Recent results on heavy-ion induced reactions of interest for neutrinoless double beta decay at INFN-LNS

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NSD2019

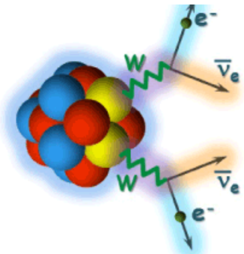
13-17 May, 2019 - Venice, Italy

IV International Conference on Nuclear Structure and Dynamics

Double β-decay

Two-neutrino double beta decay

M. Goeppert-Mayer, Phys Rev. 48 (1935) 512



Observed in 11 isotopes since 1987

Ordinary 2° order β decay

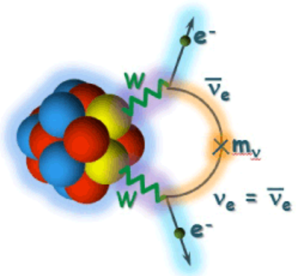
$$^{A}_{Z}X_N \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^- + (2\bar{\nu})$$

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

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

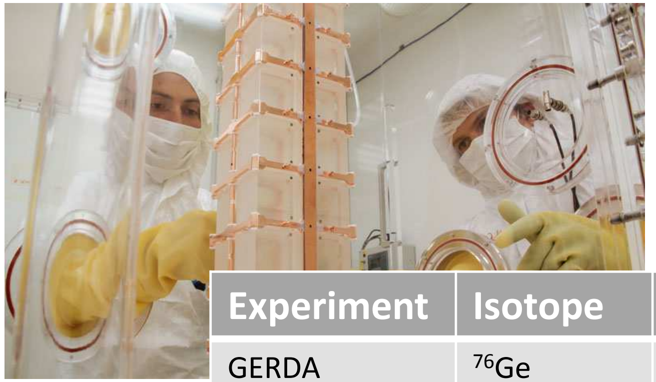
Neutrinoless double beta decay

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



Still not observed

Beyond standard model

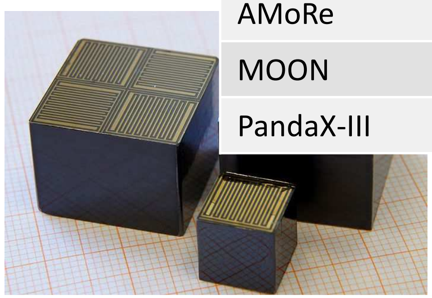


Search for 0νββ decay: A worldwide competition

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]

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**

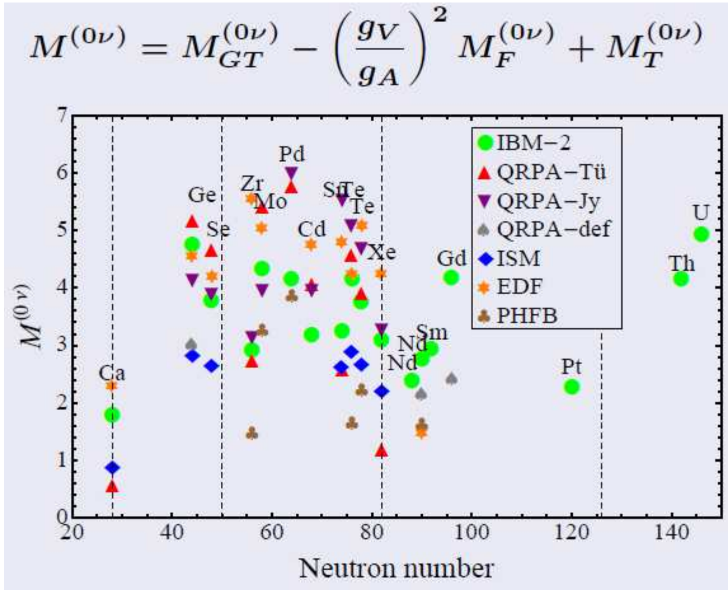
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

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

Nuclear physics plays a key role!



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

A new experimental tool

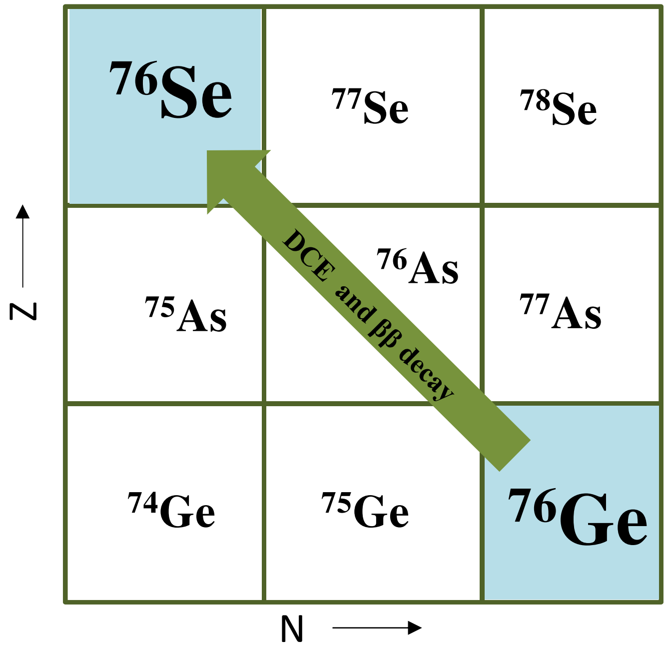
Nuclear reactions
Heavy-Ion induced Double Charge Exchange reactions (DCE)
to stimulate in the laboratory the same nuclear transition
(**g.s. to g.s.**) occurring in 0νββ

NUMEN

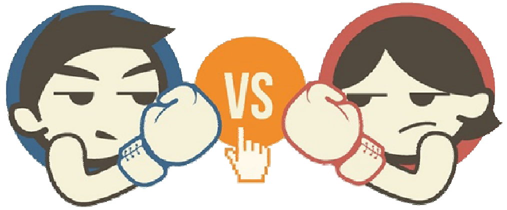
European Commission

erc NURE

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



$0\nu\beta\beta$ vs DCE



Differences

- DCE mediated by **strong interaction**, $0\nu\beta\beta$ by **weak interaction**
- Decay vs reaction **dynamics**
- DCE includes **sequential** transfer **mechanism**

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 Goals of the Research Program

The dream:

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

Mid term goals:

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

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 to constrain the theory

Transfer reactions
for constraining Ψ_i, Ψ_f

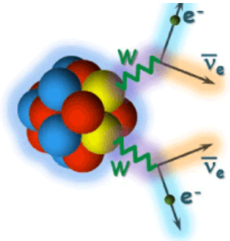
Double charge-exchange
induced by **pions** ($\pi^{\pm}$, $\pi^{\mp}$)
abandoned in the 80's due to the large differences in the momentum available and lack of direct GT component in the operators

Heavy-ion induced **double charge-exchange**

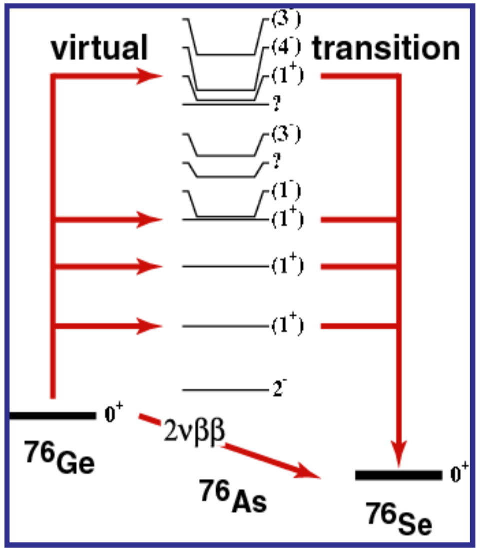
Limited in the past due to low cross-sections

Renewed interest thanks to availability of modern technology (INFN-LNS, RCNP, RIKEN)

2νββ - decay

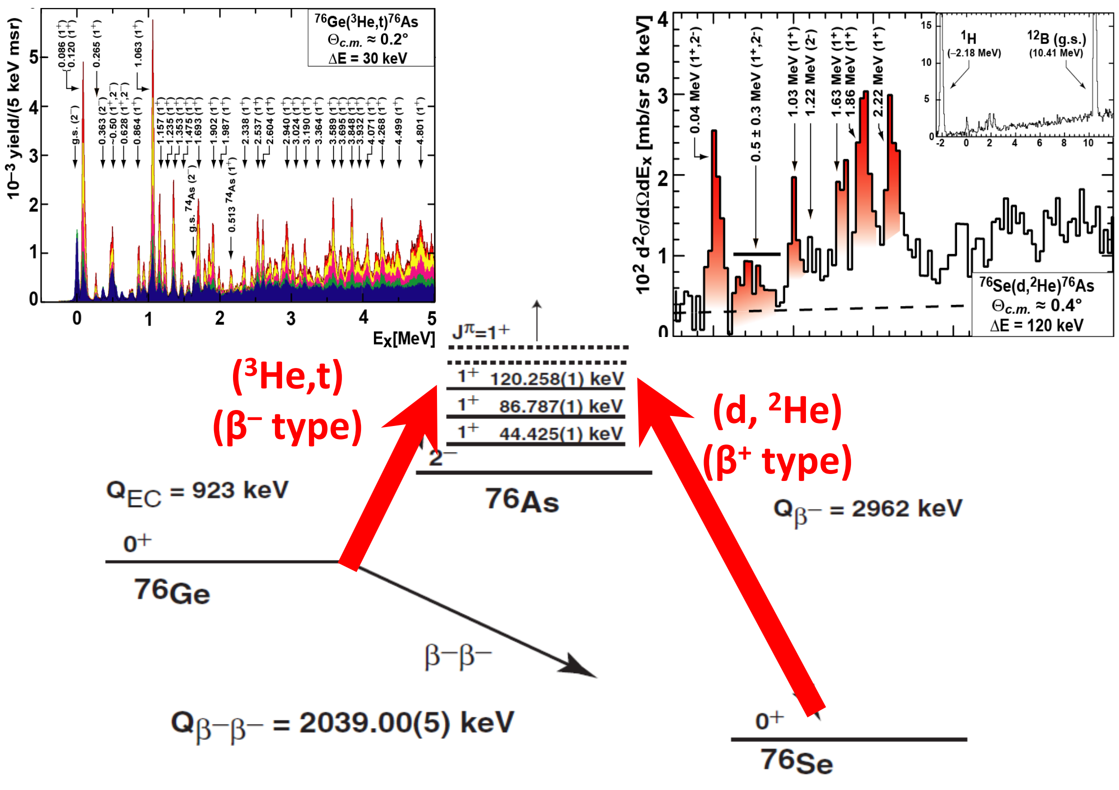


q-available like ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
only allowed decays are possible (L = 0)



Single state dominance

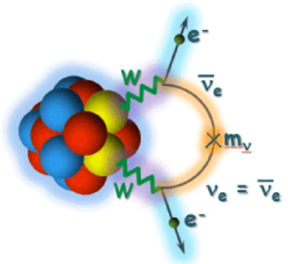
Methodology:
Single CEX to populate intermediate states and approximation (SSD / all positive signs in the coherent sum of the amplitudes)



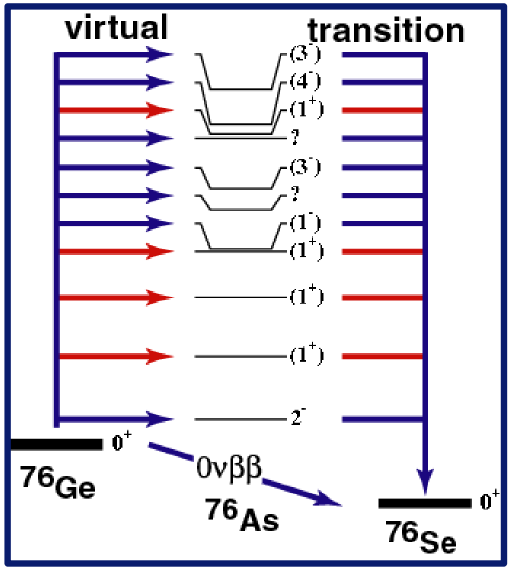
$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

