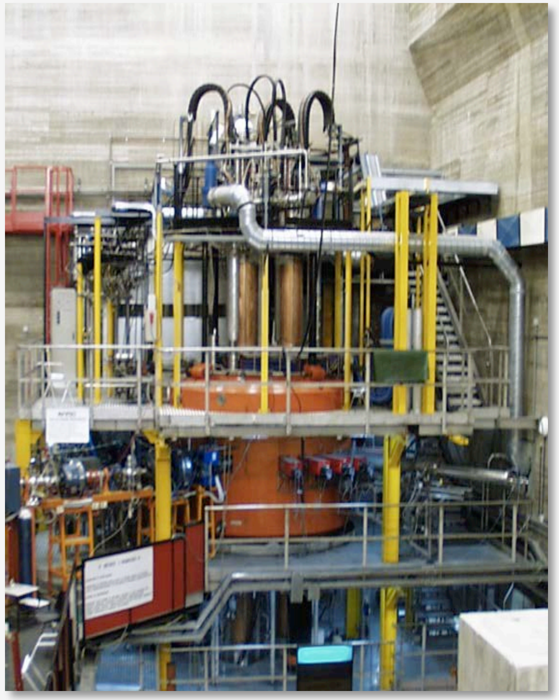
V. Soukeras on Thursday

Optical characteristics	Measured values
Angular acceptance (Solid angle)	50 msr
Angular range	–20° - +85°
Momentum (energy) acceptance	-14%, +10% (-28%,+20%)
Momentum dispersion for k= - 0.104	3.68 cm/%
Maximum magnetic rigidity	1.8 T m

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

- **Wide mass range** (protons to medium-mass)
- Measurement at **zero-degrees**

A. Badalà et al., Riv. Nuovo Cim. (2020)



K800 Superconducting Cyclotron

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

Background: **0νββ** decay and **DCE** reactions

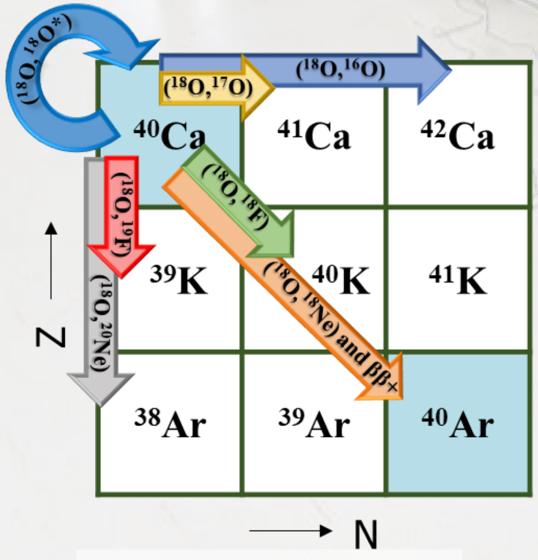
Methods: the **multi-channel** strategy

Results: DCE measured **cross-sections**

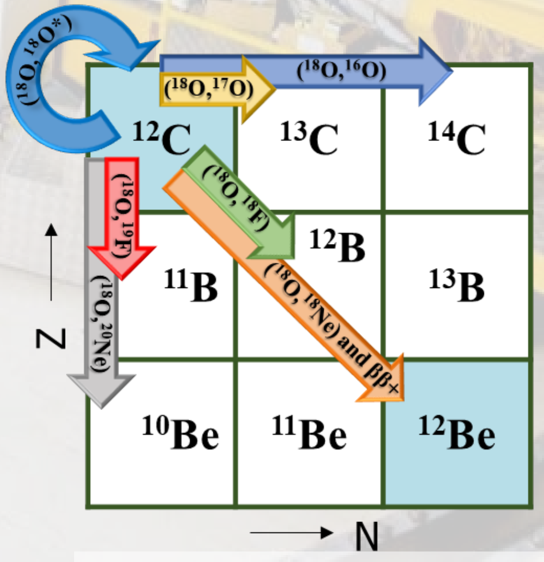
Conclusions and **perspectives**

The NUMEN Experimental campaign

^{40}Ca - ^{40}Ar	^{12}C – ^{12}B
F. Cappuzzello et al. EPJ J A (2015) 51:145 *J. Bellone et al., PLB 807 (2020) 135528* *M. Cavallaro et al., Front. Astron. Space Sci. 8 (2021)* *S. Calabrese et al., PRC 104 (2021) 064609* *J. Ferreira et al., PRC 103 (2021) 054604* *B. Urazbekov et al., PRC 108 (2023) 064609* ***B. Urazbekov et al., PRC 111 (2025) 044603*** ***J. Ferreira et al., PRC 111 (2025) 054609***	A. Spatafora, Il Nuovo Cimento 45 (2022) 131 A. Spatafora et al., PRC 107 (2023) 024605 **A. Spatafora et al., PRC 111 (2025) 064612**



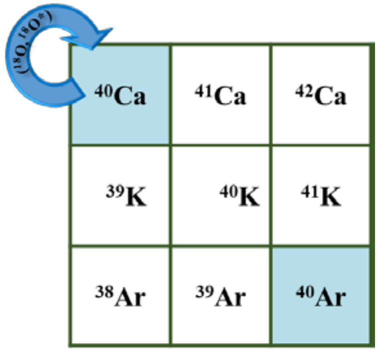
E_{beam} = 15 AMeV
- ^{18}O + ^{40}Ca

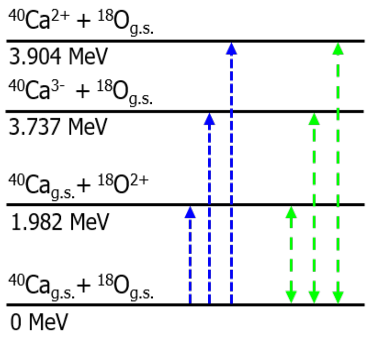


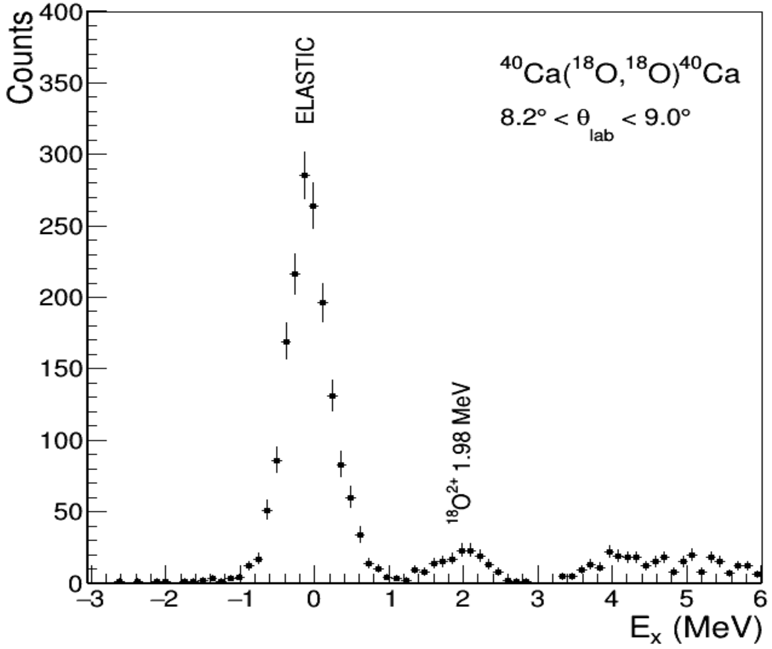
E_{beam} = 15 and 22 AMeV
- ^{18}O + ^{12}C

