NURE

Heavy-ion induced quasi-elastic reactions in view of the NUMEN project

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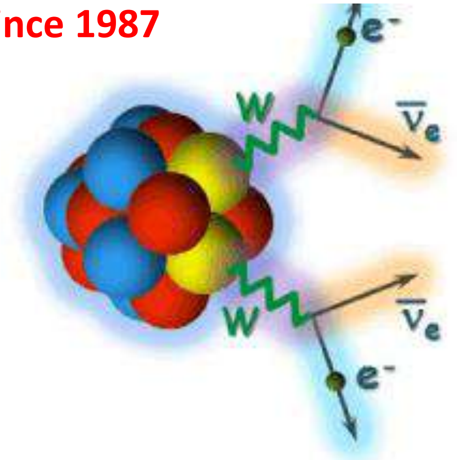
6th workshop of the Hellenic Institute of Nuclear Physics
New Aspects and Perspectives in Nuclear Physics
Zoom Conference
National and Kapodistrian University of Athens
HINPw6 - 14-16 May 2021

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



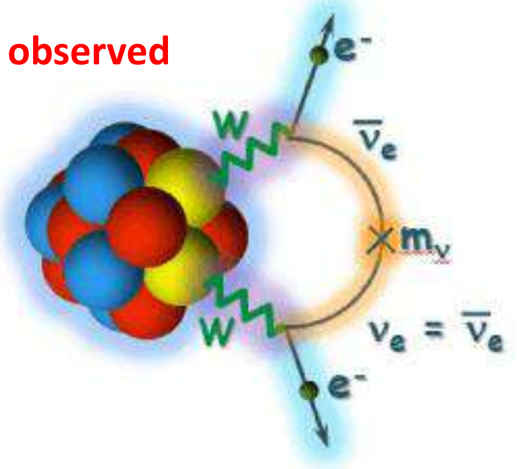
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

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

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

Neutrinoless double beta decay

Still not observed



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

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**

$$1/T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

The Nuclear Matrix Element

New physics for the next decades

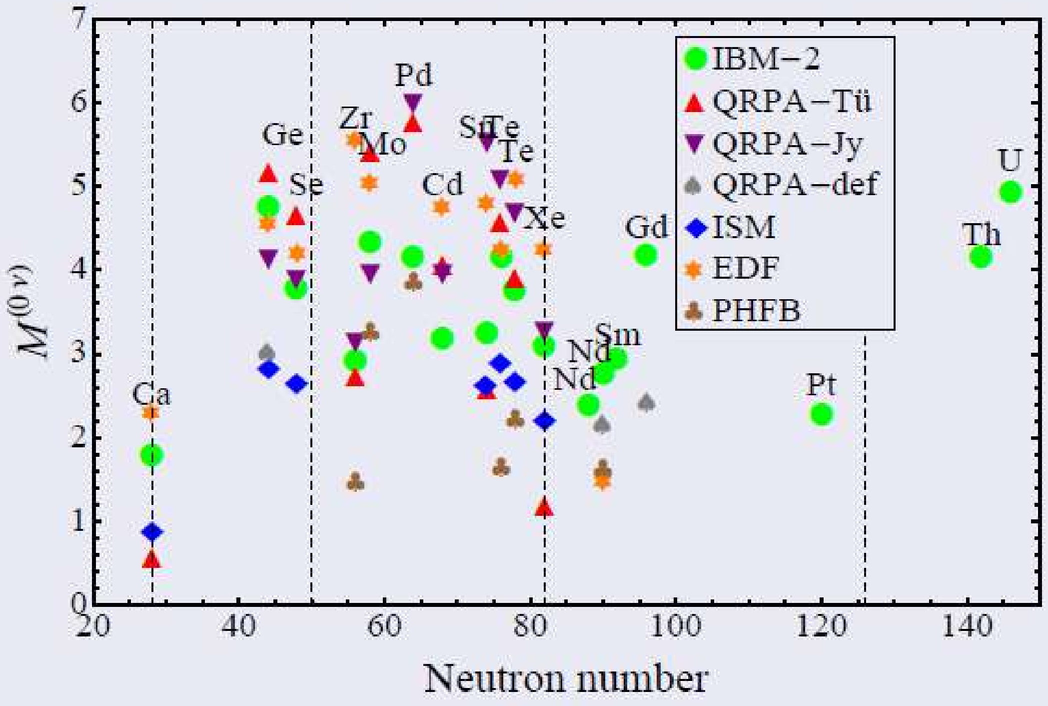
requiring

Nuclear Matrix Element (NME)!

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

State of the art NME calculations

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



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

Support from the experiments

Measurements (still not conclusive for 0νββ NME):

✓ β-decay and 2νββ decay

1st order isospin probes

2nd order isospin probes

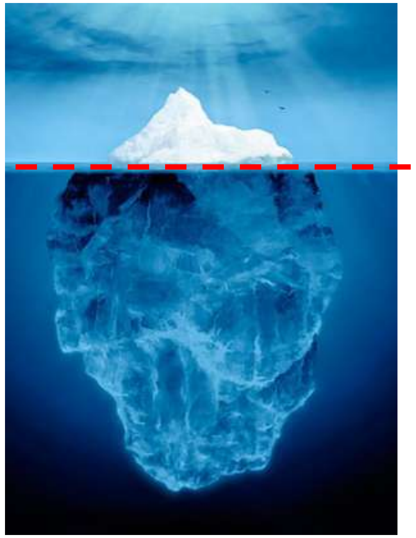
✓ (π^+, π^-), single charge exchange (^{3}He,t), (d,^{2}He), HI-SCE, electron capture, transfer reactions, μ-nucleus scattering, γ-ray spectroscopy, double γ-decay etc..

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

Heavy-ion DCE as surrogate processes of ββ-decay

- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order: Kinematical matching conditions
- ✓ Meson exchange mechanism 1st or 2nd order
- ✓ Possibility to go in both directions
- ✓ Low cross section

Tiny amount of DGT strenght for low lying states

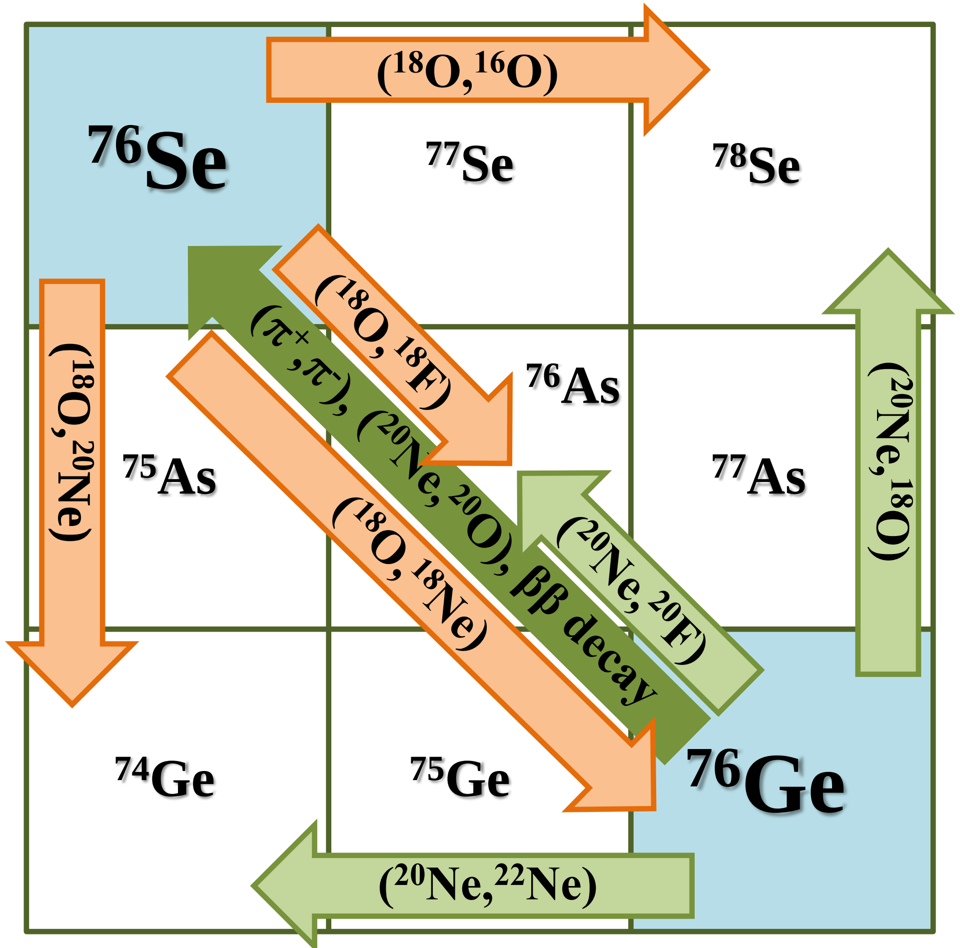


NUMEN

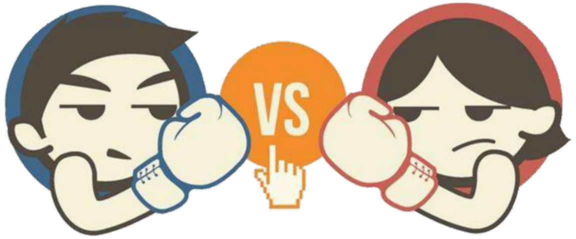
Sum rule almost exhausted by DGT Giant Mode, still not observed

RIKEN

RCNP



$0\nu\beta\beta$ vs DCE



Differences

- DCE mediated by **strong interaction**, $0\nu\beta\beta$ 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**: Constraint 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 in principle:

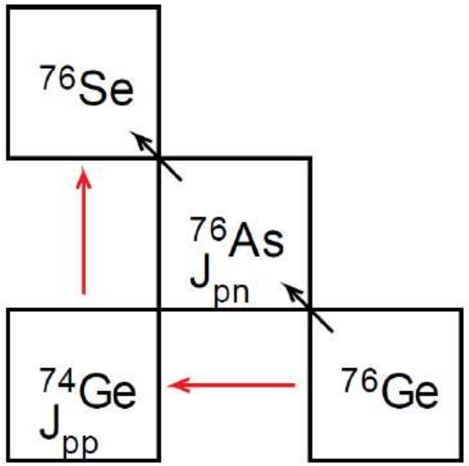
- Sequential multi-nucleon transfer
- Collisional processes
    - Double single charge exchange (DSCE): two consecutive single charge exchange processes
    - Two-nucleon mechanism (MDCE): relying on short range NN correlations, leading to the correlated exchange of two charged mesons between projectile and target.

