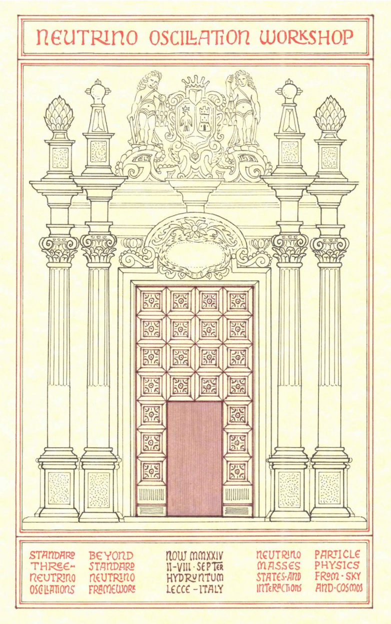
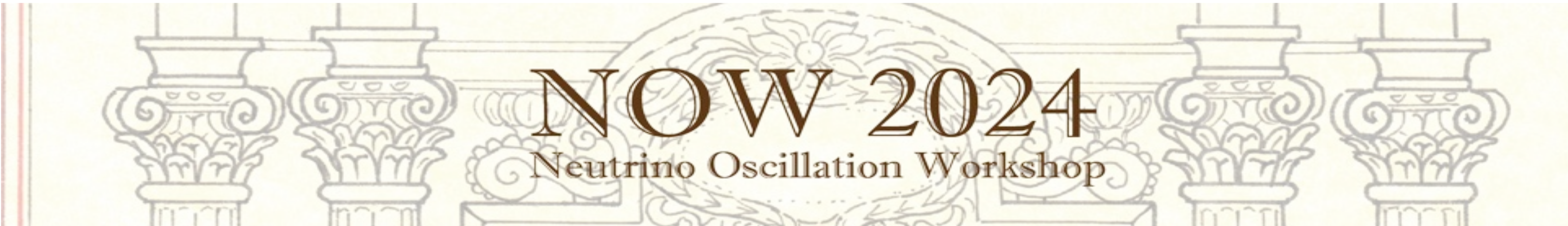


NUMEN

NUMEN project: status and perspective



Clementina Agodi – Otranto 2-8 Settembre 2024

NUMEN

NUclear **M**atrix **E**lement for **N**eutrinoless double beta decay

NURE

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

Fotografia di Ettore Majorana dalla tessera universitaria datata 3 novembre 1923

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

0νββ decay half-life

Phase space factor

contains the average **neutrino mass**

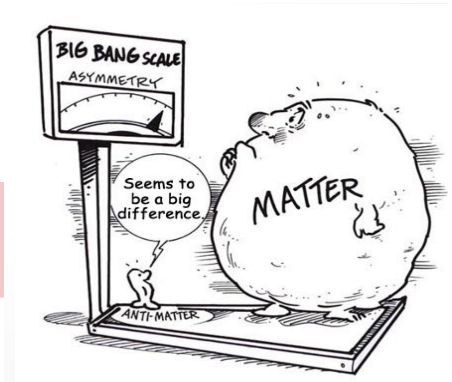
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

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

Transition probability of a **nuclear** process

Use of nuclear reactions **(Double Charge Exchange reactions)** to stimulate in the laboratory the same nuclear transition occurring in 0νββ



what NEXT?

The Nuclear Matrix Element

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

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

Support from the experiments:

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

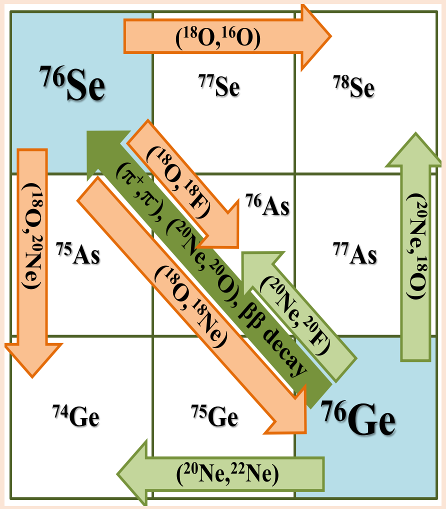
- β-decay and $2\nu\beta\beta$ decay
- (π^+, π^-), single charge exchange (3He,t), (d,2He), HI-SCE, electron capture, transfer reactions, μ – nucleus scattering, γ-ray spectroscopy, double γ-decay etc…
- A promising experimental tool : Heavy-Ion Double Charge-Exchange (DCE)

1st order isospin probes

2nd order isospin probes

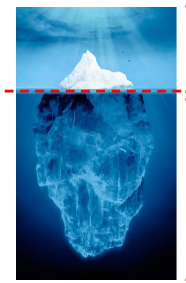
HI - DCE as surrogate processs of $0\nu\beta\beta$

HI - DCE



- ✓ 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



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

RIKEN

RCNP

Heavy-Ion DCE vs $0\nu\beta\beta$

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

DCE @ INFN - LNS

The tiny values of the DCE cross-sections and the resolution requirement demand the use of precise equipment with a **high capacity to select rare events**.

- 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

crucial for the experimental challanges !

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 ⇨

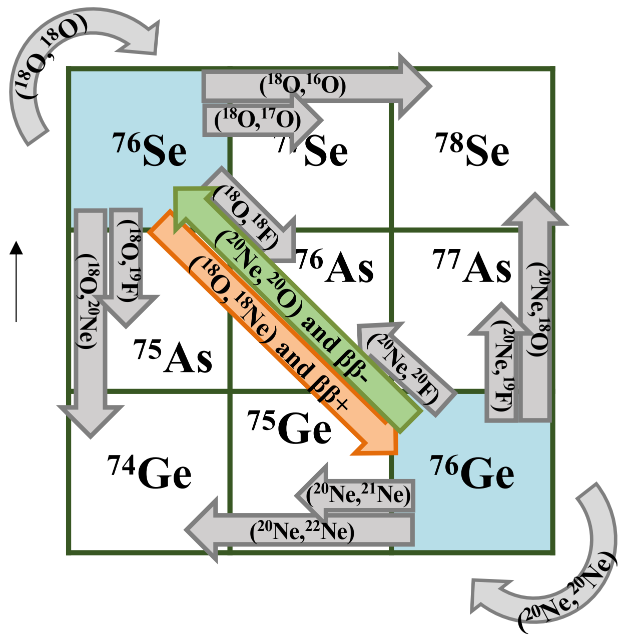
Measured resolutions:
- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/300$

Advanced spectroscopy accessible by direct reactions can provide precious information on **key $0\nu\beta\beta$ nuclear structure aspects**

The experimental strategy in a nutshell

The **full understanding of the DCE** reaction mechanism implies the study of a wide network of nuclear reactions: the new methodology proposed is the ***multi-channel approach***

- **Several scattering and reaction channels open** in heavy-ion collisions above Coulomb barrier.
- **Each reaction channel gives relevant information** on the nuclear structure and help us to study **DCE reactions**



NUMEN measure in a **unique experimental setup**
the energy spectra and cross-section angular distributions of:

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)

