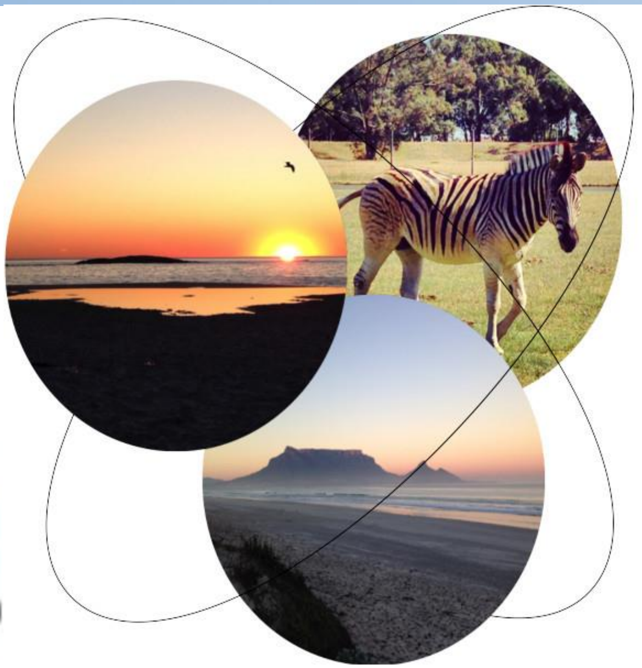
Conference on Neutrino and Nuclear Physics 2020

(CNNP2020)
Cape Town (South Africa)
24-28 February 2020



Recent results on nuclear reactions of interest for $0\nu\beta\beta$ at INFN-LNS within the NUMEN project

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Outline

- The idea of NUMEN (**NU**clear **M**atrix **E**lements for **N**eutrinoless double beta decay)
- The experimental challenges of DCE reactions
- First results on systems of interest for $0\nu\beta\beta$
- The upgrade of INFN-LNS infrastructures

0νββ decay

Consequences of 0νββ observation

- Beyond standard model
- Neutrino is its own anti-particle
- Access to effective neutrino mass
- Violation of lepton number conservation
- CP violation in lepton sector
- A way to leptogenesis and GUT

Open problem in modern physics:

Neutrino absolute mass scale

Neutrino nature

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

0νββ decay **half-life**

Phase space factor

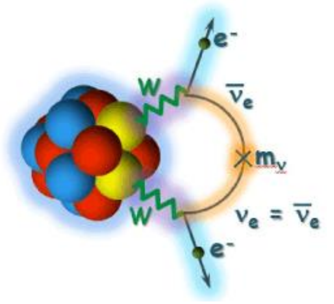
contains the average neutrino **mass**

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

Nuclear Matrix Element (NME)

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

Transition probability of a **nuclear** process



Nuclear physics plays a key role!

A new experimental tool

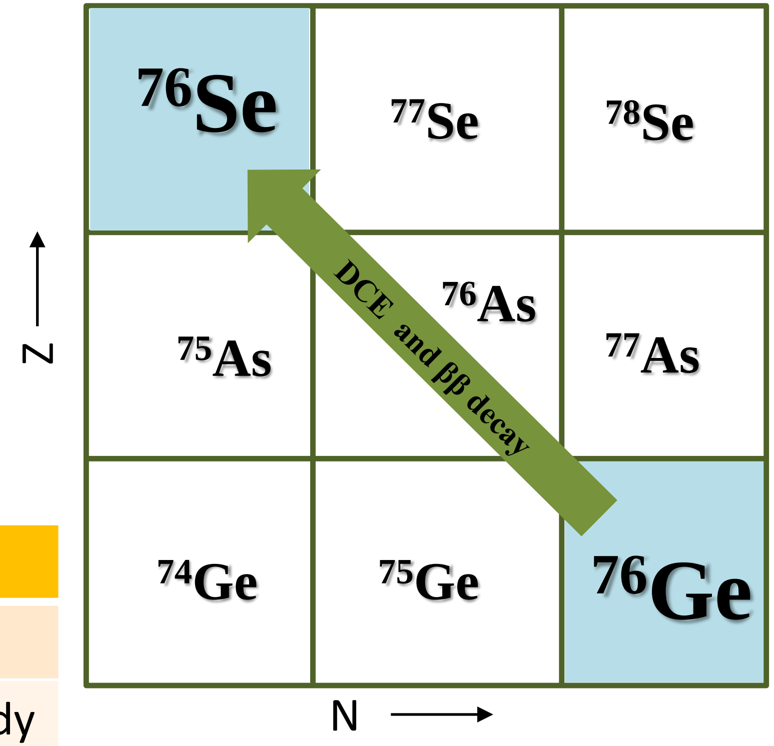
Nuclear reactions

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

NUMEN

European Commission

erc NURE



NUMEN phases			
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Feasibility study	Study of few cases + development of theory + R&D activity	Shutdown & Upgrade	Systematic study of all the targets
2013-2015	2015-2020	2020-2022	2022-…

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

The Goals of the Research Program

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

Mid term goals:

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

$0\nu\beta\beta$ vs DCE

Differences

- DCE mediated by **strong interaction**, $0\nu\beta\beta$ by **weak interaction**
- Decay vs reaction **dynamics**
- DCE includes **sequential** transfer **mechanism**
- **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:** 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**
- **Off-shell propagation** through virtual intermediate channels

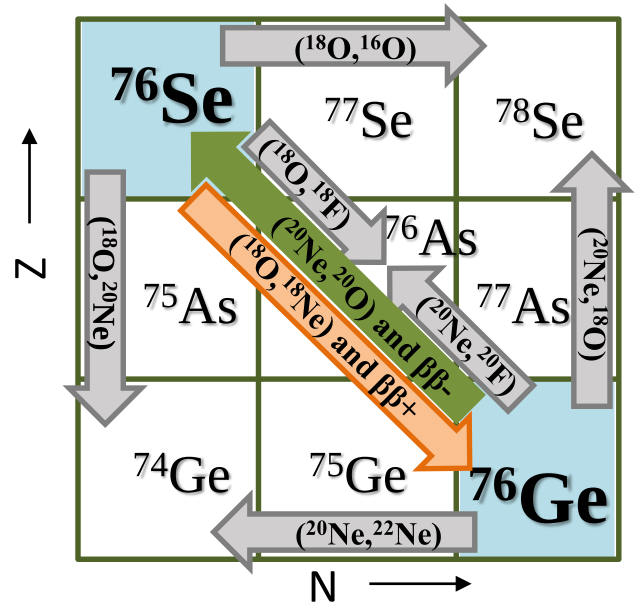
The experiments

- **Transitions of interest for 0νββ:**
  Limited number of targets in phase 2,
  systematic exploration of all the targets in phase 4

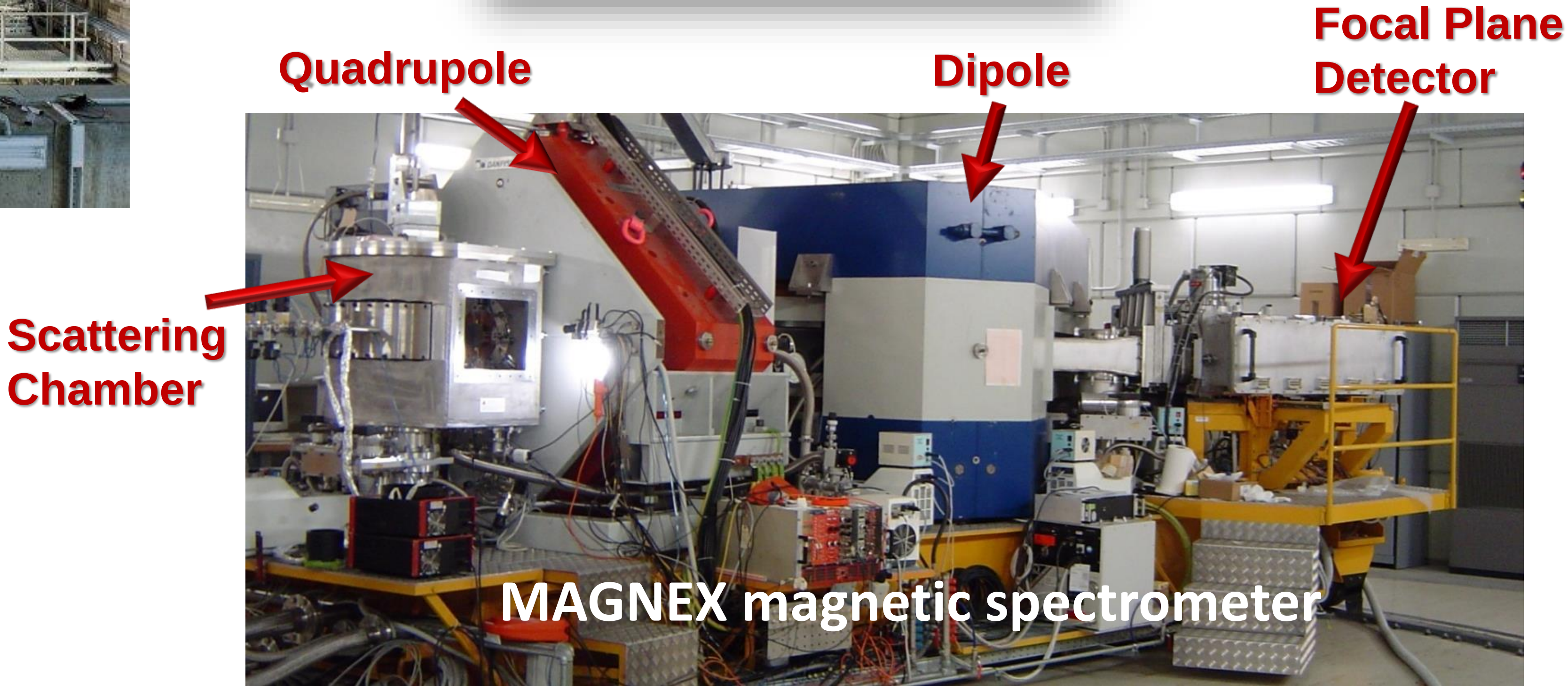
- **Two directions**:
  ββ$^-$ via (^{20}Ne,^{20}O) and ββ$^+$ via (^{18}O,^{18}Ne)

