Towards double-beta decay matrix elements with nuclear reactions

Manuela Cavallaro INFN – LNS (Italy)

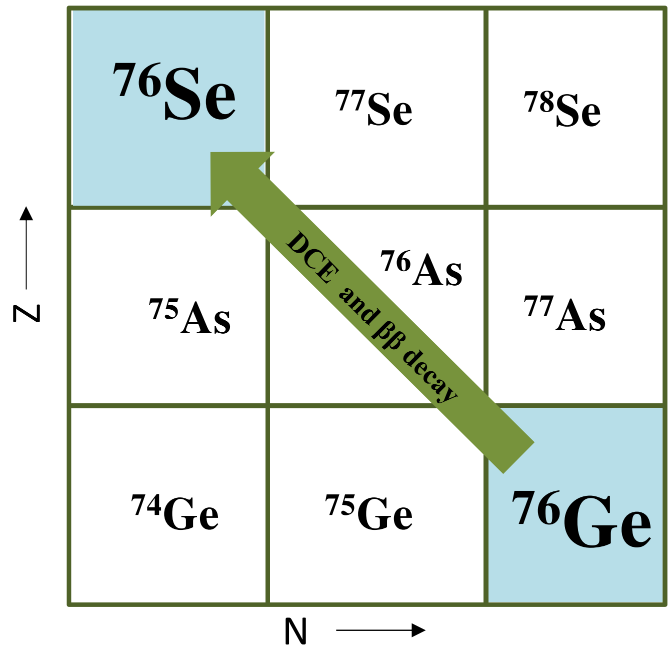
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Progress and Challenges in Neutrinoless Double Beta Decay

15 - 19 July 2019

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



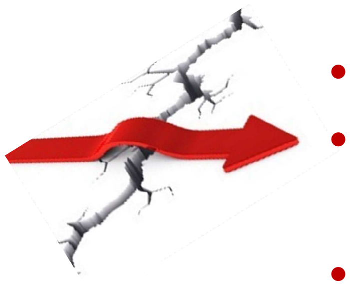
F. Cappuzzello et al., EPJ A (2018) 54:72

The Goals of the Research Program

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

Nuclear Matrix Element (NME)

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



- 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 NUMEN collaboration

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

Proponents: C. Agodi, J. Bellone, D. Bonanno, V. Branchina, S. Brasolin, G. Brischetto, O. Brunasso, S. Burrello, S. Calabrese, L. Calabretta, D. Calvo, V. Capirossi, F. Cappuzzello, D. Carbone, M. Cavallaro, I. Ciraldo, M. Colonna, G. D'Agostino, N. Deshmukh, C. Ferraresi, J. Ferretti, P. Finocchiaro, M. Fisichella, A. Foti, G. Gallo, H. Garcia-Tecocoatzi, F. Iazzi, G. Lanzalone, F. La Via, F. Longhitano, D. Lo Presti, P. Mereu, L. Pandola, F. Pinna, S. Reito, A.D. Russo, G. Russo, E. Santopinto, O. Sgouros, V. Soukeras, A. Spatafora, D. Torresi, S. Tudisco, R.I.M. Vsevolodovna

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Italy
Dipartimento di Fisica e Astronomia, Università di Catania, Italy
Dipartimento di Fisica, Università di Genova, Italy
DISAT, Politecnico di Torino, Italy
Università degli Studi di Enna "Kore", Enna, Italy
CNR-IMM, Sezione di Catania, Italy

T. Borello-Lewin, P.N. de Faria, J.L. Ferreira, R. Linares, J. Lubian, N.H. Medina, D.R. Mendes, M. Moralles, J.R.B. Oliveira, M.R.D. Rodrigues, R.B.B. Santos, M.A.G. da Silveira, V.A.B. Zagatto

Instituto de Fisica, Universidade de Sao Paulo, Brazil
Instituto de Fisica, Universidade Federal Fluminense, Niteroi, Brazil
Instituto de Pesquisas Energeticas e Nucleares IPEN/CNEN, Brazil
Centro Universitario FEI Sao Bernardo do Brazil, Brazil

I. Boztosun, H. Djapo, S. Firat, A. Hacisalihoglu, Y. Kucuck, S.O. Solakcı, A. Yildirin

Akdeniz University, Antalya, Turkey
Institute of Natural Sciences, Karadeniz Teknik University, Turkey

L. Acosta, P. Amador, R. Bijker, E.R. Chávez Lomelí, R. Espejel, A. Huerta, H. Vargas, A. Flores, S. Martínez, C. Ordoñez, D. Marín-Lámbarri, B. Góngora, G. Reza, J. Mas, G. Vega, D. Belmont, S. Sandoval

Instituto de Física, Universidad Nacional Autónoma de México, México
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, México Instituto Nacional de Investigaciones Nucleares, México

A. Pakou, G. Souliotis

Department of Physics, University of Ioannina, Greece
Department of Chemistry, National and Kapodistrian University of Athens, Greece

H. Lenske, P. Ries, N. Pietralla, V. Werner

Department of Physics, University of Giessen, Germany
Institut fur Kernphysik, Technische Universitat Darmstadt, Germany

N. Auerbach

School of Physics and Astronomy Tel Aviv University, Israel

H. Petrascu, L. Serbina

IFIN-HH, Bucarest, Romania

J.A. Lay

Departamento de FAMN, University of Seville, Spain

F. Delaunay,

LPC Caen, Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, France

Z.J. Kotila,

University of Jyväskylä, Jyväskylä, Finland

G. De Geronimo

Stony Brook University, US

J. Barea

Universidad de Conception, Chile

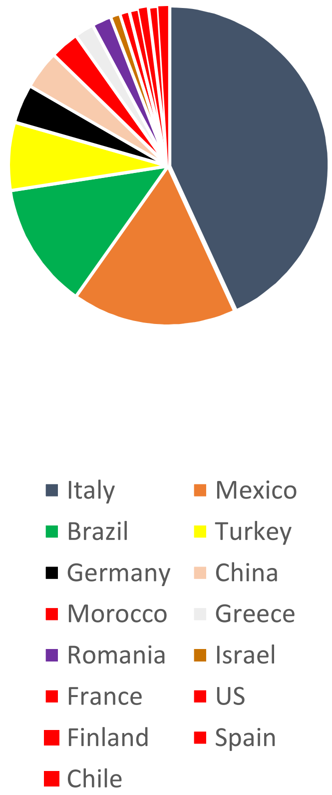
R. Chen, J. Ma, J.S. Wang, Y.Y. Yang

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China

A. Khouaja, J. Inchaou, M.L.Bouhssa

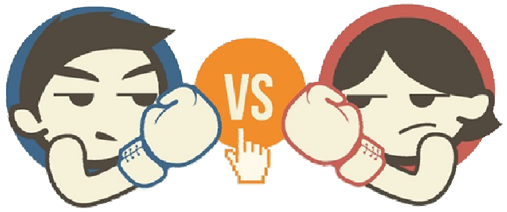
Université Hassan II – Casablanca, Morocco

102 Researchers
34 Institutions
15 Countries



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-…

$0\nu\beta\beta$ vs DCE



Differences

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

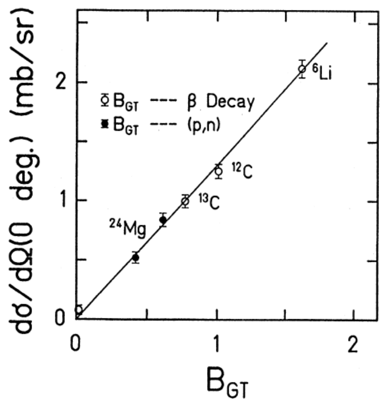
Similarities

- **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:** 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
- **Same nuclear medium**: Constraint on the theoretical determination of quenching phenomena on $0\nu\beta\beta$
- **Off-shell propagation** through virtual intermediate channels

Connection between β-decay and SCE

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

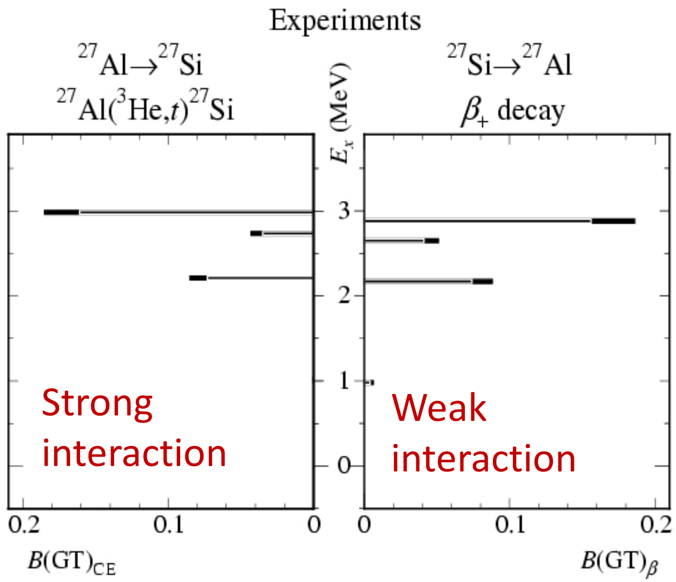
- **For (p,n), (n,p), (d,²He)**



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)



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

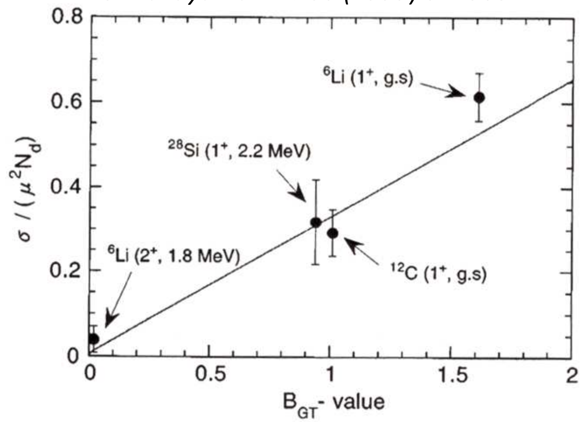
(In general for B(GT)>0.05)