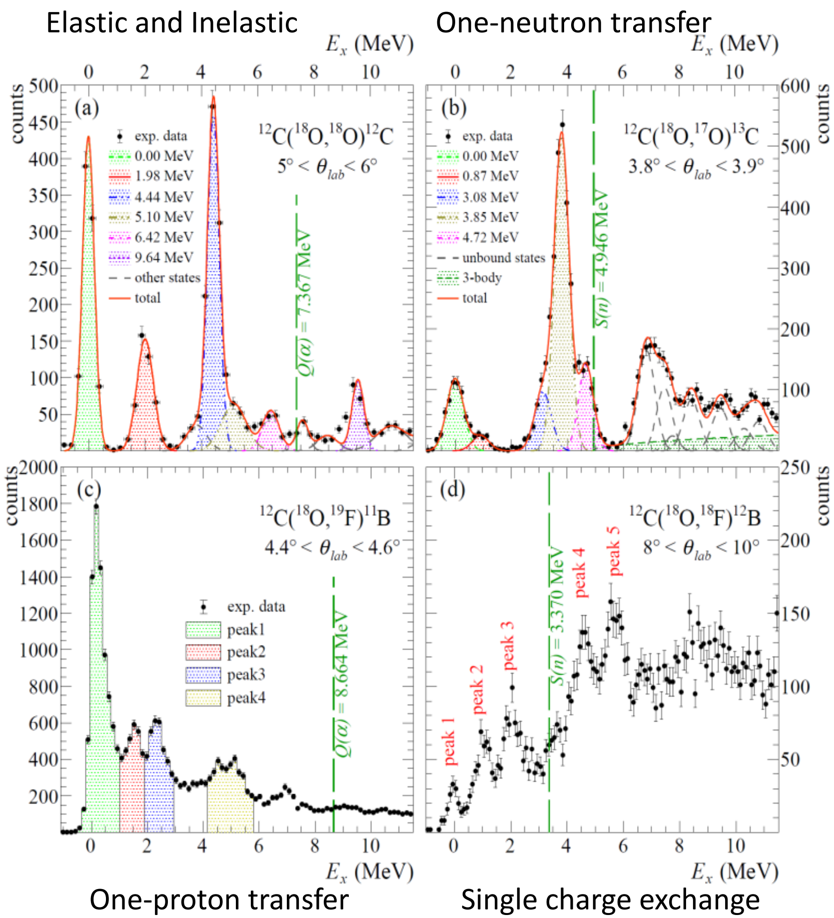
Constraints on experimental data and theoretical analysis in a coherent way

The multichannel approach: $^{18}O+^{12}C$ an ideal benchmark system

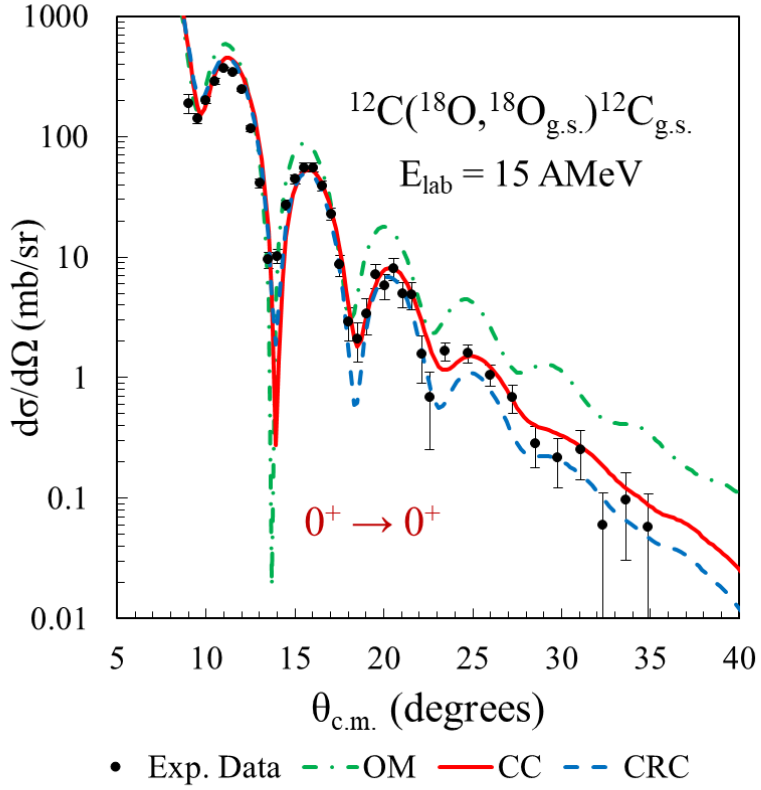
A. Spatafora et al. PRC 107, 024605 (2023)
A. Spatafora et al., submitted

NUMEN

Excitation energy spectra for the network of the nuclear reactions involved in the multichannel study of the SCE reactions coming from the **$^{18}O+^{12}C$ collision @275 MeV** incident energy



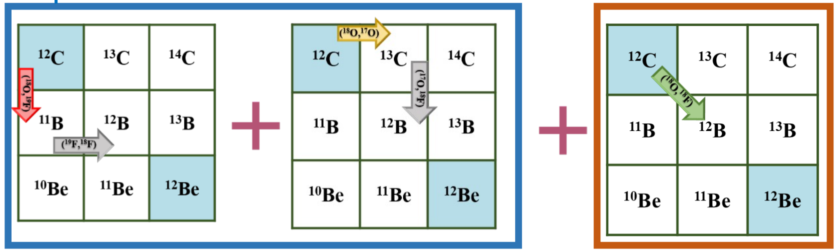
Experimental cross-section angular distribution of the **elastic scattering** exctracted for the ground-state



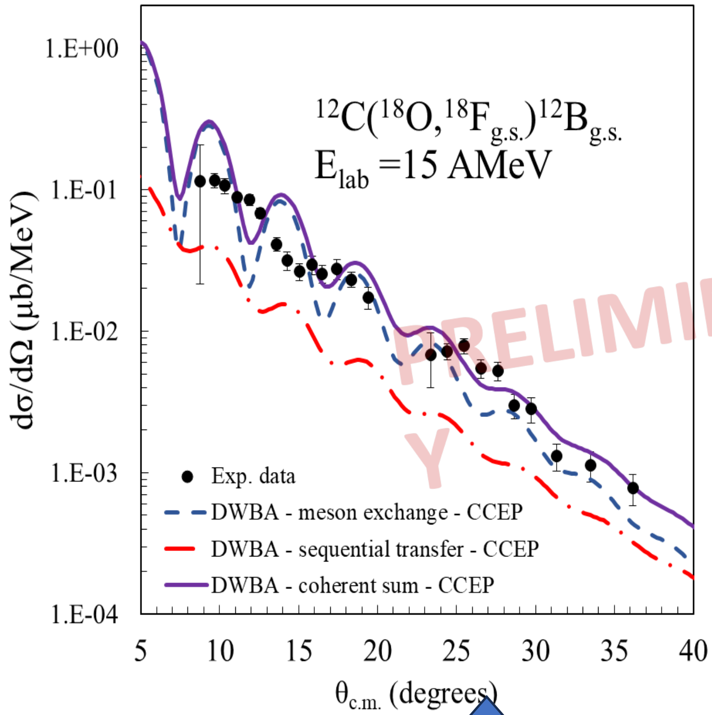
The multichannel approach: SCE reaction study