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

0νββ - decay



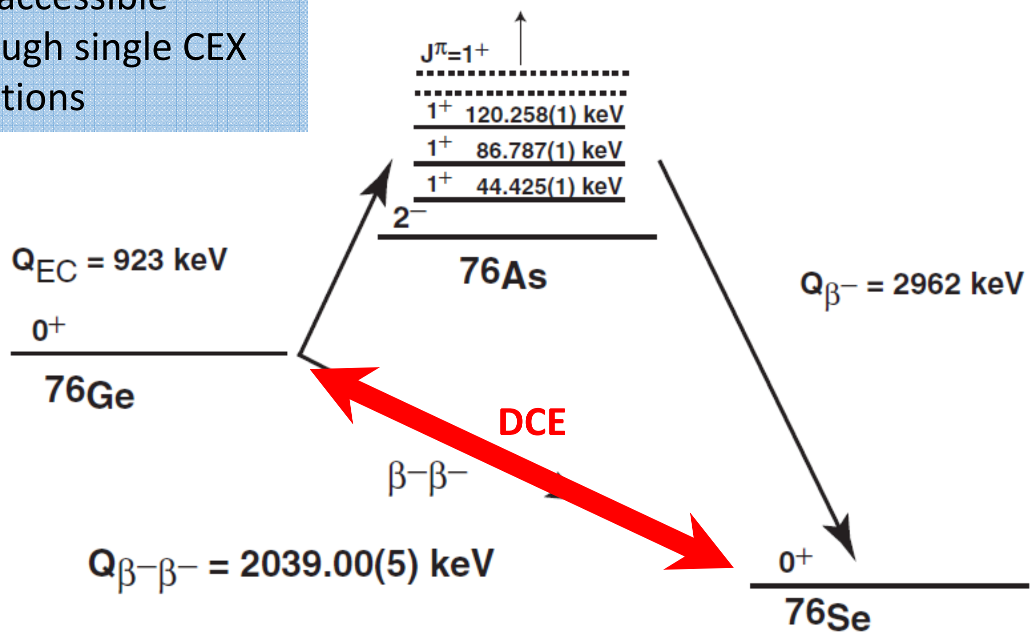
neutrino enters as virtual particle,
q ~ 0.5fm^{-1} (~ 100 MeV/c)
forbiddeness weakened L = 0, 1, 2…



Closure approximation

High multipolarities not accessible through single CEX reactions

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



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

New theorethical development within NUMEN

See H. Lenske's talk

Single Charge Exchange (SCE)

Lenske, Bellone, Colonna, Lay, PRC 98 (2018) 044620

At small momentum transfer, distorsion effects (due to the strong absorption) reduce to a simple scaling factor, allowing to define a reduced cross-section, given by NME of βdecay type

Double Single Charge Exchange (DSCE)

Bellone, Colonna, Lenske, Lay, J.Phys. Conf. Ser. 1056 (2018) 012004

The factorization is shown to survive for momentum transfer lower than 50 MeV/c, with a microscopic quantum description of DCE as two step SCE mechanism. Similarities with $2\nu\beta\beta$

Double Charge Exchange

Santopinto, Garcia-Tecocoatzi, Magana Vsevolodovna, Ferretti, PRC 98, 061601(R) (2018)

Factorization of DCE cross section as the product of a nuclear structure matrix element times a reaction factor is demonstrated for a simplified reaction model, assuming also closure approximation

Majorana Double Charge Exchange (MDCE)

Lenske, CERN Proceedings 2019-001 (2019)
Lenske, Cappuzzello, M.C., Colonna, PPNP (submitted)

DCE modeled as two-step DSCE and as a one-step (Majorana) reaction mechanism, this latter being a newly introduced reaction promisingly probing a similar nuclear response as $0\nu\beta\beta$ decay

The experiments

NURE

NUMEN

The experiments

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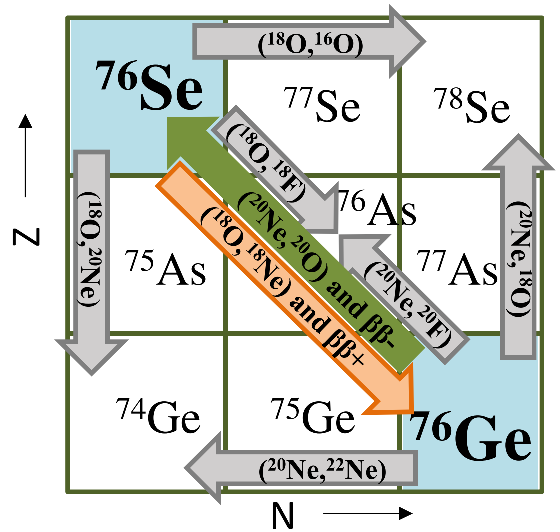
- **Transitions of interest for 0νββ:**
  Limited number of targets in phase 2,
  systematic exploration of all the targets in phase 4

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

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

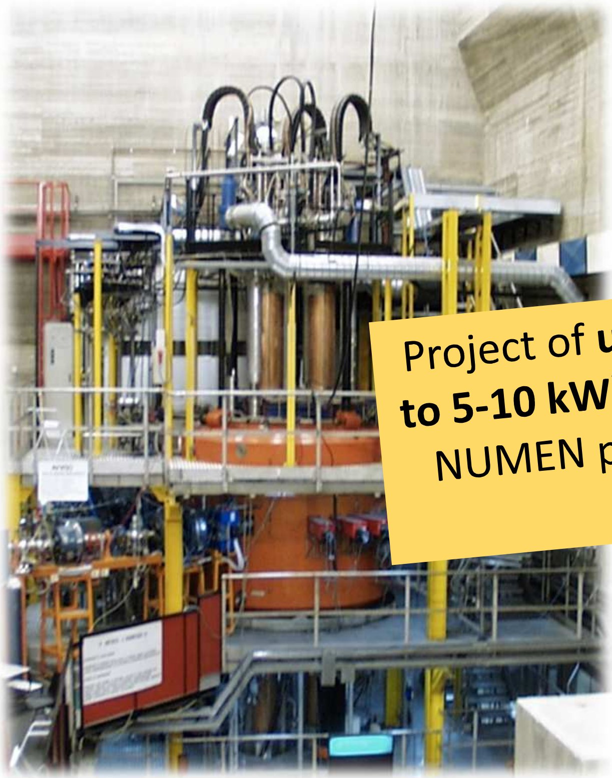
- **Two (or more) incident energies**
  to study the reaction mechanism



