Nuclear Physics Mid Term Plan in Italy

LNS – Session

Catania, April 4th-5th 2022

Nuclear Physics
Mid Term Plan in Italy

Selective study of nuclear structure response with high intensity beams and advanced spectrometry

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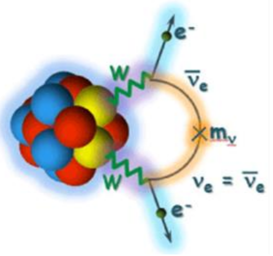
On behalf of

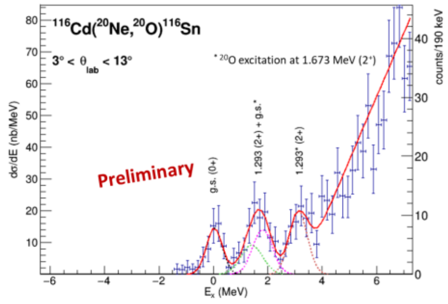
C. Agodi, J.I. Bellone, G.A. Brischetto, S. Calabrese, D. Calvo, V. Capirossi, F.C, D. Carbone, I. Ciraldo, F. Delaunay, M. Cavallaro, M. Fisichella, F. Pinna, D. Sartirana, O. Sgouros, V. Soukeras, A. Spatafora, J.J. Valiente-Dobon, D. Torresi

Outline

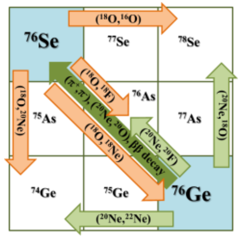
✓ The problem of $0\upsilon\beta\beta$-decay nuclear matrix elements



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



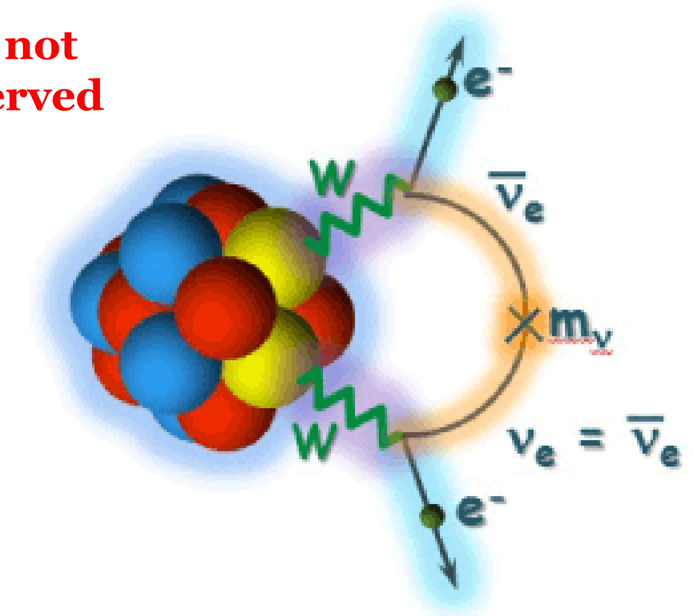
✓ The multi-channel vision. Synergies with complementary studies, such as $\gamma\gamma$-decay.



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

Neutrinoless double beta decay

Still not observed



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

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

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

Exciting new physics

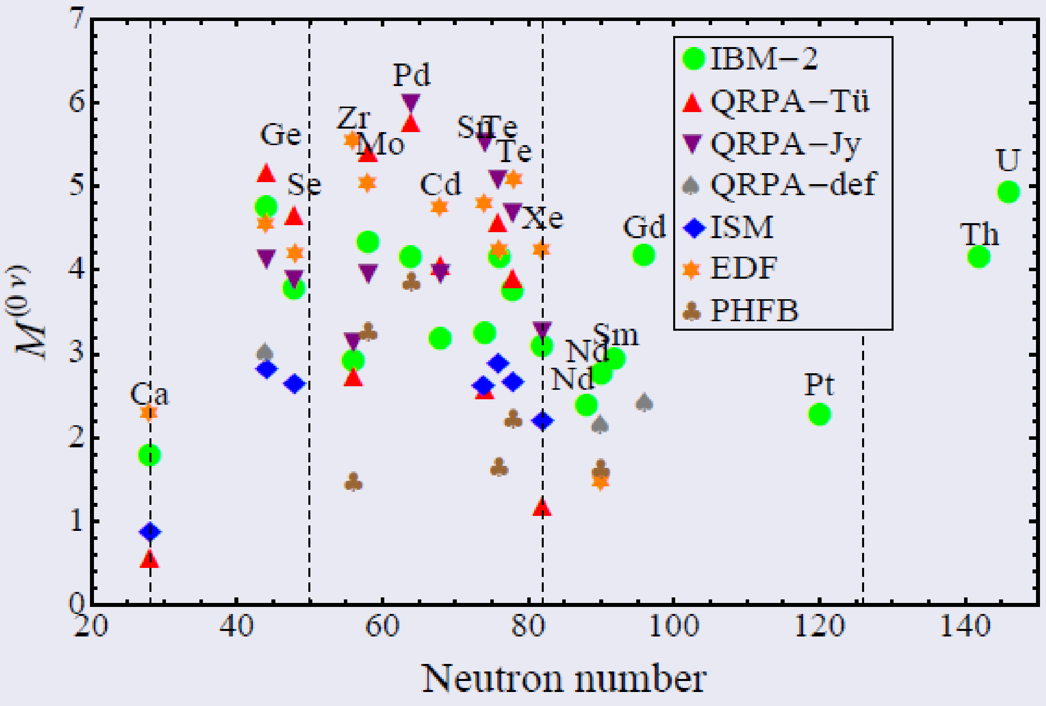
requiring

Nuclear Matrix Element (NME)!

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

State of 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** (<u>still sizeable uncertainties</u>): QRPA, Large scale shell model, IBM, EDF, ab-initio …..

Measurements (still not conclusive for **$0\nu\beta\beta$** NME):

✓ β-decay and **$2\nu\beta\beta$** decay

1^{st} order isospin probes

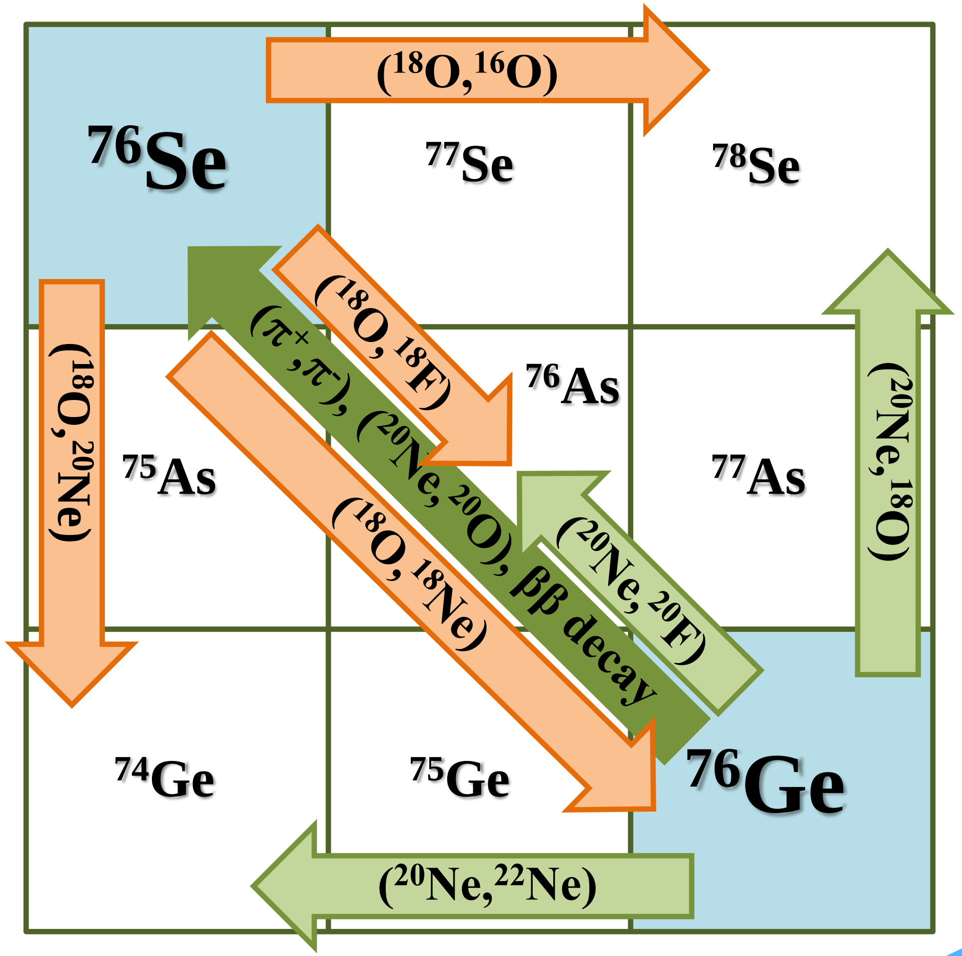
2^{nd} order isospin probes

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

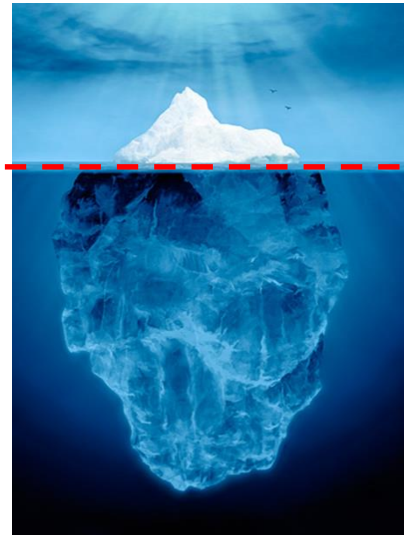
✓ A promising experimental tool: **Heavy-Ion Double Charge-Exchange (HI-DCE)**

Heavy-ion DCE as surrogate processes of ββ-decay

- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order: Kinematical matching
- ✓ 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, erc NURE

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

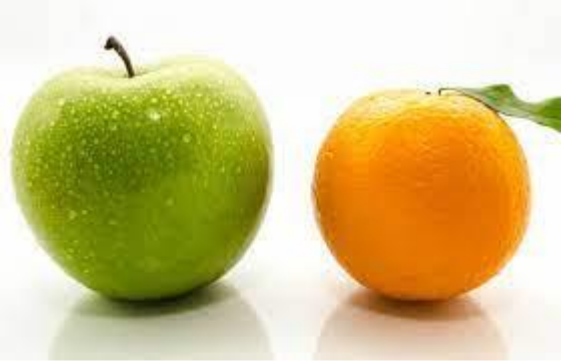
RIKEN

RCNP

Future: INFN-LNS

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Decay vs reaction **dynamics**
- DCE includes **sequential** transfer **mechanism**



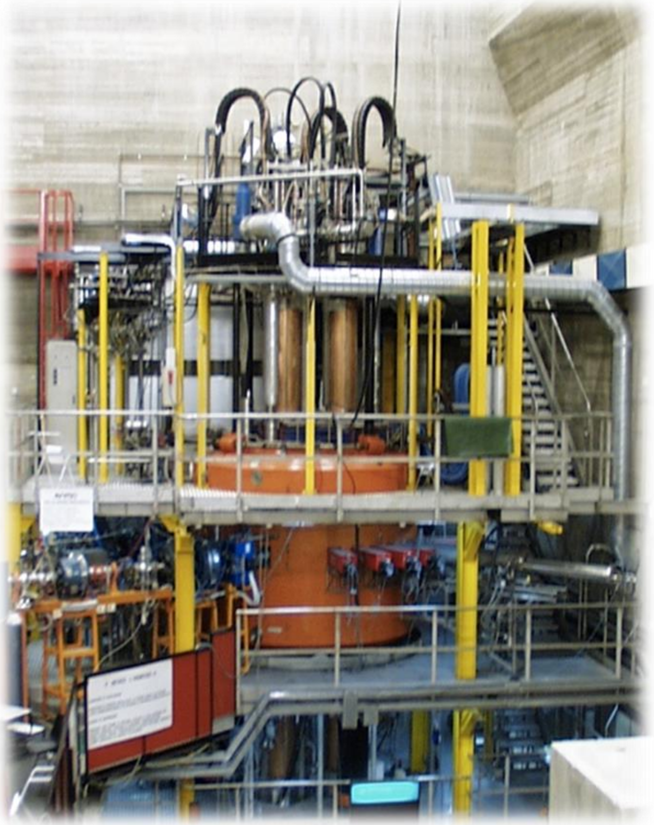
Similarities

- **Same initial and final states:** Parent/daughter states of the *0νββ* 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 *0νββ*
- **Off-shell propagation** through virtual intermediate channels

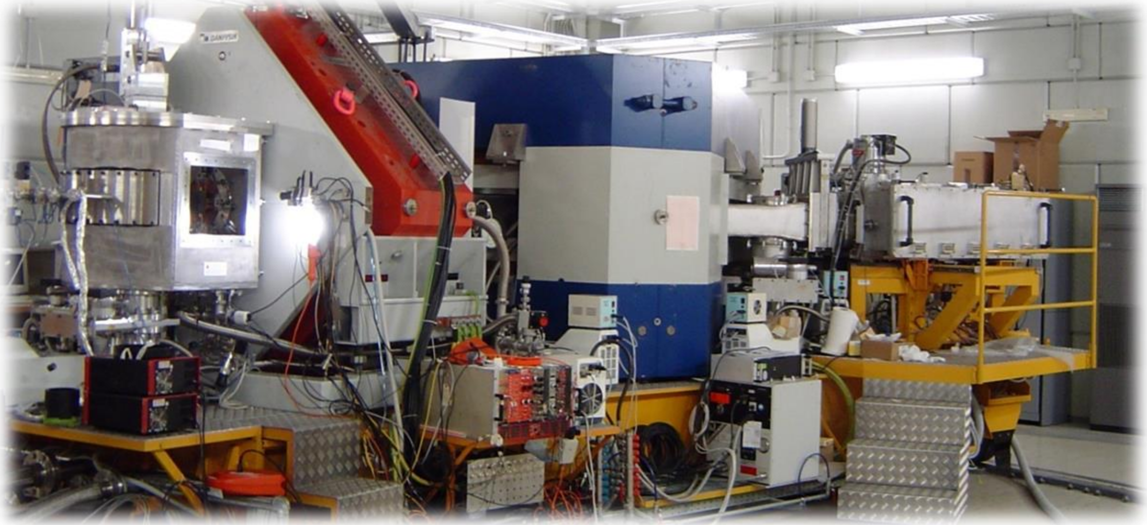
DCE @ INFN-LNS

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



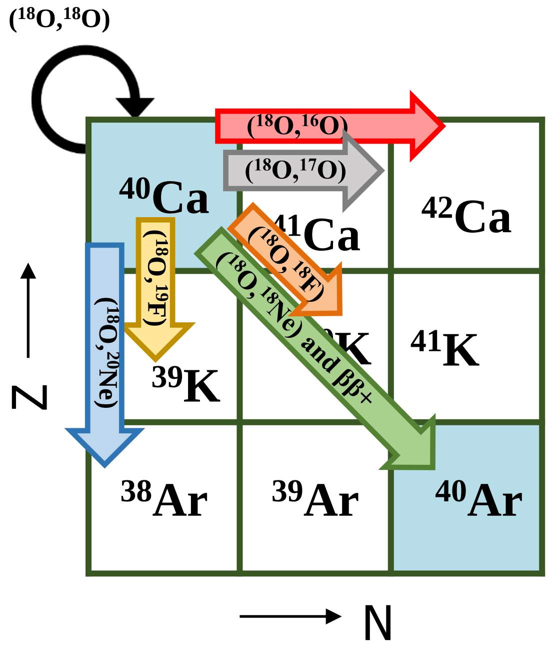
Optical characteristics	Current values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	50
Momentum acceptance	-14%, +10%
Momentum dispersion (cm/%)	3.68

Good compensation of the aberrations: Trajectory reconstruction

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

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 provide important 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

