Double Charge Exchange Reactions and their connections to neutrinoless double beta decay

INFN LNS — European Commission — erc NURE — NUMEN

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ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Recent advances and challenges in the description of nuclear reactions at the limit of stability

5 - 9 March 2018

0νββ decay

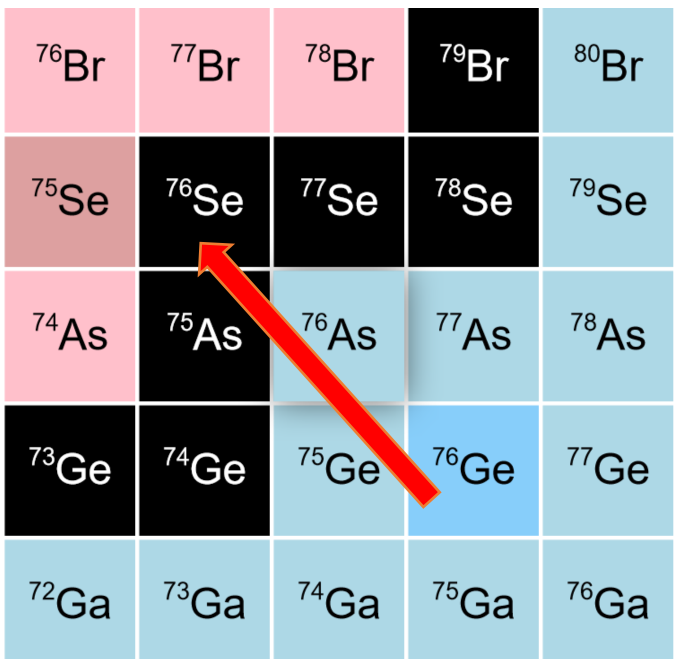
Open problem in modern physics:

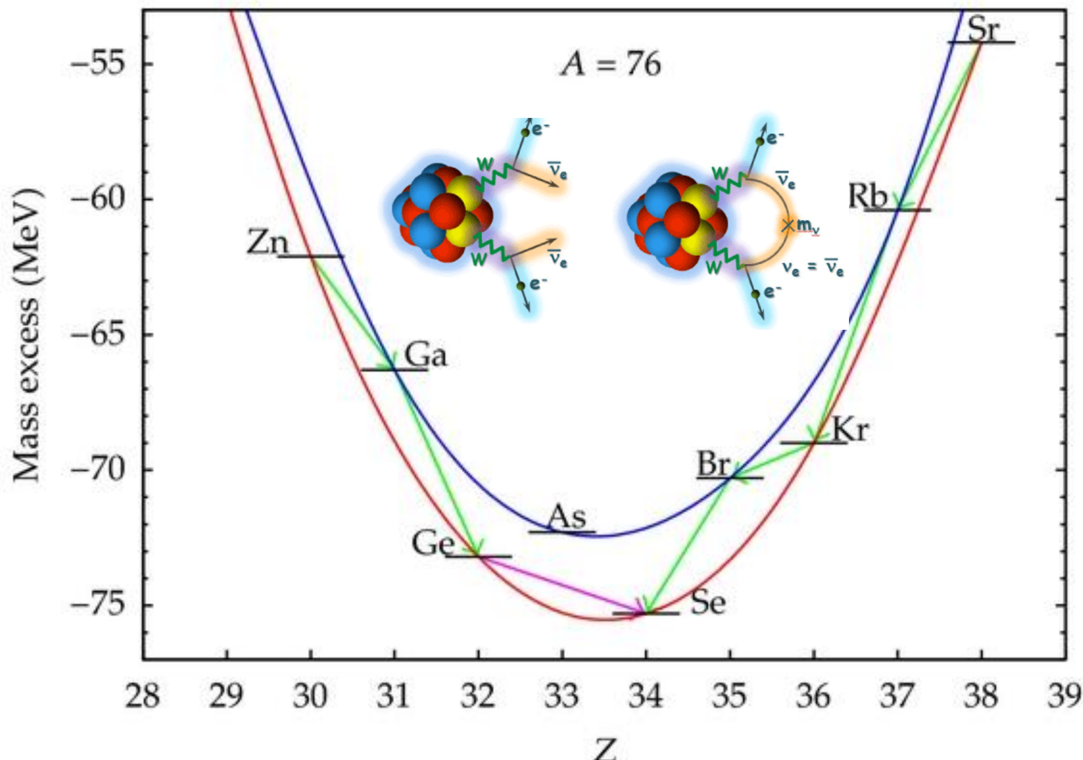
Neutrino absolute mass scale

Neutrino nature

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

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





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

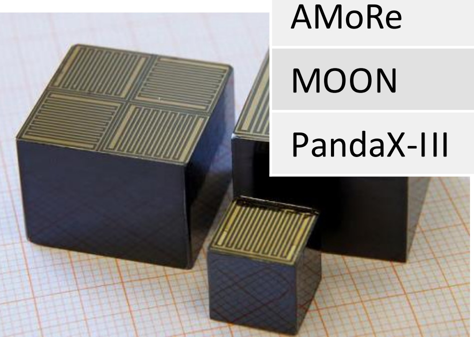
Search for 0νββ decay. A worldwide race

Experiment	Isotope	Lab
GERDA	^{76}Ge	LNGS [Italy]
CUORE	^{130}Te	LNGS [Italy]
Majorana	^{76}Ge	SURF [USA]
KamLAND-Zen	^{136}Xe	Kamioka [Japan]
EXO/nEXO	^{136}Xe	WIPP [USA]
CUPID - Lucifer	^{82}Se, ^{100}Mo	LNGS [Italy]
SNO+	^{130}Te	Sudbury [Canada]
SuperNEMO	^{82}Se	LSM [France]
CANDLES	^{48}Ca	Kamioka [Japan]
COBRA	^{116}Cd	LNGS [Italy]
DCBA	many	[Japan]
AMoRe	^{100}Mo	[Korea]
MOON	^{100}Mo	[Japan]
PandaX-III	^{136}Xe	CJPL [China]

Still not observed

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
- …



List not complete…

Nuclear Matrix Elements

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)

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

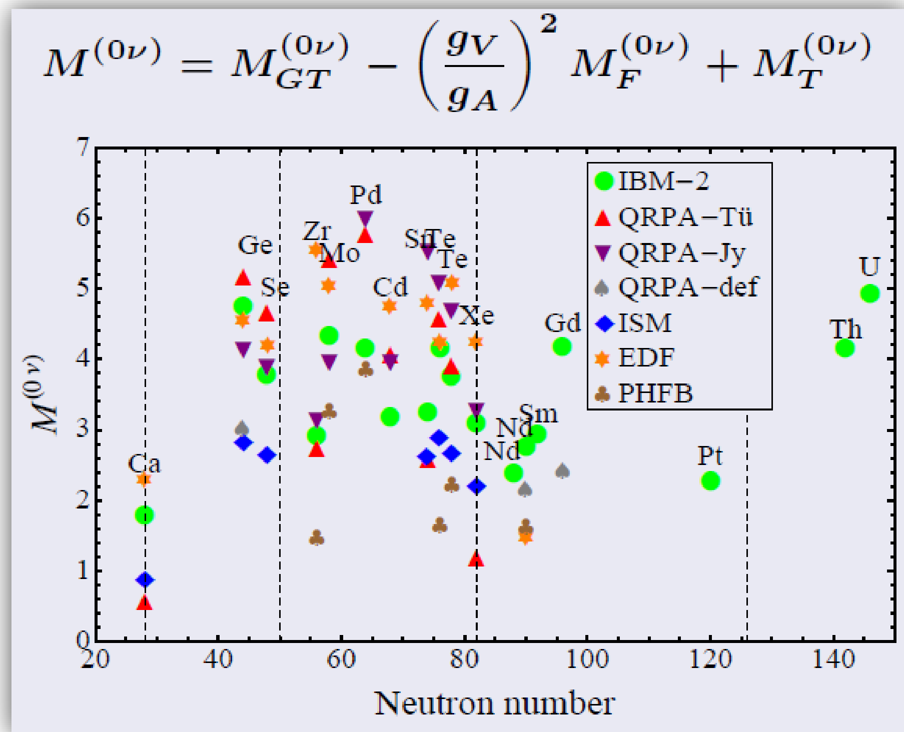
Transition probability of a **nuclear** process

Nuclear physics plays a key role!

Nuclear Matrix Elements

Nuclear Matrix Element (NME)

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



Calculations (still sizeable uncertainties):
QRPA, Large scale shell model, IBM, EDF, AB-INITIO …

Many body WaveFunctions!

A new experimental tool

Nuclear reactions
Double Charge Exchange reactions (DCE) to stimulate in the laboratory the same nuclear transition (g.s. to g.s.) occurring in 0νββ

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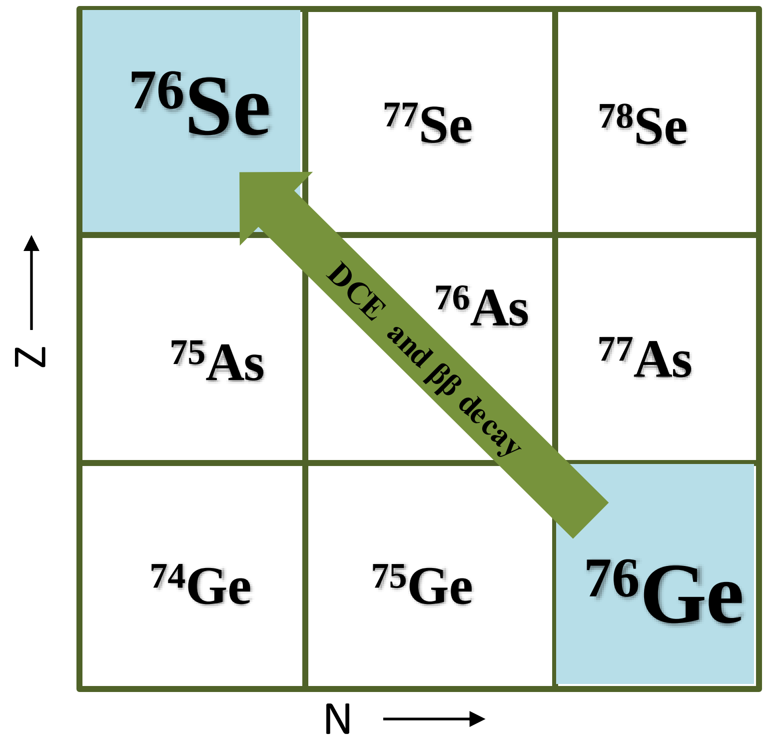


0νββ vs DCE

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Role of **neutrino** in 0νββ, role of **projectile** in DCE
- 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