The experimental facility

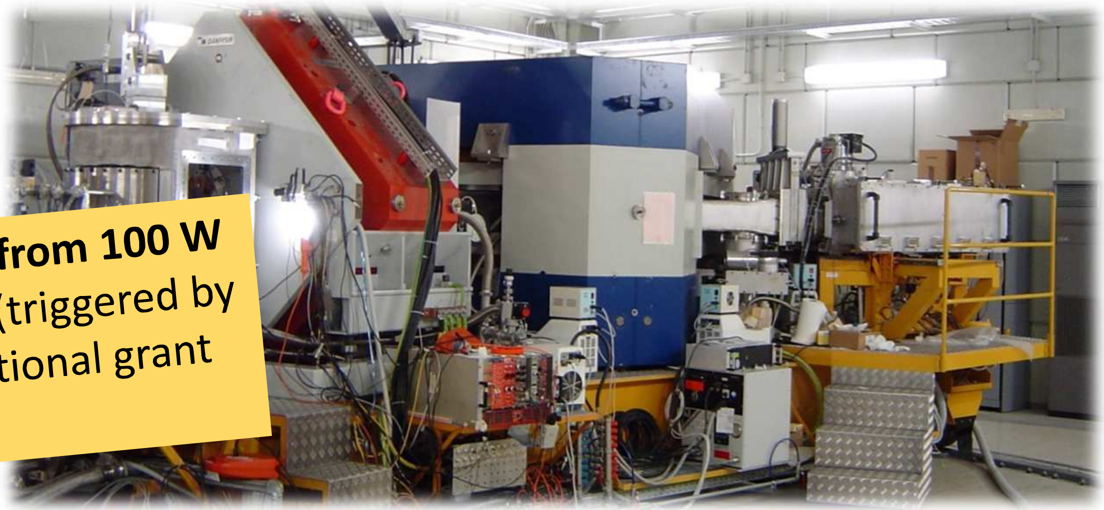
K800 Superconducting Cyclotron

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



MAGNEX magnetic spectrometer

F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167

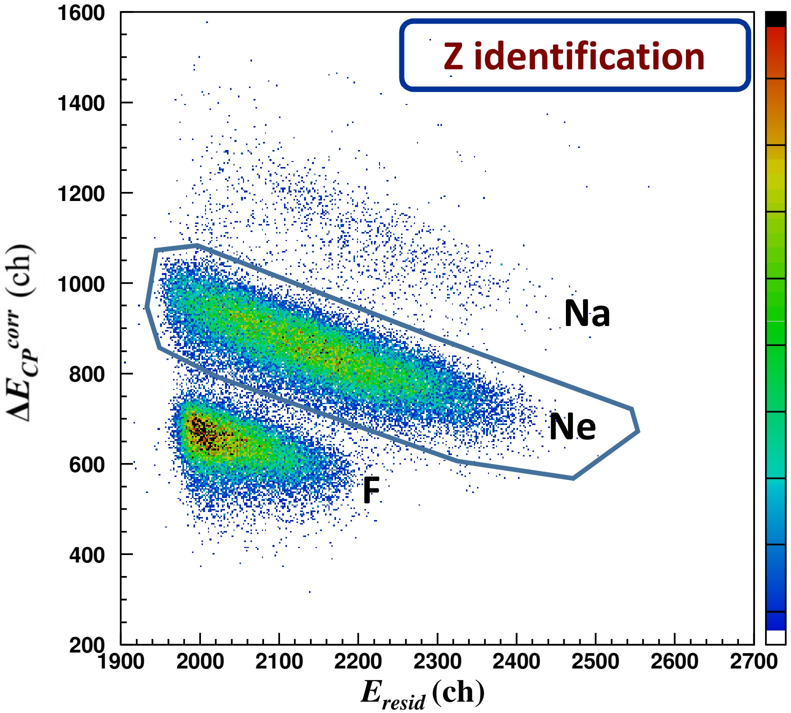


Project of **upgrade of the Cyclotron (from 100 W to 5-10 kW) and LNS infrastructures** (triggered by NUMEN physics case) funded by national grant (PON) for 19.4 M€

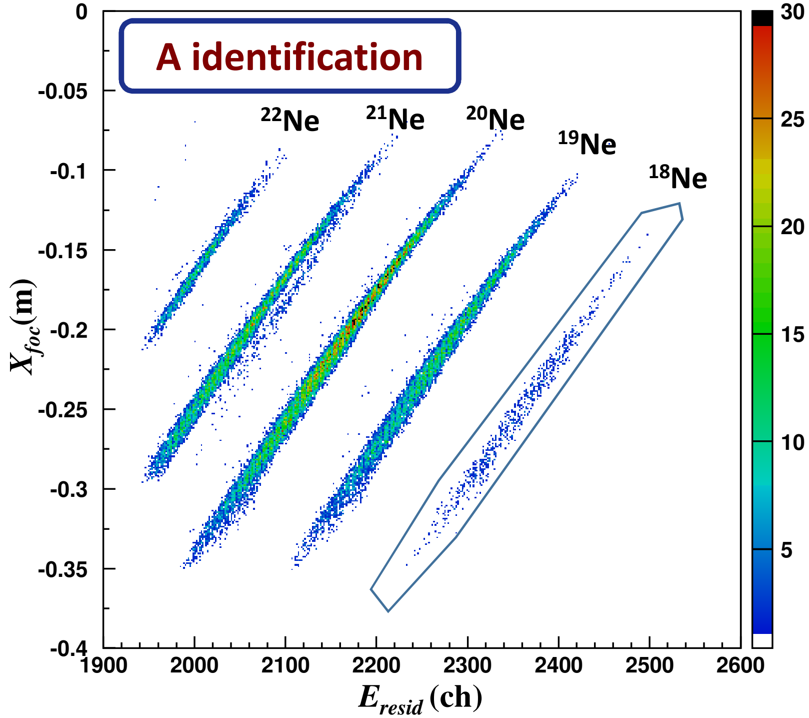
NUMEN phases			
Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Feasibility study	Study of few cases + development of theory	Shutdown & Upgrade	Systematic study of all the targets
2013-2015	2015-2020	2021-2022	2022-…