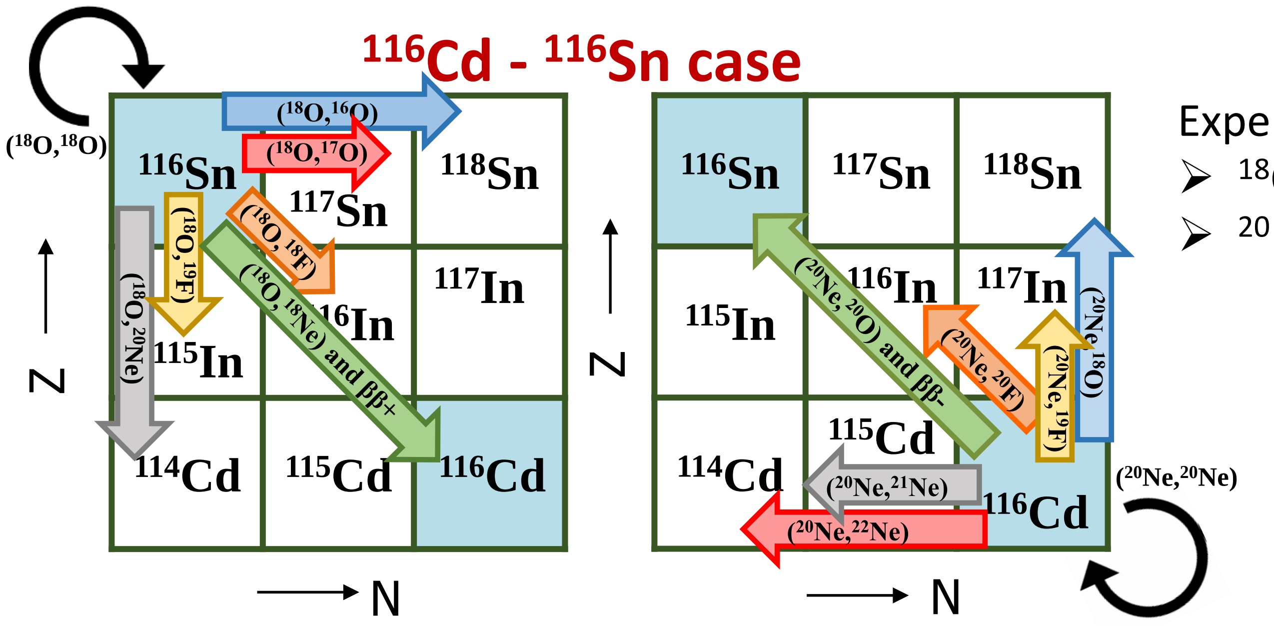
Single charge exchange (SCE) → nuclear response to 1st order isospin operators (One-Body Transition Densities)

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

- ✓ Measuring all the accessible quasielastic channels <u>all at once</u> 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

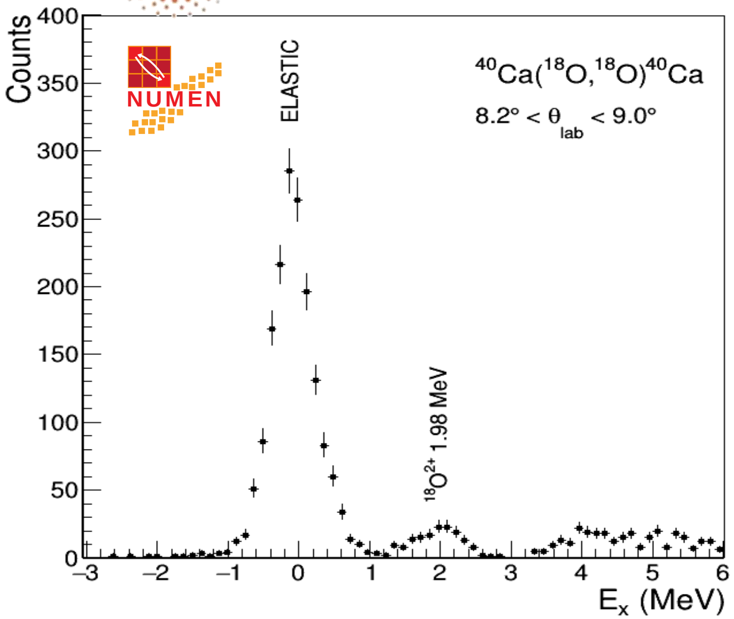
An example



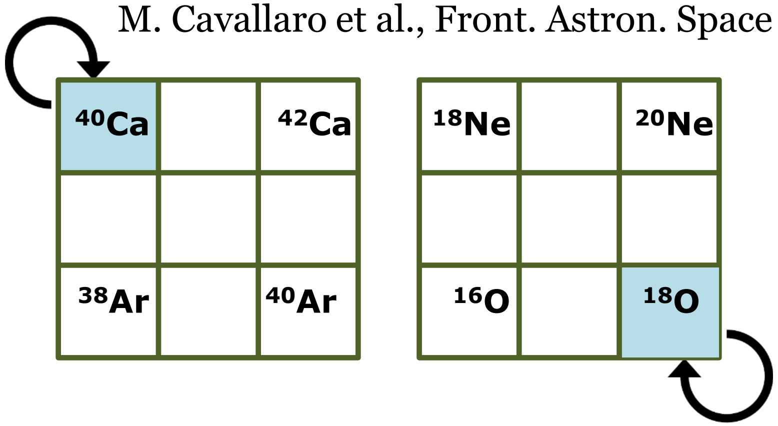
Experiments @ 15 MeV/A
- ➢ ^{18}O + ^{116}Sn
- ➢ ^{20}Ne + ^{116}Cd

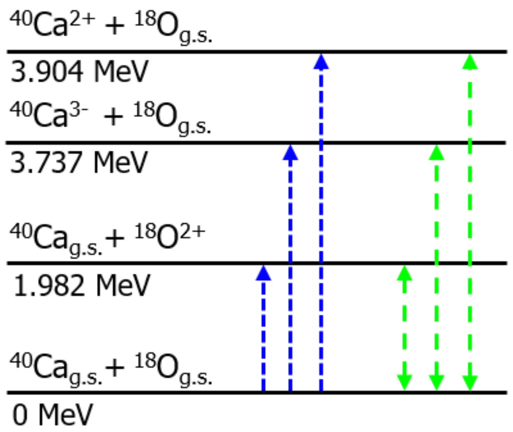
Recent NUMEN experimental results: the $^{18}O + ^{40}Ca$ @ 270 MeV case

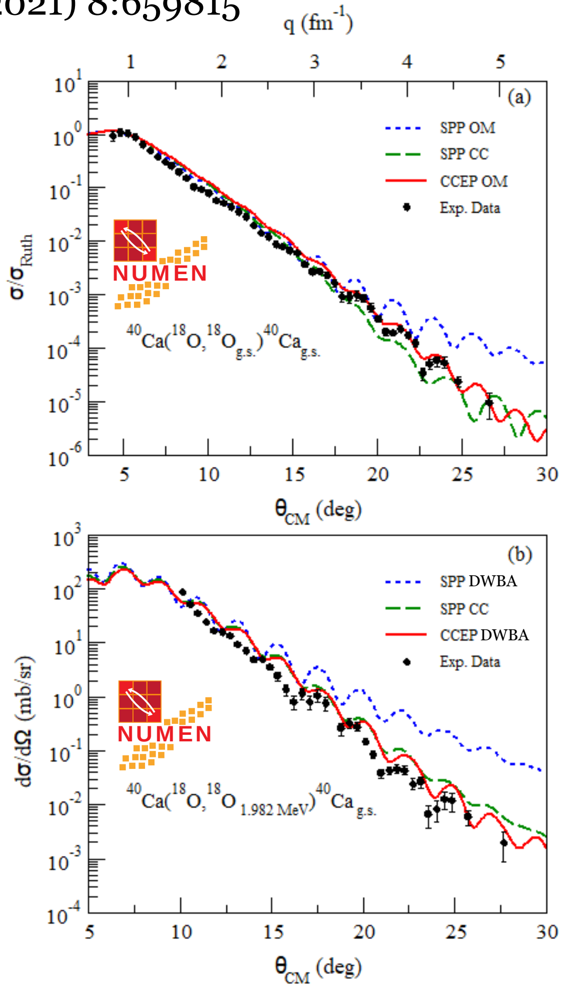
The $^{40}Ca(^{18}O,^{18}O)^{40}Ca$ elastic and inelastic scattering @ 270 MeV



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







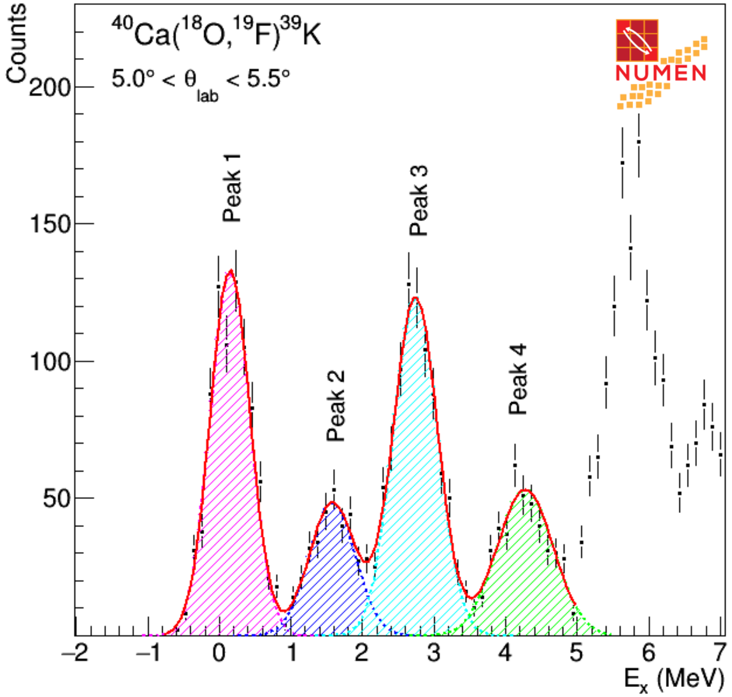
Key information from scattering data:

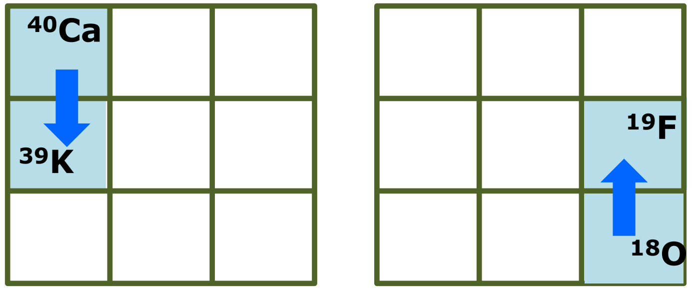
- Double folding Sao Paulo Potential works well
- **Coupling to low-lying 2^+ and 3^- states of ^{18}O and ^{40}Ca states is important**
- Effects of coupling can be accounted for in average by Coupled Channel Equivalent Potential (CCEP) approach

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

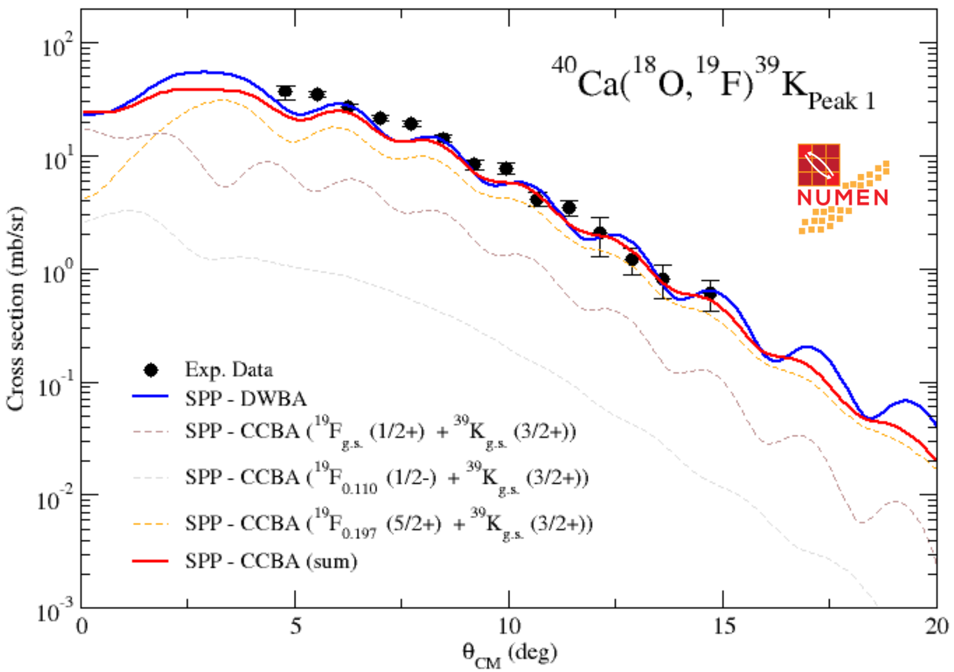
CCBA analysis based on shell model amplitudes

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





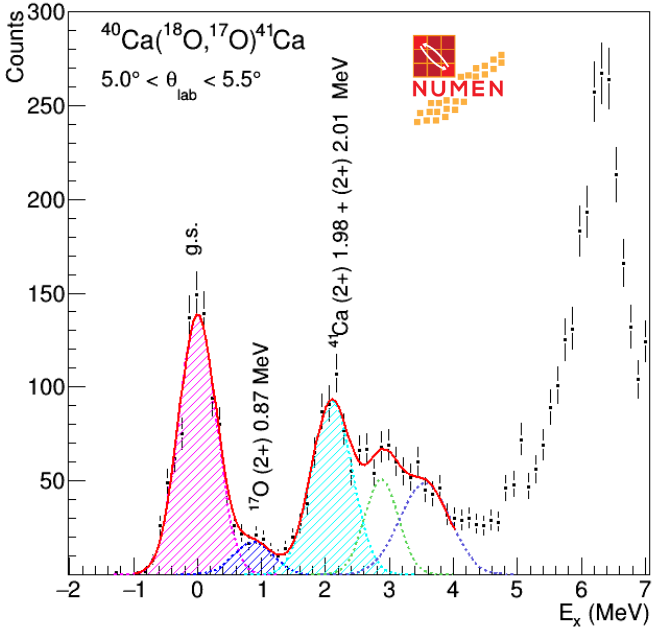
Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data

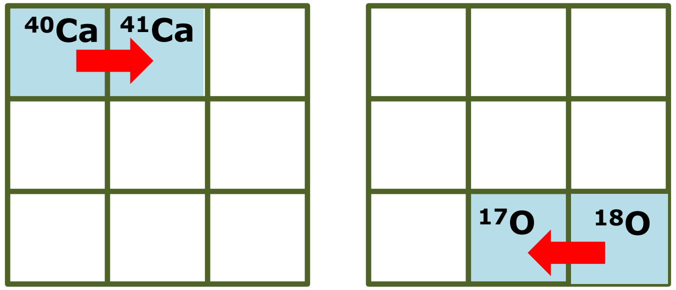


Key information from 1p data:

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

CCBA analysis based on shell model amplitudes





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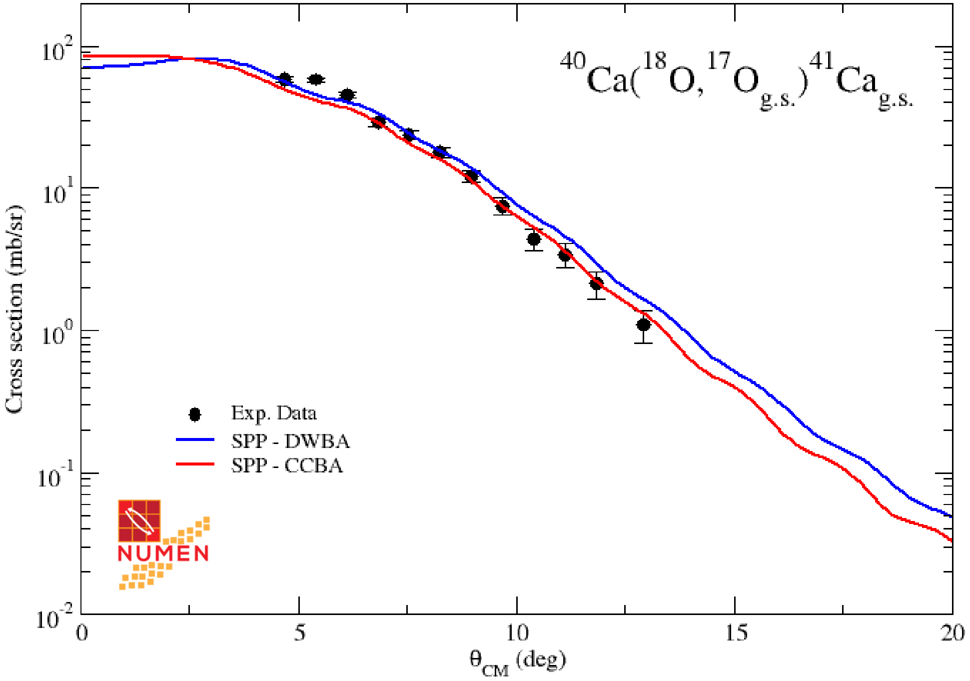
S. Calabrese et al., Phys. Rev. C 104, 064609 (2021)