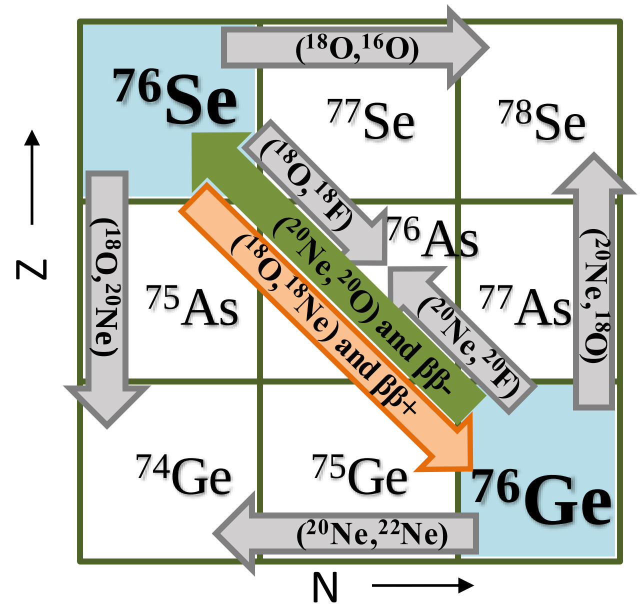
The project

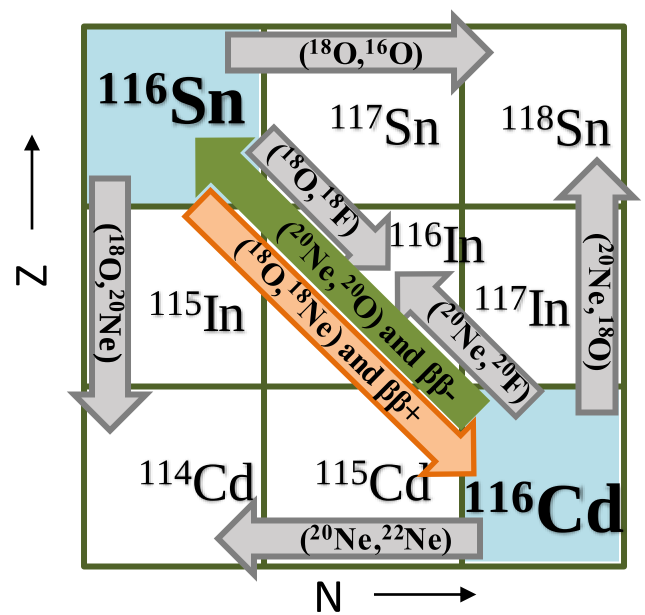
- **Transitions of interest for 0νββ:** ^{76}Ge↔^{76}Se, ^{116}Cd↔^{116}Sn, ^{130}Te→^{130}Xe

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

- **Complete net** of reactions which can contribute to the DCE cross-section: 1p-, 2p-, 1n-, 2n-transfer, single cex, DCE

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





The Goals of the Research Program

Main goal (Holy Grail):

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

The context

Single charge-exchange reactions
induced by light ions (^{3}He,t), (d,^{2}He), …

Interesting for β-decay and 2νββ!

Weak interaction probes

β, 2νββ,
μ-capture,
ν-nucleus scattering, …

Other researches

to extract information on NME from experimental data and/or constrain the theory

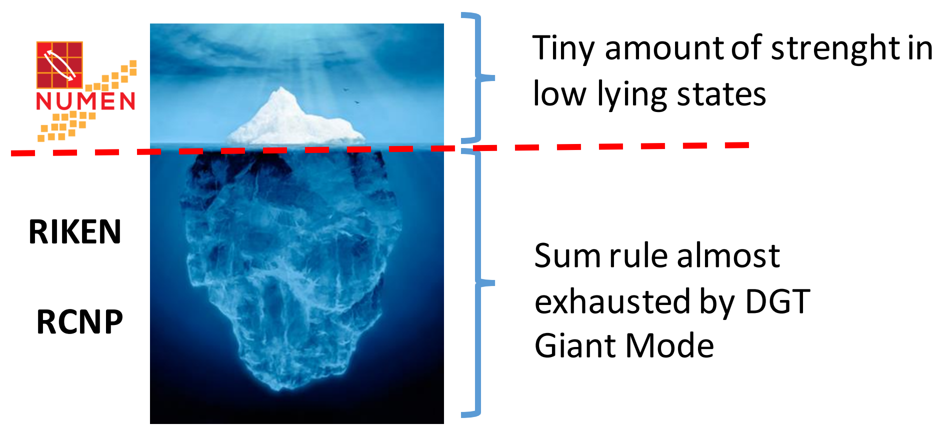
Transfer reactions

for constraining Ψ_i, Ψ_f

Double charge-exchange

induced by **pions** ($\pi^{\pm}$, $\pi^{\mp}$)
abandoned in the 80's due to the large differences in the momentum available and lack of direct GT component in the operators

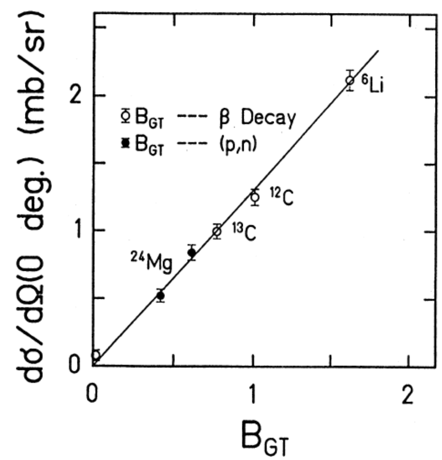
Heavy-ion induced **double charge-exchange**
limited in the past due to low cross-sections



Connection between β-decay and Single CEX

Single β-decay strenghs are proportional to single CEX cross-sections under specific conditions

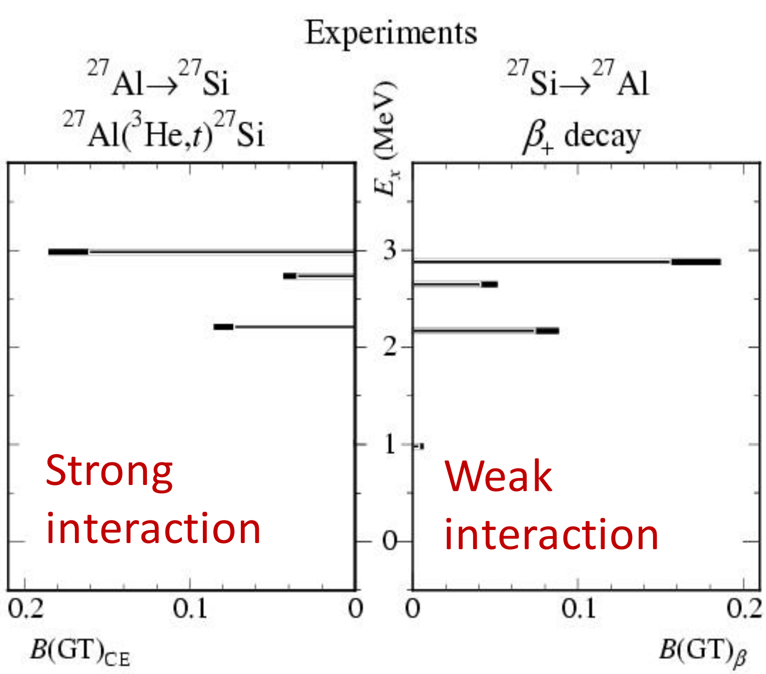
- **For (p,n), (n,p), (d,²He)**



F. Osterfeld Rev. Mod. Phys. 64 (1992) 491
T.N. Taddeucci Nucl. Phys. A 469 (1997) 125
H. Ejiri Phys. Rep. 338 (2000) 256
H.M. Xu, et al., Phys. Rev. C 52 (1995) R1161
H. Ejiri Phys. Rep. 338 (2000) 256

- **(³He,t)**

Y. Fujita Prog. Part. Nuc. Phys. 66 (2011)



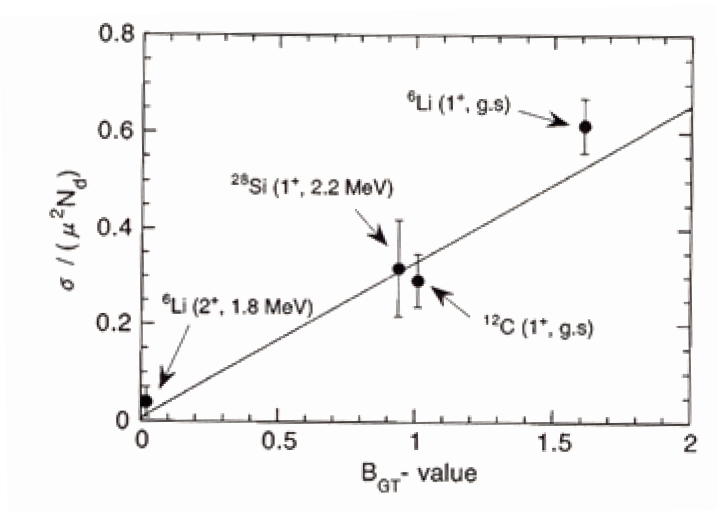
$$\frac{B(GT)_{[(3He,t);q=0]}}{B(GT)_{[\beta-decay]}} = 1 \pm 0.02$$

(In general for B(GT)>0.05)

ΔL = 0 (high energy, small angles)
Tensor components negligible

Connection between β-decay and Single CEX

- **For heavier projectiles: (^{7}Li,^{7}Be)**



S. Nakayama PRC 60 (1999) 047303

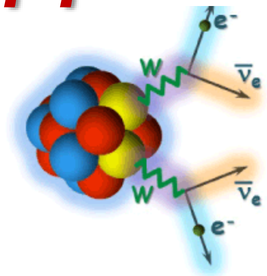
$$\frac{B(GT)_{[(^7\text{Li},7\text{Be});q=0]}}{B(GT)_{[\beta-\text{decay}]}} = 1 \pm 0.2$$

✓ **Confirmed** on different nuclei: ^{11}Be, ^{12}B, ^{15}C, ^{19}O (less accuracy)

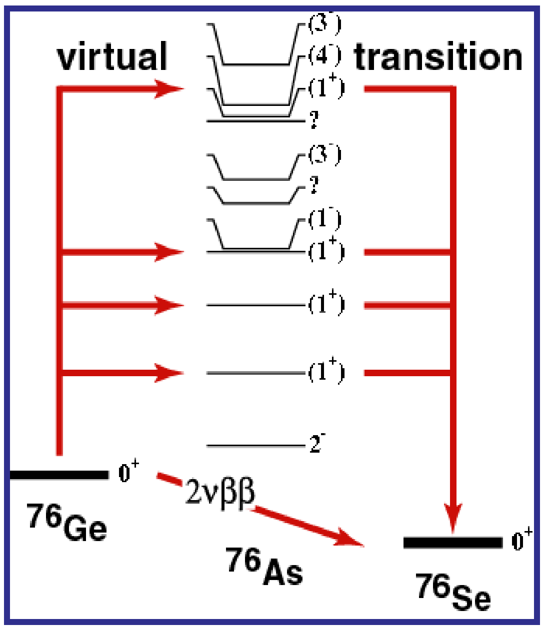
✓ **Microscopic and unified theory** of reaction and structure is mandatory for quantitative analyses

F. Cappuzzello et al., Nucl. Phys. A 739 (2004) 30-56
F.Cappuzzello et al. Phys.Lett B 516 (2001) 21-26
F.Cappuzzello et al. EuroPhys.Lett 65 (2004) 766-772
S.E.A.Orrigo, et al. Phys.Lett. B 633 (2006) 469-473
C.Nociforo et al. Eur.Phys.J. A 27 (2006) 283-288
M.Cavallaro Nuovo Cimento C 34 (2011) 1

2νββ - decay



q-available like ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
only allowed decays are possible (L = 0)