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

1. Multi-nucleon transfer (proton pick-up/stripping followed by neutron stripping/pick-up)

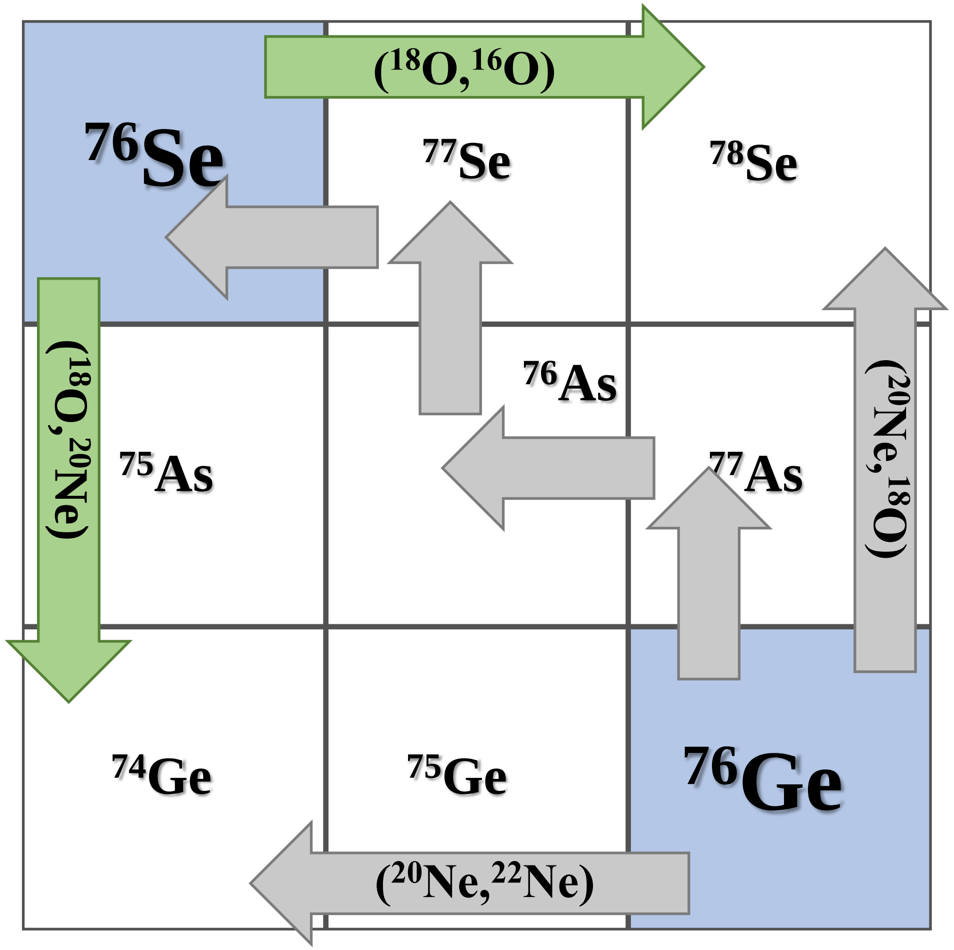
- ✓ **Probing at least twice** nucleus-nucleus Initial (**ISI**) and Final (**FSI**) State interaction (at least 2° order)
- ✓ **mean field driven**
- ✓ **Single-nucleon transfer of 4th order**
- ✓ **Sequential transfer of 2p/2n pairs is of 2nd order**
- ✓ Transfer or **2p/2n pairs followed by 2n/2p pairs** could be of **interest** for 0υββ NME

  B.A.Brown et al. PRL 113, 262501 (2014)



Expansion of NME in terms of summation over states of the (A-2) nucleus.

Role of pairing



2. Double Single Charge Exchange (DSCE)

The existence of pion-induced DCE proves that there is a reaction mechanism (other that sequential transfer) mediated by an interaction of more direct character

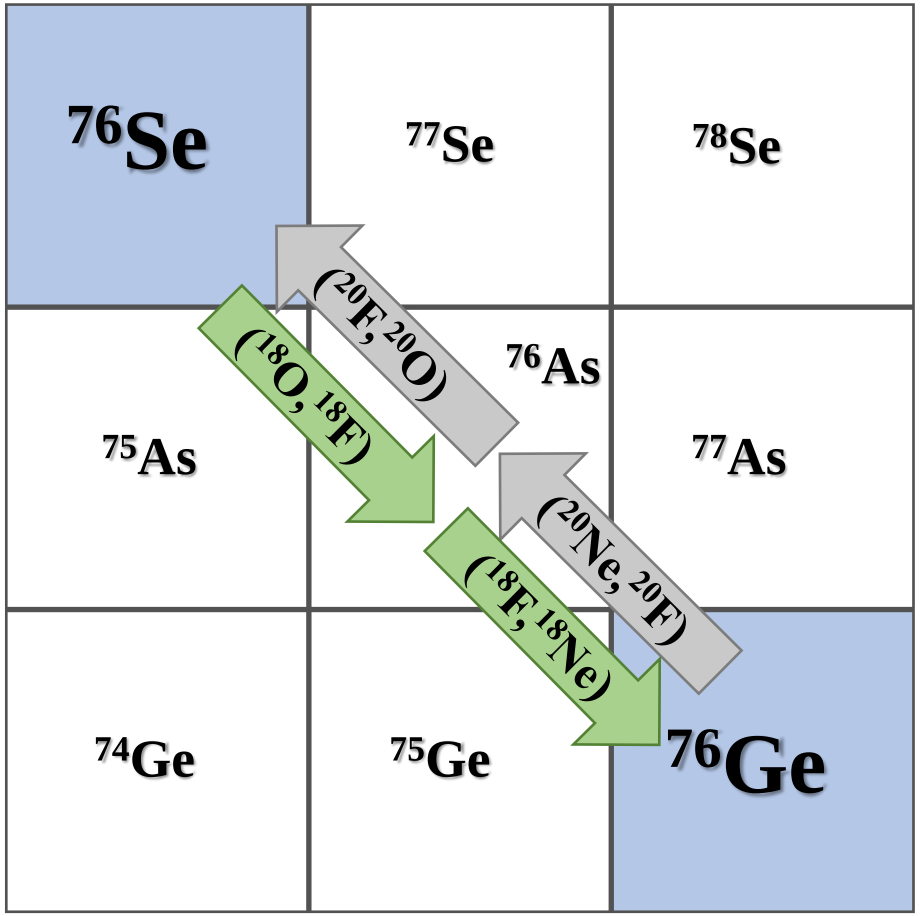
- ✓ **Two-step process (two consecutive SCE occur in an uncorrelated manner), no correlation between vertices**
- ✓ **Probing twice** nucleus nucleus Initial (**ISI**) and Final (**FSI**) State Interaction

DSCE reaction amplitude

$$M_{\alpha\beta}^{(DSCE)} = \langle \chi_{\beta}^{(-)} bB | T_{NN} \mathcal{G} T_{NN} | aA \chi_{\alpha}^{(+)} \rangle$$

$$\mathcal{G} = \sum_{cC} |cC\rangle G_{cC} \langle cC|$$

Effects of SSD and closure studied

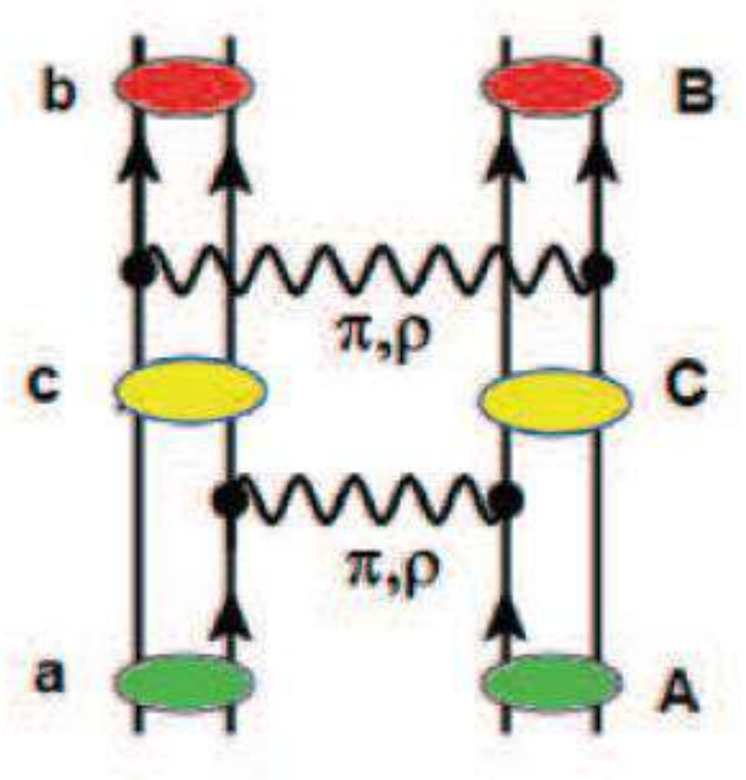


2. Double Single Charge Exchange (DSCE)

- ✓ **Analogies with 2νββ** decay which is a sequential decay process where the leptons are emitted subsequently in an uncorrelated manner

- ✓ **but sum over products of projectile and target** NME's

- ✓ The transition operator will be **dependent** on the **projectile/target combination** and on **incident energy**. These dependencies may be taken advantage of, in principle, for selecting suitable conditions such that the DSCE amplitudes are either suppressed or enhanced.



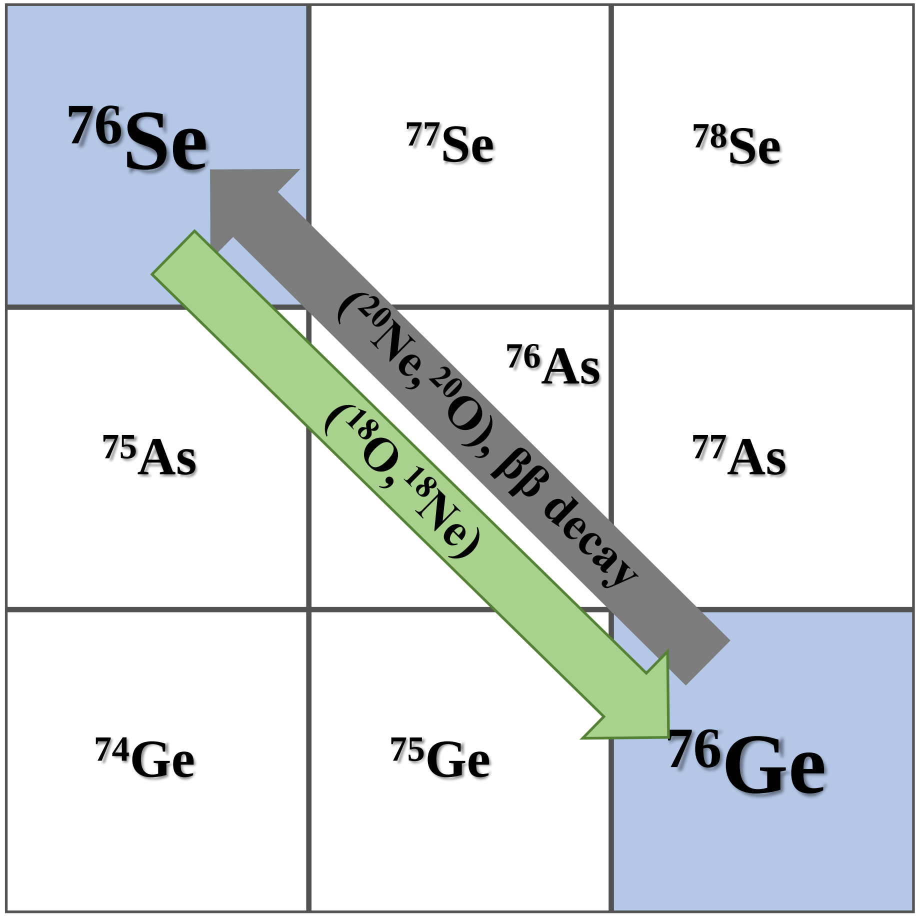
J. Bellone et al., PLB 2020, 807, 135528
H. Lenske et al., Universe 2021, 7, 98

3. Correlated Double Charge Exchange (‘*Majorana*’ mechanism MDCE)

Independent on the projectile/target combination because rely on **nucleonic short-range correlations** (universal phenomena of nuclear matter)

- ✓ **Probing once** nucleus nucleus Initial (**ISI**) and Final (**FSI**) State Interaction
- ✓ **Correspondence with 0νββ ?**