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

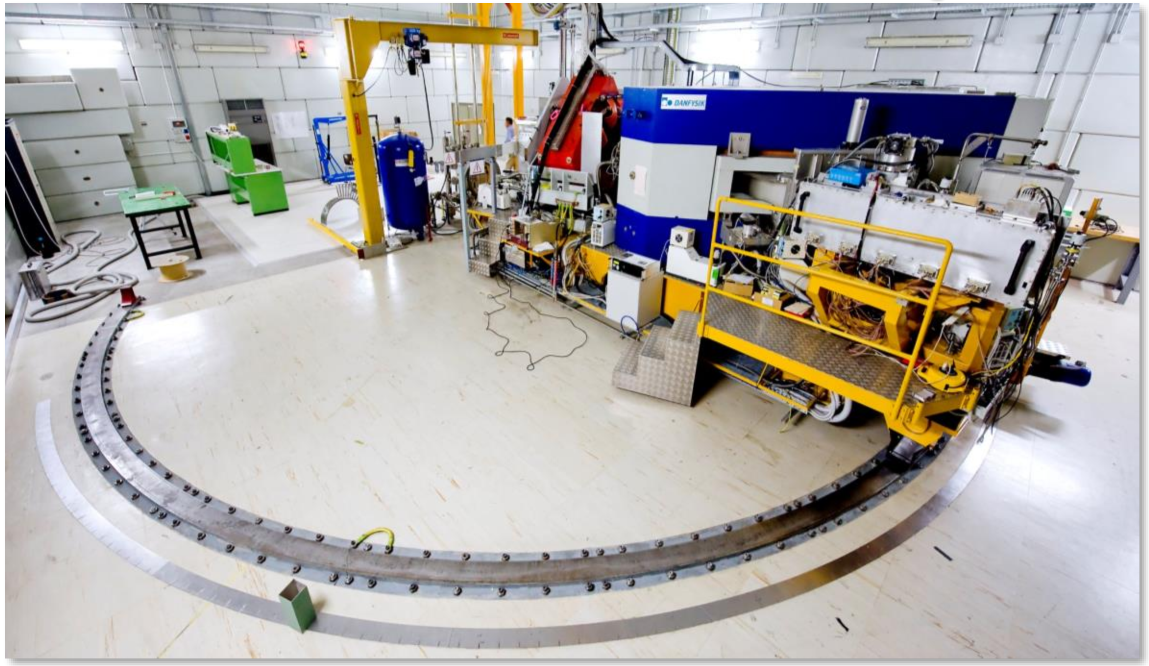
- **Two (or more) incident energies**
  to study the reaction mechanism



The experiments at INFN-LNS



The MAGNEX spectrometer



Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.3°$
Mass $\Delta m/m \sim 1/160$

- We have measured in a **wide mass range** (from protons to medium-mass nuclei)
- Measurement at **zero-degrees**

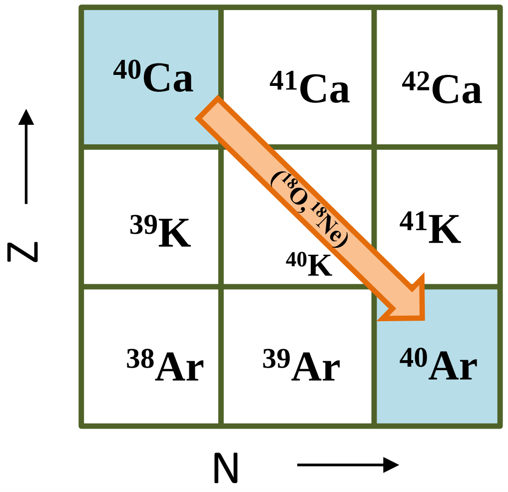
Optical characteristics	Measured values
Angular acceptance (Solid angle)	**50 msr**
Angular range	**–20° - +85°**
Momentum (energy) acceptance	**-14%, +10% (-28%,+20%)**
Momentum dispersion for k= - 0.104 (cm/%)	**3.68**
Maximum magnetic rigidity	**1.8 T m**

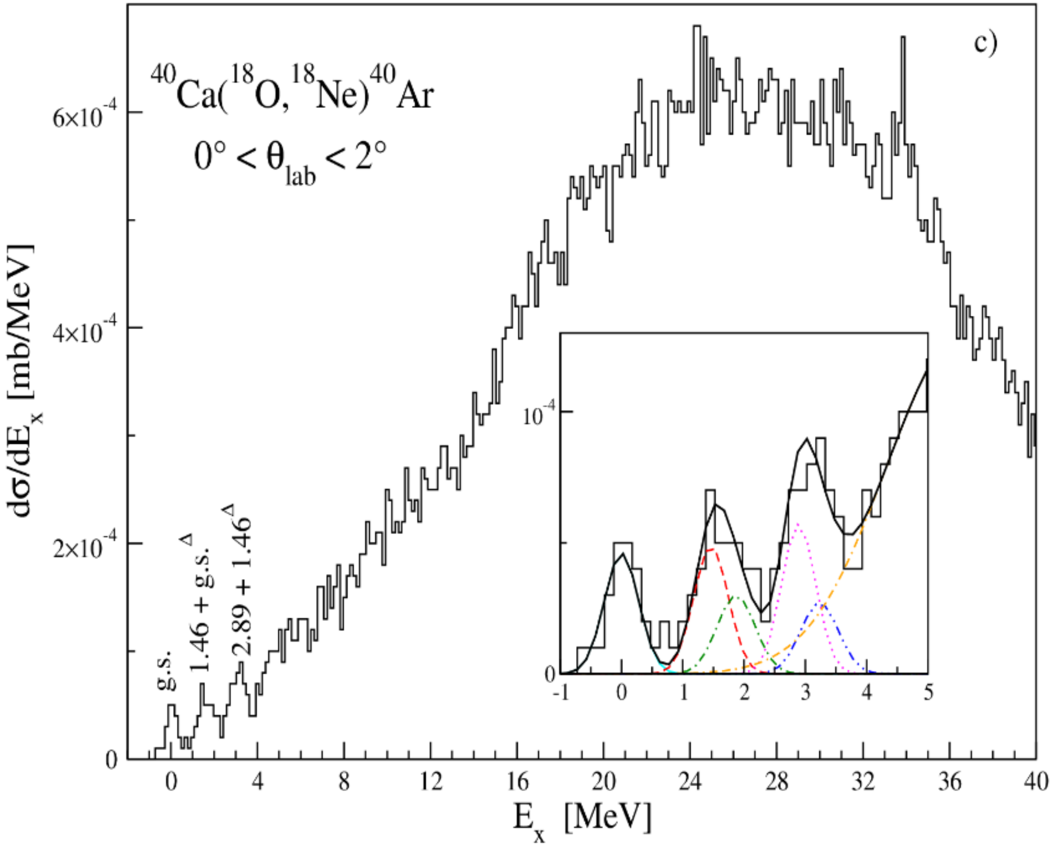
F. Cappuzzello et al., EPJ A (2016) 52:167
M. Cavallaro et al., NIM B 463 (2020) 334