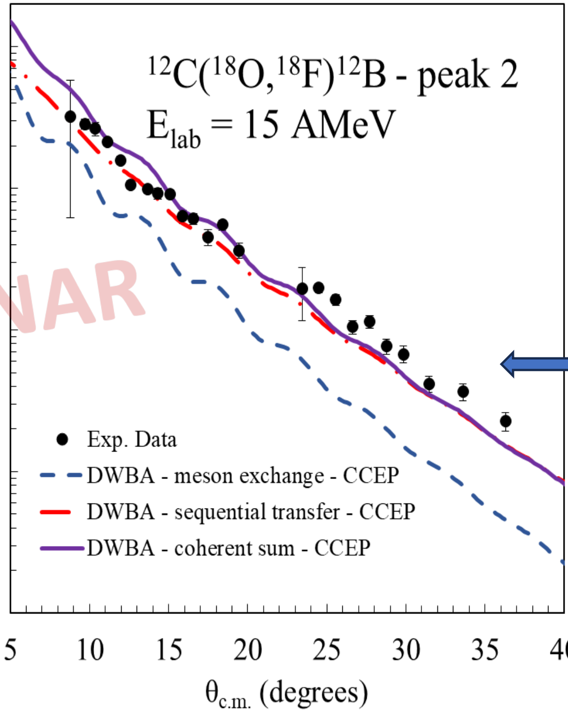
Sequential two-step transfer of two nucleons

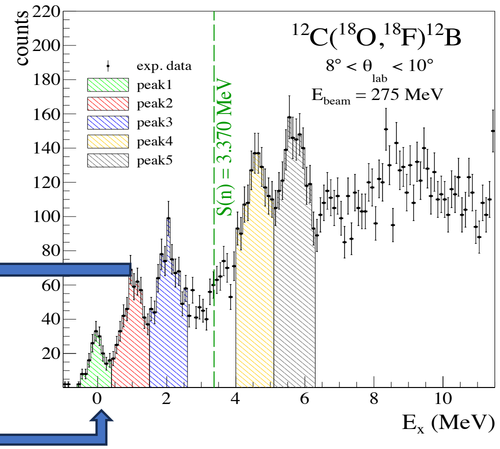
Direct meson exchange



Good description of the experimental data with
NO SCALING factor







- **ISI from elastic and inelastic scattering**
- **DWBA analysis**
- **Large-scale shell-model (transfer)+ One Body Transition Density (direct)**

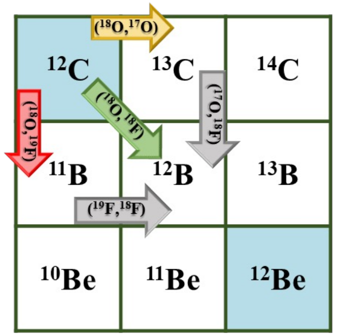
NUMEN

One of the NUMEN goals:
Coherent calculation with direct and sequential **single charge exchange** reaction mechanism **!**

The multichannel approach: SCE reaction study

A. Spatafora et al. PRC 107, 024605 (2023)
A. Spatafora et al., submitted

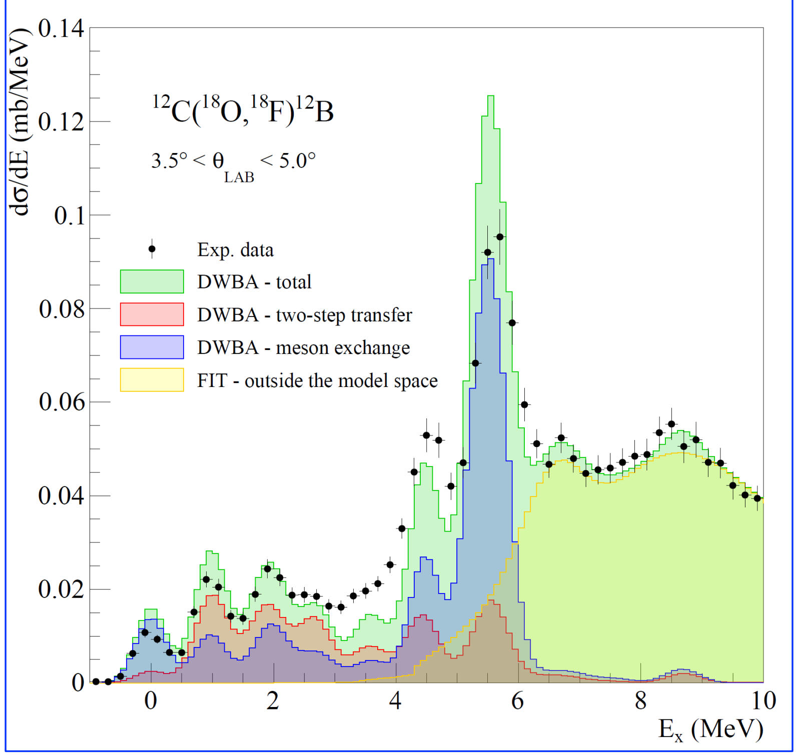
Competition between the sequential two-step transfer of two nucleons and the direct meson exchange process



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

- ✓ At 15 AMeV incident energy both reaction mechanisms are needed to describe the SCE reaction channel
- ✓ The weigth of the two analysed reaction mechanisms in each transition depends on the microscopic nature of the transition itself

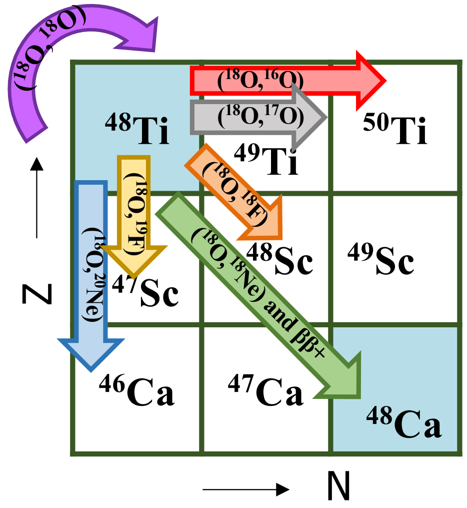
Spectral contributions of differential cross-section as a function of the excitation energy



The same approach is being applied to other SCE reactions of interest for 0νββ decay :

- ➢ **^{40}Ca(^{18}O,^{18}F)^{40}K** (sequential routes already published in B. Urazbekov et al., PRC 108, 064609 *(2023))*
- ➢ **^{116}Cd(^{20}Ne,^{20}F)^{116}In** (*H. Garcia-Tecocoatzi et al.*)