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

Connection between β-decay and SCE

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

S. Nakayama PRC 60 (1999) 047303



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

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

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

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

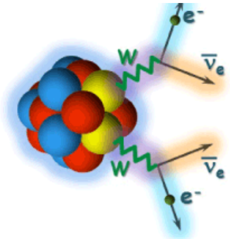
---

- **Recently, the theory of heavy-ion SCE has been reformulated (NUMEN)**

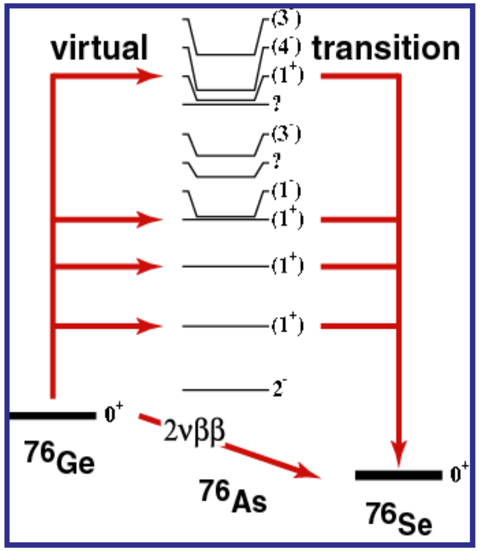
H. Lenske et al., Phys. Rev. C 98 (2018) 044620

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 β-decay type

2νββ - decay

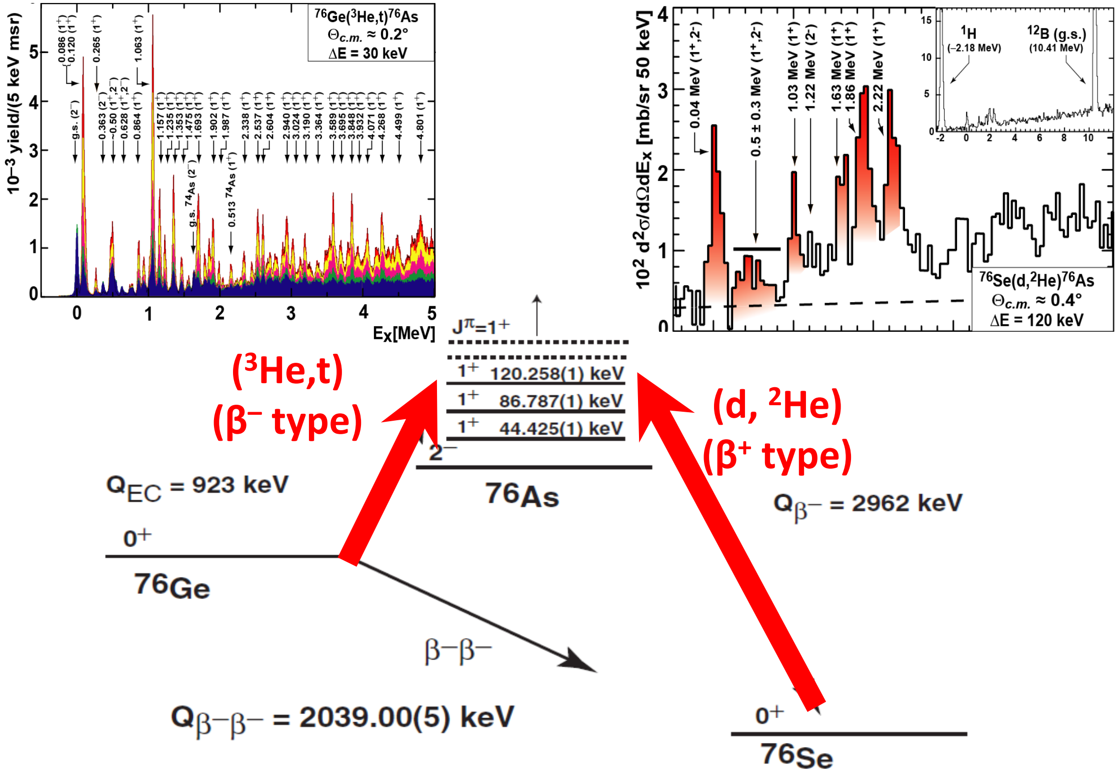


q-available like ordinary β-decay
($q \sim 0.01\ fm^{-1} \sim 2$ MeV/c)
only allowed decays are possible (L = 0)



Single state dominance

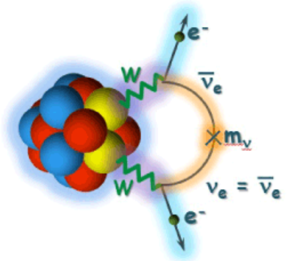
Methodology:
Single CEX to populate intermediate states and approximation (SSD / all positive signs in the coherent sum of the amplitudes)



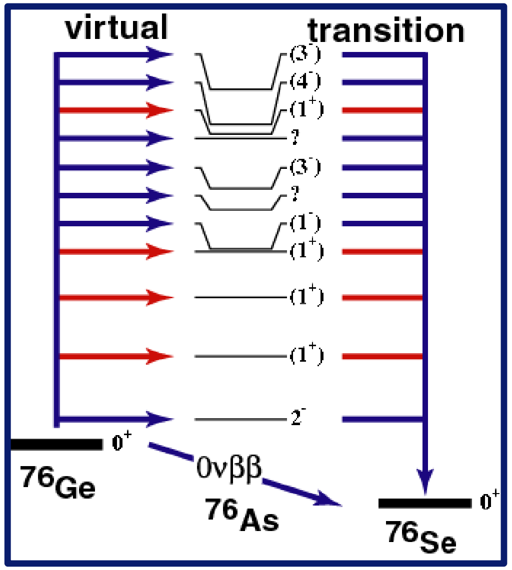
$$M^{2\nu} = \sum_m \frac{\langle 0_f^+ | \sigma\tau^- | m \rangle \langle m | \sigma\tau^+ | 0_i^+ \rangle}{E_m - (M_i + M_f)/2}$$

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

0νββ - decay

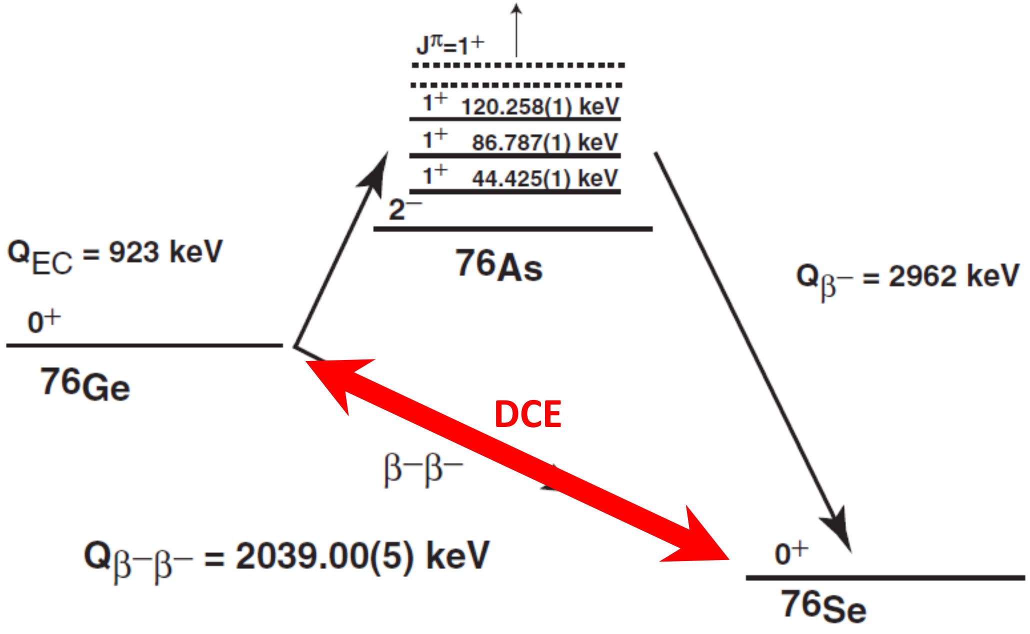


neutrino enters as virtual particle,
q ~ 0.5fm^{-1} (~ 100 MeV/c)
forbiddeness weakened L = 0, 1, 2…