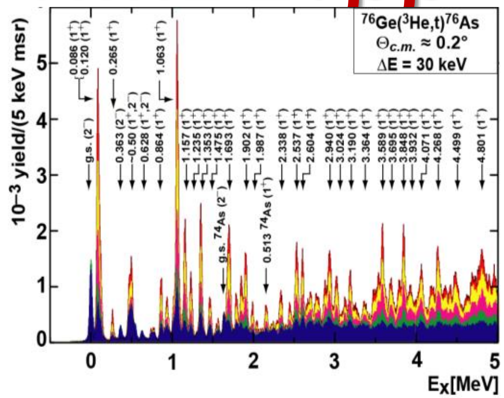


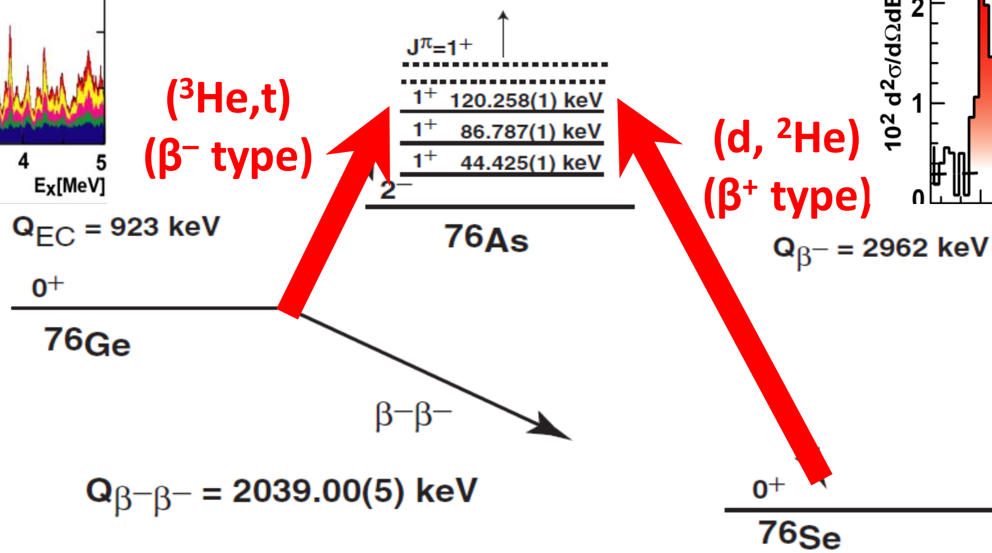
Single state dominance

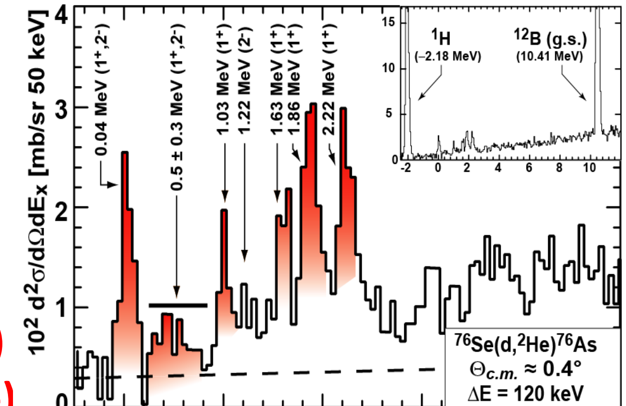
$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

Methodology for NME 2νββ - decay

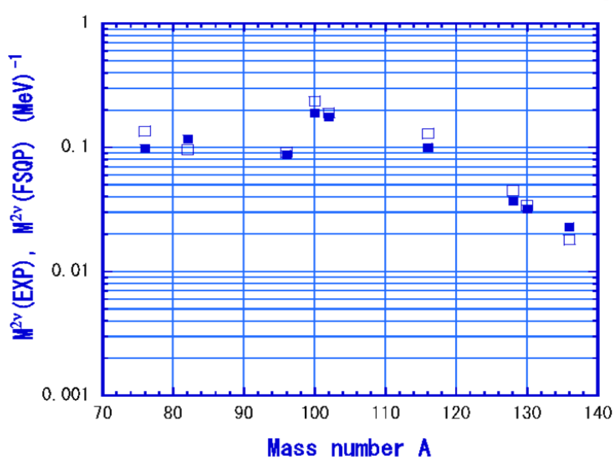
$$1/T^{2\nu}_{1/2}(0^+ \rightarrow 0^+) = G_{2\nu}\left|M^{\beta\beta 2\nu}\right|^2$$





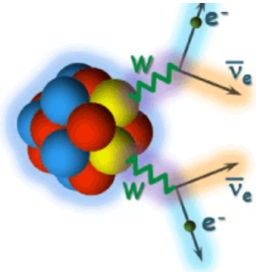


Assumption: all the signs are positive in the coherent sum of the amplitudes!

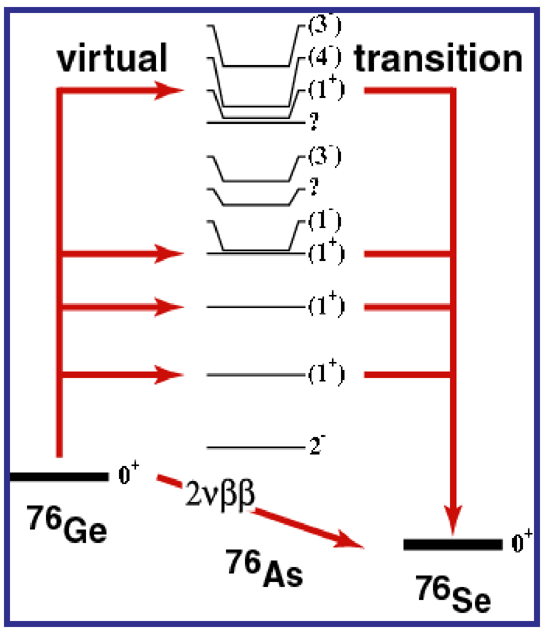


H. Ejiri Progr. Part. Nucl. Phys. 64 (2010) 249257

$2\nu\beta\beta$ - decay

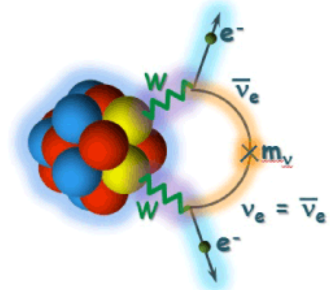


q-available like ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
only allowed decays possible (L = 0)

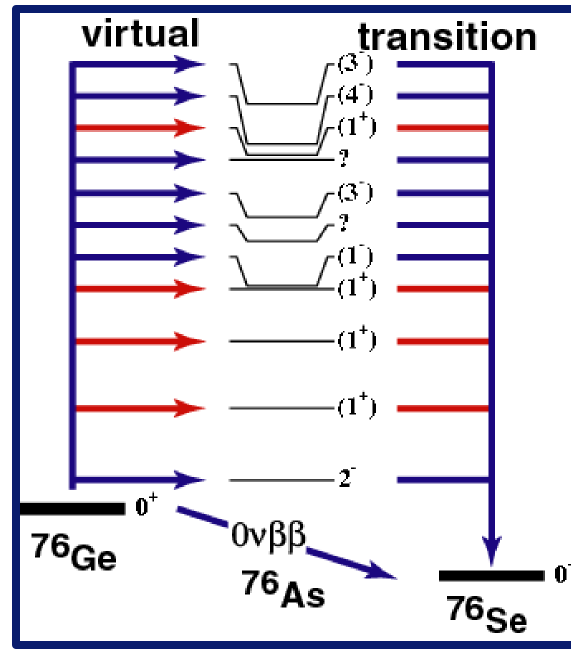


Single state dominance

$0\nu\beta\beta$ - decay



neutrino enters as virtual particle,
q ~ 0.5fm^{-1} (~ 100 MeV/c)
forbiddeness weakened L = 0, 1, 2…

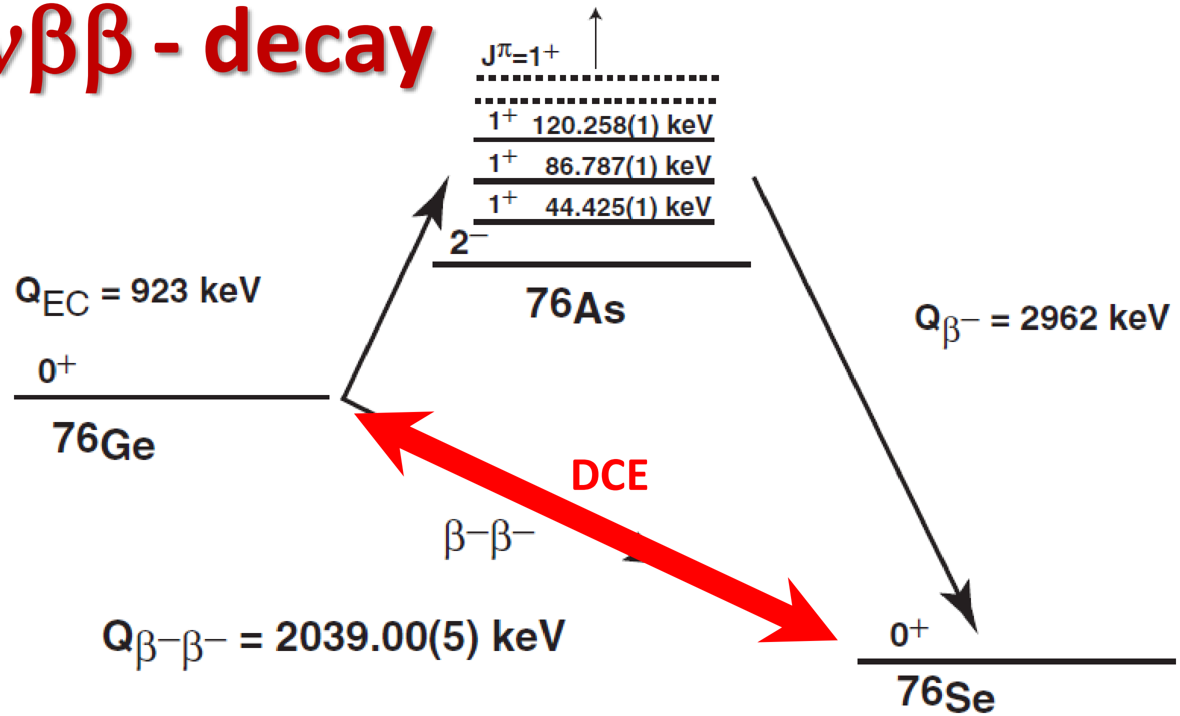


Closure approximation

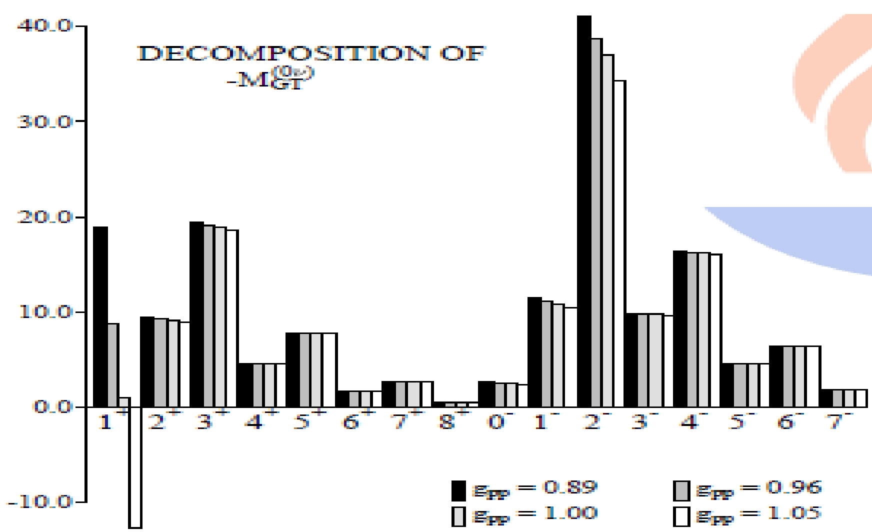
$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