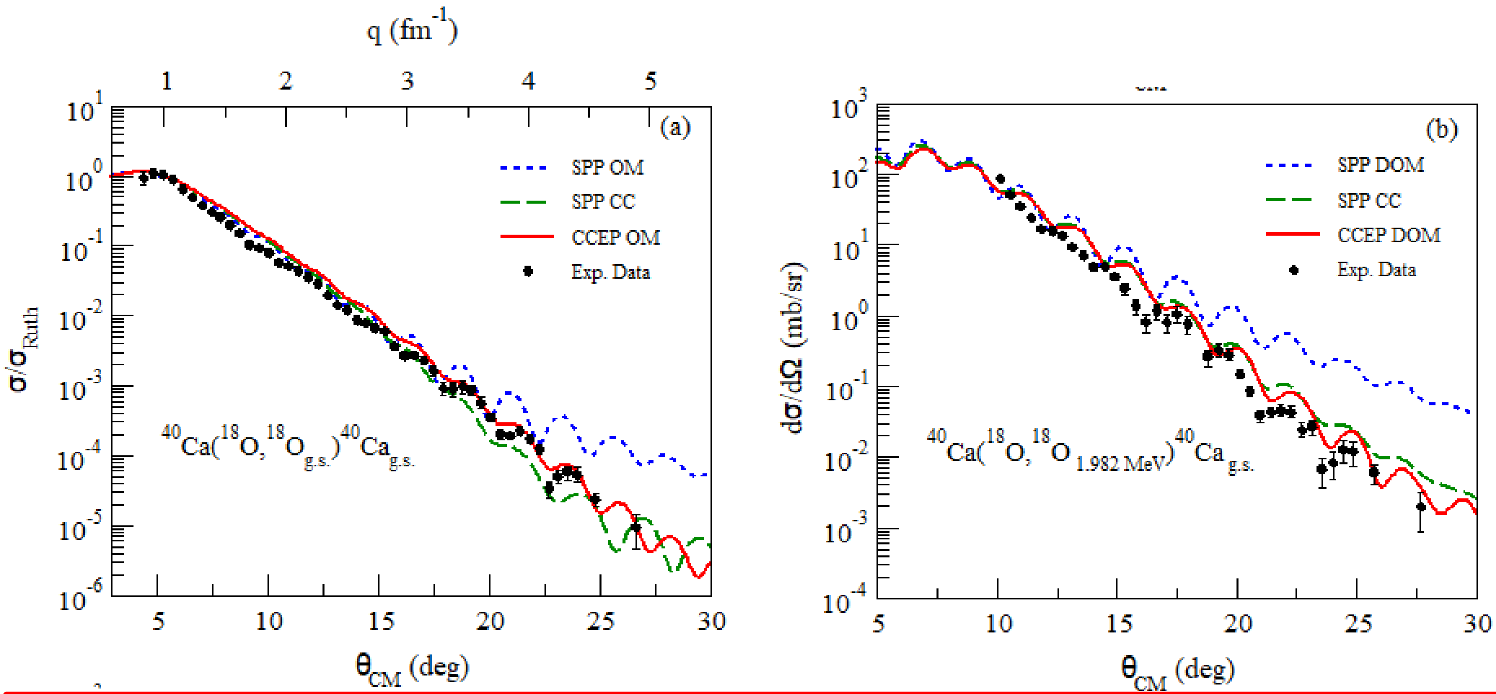
Elastic and inelastic scattering

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









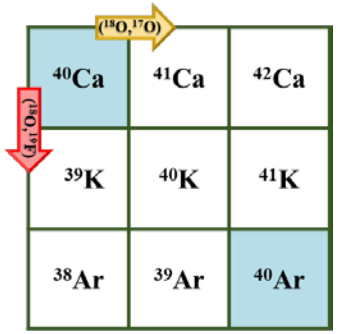
Key information from elastic and inelastic scattering:

- **Good description of data from CC approach**
- **Initial State Interaction:**

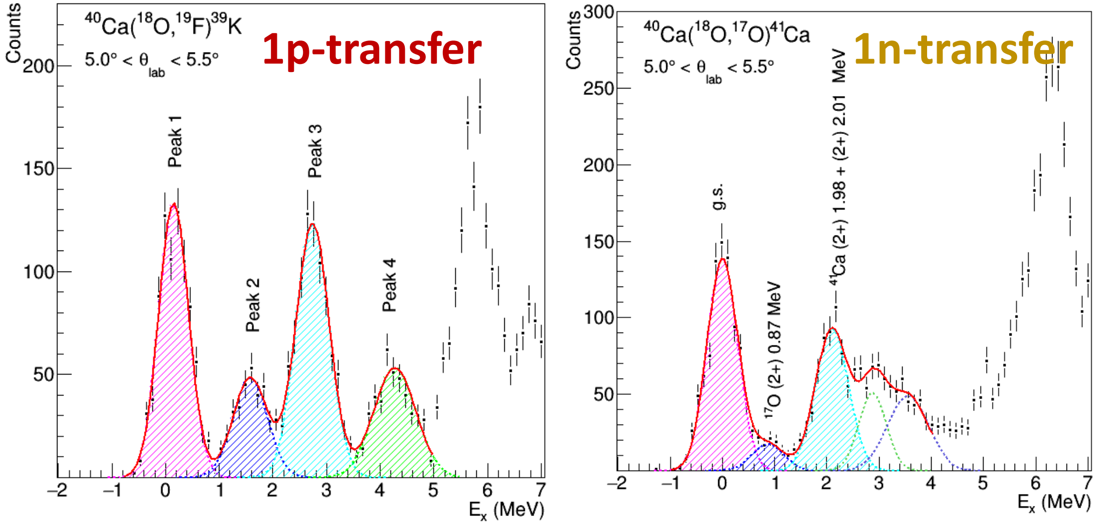
  Nucleus-nucleus optical potential (Sao Paulo)

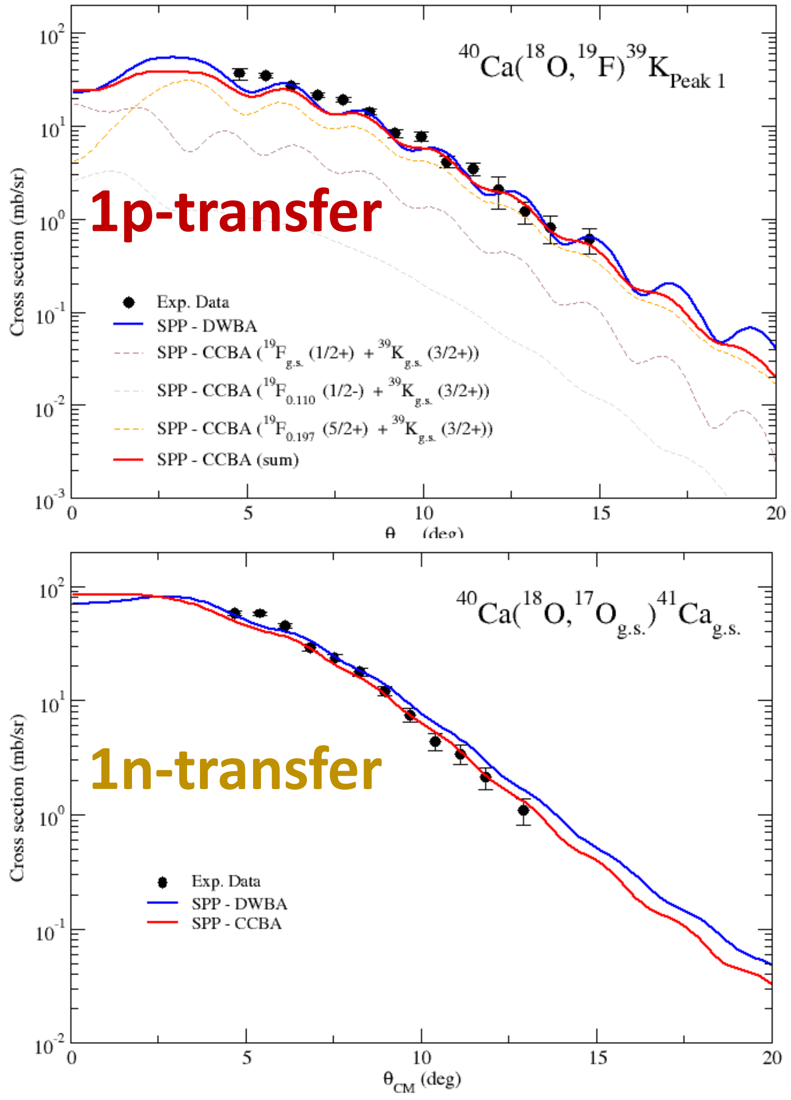
  Couplings to low-lying 2^+ and 3^- states for projectile and target

1p/1n transfer reactions



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



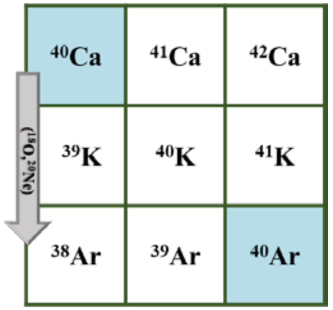


- **ISI** extracted from elastic and inelastic scattering data
- **CCBA** analysis
- **Shell model** spectroscopic amplitudes and **occupation probabilities**

Key information from one-nucleon transfer:

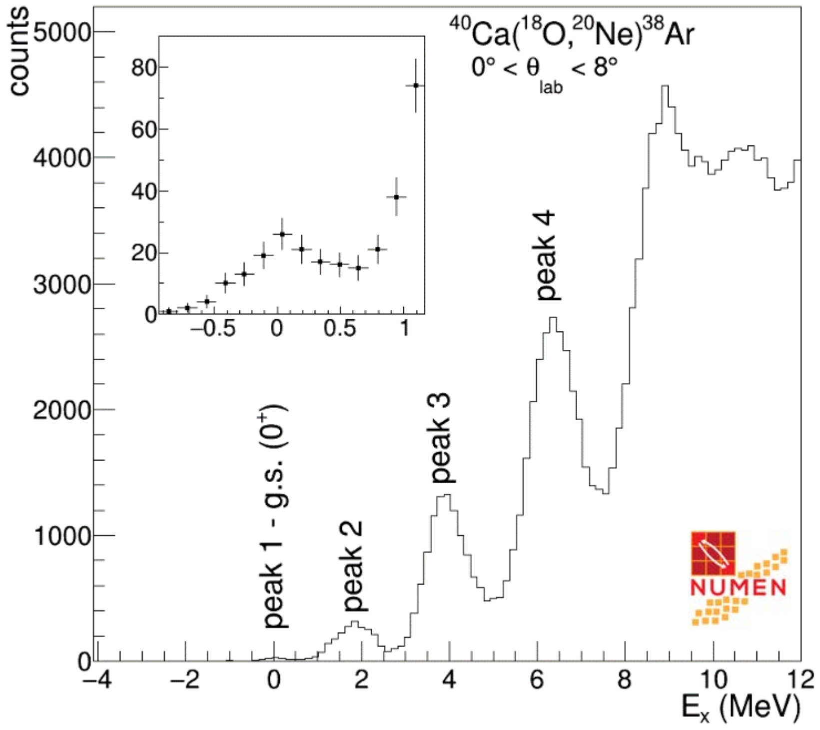
- **Good description of the data**
- Mixing of **single particle** and **core polarization** configurations
- **Nuclear structure** description under control

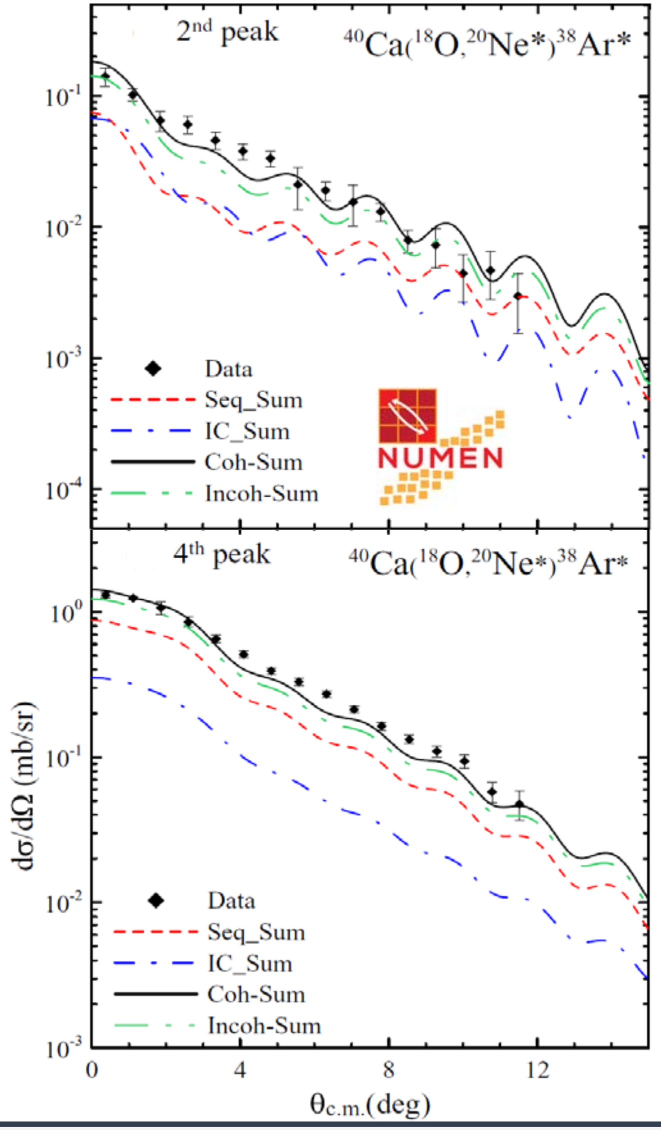
2p transfer reaction



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

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





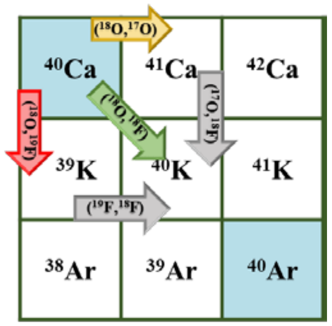
Key information from two-proton transfer:

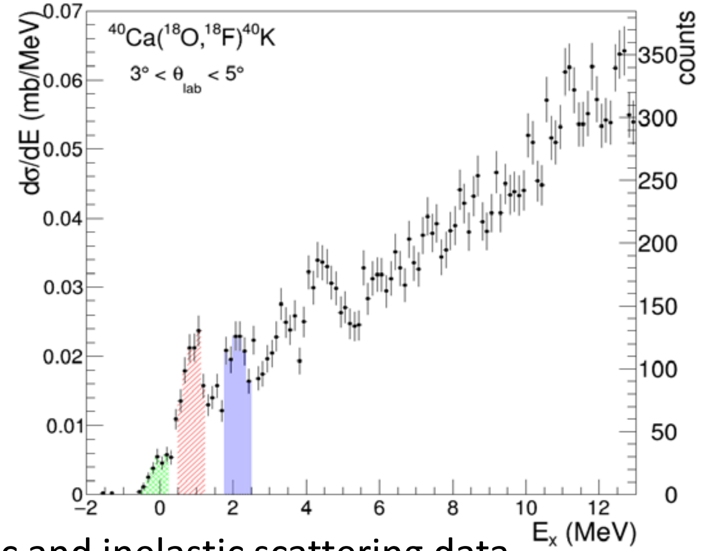
- **Good description of the data**
- Very **low cross-section** (comparable with DCE) for low-lying states
- Competition between **one-step** and **two-step** mechanisms