Particle Identification

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



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



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

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

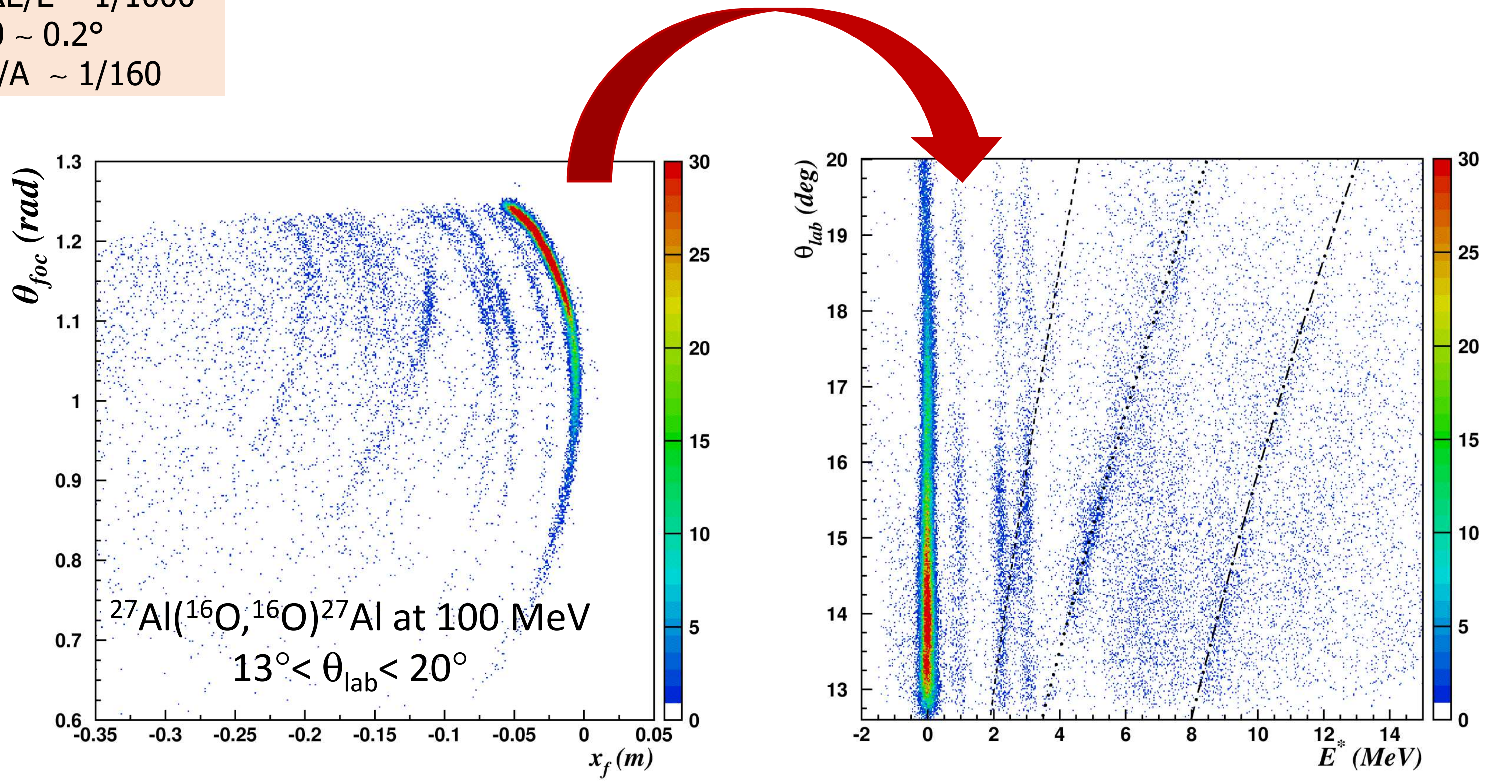
M.Cavallaro et al. EPJ A 48: 59 (2012)

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

High energy and angular resolution

Algebraic ray-reconstruction in MAGNEX

Measured resolutions:
- Energy ΔE/E ~ 1/1000
- Angle Δθ ~ 0.2°
- Mass ΔA/A ~ 1/160



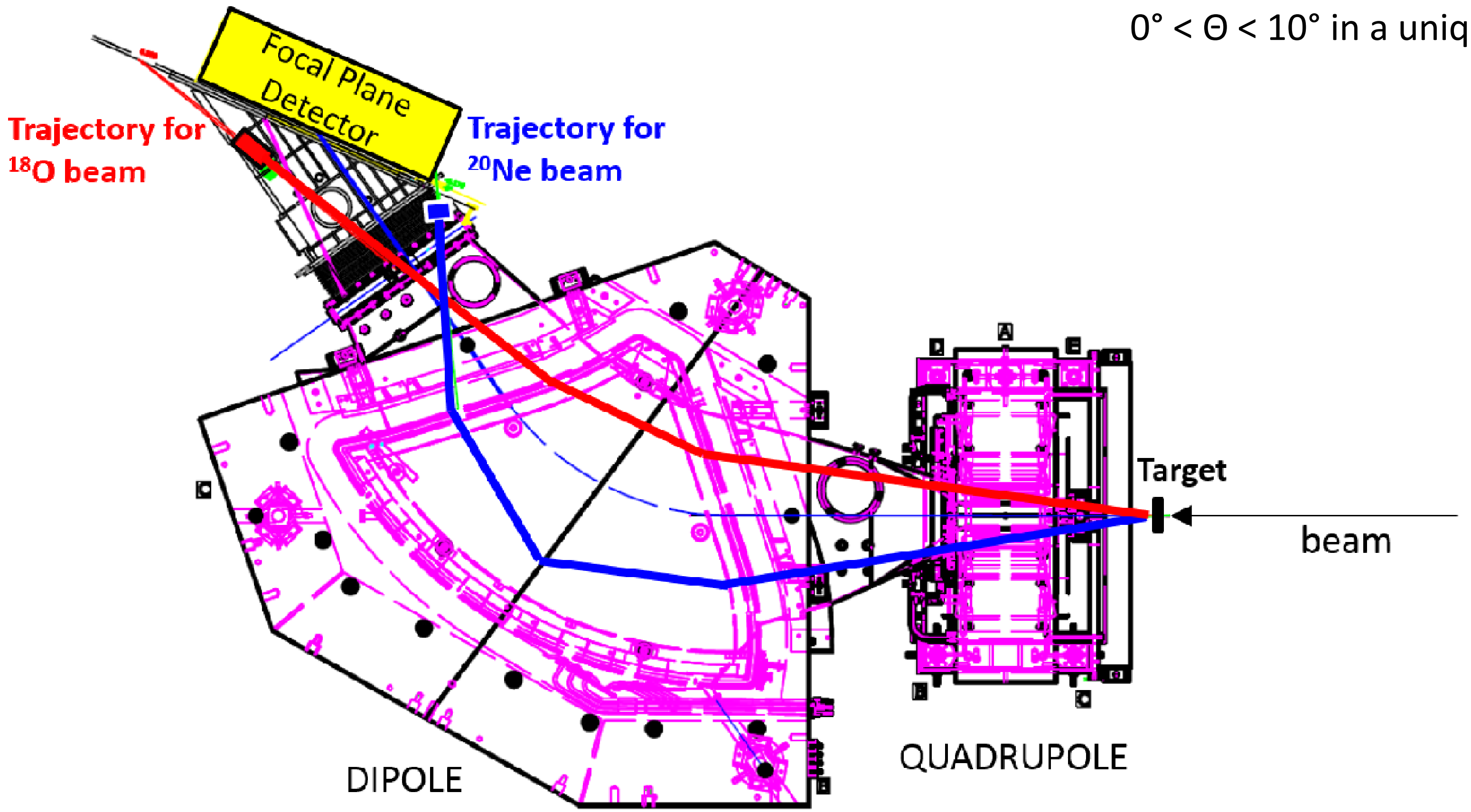
M. Cavallaro et al., NIMA 648 (2011) 46-51