Closure approximation

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



High multipolarities not accessible through single CEX reactions

The experiments

NURE

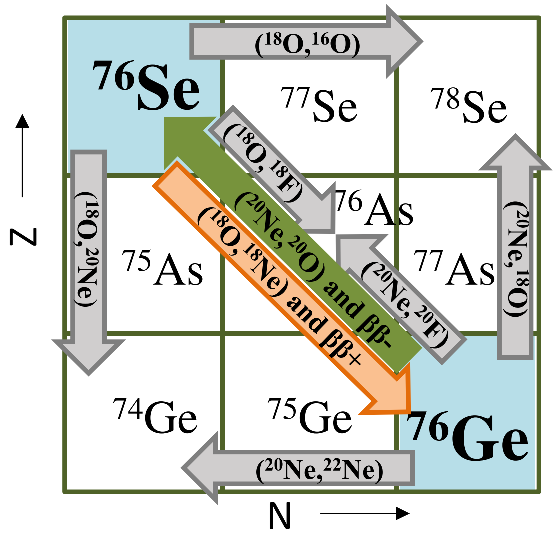
The experimental program

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

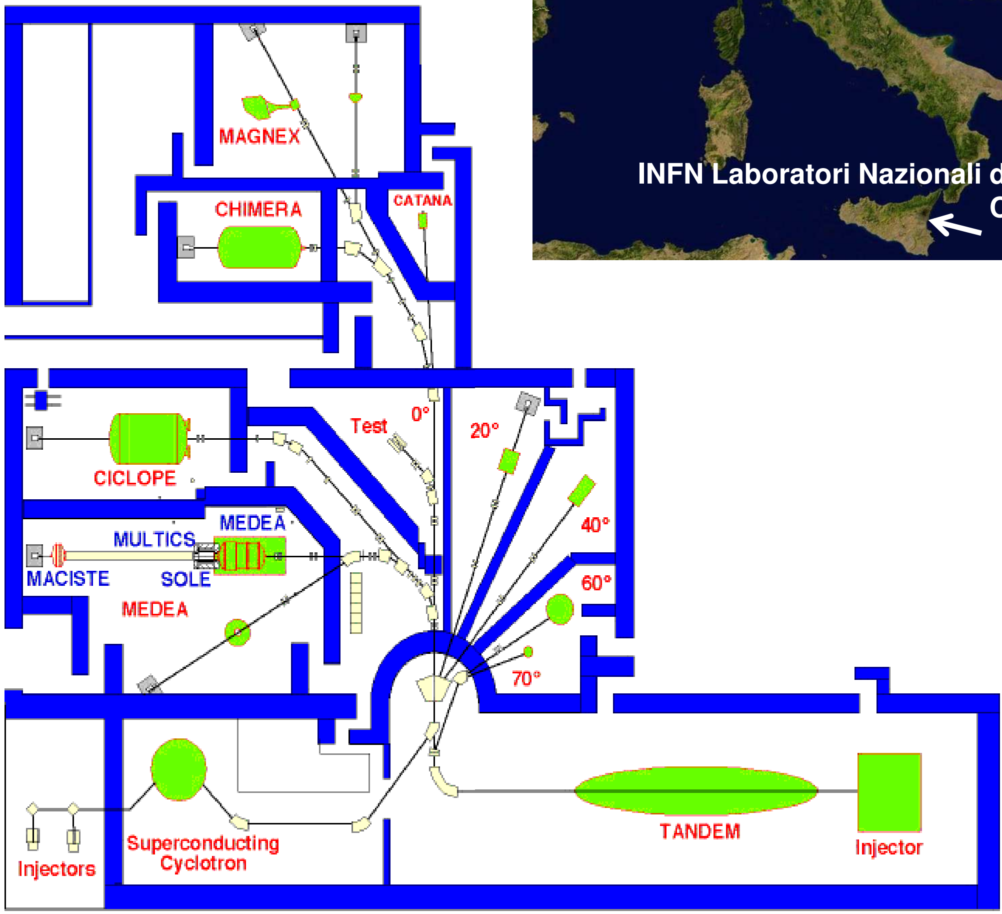
- **Two directions**:
  $\beta\beta^-$ via (^{20}Ne,^{20}O) and $\beta\beta^+$ via (^{18}O,^{18}Ne)

- **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



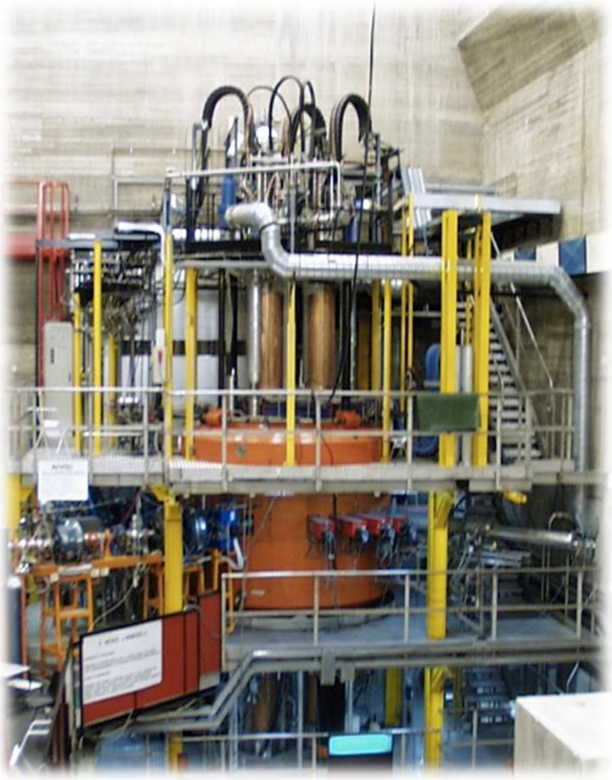
The INFN-LNS laboratory in Catania



The experimental facility

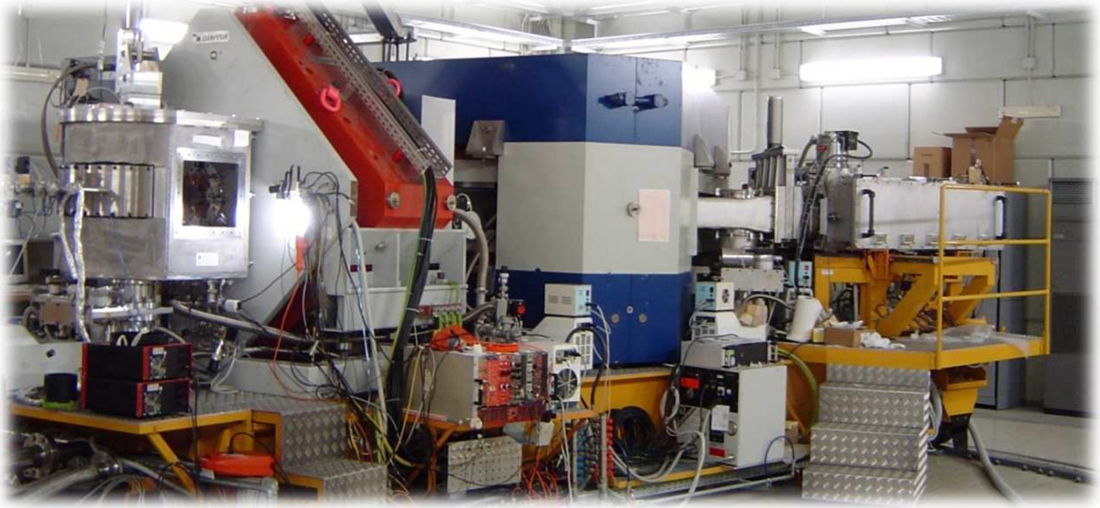
K800 Superconducting Cyclotron

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



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

Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

✓ Solution of the equation of motion for each detected particle
✓ Inversion of the transport map
✓ Application to the final measured parameters

$$F : \vec{\mathbf{X}}_{\mathbf{i}} \rightarrow \vec{\mathbf{X}}_{\mathbf{f}}$$

Inversion of the transport map

$$F^{-1} : \vec{\mathbf{X}}_{\mathbf{f}} \rightarrow \vec{\mathbf{X}}_{\mathbf{i}}$$

1) Detailed knowledge of the geometry and magnetic field

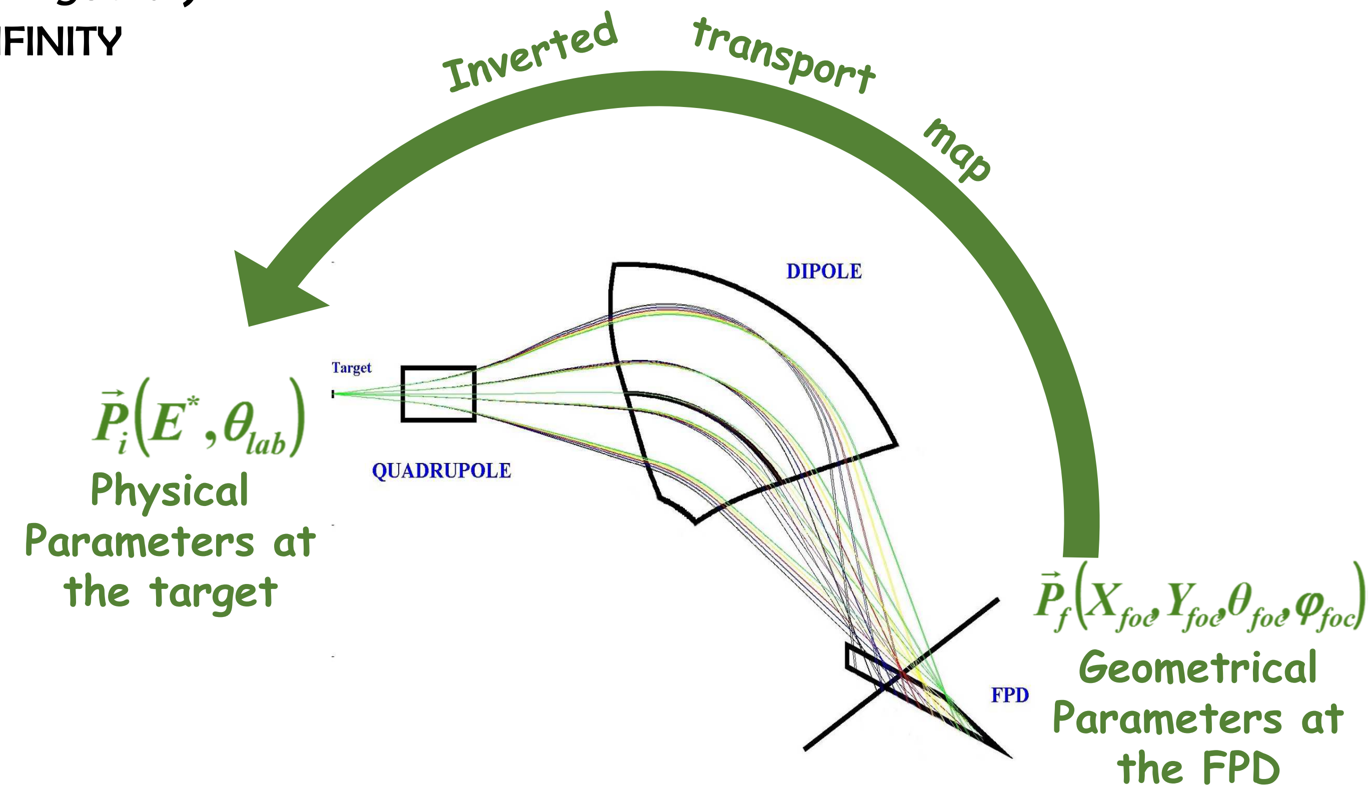
3) Algorithm to transport and invert

2) High resolution measurement at the focal plane (highly performing detectors)