Single charge exchange

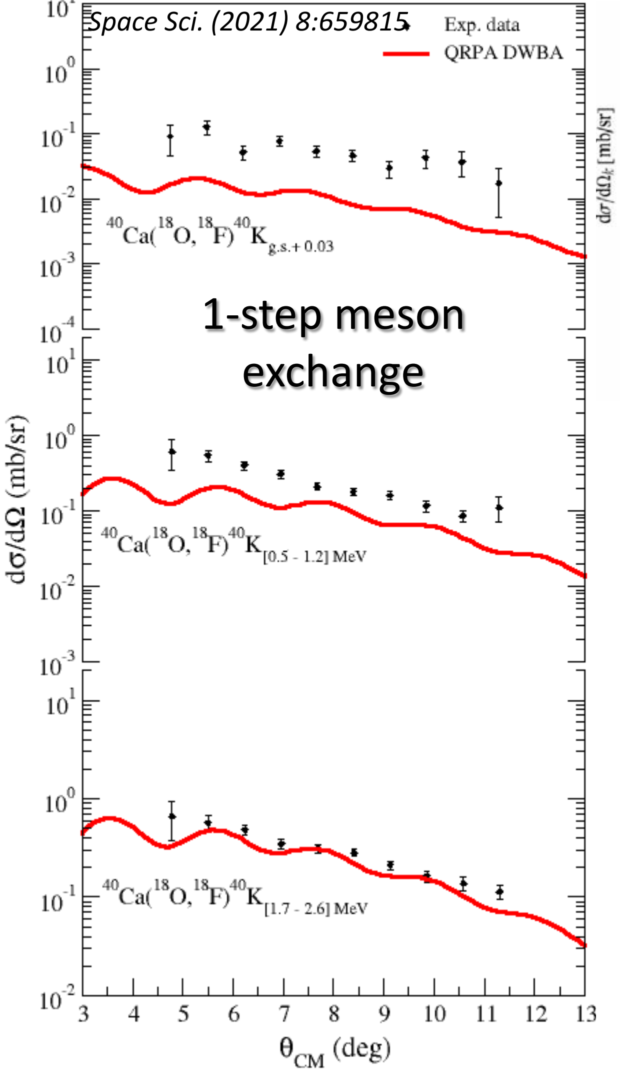
B. Urazbekov talk on Thursday

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

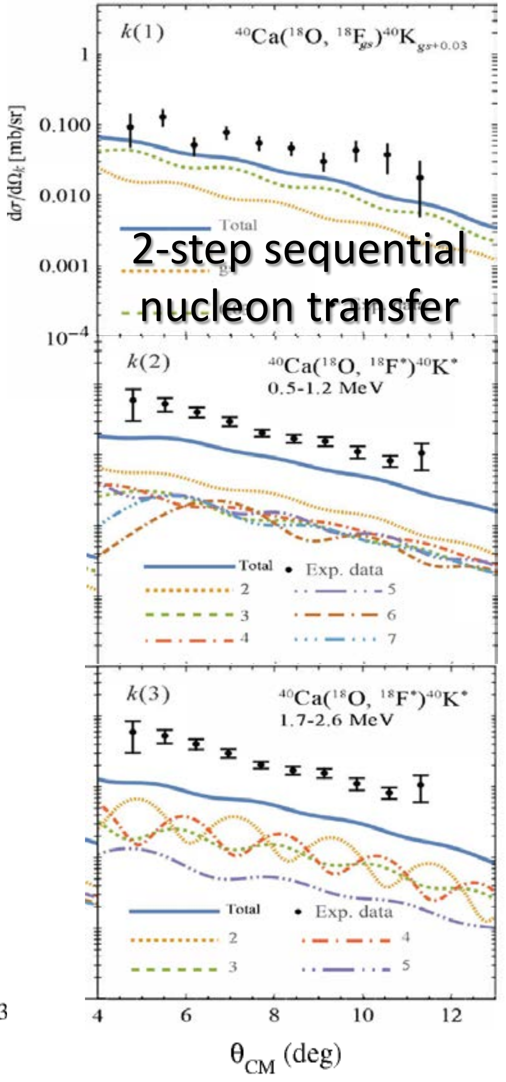




M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815



B. Urazbekov et al., PRC 108, 064609 (2023)



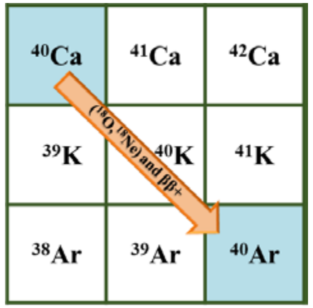
- **ISI** extracted from elastic and inelastic scattering data
- Double folding **QRPA** form factors for **meson exchange**
- **2-step DWBA** analysis for **sequential transfer** SCE
- **Shell Model** spectroscopic amplitudes (occupancies)

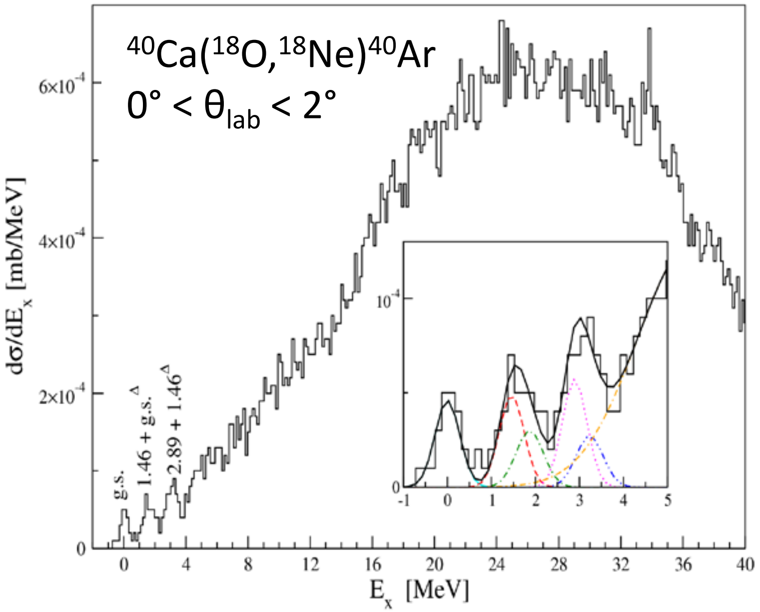
Key information from SCE:

- Competition between **one-step** and **two-step**
- **Meson exchange** important at higher E_x
- **2-step nucleon transfer** less contribute at higher E_x

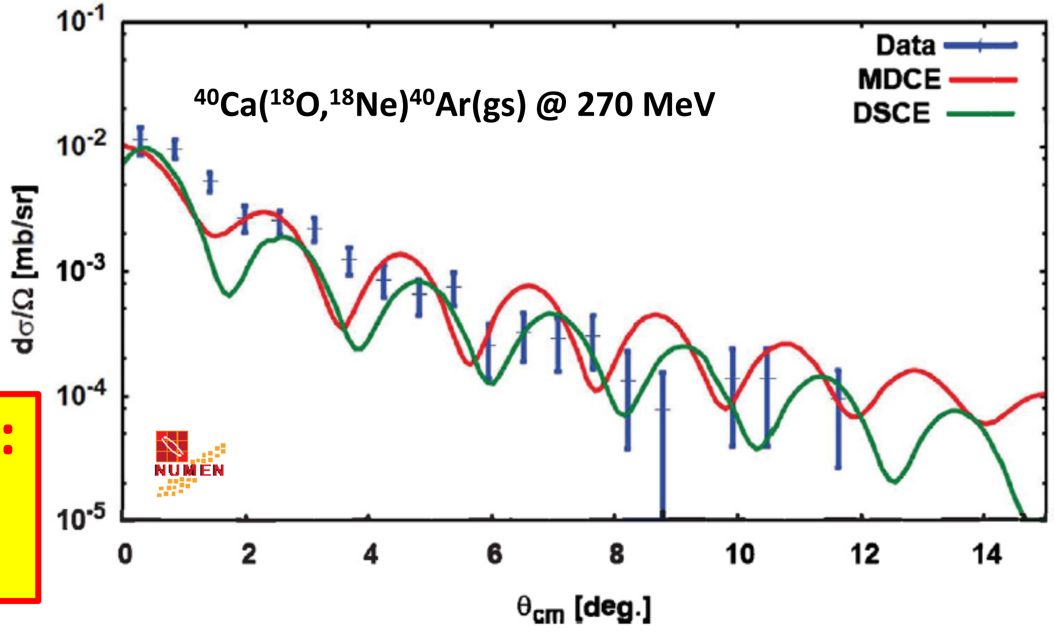
H. Lenske et al. Prog. Part. and Nucl. Phys. 109 (2019) 103716
J. Bellone et al., PLB 2020, 807, 135528
H. Lenske et al., Universe 2021, 7, 98
H. Lenske et al. Universe 2024, 10(2), 93

Double charge exchange





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



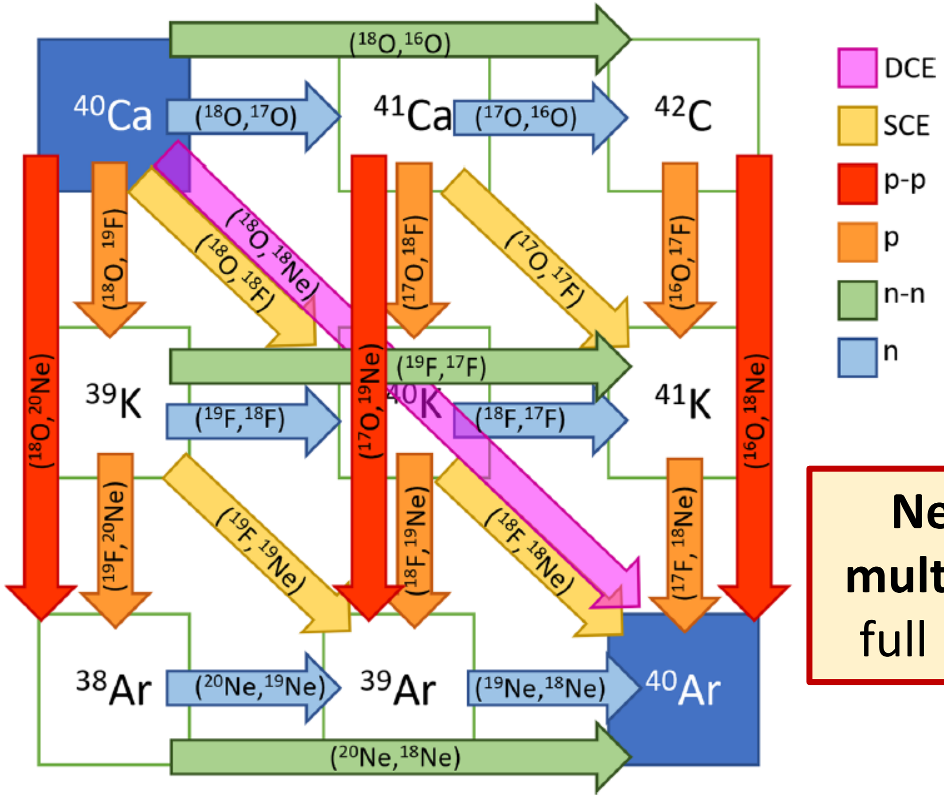
Key information from double charge-exchange:

- G.s. to g.s. **transition isolated**
- **Spectroscopic factor** extracted

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

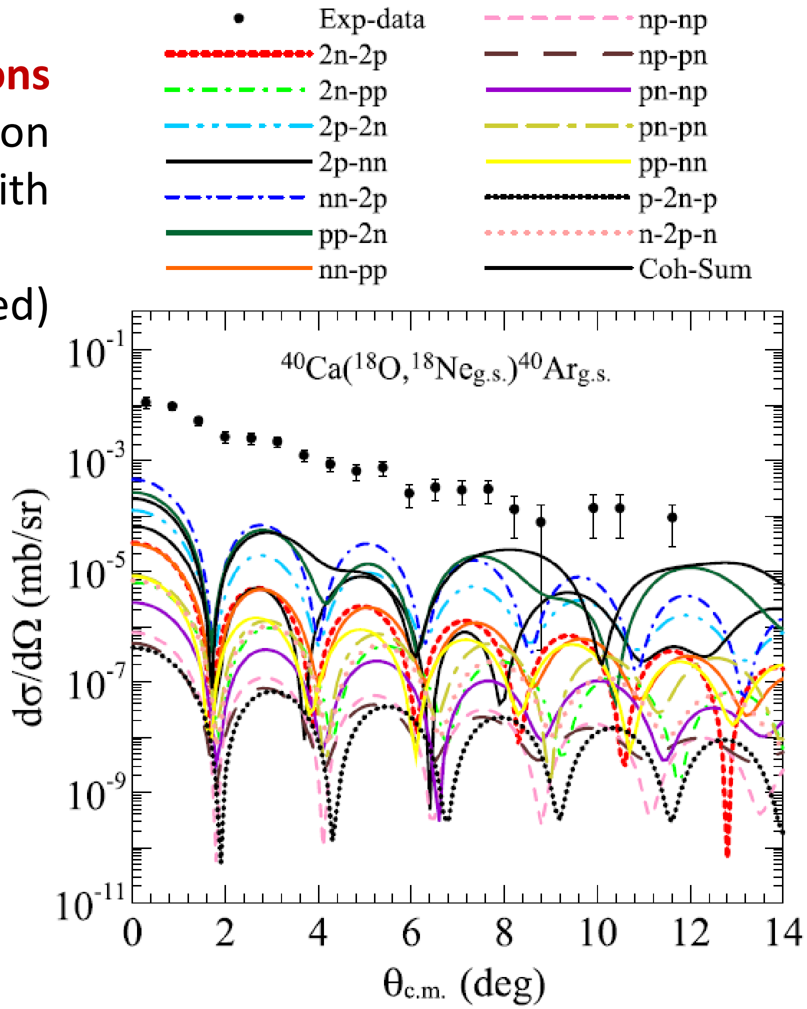
$$M^{J_A J_B I_A}_{J_a J_b I_a,\lambda\mu}(\boldsymbol{k}_\alpha, \boldsymbol{k}_\beta) \sim \sum_{S_1,S_2} \sum_{l_1,l_3,l_2,l_4} \sum_{L_{13},L_{24},} \left\langle \chi^{(-)}_\beta \middle| \left[\bar{F}^{l_2,l_4,L_{24}}_{S_2 T} G_{opt}(\omega_\alpha - \bar{\omega}_\gamma) \otimes \bar{F}^{l_1,l_3,L_{13}}_{S_1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

Double charge exchange



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

Negligible contribution of **multi-nucleon transfer** to the full DCE reaction mechanism



NEW PAPER

J. Ferreira et al., Phys. Rev. C 111, 014630 (2025)

Background: **0νββ decay** and **DCE reactions**

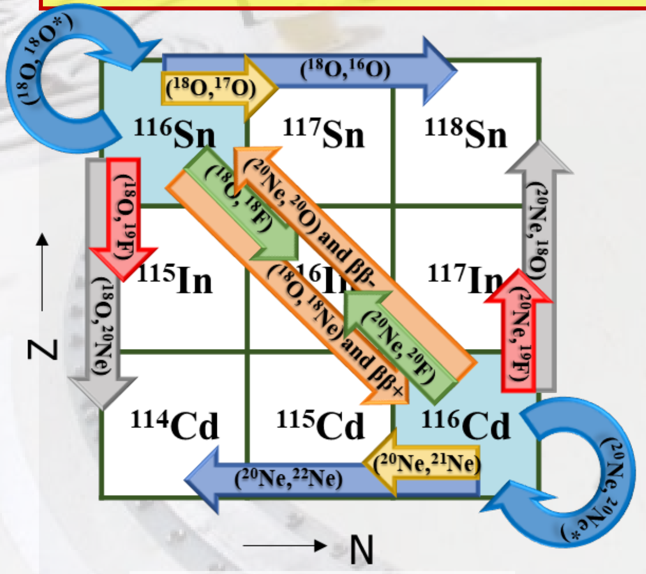
Methods: the **multi-channel** strategy

Results: DCE measured **cross-sections**

Conclusions and **perspectives**

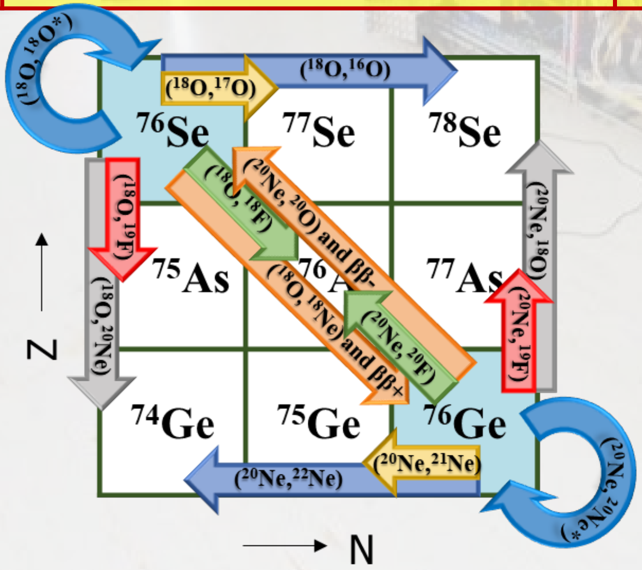
The NUMEN Experimental campaign

^{116}Cd - ^{116}Sn	^{76}Ge – ^{76}Se	^{130}Te – ^{130}Xe	^{48}Ca - ^{48}Ti
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., RP 67, 108037 (2024)**	A. Spatafora et al., PRC 100, 034620 (2019) L. La Fauci et al., PRC 104, 054610 (2021) I. Ciraldo, Nuovo Cimento 44, 38 (2021) I. Ciraldo et al., PRC 105, 044607 (2022) **I. Ciraldo et al., PRC 109, 024615 (2024)**	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)	O. Sgouros et al., PRC 104, 034617 (2021) G. A. Brischetto, Nuovo Cimento C 45, 96 (2022) O. Sgouros et al., PRC 108, 044611(2023) **G. A. Brischetto et al., PRC 109, 014604(2024)**