F. Cappuzzello et al., NIMA 638 (2011) 74-82

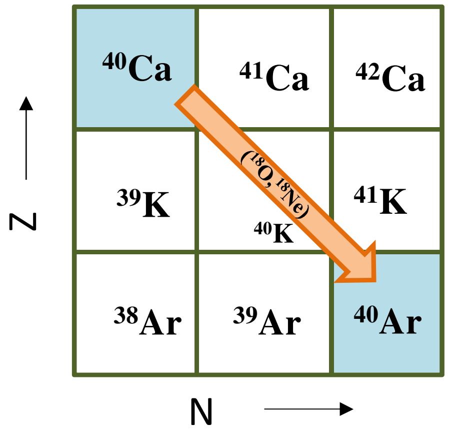
Cross-section measurement at zero-degrees

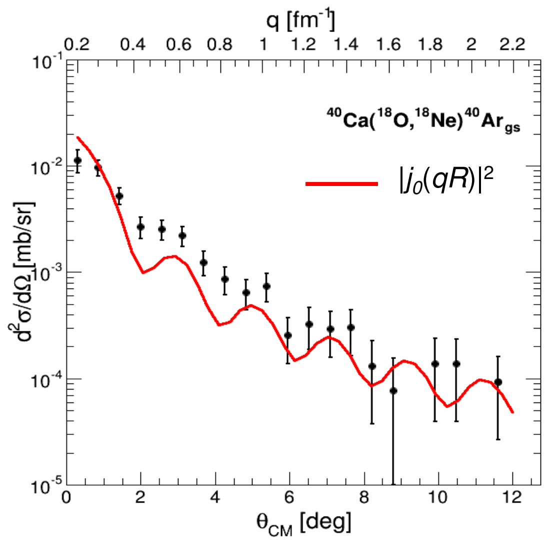
Measurement of the beam current at Faraday Cup

0° < Θ < 10° in a unique angular setting



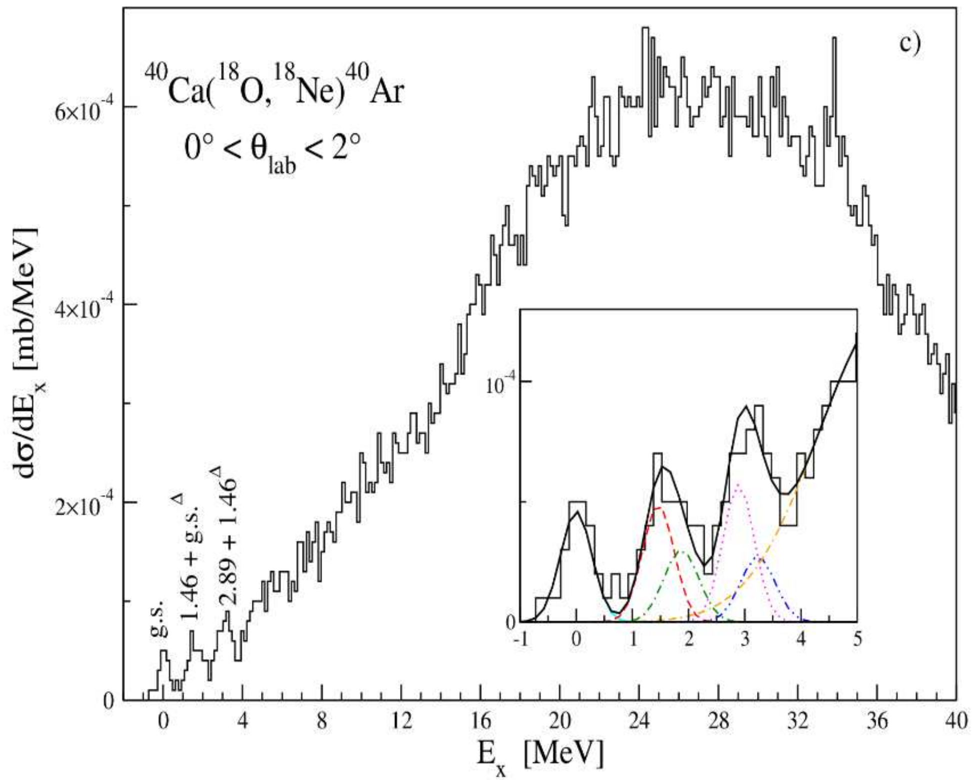
The pilot experiment





$^{18}O + {}^{40}Ca$ 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)

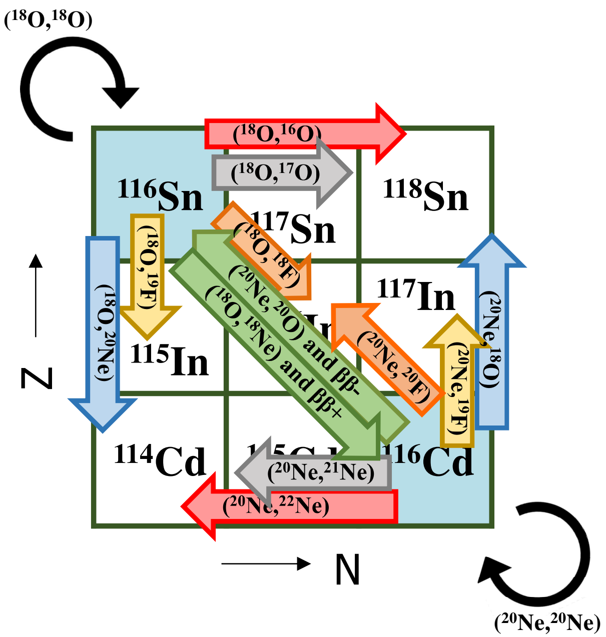
Limitations of the past HI-DCE experiments are overcome!