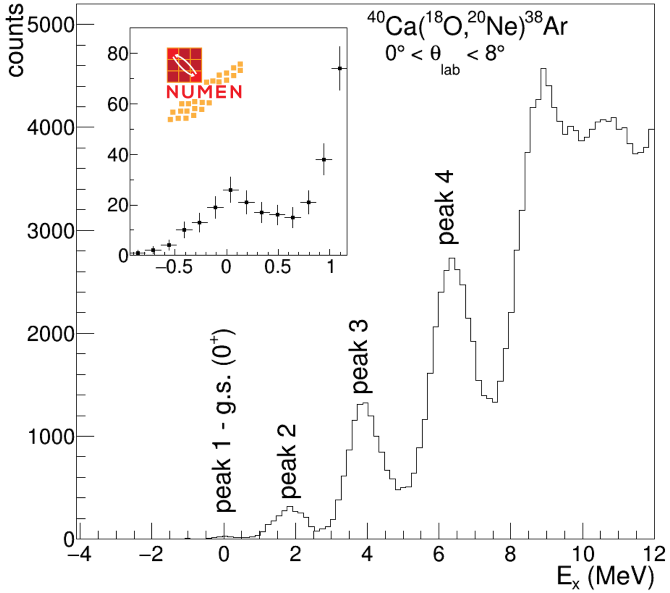
Key information from 1n data:

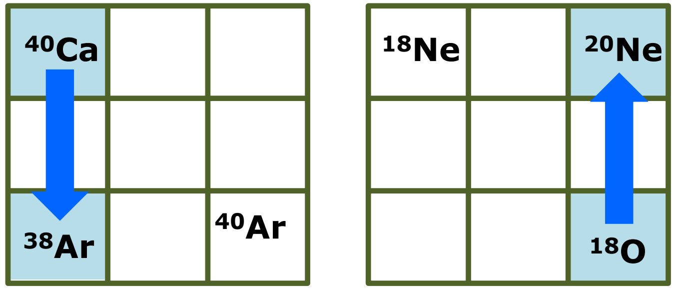
- **Very good description of the data from CCBA constrained approach**
- **Mixing of single particle and core polarization configurations**

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

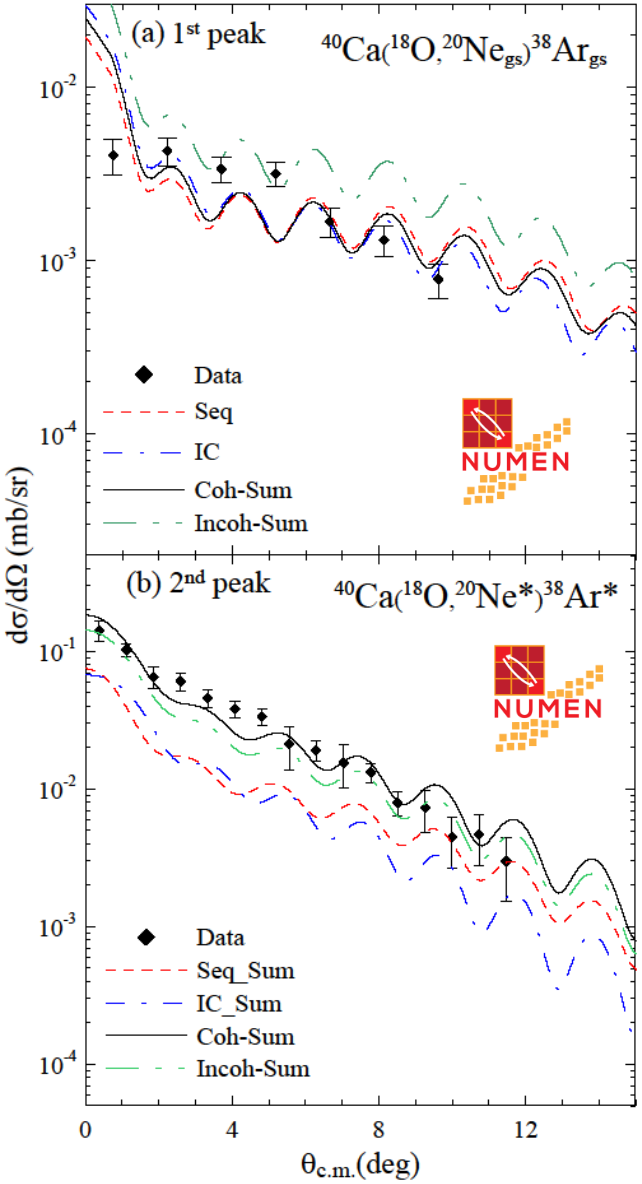
CCBA analysis based on direct and two-step tranfer with shell model amplitudes

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





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



Key information from 2p data:

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

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

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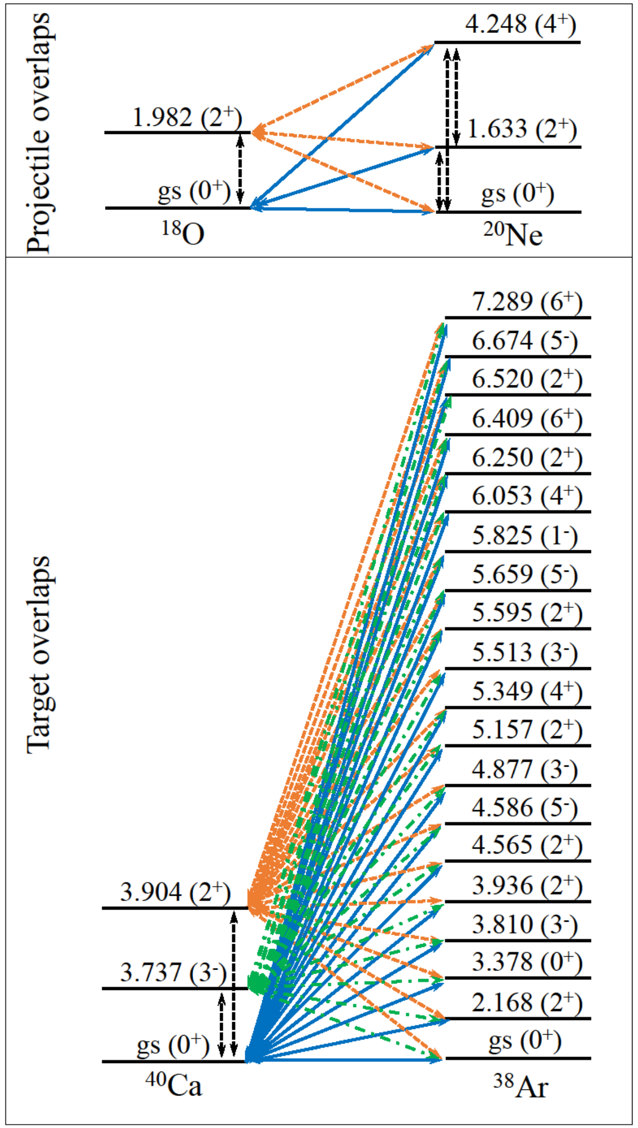
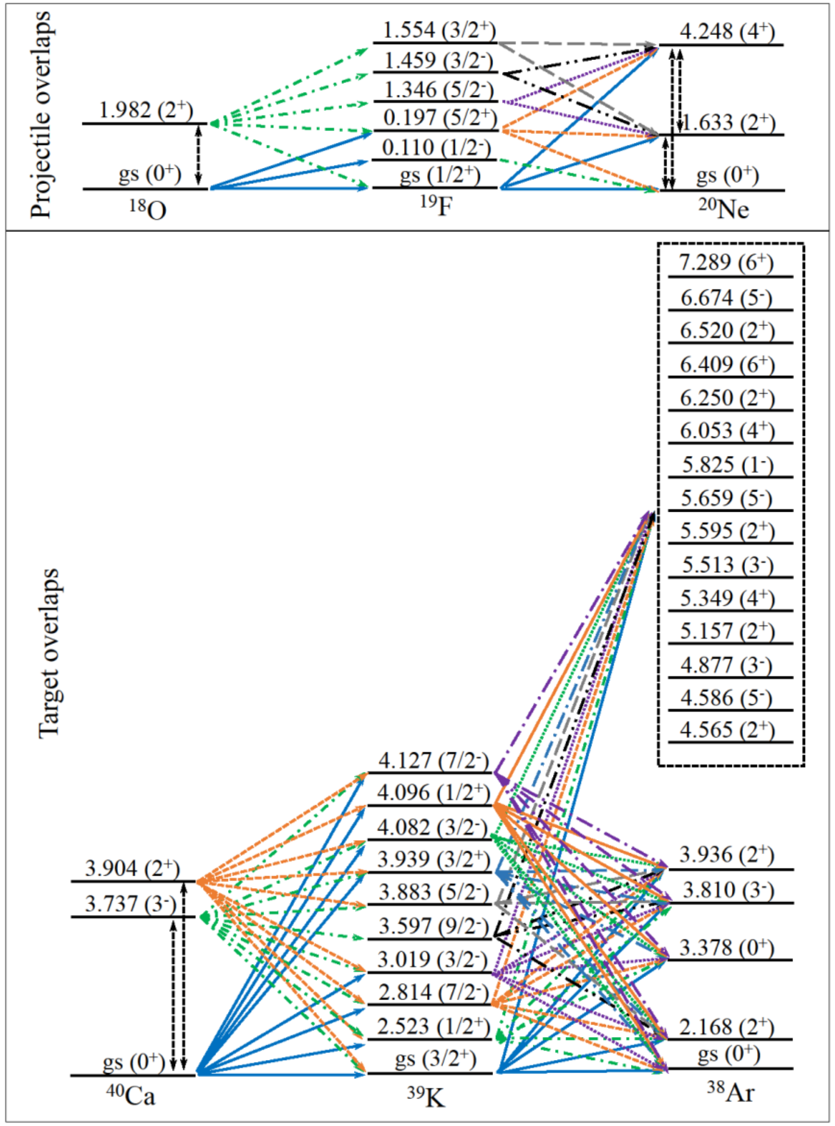
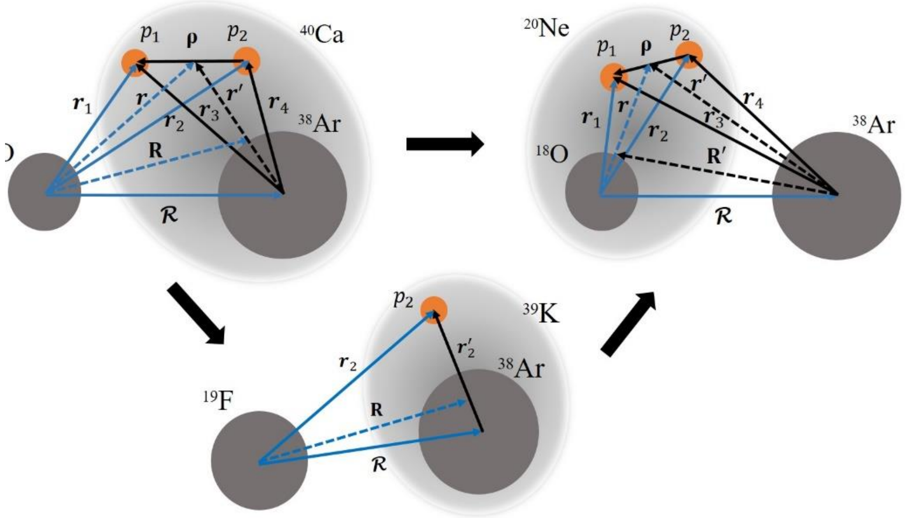
CCBA analysis based on direct and two-step tranfer with shell model amplitudes



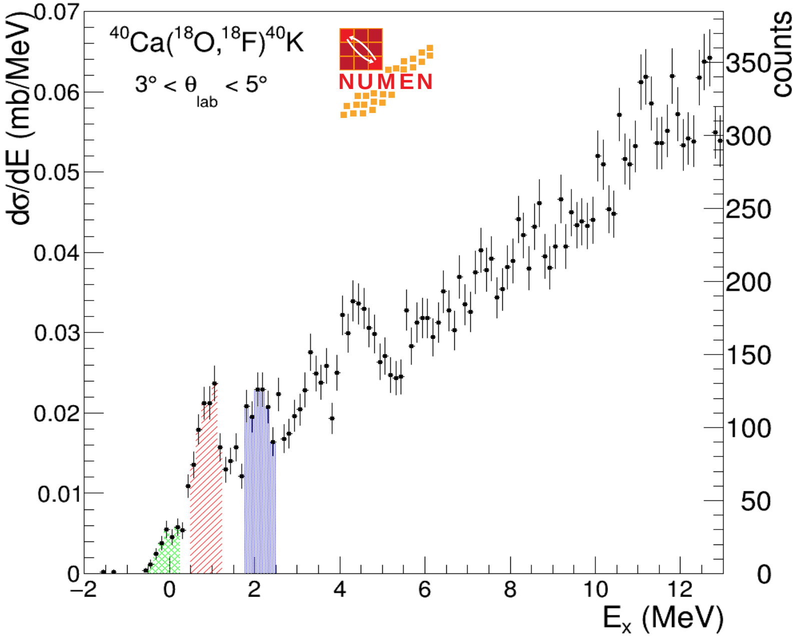


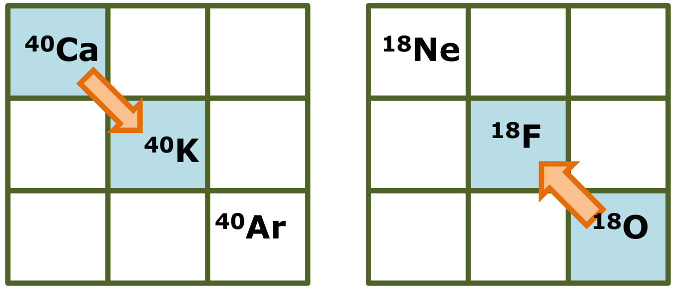


The $^{40}Ca(^{18}O,^{18}F)^{40}K$ single charge exchange @ 270 MeV

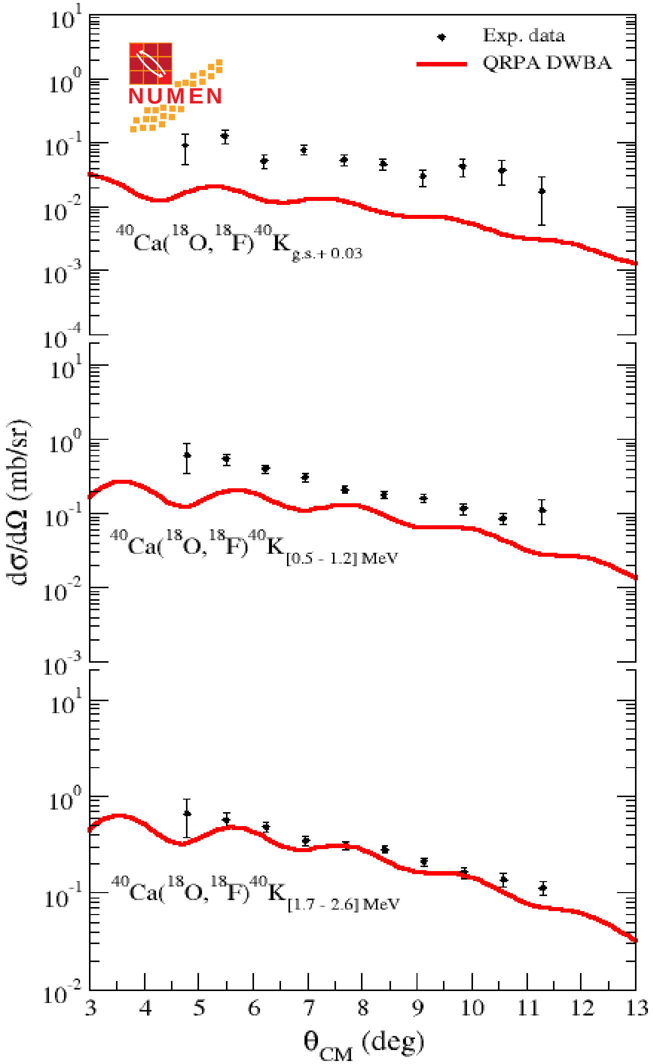
DWBA analysis based on double folding form factors of QRPA transition densities with NN isovector interaction