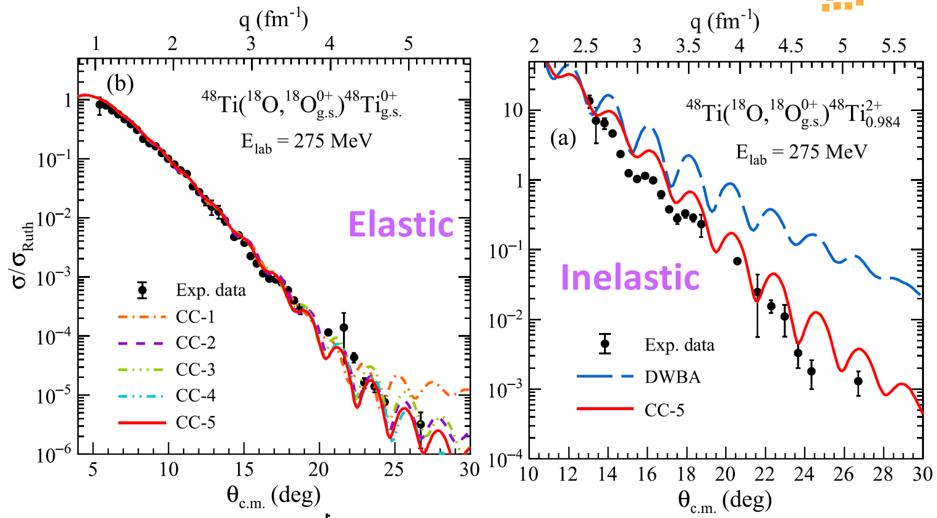
^{48}Ca-^{48}Ti system of interest for 0νββ decay

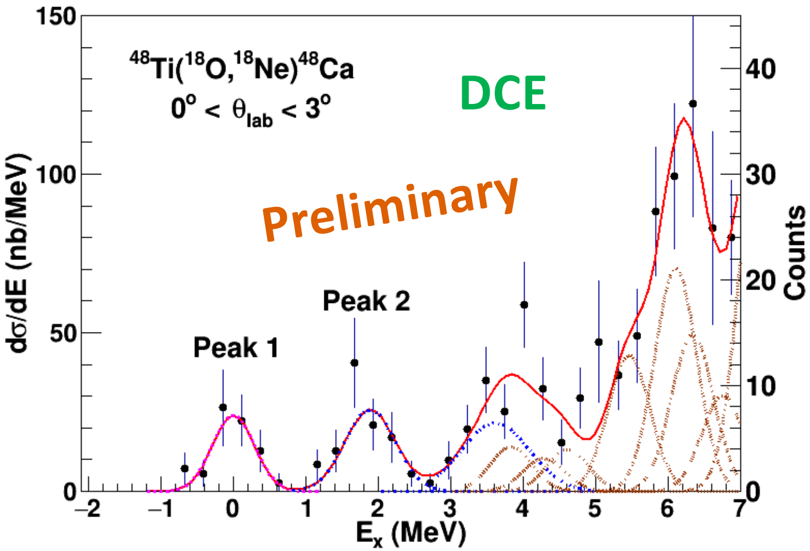


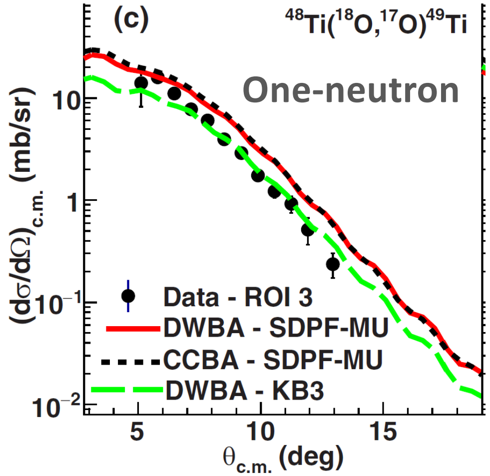
O. Sgouros et al., PRC 104, 034617 (2021)
O. Sgouros et al., PRC 108, 044611 (2023)
G. A. Brischetto et al., PRC 109, 014604 (2024)

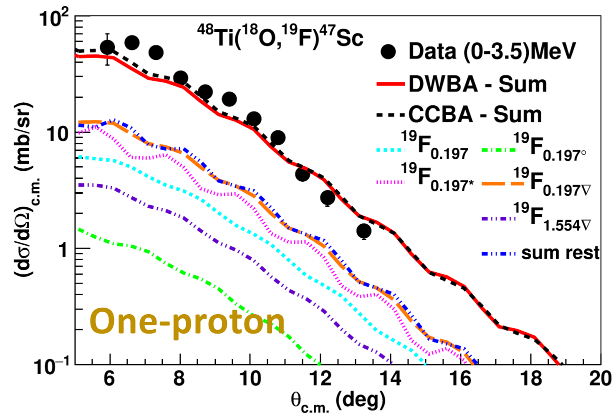
Multichannel approach

- **ISI from elastic and inelastic scattering**
- **DWBA** and **CC** analysis
- **Large-scale shell-model**





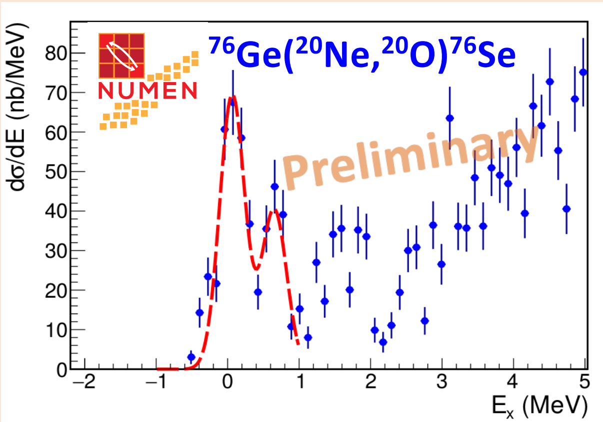




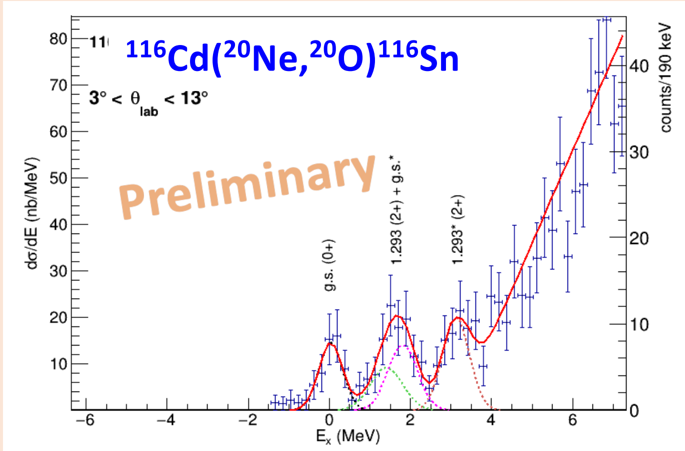
Complete and coherent description of all the measured reaction channels in the same framework !

