The NUMEN project: probing nuclear response to weak interaction by nuclear reactions

NUMEN

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for the NUMEN collaboration

Outline

- The problem of 0νββ-decay nuclear matrix elements
- The study of double charge exchange @ INFN-LNS (NUMEN and NURE)
- The multi-channel approach
- The NUMEN roadmap and perspectives

0νββ decay

Open problem in modern physics:

Neutrino absolute mass scale

Neutrino nature

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

Still not observed

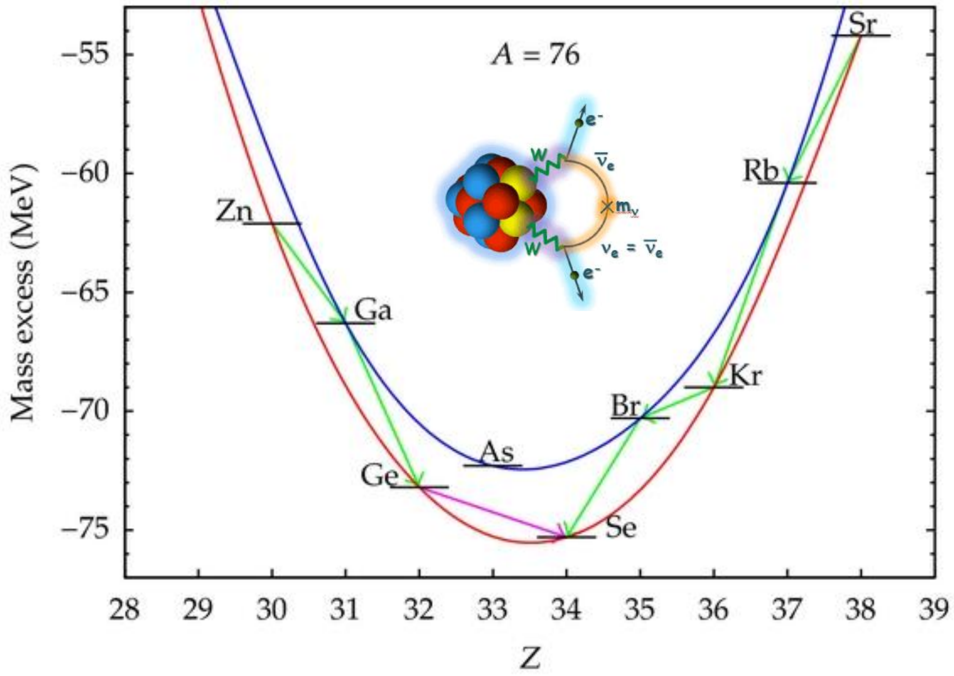
$${}^{A}_{Z}X_{N} \rightarrow {}^{\;\;A}_{Z+2}Y_{N-2} + 2e^{-}$$

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

^{76}Br	^{77}Br	^{78}Br	^{79}Br	^{80}Br
^{75}Se	^{76}Se	^{77}Se	^{78}Se	^{79}Se
^{74}As	^{75}As	^{76}As	^{77}As	^{78}As
^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge
^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga	^{76}Ga

Beyond standard model:

- Violation of lepton number conservation
- CP violation in lepton sector



- ✓ Process mediated by the **weak interaction**
- ✓ Observable in even-even nuclei where the **single β-decay** is energetically **forbidden**

0νββ decay

A worldwide challenge

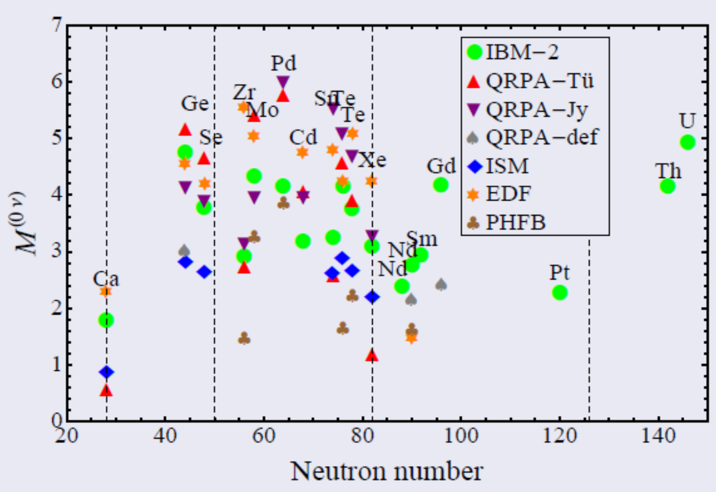
Intense activities in the searches for experimental evidence of this process

0νββ decay **half-life** — Phase space factor — contains the effective neutrino **mass**

$$\left(T^{0\nu\beta\beta}_{1/2}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

State of the art NME calculations

$$M^{(0\nu)} = M^{(0\nu)}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_F + M^{(0\nu)}_T$$



Nuclear Matrix Element (NME)

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

Transition probability of a **nuclear** process

- ✓ NMEs are not physical observables
- ✓ The challenge is the description of the **nuclear many body states**
- ✓ **Calculations** (<u>still sizeable uncertainties</u>): 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-capture, γ-ray spectroscopy, **γγ-decay** etc.

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

NUMEN

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

Extraction from measured cross-sections of *"data-driven"* information on NME for all the systems candidate for 0νββ

erc NURE

Heavy-ion DCE reactions vs 0νββ

To stimolate the same nuclear transition (g.s. to g.s.) occurring in 0νββ

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Reaction dynamics vs. decay
- DCE includes **sequential** multinucleon transfer **mechanism**
- **Projectile and target** contributions in the NME

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:** 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**
- **Off-shell propagation** through virtual intermediate channels

Heavy-ion DCE reactions vs 0νββ

E. Santopinto et al., PRC 98 (2018) 061601

Factorization of the DCE cross section

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

Reaction part

Structure part

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

- Confirmed in a fully quantum mechanical approach

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

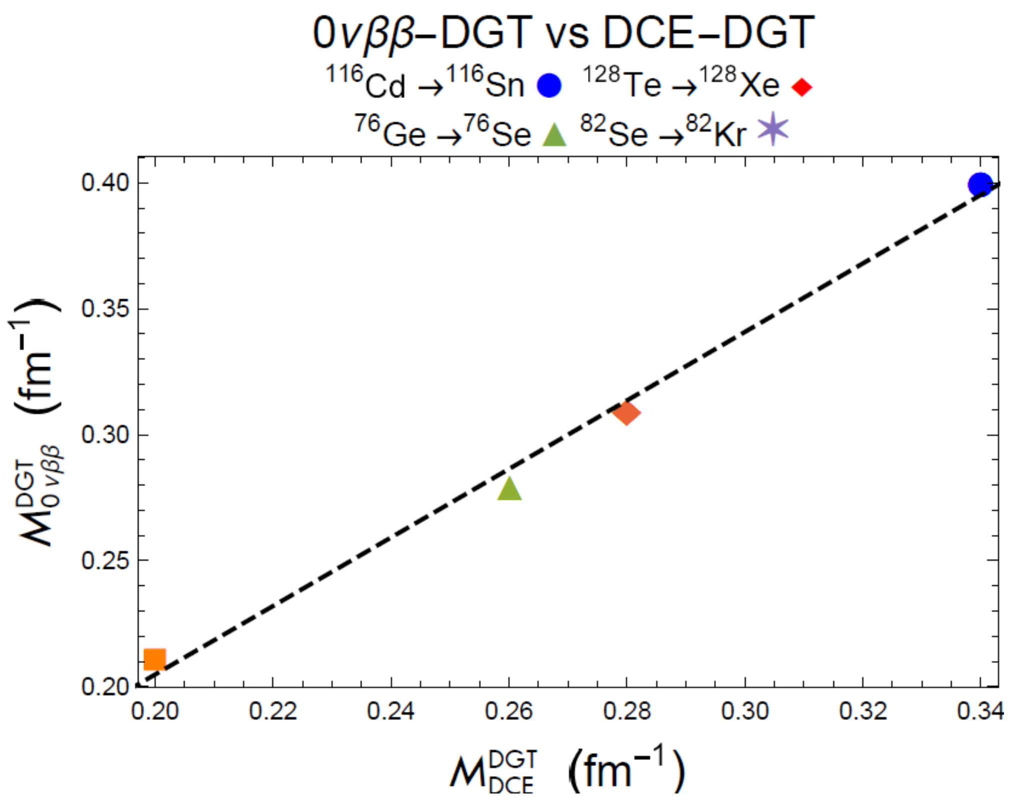
See J. Bellone talk

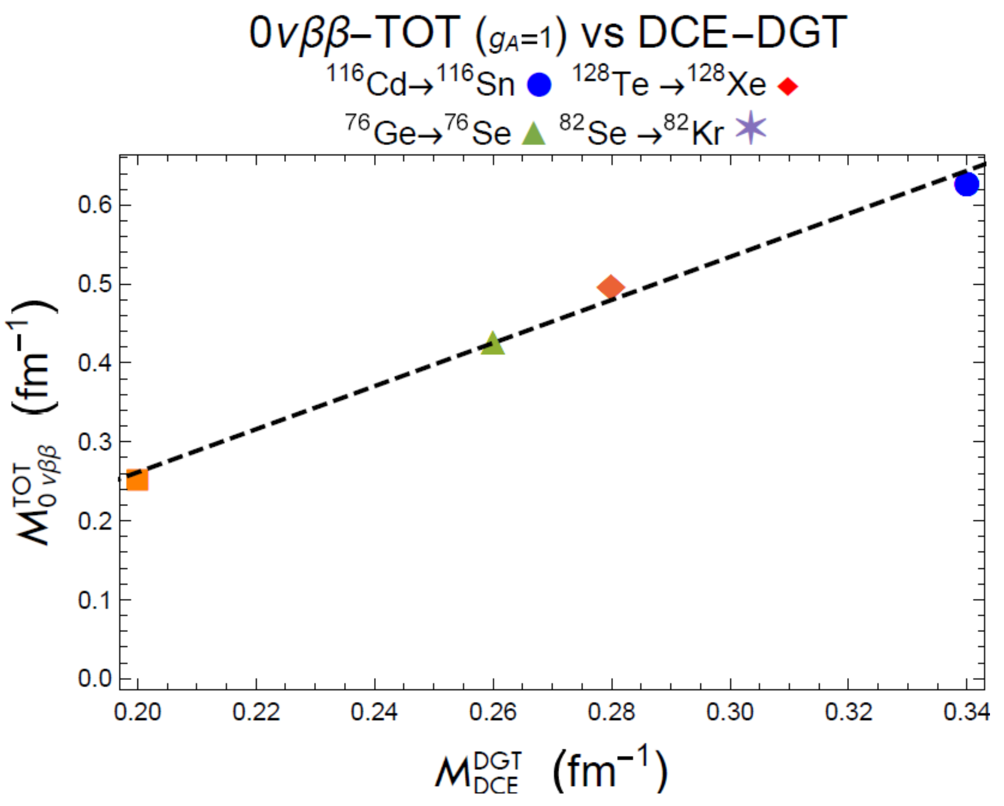
Heavy-ion DCE reactions vs 0νββ

Linear correlation between DCE DGT and 0νββ DGT and Total NMEs

Structure models adopted

- IBM formalism *E. Santopinto et al., PRC 98 (2018) 061601*
- Large scale shell model formalism *N. Shimizu, et al. PRL 120 (14) (2018) 142502*





Theory for DCE reactions

F. Cappuzzello et al., Progr. Part. and Nucl. Physics (submitted)

Heavy ion DCE can proceed:

1) Sequential **multi-nucleon transfer** (defined by mean-field dynamics, its contribution can be tuned by kinematics conditions)

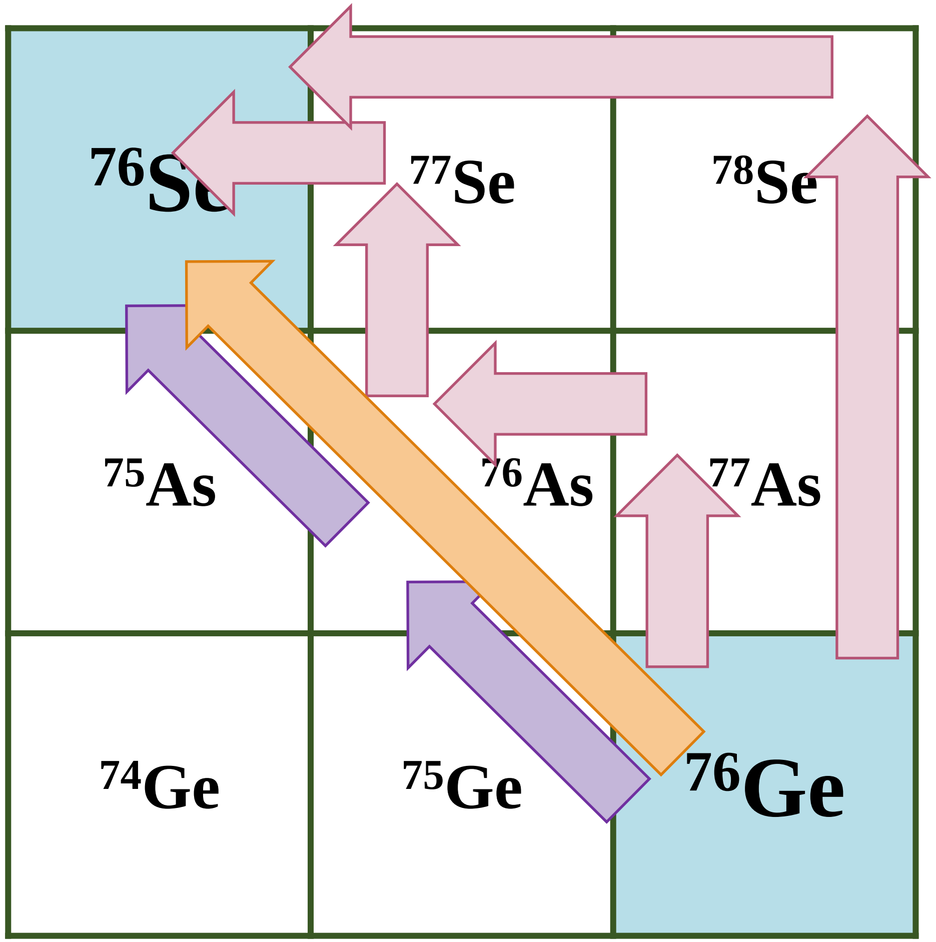
J. Ferreira et al., PRC 105 (2022) 014630

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

E. Santopinto et al., Phys. Rev. C 98 (2018) 061601
J.I.Bellone et al., PLB 807 (2020) 135528
H. Lenske et al., Universe 7 (2021) 98

3) One-step DCE - Two-nucleon 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)