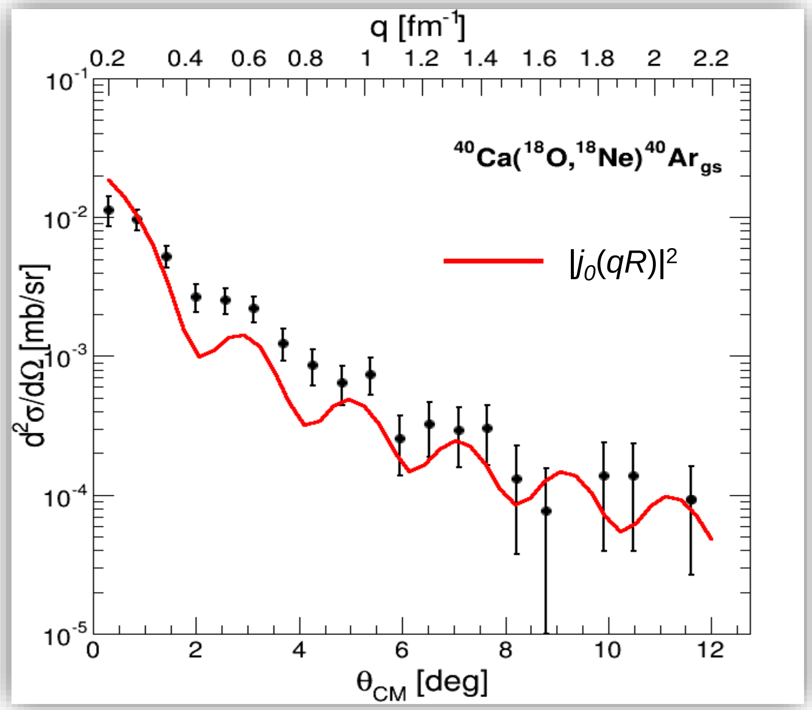
The pilot experiment

^{40}Ca (^{18}O, ^{18}Ne) ^{40}Ar + at 270 MeV

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







Experimental feasibility: zero-deg, resolution (500 keV), low cross-section (µb/sr)

Limitations of the past HI-DCE experiments are overcome!

DCE NME extracted for ^{40}Ca in *F. Cappuzzello et al. EPJ J A (2015) 51:145*

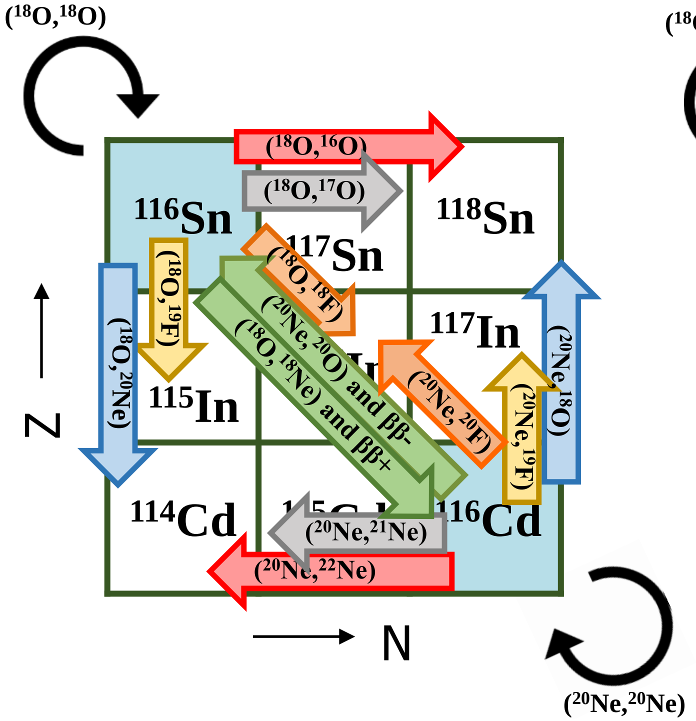
Further theoretical developement in *J. Bellone et al., submitted to PLB*

NUMEN runs – Phase 2

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

@ 15 AMeV

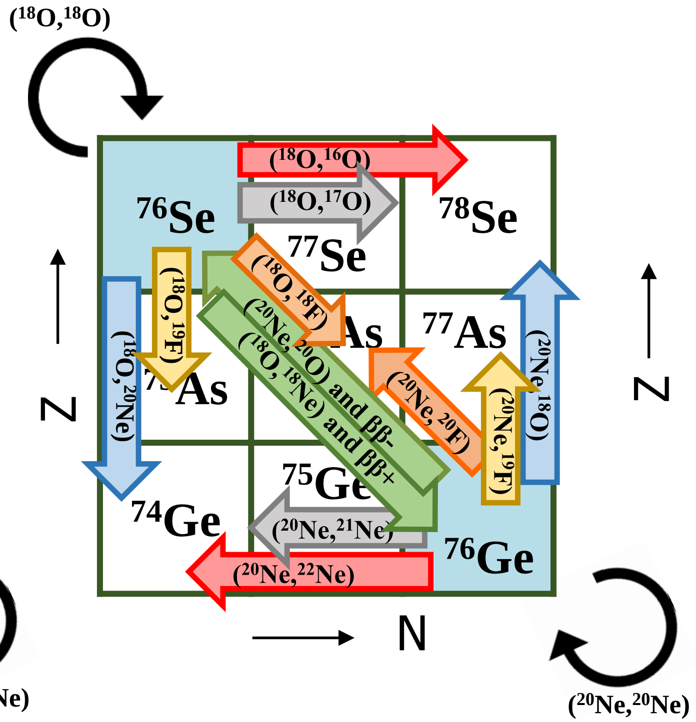
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



^{76}Ge – ^{76}Se case

@ 15 AMeV

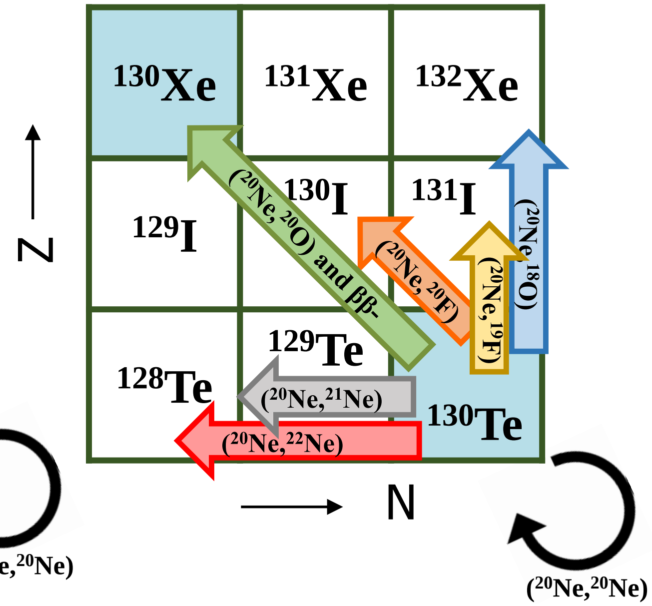
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