Phase 2 NUMEN experimental runs – DCE spectra

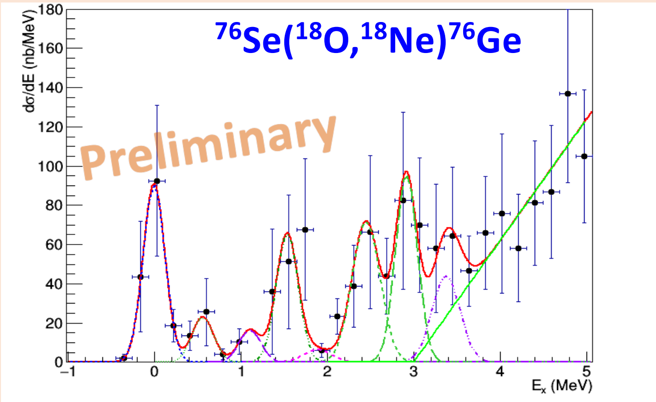
Check for time invariance



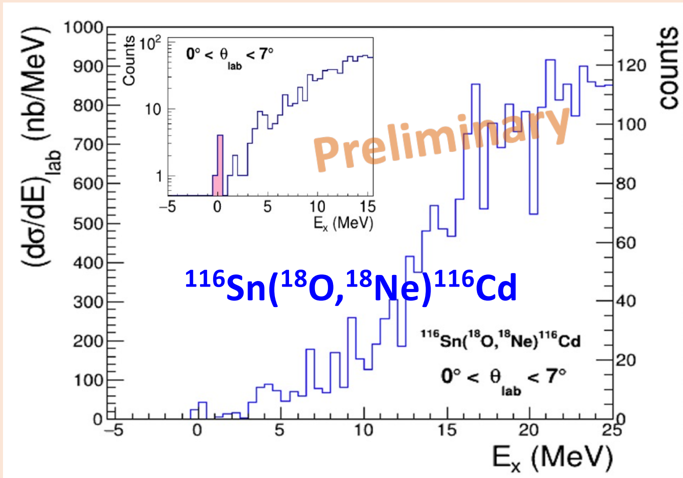
R. Linares et al.



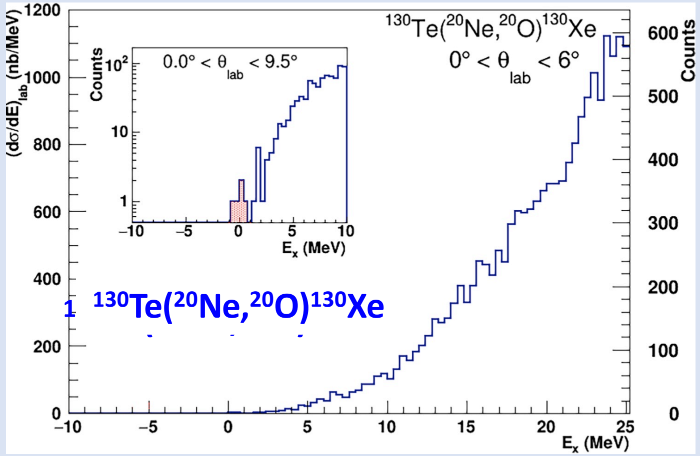
S. Calabrese et al.



A. Spatafora et al.



C. Eke, I. Ciraldo et al. Res. Phys. (submitted)



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

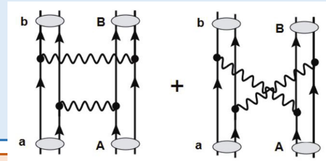
NUMEN theoretical developments

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

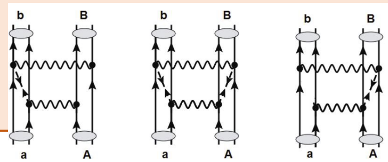
2) Two-step DCE - Double single charge exchange (DSCE): two consecutive single charge exchange processes

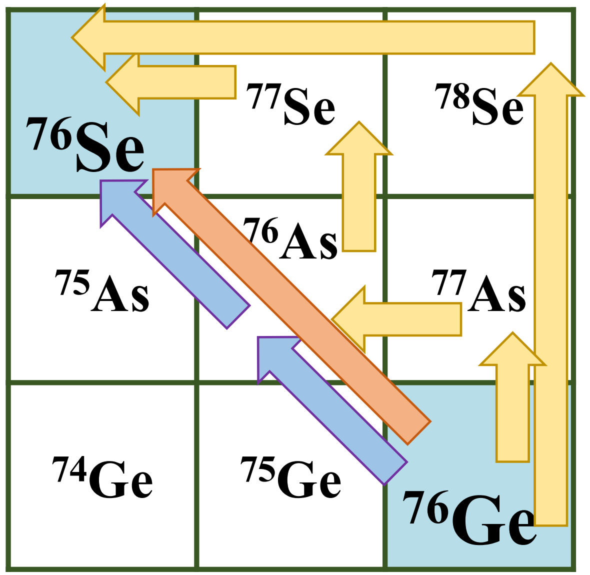
E. Santopinto et al., Phys. Rev. C 98 (2018) 061601
J.I.Bellone et al., PLB 807 (2020) 135528
H. Lenske et al., Universe 7 (2021) 98



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. Nucl. Phys. 109 (2019) 103716
H. Lenske, CERN Proceedings 2019-001 (2019)





Recent theoretical developments

F. Cappuzzello et al., Prog. Part. Nucl. Phys. 128, 103999 (2023)
H. Lenske et al., Universe 10, 93 (2024)
H. Lenske et al., Universe 10, 202 (2024)
J. Ferreira et al., Multi-nucleon transfer in ^{18}O + ^{40}Ca DCE reaction (in preparation)

universe **H. Lenske et al., Universe 10, 202 (2024)** MDPI

Article

Theory of Majorana-Type Heavy Ion Double Charge Exchange Reactions by Pion–Nucleon Isotensor Interactions

Horst Lenske [1,*,†], Jessica Bellone [2,†], Maria Colonna [2,†] and Danilo Gambacurta [2,†]

Present limitations and perspectives

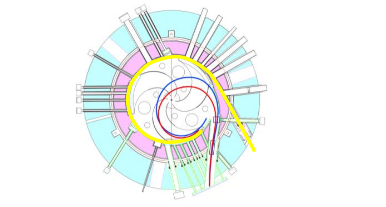
- The results obtained by NUMEN so far indicate that suitable information from DCE reactions can be extracted
- However, the tiny values of such cross sections (few nb) and the resolution requirements demand **beam intensities much higher than those manageable with the present facility**

The goal:
systematic study of all the hot-cases

The way:
high current beams and advanced spectrometry

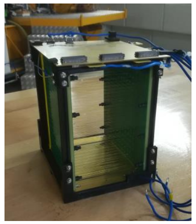
The main MAGNEX R&D activities are focused on:

- ✓ A new focal plane detector, **Tracker+PID-Wall**;
- ✓ **a new target system**, resistant to high radiation and heat;
- ✓ a new-gamma ray detector, **G-NUMEN**;
- ✓ Front-End e Read-Out **electronics**;
- ✓ **mechanical integration and assembly** of the new set-up
- ✓ **DAQ and characterization** of the high-speed signal reading system

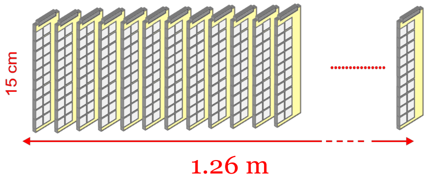


Superconducting cyclotron
Extraction by stripping (5-10 kW)

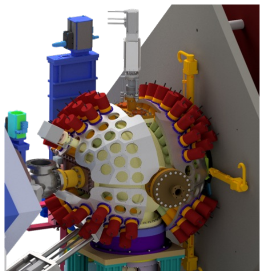
- **CS** accelerator current (from 100 W to 5-10 kW); from elecrostatic to extraction by stripping
- **beam transport line** transmission efficiency to nearly 100%.