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

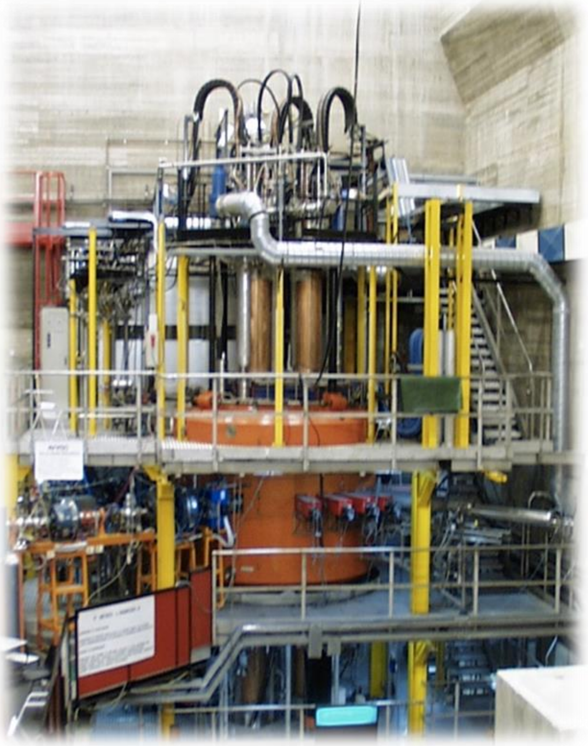
DCE @ INFN - LNS

The experiments @ INFN-LNS

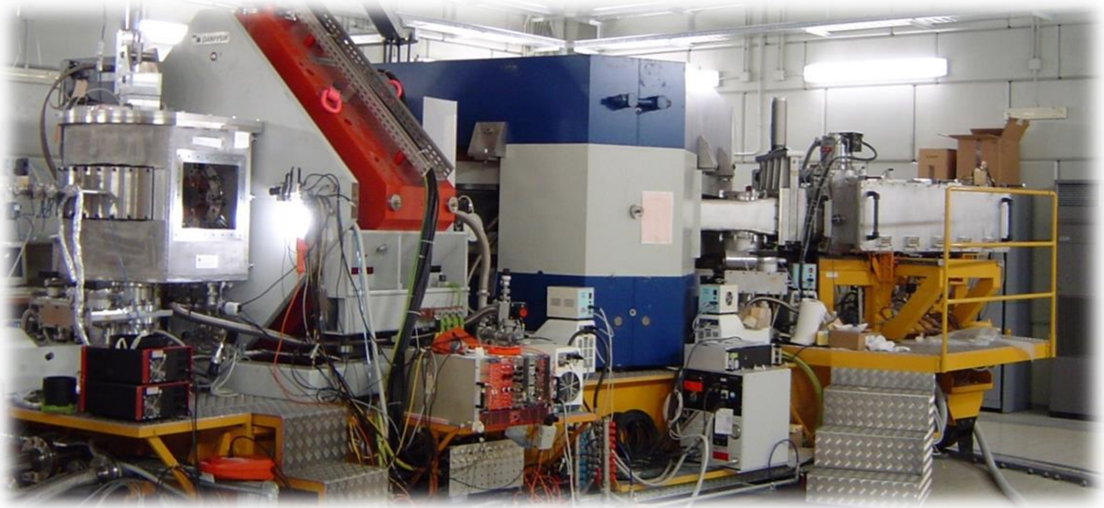
Crucial for the experimental challenges

K800 Superconducting Cyclotron

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



MAGNEX magnetic spectrometer



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

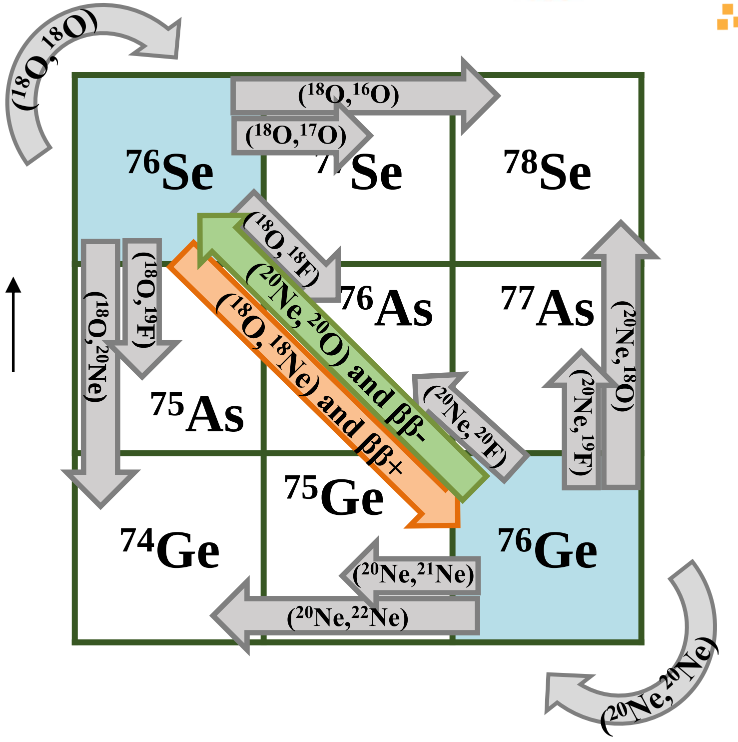
Measured resolutions:

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

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

The multi-channel strategy

- **Transitions of interest for 0νββ in two directions**
  $\beta\beta^-$ via (^{20}Ne,^{20}O) and $\beta\beta^+$ via (^{18}O,^{18}Ne)
- **Two (or more) incident energies**
  to study the reaction mechanism
- **Complete net** of reactions which provide important information



Elastic scattering → nucleus-nucleus optical potential

Inelastic scattering → coupling strenght to low-lying states

One-nucleon transfer reactions → single-particle spectroscopic amplitudes

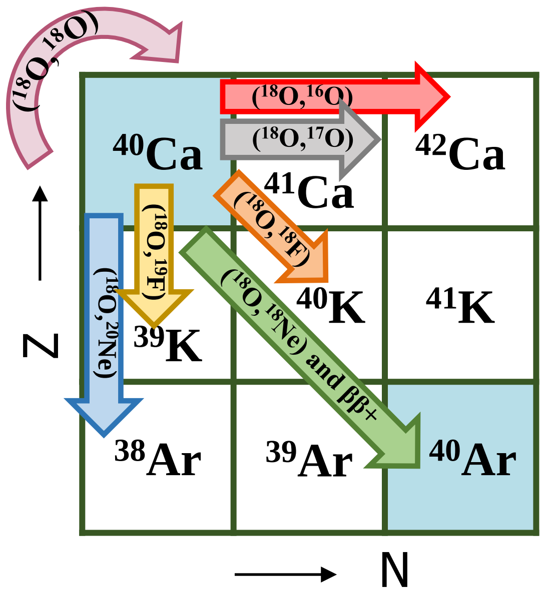
Two-nucleon transfer reactions → strenght of pairing correlations

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)

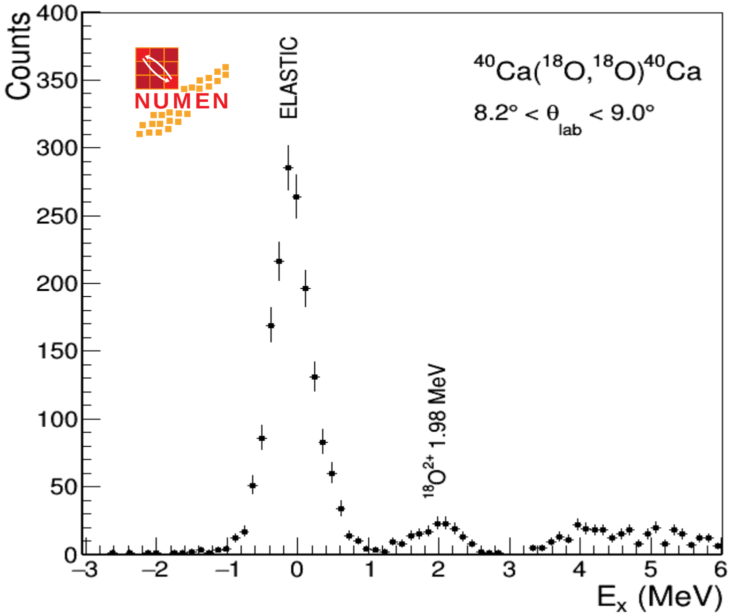
The multi-channel strategy

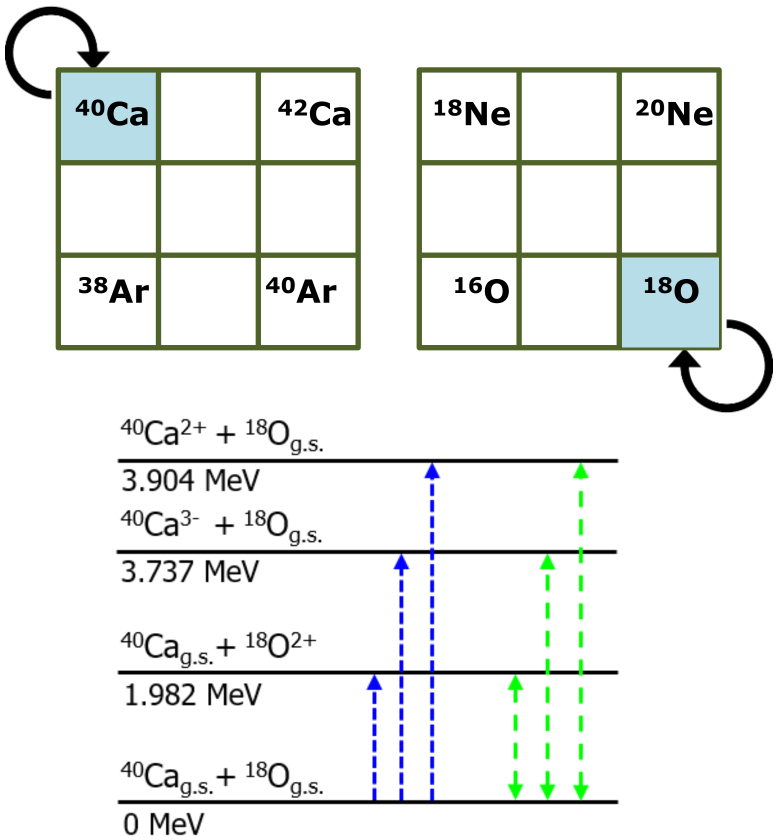
The $^{18}O + ^{40}Ca$ @ 275 MeV case

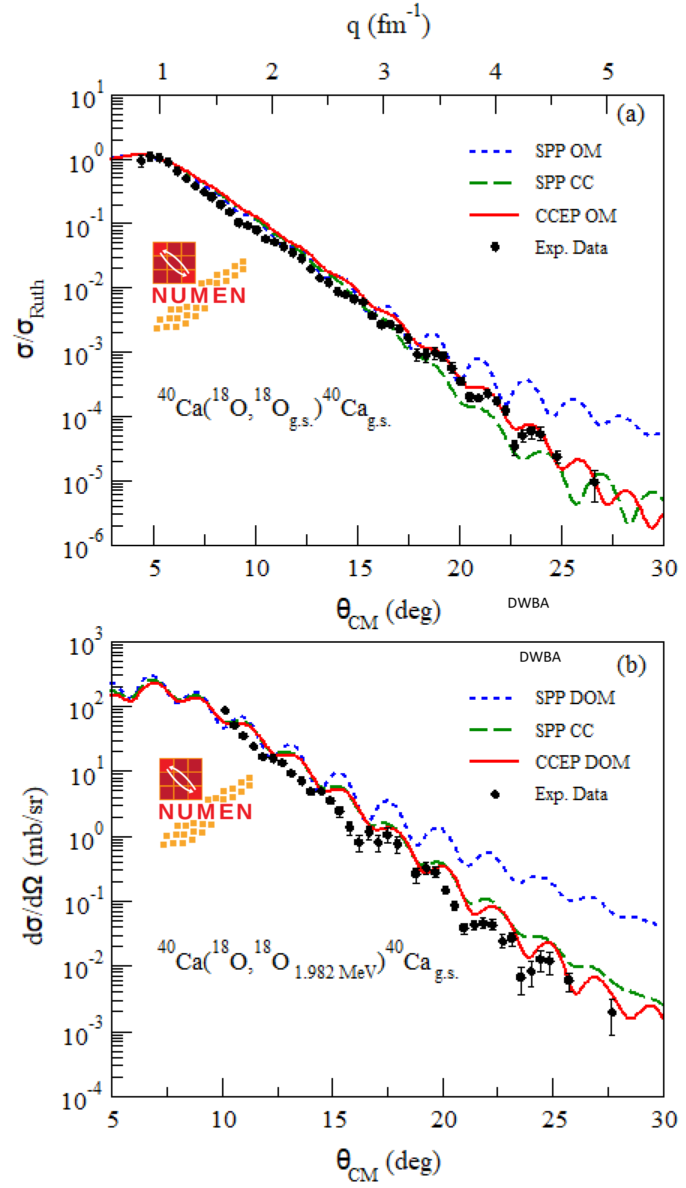


Elastic and inelastic scattering

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





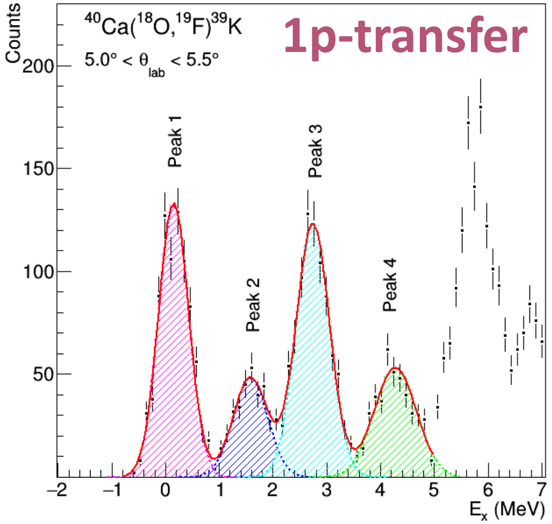


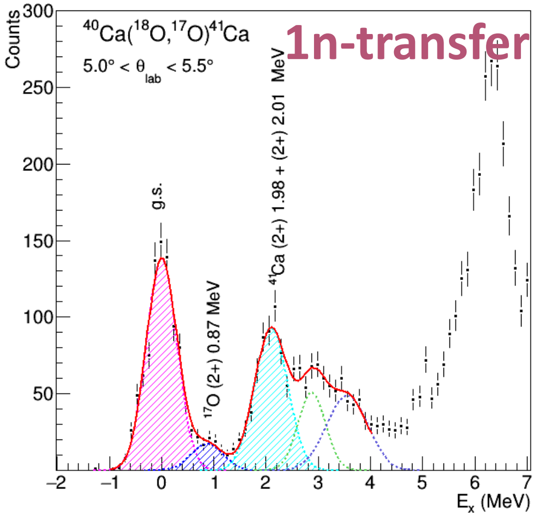
Key information elastic and inelastic scattering data

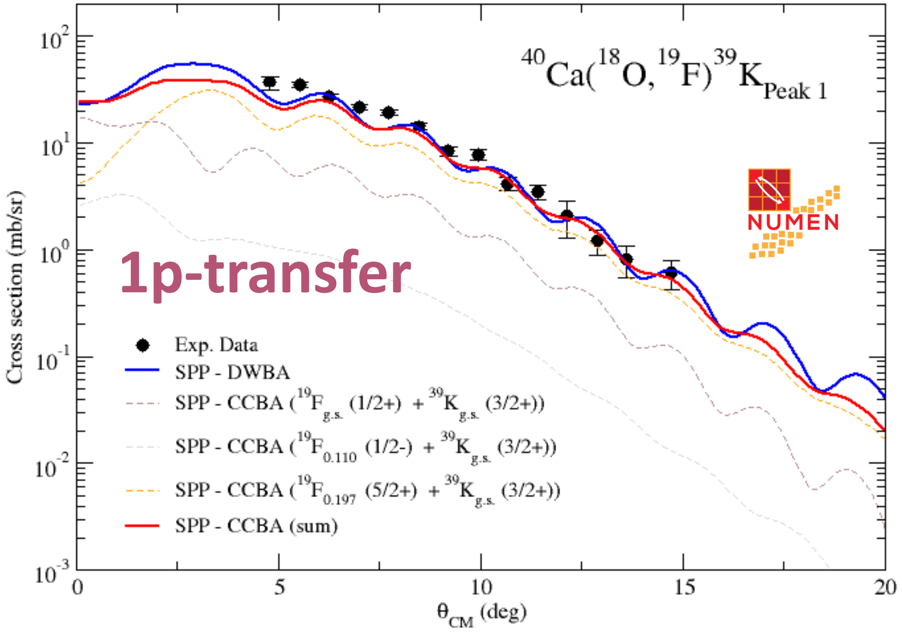
- ✓ **Double folding** Sao Paulo Potential works well
- ✓ **Coupling to** low-lying **2^+ and 3^- states** of ^{18}O and ^{40}Ca states is important
- ✓ Effects of coupling can be accounted for in average by **CCEP approach**