^{130}Te – ^{130}Xe case

@ 15 AMeV

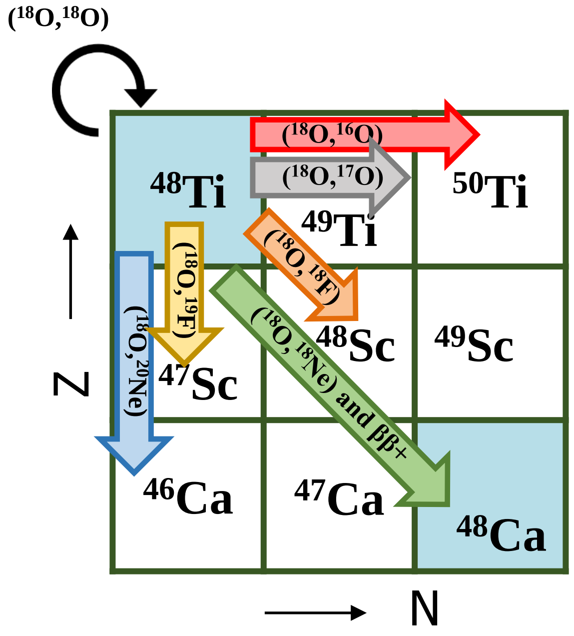
- ^{20}Ne + ^{130}Te



^{48}Ti – ^{48}Ca case

@ 15 AMeV

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

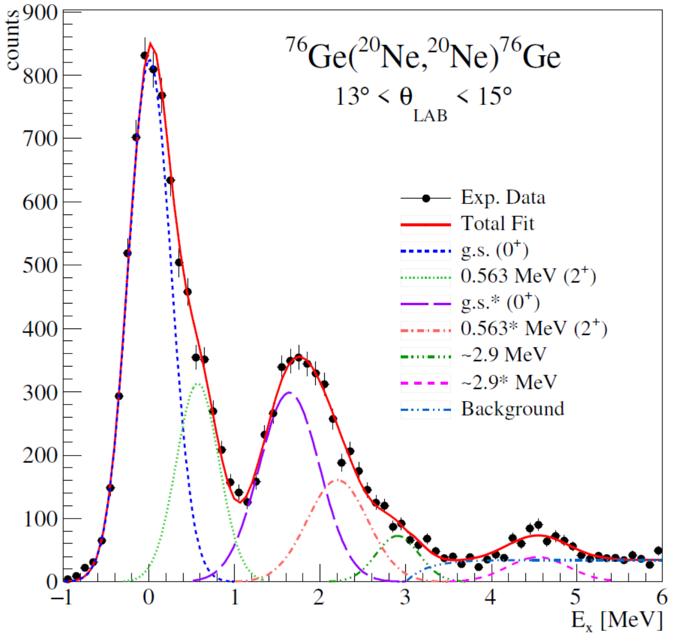


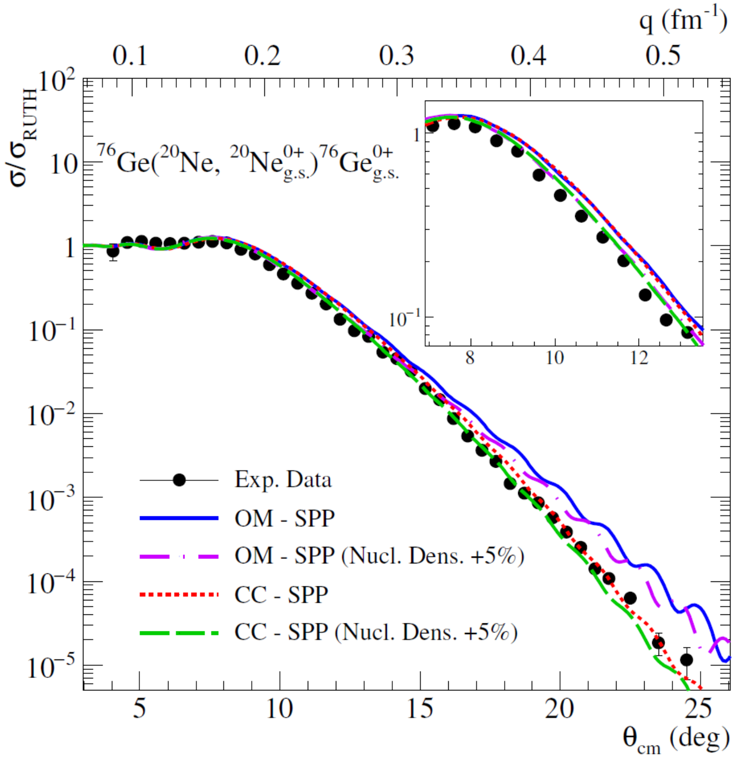
Experimental results

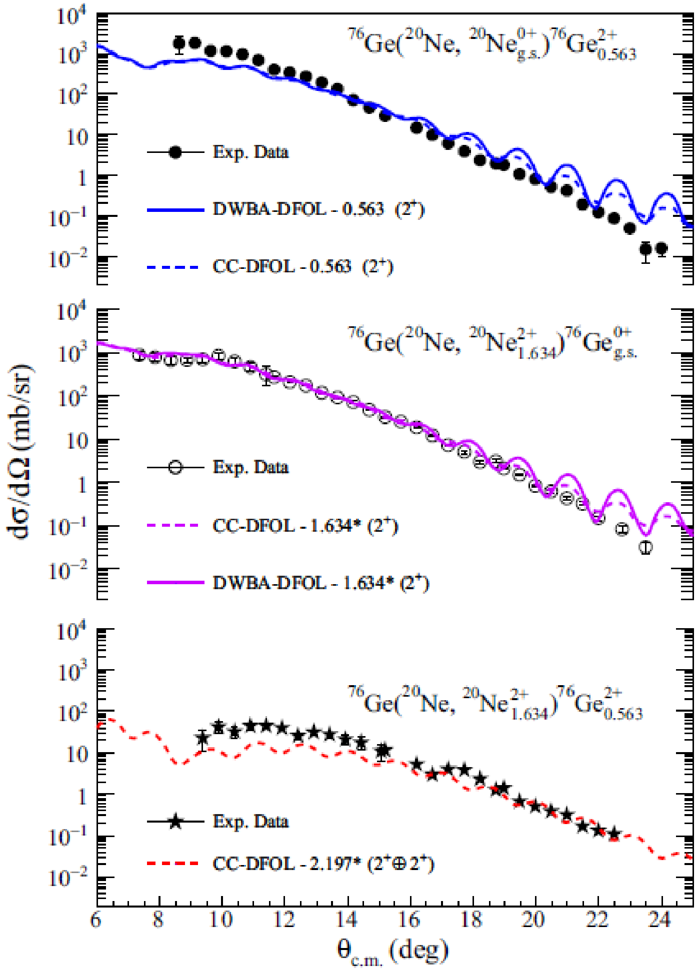
Elastic and inelastic scattering $^{76}Ge(^{20}Ne,^{20}Ne)^{76}Ge$ @ 15 AMeV

A. Spatafora et al., Phys. Rev. C 100 (2019) 034620

Distorsion of the incoming and outcoming waves due to the nucleus–nucleus interaction



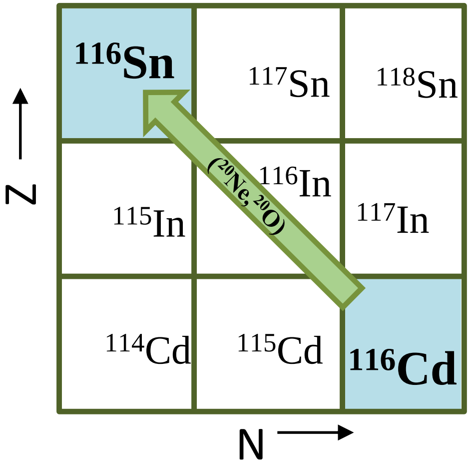




- Importance of Coupled Channel approach
- Different double folding optical potential

Experimental results

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



- g.s. → g.s. transition isolated
- Absolute cross section measured
- Angular distribution
- 0 deg < θ_{cm} < 14 deg

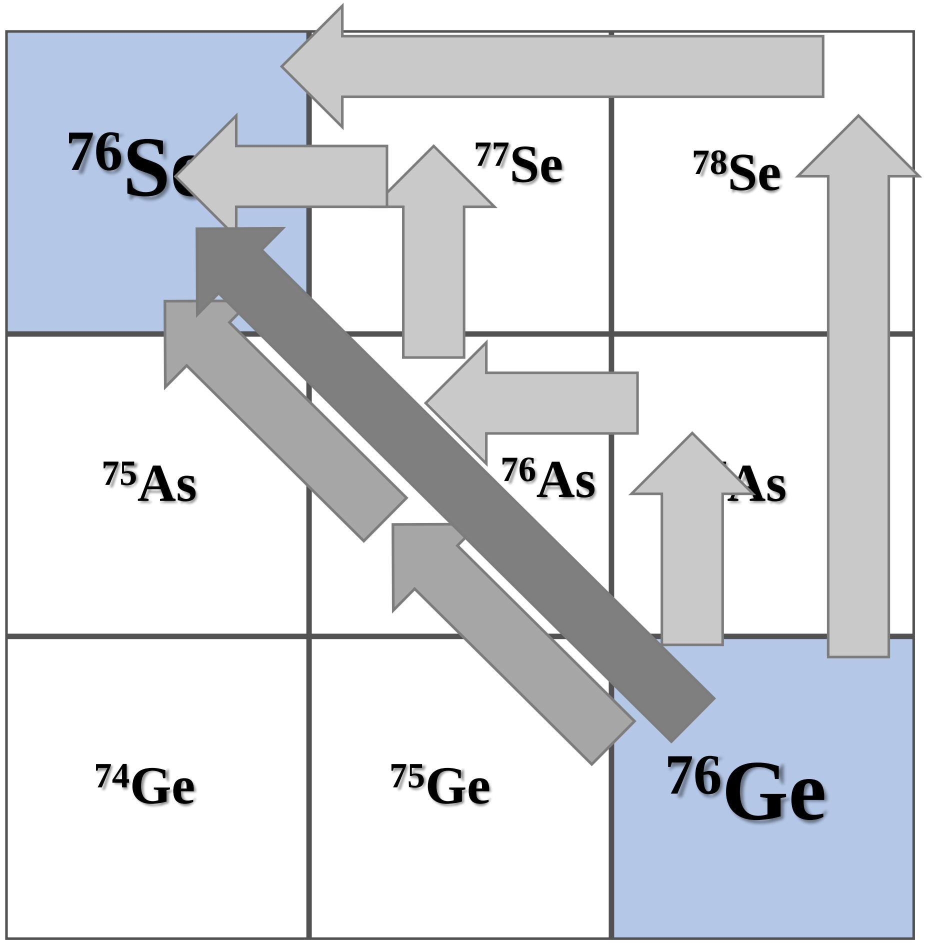
S. Calabrese, O. Sgouros et al.