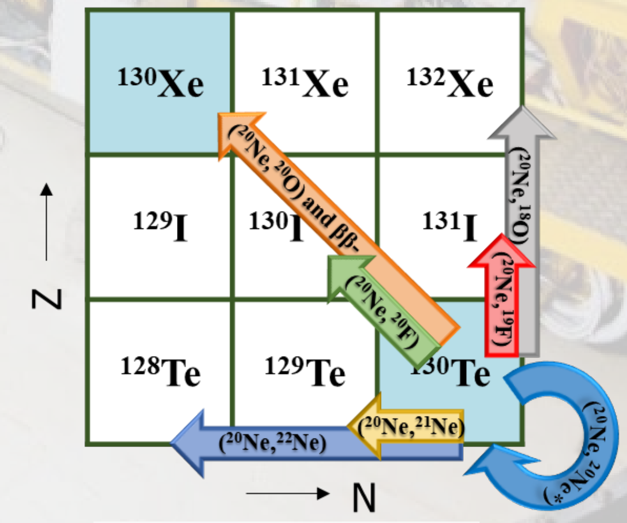
Eberam = 15 AMeV

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



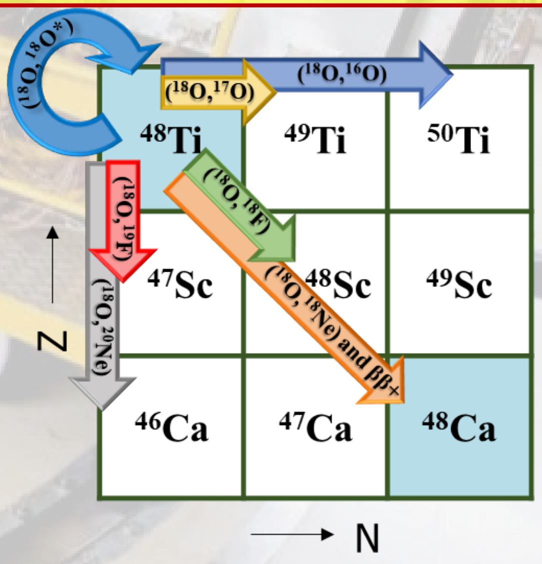
E_{beam} = 15 AMeV

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



E_{beam} = 15 AMeV

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

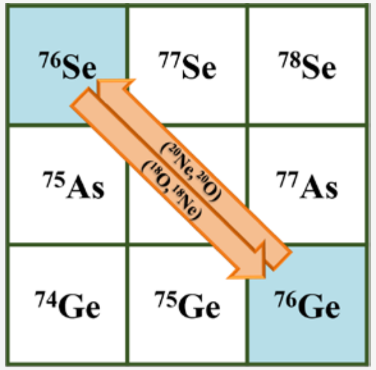


E_{beam} = 15 AMeV

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

Study 0νββ cadidates: ^{76}Ge

TIME INVARIANCE

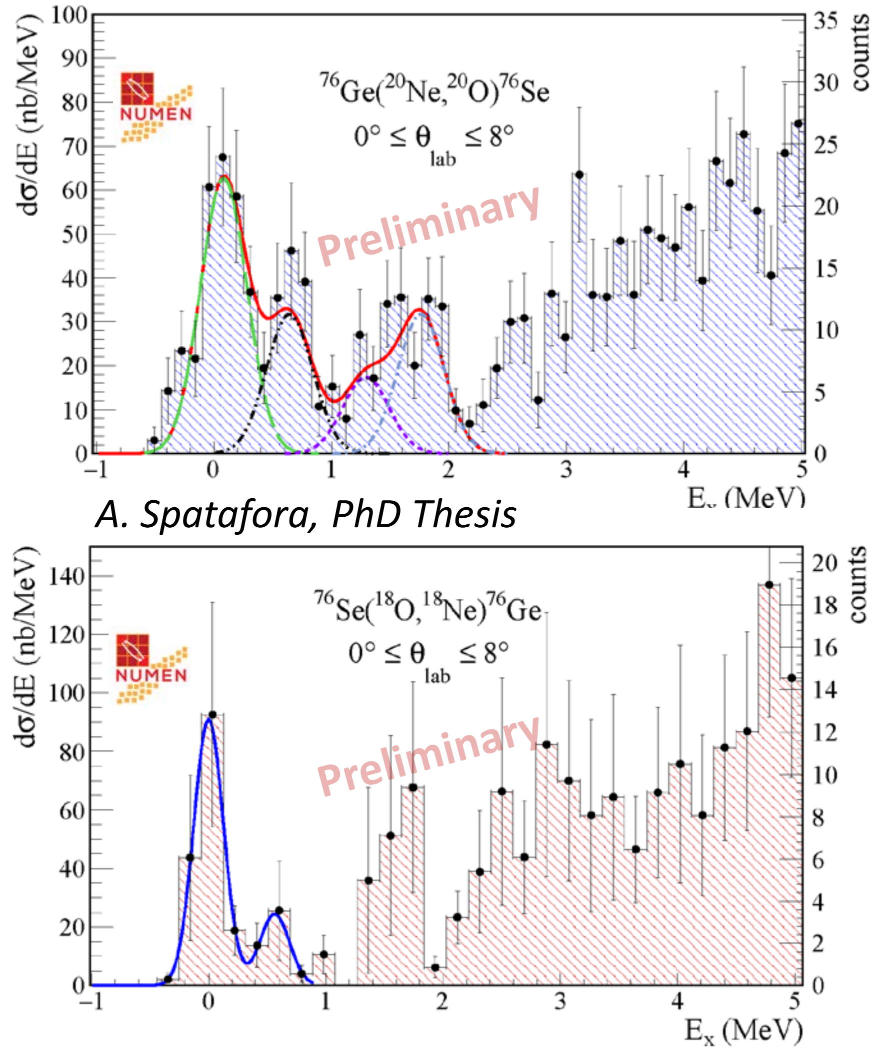


^{76}Ge ↔ ^{76}Se

Integrated cross-section ($0° < \theta_{lab} < 8°$)	$0^+ \rightarrow 0^+$
^{76}Ge(^{20}Ne, ^{20}O$_{g.s.}$)^{76}Se$_{g.s.}$	30 ± 4 nb
^{76}Se(^{18}O, ^{18}Ne$_{g.s.}$)^{76}Ge$_{g.s.}$	29 ± 6 nb

- **Same cross** sections for different directions
- G.s. to g.s. transition: **isolated!**
- Similar **distortion factors**

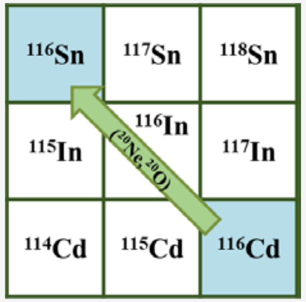
→ Same NME (encouraging test of **time invariance!**)