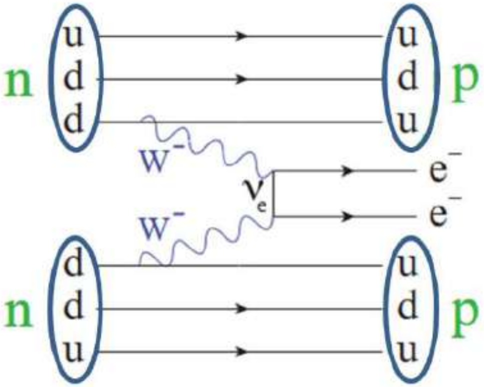
H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
H. Lenske, CERN Proceedings 2019-001 (2019)

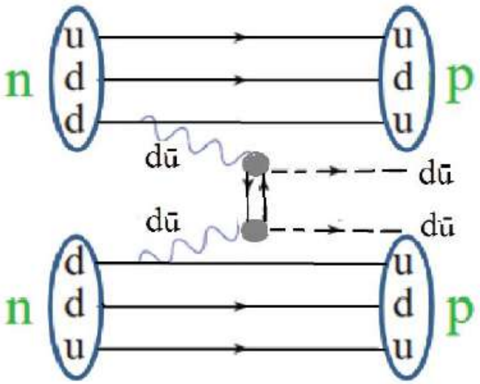


The “Majorana” hadron mechanism for HI-DCE

H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716

Elementary **weak interaction** process mediating 0νββ





Elementary **strong interaction** process mediating 1-step DCE

Similar diagrammatic structure

The $pp \rightarrow nn\pi^+\pi^+$ reaction and other double-pion production channels have been investigated at CELSIUS, COSY, HADES

Special class of **two-body correlation**

- emission of virtual weak gauge boson $W^{\pm}$,
- exchange of a Majorana neutrino between two nucleons
- and emission of electrons

Can occur, in principle, in an isolated nucleus

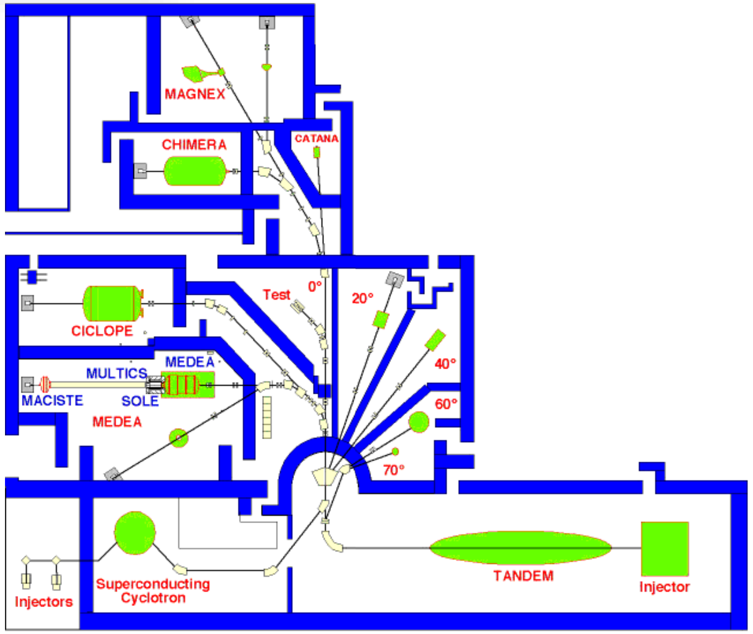
Also **two-body correlation**

- emission of virtual $q\bar{q}$ (π^-, ρ^-)
- exchange of a virtual charge-neutral $q\bar{q}$ pair (π^0,ρ^0, σ)
- and emission of charged $q\bar{q}$

Inhibited by energy conservation, it requires a reaction partner which take care of the virtuality of the process by absorbing the two charged virtual mesons

DCE @ INFN-LNS

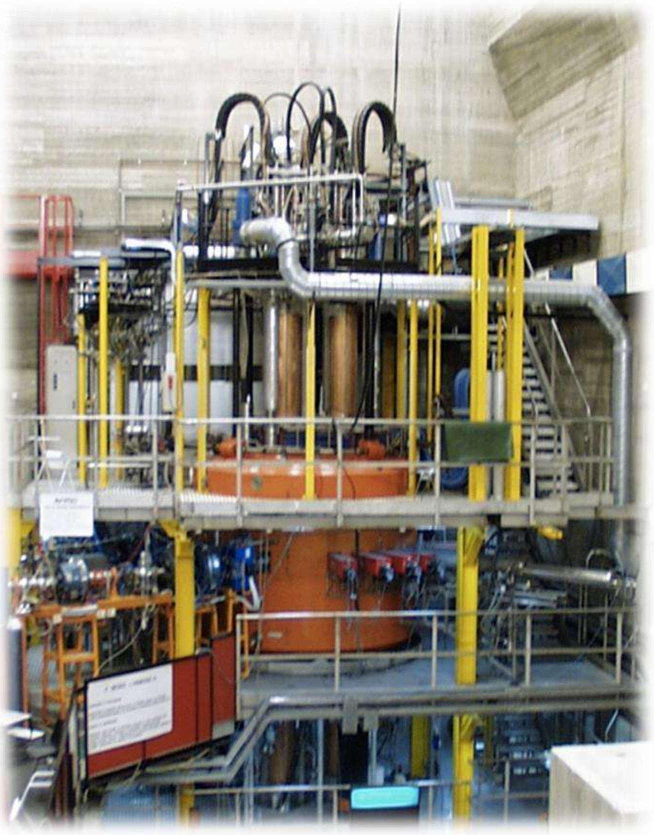
The LNS laboratory in Catania



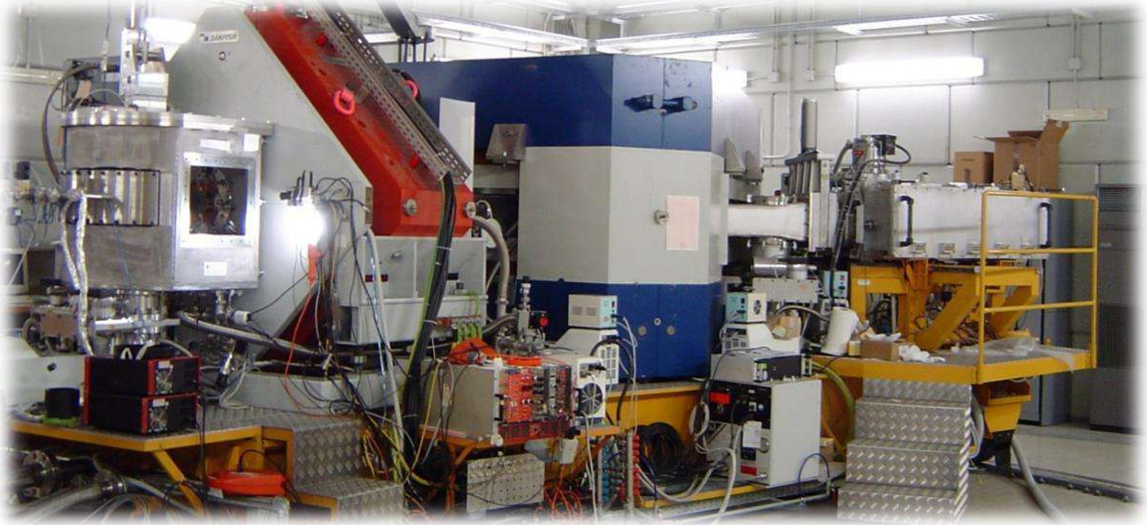
Superconducting Cyclotron and MAGNEX spectrometer @ LNS

Crucial for the experimental challenges

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



F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167



See talk of M. Cavallaro, O. Sgouros, V. Soukeras and S. Koulouris

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

Good compensation of the aberrations: Trajectory reconstruction

⇒

Measured resolutions:

- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/160$

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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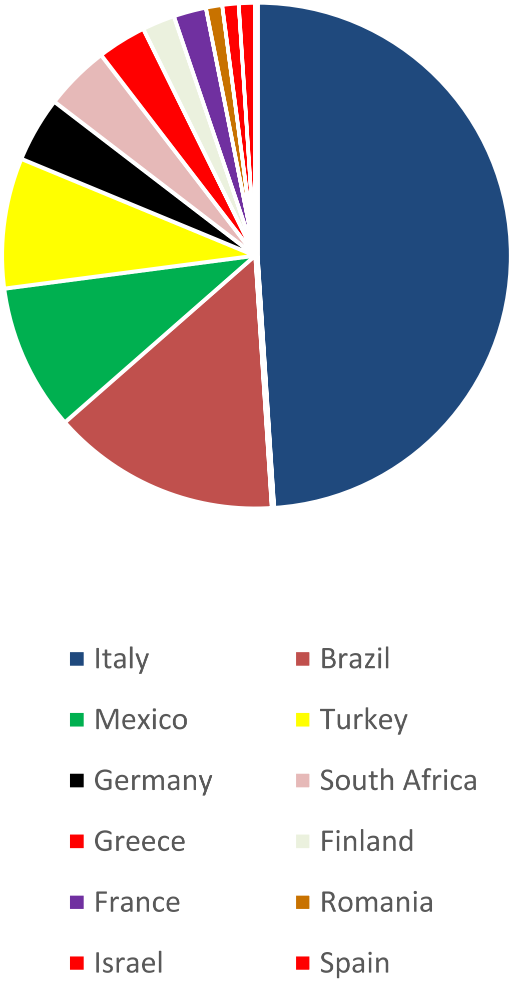
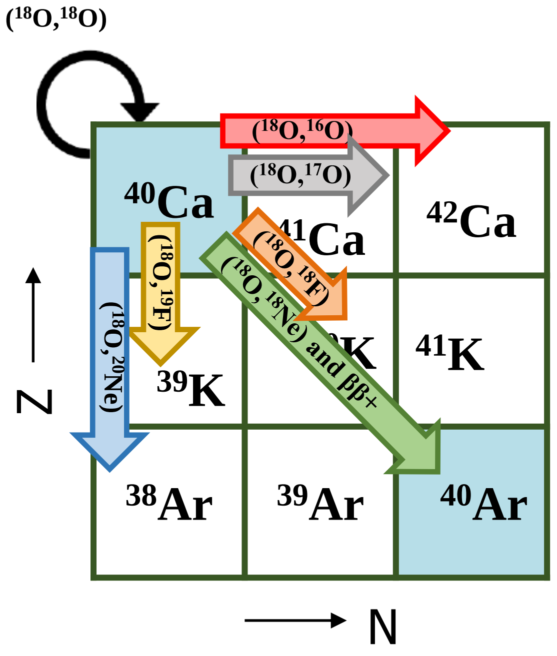


The NUMEN multi-channel approach

Several scattering and reaction channels open in a 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 → strenght of pairing correlations