Methodology for NME 0νββ - decay

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



Not accessible through CEX reactions

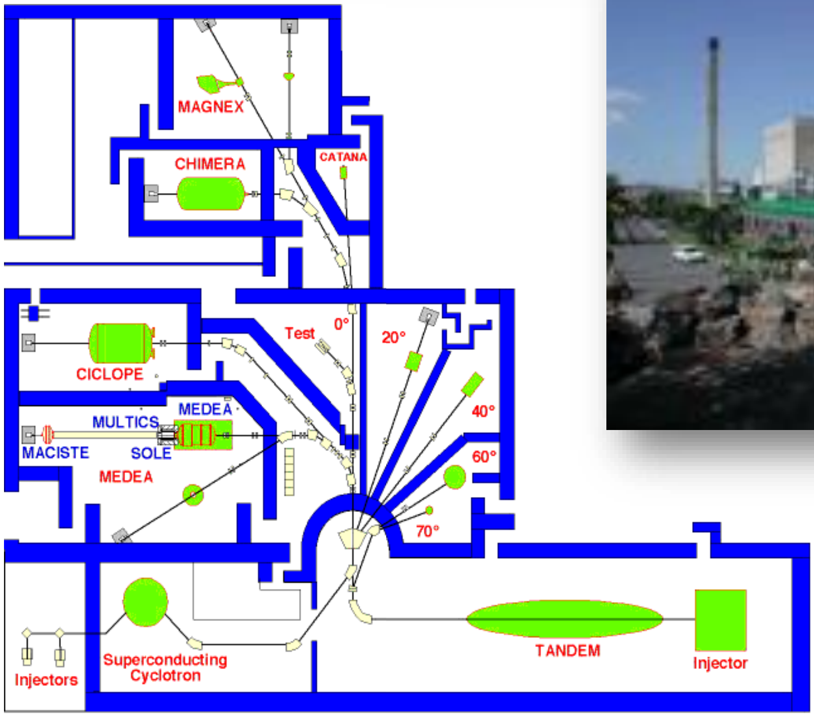


J.Hyvarinen and J.Suhonen PHYS. REV. C 91, 024613 (2015)

The experiments

NURE

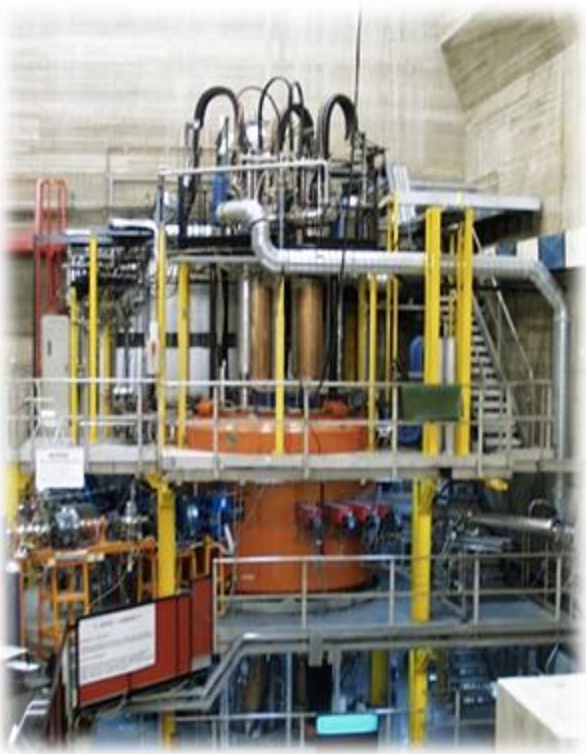
The LNS laboratory in Catania



The experimental facility

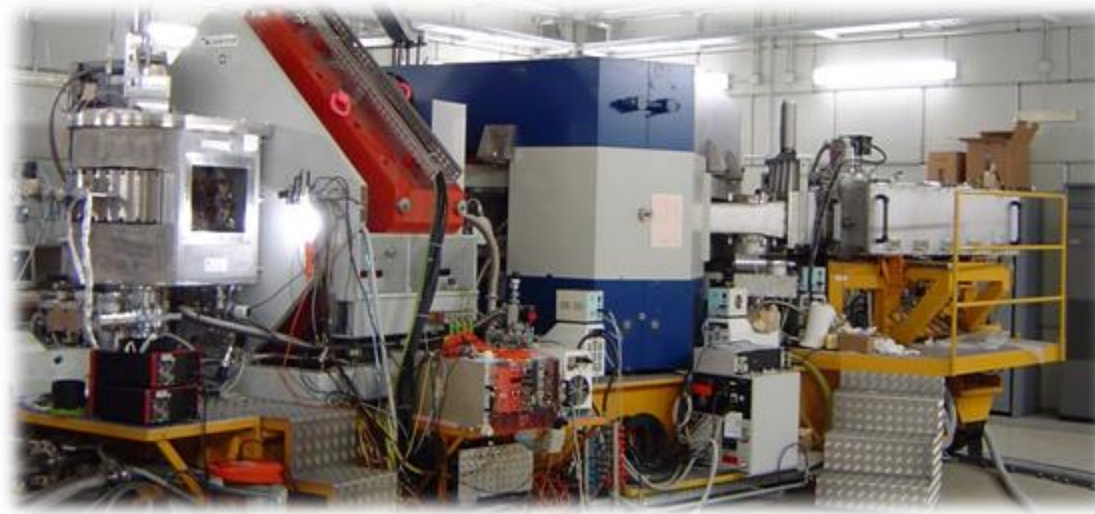
K800 Superconducting Cyclotron

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



MAGNEX spectrometer

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 $\Delta m/m \sim 1/160$

The pilot experiment

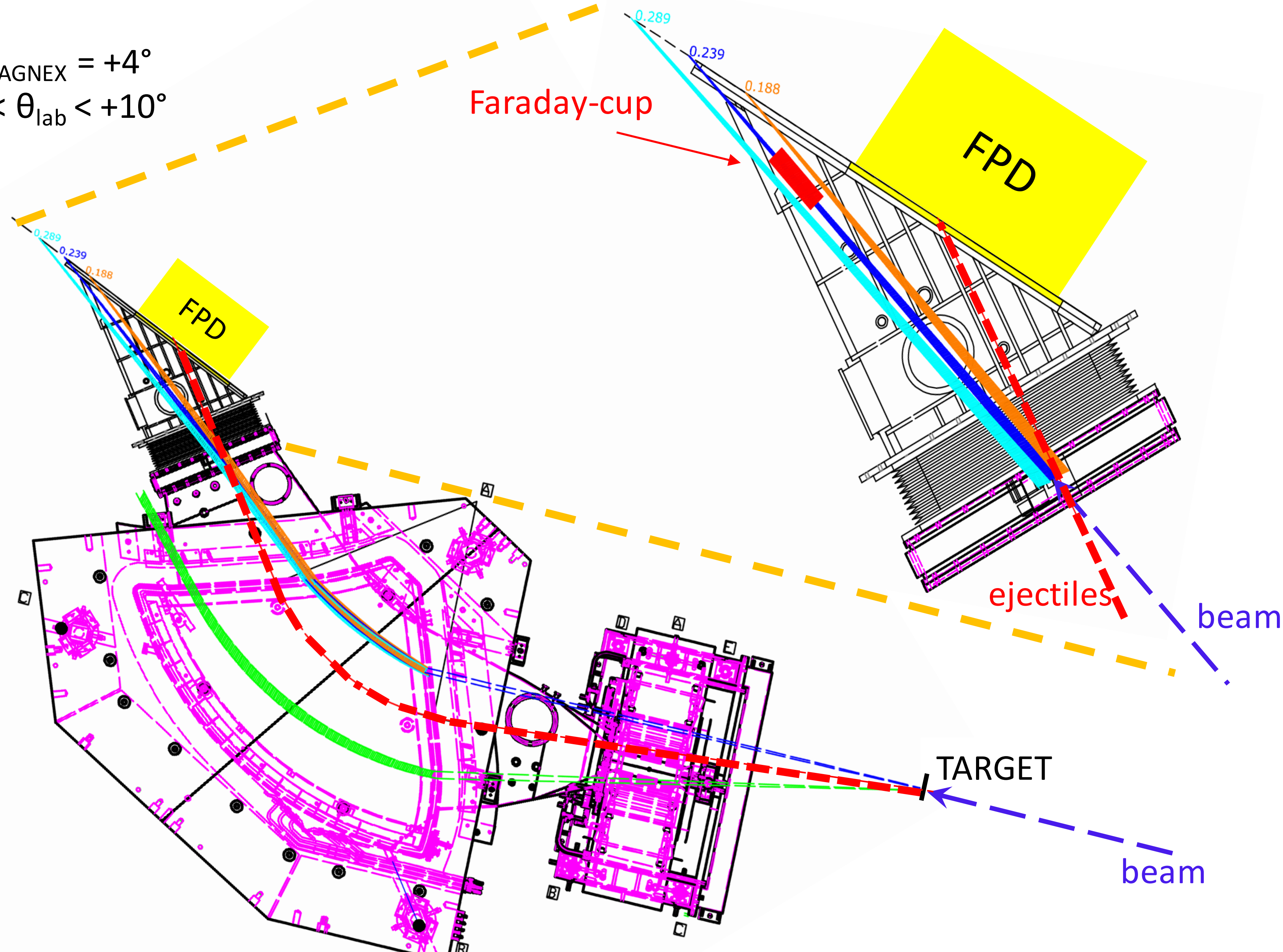
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV

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

- **$^{18}O^{7+}$** beam from Cyclotron at **270 MeV** (10 pnA, 3300 μC in 10 days)
- **^{40}Ca** target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer $0° < \vartheta_{lab} < 10°$