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





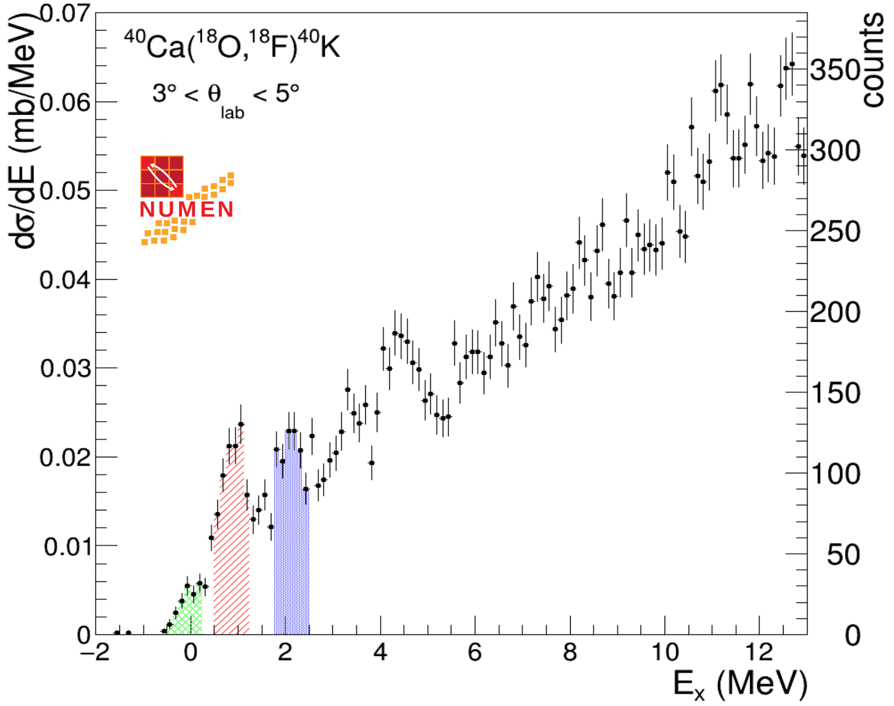
Note: the optical potential is extracted from our CCEP data analysis of elastic and inelastic scattering data

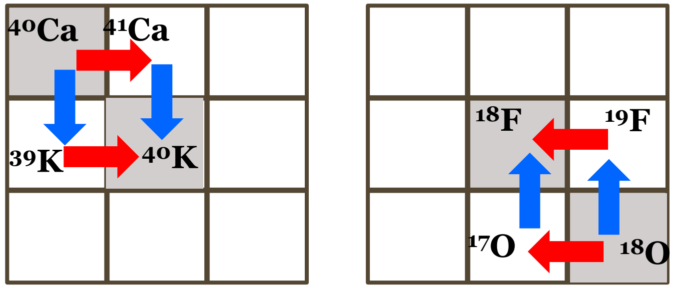


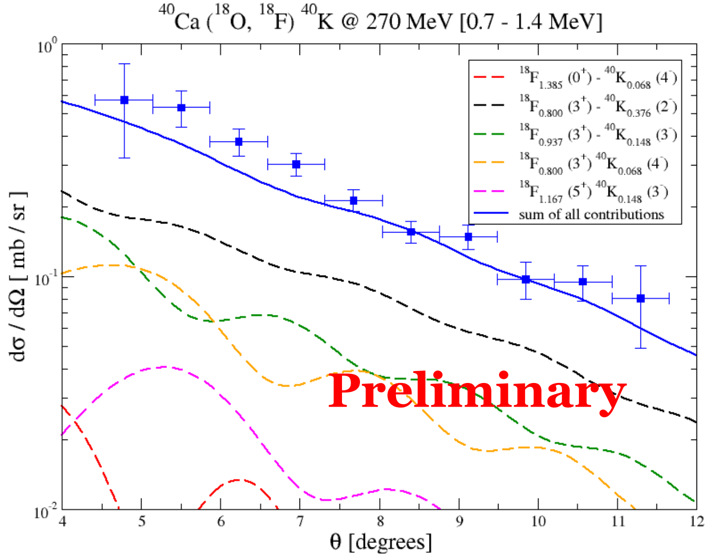
Key information from SCE data:

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

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

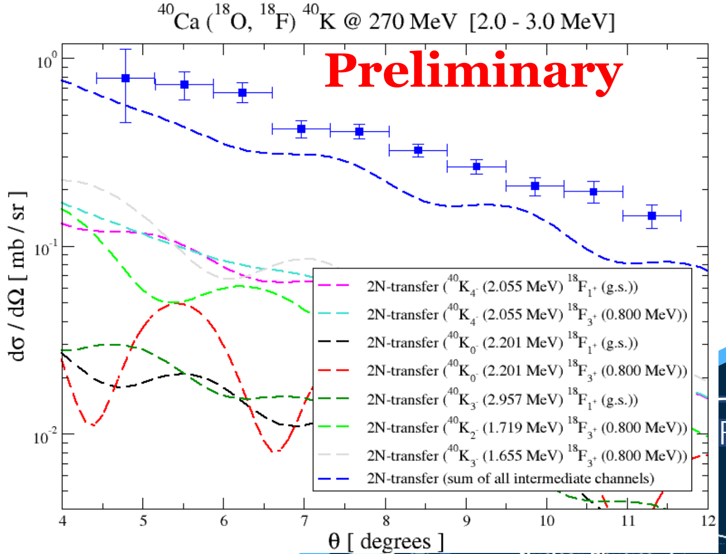






Note: the optical potential is extracted from our CC data analysis of elastic and inelastic scattering data

Calculations still ongoing



Key information from SCE data:

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

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

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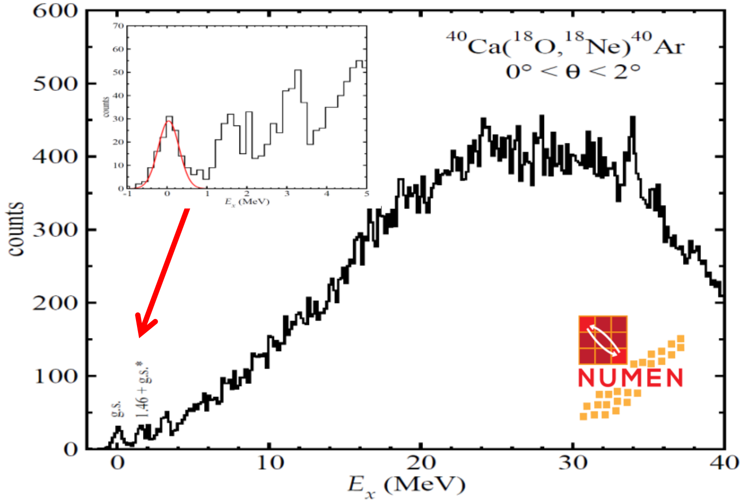
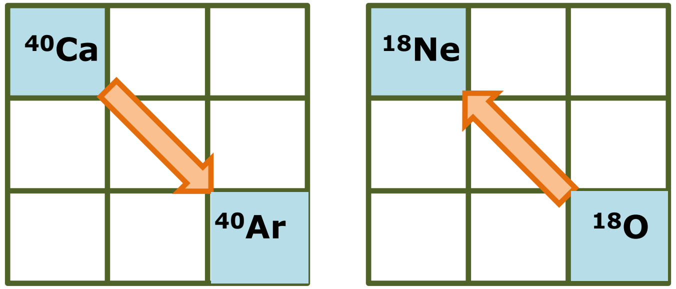
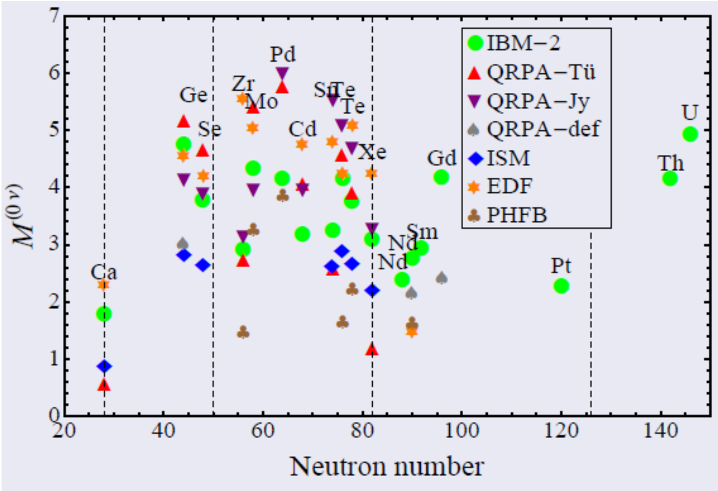
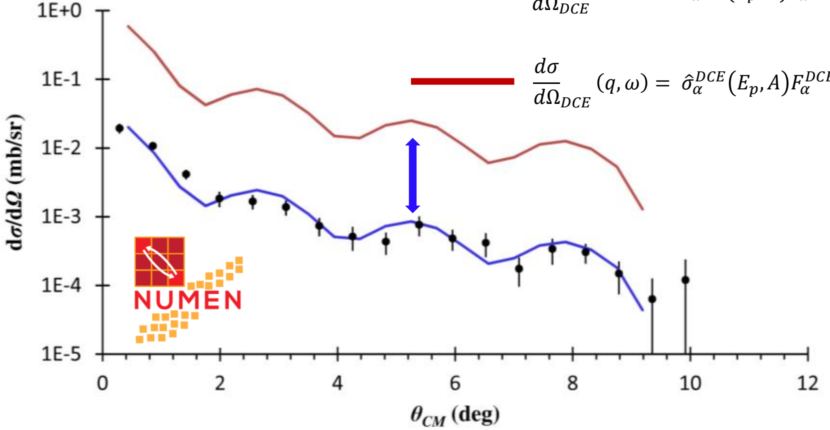
Access to ground-to-ground state transition









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

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

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

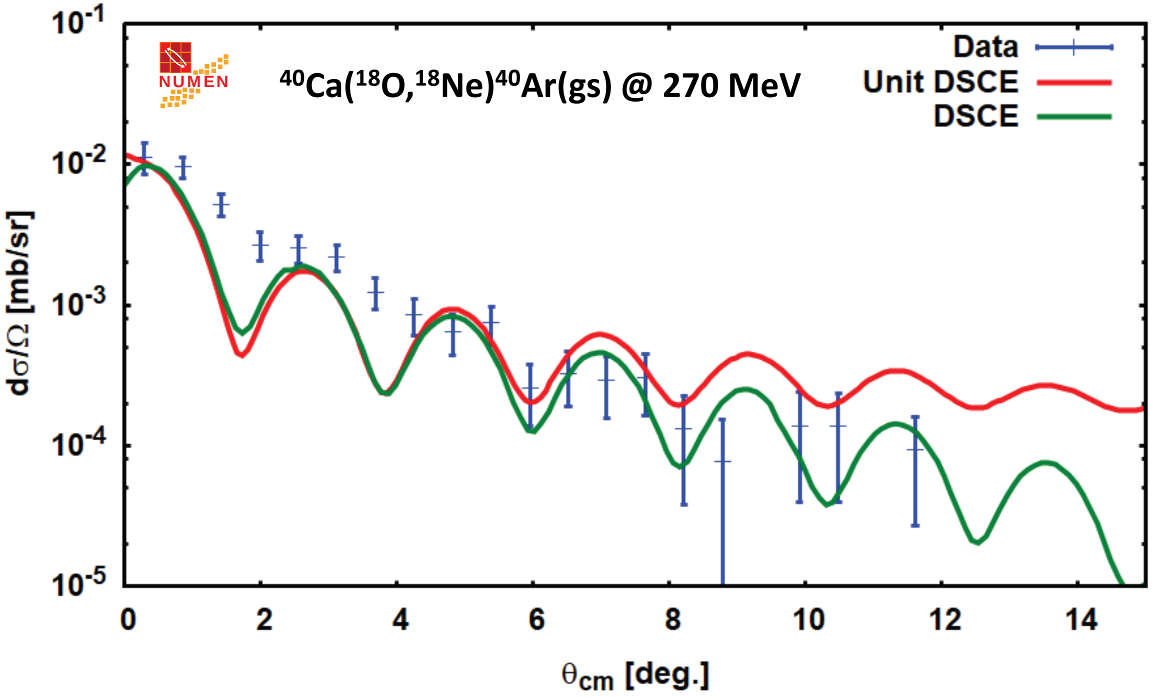
$$\left|M_{\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 1.1 \pm 0.5$$

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

NUMEN

Just a feeling of DCE spectroscopy

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



- *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*
- *F. Cappuzzello et al. Prog. Part. and Nucl. Phys, in preparation*

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 $L_{13} = L_{24} = \lambda = 0$

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

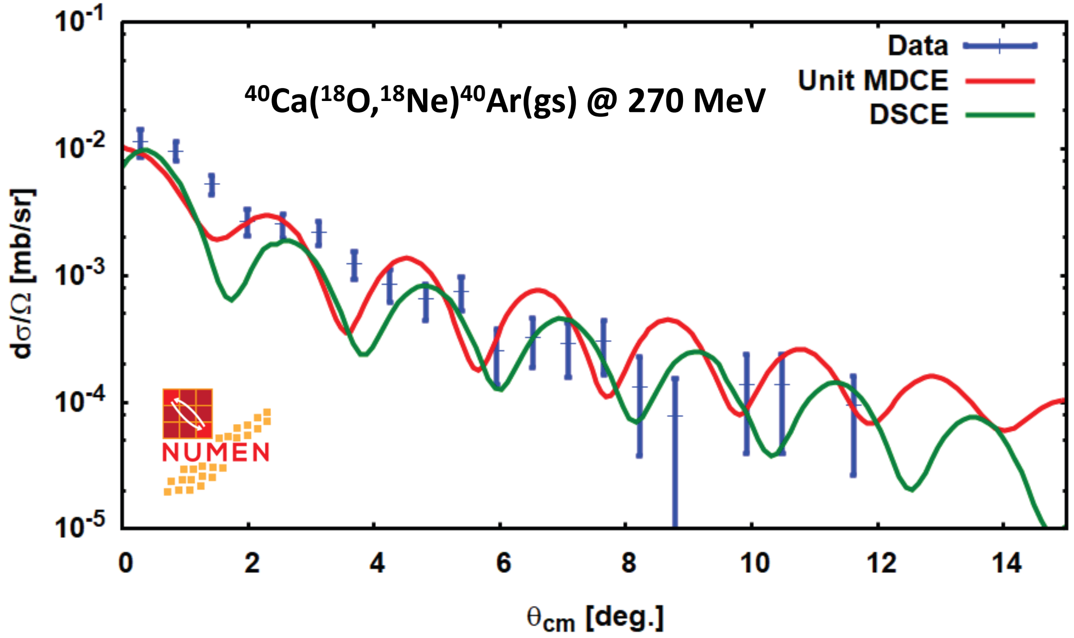
The MDCE mechanisms for the $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ reaction