New tracker for the FPD
(THGEM technology)



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



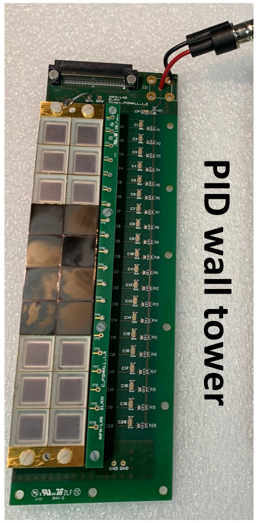
G-NUMEN

New system targets

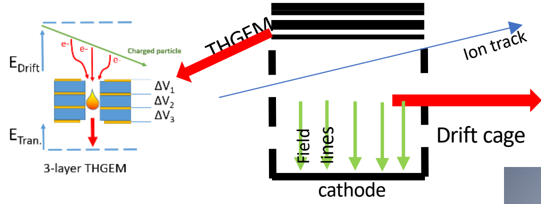
NUMEN Technical Design Report *F. Cappuzzello, C. Agodi et al., Intern. Journ. of Mod. Phys. A 36, 30 (2021) 2130018*

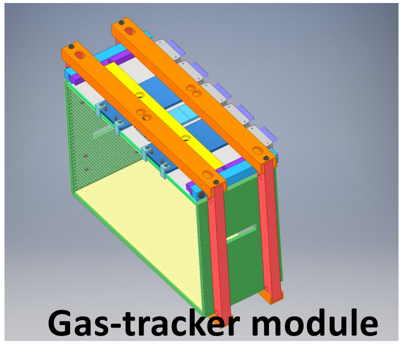
MAGNEX future detectors and infrastructures

- The construction of a New **Focal Plane Detector**



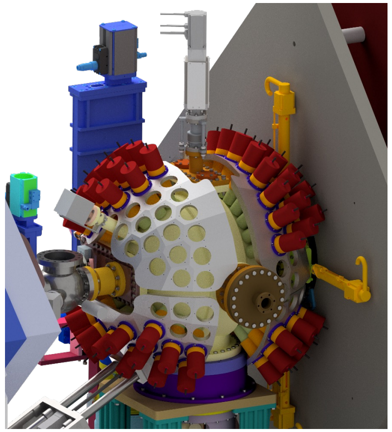
- New **Gas-Tracker**, based on M-THGEM technology





- New wall of telescopes of SiC-CsI detectors for ion identification (**PID-wall**)

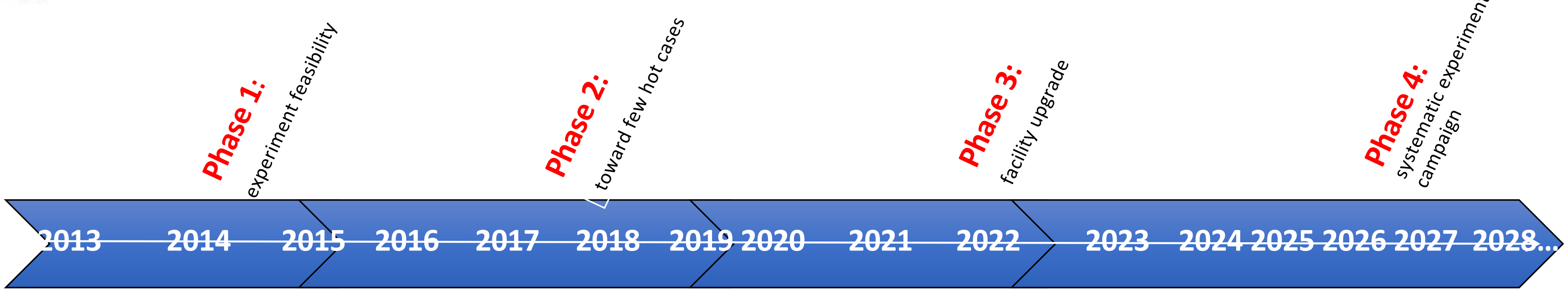
- The introduction of a gamma-array Calorimeter of $LaBr_3$(**G-NUMEN**);



- The development of suitable **front-end and read-out electronics**, for a fast read-out of the detector signals, a high signal to noise ratio and adequate hardness to radiation;
- The implementation of a suitable architecture for **data acquisition, storage and data handling**;
- The development of the technology for **suitable nuclear targets** to be used in the experiments

NUMEN status

- 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



Phase 1 completed:

✓ Experimental feasibility demostrated

Phase 2 completed:

✓ All the **experiments** in present condition recommended by IAC successfully performed.

✓ **R&D for MAGNEX** upgrade completed. New technologies, e.g. SiC, MTHGEM, HOPG etc..

✓ **Theory** deeply developed.

Phase 3– Moving towards «ready-to-beam» condition:

✓ **Procurements and integration** in advanced status (mechanics, electronics, DAQ, detectors, targets …)

The NUMEN collaboration

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

Proponents: C.Agodi, C.Altana, J.I.Bellone, S.Brasolin, G.A.Brischetto, O.Brunasso, M.P.Bussa, S.Calabrese, L.Calabretta, D.Calvo, L.Campajola, V.Capirossi, F.Cappuzzello, D.Carbone, M.Cavallaro, S.Ciociola, I.Ciraldo, M.Colonna, M.Cutuli, F.Dumitrache, C.Ferraresi, P.Finocchiaro, M.Fisichella, A.Foti, S.Gallian, D.Gambacurta, E.M.Gandolfo, F.Iazzi, L.La Fauci, G.Lanzalone, A.Lavagno, F.La Via, P.Mereu, L.Neri, L.Pandola, F.Pinna, D.Rosato, A.D.Russo, G.Russo, E.Santopinto, D.Sartirana, O.Sgouros, V.Soukeras, A.Spatafora, D.Torresi, S.Tudisco, R.I.M. sevolodovna