Algorithm to transport and invert

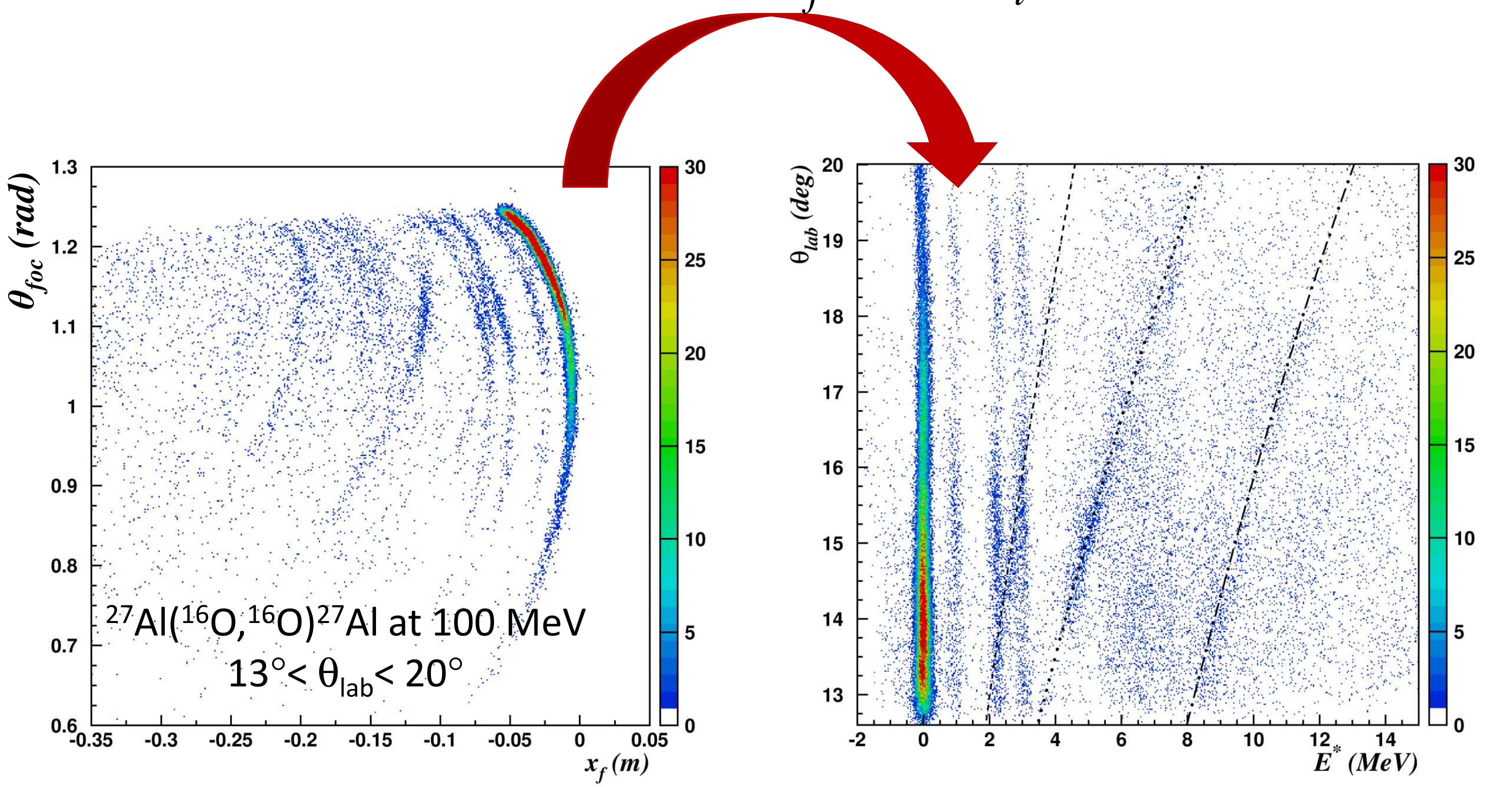
ALGEBRIC
RAY-RECONSTRUCTION
(*Differential Algebras*)
COSY-INFINITY

$$F^{-1} : \vec{X}_f \rightarrow \vec{X}_i$$



High energy and angular resolution

$$F^{-1} : \vec{X}_f \rightarrow \vec{X}_i$$

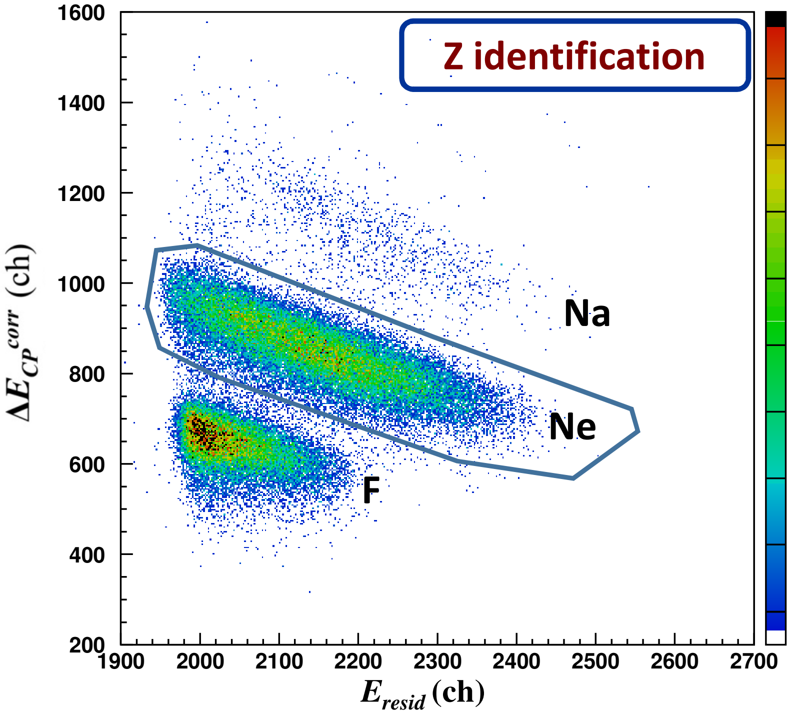


M. Cavallaro et al., NIMA 648 (2011) 46-51

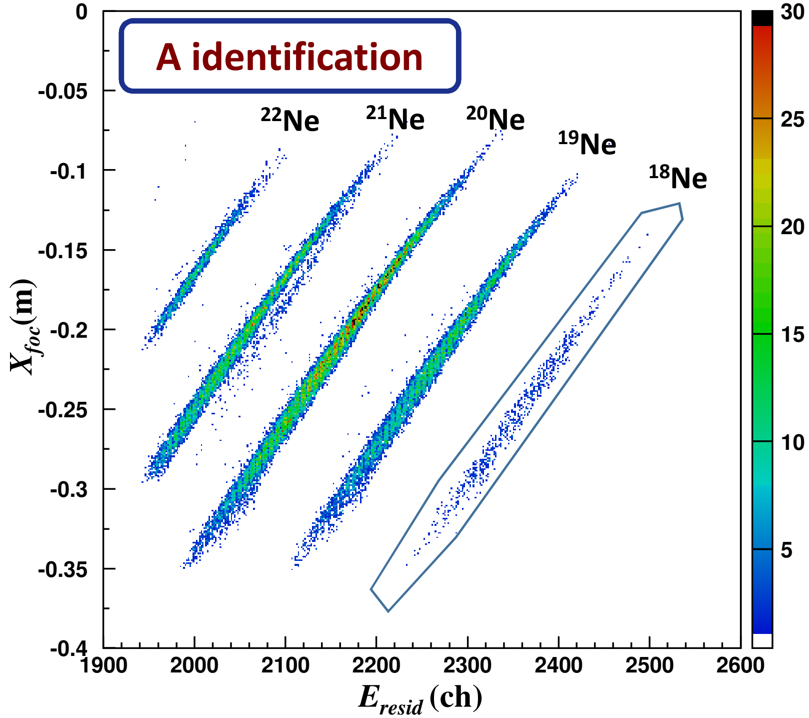
F. Cappuzzello et al., NIMA 638 (2011) 74-82