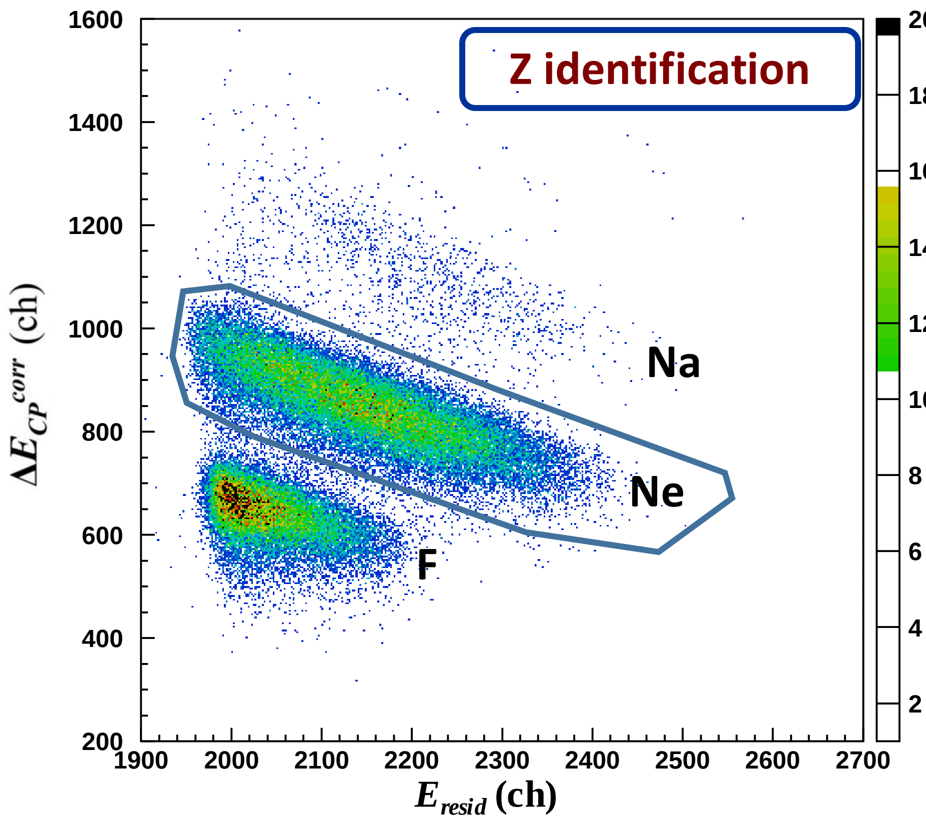
Zero-degree measurement

$\Theta_{MAGNEX} = +4°$
$-1° < \theta_{lab} < +10°$

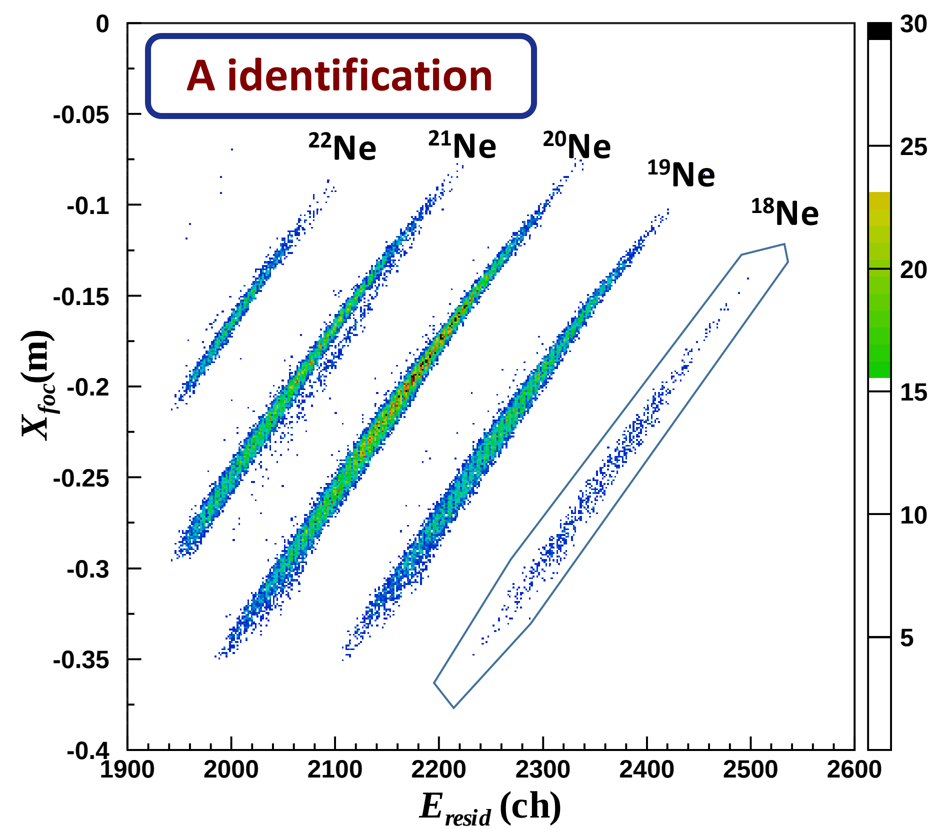


Particle Identification

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



$$Br = \frac{p}{q} \rightarrow X_{foc}^{2} \,\mu\, \frac{m}{q^{2}} E_{resid}$$



F. Cappuzzello et al., NIMA621 (2010) 419

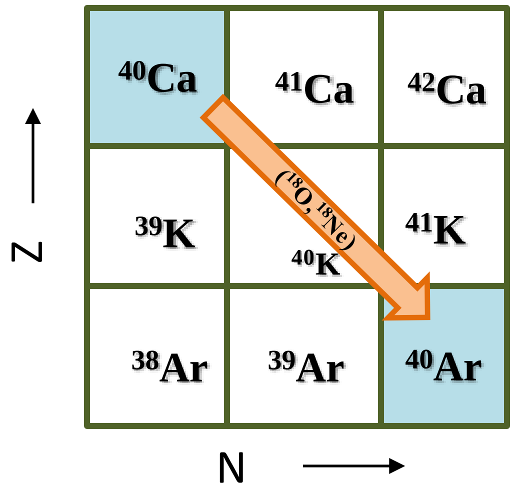
F. Cappuzzello, et al. NIMA638 (2011) 74

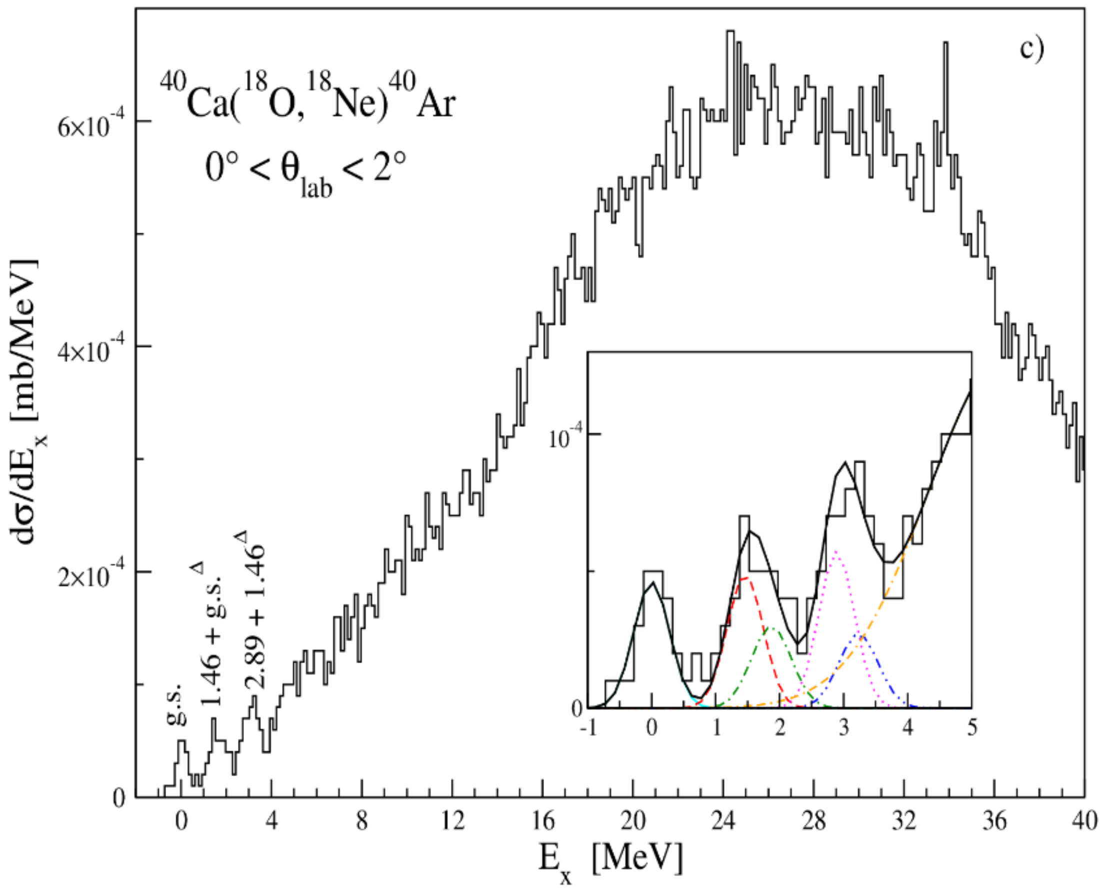
M.Cavallaro et al. EPJ A 48: 59 (2012)

D.Carbone et al. EPJ A 48: 60 (2012)

The pilot experiment

$^{18}O + ^{40}Ca$ at 270 MeV





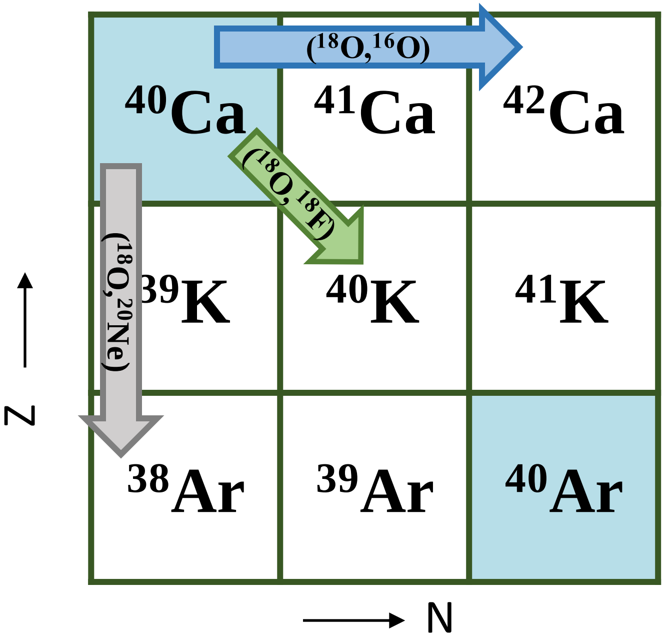
- **Experimental feasibility:** zero-deg, resolution (500 keV), low cross-section (μb/sr)

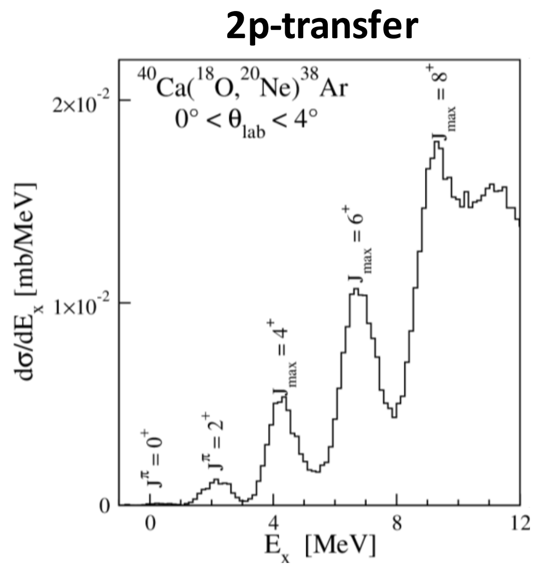
Limitations of the past HI-DCE experiments are overcome!

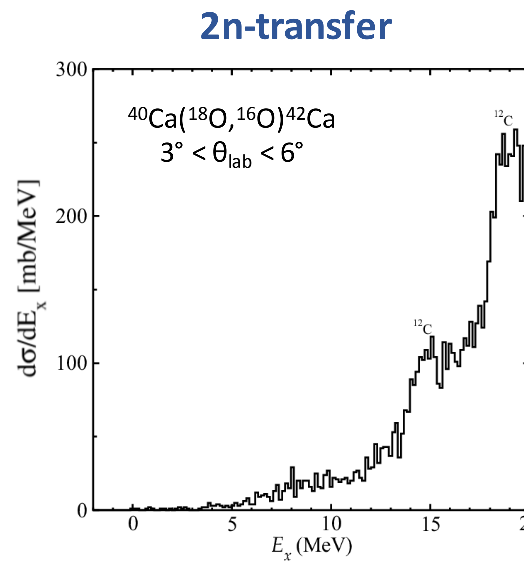
F. Cappuzzello, et al., Eur. Phys. J. A (2015) 51:145