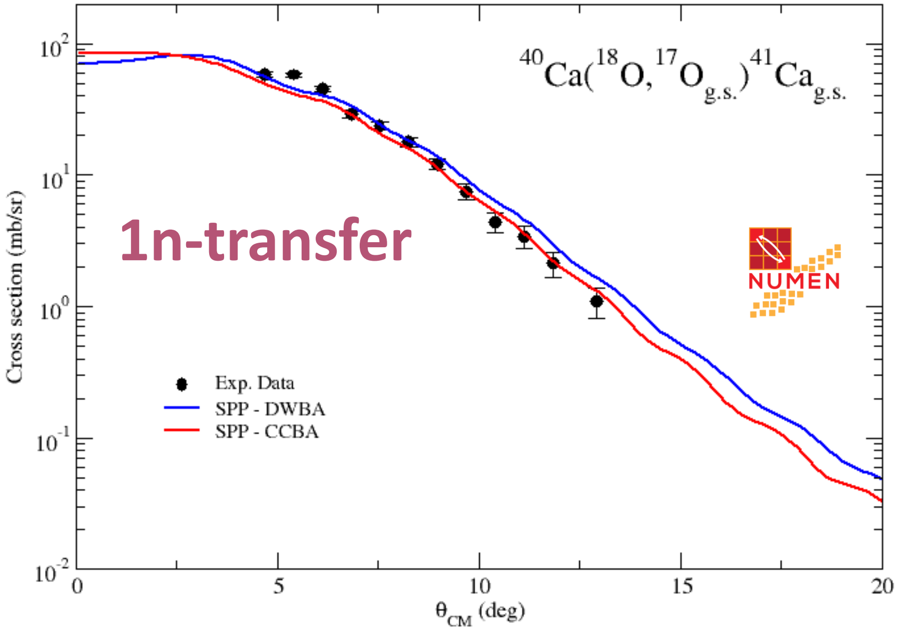
1p- and 1n-transfer reactions

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









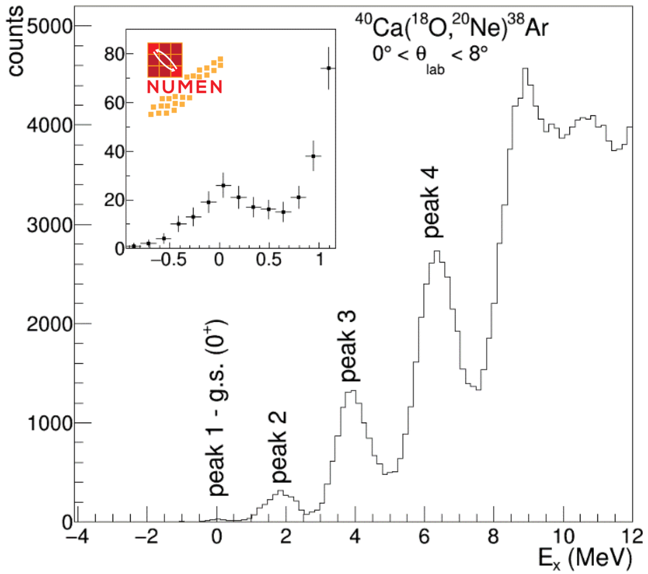
- OP extracted from elastic and inelastic scattering data
- **CCBA** analysis
- **Shell model** spectroscopic amplitudes

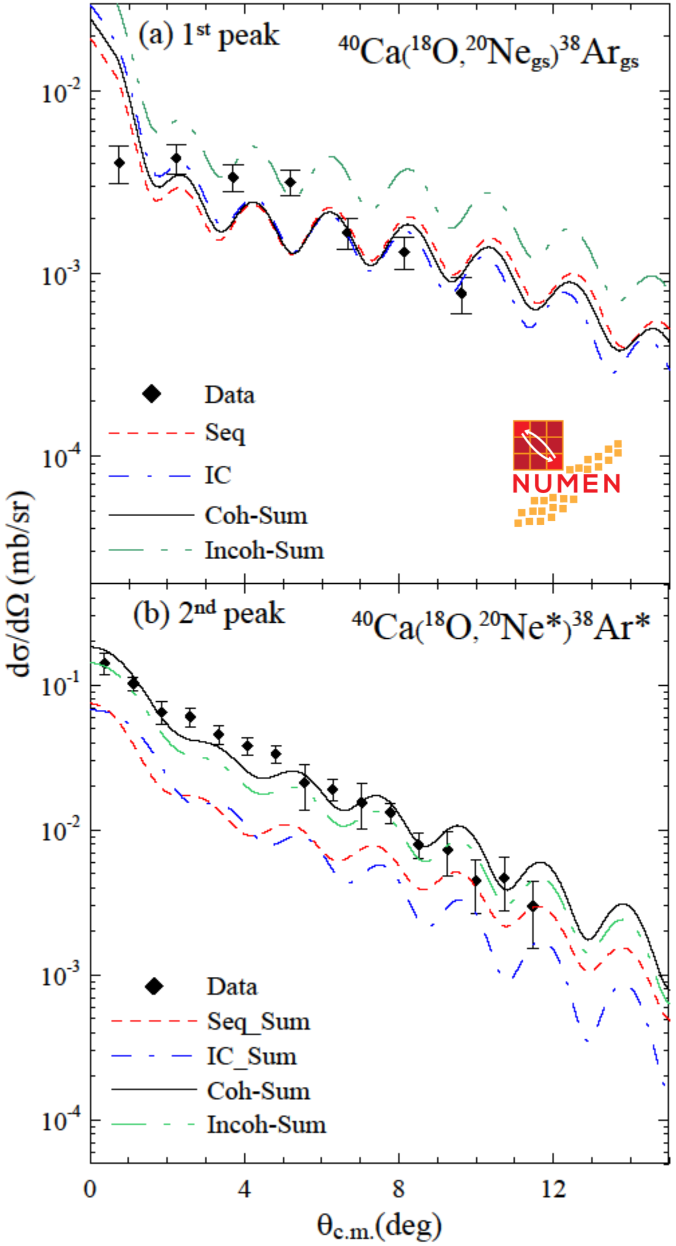
Key information one-nucleon transfer data

- ✓ Very good description of the data
- ✓ Mixing of single particle and core polarization configurations

2p-transfer reaction

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





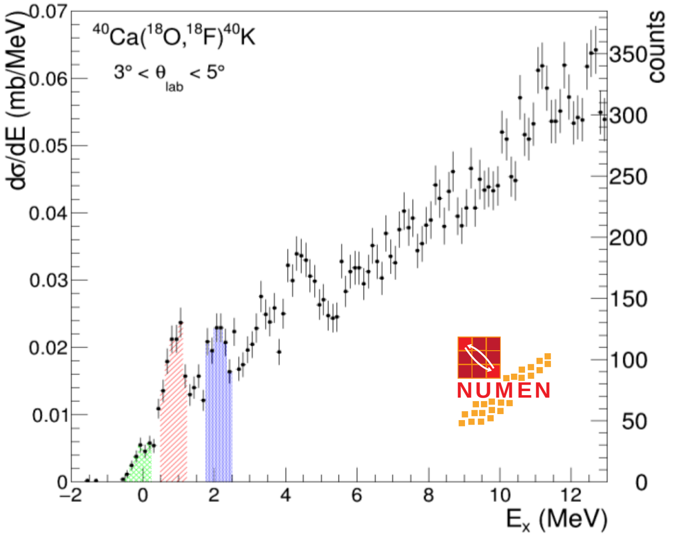
- OP extracted from elastic and inelastic scattering data
- **CCBA** analysis **direct** and **two-step transfer**
- **Shell model** spectroscopic amplitudes

Key information two-proton transfer data

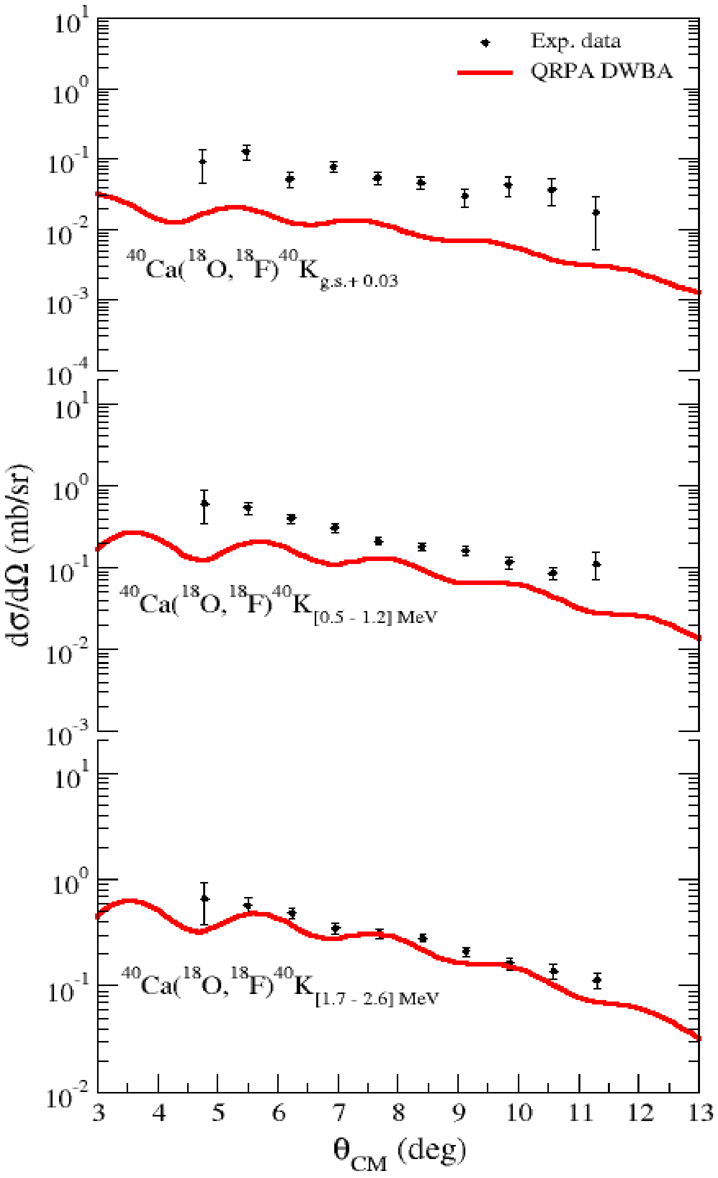
- ✓ Very low cross section (comparable with DCE) for low-lying states
- ✓ Competition between one-step and two-step mechanisms
- ✓ Good description of the data

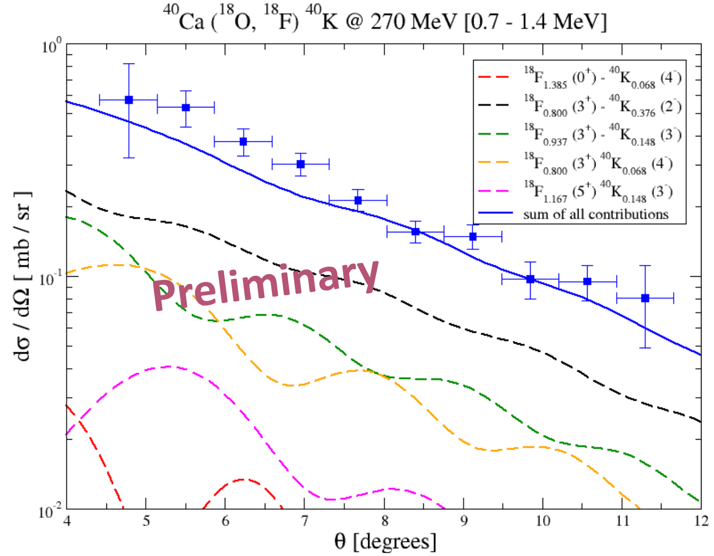
Single charge exchange reaction

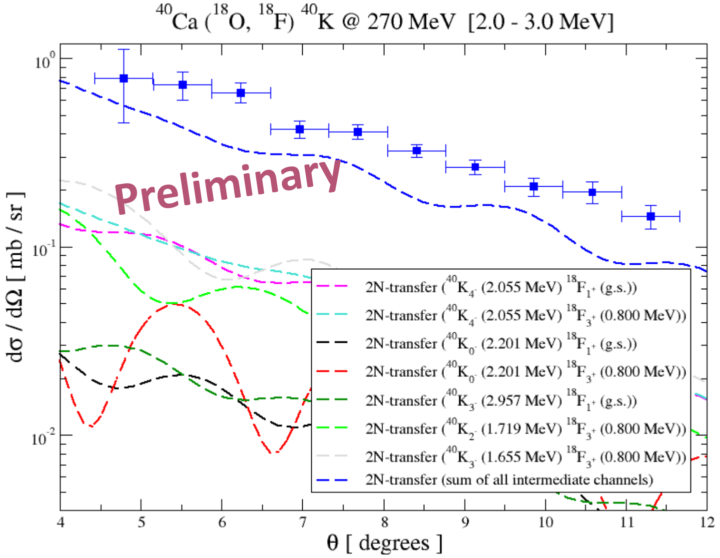
M. Cavallaro et al., Front. Astron. Space Sci. (2021) 8:659815



Direct vs Two-step transfer







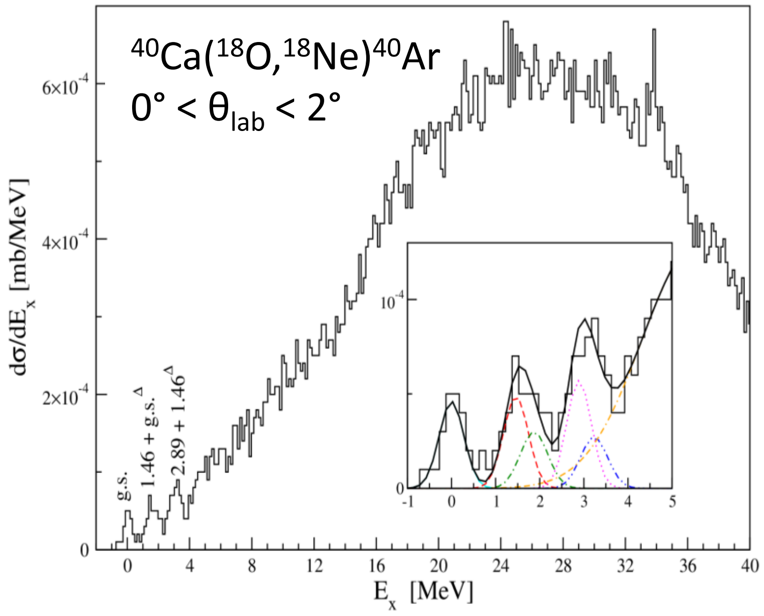
- OP extracted from elastic and inelastic scattering data
- **DWBA** analysis with double folding form factors for **direct**
- **QRPA** transition densities with NN isovector interaction
- **CCBA** approach for **two-step transfer**