Particle Identification

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



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



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

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

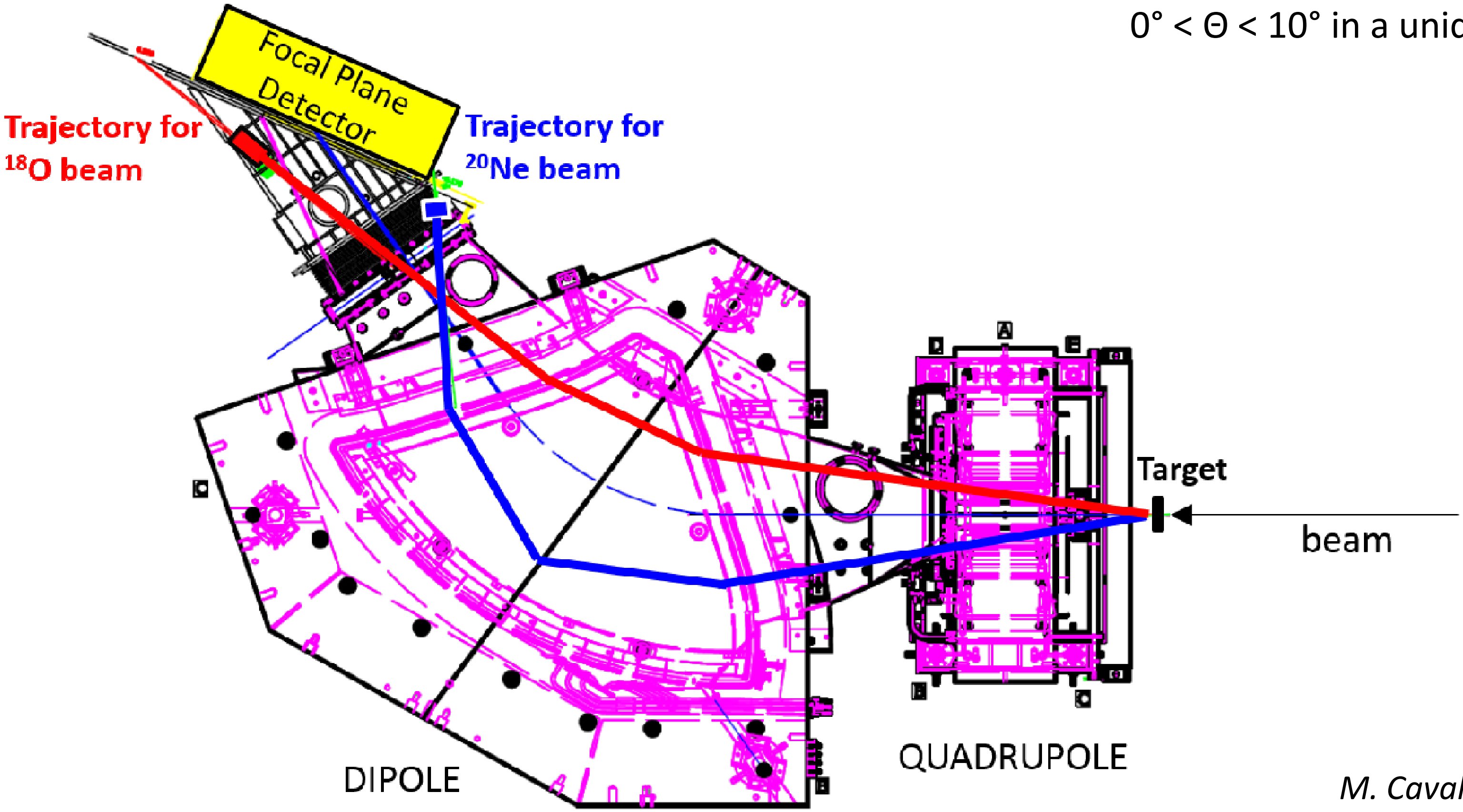
M.Cavallaro et al. EPJ A 48: 59 (2012)

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

Cross-section measurement at zero-degrees

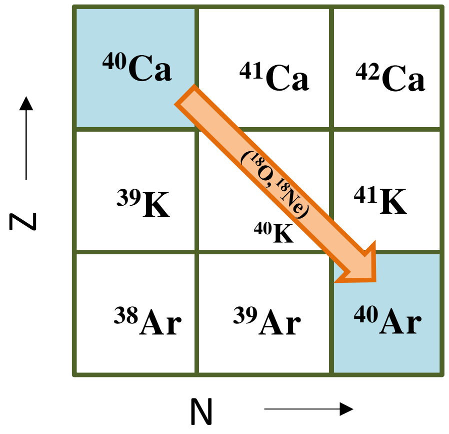
Measurement of the beam current at Faraday Cup

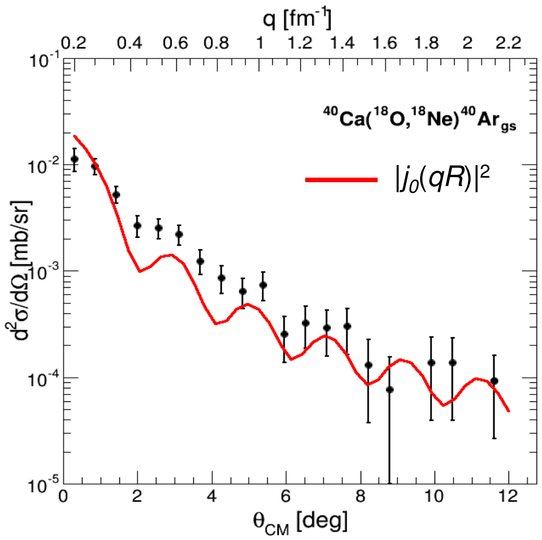
0° < Θ < 10° in a unique angular setting



M. Cavallaro et al., NIM B (in press)
https://doi.org/10.1016/j.nimb.2019.04.069

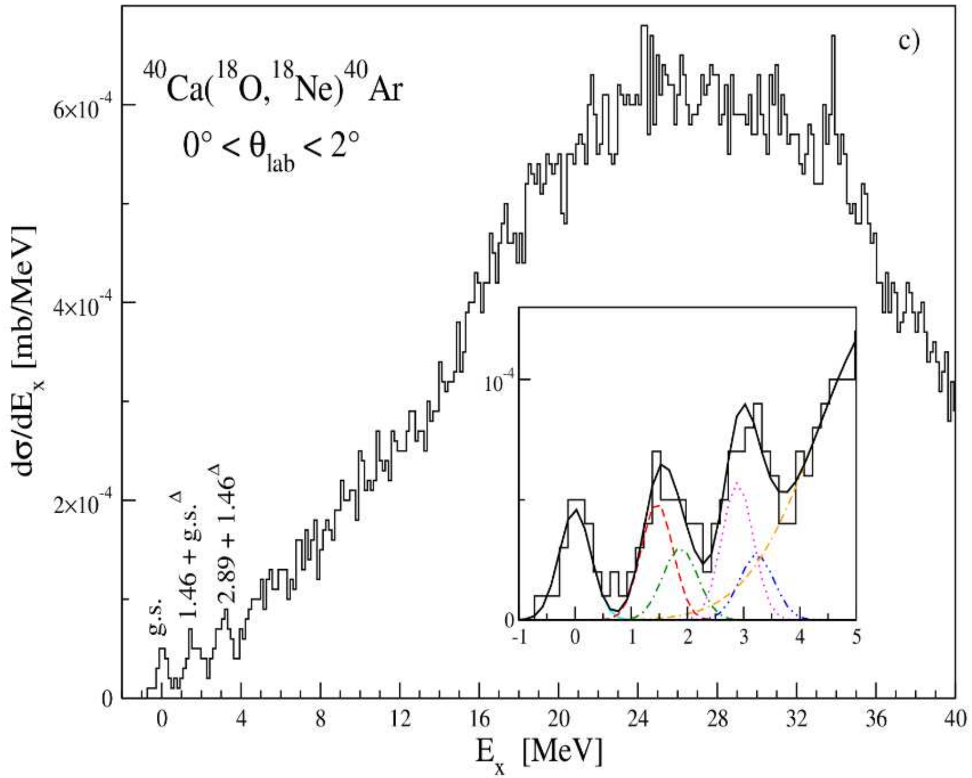
The pilot experiment





^{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!

HI-DCE reaction mechanism

NURE

H. Lenske	Giessen (Gemany)
M. Colonna et al.	INFN-LNS (Italy)
J.A. Lay	Sevilla (Spain)
E.Santopinto et al.	Genova (Italy)
J. Lubian et al.	UFF (Brasil)

A fundamental property of direct reactions

The complicated many-body heavy-ion scattering problem is largely simplified for direct quasi-elastic reactions

$$V_\alpha (r_\alpha, \chi_\alpha) = U_\alpha (r_\alpha) + W_\alpha(r_\alpha, \chi_\alpha)$$

Optical potential ($U_\alpha (r_\alpha)$) — Residual interaction ($W_\alpha(r_\alpha, \chi_\alpha)$)

For **charge exchange** reactions, $W_\alpha(r_\alpha, \chi_\alpha)$ is 'small' and can be treated perturbatively

In addition the reactions are strongly localized at the surface of the colliding systems and consequently large overlap of nuclear densities are avoided

↓

Accurate description in **fully quantum approach**, eg. Distorted Wave techniques

Microscopic derived double folding potentials are good choices for $U_\alpha (r_\alpha)$

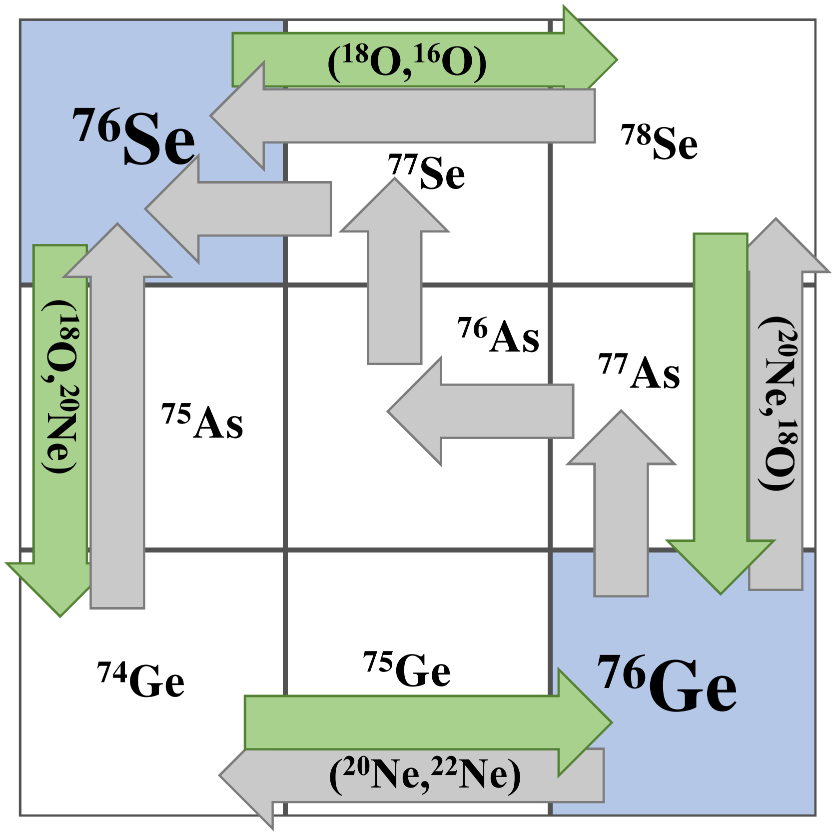
Microscopic form factors work for charge exchange reactions