NUMEN runs – Phase 2

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

@ 15 MeV/A

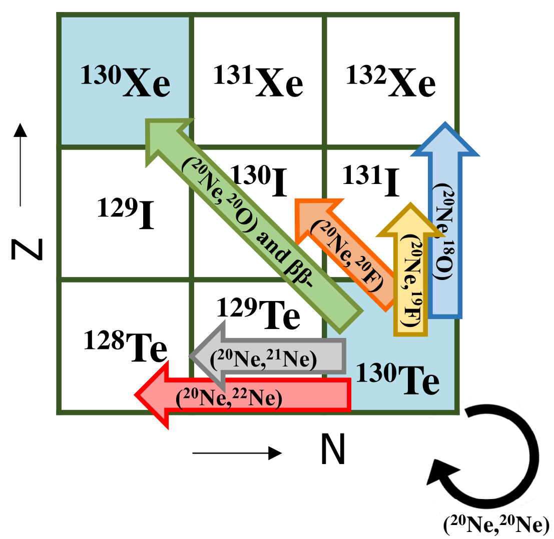
- $^{18}O + ^{116}Sn$
- $^{20}Ne + ^{116}Cd$



^{130}Te – ^{130}Xe case

@ 15 MeV/A

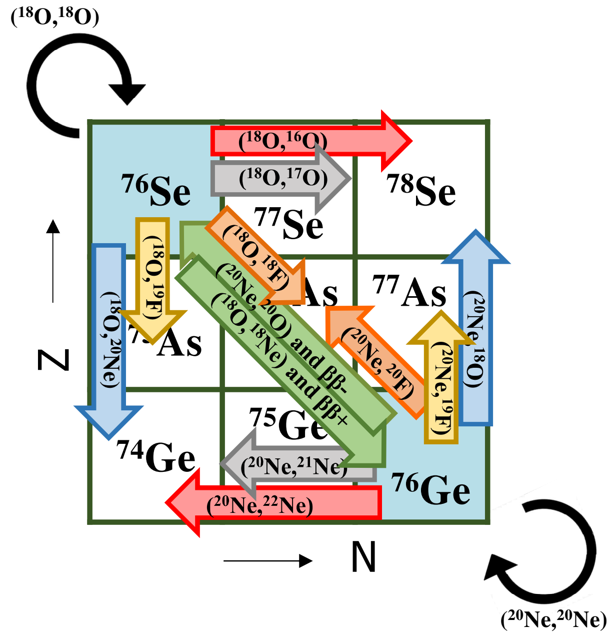
- $^{20}Ne + ^{130}Te$



^{76}Ge – ^{76}Se case

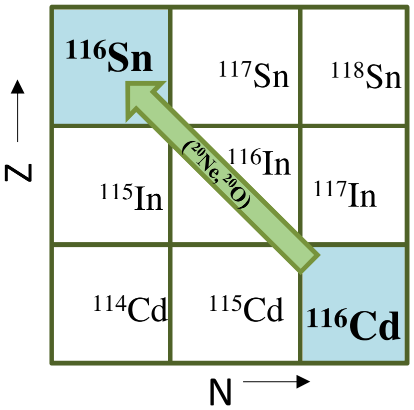
@ 15 MeV/A

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



Experimental results

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



- g.s. → g.s. transition isolated (FWHM 800keV)
- Absolute cross section measured

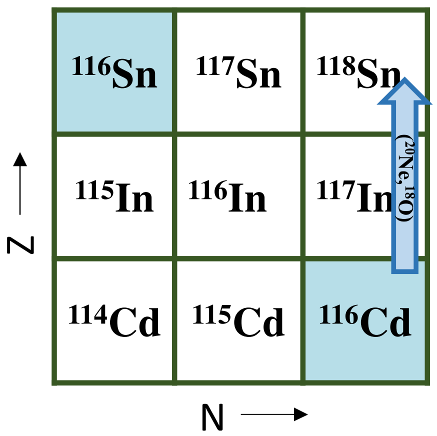
Analysis of cross-section sensitivity
<0.1 nb in the Region Of Interest

Multi-nucleon transfer

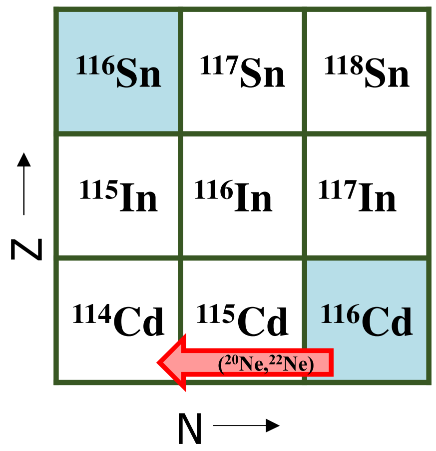
EXP. DATA:
33 ± 10 nb

CALCULATIONS:
~ 26 nb

2p-transfer



2n-transfer



EXP. DATA:
450 ± 200 nb

CALCULATIONS:
~ 340 nb

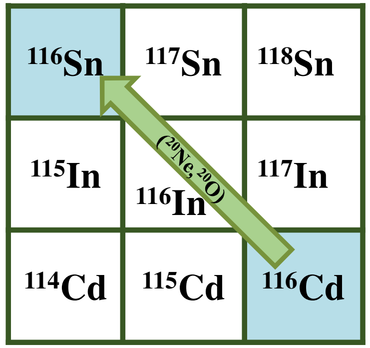
See J. Lubian's talk

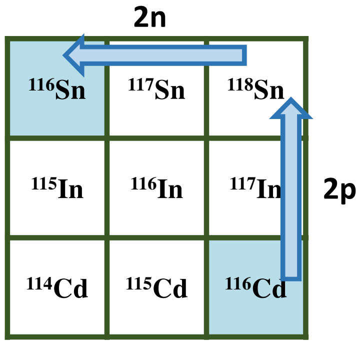
Cross section calculations (DWBA)
ISI and FSI from double folding
SA from IBM, shell model, QRPA)

Agreement!

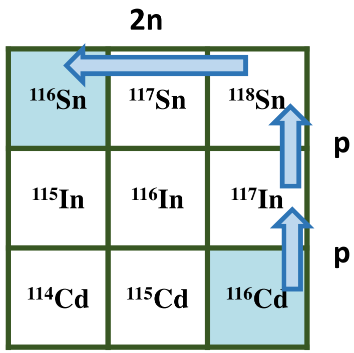
Multi-nucleon transfer routes
vs
Diagonal process

(exp. cross section **12 ± 2 nb**)