A. Spatafora, PhD Thesis

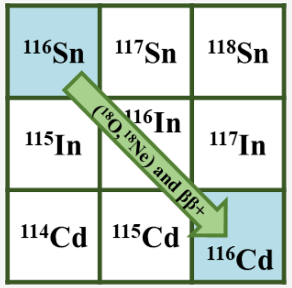
Study 0νββ cadidates: ^{116}Cd

TIME INVARIANCE



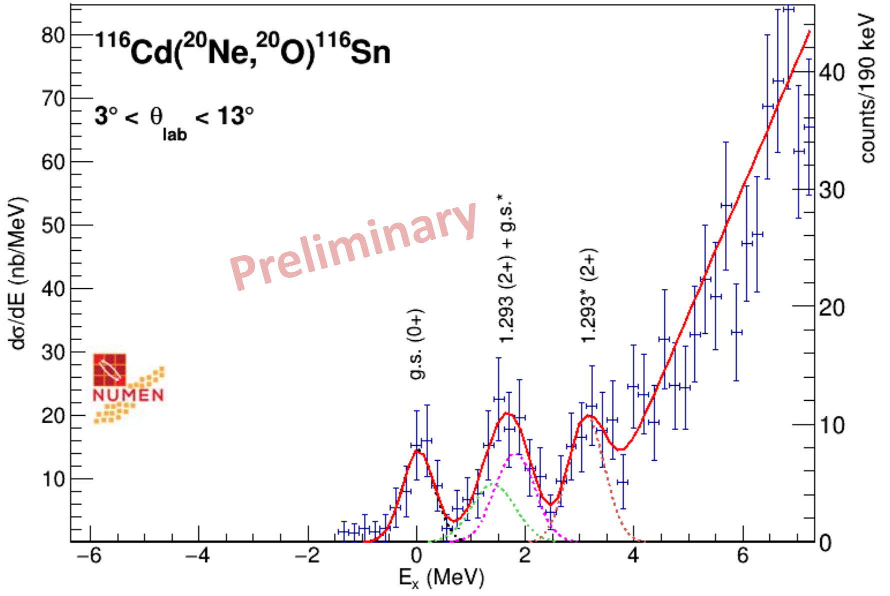
^{116}Cd → ^{116}Sn

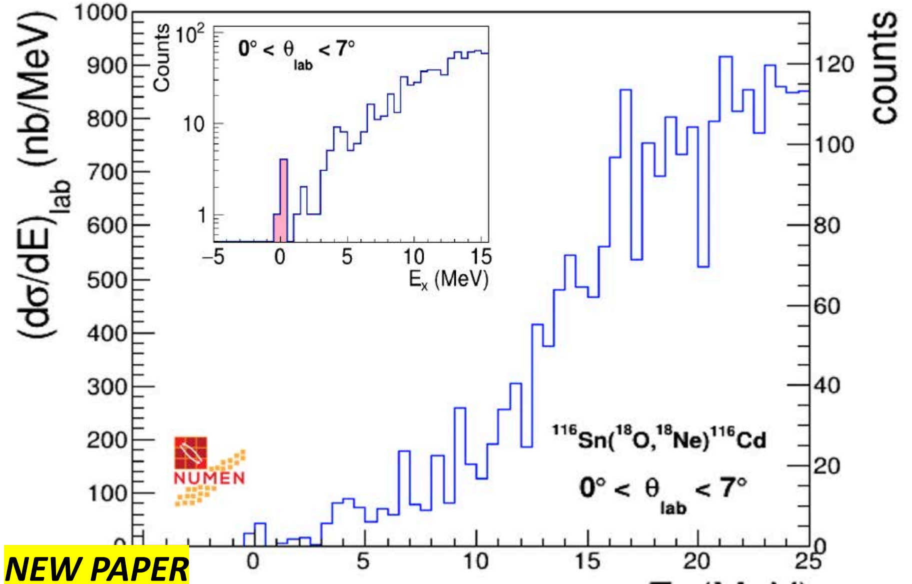
State (MeV)	Counts	Absolute cross section (nb)
$^{116}Sn_{gs}\ (0^+) + {}^{20}O_{gs}\ (0^+)$	31	12 ± 2
$^{116}Sn_{1.293}\ (2^+) + {}^{20}O_{gs}\ (0^+)$ $^{116}Sn_{gs}\ (0^+) + {}^{20}O_{1.673}\ (2^+)$	67	24 ± 3



^{116}Sn → ^{116}Cd

E_x range (MeV)	Counts	Int. cross-section (nb)	Cross-section 95% C.L. (nb)
-1 ÷ 1	5	36	[4--46]

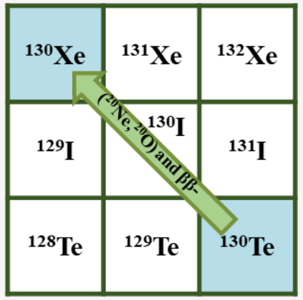




NEW PAPER

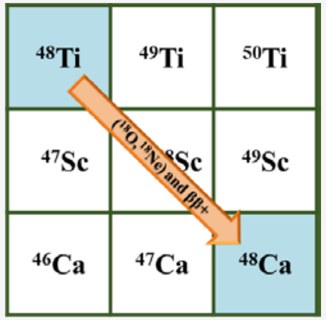
C. Eke et al., RP 67, 108037 (2024)

Study 0νββ cadidates: ^{130}Te and ^{48}Ti



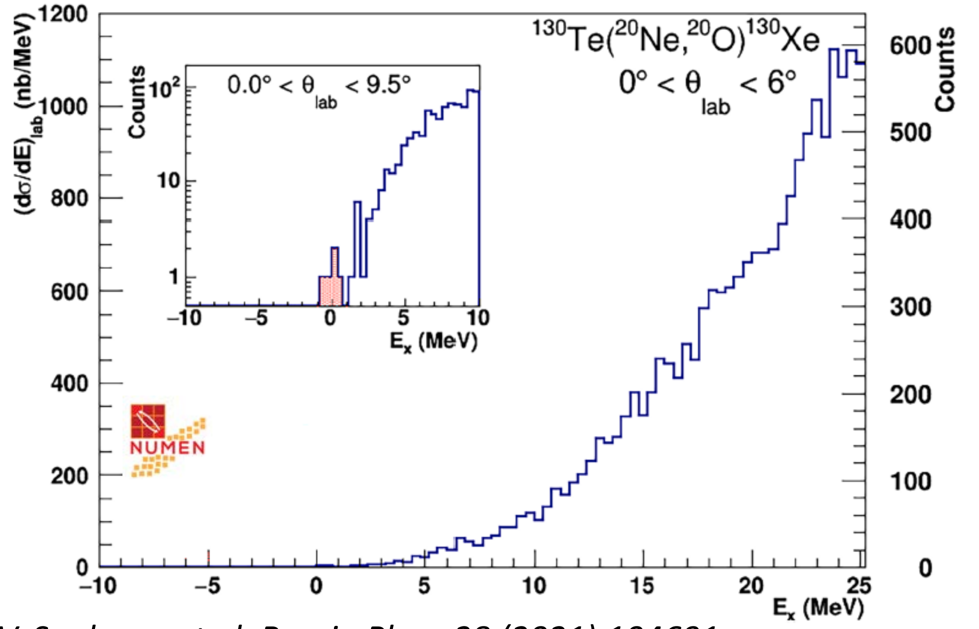
$^{130}Te \rightarrow ^{130}Xe$

E_x range (MeV)	Counts	Int. cross-section (nb)	Cross-section 95% C.L. (nb)
-1 ÷ 1	5	13	[3--18]

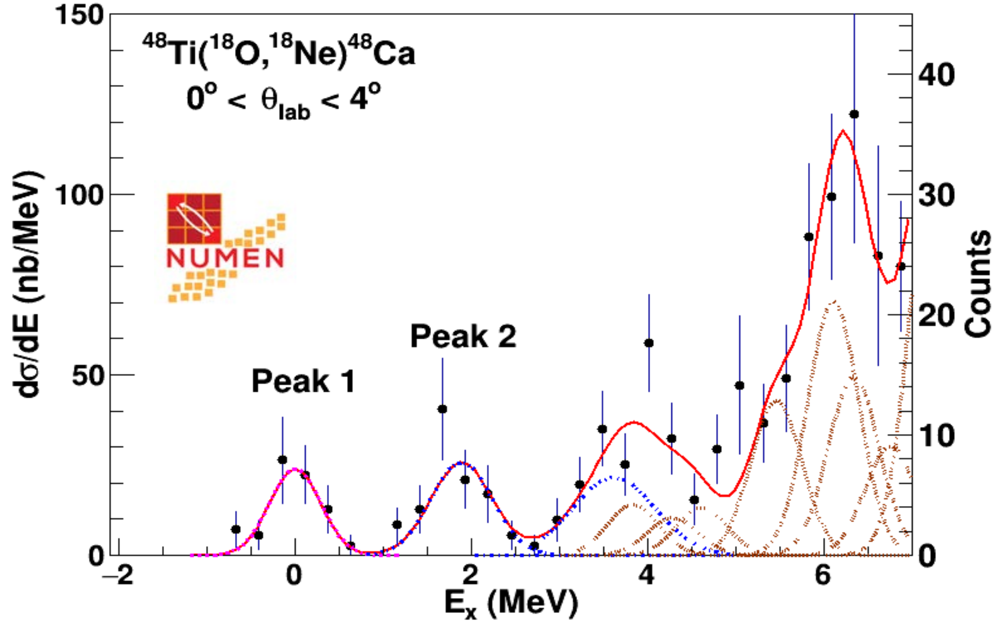


$^{48}Ti \rightarrow ^{48}Ca$

Peak label	Integrated yield (counts)	Int. cross-section (nb)
1	24	20 ± 4
2	32	28 ± 5



V. Soukeras et al. Res. in Phys. 28 (2021) 104691



O. Sgouros et al., in preparation

Background: **0νββ** decay and **DCE** reactions

Methods: the **multi-channel** strategy

Results: DCE measured **cross-sections**

Perspectives and conclusions

PERSPECTIVES:

- MAGNEX FPD @ **iThemba LABS: new measurement** of ^{18}O + ^{76}Se @ 22 AMeV
- LNS experimental campaign: CS and MAGNEX FPD **upgrade** to study all the 0νββ decay cadidates with the **high intensity beams**
- TREFLE: Transfer REactions For neutrinoless doubLE beta decay @IJCLab Orsay (O. Sgouros *et al.*)

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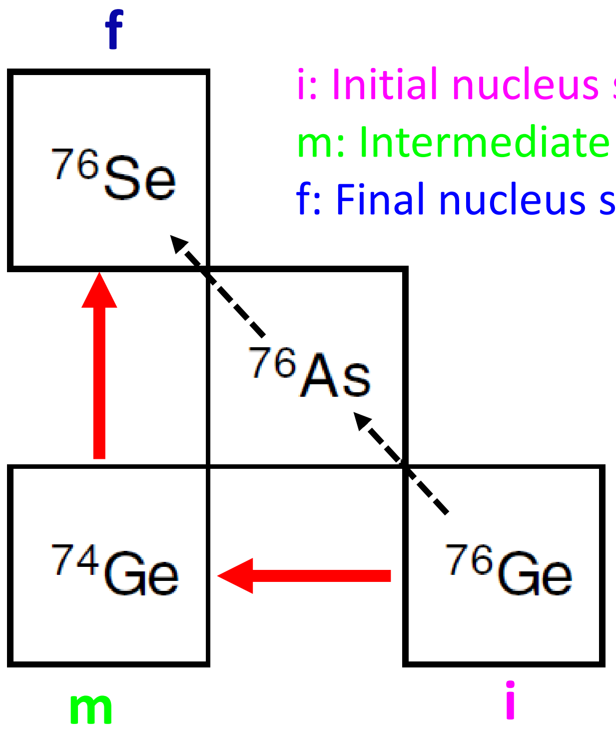
IDEA (by B. A. Brown, Phys. Rev. Lett. 113, 262501 (2014))

$$M^{0\nu} = \sum_{E_m J_m} V(f, i, m)$$

$$V(f, i, m) = \sum \langle k_\alpha, k_\beta, J_m | V | k_\gamma, k_\delta J_m \rangle$$

$$\times TNA(f, m, k_\alpha, k_\beta, J_0)\, TNA(i, m, k_\gamma, k_\delta, J_0)$$