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

1. Multi-nucleon transfer (proton pick-up/stripping followed by neutron stripping/pick-up)

- ✓ **Single-nucleon transfer** (mean field driven) suppressed because of 4th order
- ✓ **Sequential transfer of 2p/2n pairs is of 2nd order**
- ✓ Transfer or **2p/2n pairs followed by 2n/2p pairs** could be of **interest** for 0υββ NME

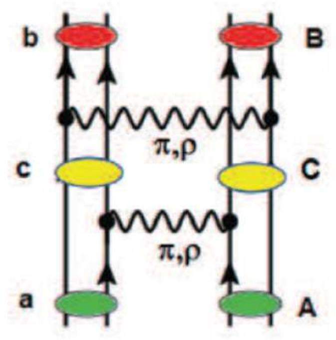
  B.A.Brown et al. PRL 113, 262501 (2014)



2. Double Single Charge Exchange (DSCE)

DSCE reaction amplitude

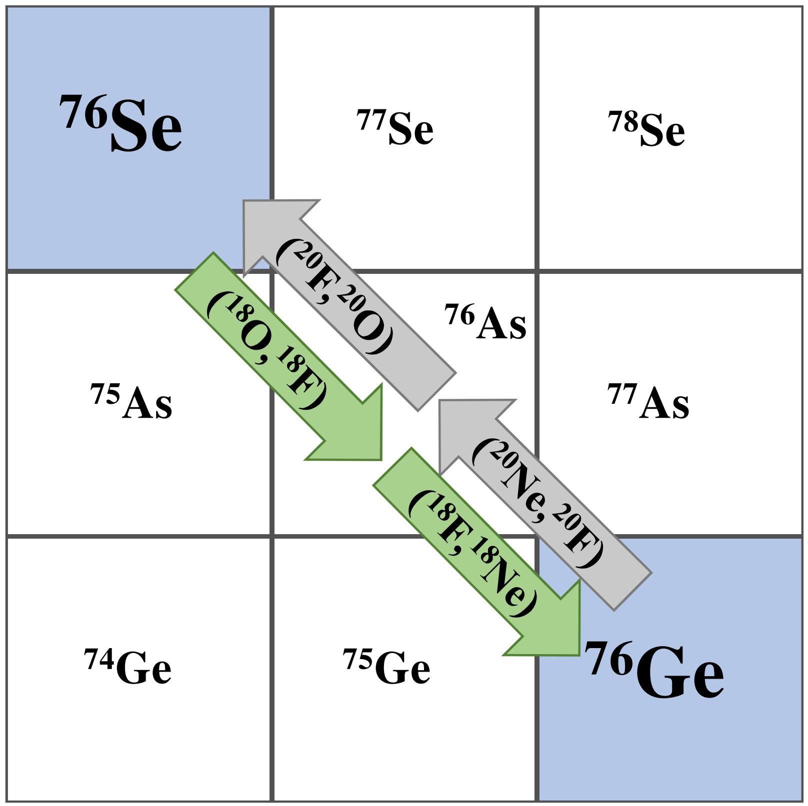
$$M^{(DSCE)}_{\alpha\beta} = \langle \chi^{(-)}_{\beta} bB | T_{NN} \mathcal{G} T_{NN} | aA \chi^{(+)}_{\alpha} \rangle$$



H. Lenske et al., PRC 98 (2018) 044620

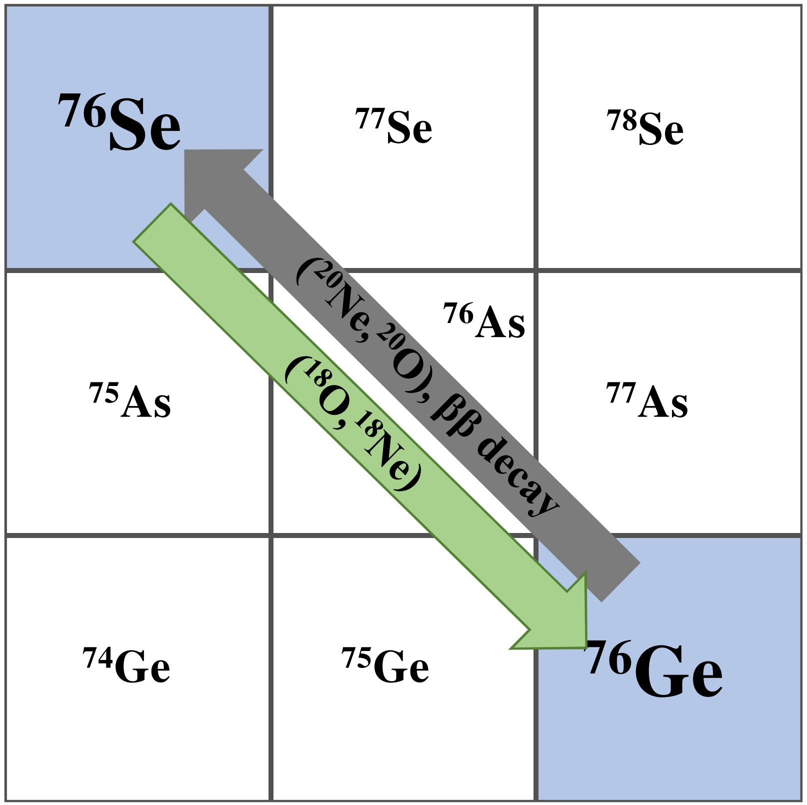
J. Bellone et al., J. Phys.: Conf. Ser. 1056 (2018) 012004

- ✓ **Two-step process** (two consecutive uncorrelated SCE), no correlation between vertices
- ✓ **Probing twice isovector nucleon-nucleon interaction** between a pair of uncorrelated nucleon in the target and projectile
- ✓ **Analogies with 2νββ** decay which is a sequential decay process where the leptons are emitted subsequently in an uncorrelated manner.
- ✓ The transition operator will be **dependent on the projectile target combination and on incident energy.** The angular distributions will show the typical behaviour of a two-step reaction, namely a broader and flatter shape. These dependencies may be taken advantage of, for selecting suitable conditions to suppress or enhance DSCE.



3. Correlated Double Charge Exchange ('*Majorana*' mechanism MDCE)

- ✓ **Probing nucleonic short-range correlations** in the target and projectile (universal phenomena of nuclear matter) independent on the projectile target combination
- ✓ **Probing** nucleus-nucleus Initial (**ISI**) and Final (**FSI**) State Interaction
- ✓ **Correspondence with 0νββ**



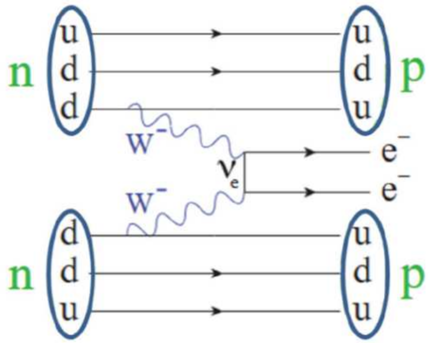
H. Lenske, CERN Proceedings 2019-001 (2019)
H. Lenske et al., Prog. Part. Nuc. Phys. (submitted)
E.Santopinto et al., Phys. Rev. C 98 (2018) 061601(R)

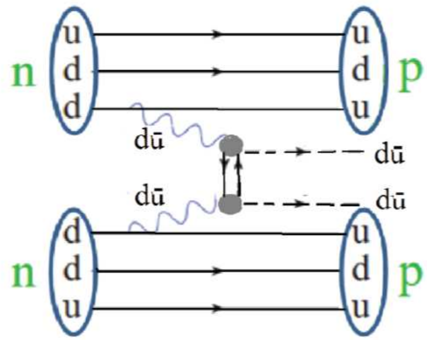
The "*Majorana*" mechanism for HI-DCE

From H. Lenske, CERN Proceedings 2019-001 (2019)

Attempt to identify at elementary level a correspondence between strong and weak interaction

Elementary **weak interaction** process mediating $0\nu\beta\beta$





Elementary **strong interaction** process mediating 1-step DCE

The $pp \rightarrow nn\pi^+\pi^+$ reaction and other double-pion production channels have been investigated at CELSIUS, COSY, HADES

Special class of two-body correlation:

- emission of virtual weak gauge boson W,
- exchange of a Majorana neutrino between two nucleons
- and emission of electrons

Also two-body correlation:

- emission of virtual $q\bar{q}$ (π^-, ρ^-)
- exchange of a virtual charge-neutral $q\bar{q}$ pair (π^0,ρ^0, σ)
- and emission of charged $q\bar{q}$

Can occur, in principle, in an **isolated nucleus**

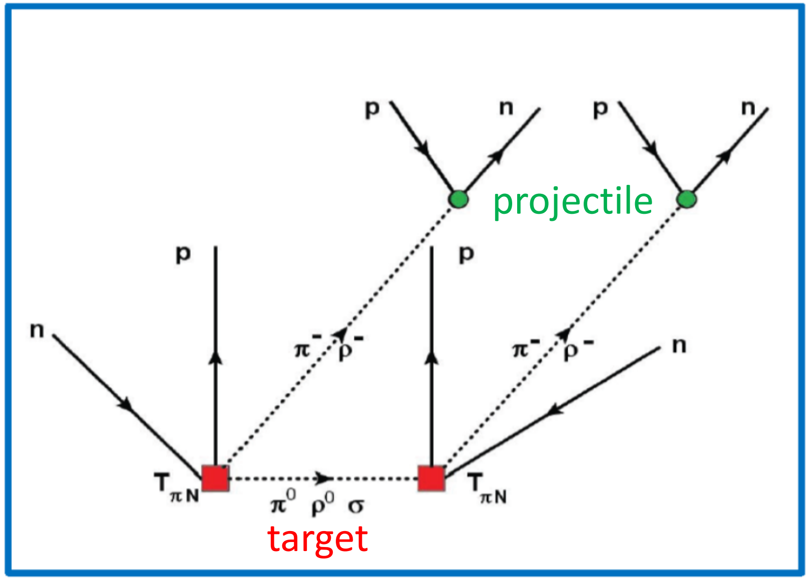
Inhibited by energy conservation, it **requires a reaction partner** which take care of the virtuality of the process by absorbing the two charged virtual mesons (->HIDCE)