NUMEN

... more

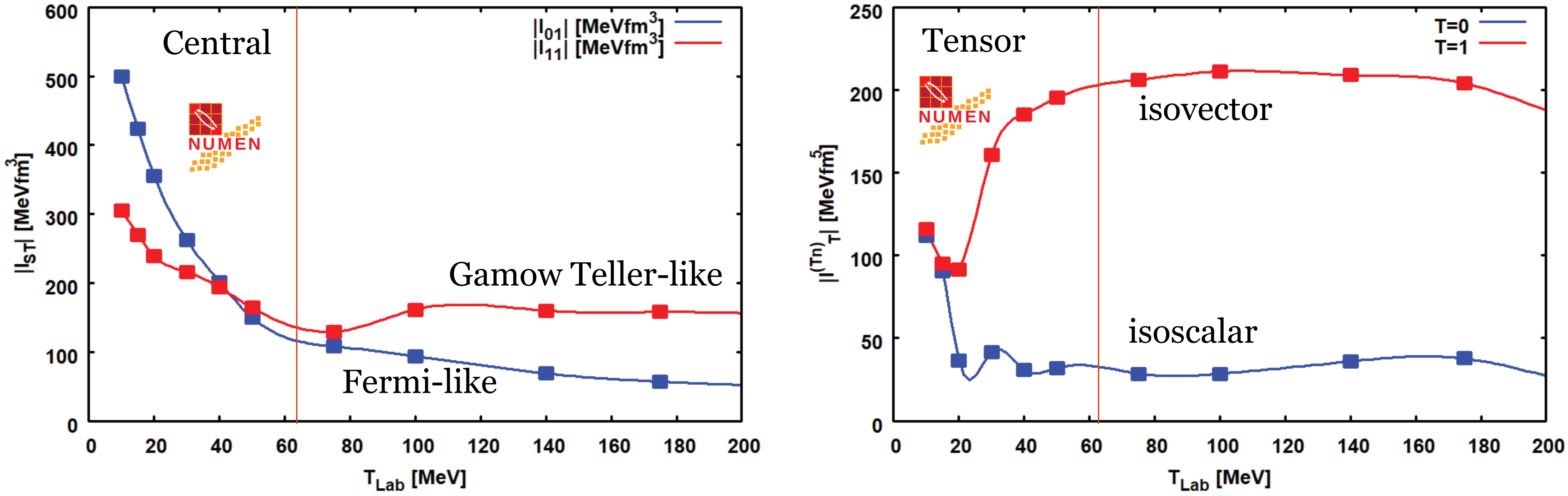
- ✓ ISI and FSI ion-ion interaction from double folding (available new elastic and inelastic data)
- ✓ QRPA transition densities for microscopic form factors up to $J^{\pi} = 5^{\pm}$
- ✓ One-step DWBA for the MSCE amplitudes

- ✓ 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 $L = S = 0$



- *H. Lenske et al. Prog. Part. and Nucl. Physics 109 (2019) 103716*
- *F. Cappuzzello et al. Prog. Part. and Nucl. Phys., in preparation*

... and more



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

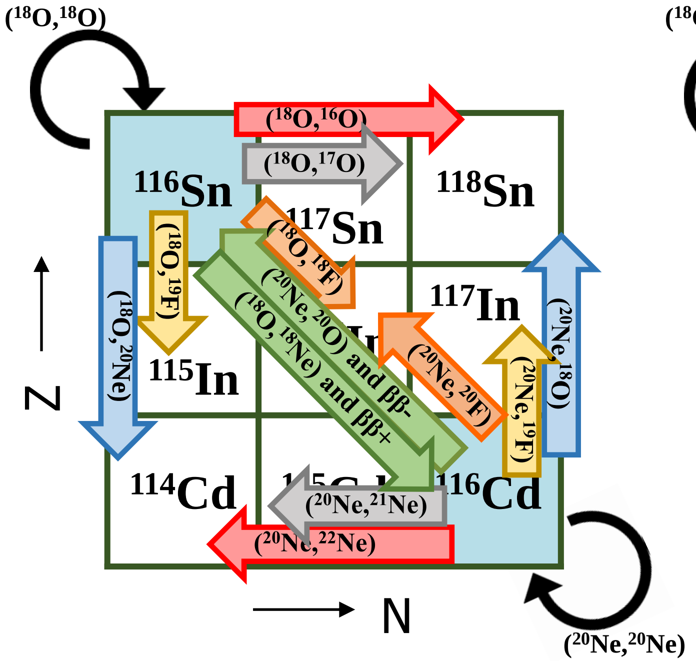
At the energy spanned by NUMEN the NN-T matrix changes significantly, making it easier to disentangle the individual components from experiments at different incident energy

- *F. Cappuzzello et al. Prog. Part. and Nucl. Phys., in preparation*

Systems of interest for $0\nu\beta\beta$ already explored

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

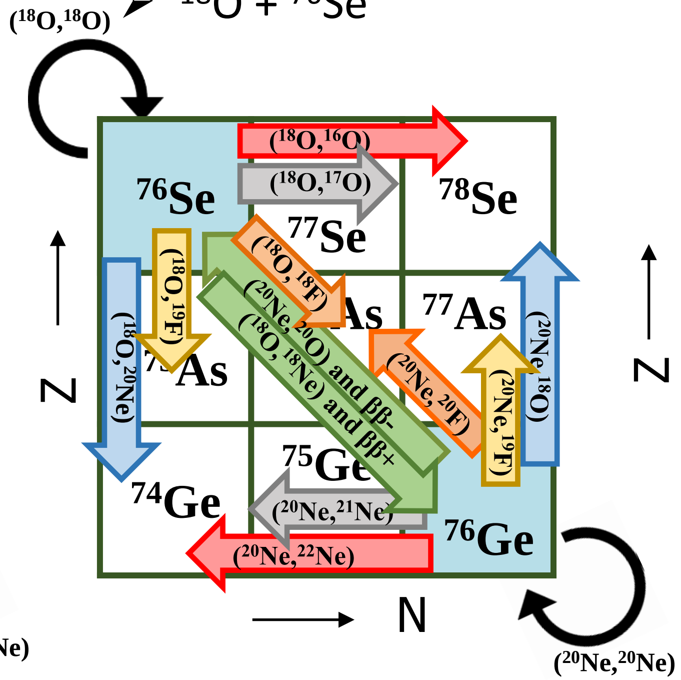
@ 15 AMeV
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



- ✓ D. Carbone et al., PRC 102 (2020) 044606
- ✓ S. Calabrese et al., NIM A 980 (2020) 164500
- ✓ S. Burrello et al. PRC 105, 024616 (2022)
- ✓ D.Carbone et al., Universe 7 (2021) 58
- ✓ J.L.Ferreira, et al. PRC 105, 014630 (2022)

^{76}Ge – ^{76}Se case

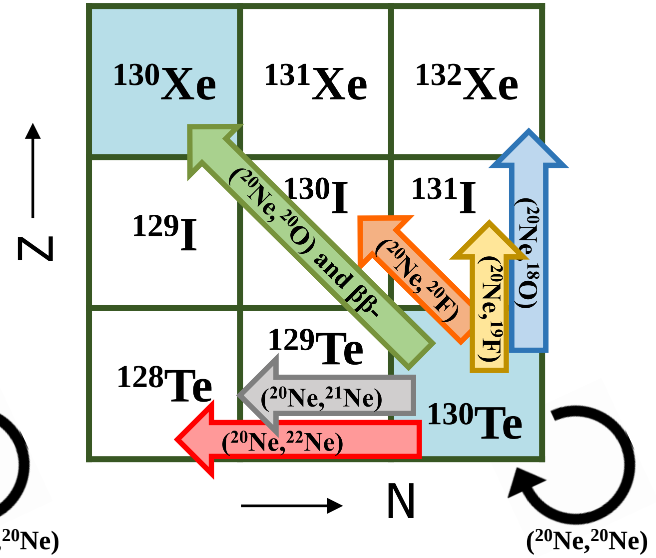
@ 15 AMeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



- ✓ A.Spatafora et al., PRC 100 (2019) 034620
- ✓ I. Ciraldo et al., PRC (2022) accepted

^{130}Te – ^{130}Xe case

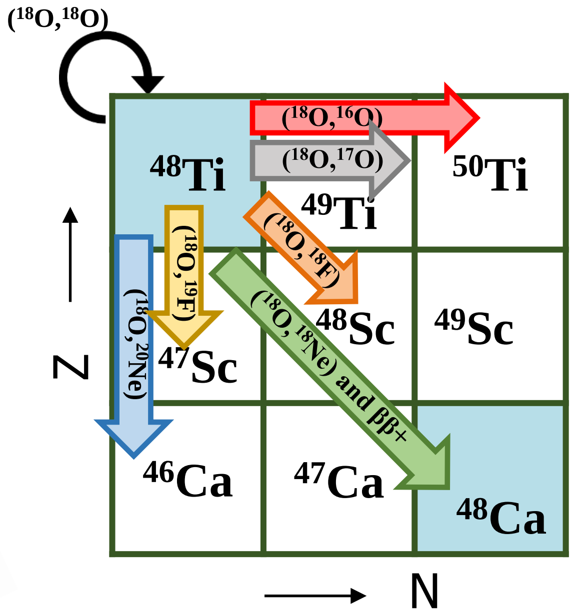
@ 15 AMeV
- ^{20}Ne + ^{130}Te



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

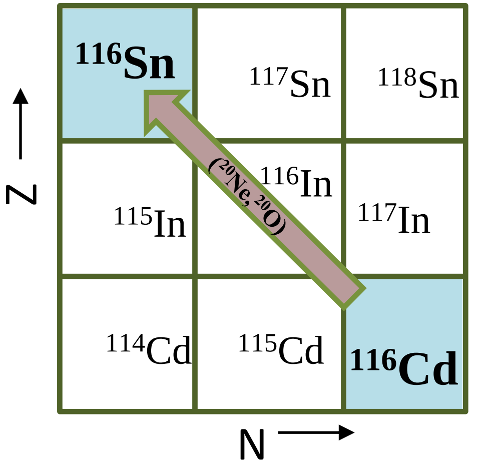
^{48}Ti – ^{48}Ca case

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

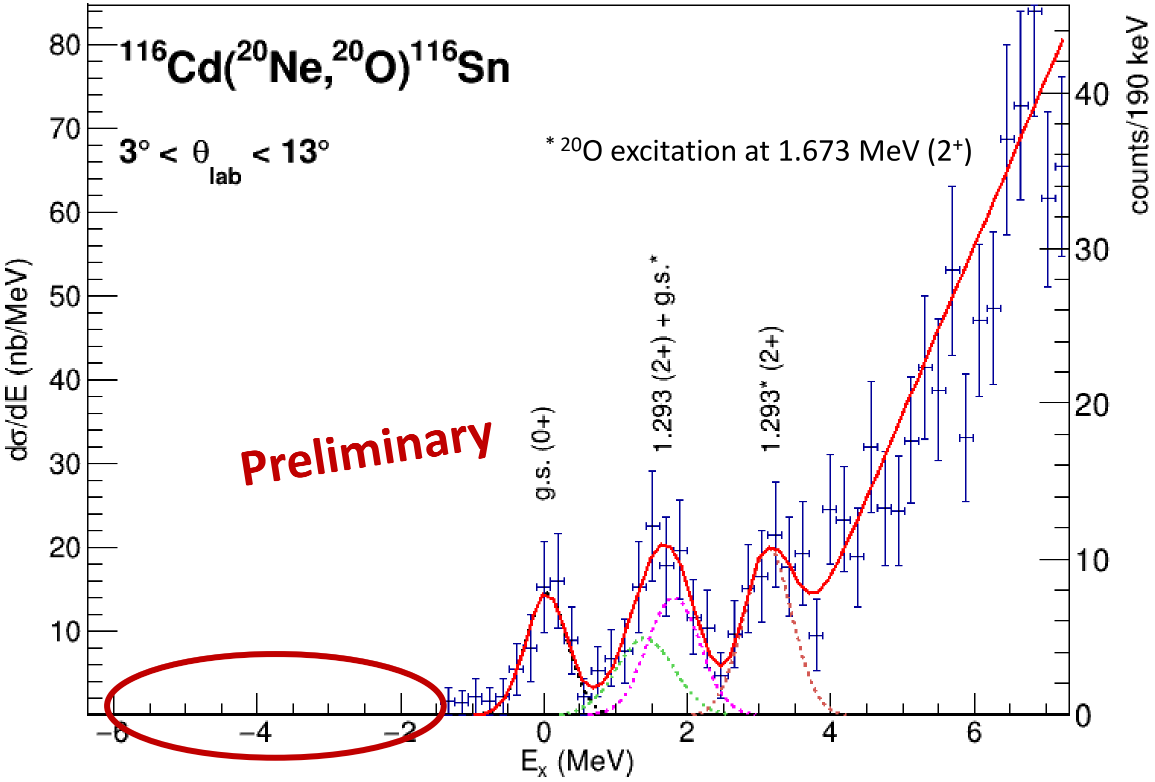


- ✓ O. Sgouros et al., PRC 104 (2021) 034617

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



- g.s. → g.s. transition isolated
- Absolute cross section measured



Energy Resolution ~ 800 keV FWHM

No spurious counts at-7 < E_x < -2 MeV

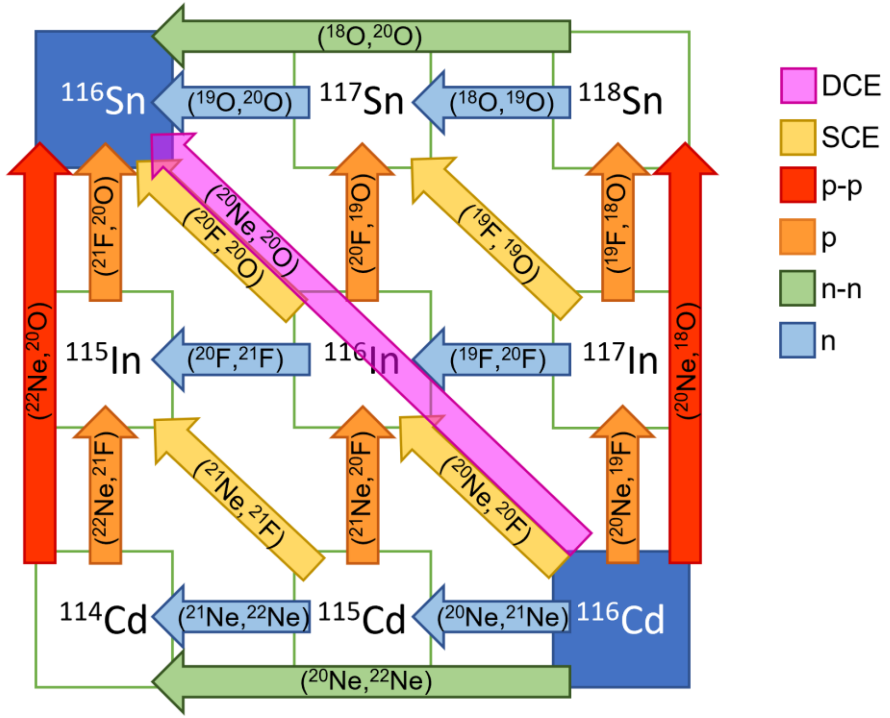
State (MeV)	Counts	Absolute cross section (nb)
g.s. (0^+)	31	**12 ± 2**
$^{116}Sn_{1.293}(2^+) + {}^{20}O_{gs}(0^+)$ $^{116}Sn_{gs}(0^+) + {}^{20}O_{1.673}(2^+)$	67	**24 ± 3**

Analysis of cross-section sensitivity
< 0.1 nb in the Region Of Interest

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

Multi-nucleon transfer routes

- DWBA and CRC calculations of all the multi-nucleon transfer routes competing with meson-exchange processes.
- Calculations compared with exp. data (first steps exp. available)
- Coherent (and constrained) approach



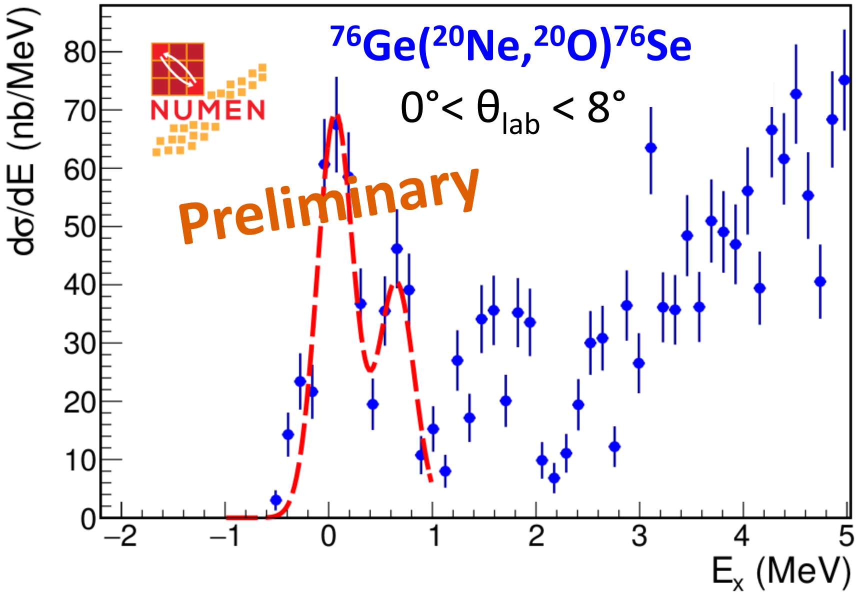
J.L.Ferreira, et al. PRC ***105****, 014630 (2022)*