Heavy-Ion induced Double Charge Exchange

Heavy ion DCE can proceed:

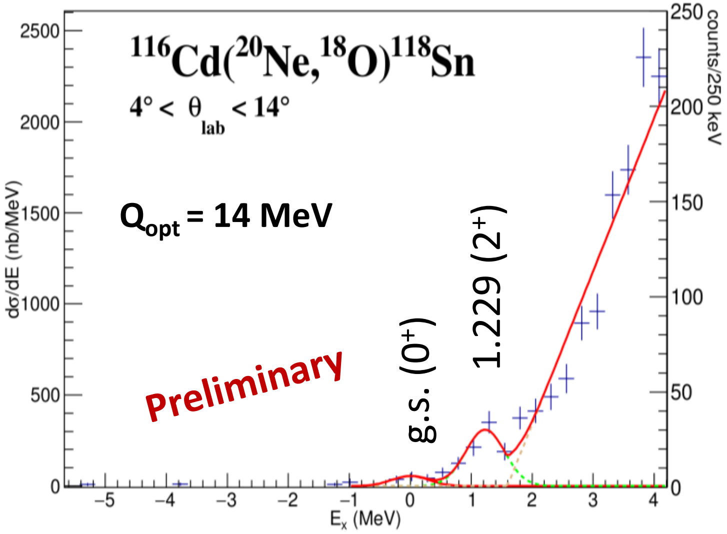
- Sequential **multi-nucleon transfer**
- Collisional processes
  - **Double single charge exchange (DSCE)**: two consecutive single charge exchange processes
  - **Two-nucleon mechanism (MDCE)**: relying on short range NN correlations, leading to the correlated exchange of two charged mesons between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

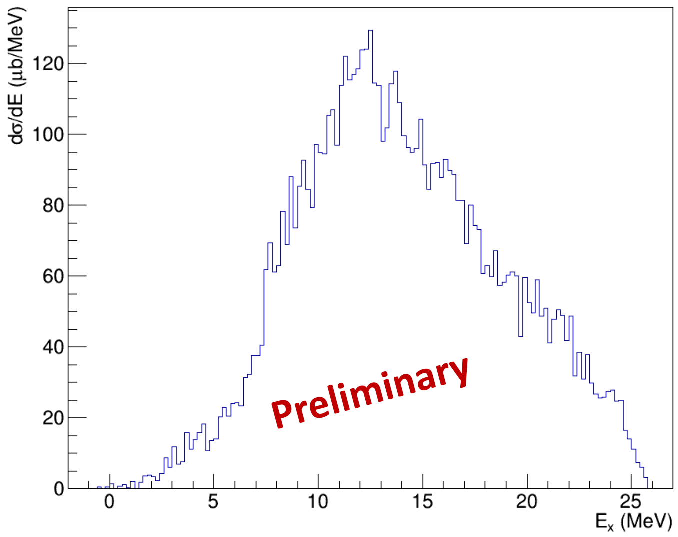
See talk H. Lenske



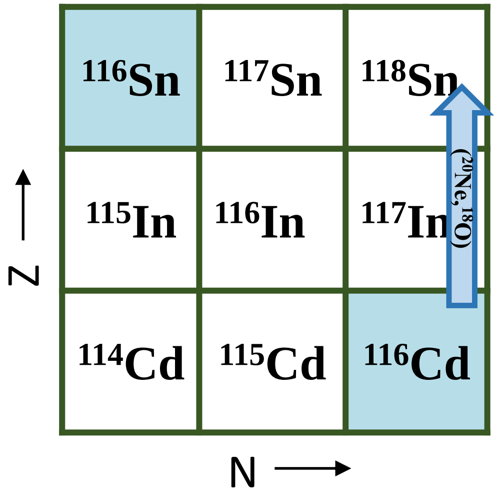
Cross section is a combination of the three different kinds of reaction dynamics

Multi-nucleon transfer





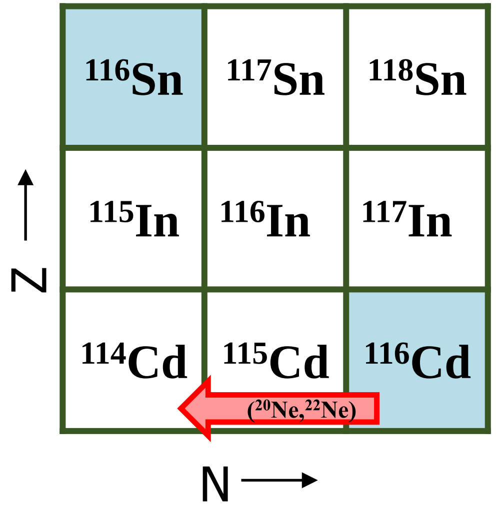
2p-transfer



EXP. DATA:
33 ± 10 nb

CALCULATIONS:
~ 26 nb

2n-transfer



EXP. DATA:
450 ± 200 nb

CALCULATIONS:
~ 340 nb

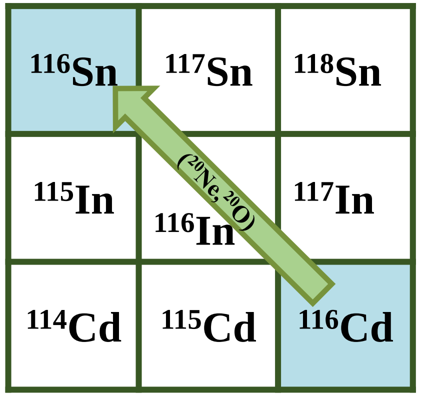
Cross section calculations (DWBA)
ISI and FSI from double folding
SA from IBM, shell model, QRPA

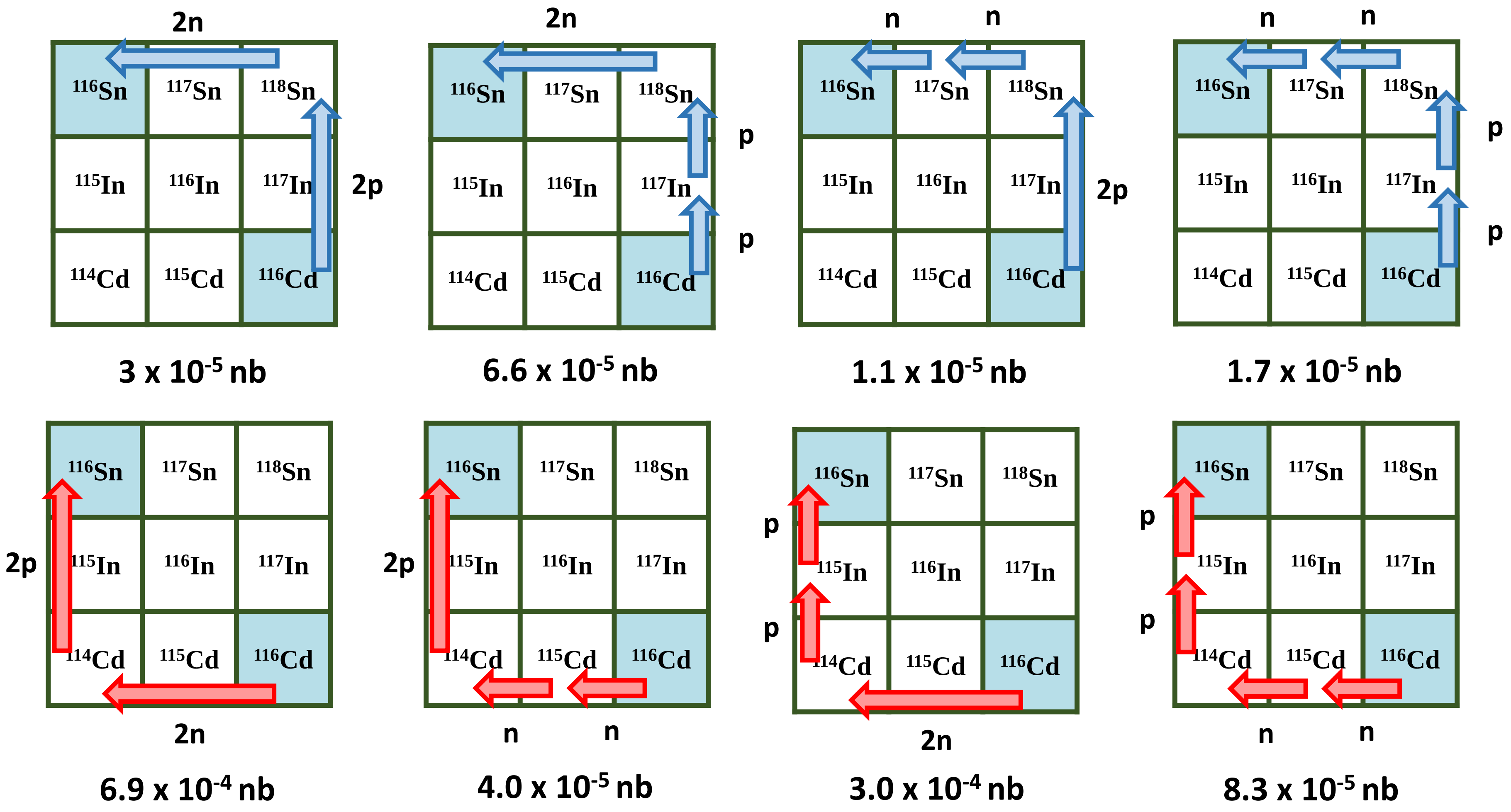
Agreement!