The “*Majorana*” mechanism for HI-DCE

From H. Lenske, CERN Proceedings 2019-001 (2019)

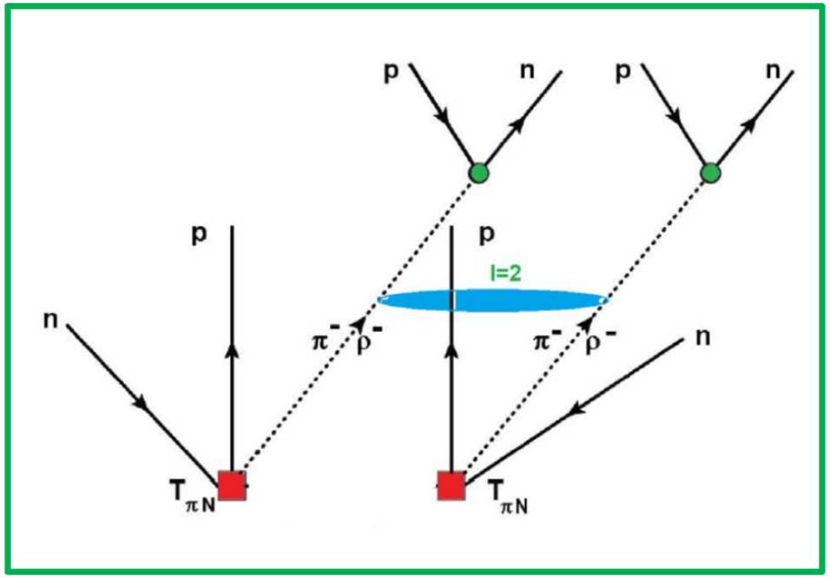
The target undergoes a correlated double meson pair decay and the projectile absorbs it

Correlation between nucleons



Universal because of generic **Short Range Correlation NN** dynamics

The nucleons emit the charged mesons independently and the mesons correlate



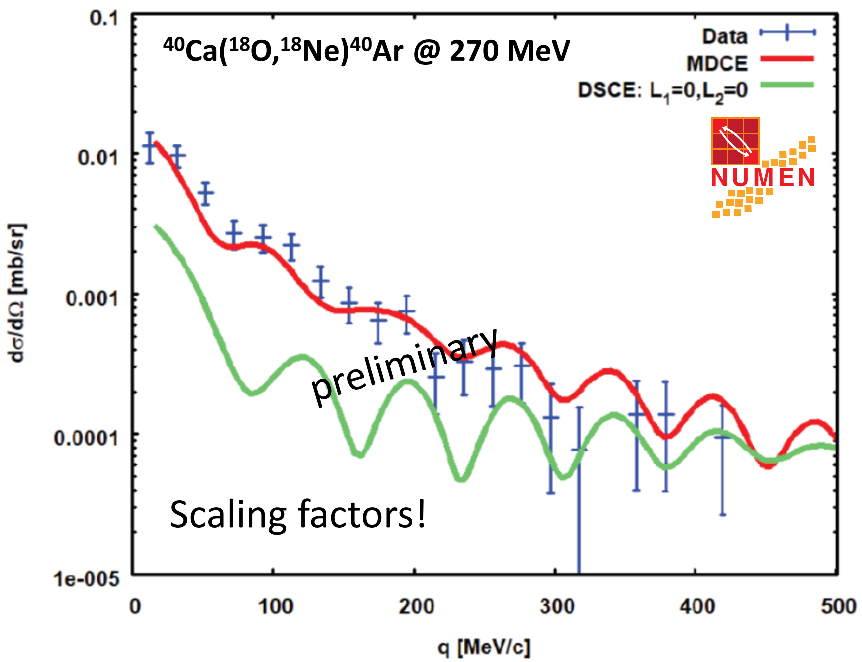
Universal because of generic **meson** dynamics

The "*Majorana*" mechanism for HI-DCE

H. Lenske, CERN Proceedings 2019-001 (2019)

- ✓ **ISI and FSI ion-ion interaction** from double folding
- ✓ **QRPA transition densities** for microscopic form factors
- ✓ One-step **DWBA** for the MDCE amplitudes and two-step DWBA for DSCE

First exploratory calculation



Shape of the measured angular distribution to disentagle the two processes??

Caveat:

- ✓ Only π-correlations included
- ✓ Off shell momentum structure approximated with on-shell component

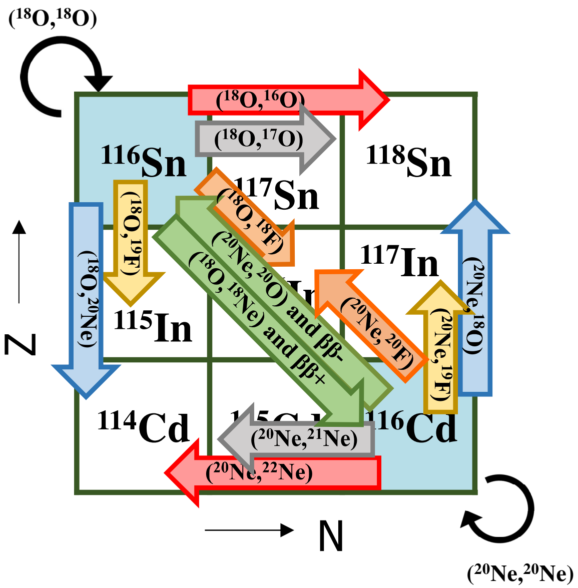
Encouraging results, but still room for refinements

NUMEN runs – Phase 2

NUMEN runs – Phase 2

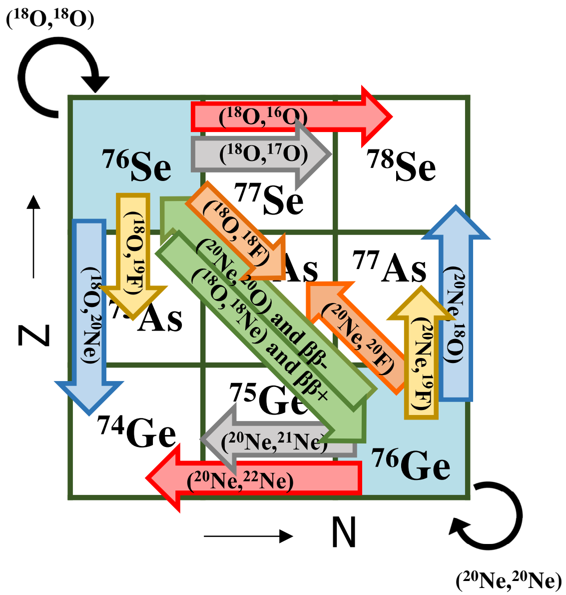
^{116}Cd - ^{116}Sn case

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



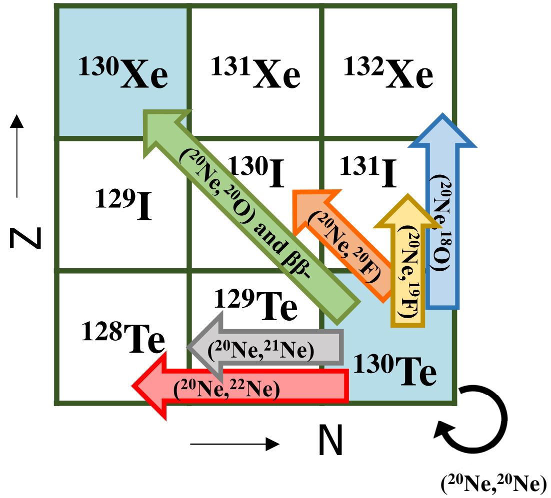
^{76}Ge – ^{76}Se case

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



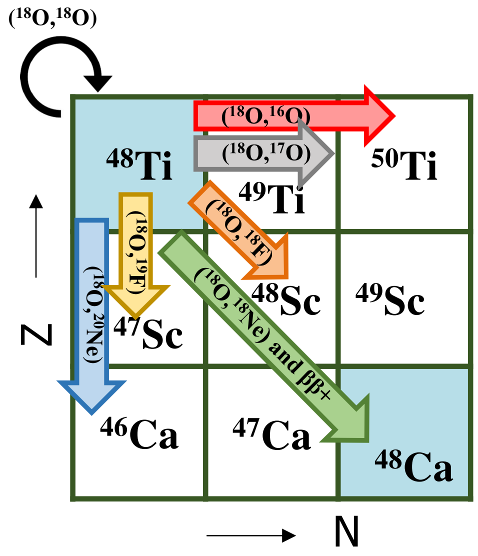
^{130}Te – ^{130}Xe case

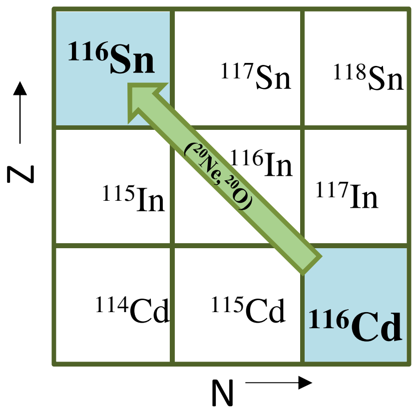
@ 15 AMeV
- ^{20}Ne + ^{130}Te



^{48}Ca – ^{48}Ti case

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

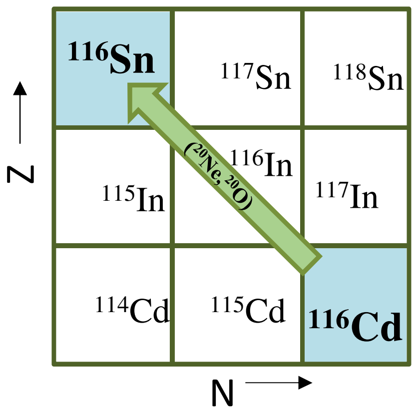




Experimental results

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

- g.s. → g.s. transition isolated (FWHM 800 keV)
- Absolute cross section measured
- Analysis of cross-section sensitivity
  <0.1 nb in the Region Of Interest