Key information SCE data

- ✓ Direct meson exchange mechanism important at low excitation energy
- ✓ Two-step nucleonic SCE plays a role, expected to contribute less at higher E_x

Double charge exchange reaction

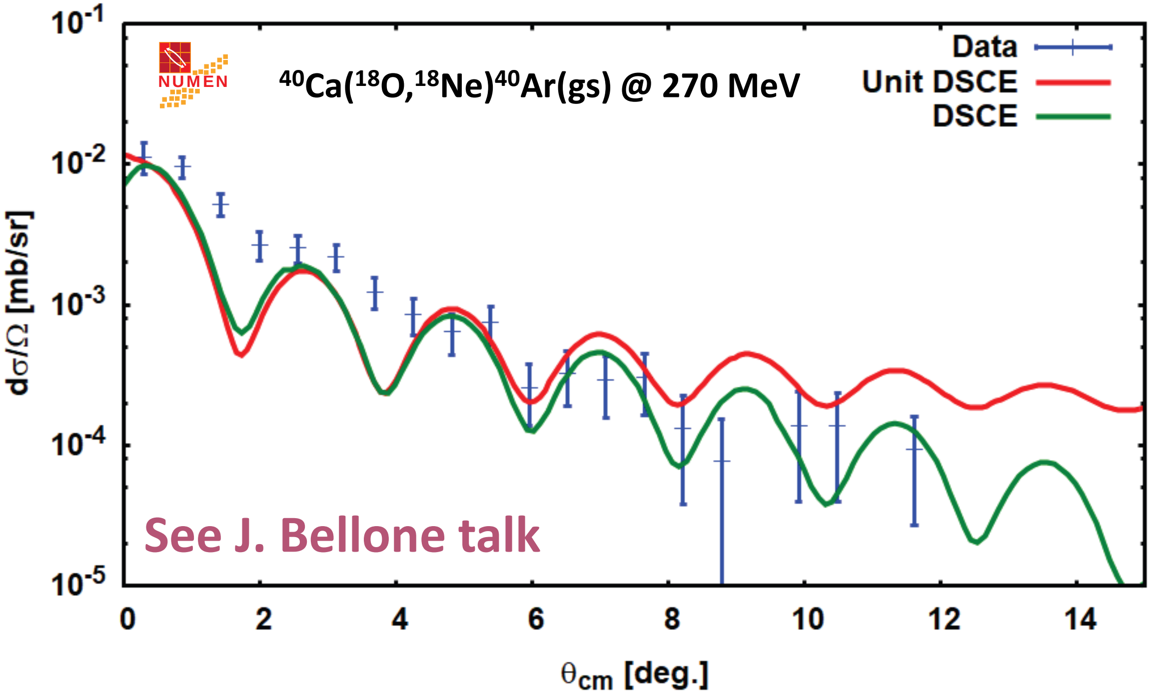
F. Cappuzzello et al. EPJ J A (2015) 51:145
J. Bellone et al., PLB 807 (2020) 135528
H. Lenske et al., Universe 7 (2021) 98
F. Cappuzzello et al., PPNP (submitted)



Key information DCE data

- ✓ G.s. to g.s. transition isolated
- ✓ Spectroscopic factor extracted
- ✓ Good description of the data

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



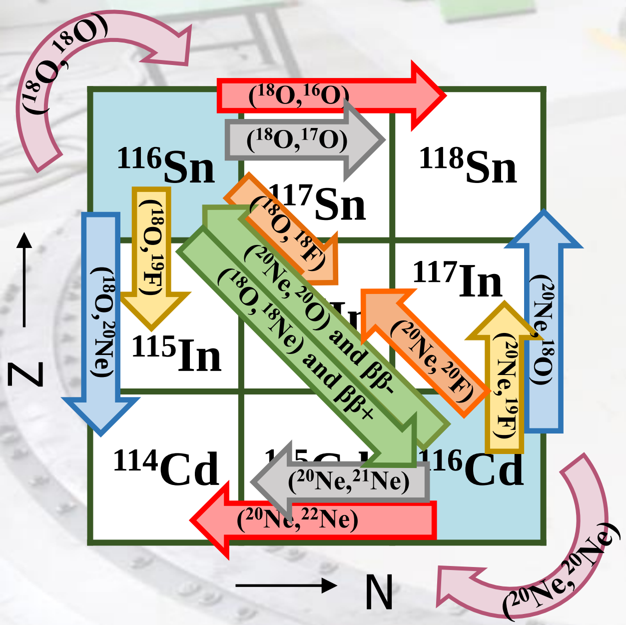
A spectroscopic factor of $\beta^2 = S^{I_A I_a S_1 S_2}_{J_A J_B j_a j_b} = 0.024$ is obtained, assuming closure approximation for $L_{13} = L_{24} = \lambda = 0$

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

NUMEN experimental runs

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

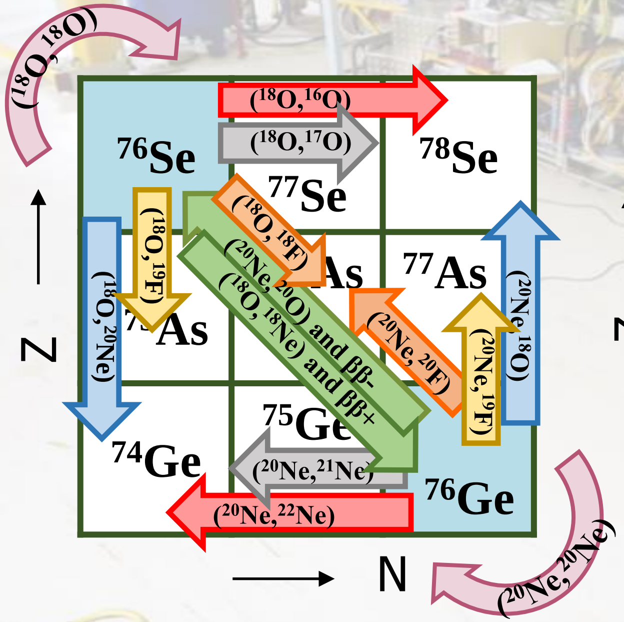
@ 15 AMeV
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



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)

^{76}Ge – ^{76}Se case

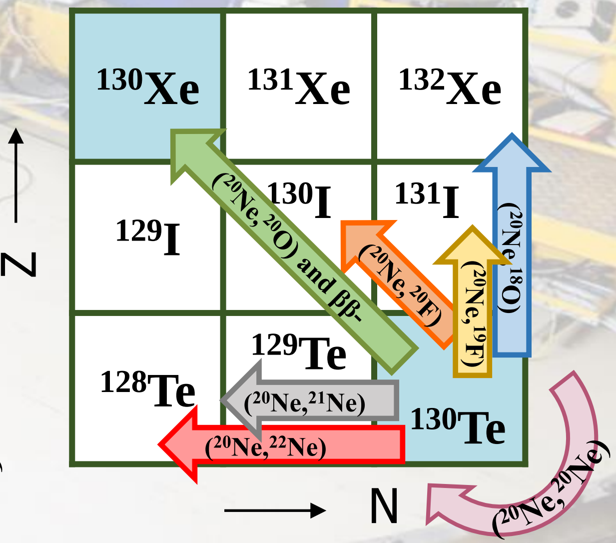
@ 15 AMeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



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

^{130}Te – ^{130}Xe case

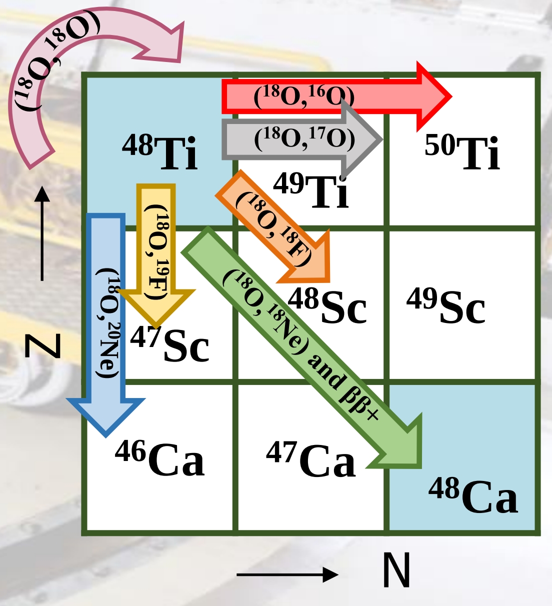
@ 15 AMeV
- ^{20}Ne + ^{130}Te



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)

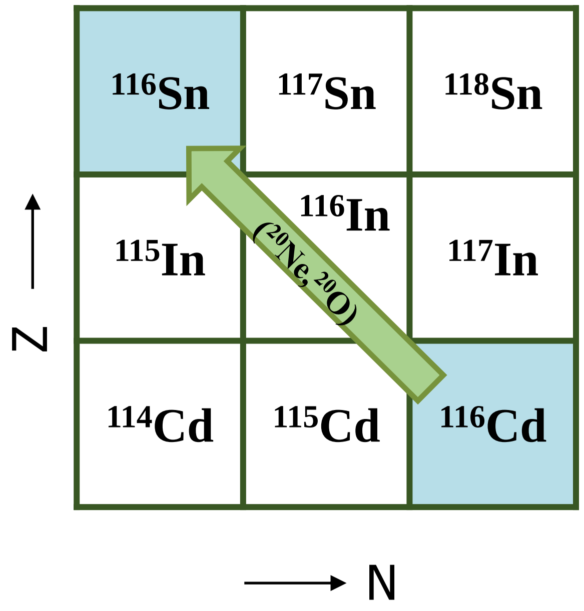
^{48}Ca - ^{48}Ti case

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

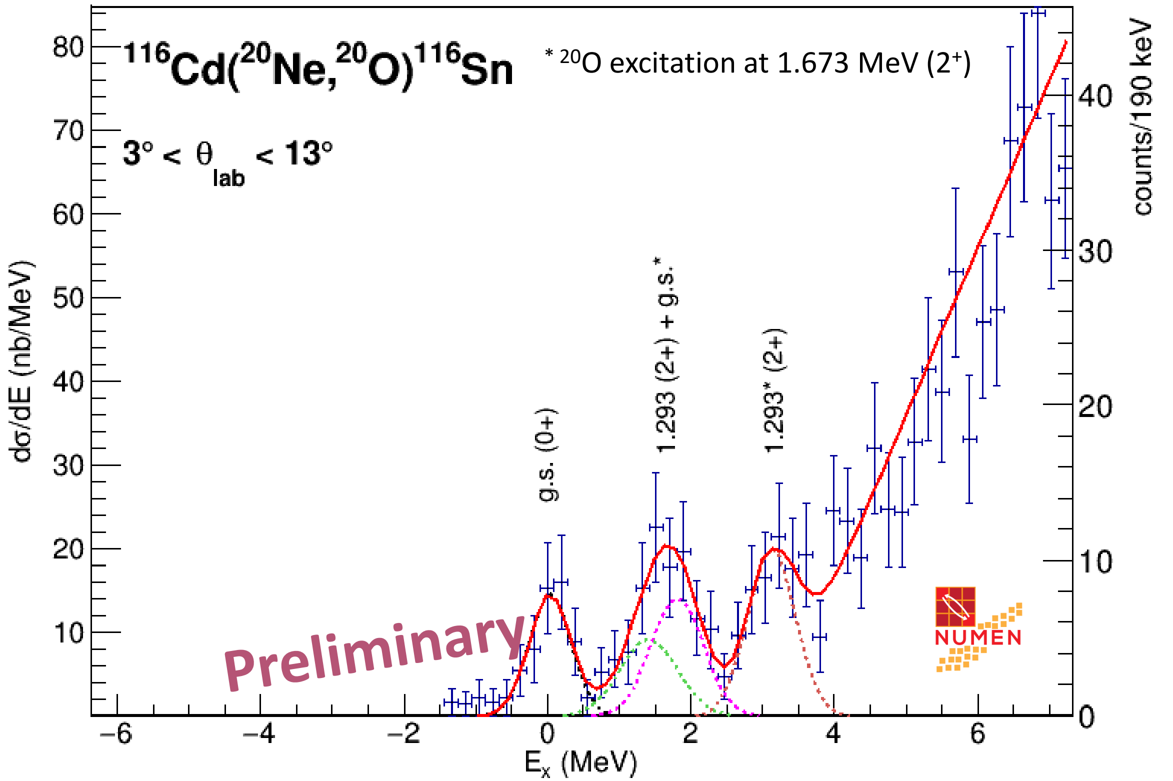


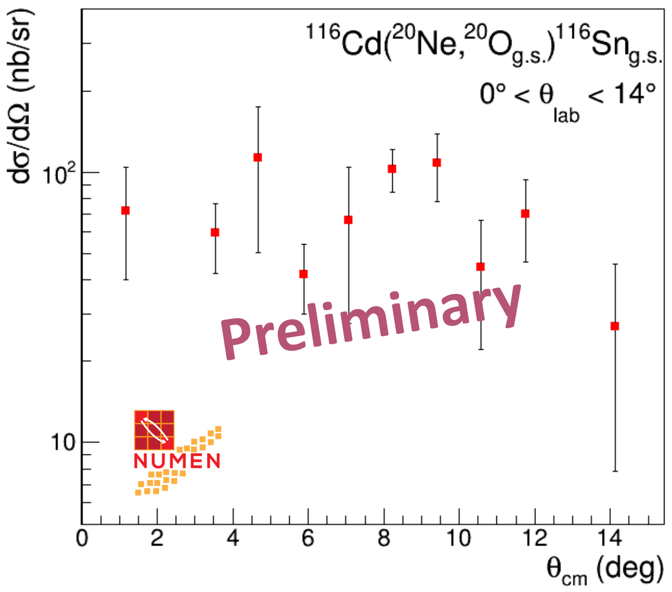
O. Sgouros et al., PRC 104, 034617 (2021)

Experimental results



DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$



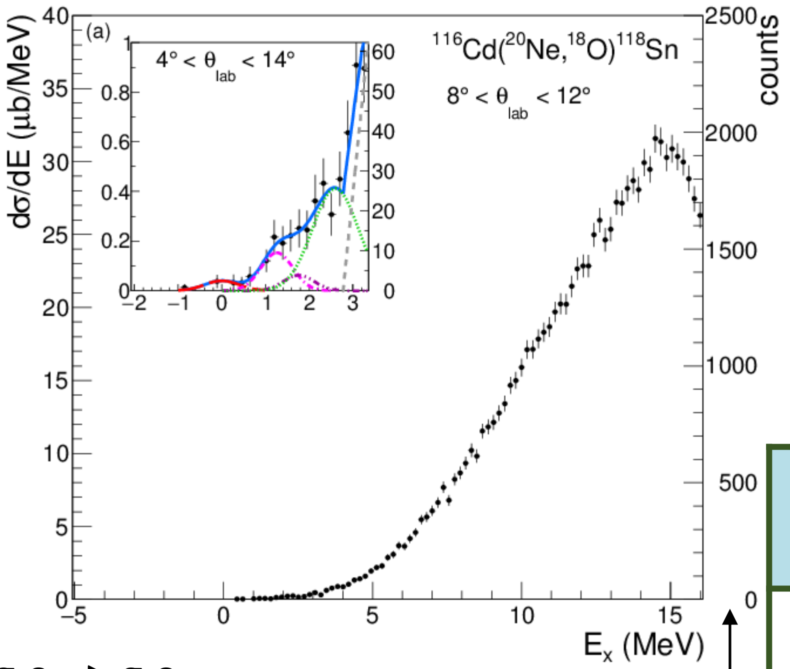


State (MeV)	Counts	Absolute cross section (nb)
$^{116}Sn_{gs}$ (0^+) + $^{20}O_{gs}$ (0^+)	31	12 ± 2
$^{116}Sn_{1.293}$ (2^+) + $^{20}O_{gs}$ (0^+) $^{116}Sn_{gs}$ (0^+) + $^{20}O_{1.673}$ (2^+)	67	24 ± 3