(exp. cross section DCE **12 ± 2 nb**)

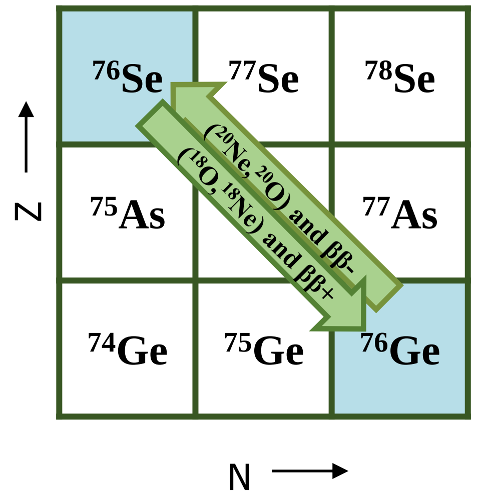
Mechanism	$^{20}\mathrm{O}_{g.s.}(0^+) + ^{116}\mathrm{Sn}_{g.s.}(0^+)$
$2p-2n$	$1,28 \times 10^{-4}$
$2n-2p$	$3,13 \times 10^{-4}$
$p-p-n-n$	$6,63 \times 10^{-5}$
$n-n-p-p$	$1,00 \times 10^{-5}$
$p-p-2n$	$4,15 \times 10^{-5}$
$n-n-2p$	$1,72 \times 10^{-6}$
$2p-n-n$	$9,26 \times 10^{-5}$
$2n-p-p$	$2,66 \times 10^{-4}$
$p-n-p-n$	$1,38 \times 10^{-7}$
$p-n-n-p$	$1,15 \times 10^{-6}$
$n-p-n-p$	$2,53 \times 10^{-7}$
$n-p-p-n$	$1,69 \times 10^{-7}$
$p-2n-p$	$2,51 \times 10^{-7}$
$n-2p-n$	$5,71 \times 10^{-6}$
Incoh. Sum	$9,60 \times 10^{-4}$

Negligible contribution of multi-nucleon transfer on the DCE process

A check for the time invariance

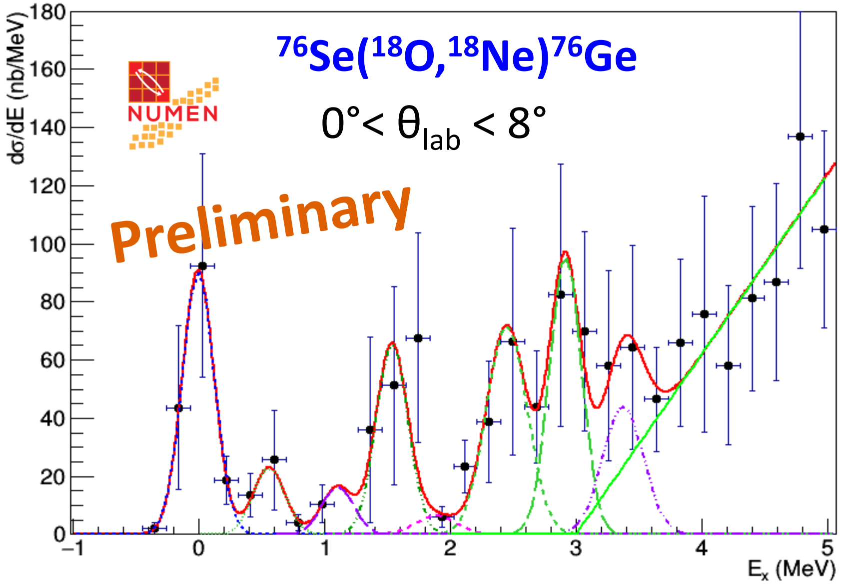


$\sigma_{g.s.\to g.s.}$ = 30 ± 4 nb



- Same cross sections for different directions
- Similar distortion factors

→ Same NME for the target transition (encouraging test of time invariance!)



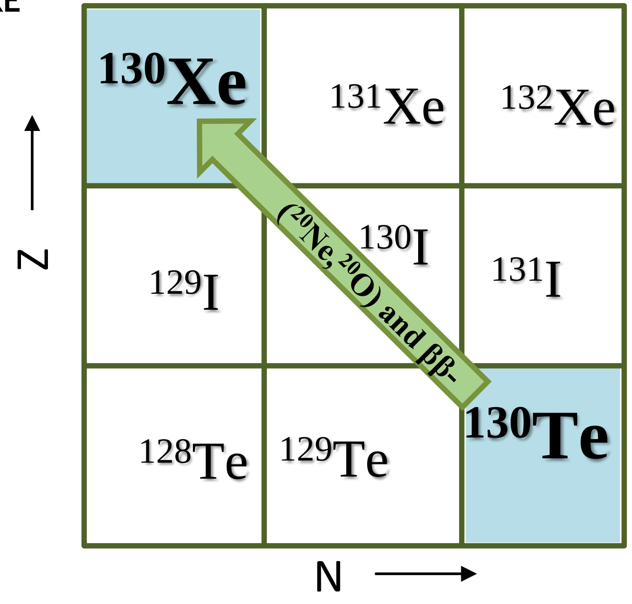
$\sigma_{g.s.\to g.s.}$ = 29 ± 6 nb

Warning:

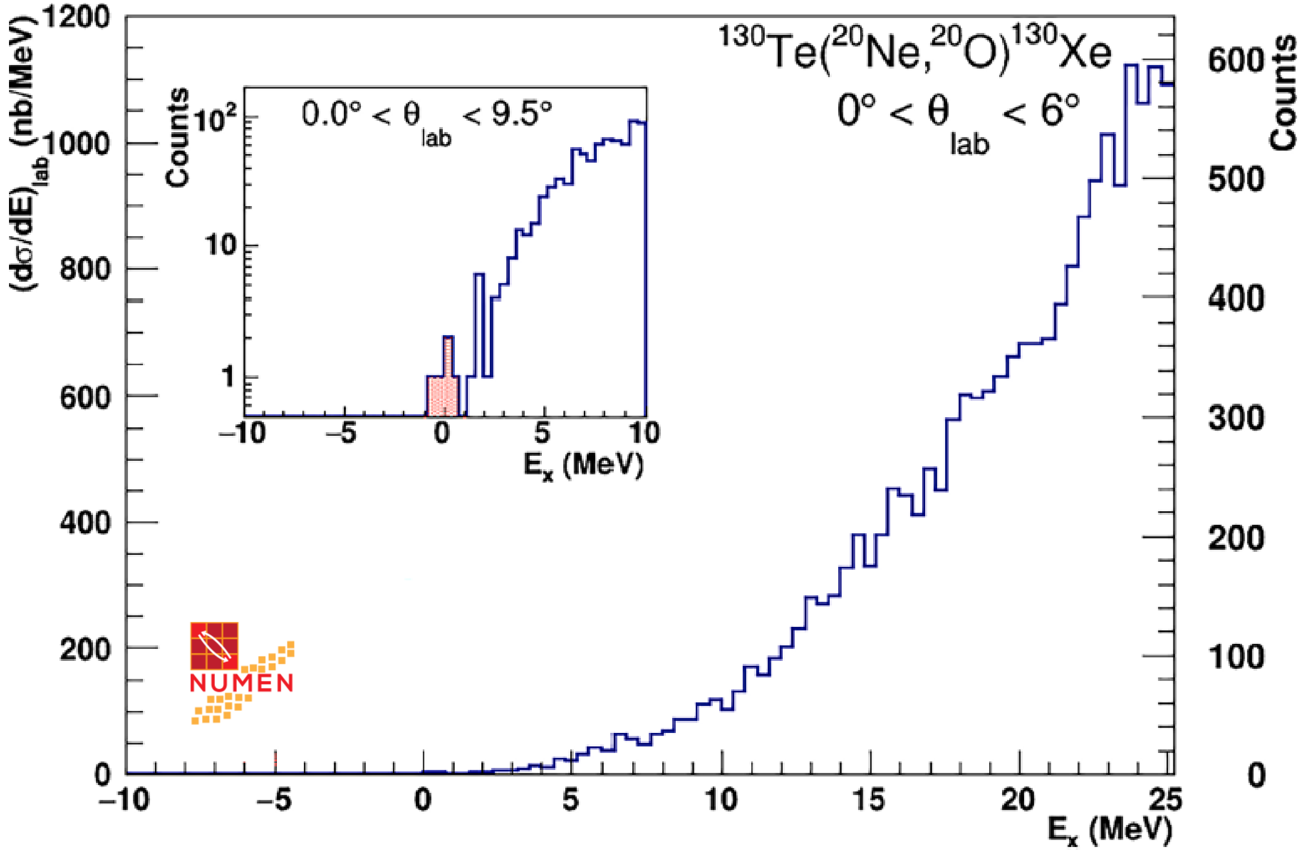
- Only one case
- Reaction calculations in progress

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

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



- g.s. → g.s. transition maybe isolated
- Absolute cross section measured



Resolution ~ 500 keV FWHM

No spurious counts at -10 < E_x < -2 MeV

Analysis of cross-section sensitivity
< 0.1 nb in the Region Of Interest

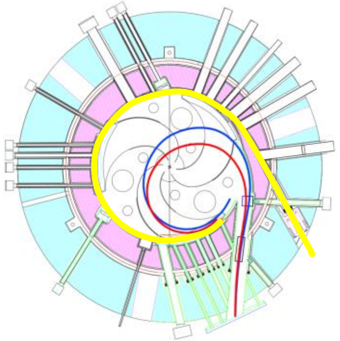
State (MeV)	Counts	Absolute coss section (nb)	Coss section 95% limit (nb)
g.s. (0$^+$) + 2$^+$ (536 keV)	5	13	[3--18]

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

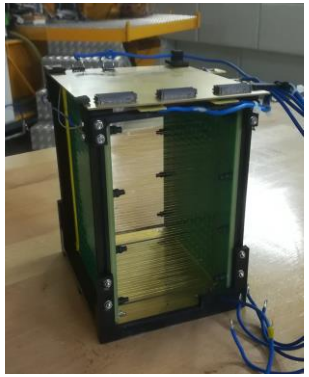
The goal:
systematic study of all the hot-cases

The way:
high current beams and advanced spectrometry

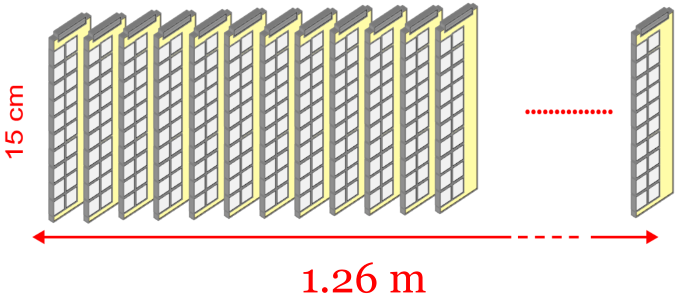
Scientific motivation for the **upgrade of the LNS superconducting cyclotron** and related infrastructures to deliver high intense beams (10kW)



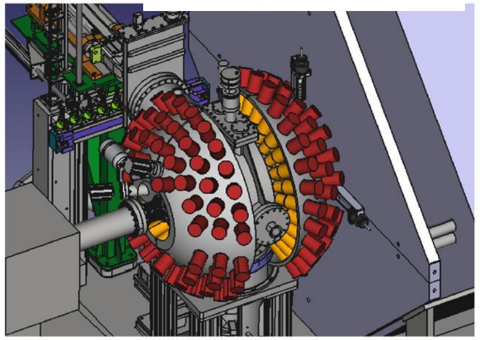
Superconducting cyclotron
Extraction by stripping (5-10 kW)



New tracker for the FPD
(THGEM technology)



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



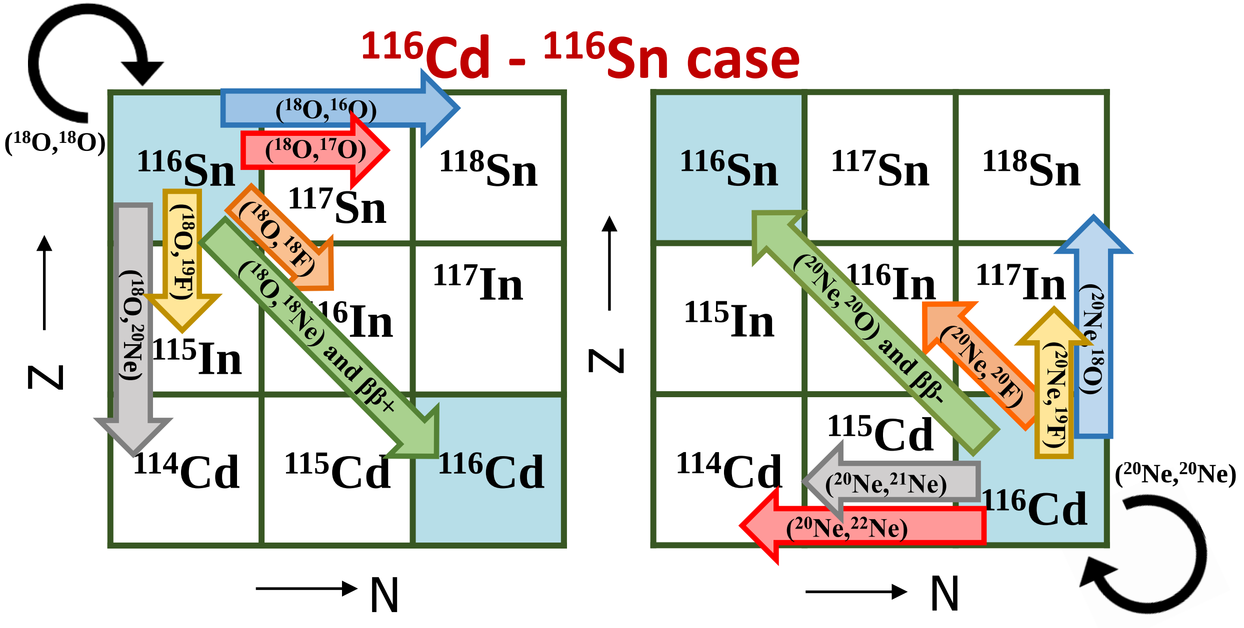
New gamma-ray calorimeter
(LaBr3 scintillators)

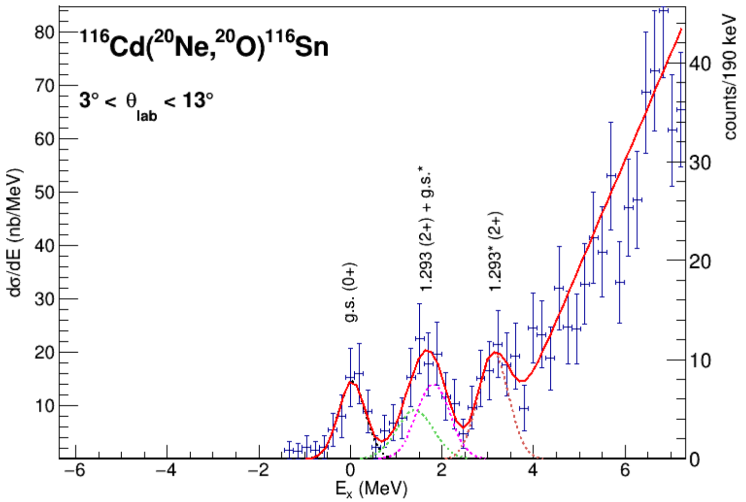
NUMEN TDR
F. Cappuzzello, C. Agodi et al., Intern. Journ. of Mod. Phys. A 36, 30 (2021) 2130018