Experimental results

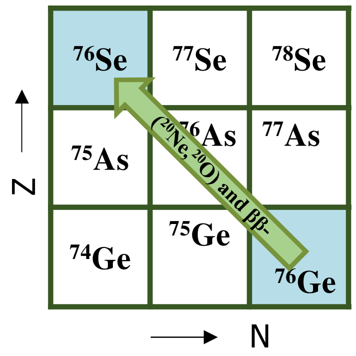
DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$

Selective enhancement of the g.s. (scaled for level density)

- Selectivity of the **reaction mechanism** (no fusion, direct process)
- And/or effect of **nuclear structure**
- Importance to describe the **full spectrum** (interference effects on gs NME, collective modes)

Experimental results

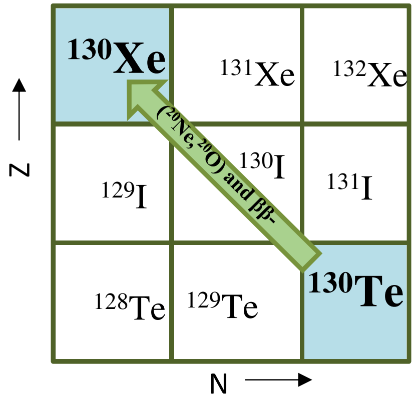
DCE $^{76}Ge(^{20}Ne,^{20}O)^{76}Se$ @ 15 AMeV



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

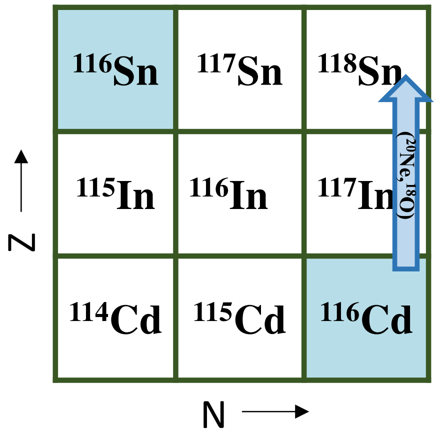
Resolution ~ 500 keV FWHM

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

Experimental results

Multi-nucleon transfer

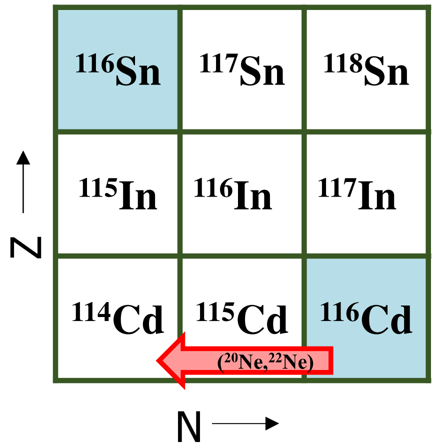
2p-transfer



EXP. DATA:
33 ± 10 nb

CALCULATIONS:
~ 26 nb

2n-transfer



EXP. DATA:
450 ± 200 nb

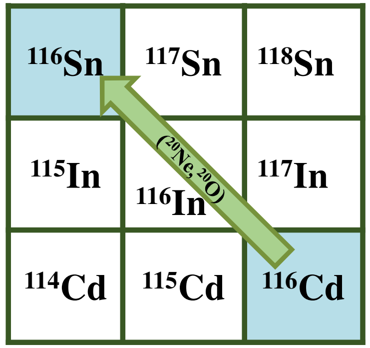
CALCULATIONS:
~ 340 nb

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

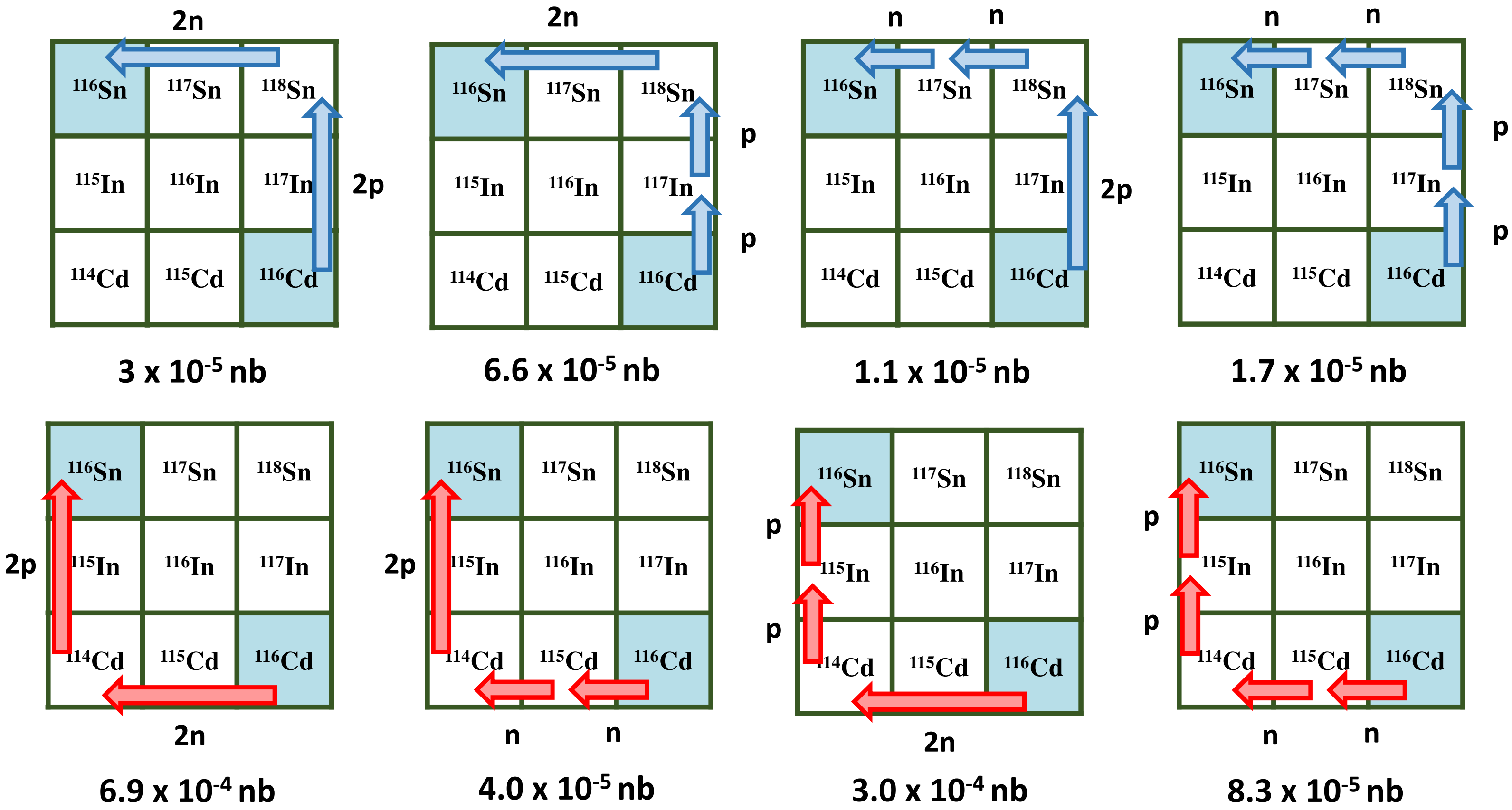
Agreement!

Multi-nucleon transfer routes
vs
Diagonal process

(exp. cross section **12 ± 2 nb**)



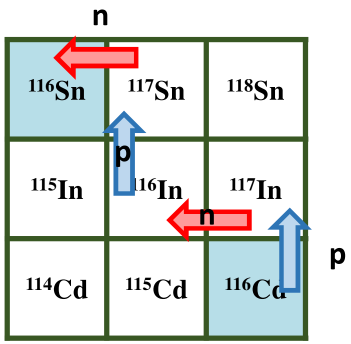
J.L. Ferreira, J. Lubian (UFF)



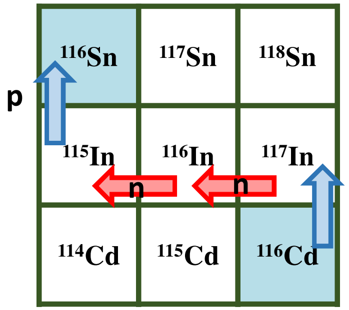
Multi-nucleon transfer routes
vs
Diagonal process

J.L. Ferreira, J. Lubian (UFF)

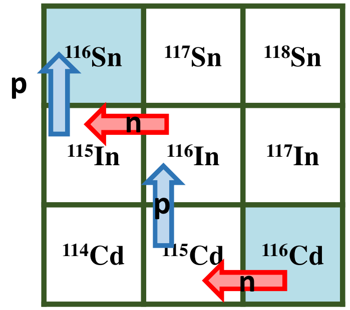
(exp. cross section **12 ± 2 nb**)



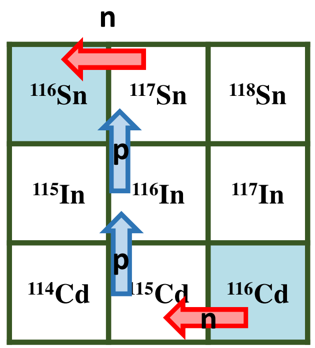
9.4×10^{-8} nb



1.5×10^{-6} nb



3.2×10^{-7} nb



1.1×10^{-7} nb

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

---

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

Experimental results

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

A. Spatafora et al., PRC (submitted)

Coupling with first low-lying exc. states (CC) to describe ang. distr. at large momentum transfer

Present experimental limitations

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

Moving towards hot-cases

Much higher beam current is needed

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€
To work with two orders of magnitude more intense beam

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**
- **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 $0\nu\beta\beta$

Thank you!