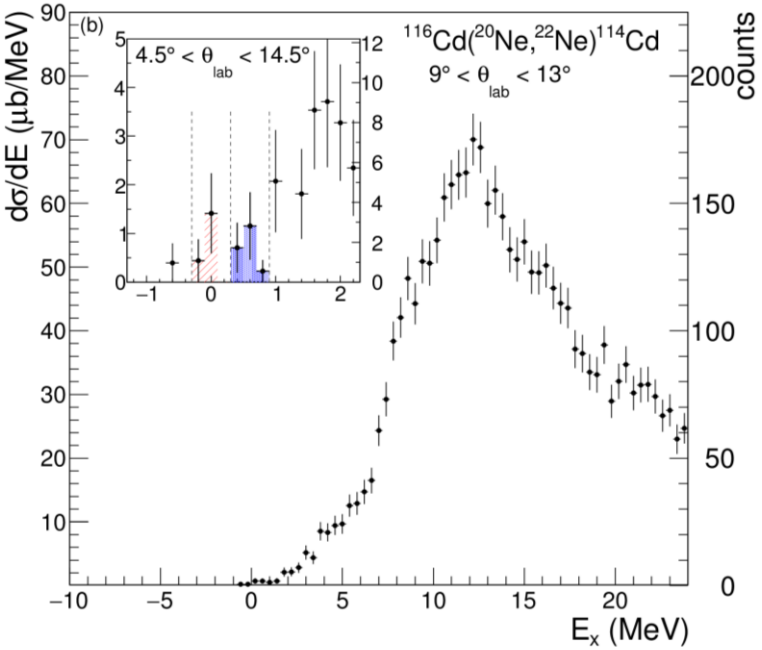
- g.s. → g.s. transition isolated (resolution ~ 800 keV FWHM)
- Absolute cross section measured
- Angular distribution
- Zero-degree measurement

S. Calabrese et al., NIM A 980 (2020) 164500

Multi-nucleon transfer



D. Carbone et al., PRC 102, 044606 (2020)

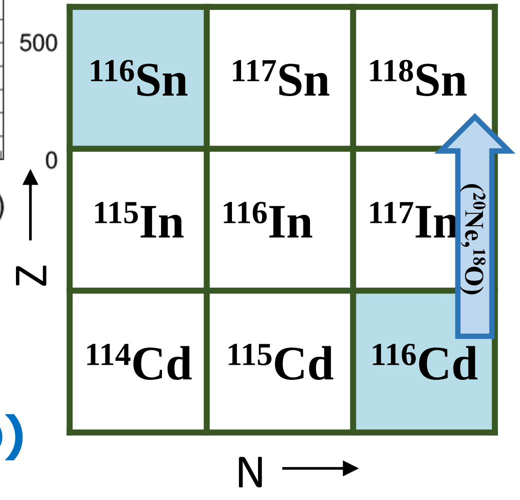


g.s. -> g.s.

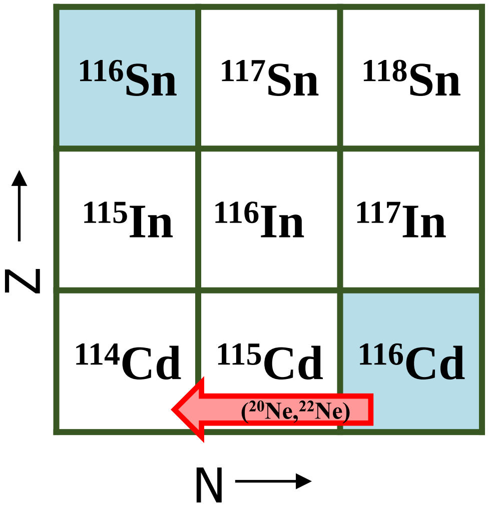
EXP. DATA **40 ± 15 nb**

CALCULATIONS: ~ 40 nb (1 step)

2p-transfer



2n-transfer



g.s. -> g.s.

EXP. DATA **370 ± 190 nb**

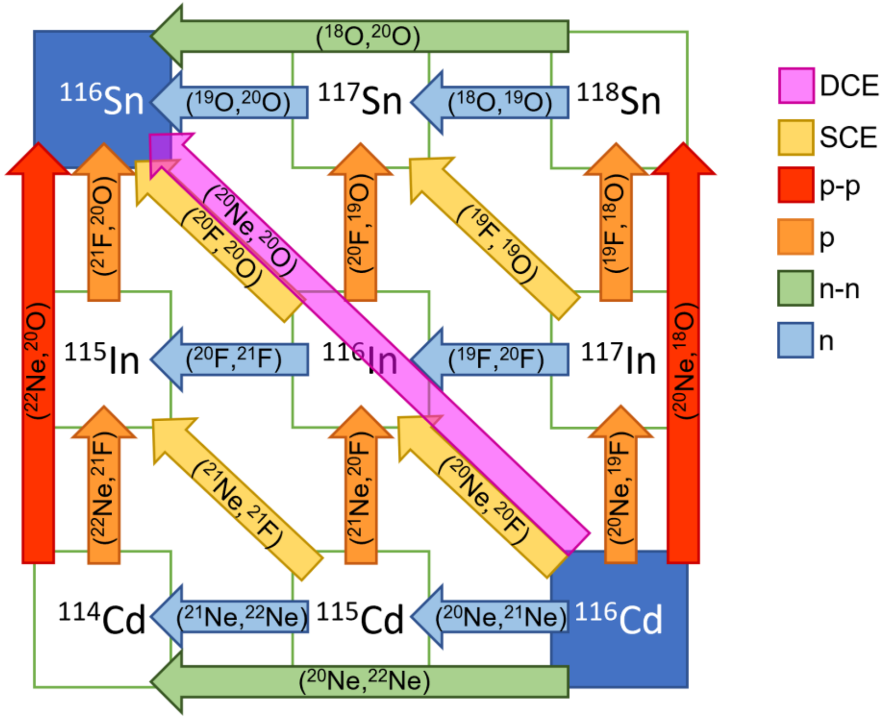
CALCULATIONS: ~ 210 nb (1 step)

One-step and seq. cross section calculations (DWBA, CRC, CCBA)
ISI and FSI from double folding
SA from IBM, shell model, QRPA

This framework is used to predict the multi-nucleon transfer cross section leading to the same DCE channels, for such steps where experimental information is missing

Multi-nucleon transfer routes

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



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

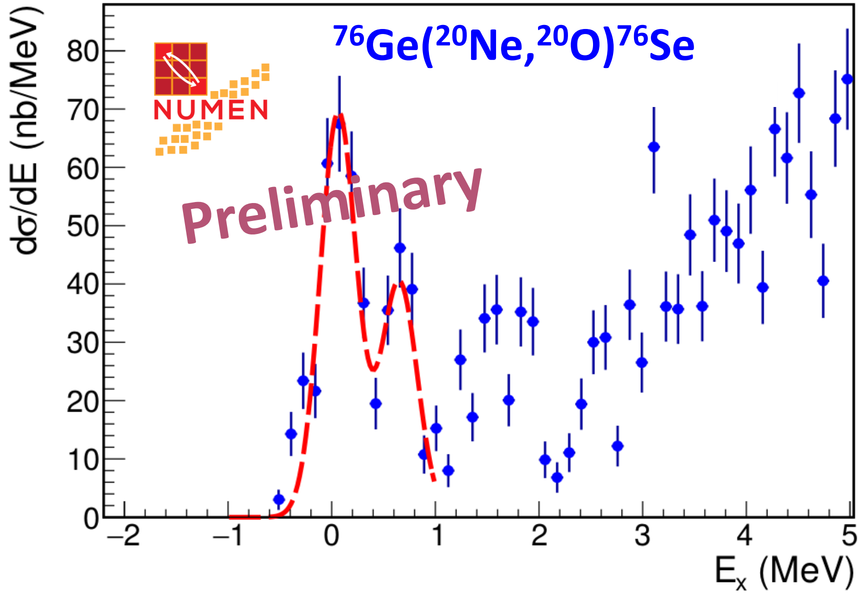
(Exp. cross section DCE 12 ± 2 nb)

Mechanism	Int. cross section (nb) $^{20}O_{g.s.}(0^+) + ^{116}Sn_{g.s.}(0^+)$
$2p-2n$	$1,28\times10^{-4}$
$2n-2p$	$3,13\times10^{-4}$
$p-p-n-n$	$6,63\times10^{-5}$
$n-n-p-p$	$1,00\times10^{-5}$
$p-p-2n$	$4,15\times10^{-5}$
$n-n-2p$	$1,72\times10^{-6}$
$2p-n-n$	$9,26\times10^{-5}$
$2n-p-p$	$2,66\times10^{-4}$
$p-n-p-n$	$1,38\times10^{-7}$
$p-n-n-p$	$1,15\times10^{-6}$
$n-p-n-p$	$2,53\times10^{-7}$
$n-p-p-n$	$1,69\times10^{-7}$
$p-2n-p$	$2,51\times10^{-7}$
$n-2p-n$	$5,71\times10^{-6}$
Incoh. Sum	$9,60\times10^{-4}$

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

Experimental results

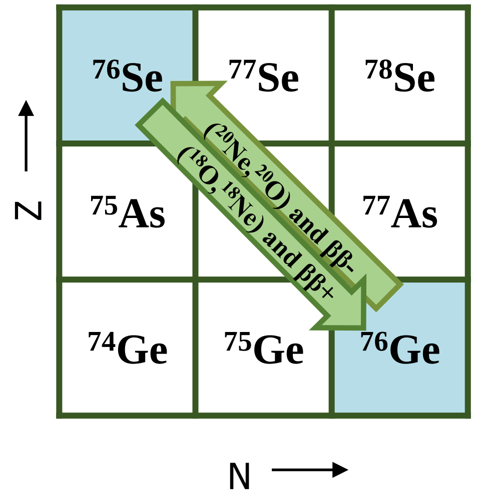
^{76}Ge – ^{76}Se case

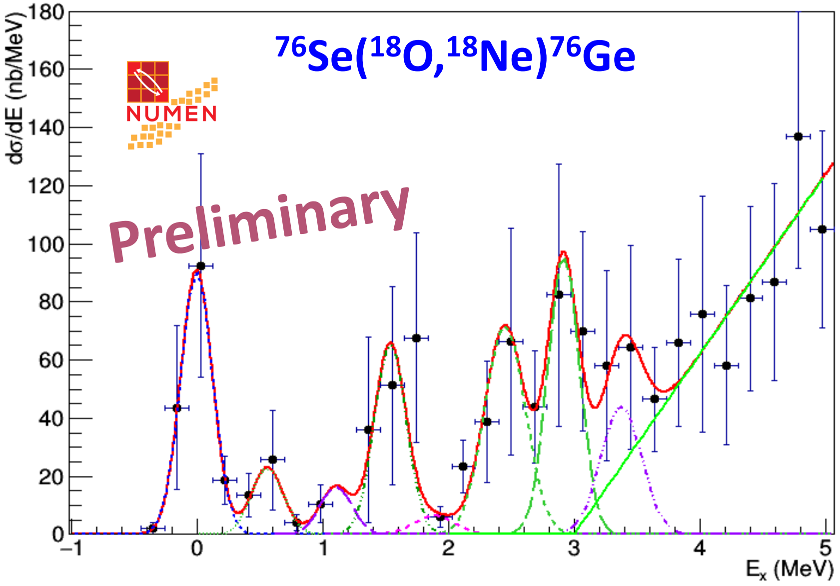


$0° < \theta_{lab} < 8°$

$\sigma_{g.s.\to g.s.}$ =30 ± 4 nb

R. Linares et al.





$\sigma_{g.s.\to g.s.}$ =29 ± 6 nb

A. Spatafora et al.

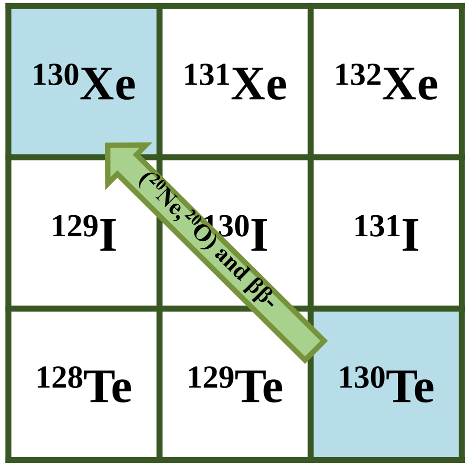
- Same cross sections for different directions
- Similar distorsion factors

→ Same NME (encouraging test of time invariance!)

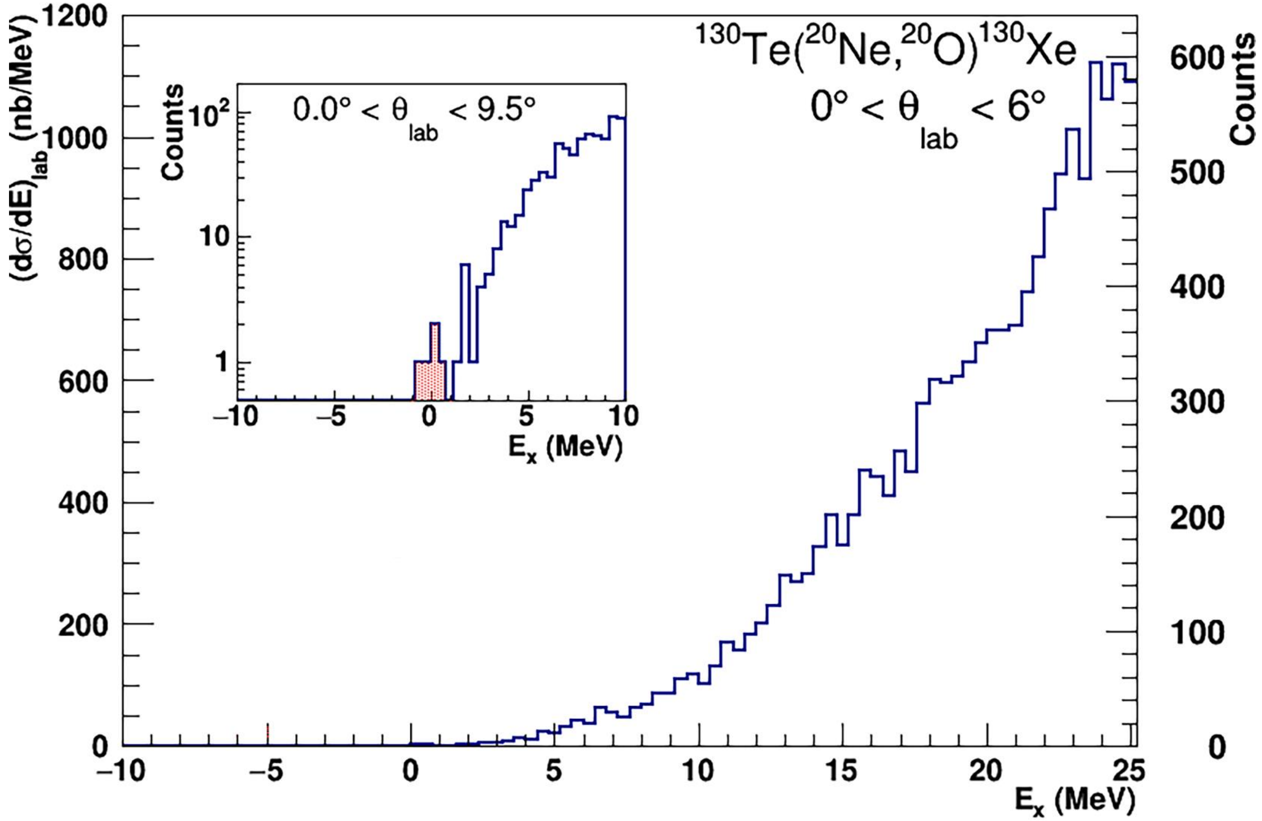
Warning:

- Only one case
- Reaction calculations in progress

Experimental results



DCE reaction $^{130}Te(^{20}Ne,^{20}O)^{130}Xe$



$\sigma_{-1\ MeV \rightarrow 1\ MeV}$ = 13 nb ([3,18] nb at 95% CL)

- Resolution ~ 500 keV FWHM
- No spurious counts at -10 < E_x < -2 MeV

V. Soukeras et al., Results in Physics 28, 104691 (2021)

Present limitations

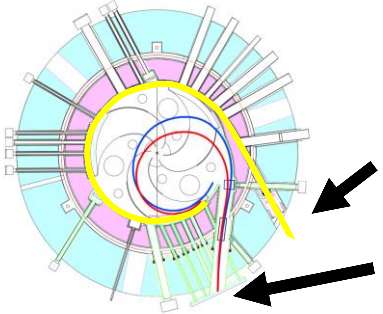
DCE reactions are characterized by very **low cross-sections**

→ In NUMEN Phase 2 only few systems were studied

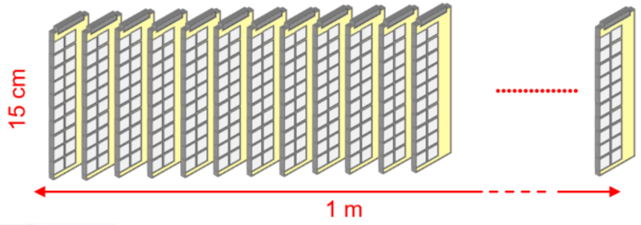
Much higher beam current is needed

Project of **upgrade of the LNS Cyclotron (from 100 W to 5-10 kW) and infrastructures** (triggered by NUMEN physics case) funded by national grant (PON)

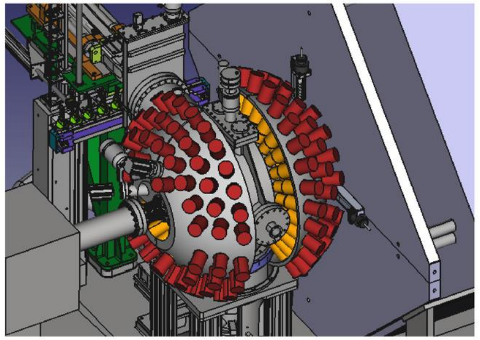
Upgrade of LNS facilities



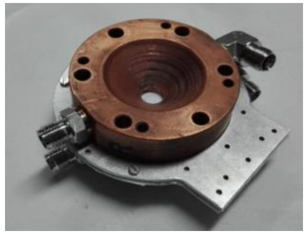
- **Upgrade of the LNS accelerator and beam lines**
  - CS accelerator **current** (from 100 W to 5-10 kW)
  - Beam transport line **trasmission efficiency** to nearly **100 %**



- **The MAGNEX Focal Plane Detector** (from 2 kHz to several MHz)
  - Gas tracker based on **multiple THGEM**
  - **SiC-CsI** telescopes for PID



- **Array of scintillators for γ-rays (G-NUMEN)**
  - LaBr3 scintillators
  - Measurement in coincidence with MAGNEX



- **Radiation tolerant targets**
  - Substrate of Highly Oriented Pyrolitic Graphite (HOPG)
- **New electronics**
  - CAEN VX2740 Digitizer module

NUMEN TDR

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

NUMEN roadmap

NUMEN phases			
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Feasibility study	Study of few cases + development of theory + R&D activity	Shutdown and upgrade of LNS facilities	Commissioning and systematic study of all the targets
2014-2015	2015-2020	2020-2023	2023-…

Conclusions and Outloooks

Use of HI-DCE reaction for 0νββ decay

- Promising results from the experiments of Phase 2
- Multi-channel approach for the data analysis
- **DCE reactions on ^{116}Cd, ^{76}Ge, ^{76}Se** measured for the first time
  - ✓ Good energy resolution to isolate the g.s. → g.s. transition
  - ✓ Absolute cross section measured
- Role of **multi-nucleon transfer** routes **negligible** with respect to the diagonal DCE in the case of ^{116}Cd -^{116}Sn system

Outlooks

- CS and MAGNEX FPD **upgrade** ongoing for reaching high intensity
- Full experimental exploration of all the nuclei candidate for 0νββ decay with the **high intensity beams**

Thank you

The NUMEN collaboration

(NUclear Matrix Elements for Neutrinoless double beta decay)

NUMEN

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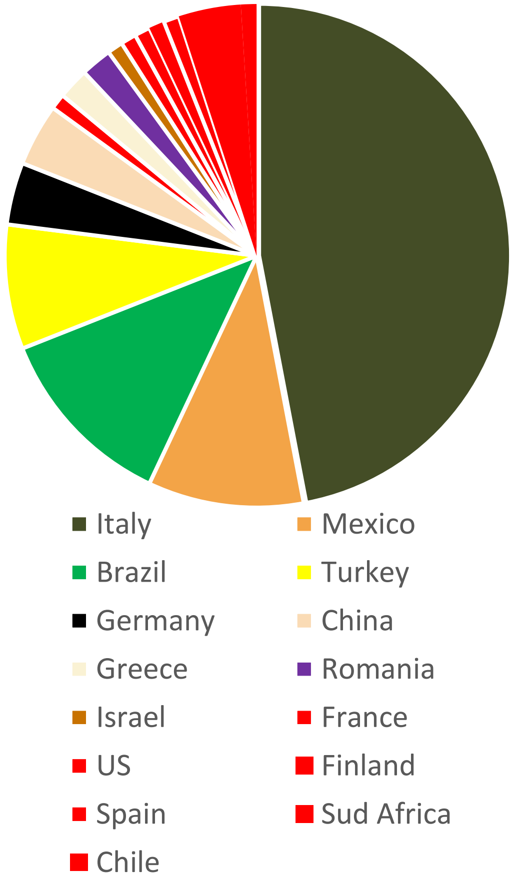
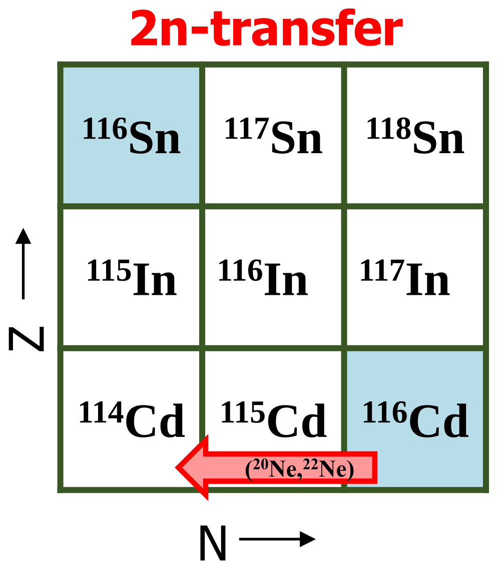
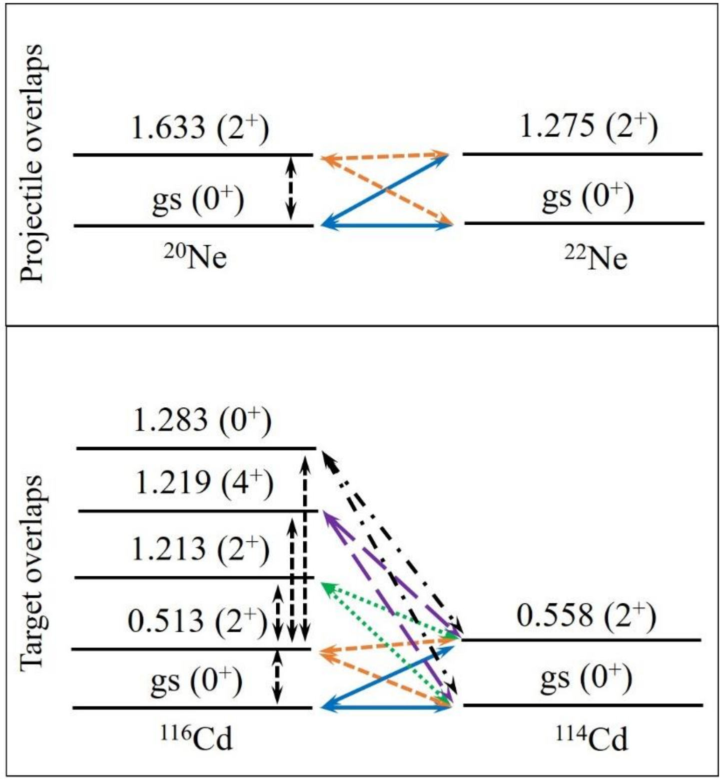
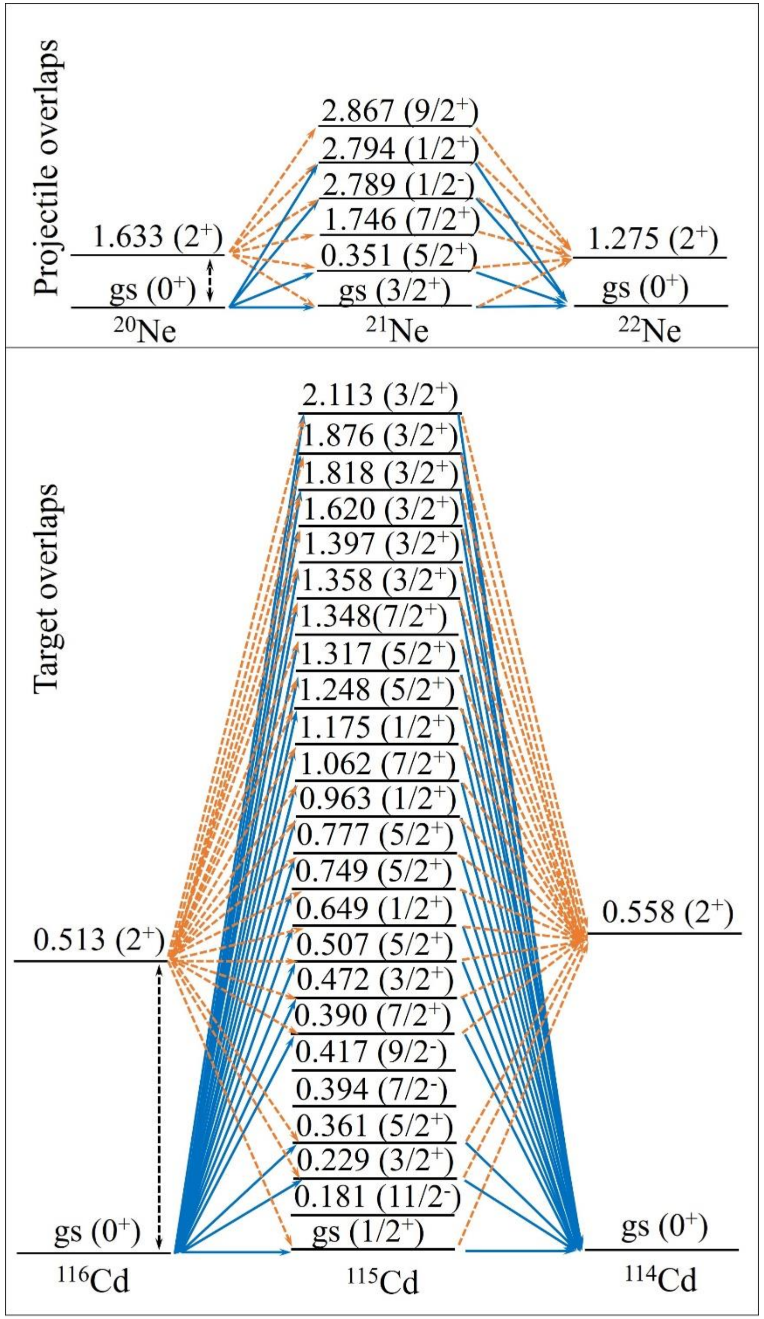
100 Researchers
40 Institutions
15 Countries