The NUMEN timeline

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

- Second order isospin **processes such as HI-DCE, πDCE and DIAS $\gamma\gamma$-decay** provide key information **bridging the gap between nuclear and neutrino physics**
- **HI-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 our opinion, **should be generalized** to many other aspect of nuclear research





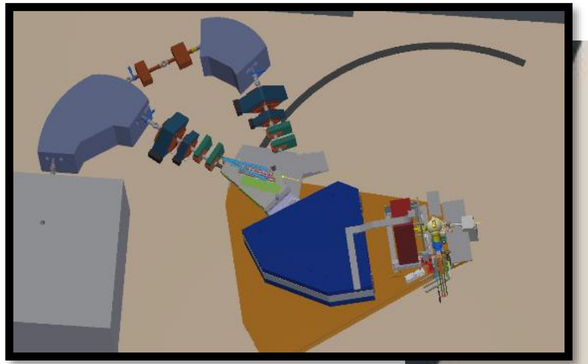
Thank you

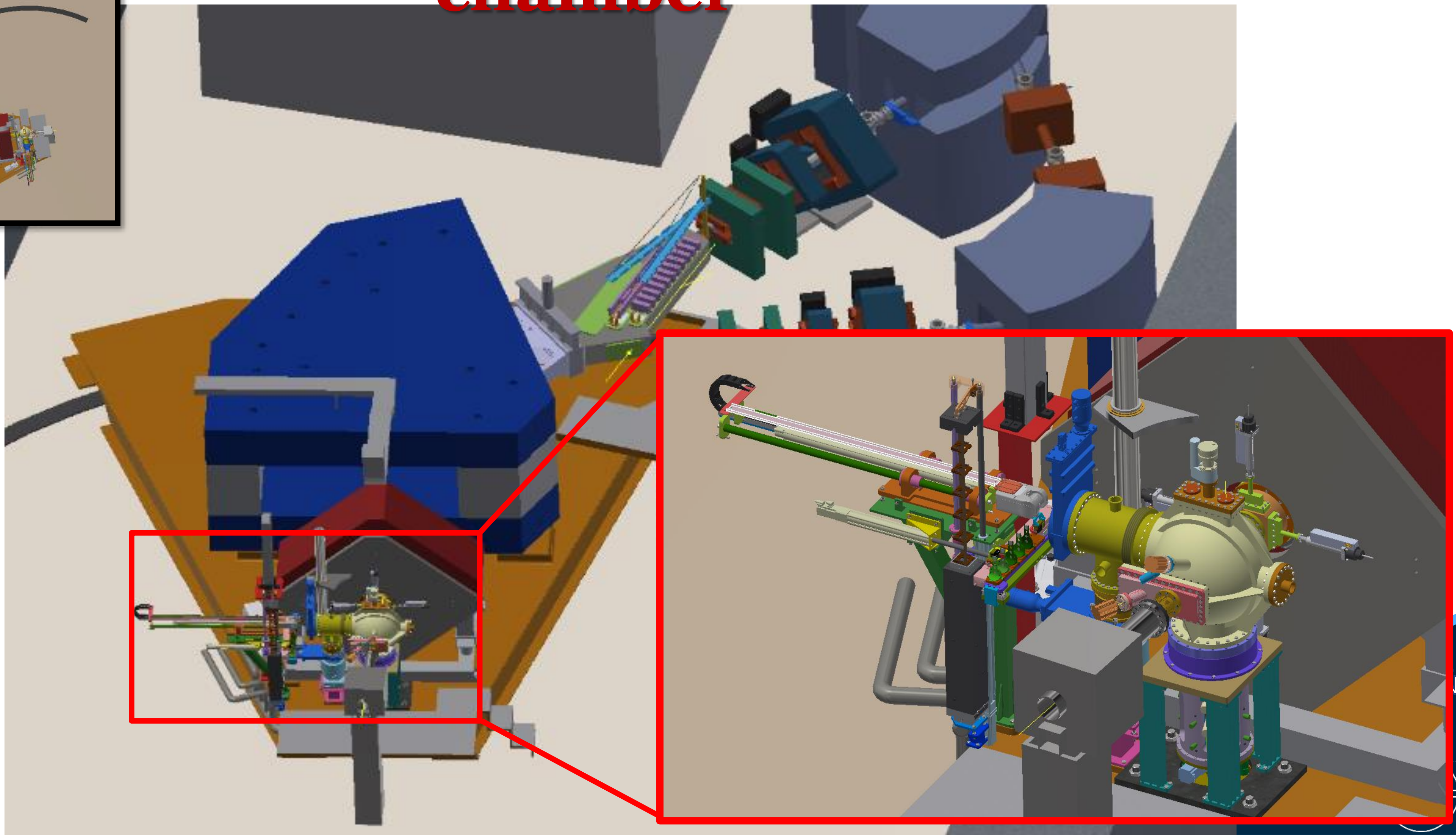
Highlights - Selective study of nuclear structure response with high intensity beams and advanced spectrometry

- **a0:** Study of $\beta\beta^{++}$ and $\beta\beta^{--}$ DCE differential cross sections on selected systems, e.g. $^{76}Ge \Longleftrightarrow {}^{76}Se$ and $^{116}Cd \Longleftrightarrow {}^{116}Sn$. Experiments performed at high beam intensity and incident energy of 15 AMeV. Use of the multi-channel approach from the access to elastic and inelastic scattering, 1p-, 2p-, 1n-, 2n-transfer and SCE
- **a1:** Study of the energy dependence of (^{20}Ne,^{20}O) and (^{18}O,^{18}Ne) DCE cross sections. Experiments performed at high beam intensity and different incident energies on selected systems, e.g. $^{76}Ge \Longleftrightarrow {}^{76}Se$ and $^{116}Cd \Longleftrightarrow {}^{116}Sn$
- **b0:** Study of the ^{100}Mo response to (^{20}Ne,^{20}O) DCE for the first time
- **c0:** Test study of DIAS $\gamma\gamma$-decay for selected cases of interest for $0\nu\beta\beta$

Phase a: research activties/experiments almost ready to be performed
Phase b: other research still requiring some test and feasibility study
Phase c: research activities requiring R&D and/or development of devoted apparata/facilities of on-construction infrastructures

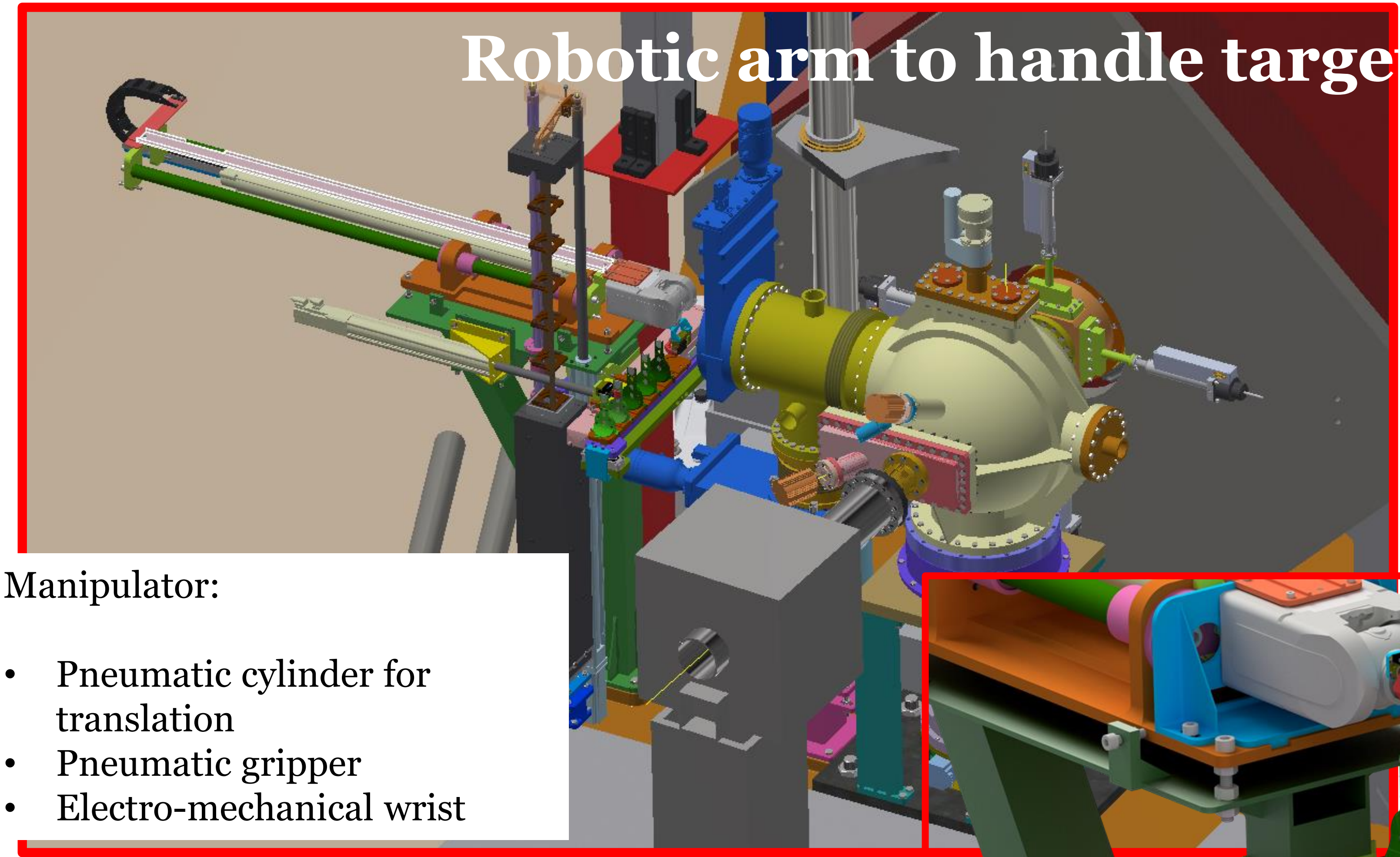
Upgrade of the LNS facilities: the scattering chamber





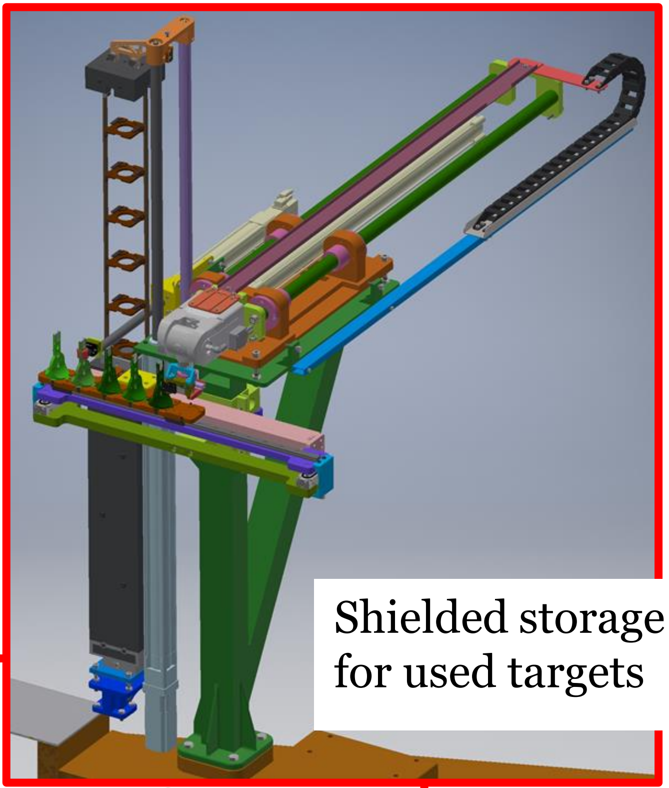
Upgrade of the LNS facilities: the scattering chamber

Robotic arm to handle targets

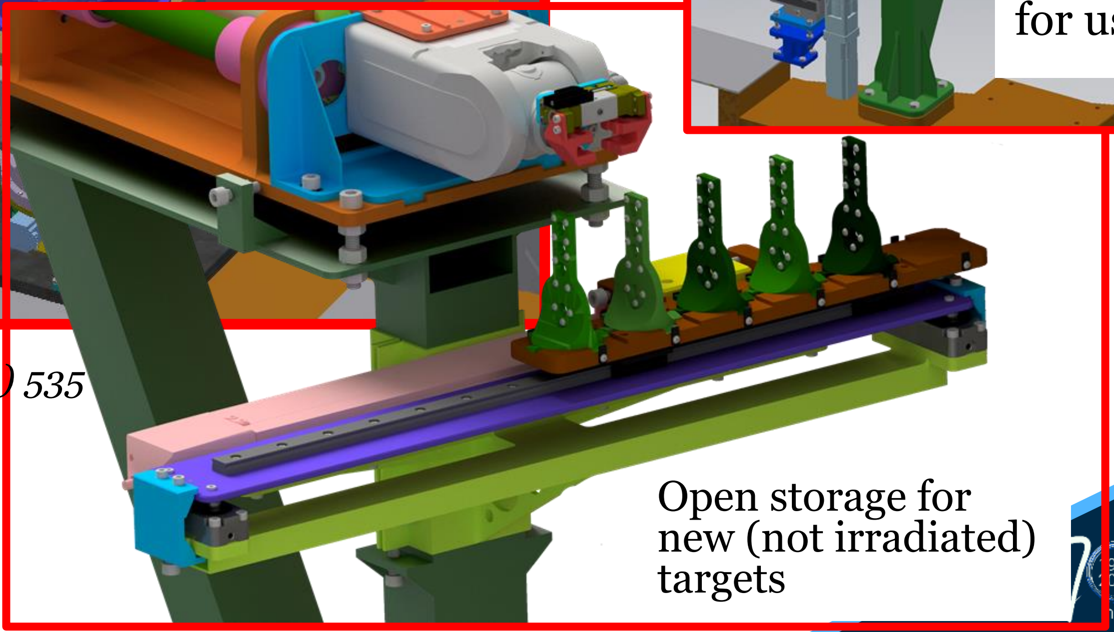


Manipulator:

- Pneumatic cylinder for translation
- Pneumatic gripper
- Electro-mechanical wrist



Shielded storage for used targets



Open storage for new (not irradiated) targets

D. Sartirana et al., Mechanisms and Machine Science 84 (2020) 535

Automatic system to handle the targets and manage the target replacement avoiding human presence in the experimental hall

An innovative approach to high-intensity beams: evaporation on HOPG

- Substrate made of Highly Oriented Pyrolytic Graphite(HOPG) featuring high thermal conductivity (1930 $Wm^{-1}K^{-1}$)
- Target encased in a Cu holder, mounted on top of a cryocooler and kept at 40 K
- Numerical codes for equilibrium temperature
- Tests with heavy-ion beams (radiation damage)
- Non-trivial evaporation technology to guarantee uniformity

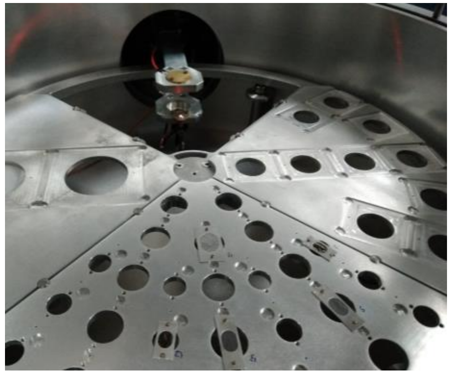
Target holder assembly

Iazzi et al., WIT Trans. on Eng. Sciences 116 (2017) 61

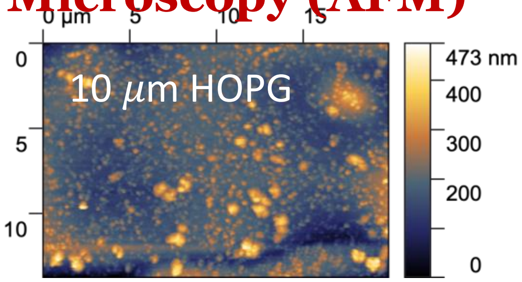
Advantages:

- Thin targets (resolution issues)
- Small emcumbrance (γ detectors around target)
- Small quantities and reduced waste of isotopically enriched material