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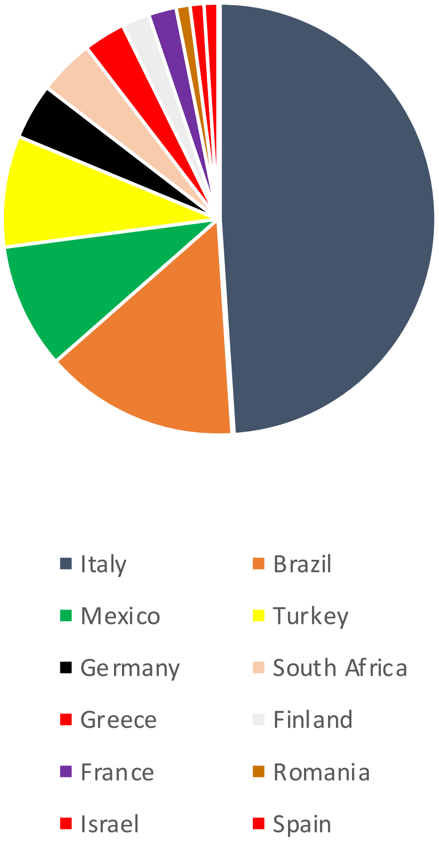
12 Countries



F. Cappuzzello, C. Agodi et al. The NUMEN project: NUclear Matrix Elements for Neutrinoless double beta decay Eur. Phys. J. A (2018) 54: 72

Conclusions and Outlook

- **Multi-channel reaction approach is quite appealing** for accurate investigations of direct reactions originating in heavy-ion collisions and **for precise spectroscopy of HI proposed by NUMEN** with its challenging commitment **to provide valuable information on neutrinoless double beta decay NME from SCE and DCE cross-section measurements.**

- **The upgrade** of MAGNEX and of the INFN-LNS CS and research infrastructure will allow to **significantly improve the overall NUMEN discovery potential !**

NOW 2024
Neutrino Oscillation Workshop

THANK YOU!

NOW 2024

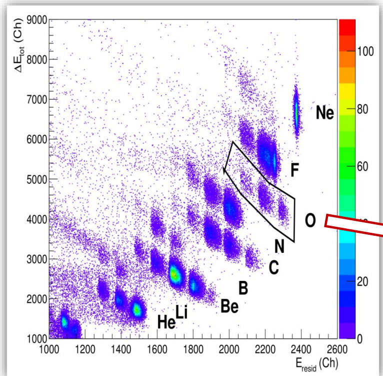
Neutrino Oscillation Workshop

SPARE

MAGNEX: large acceptance magnetic spectrometer

Particle Identification

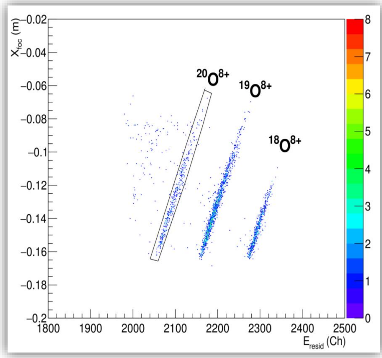
Z Identification



A, q Identification

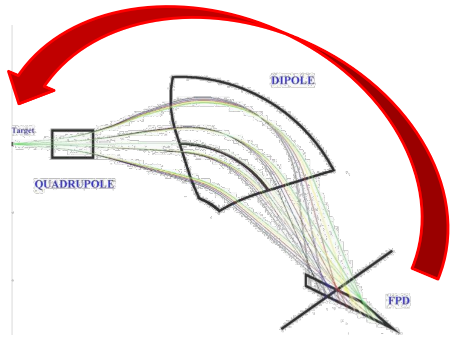
Ion trajectory in a magnetic spectrometer

$$B\rho = \frac{p}{q} \rightarrow X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



RAY-RECONSTRUCTION TECHNIQUE

Determination of the **ion trajectory** inside the spectrometer



Requires:

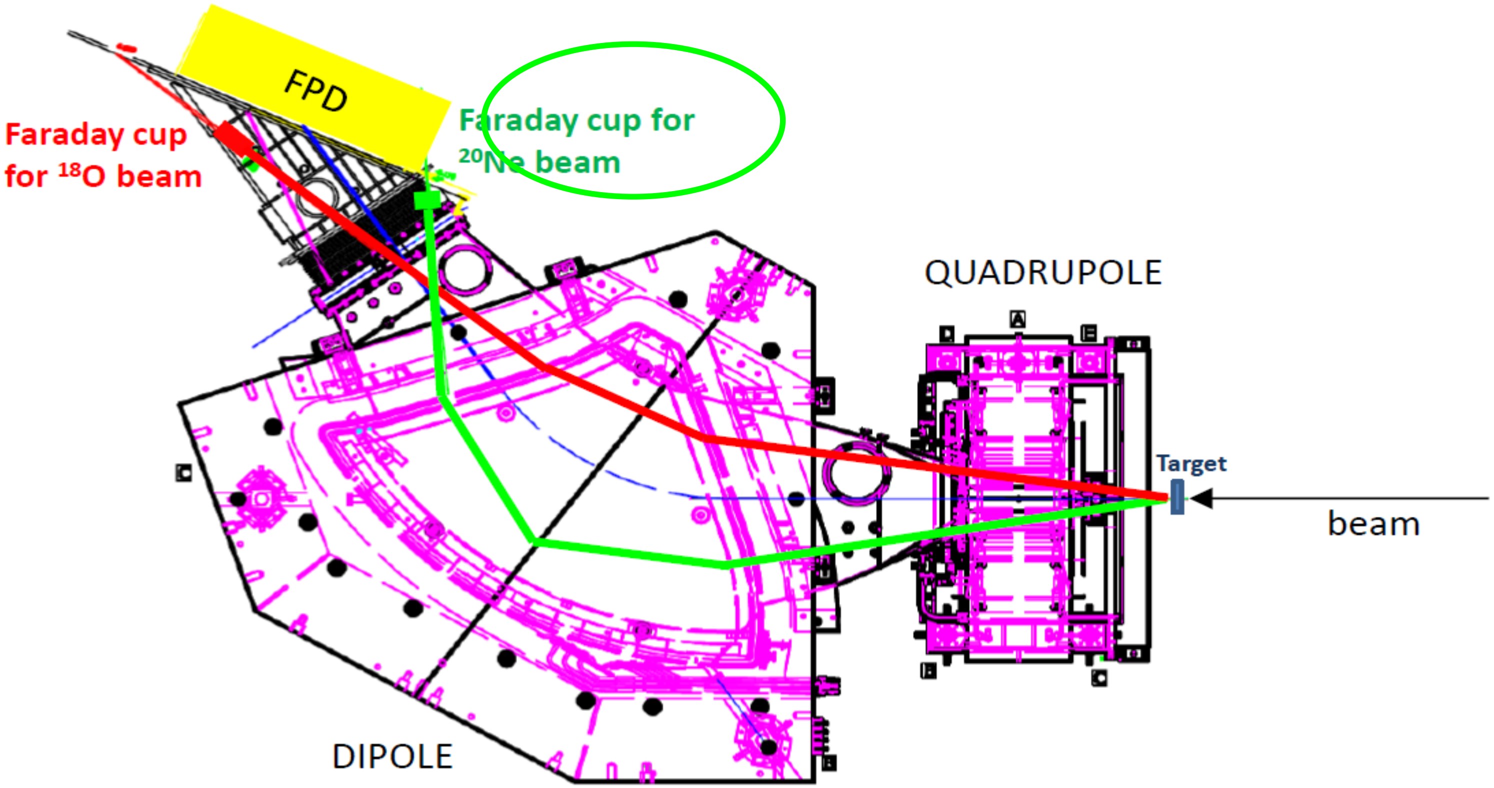
- Detailed knowledge of magnetic fields
- Powerful algorithms for solving the transport equations
- High performance detectors