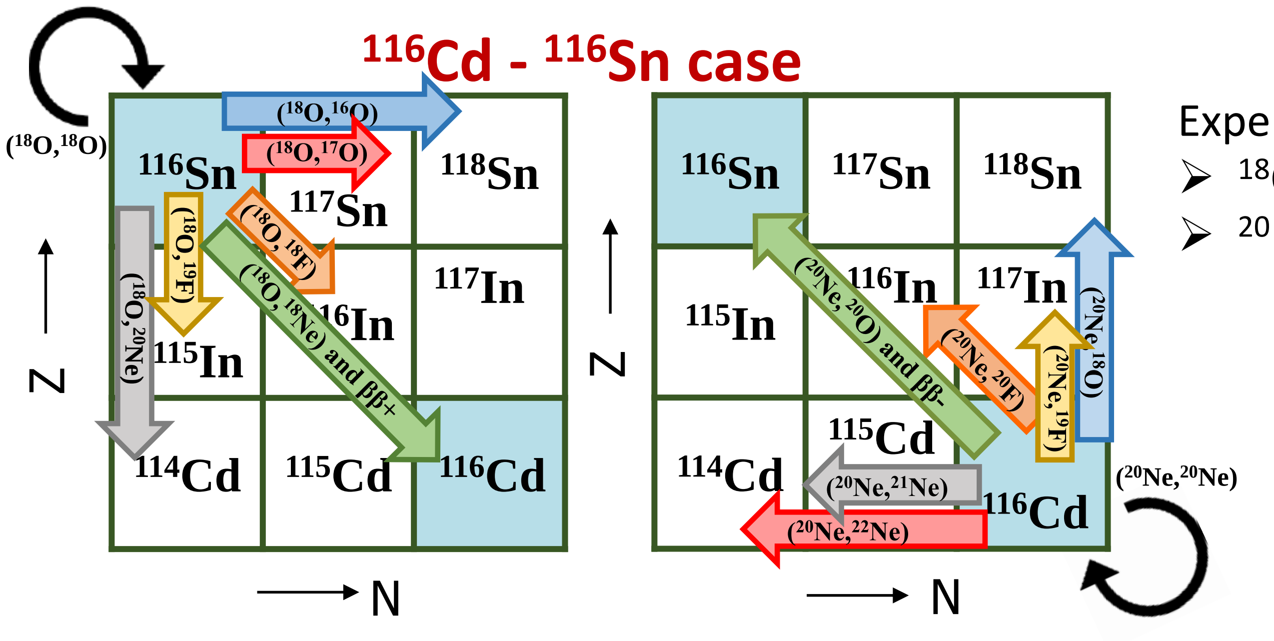
Single charge exchange (SCE) → nuclear response to 1st order isospin operators (One-Body Transition Densities)

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

The NUMEN multi-channel vision

- ✓ Measuring all the accessible quasielastic channels all at once gives a **high reliability of the measured observables**, since systematic errors are largely cancelled thanks to the many possible cross checks in the data
- ✓ From the theory side, **constrained data analyses can be performed**, such as coupled channel approaches, largely reducing the possibilities of free parameters in both nuclear structure and reaction models

An example



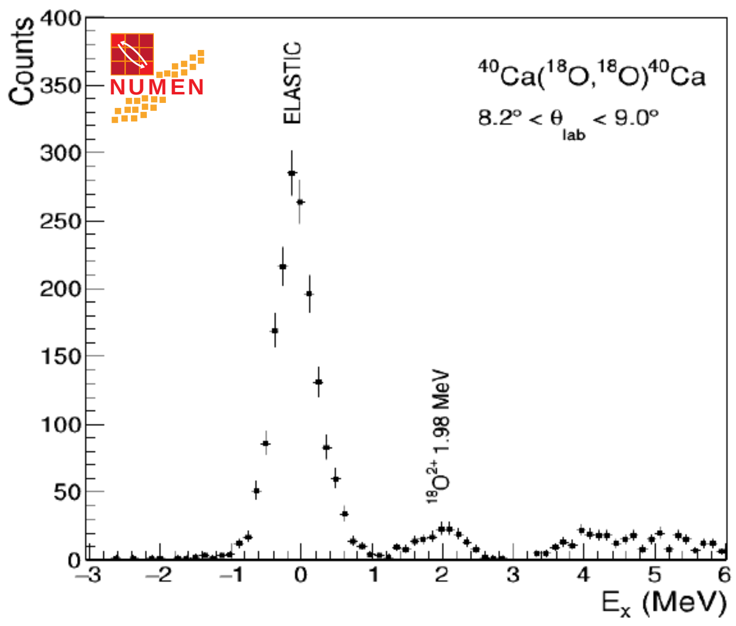
Experiments @ 15 MeV/A

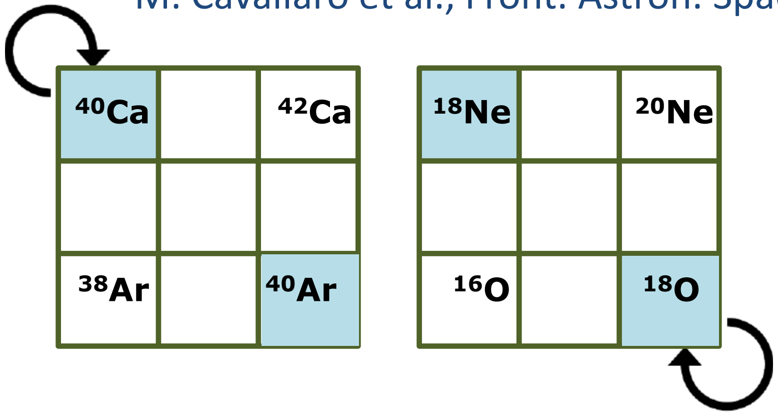
- ➢ ^{18}O + ^{116}Sn
- ➢ ^{20}Ne + ^{116}Cd

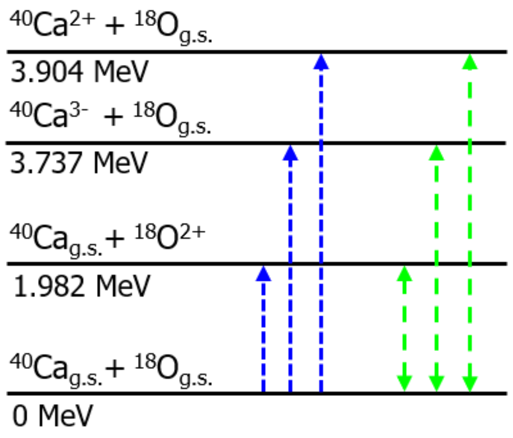
Recent NUMEN experimental results: the ^{18}O + ^{40}Ca @ 270 MeV case

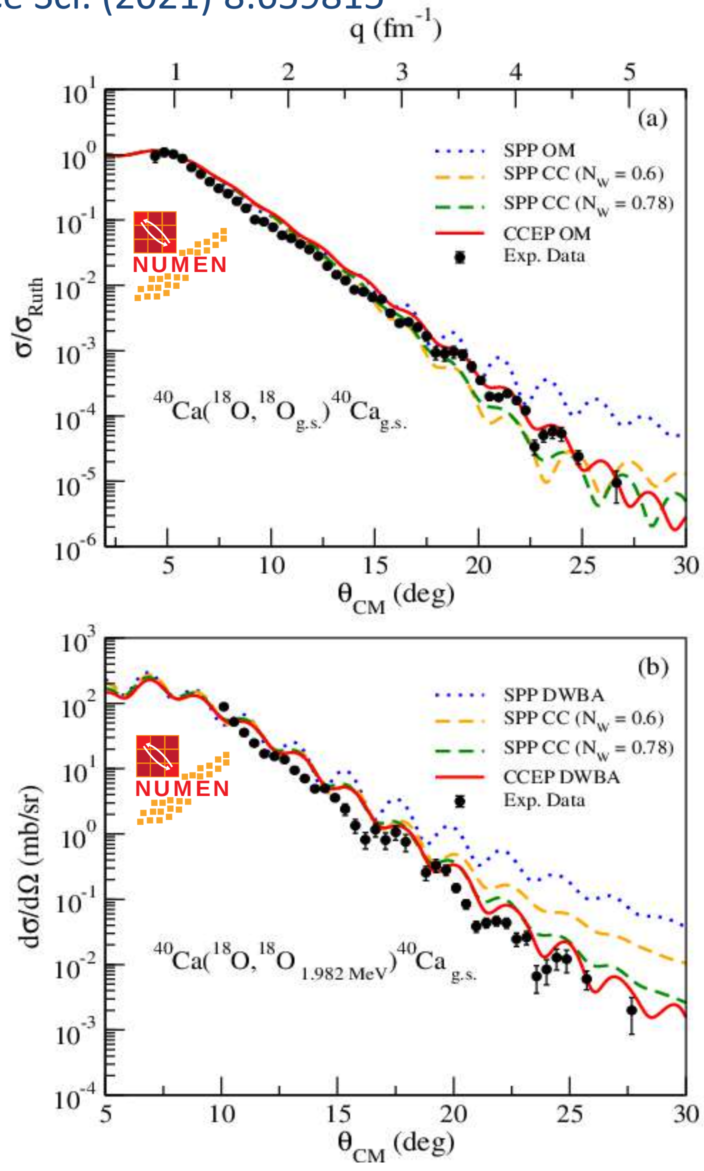
The $^{40}Ca(^{18}O,^{18}O)^{40}Ca$ elastic and inelastic scattering @ 270 MeV

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







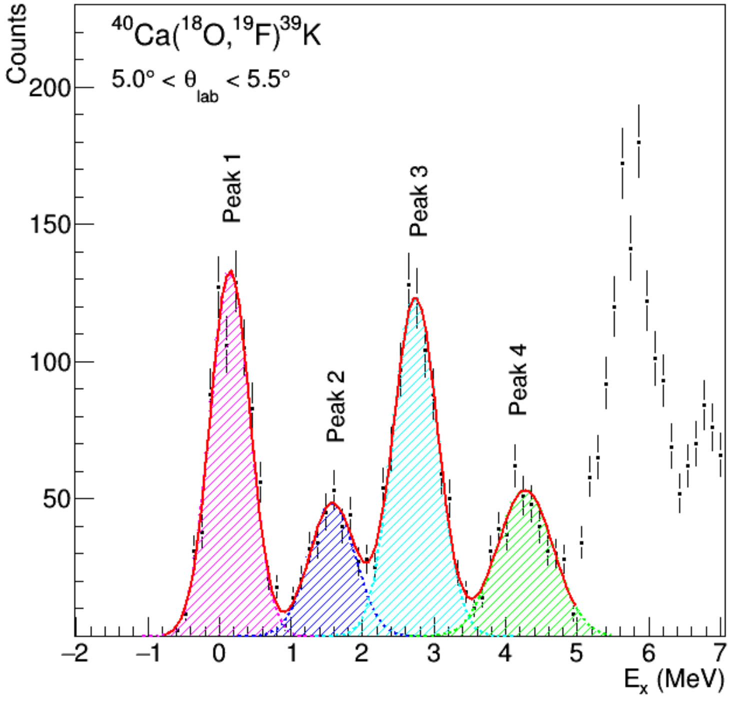


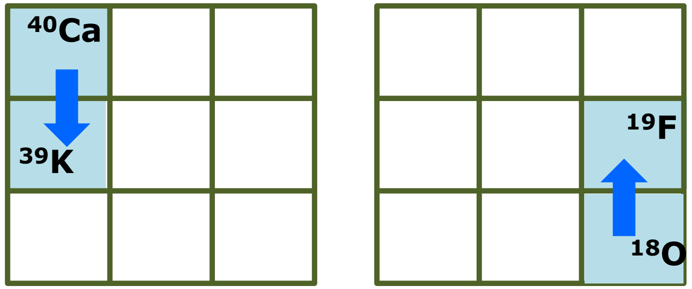
Key information from scattering data:

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

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

Calculations still under way

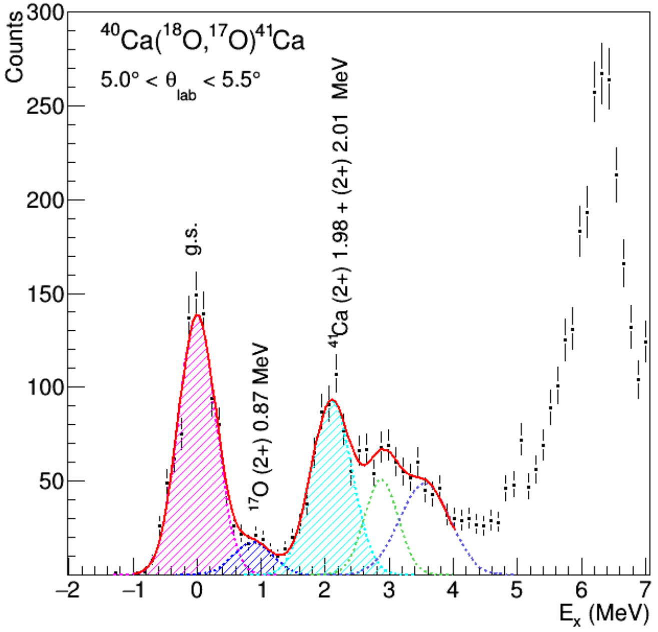
Key information from 1p data:

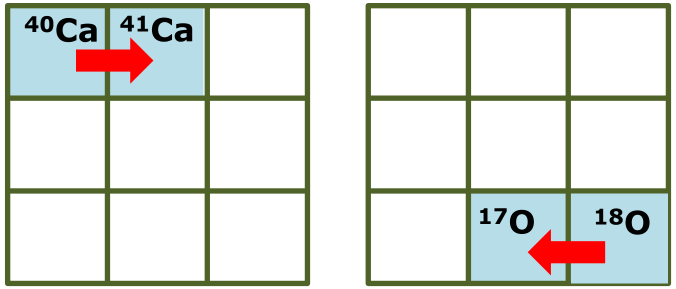
- **Very good description of the data from CCBA constrained approach**
- **Mixing of single particle and core polarization configurations**

See also talk of O. Sgouros

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

CCBA analysis based on shell model amplitudes





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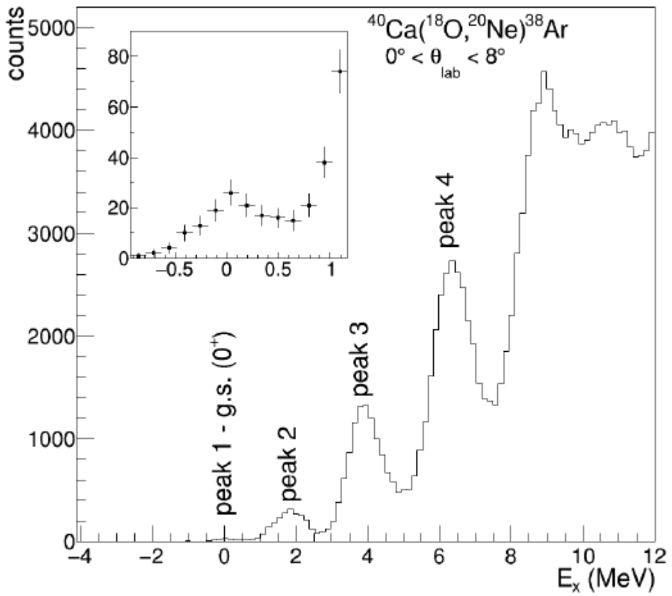
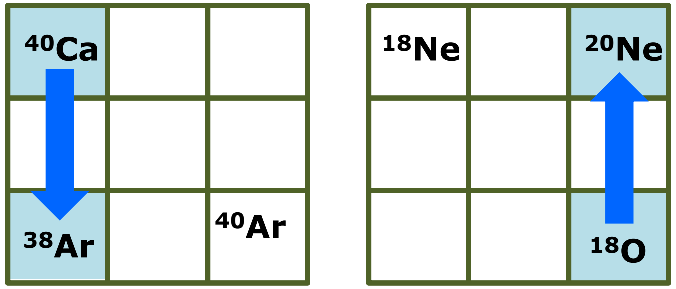
The $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ 2p transfer @ 270 MeV

CCBA analysis based on direct and two-step tranfer with shell model amplitudes





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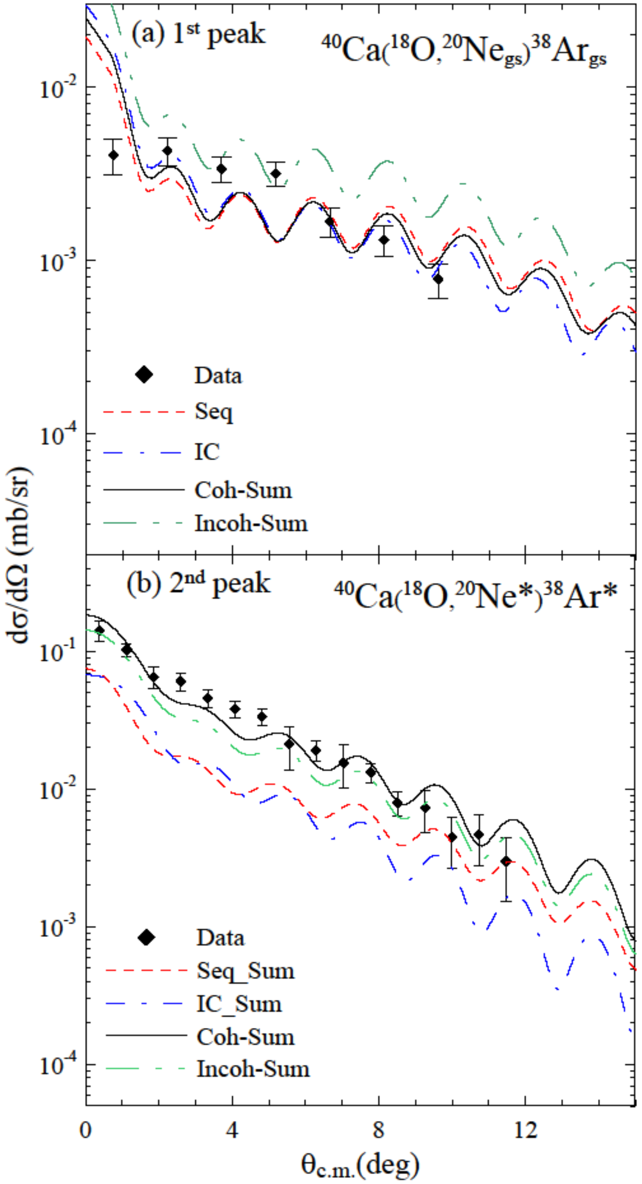


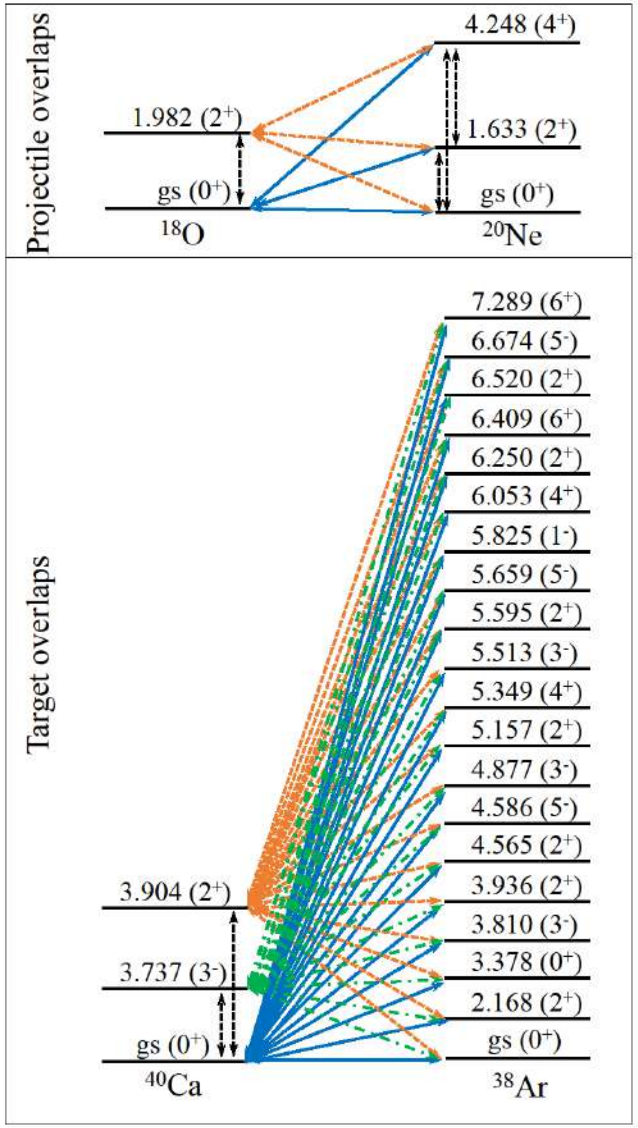
Key information from 2p data:

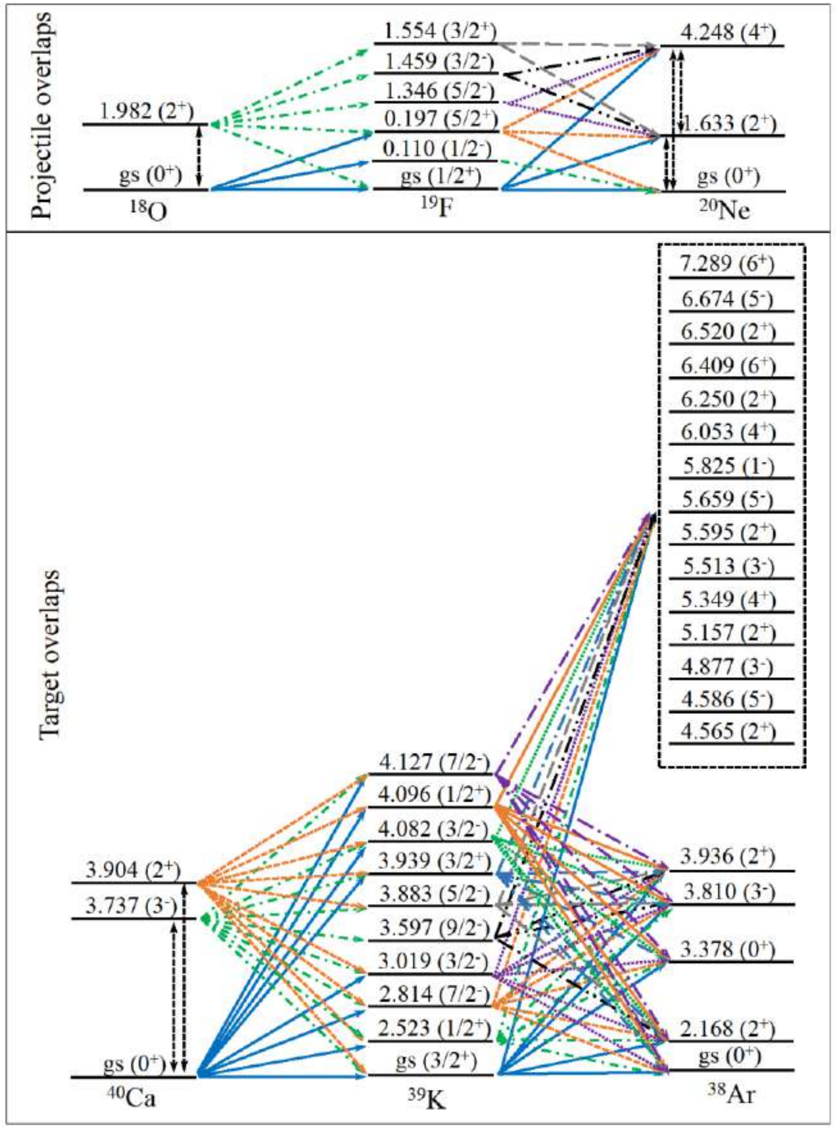
- **Very low cross section** (comparable with DCE) for low-lying states (poorly matched)
- **Very good description of the data from CCBA constrained approach**