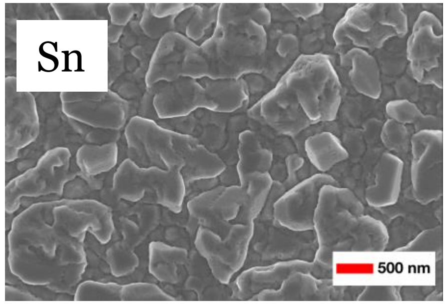
Alpha Particle Transmission



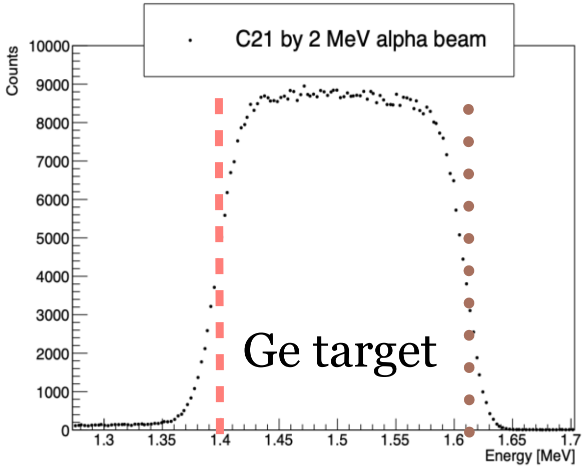
Atomic Force Microscopy (AFM)



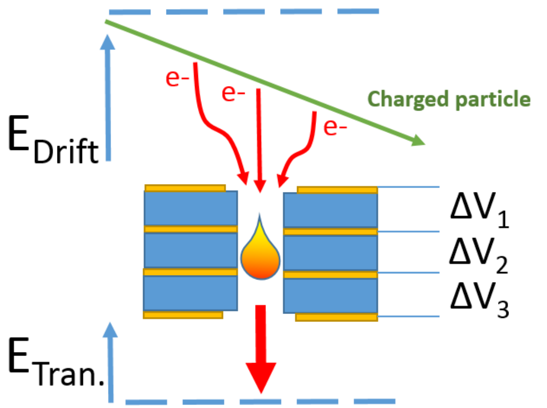
FESEM



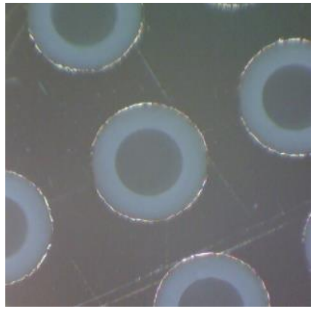
RBS



The new tracker

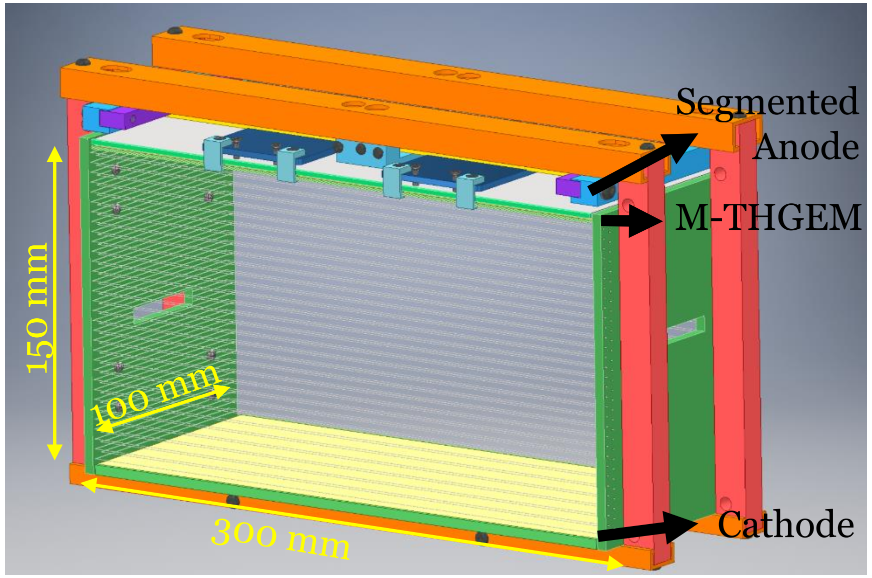


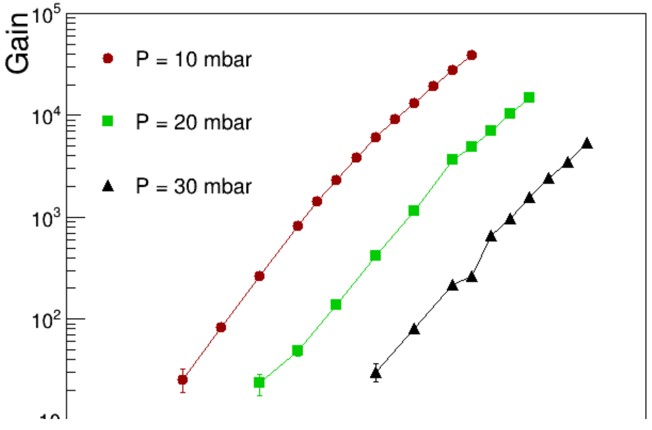
3-layer THGEM



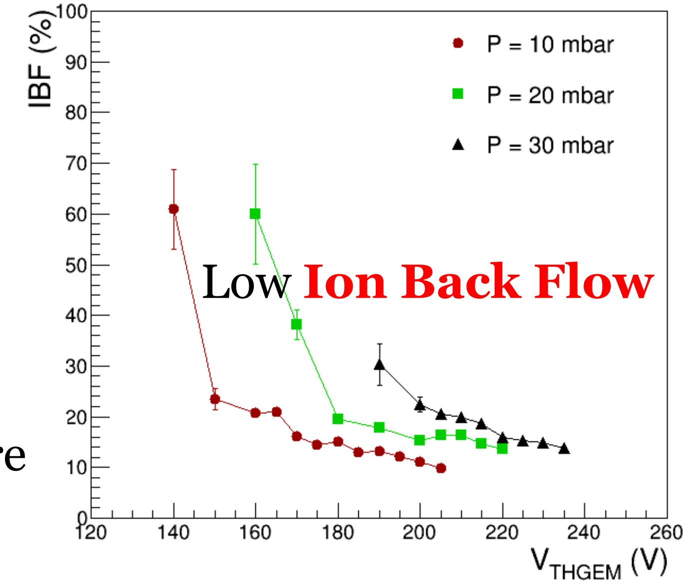
Rate
from few kHz to MHz
preserving low-pressure operation

Multiple Thick Gas Electron Multiplier (M-THGEM)





High gain at low voltage and pressure



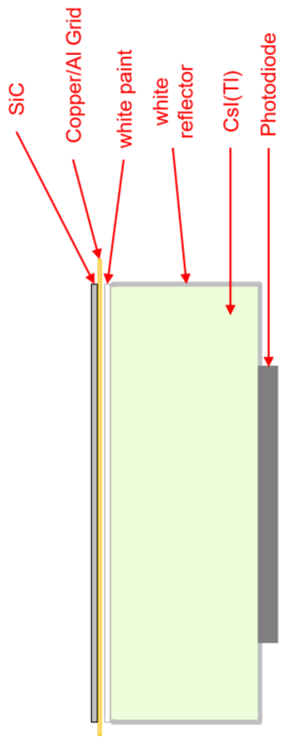
Low **Ion Back Flow**

The new FPD PID wall

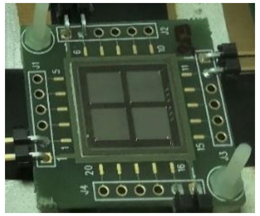
- PID capabilities for heavy ions
- Working in gas environment
- Large area
- High energy resolution (2%)
- Timing resolution (few ns)

Radiation hardness

➢ SiC-CsI telescopes

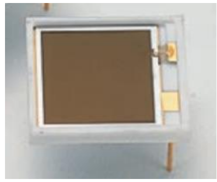


SiC
Thickness 100 μm
Area 1.54 x 1.54 cm²
Bias -600/-1000 V

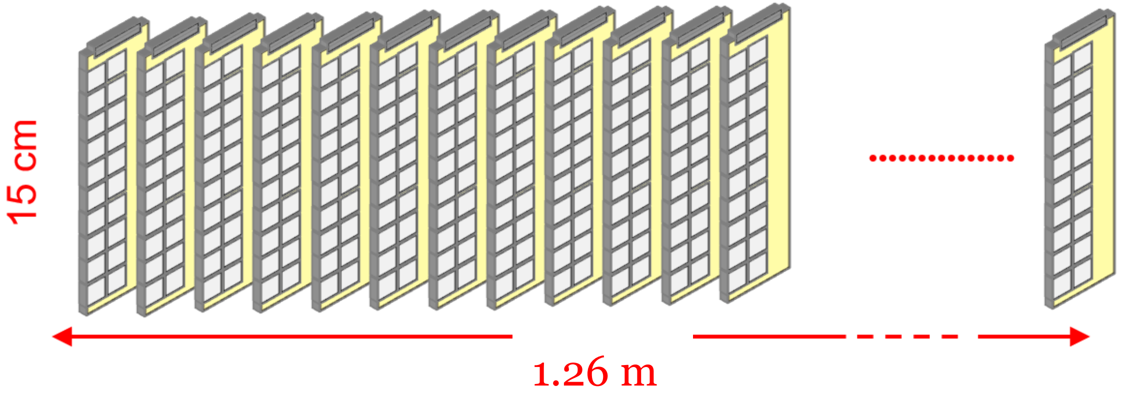


CsI (Tl)
Thickness 5 mm
Area 1.5 x 1.5 cm²

Hamamatsu Photodiode S3590
Area ~ 1 x 1 cm²
Bias -70 V



Total 720 telescopes



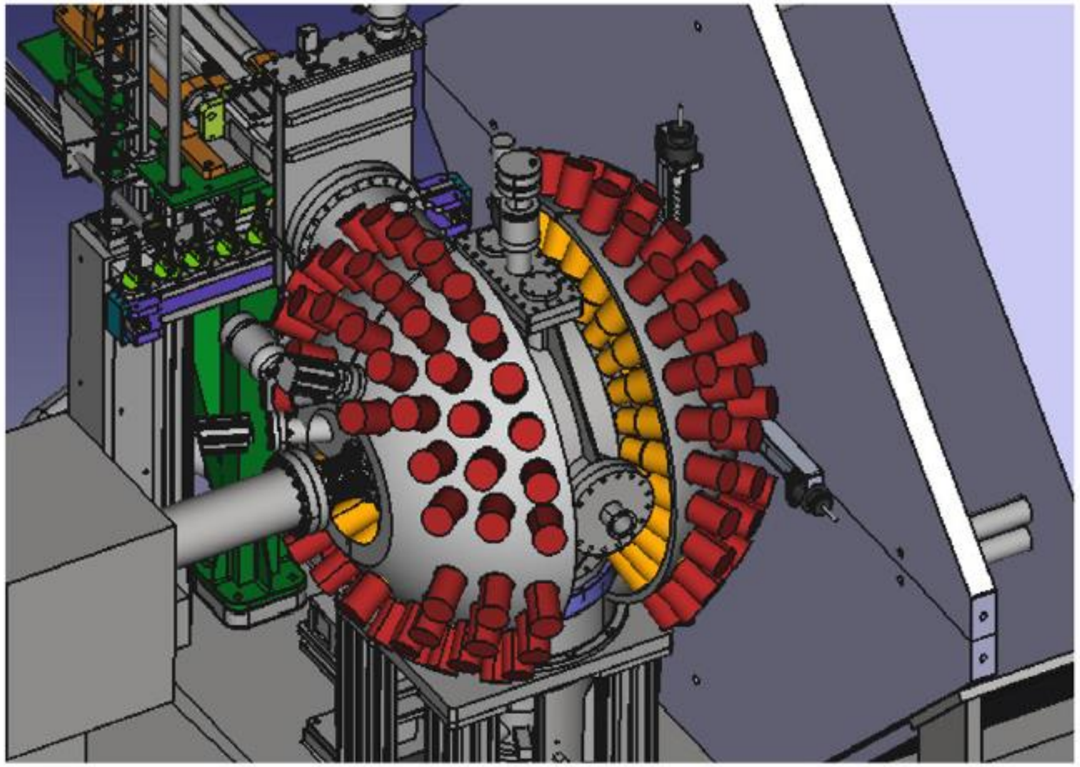
Typical MAGNEX energy resolution for a NUMEN experiment ~500 keV (FWHM) at 15 MeV/u $\rightarrow$ enough for many systems.
For deformed nuclei and for all experiments at high beam energies energy resolution $\rightarrow$ array of γ-detectors

Requirements

- High photo-peak detection efficiency
- Gamma and neutron radiation tolerance
- High timing resolution (separate events from subsequent beam bunches)

Array of ~100 $LaBr_3$(Ce) scintillator crystals coupled to **PM tubes** disposed in rings covering a total solid angle of 20% of the unit sphere

38 mm diameter, 50mm length, 245 mm distance from the target



J.R.B. Oliveira et al., Eur. Phys. J. A (2020) 56:153
F. Cappuzzello et al., Front. Astr. Space Sc. 8 (2021) 668587

The present Focal Plane Detector (FPD)

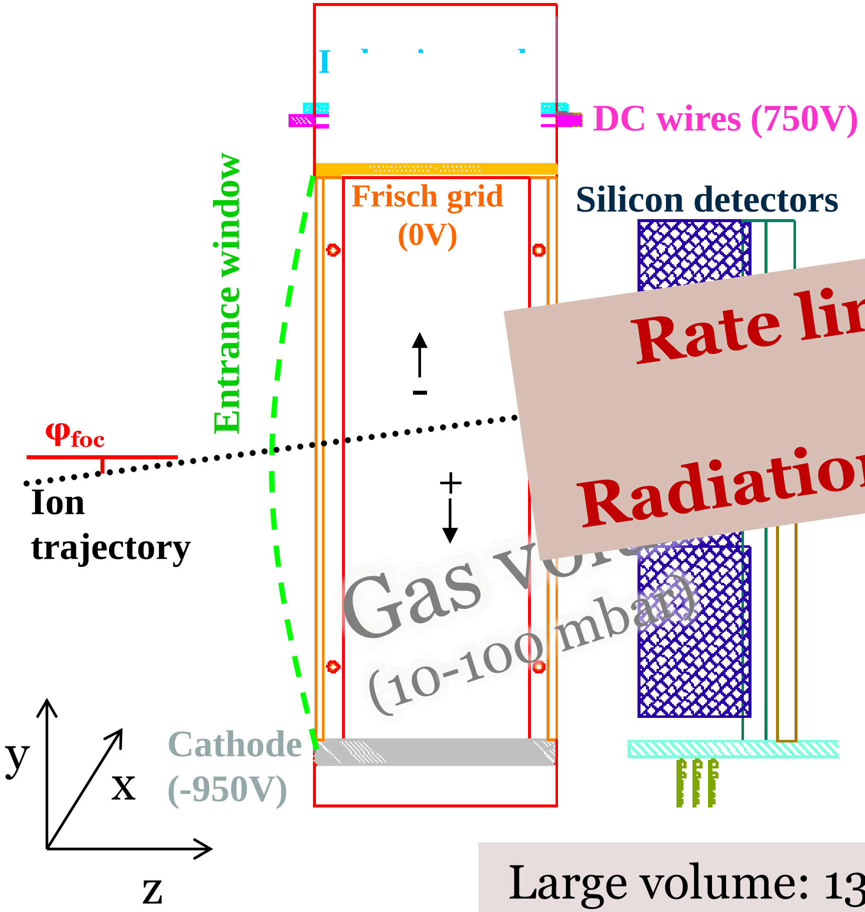
Two tasks to accomplish:

1) High resolution measurement at the focal plane of the phase space parameters (X_{foc}, Y_{foc}, θ_{foc}, φ_{foc})
2) Identification of the reaction ejectiles (Z, A) - crucial aspect for heavy ions

Hybrid detector:
Low pressure Gas section
proportional wires and drift chambers
\+
Stopping wall of **silicon detectors**

M. Cavallaro et al. EPJ A 48: 59 (2012)

D. Torresi et al. NIM A 989 (2021) 164918



Rate limit (few kHz)
and
Radiation hardness limit

Large volume: 1360mm X 200mm X 96mm