Multi-nucleon transfer routes
vs
Diagonal process

(exp. cross section **12 ± 2 nb**)

J. Lubian, J.Ferreira et al.

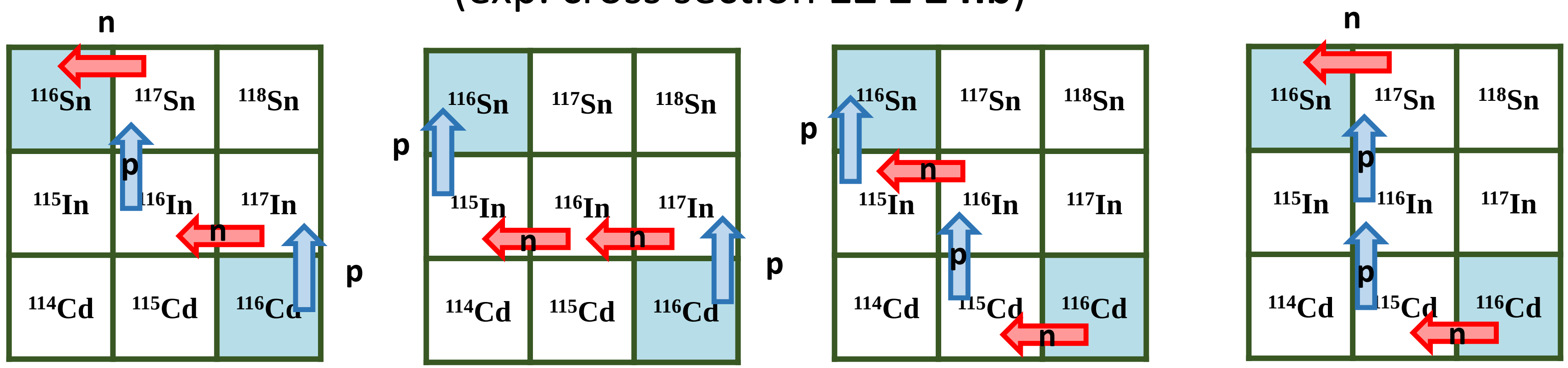




Multi-nucleon transfer routes
vs
Diagonal process

J. Lubian, J.Ferreira et al.

(exp. 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**

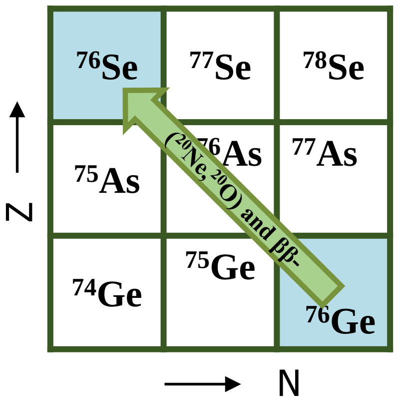
Negligible contribution of multi-nucleon transfer on the diagonal DCE process

Interplay between CEX + 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

Experimental results

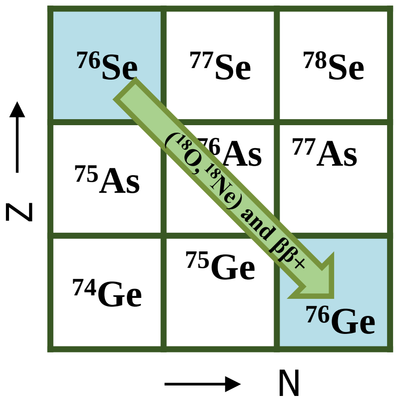
DCE $^{76}Ge(^{20}Ne,^{20}O)^{76}Se$ @ 15 AMeV



R. Linares et al.

Experimental results

DCE $^{76}Se(^{18}O,^{18}Ne)^{76}Ge$ @ 15 AMeV



$0° < \theta_{lab} < 8°$

- Same cross sections for different directions
- Similar distorsion factors

→ Same NME (encouraging test of time invariance!)

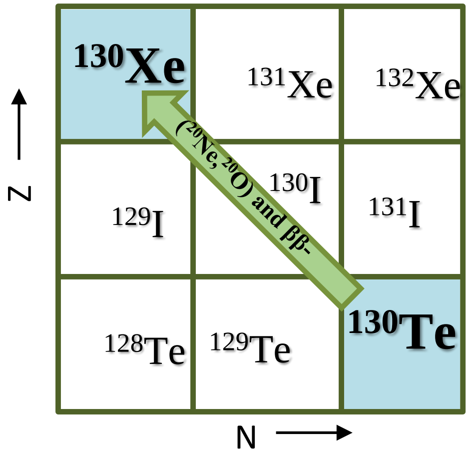
Warning:

- Only one case
- Reaction calculations in progress

A. Spatafora et al.

Experimental results

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



V. Soukeras et al.

Present limitations

- An accurate job on the **theory** is needed and is on-going Talk H. Lenske

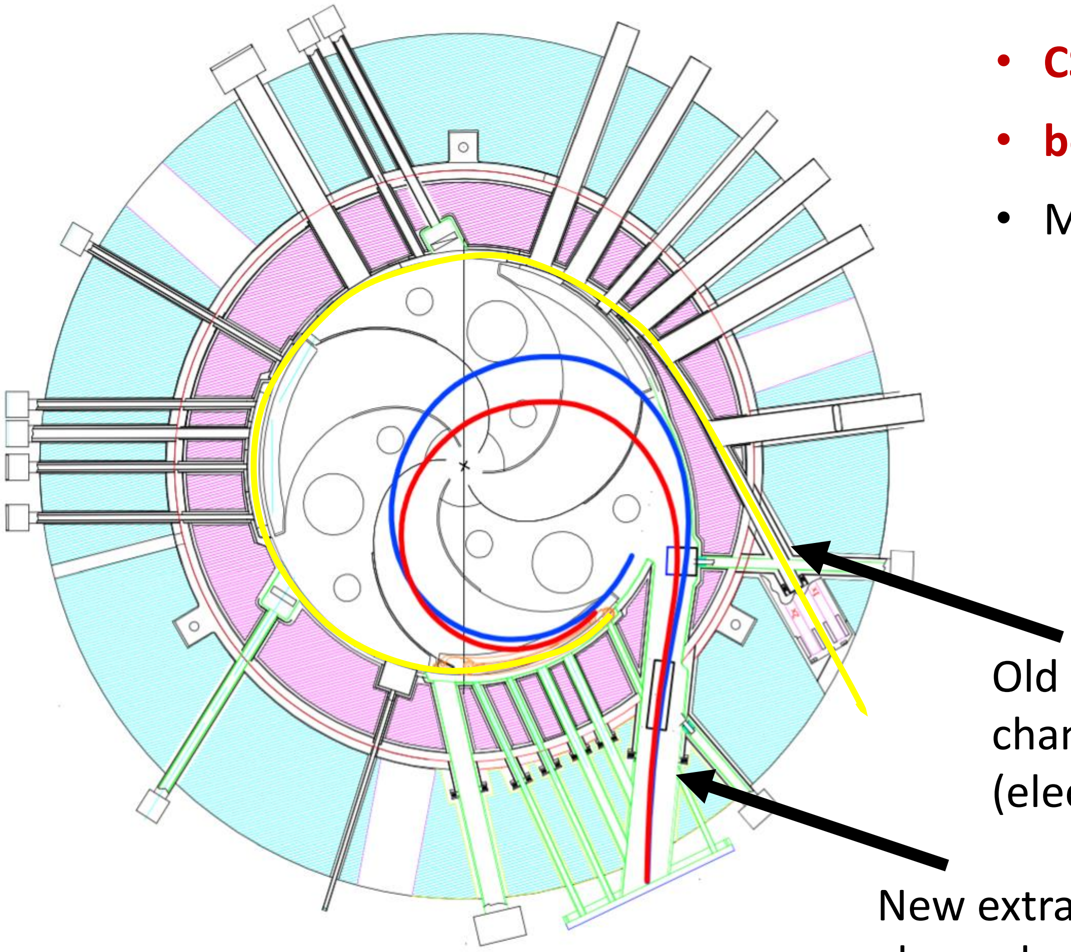
- Only few systems can be studied in the present condition (due to the **low cross-sections**)