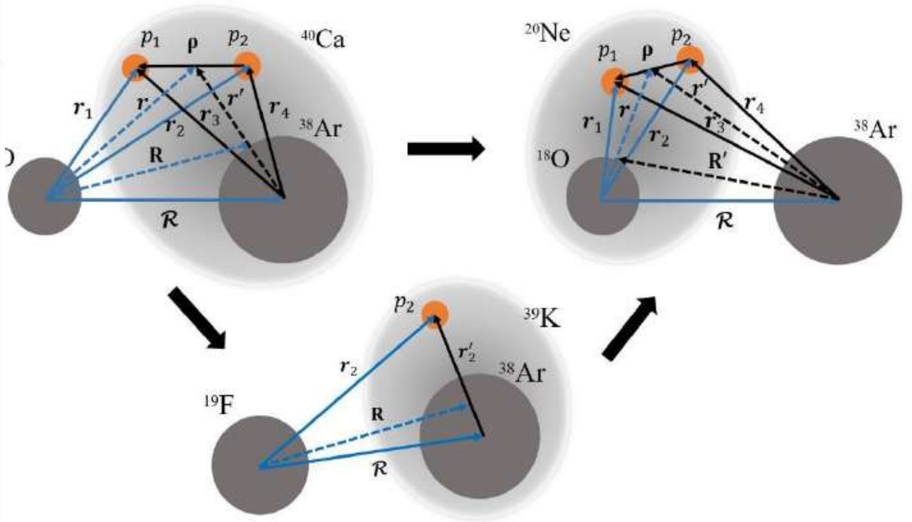
J.L. Ferreira et al., Phys. Rev. C 103 (2021) 054604

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

CCBA analysis based on direct and two-step tranfer with shell model amplitudes

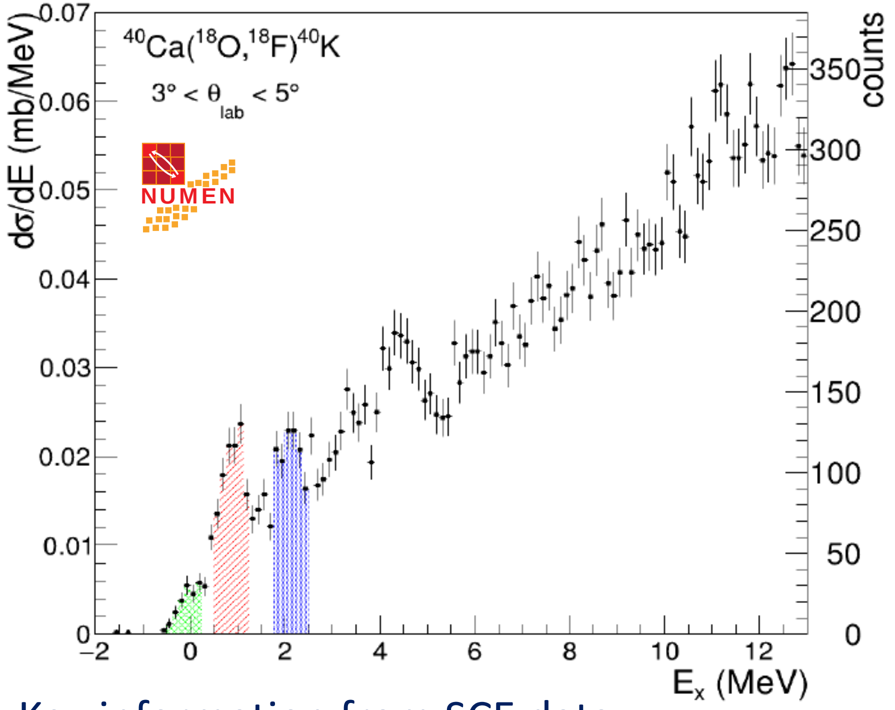


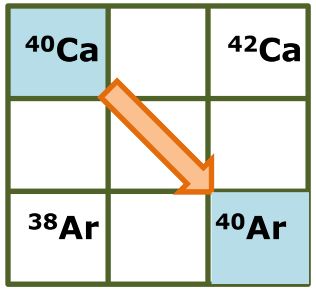


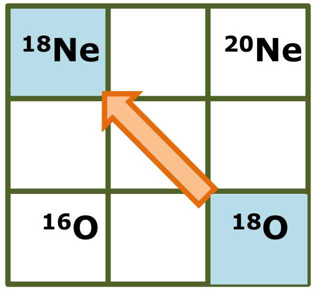


The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 270 MeV

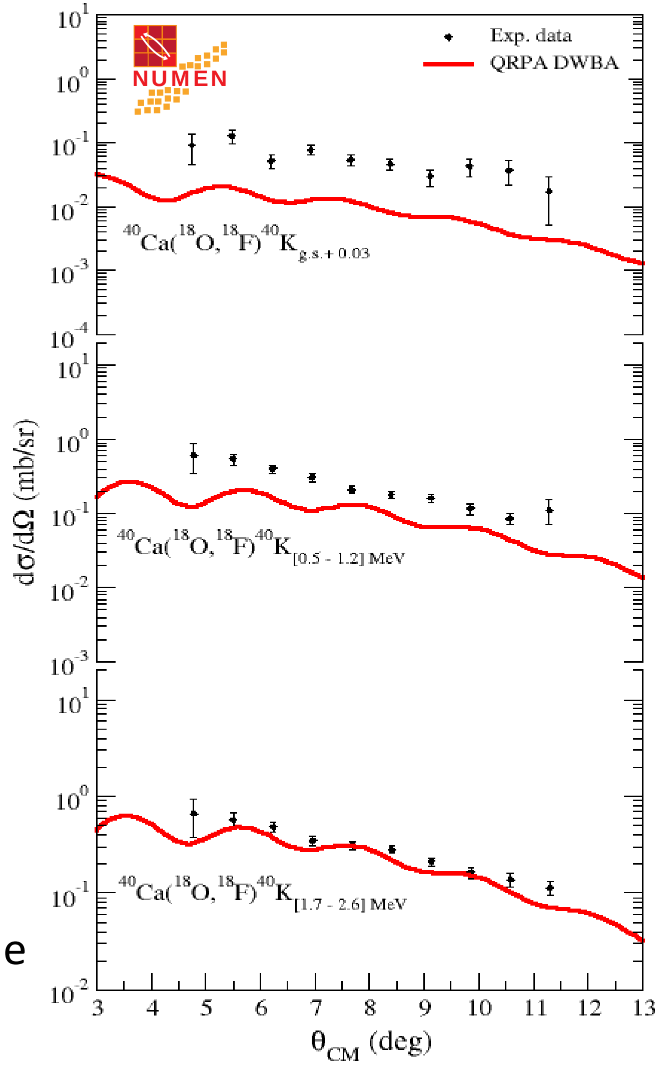
DWBA analysis based on double folding form factors of QRPA transition densities with NN isovector interaction







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



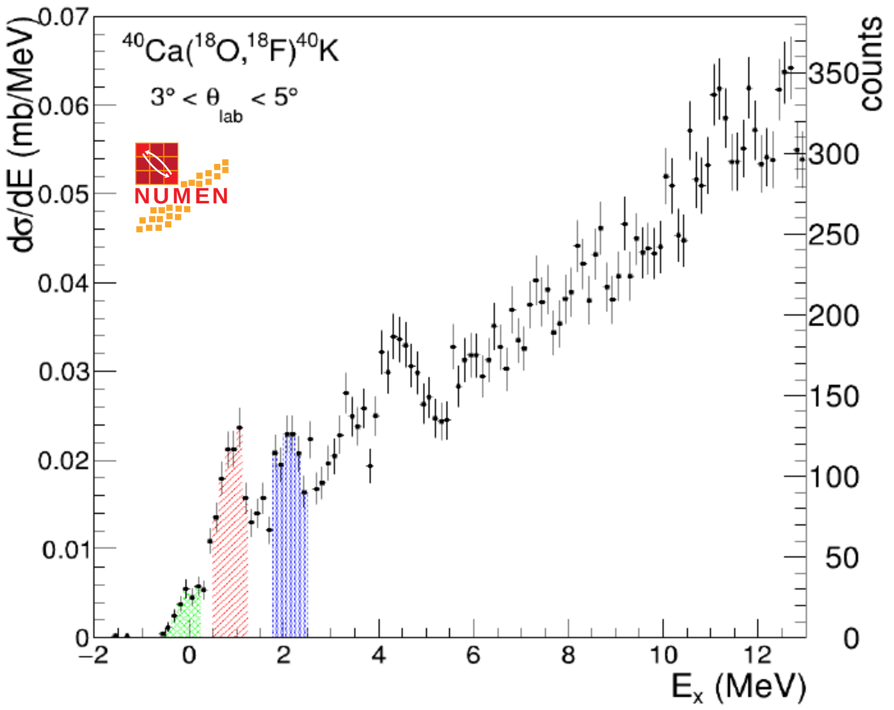
M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815

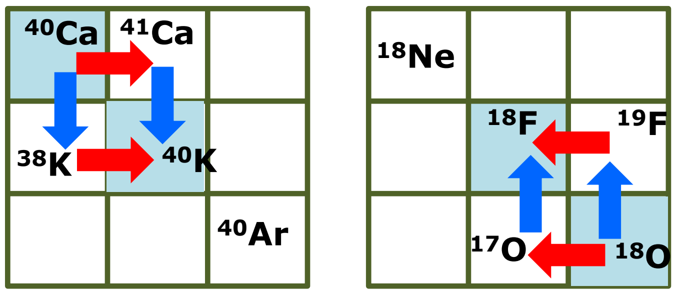
Key information from SCE data:

- **Direct meson exchange mechanism important at low excitation energy**
- Two-step nucleonic SCE is expected to contrbute less at higher excitation energy due to the progressively worse kinematical matching
- **Access to** Fermi, Gamow-Teller as well as **to high-multipole isospin response, relevant for $0\nu\beta\beta$**

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

CCBA analysis based on direct and two-step tranfer with shell model amplitudes





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

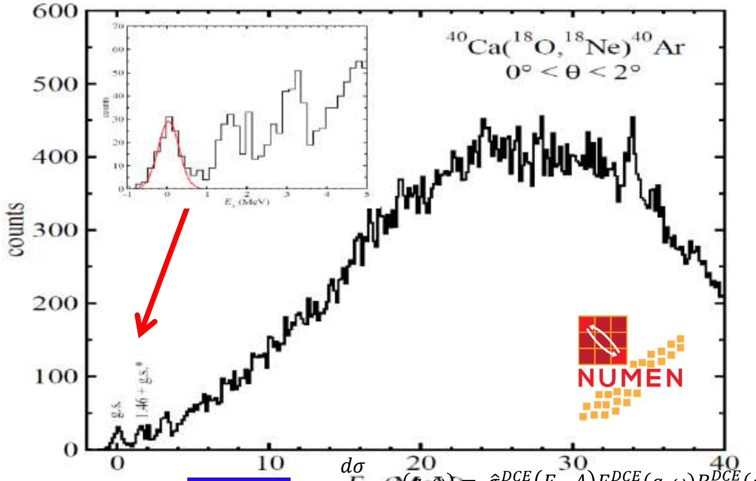
Calculations still under way

Key information from SCE data:

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

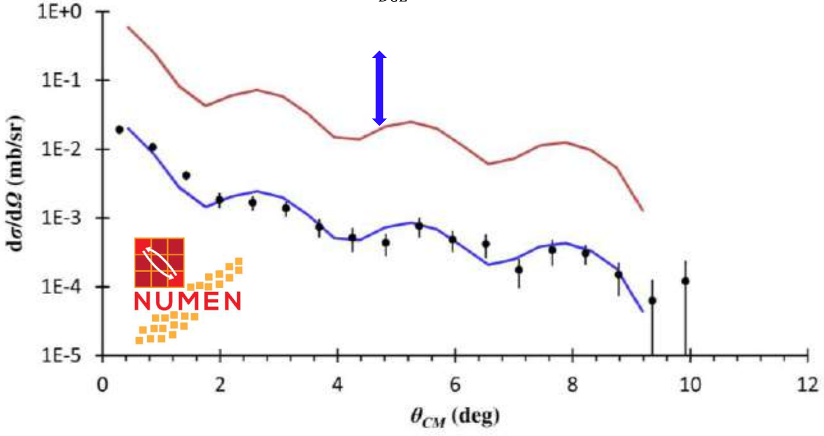
The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ double charge exchange @ 270 MeV