2n-transfer coupling schemes

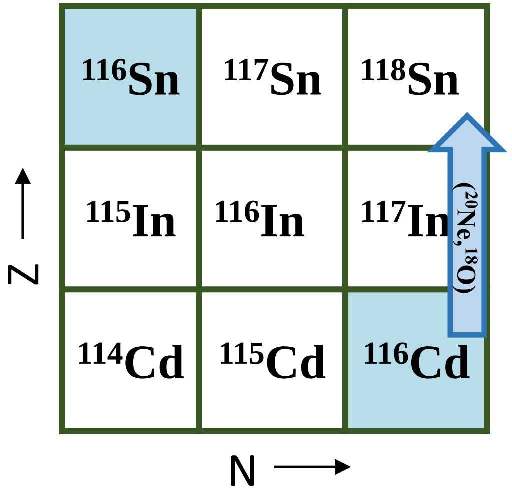


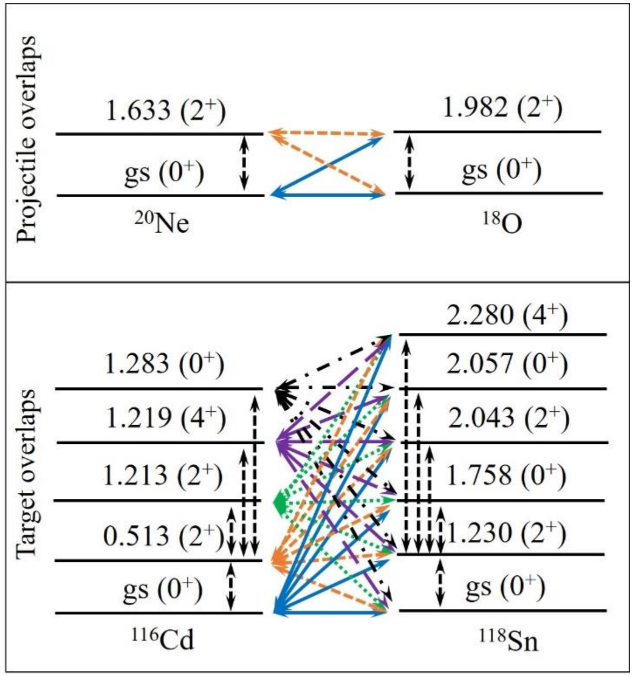


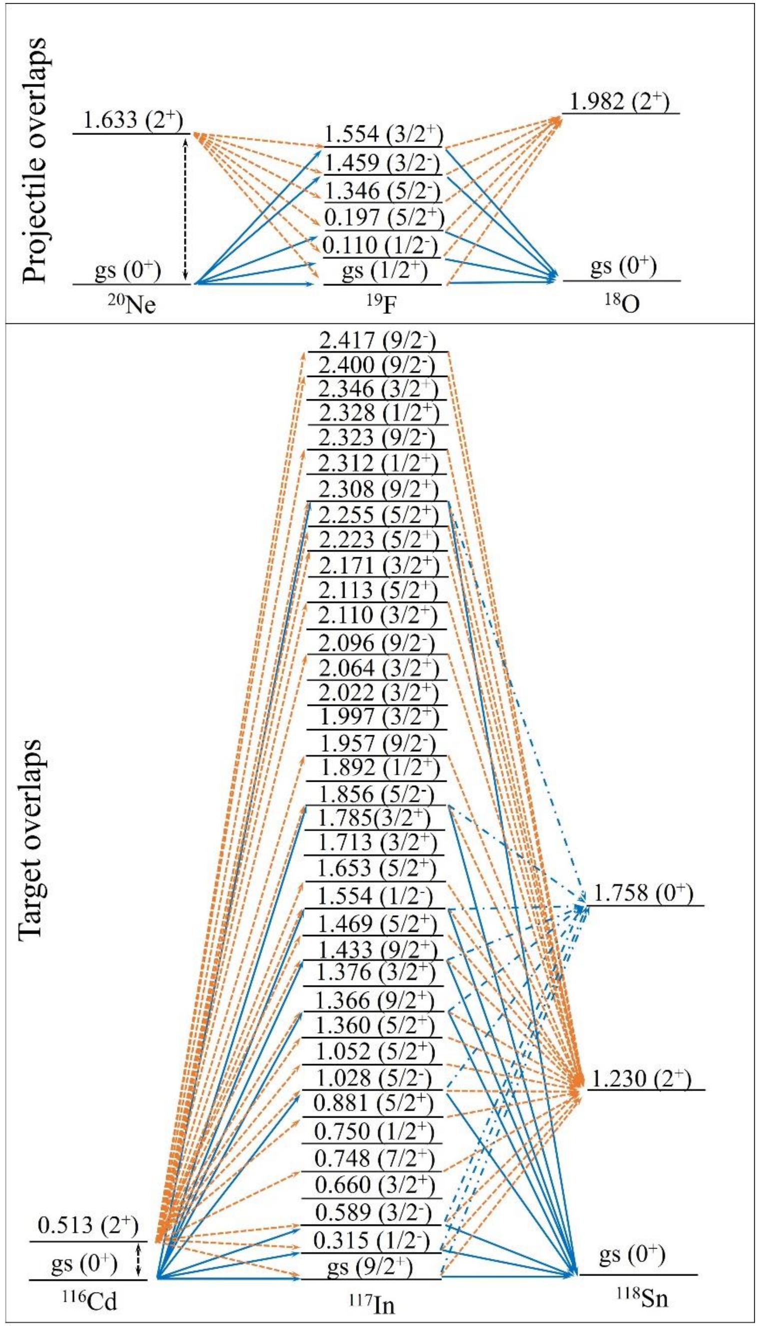


2p-transfer coupling schemes

2p-transfer







Shell model interactions

$^{20}Ne + ^{116}Cd$

Projectile

p-sd-mod interaction ^{4}He closed core

Orbitals: $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$

Target

jj45pna interaction ^{78}Ni closed core

Protons: $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$
Neutrons: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$

88Sr45 interaction ^{88}Sr closed core

Protons: $2p_{1/2}$, $1g_{9/2}$, $1g_{7/2}$, $2d_{5/2}$
Neutrons: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$

Expected beam intensity

Ion	Energy	Isource	Iacc	Iextr	Iextr	Pextr
	MeV/u	emA	emA	emA	pps	watt
^{12}C q=5+	30	200	30 (4+)	45 (6+)	$4.7 \cdot 10^{13}$	2700
^{12}C q=4+	45	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	8100
^{12}C q=4+	60	400	60 (4+)	90 (6+)	$9.4 \cdot 10^{13}$	10800
^{18}O q=6+	20	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	3600
^{18}O q=6+	29	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	5220
^{18}O q=6+	45	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	8100
^{18}O q=6+	60	400	60 (6+)	80 (8+)	$6.2 \cdot 10^{13}$	10800
^{18}O q=7+	70	200	30 (7+)	34.3 (8+)	$2.7 \cdot 10^{13}$	5400
^{20}Ne q=7+	28	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	4800
^{20}Ne q=7+	70	400	60 (7+)	85.7 (10+)	$5.3 \cdot 10^{13}$	10280
^{40}Ar q=14+	60	400	60 (14+)	77.1 (18+)	$2.7 \cdot 10^{13}$	10280

Present performance $^{13}C^{4+}$ @ 45 MeV/u Pextr = 100 watt I= 1×10^{12} pps

Characteristics of the beam extracted by stripper

Energy spread FWHM 0.23%

Beam specification requested by NUMEN experiment

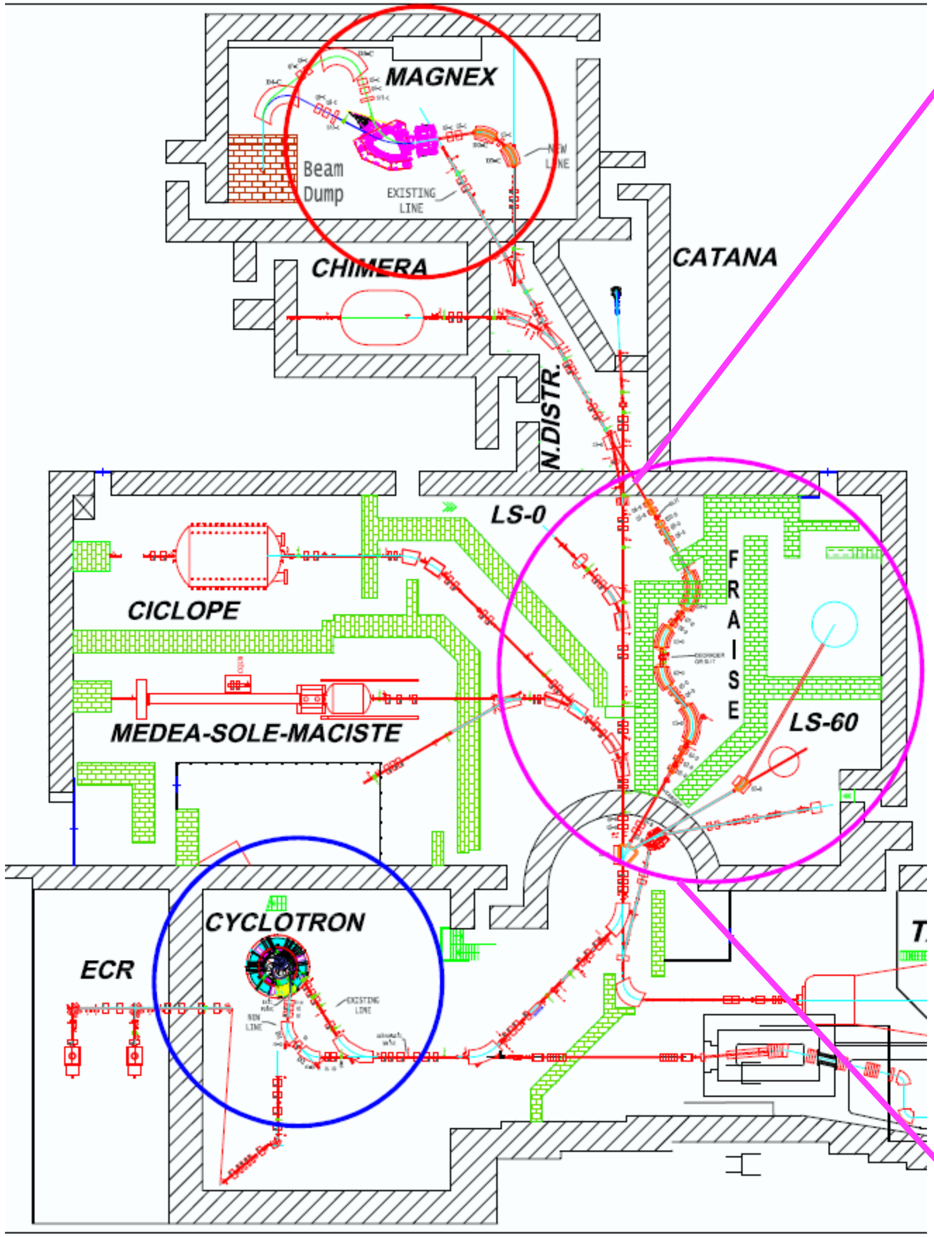
Radial Beam size FWHM 1.0 mm
Radial Divergence FWHM ± 4 mrad

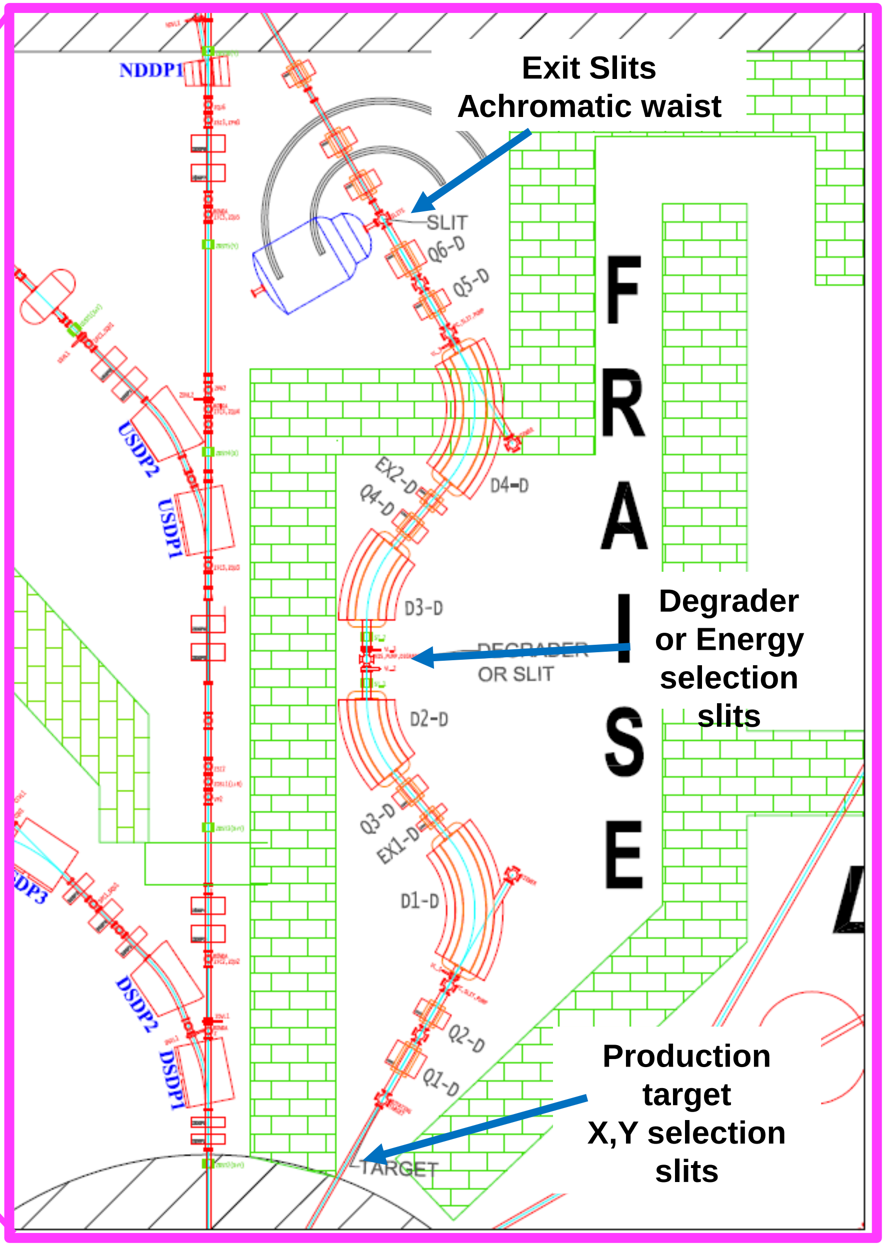
Vertical Beam size FWHM 2.5 mm
Vertical divergence FWHM ± 7.5 mrad

Energy spread FWHM 0.1%

FRAISE: a new FRAgment In-flight SEparator

N. Martorana talk





Main features:

- 4 dipoles and 6 quadrupoles, arranged in a symmetrical configuration
- maximum magnetic rigidity 3.2 *Tm*
- momentum acceptance ±1.2%
- solid angle acceptance ±2.5 *msr*,
- energy resolution 2500 for a beam spot size of 1 *mm*.

$$RP = \left|\frac{R_{16}}{2x_0 R_{11}}\right| = 2500$$
(beam spot ±1 mm)

- thanks to high energy dispersion value at the symmetry plane, it will allow to deliver stable beams with an **energy spread of 0.1 %**

Courtesy of P. Russotto

Expected beams with FRAISE

Main Beam	Primary Beam/Energy (AMeV)	Thickness Be target (um)	Thickness Al wedge (um)	Yield (kHz)	Beam energy after tagging (AMeV)	Purity (%)
14Be	18O/55	1500	0	2.6	46	2
14Be	18O/55	1500	1000	2.2	43	70
13N	16O/40	700	600	1230	4	54
14O	16O/40	700	600	807	4	36
16C	18O/55	1500	1000	6800	40	60
18Ne	20Ne/60	1000	0	16700	43	16
18Ne	20Ne/60	1000	1000	3120	24	47
17F	20Ne/60	1000	1000	3300	23	49
34Si	36S/40	500	500	980	11	81
38S	40Ar/40	500	300	1840	17	66
34Ar	36Ar/50	250	0	2800	41	4
34Ar	36Ar/50	250	500	426	41	12
46Ar	48Ca/50	500	500	1000	38	50
68Ni	70Zn/40 (1 kW)	250	200	490	18	50