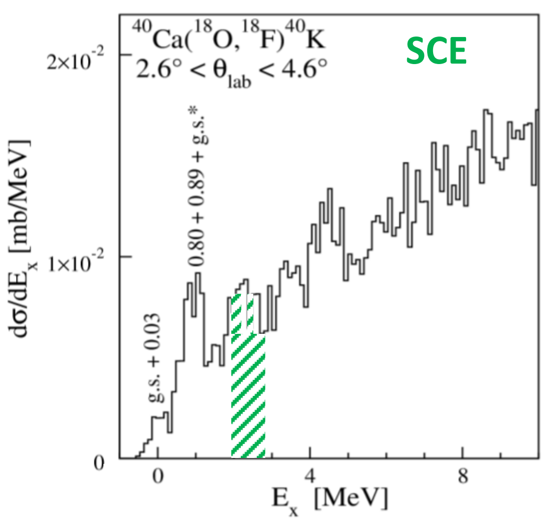
The pilot experiment

The role of the competing processes









x-section (2MeV < E_x < 3MeV)
≈ 0.5 mb/sr

Extracted B(GT) = 0.087 ± 0.02
B(GT) from (^{3}He,t) = 0.083
Y. Fujita

Present limitations

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

- An accurate job on the **theory** is mandatory

Moving towards hot-cases

- Reaction Q-values normally more negative than in the ^{40}Ca case
- (^{18}O,^{18}Ne) reaction particularly advantageous, but is of $\beta^+\beta^+$ kind
- Reactions of $\beta^-\beta^-$ kind are likely not as favourable as the (^{18}O,^{18}Ne):
  - (^{18}Ne,^{18}O) requires a radioactive beam
  - (^{20}Ne,^{20}O) or (^{12}C,^{12}Be) have smaller B(GT)
- In some cases gas or implanted target necessary (e.g. ^{136}Xe or ^{130}Xe)
- In some cases MAGNEX energy resolution not enough to separate the g.s. from the excited states in the final nucleus $\rightarrow$ Detection of γ-rays

Much higher beam current is needed

A broader view

The **NUMEN** project

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

TeBe

Theory

NUMEN_gr3
(R&D and experiments)
INFN CSN-III

CS-upgrade

NUMEN

NURE

SiCILIA INFN call

Other national and
regional projects

Operating in a wider context, in a longer time scale (10-15 yr), in close synergy with NURE

The **NUMEN** project

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

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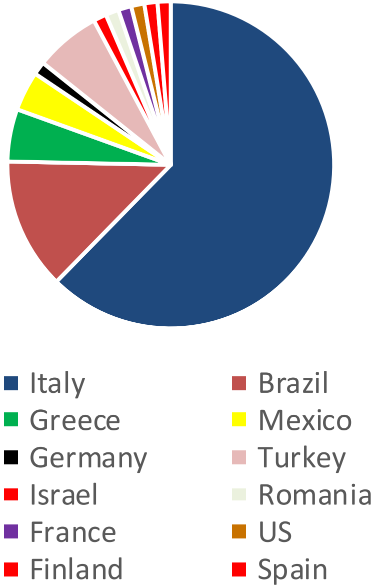
77 Researchers
25 Institutions
12 countries



The **NUMEN** project

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

- **Phase1**: The experimental **feasibility** (completed)

- **Phase2**: **Experimental exploration** of few cases (NURE), **work on theory** and **R&D** activity

- **Phase3**: **Facility upgrade** (Cyclotron, MAGNEX, beam line, …) to work with two orders of magnitude more intense beam

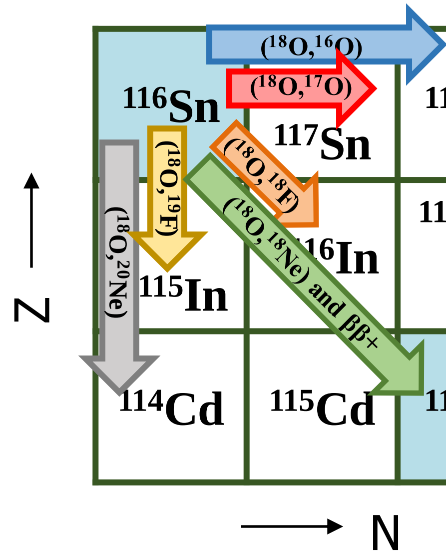
- **Phase4**: **Systematic experimental campaign** on all the systems with the upgraded facility

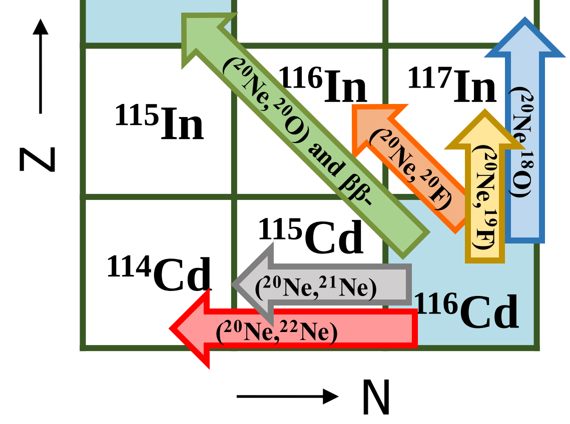
year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Phase1	done									
Phase2				Approved						
Phase3										
Phase4										

NUMEN runs – Phase 2

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

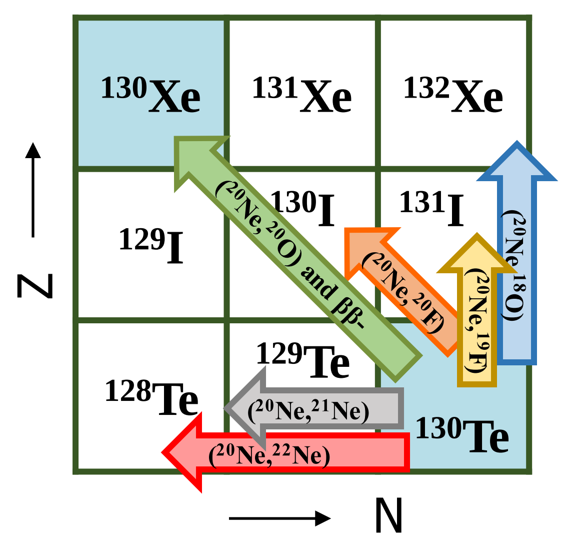
- Two experiments @ 15 MeV/A
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd





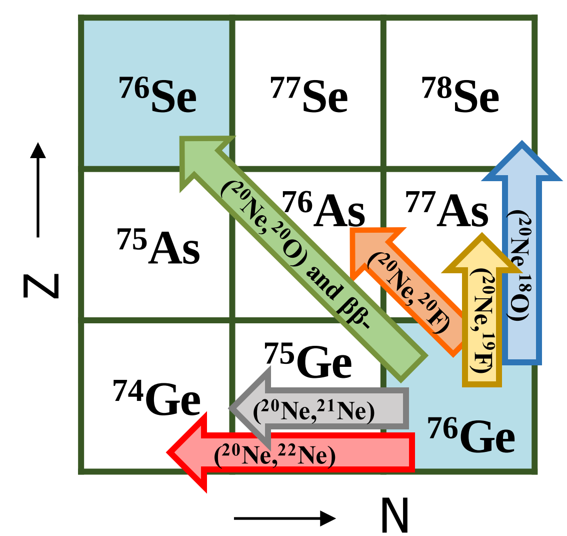
^{130}Te – ^{130}Xe case

- One experiment @ 15 MeV/A
- ^{20}Ne + ^{130}Te

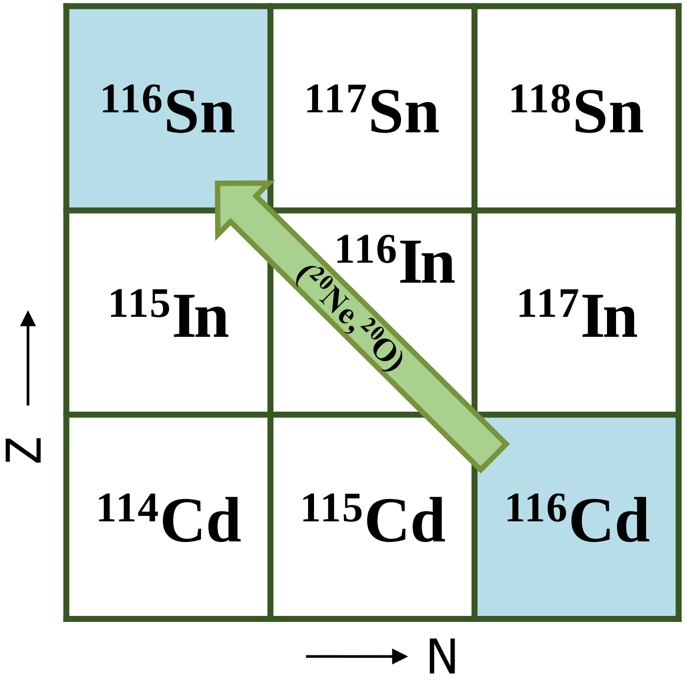


^{76}Ge – ^{76}Se case

- One experiment @ 15 MeV/A
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se at the end of 2018



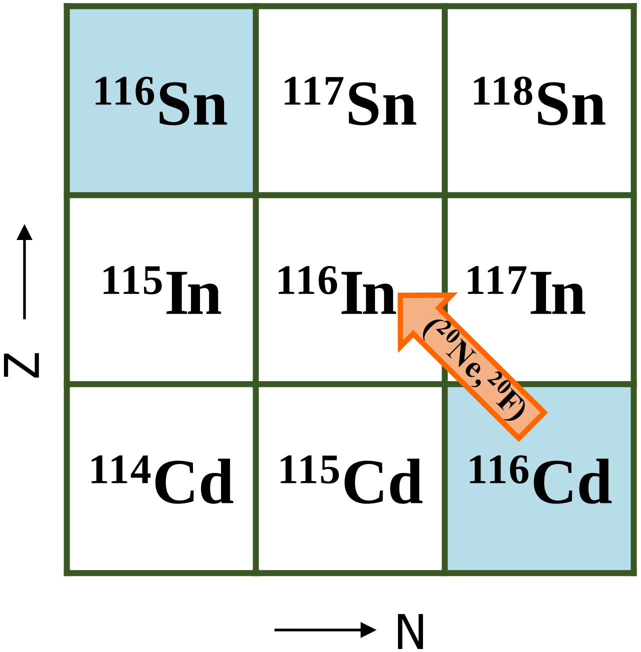
Experimental results



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

- g.s. → g.s. transition isolated
- Absolute cross section measured
- Cross-section sensitivity (<1nb at 5σ)

Experimental results



SCE reaction ^{116}Cd(^{20}Ne,^{20}F)^{116}In

^{116}In

E_x (MeV)	J^π
g.s.	1^+
0.127	5^+
0.223	4^+
0.272	2^+
0.289	8^-

^{20}F

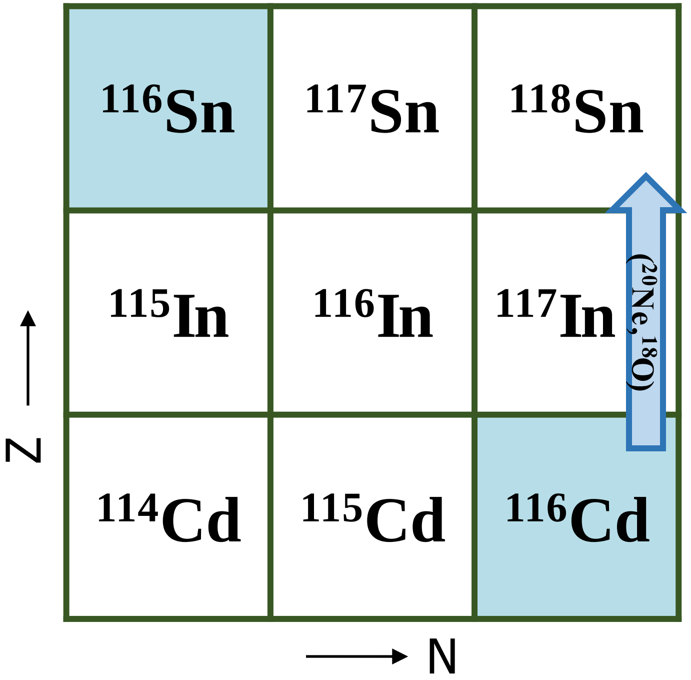
E_x (MeV)	J^π
g.s.	2^+
0.656	3^+
0.822	4^+
0.983	1^-