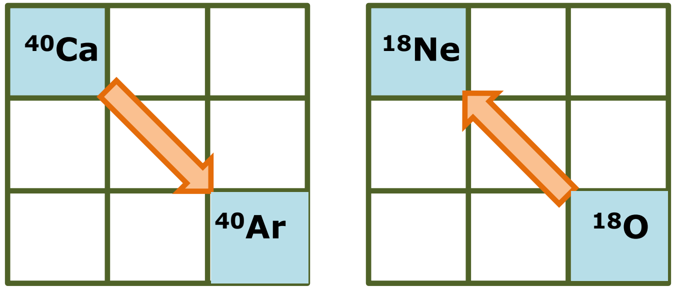
Access to ground-to-ground state transition

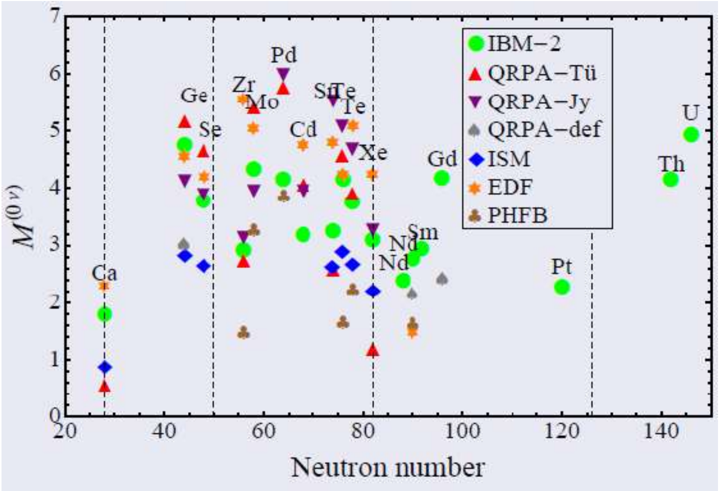


$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_{\alpha}^{DCE}(E_p,A)F_{\alpha}^{DCE}(q,\omega)B_T^{DCE}(\alpha)B_P^{DCE}(\alpha)$$

$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_{\alpha}^{DCE}(E_p,A)F_{\alpha}^{DCE}(q,\omega)$$







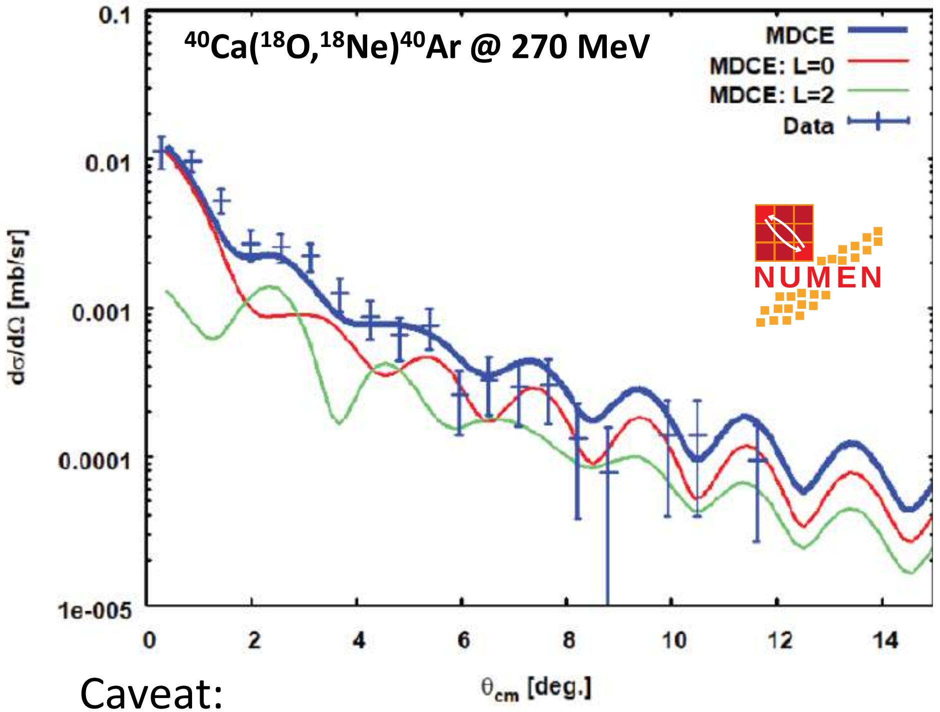
$$\left|M_{\sigma\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.2 \pm 0.6$$

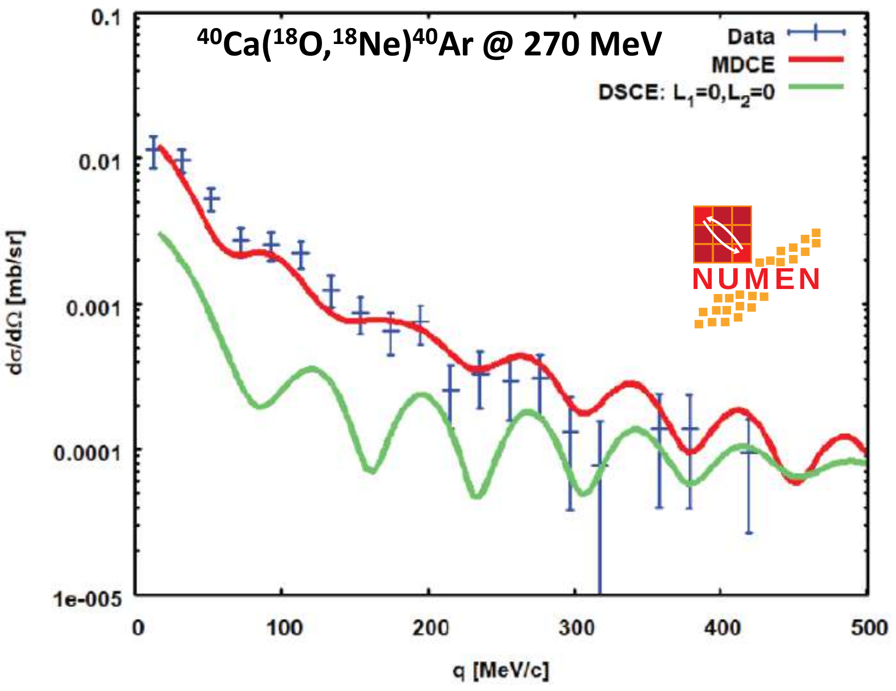
$$\left|M_{\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.1 \pm 0.5$$

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

The DSCE and “Majorana” mechanisms for the $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$

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





- *H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716*
- *J. Bellone et al., PLB 2020, 807, 135528*
- *H. Lenske et al., Universe 2021, 7, 98*

Caveat:

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

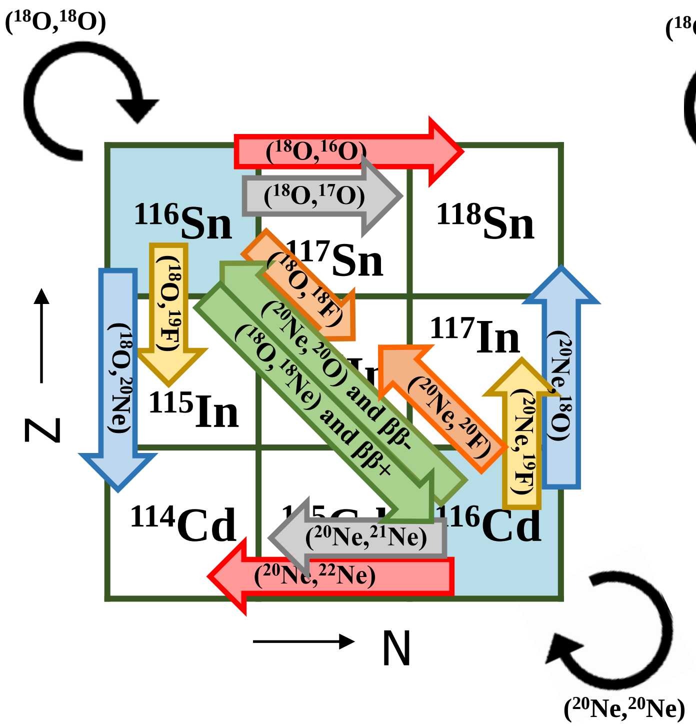
→ **Scaling factor**

Encouraging results, but still room for improvements

NUMEN runs – Phase 2

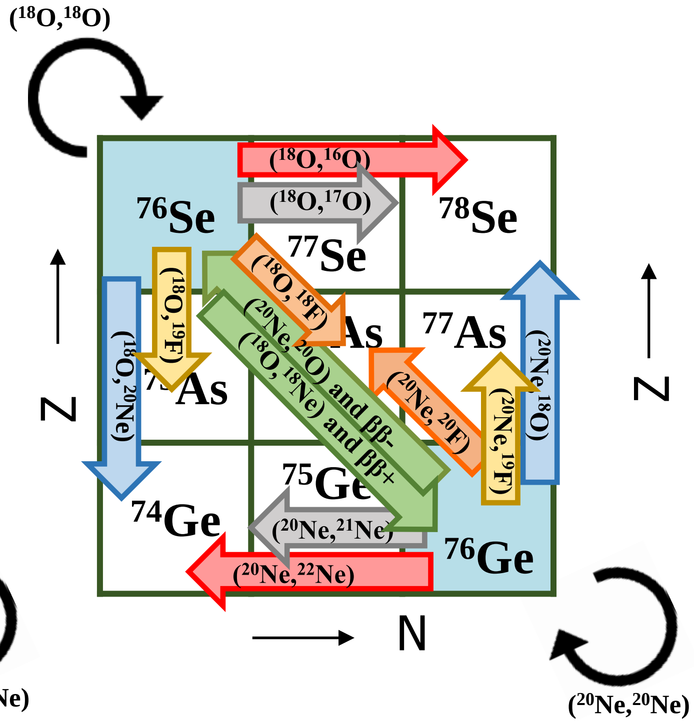
^{116}Cd - ^{116}Sn case

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



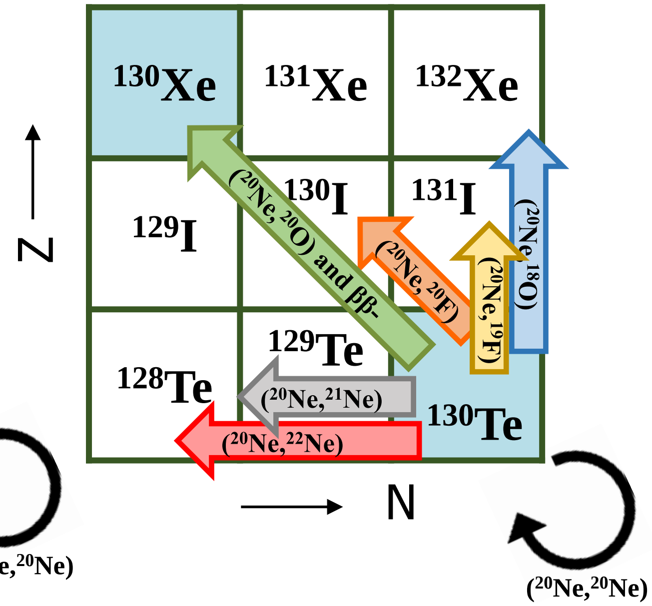
^{76}Ge – ^{76}Se case

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



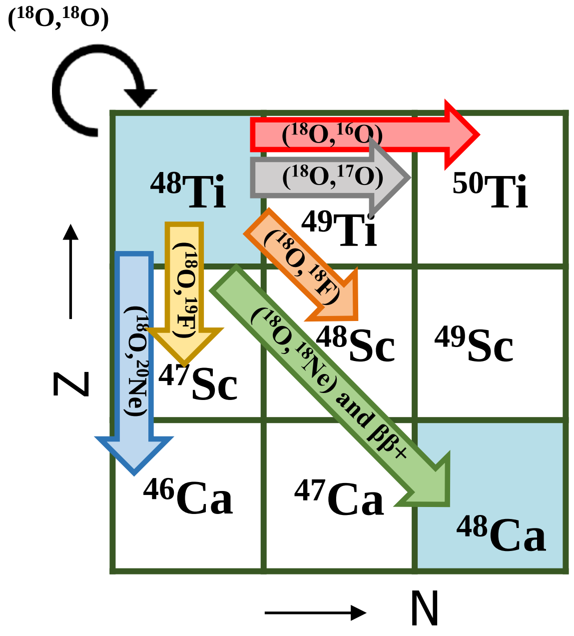
^{130}Te – ^{130}Xe case

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



^{48}Ti – ^{48}Ca case

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

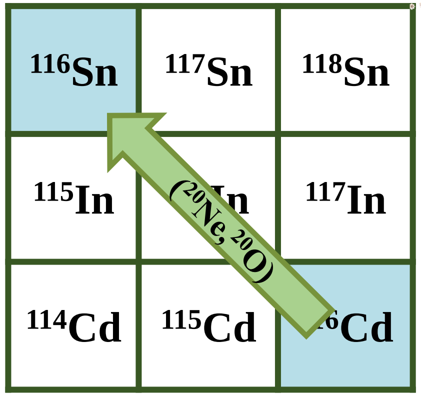


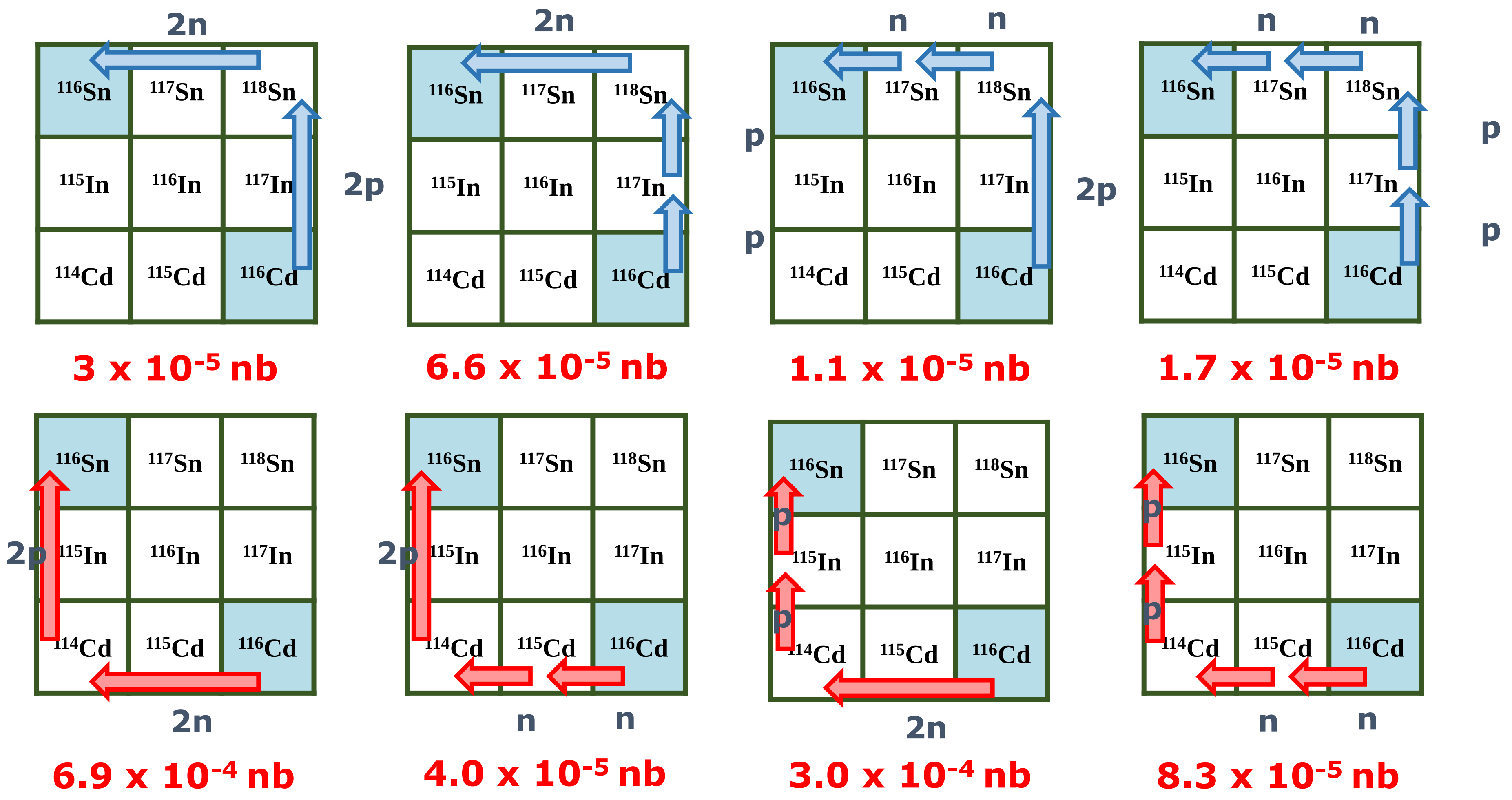
Calculation for DCE multi-nucleon transfer mechanism

Multi-nucleon transfer routes

vs

Diagonal process (experimental cross section 12 ± 2 nb)





J. Lubian, J.Ferreira et al., in preparation

Calculation for DCE multi-nucleon transfer mechanism

Multi-nucleon transfer routes

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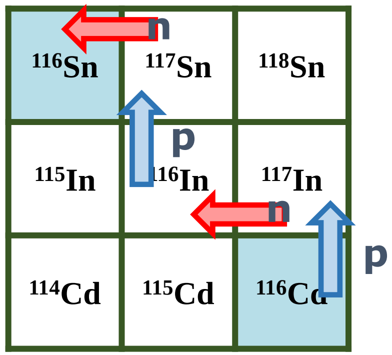
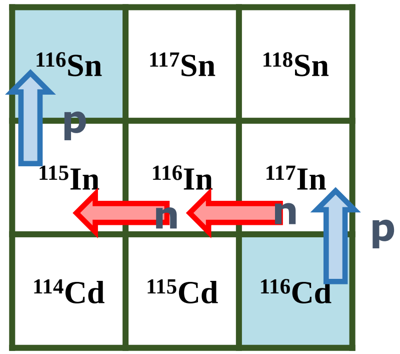
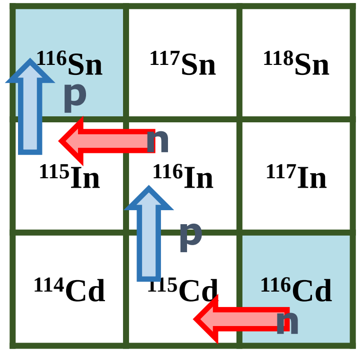
Diagonal process (experimental cross section 12 ± 2 nb)



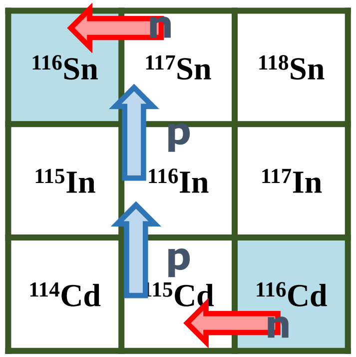
9.4 x 10^{-8} nb



1.5 x 10^{-6} nb



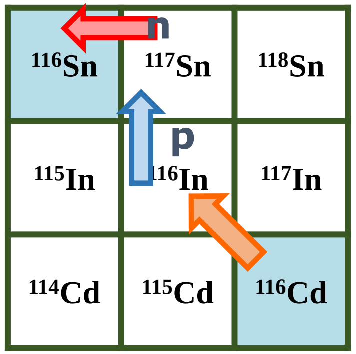
3.2 x 10^{-7} nb



1.1 x 10^{-7} nb

Negligible contribution of multi-nucleon transfer on the diagonal DCE process

J. Lubian, J.Ferreira et al.



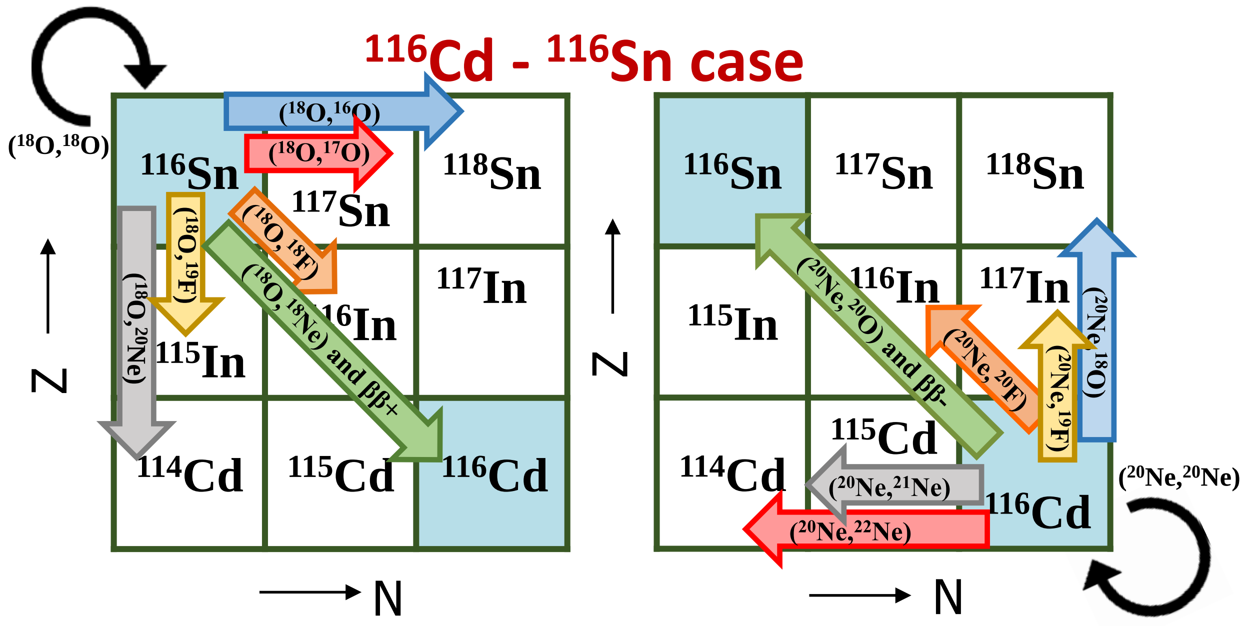
Interplay between SCE + multi-nucleon transfer (Work in progress)

J.A.Lay et al., Journ. Of Phys. Conf. Series 1056 (2018) 012029

S. Burrello, S. Calabrese, et al., in preparation

Conclusions and Outlooks

- **Second order isospin excitations** of nuclei are key information **bridging the gap between nuclear and neutrino physics**
- **Heavy-ion DCE reactions are promising tools 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