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) for 19.4 M€
To work with two orders of magnitude more intense beam

Upgrade of the LNS facilities

➢ Upgrade of the LNS accelerator and beam lines



Old extraction channel (electrostatic)

New extraction channel

- **CS** accelerator current (from 100 W to 5-10 kW);
- **beam transport line** transmission efficiency to nearly 100%
- Maintaining the present beam energy resolution in MAGNEX

Extraction by stripping

Extraction by stripping is based on the instantaneous change of the magnetic rigidity of the accelerated ion, when its charge state increases after crossing a thin stripper foil

For ions with A<40, and energies higher than 15 MeV/u, the abundance of q=Z exceeds 99%

Expected beam intensity

INFN LNS

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

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%

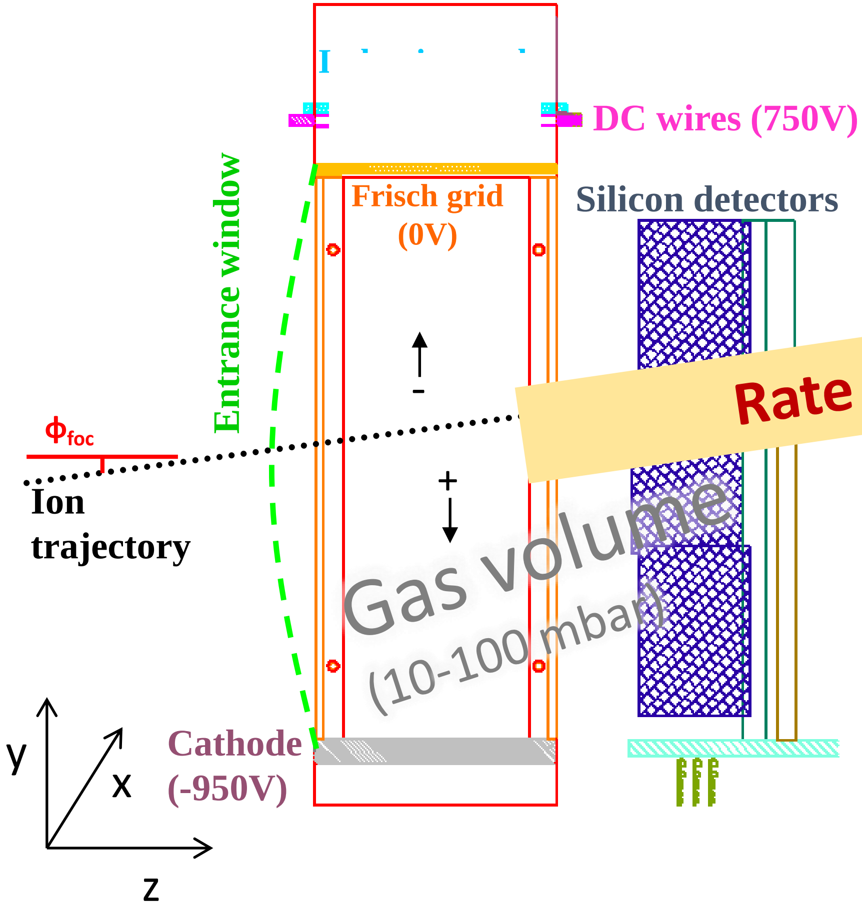
Upgrade of MAGNEX

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**



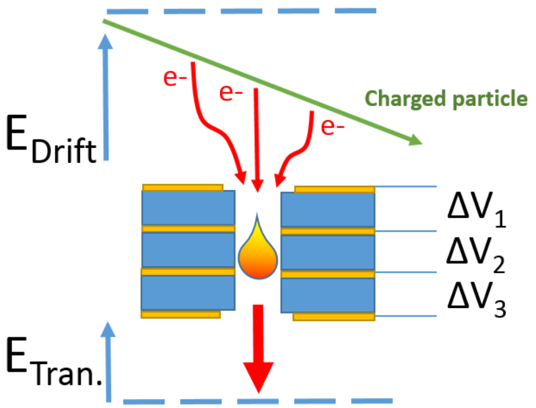
Rate limit few kHz

Large volume: 1360mm X 200mm X 96mm

Upgrade of MAGNEX

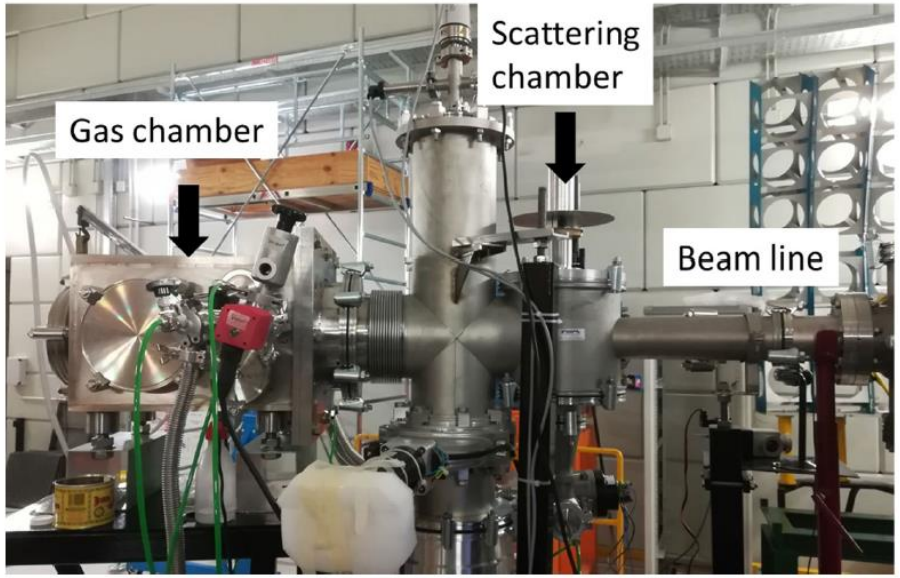
- **The Focal Plane Detector tracker**

Rate
from few kHz to MHz
preserving low-pressure operation



3-layer THGEM

Prototype assembled at LNS



Multiple THGEM

Assembly of several THGEM elements stacked together

No loss of charge ➔ <u>high gain @ low voltage</u>
Robust avalanche confinement
➔ lower <u>secondary effects</u>
Long avalanche region
➔ <u>high gain @ low pressure</u>
Field geometry stabilized by inner electrodes
➔ <u>reduced charging up</u>

Upgrade of MAGNEX

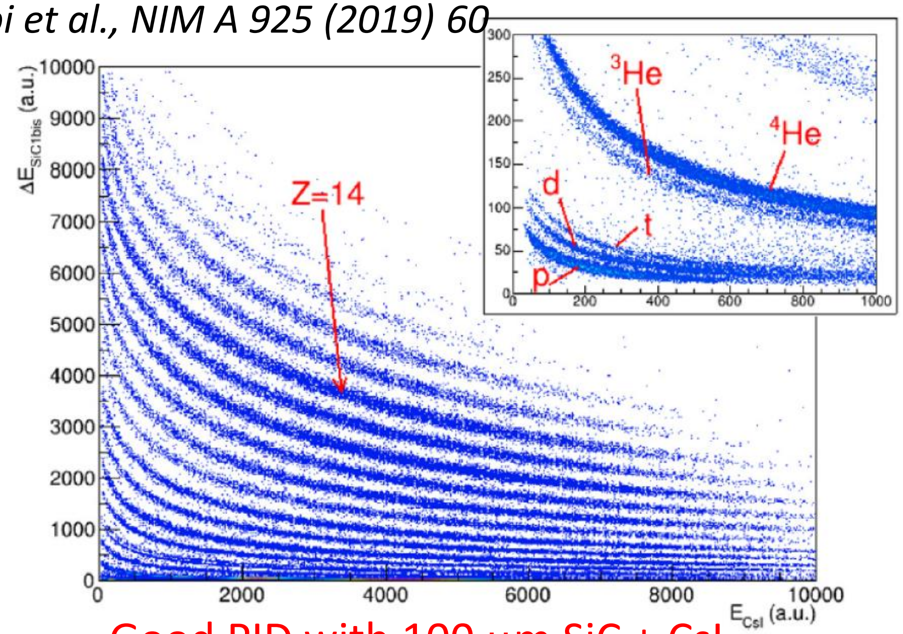
➢ The Focal Plane Detector PID wall

Radiation hardness
expected 10^{13} ions/cm^2 in 10 years activity
(silicon detectors dead at 10^9 implanted ions/cm^2
heavy ions not MIP!!)