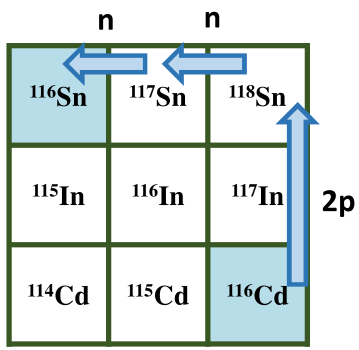




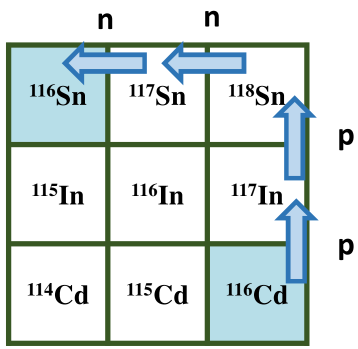
3×10^{-5} nb



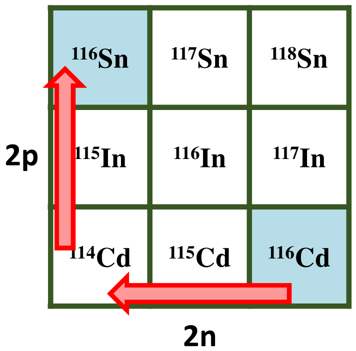
6.6×10^{-5} nb



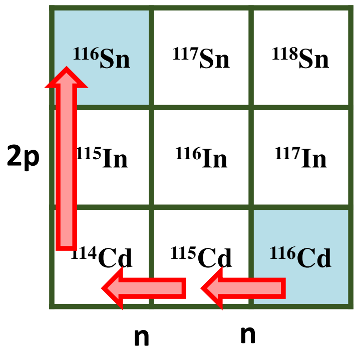
1.1×10^{-5} nb



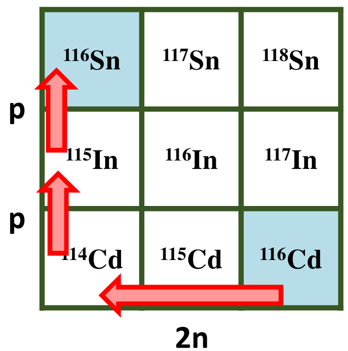
1.7×10^{-5} nb



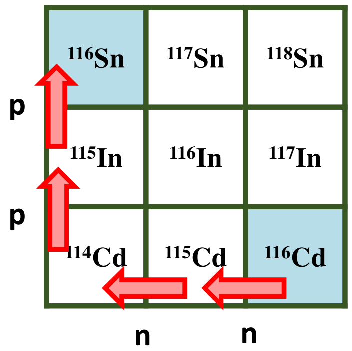
6.9×10^{-4} nb



4.0×10^{-5} nb



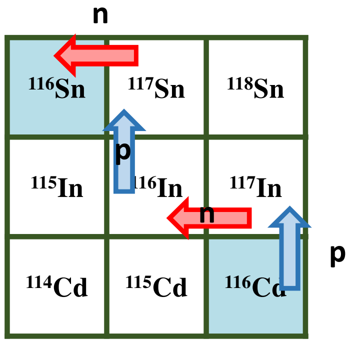
3.0×10^{-4} nb



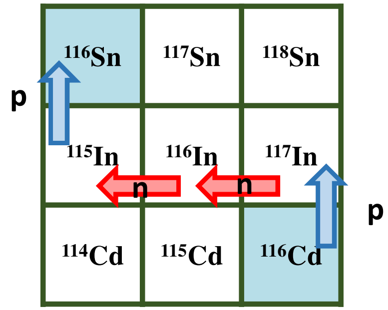
8.3×10^{-5} nb

Multi-nucleon transfer routes
vs
Diagonal process

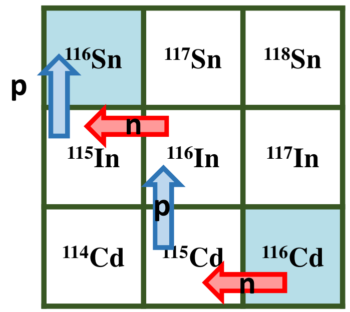
(exp. cross section **12 ± 2 nb**)



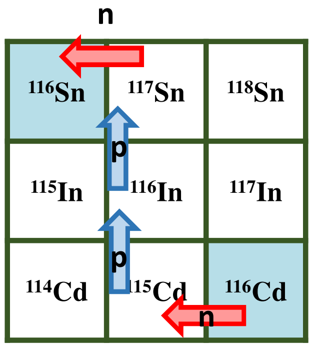
9.4 x 10^{-8} nb



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

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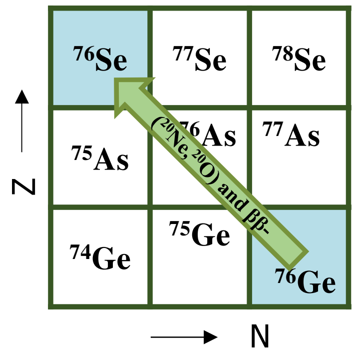
Interplay between CEX + multi-nucleon transfer
(Work in progress)

Experimental results

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

Experimental results

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

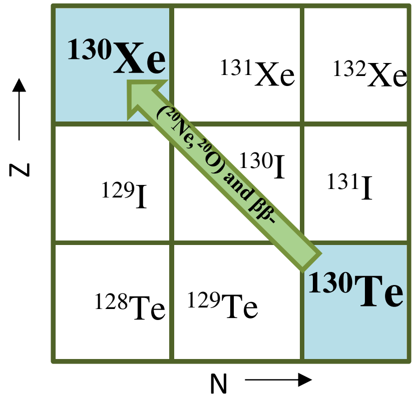


Still very preliminary!

About 50 counts in the ^{76}Se ground state region

Experimental results

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



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

Resolution ~ 500 keV FWHM

No spurious counts in the region -10 < E_x < -2 MeV

Conclusions and Outlooks

- **Second order isospin excitations of nuclei are key information for interest for nuclear physics and neutrino physics**
- **Challenging projects on HI-DCE have started (Italy, Japan)**
- **New results coming out for different systems**
- **A big challenge for experiments and nuclear 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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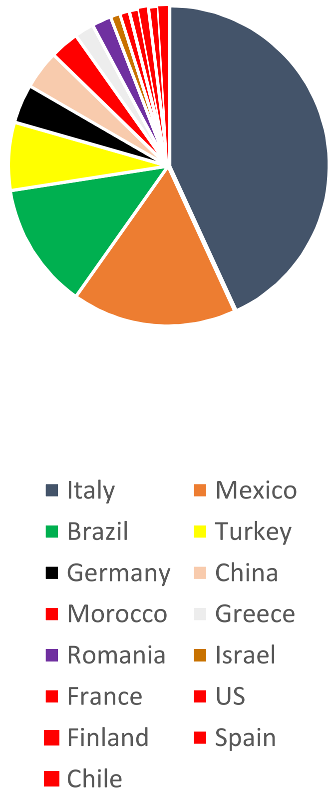

Thank you!