Assures:

- Good compensation of aberrations
- Excellent quality of reconstructed parameters

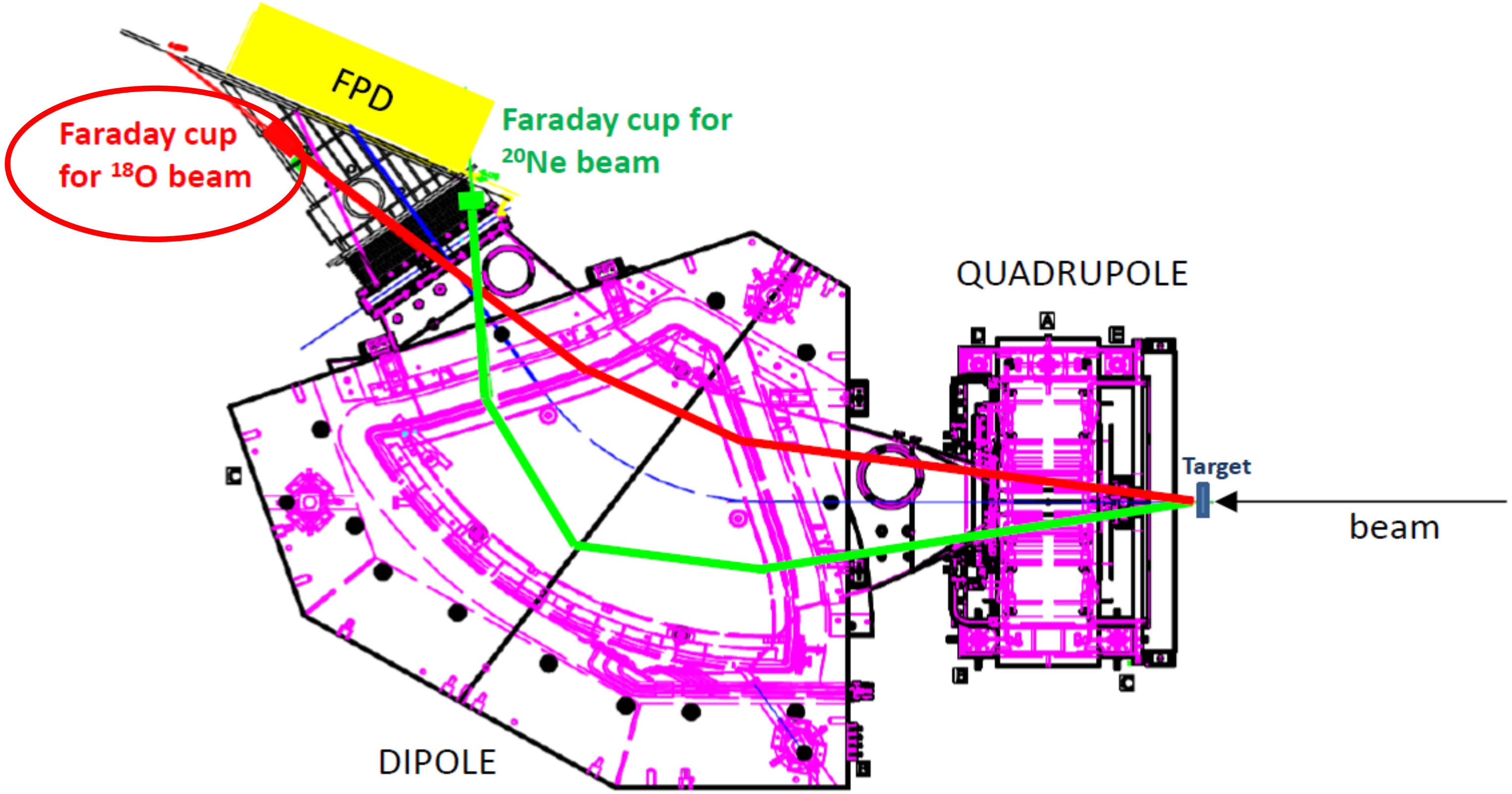
^{20}Ne @ 15 MeV/u

The incident beam ($^{20}Ne^{10+}$) has Bρ lower than the ejetiles of interest
Faraday Cup in the **«low Bρ»** region of the FPD



^{18}O @ 15 MeV/u

The incident beam ($^{18}O^{8+}$) has Bρ higher than the ejetiles of interest
Faraday Cup in the **«high Bρ»** region of the FPD



Nuclear Matrix Elements towards *0νββ*: theoretical model development

- Nuclear structure models and *0νββ* NME

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)

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

Transition probability of a **nuclear** process

- ✓ **Shell Model (SM)**
- ✓ **Approaches based on Energy Density Functional (i.e. RPA and extensions)**
- ✓ **Interacting boson model (IBM)**

One needs to resort to **nuclear structure models to simplify the computational problem** by reducing the number of active degrees of freedom (nuclear many-body problem)

- How to better constrain nuclear models?

1 Spectroscopy well described

- ✓ Masses
- ✓ Spectra
- ✓ Electromagnetic properties
- ✓ 1or 2 particle separation energies
- ✓ Occupation numbers
- ✓ …

2 Can we reduce the uncertainties on 0νββ NME by studying nuclear related properties?

In this persective **γγ** decay as well as **CE reactions** induced heavy ions may represent a key tool

As a probe of ***0νββ*** decay NME:

- ***M*** **DGT from heavy-ion DCE reactions :**

➢ DCE cross section can be factorized in terms of reaction and nuclear structure parts
➢ Nuclear structure part can be factorized in terms of target and projectile matrix elements

- **DGT transition :** correlation between M^{DGT} and $M^{0\nu}$

- **Double gamma decay** : a good correspondence between the Double Isobaric Analog State (DIAS) and the initial *ββ* state

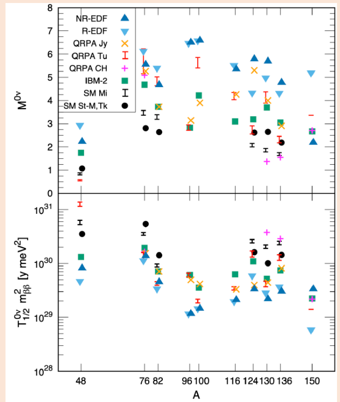
$${}^{A}_{Z}Y^{*}_{N} \longrightarrow {}^{A}_{Z}Y_{N} + 2\gamma$$

- Nuclear Matrix Elements for 0νββ decay candidates

Results produced by different models show a large spread, **a factor of about three,** that leads to big uncertainties

➢ on the amount of material required in the experiments
➢ on the neutrino mass in case *0νββ* will be observed

Great efforts, in various directions, should be made to improve the NME calculations

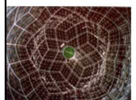


J. Engel and J. Menendez, Rep. Prog.r Phys. **80** (2017) 4 046301

CUORE

EXO200

KamLAND Zen



Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - 1k	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA

SNO+