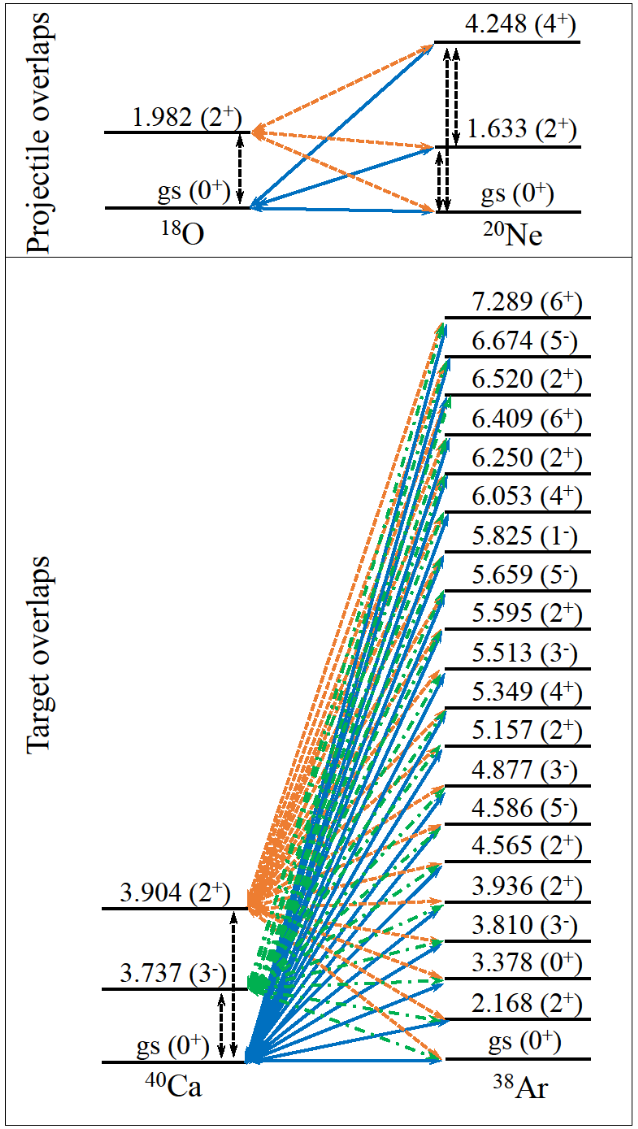
Supposing 2 kW primary beam

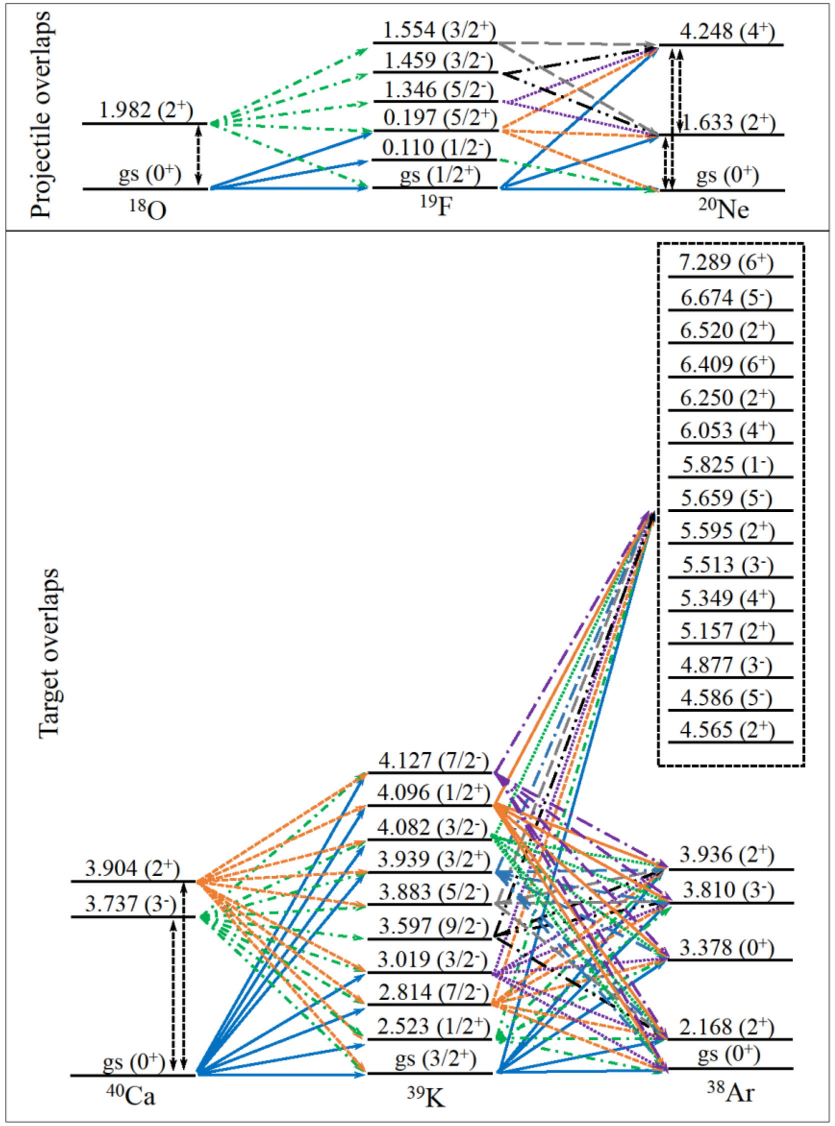
FRAISE will be competitive in the production of medium-light (A<70) RIBs at Fermi energy

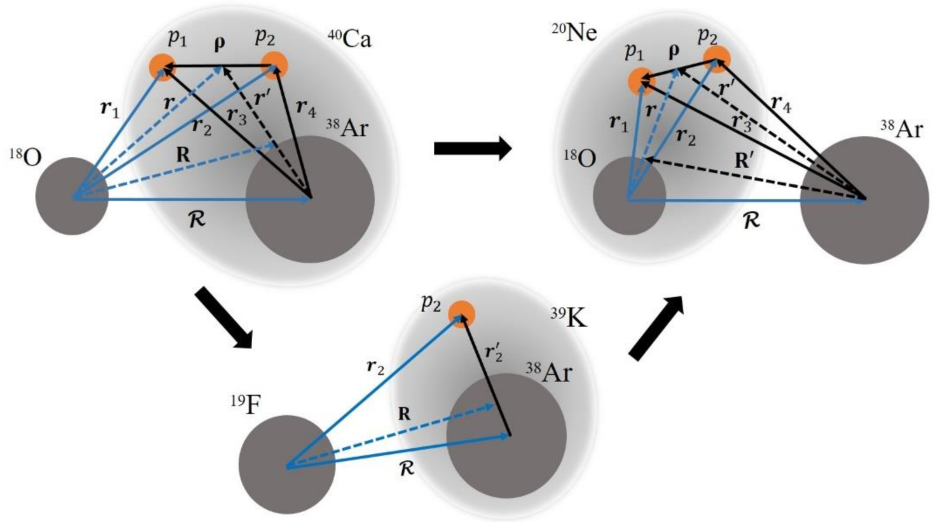
Rate will increase by 2 order of magnitudes with respect to old FRIBs!

Courtesy of P. Russotto

2p-transfer reaction



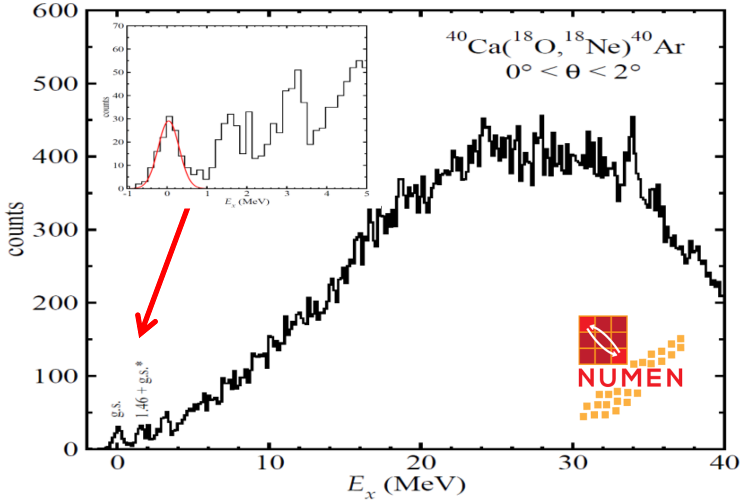


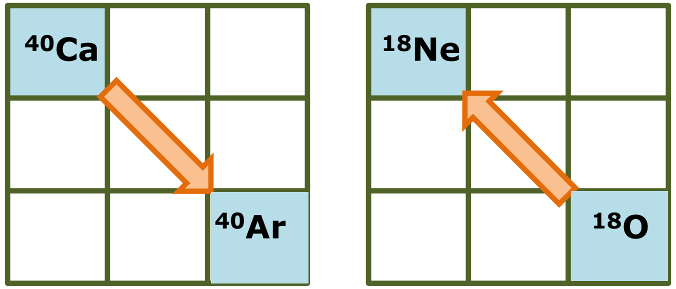


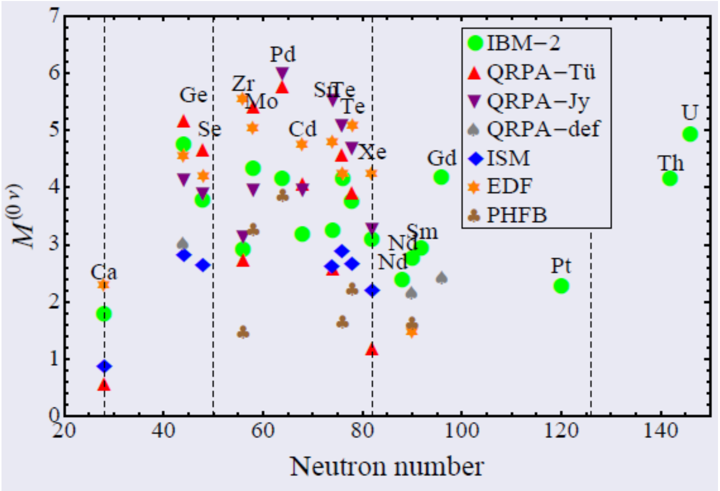
Double charge exchange reaction

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

Access to ground-to-ground state transition

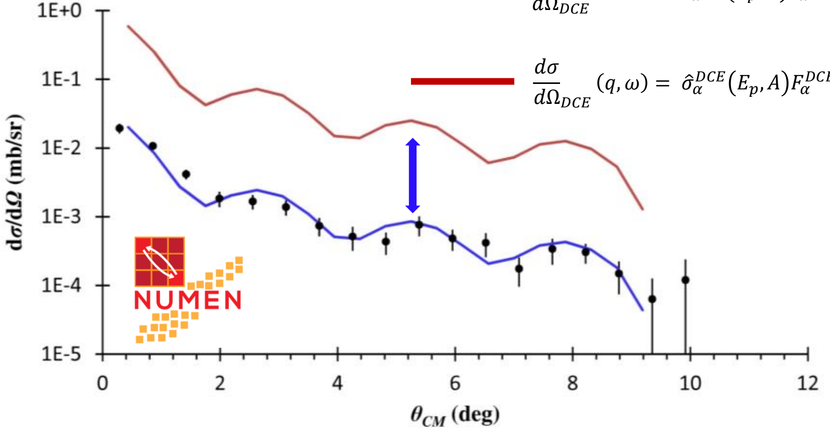






$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_{\alpha}^{DCE}(E_p,A)F_{\alpha}^{DCE}(q,\omega)B_T^{DCE}(\alpha)B_P^{DCE}(\alpha)$$

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



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

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

Double charge exchange reaction

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

F. Cappuzzello et al. Prog. Part. and Nucl. Phys. (submitted)

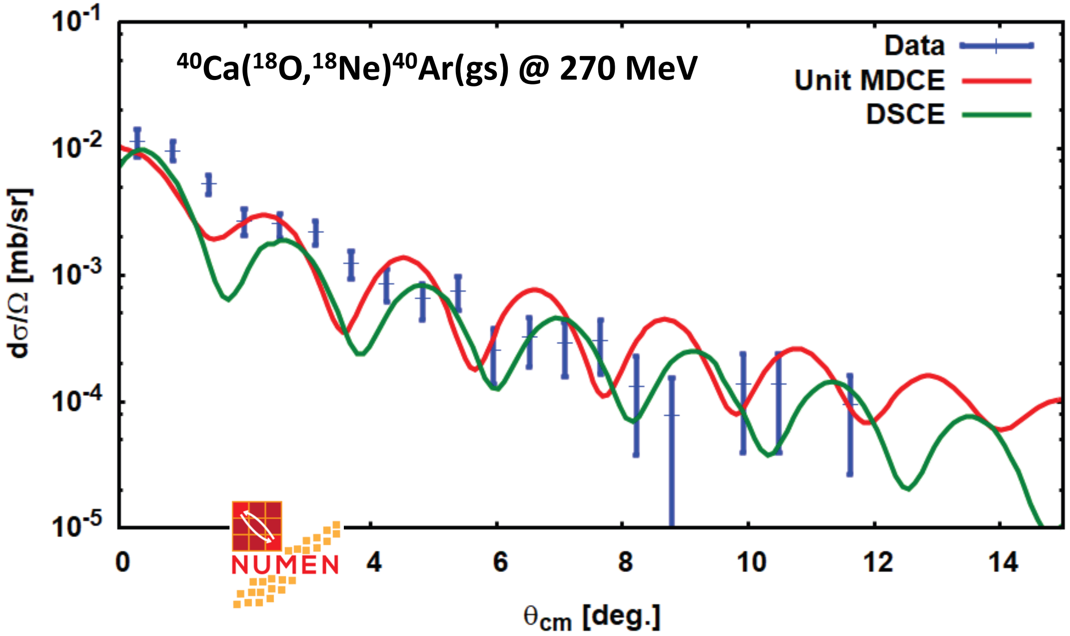
- ✓ ISI and FSI ion-ion interaction from double folding (available new elastic and inelastic data)
- ✓ QRPA transition densities for microscopic form factors up to $J^{\pi} = 5^{\pm}$
- ✓ One-step DWBA for the MSCE amplitudes

- ✓ Scaling of 0.72 applied to the MDCE

- ✓ Preliminary results from diagonal πN potentials shown in the Figure

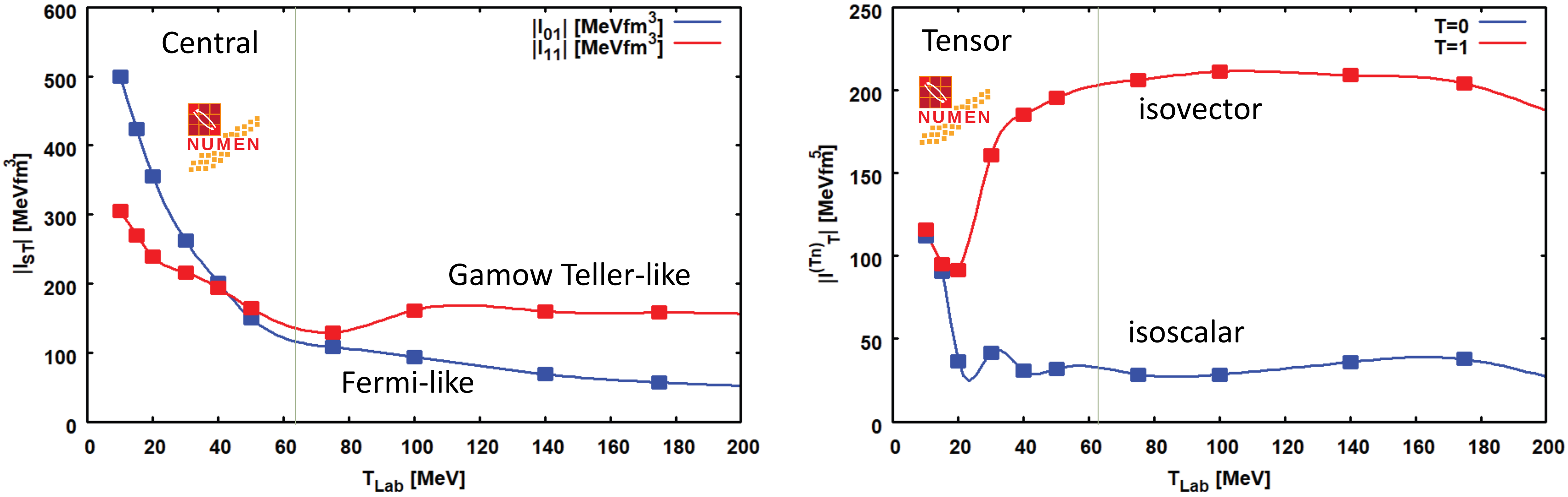
- ✓ $L = S = 0$ and $L = S = 2$ combinations included

- ✓ MDCE is dominated by the spin-stretched mechanism $L = S = 2$, while the DSCE from the spinless component $L = S = 0$



Double charge exchange reaction

F. Cappuzzello et al. Prog. Part. and Nucl. Phys. (submitted)



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