Two-nucleon spectroscopic amplitudes



i: Initial nucleus states
m: Intermediate nucleus states
f: Final nucleus states

PERSPECTIVES:

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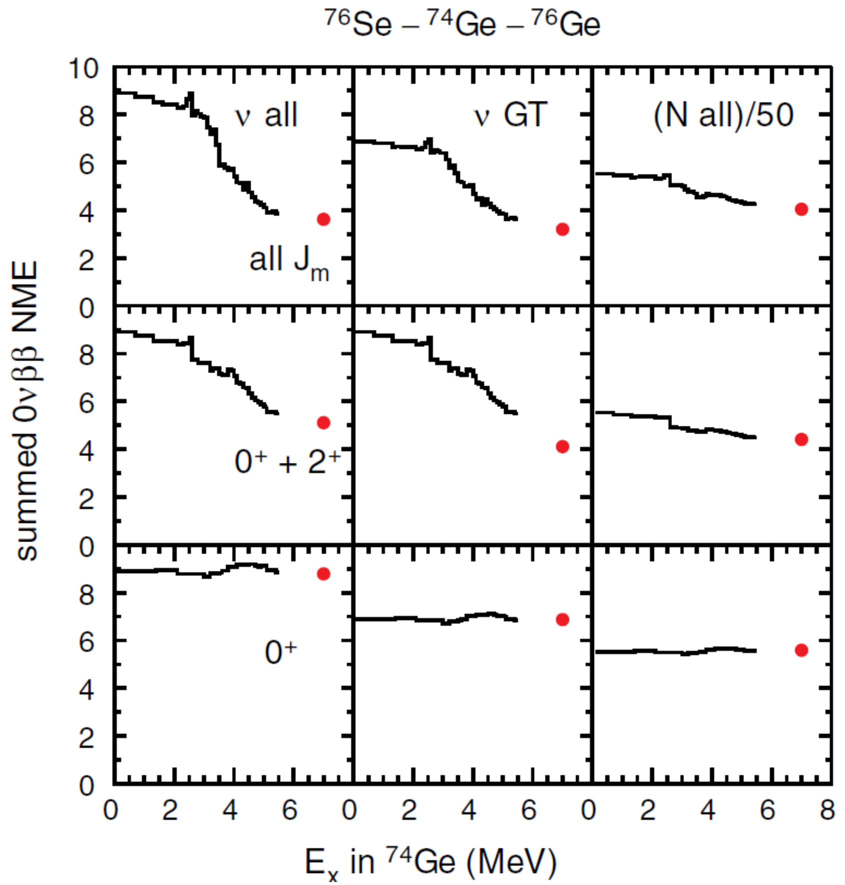

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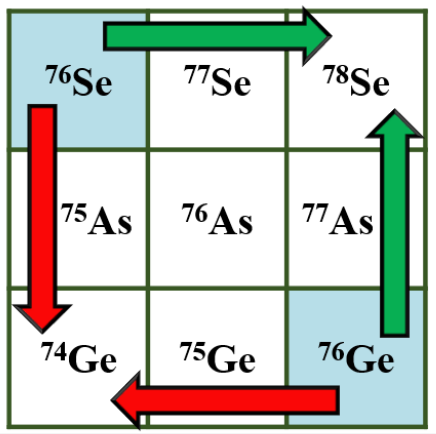


Cross section measurements for:

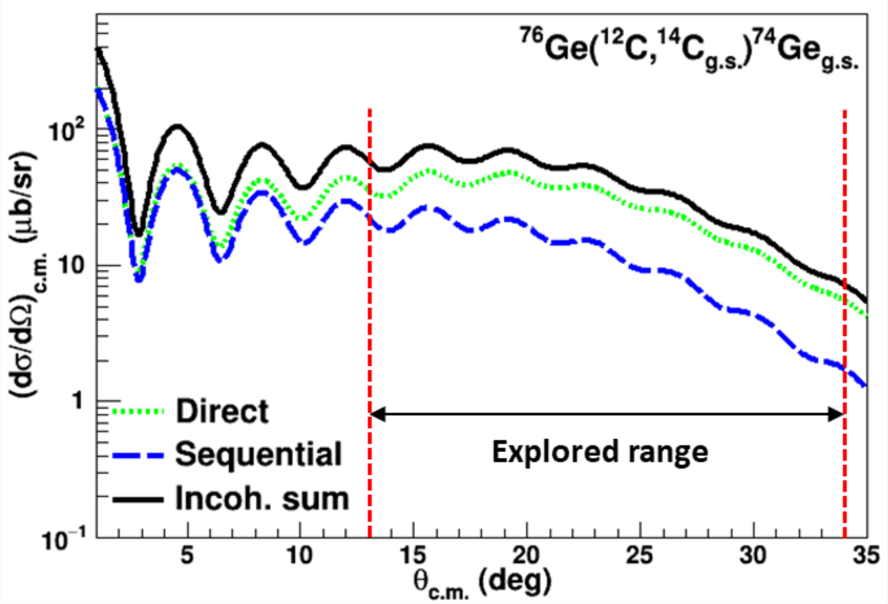
- ^{76}Ge→^{74}Ge two-neutron transfer
- ^{76}Se→^{74}Ge two-proton transfer

Validate <^{74}Ge|^{76}Ge> and <^{74}Ge|^{76}Se> TNA → Calculate NME (A)

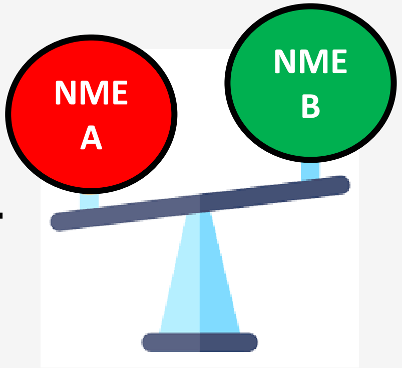
Cross section measurements for:

- ^{76}Se→^{78}Se two-neutron transfer
- ^{76}Ge→^{78}Se two-proton transfer

Validate <^{78}Se|^{76}Se> and <^{78}Se|^{76}Ge> TNA → Calculate NME (B)



Experimental check for the NMEs **time invariance** !



CRC reaction calculations by O. Sgouros

Large-scale shell-model calculations by G. De Gregorio

Compare the values of calculated NMEs

PERSPECTIVES:

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CONCLUSIONS:

- Multichannel approach for the data analysis: a way to the full **DCE reaction mechanism**
- **DCE cross-sections on ^{116}Cd, ^{76}Ge, ^{76}Se, ^{48}Ti, ^{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 (tens of nb!)
  - Time invariance
- New **theory** of DCE (**DSCE**, **MDCE** and **multi-nucleon transfer**)
- New **experimental campaigns** at LNS, iThemba LABS and ICJLab Orsay

The **NUMEN** collaboration

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

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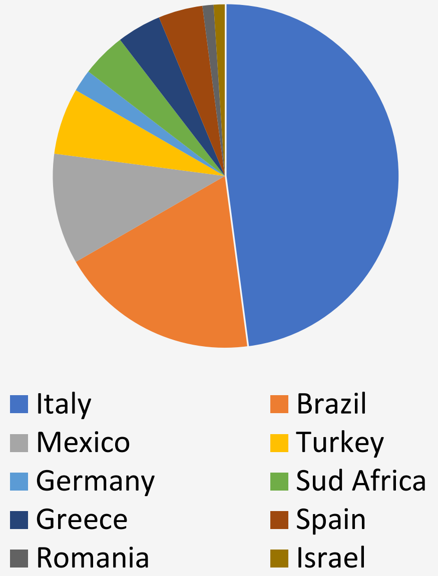

Grazie

Now, it is time for questions!