- Radiation hard
- Heavy ions
- Working in gas environment
- Large area
- High energy resolution (2%)
- Timing resolution (few ns)

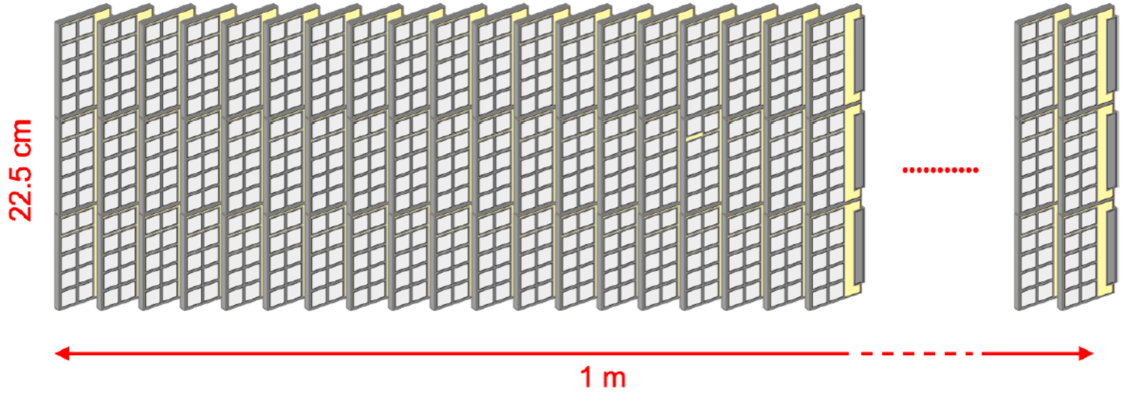
➢ SiC-CsI telescopes

S. Tudisco et al., Sensors 18 (2018) 2289
C. Ciampi et al., NIM A 925 (2019) 60



Good PID with 100 μm SiC + CsI

Total 1230 telescopes

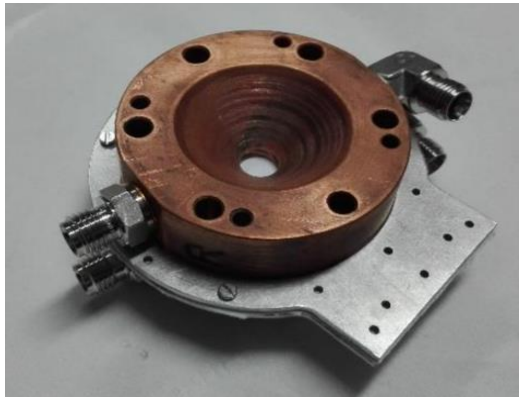


Targets

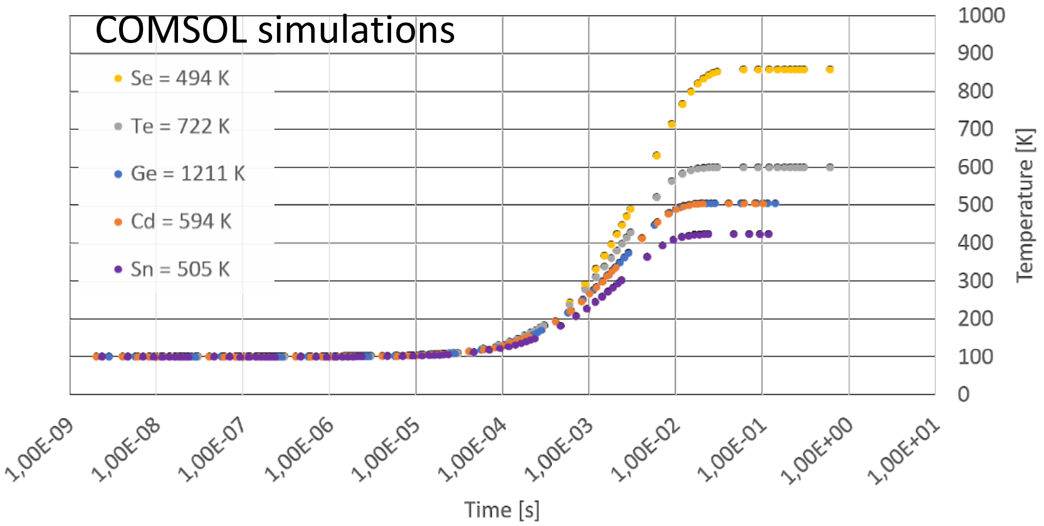
F. Iazzi et al., WIT Trans. on Eng. Sciences 116 (2017) 61

Melting and radiation tolerance

- Substrate made of *Highly Oriented Pyrolytic Graphite*(HOPG) featuring high thermal conductivity (1930 $Wm^{-1}K^{-1}$)
- Heat sink at a temperature of the *cryocooler*
- Test performed with heavy-ion beams at UNAM, ININ and USP

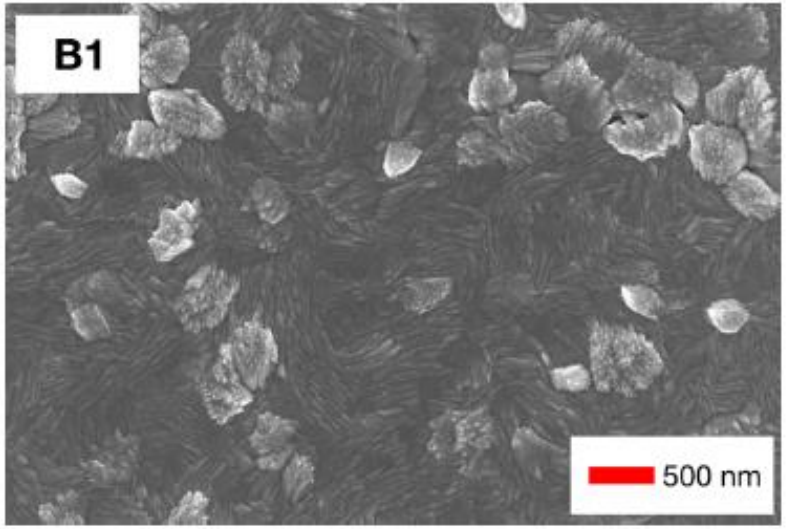


Target holder assembly



Thickness Uniformity

- Non-trivial evaporation technology to guarantee uniformity



FESEM image of Te target on 5 μm HOPG

NUMEN

Conclusions and Outlooks

- Challenging project on HI-DCE has started and new physics results are coming
- The upgrade for the INFN-LNS cyclotron and MAGNEX will allow to build a unique facility for a systematic exploration of all the nuclei candidate for $0\nu\beta\beta$
- A big opportunity not only for $0\nu\beta\beta$ physics applications but also for genuine nuclear physics (including nuclear technology and nuclear theory)
- High-intensity beams facility at INFN-LNS for many users

The NUMEN collaboration

Spokespersons: F. Cappuzzello (cappuzzello@lns.infn.it) and C. Agodi (agodi@lns.infn.it)

100 Researchers
40 Institutions
15 Countries

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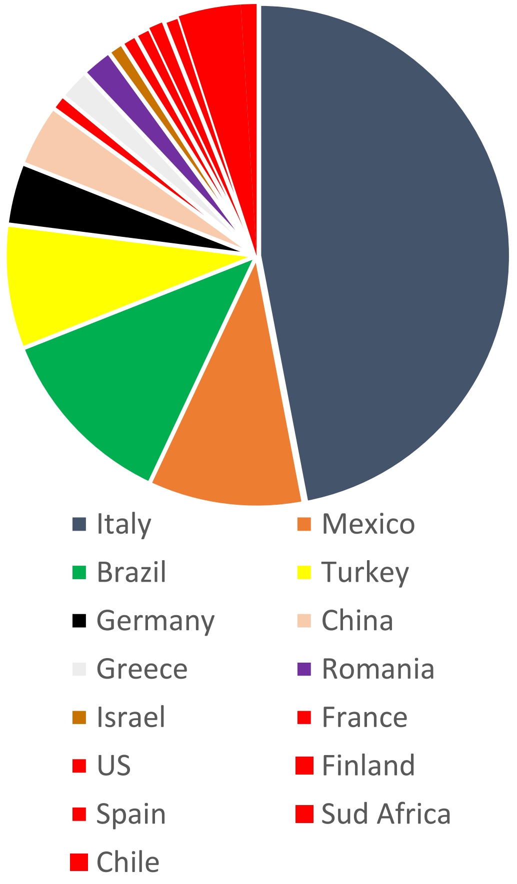

Thank you!