High level density in residual and ejectile

- **Population of high multipolarity states**
- **Multipole decomposition analysis needed**

Experimental results

2p-transfer ^{116}Cd(^{20}Ne,^{18}O)^{118}Sn



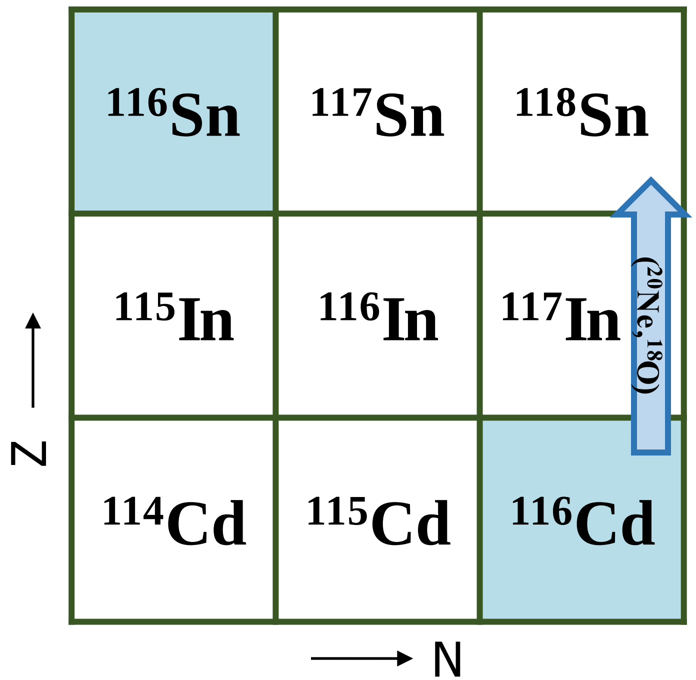
Cross section towards g.s. comparable with the DCE channel (12 ± 2 nb) similar to the ^{40}Ca experiment

Work on the theory

- M. Colonna (INFN-LNS)
- H. Lenske (Giessen)
- E. Santopinto (INFN-Genova)
- J. Lubian (UFF)
- J. Ferreira (UFF)
- J. A. Lay (Sevilla)
- S. Burrello (INFN-LNS)
- J. Bellone (INFN-LNS)

Talk of S. Burrello

Calculations for multi-nucleon transfer

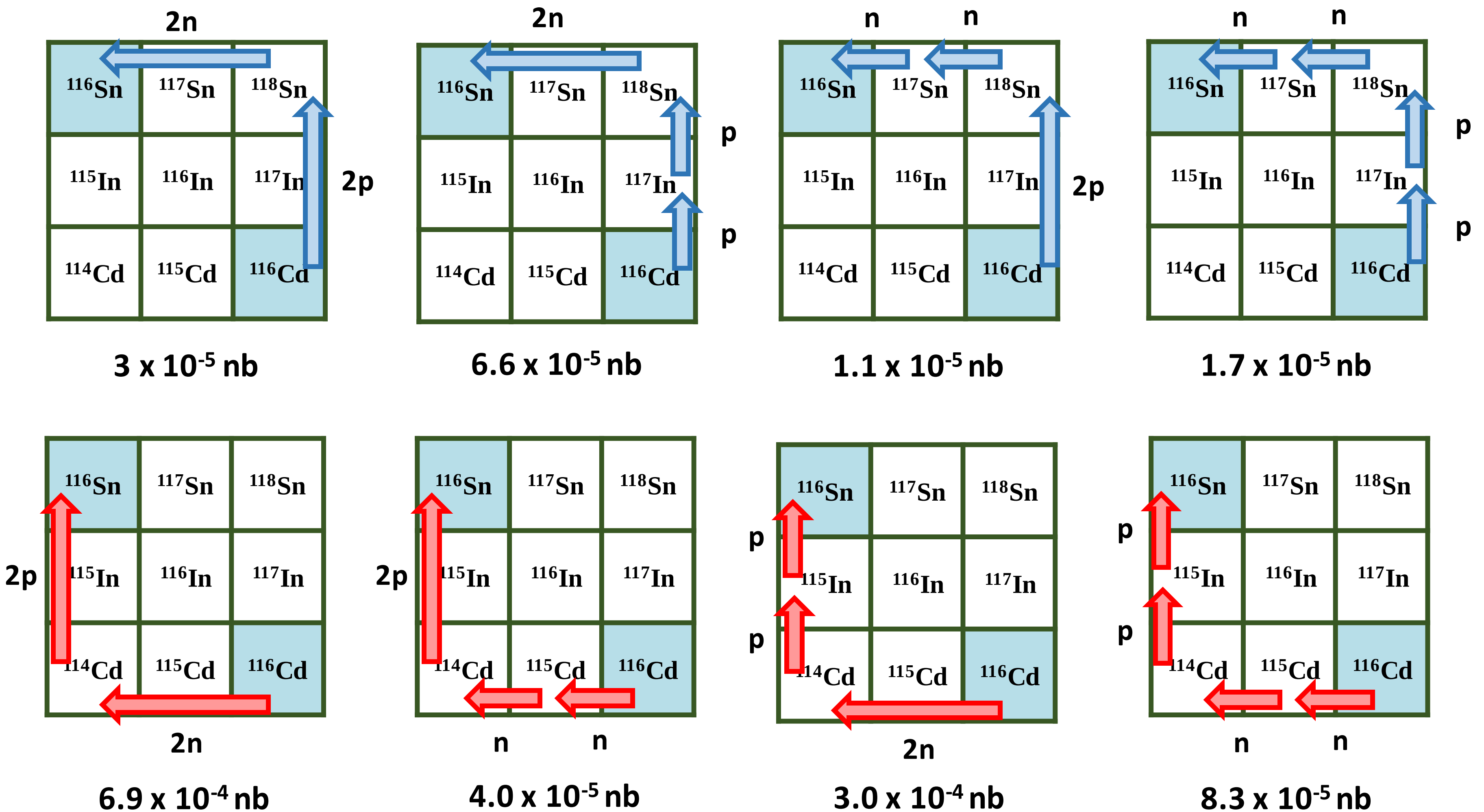


Calculations for multi-nucleon transfer

The role of multi-nucleon transfer routes

vs

The diagonal process (experimental cross section 12 ± 2 nb)



Calculations for multi-nucleon transfer

The role of multi-nucleon transfer routes

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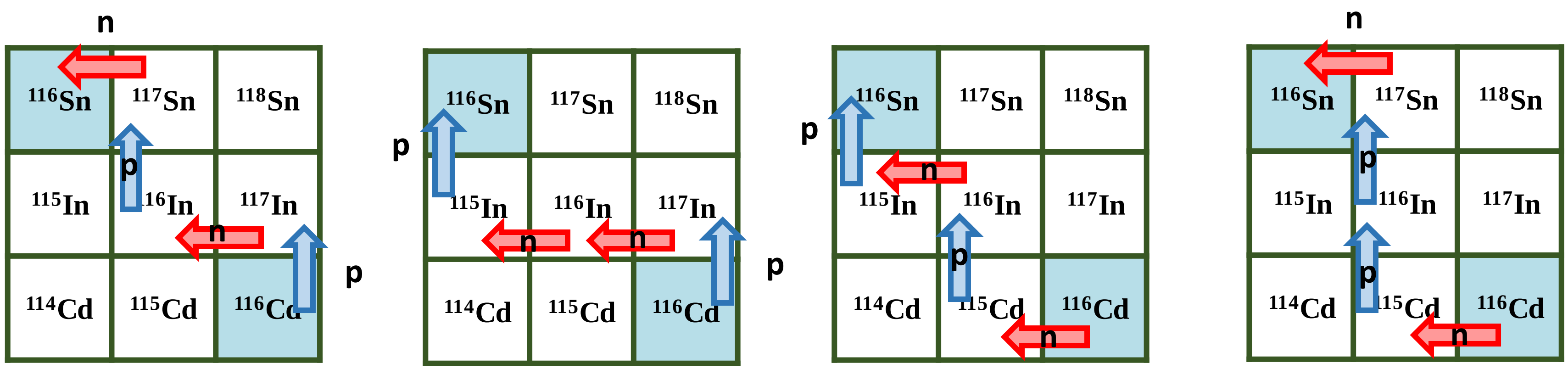
The diagonal process (experimental cross section 12 ± 2 nb)



9.4 x 10^{-8} nb   1.5 x 10^{-6} nb   3.2 x 10^{-7} nb   1.1 x 10^{-7} nb

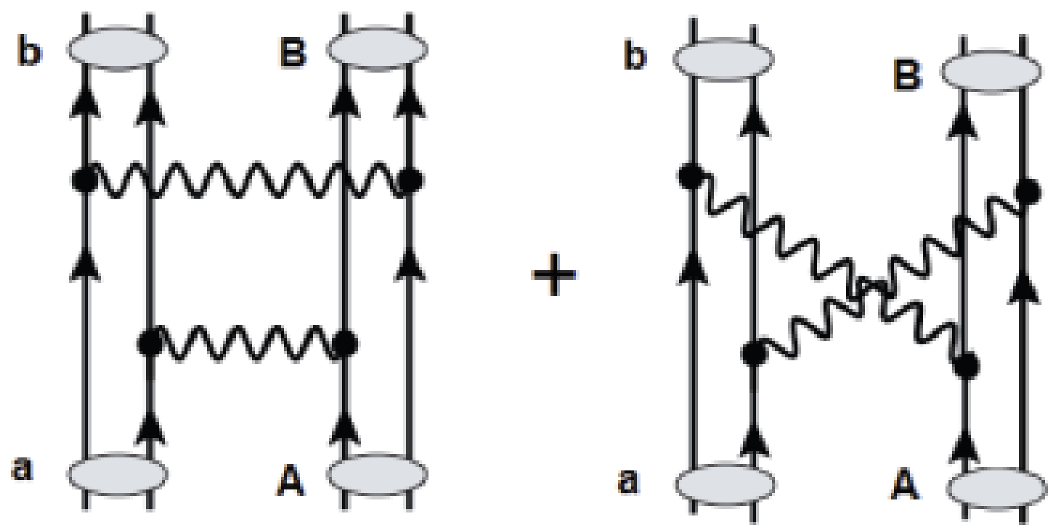
Negligible contribution of multi-nucleon transfer on the diagonal DCE process

Interplay between CEX + multi-nucleon transfer

What about double charge exchange process?

1. Double Single Charge Exchange (DSCE)

-two-step process, two uncorrelated single charge exchange,
-no correlation between the vertices
-analogies with 2νββ decay which is a is a sequential decay process where the leptons are emitted subsequently in an uncorrelated manner.

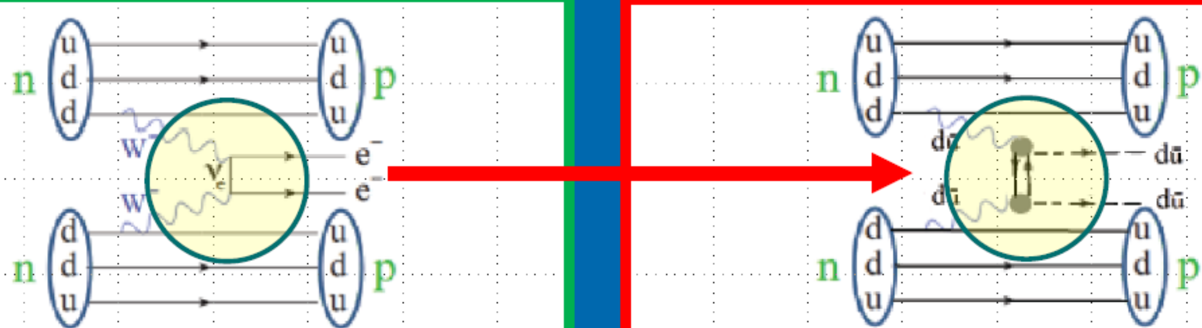


What about double charge exchange process?

2. Majorana double charge exchange (MDCE)

The two charge changing nucleons in the target (or in the projectile) are correlated through the exchange of a neutral meson → **Short range correlations**

weak 0ν2β decay | **Hadronic analogue**



From H. Lenske

weak 0ν2β decay

- simultaneous d→u Δq=+1 transitions by emission of a virtual weak gauge boson W^-
- $W^- \to e^- + \bar{\nu}_e / \nu_e$: decay into electron and Majorana neutrino
- Correlation of the two events by exchange of the virtual $\nu_e \bar{\nu}_e$ pair
- Emission of two electrons ON their mass-shell: $p^2_e = m^2_e$
- Direct observation (GERDA@LNGS...)

Hadronic analogue

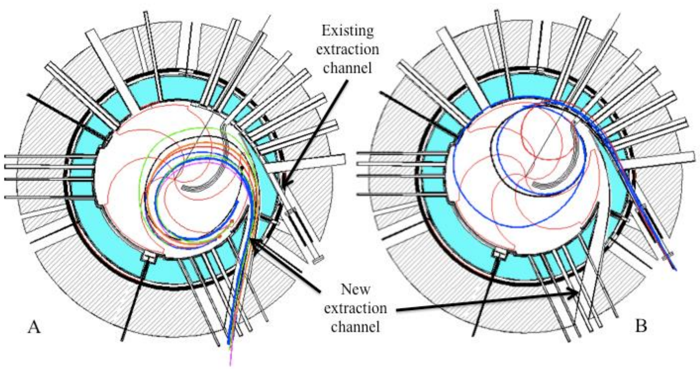
- simultaneous d→u Δq=+1 transitions by emission of a virtual $d\bar{u}$ vector pair ↔ ρ^- meson
- $\rho^- \to \pi^- + \pi^0$: decay into a pair of pions
- Heavy vector mesons ρ^{-*}
- Correlation of the two events by exchange of the virtual $q\bar{q}$ pair as contained in $\pi^0 \cong (d\bar{d}+u\bar{u})/\sqrt{2}$
- Emission of two π^- OFF their mass-shell: $p^2_\pi \neq m^2_\pi$
- No direct observation

The upgrade of the experimental facility

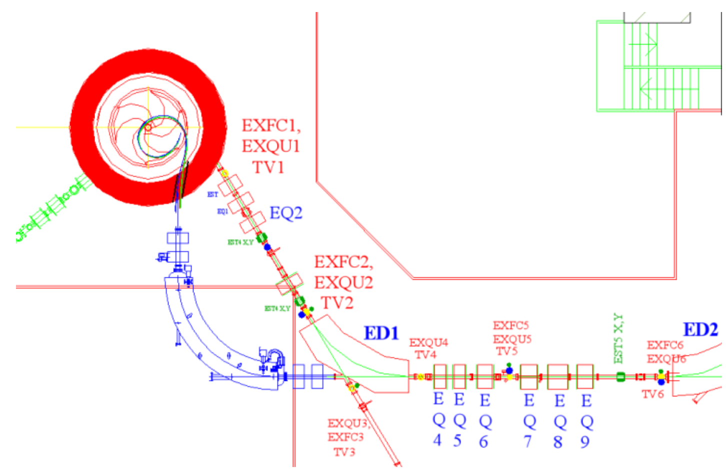
NUMEN

Upgrade of the LNS facility

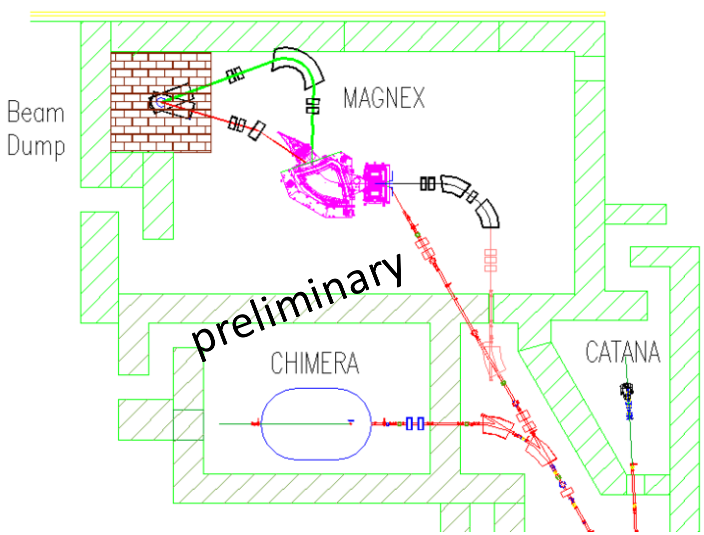
➢ Upgrade of the LNS accelerator and beam lines



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



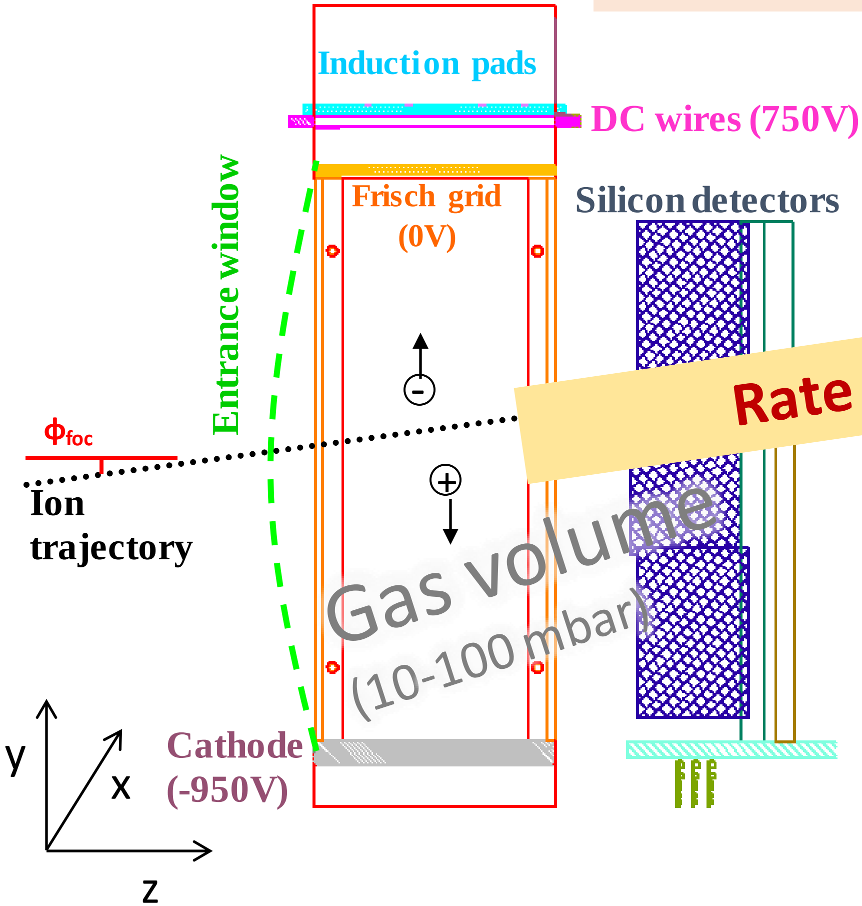
➢ Beam dump for the MAGNEX hall



Upgrade of MAGNEX

- The Focal Plane Detector

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



Rate limit few kHz

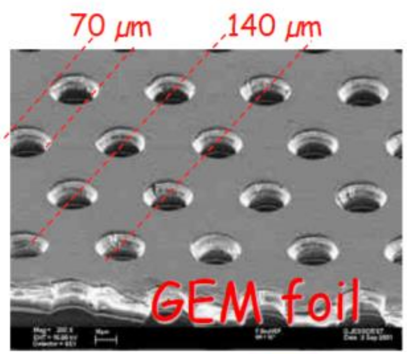
Large volume: 1360mm X 200mm X 96mm

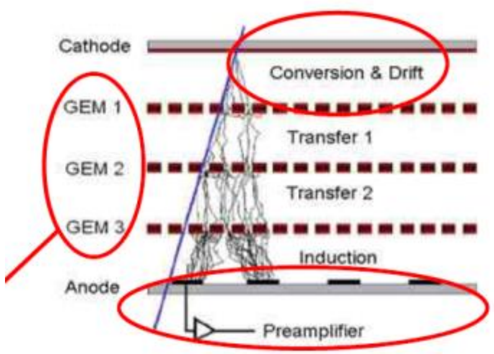
Upgrade of MAGNEX

➢ The Focal Plane Detector

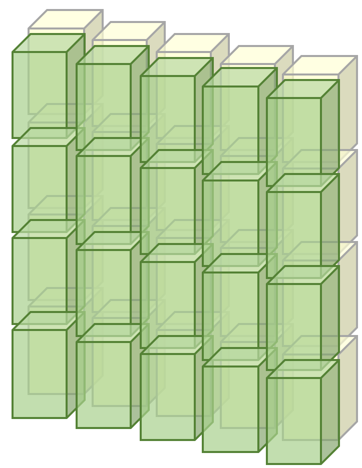
Rate
from few kHz to MHz
preserving low-pressure operation

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!!)





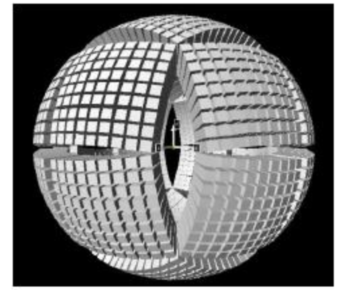
Micro-pattern tracker
low pressure and **wide dynamic range**



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

➢ SiC-SiC pad telescopes
➢ Phoswich detectors
➢ SiC (ΔE) + scintillator (E)

Upgrade of MAGNEX



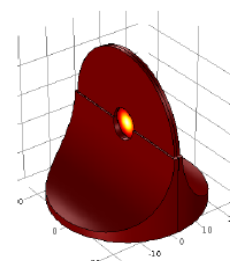
➢ Array of scintillators for γ-rays

- Measurement in coincidence with MAGNEX

➢ New electronics

- ASIC front–end chip **VMM2(3)**
- Read – out: new generation of **FPGA** and System On Module (**SOM**)

➢ Radiation tolerant Targets



- Evaporation on a **Graphite backing** (good properties)
- **Cooling** system

➢ Magnets upgrade

- **Increase** of the maximum **magnetic rigidity** from 1.8 Tm to 2.5 Tm

A challenging program

Theory:
Formal development and calculations

Accelerator and beam lines:
Upgrade of the Superconducting Cyclotron for high power

Detectors:
- Gas tracker for high rate heavy ions at low pressure (MPGD)
- PID wall covering a large area made of radiation hard and high resolution detectors (SiC)
- Gamma detectors

Mechanics:
Beam dump for zero-degree beam downstream of the spectrometer

Targets:
For intense heavy-ion beams

Conclusions and Outlooks

- Many **experimental facilities** for $0\nu\beta\beta$ half-life, but not for the **NME**
- Pioneering experiments shown that **DCE cross sections can be suitably measured** and **quantitative information on $0\nu\beta\beta$ NME** are not precluded
- **Experimental campaign** on nuclei candidates for $0\nu\beta\beta$ and work on the **theory**
- The **upgrade** for the INFN-LNS cyclotron and the MAGNEX spectrometer will allow to build a **unique facility** for a systematic exploration of all the nuclei candidate for $0\nu\beta\beta$

The NUMEN collaboration

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