Search for nuclear response to isospin probes and their connection to double-beta decay

NURE

Manuela Cavallaro and Francesco Cappuzzello

INFN – LNS and University of Catania

Selected Topics in Nuclear and Atomic Physics 2019

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Fiera di Primiero (TN)

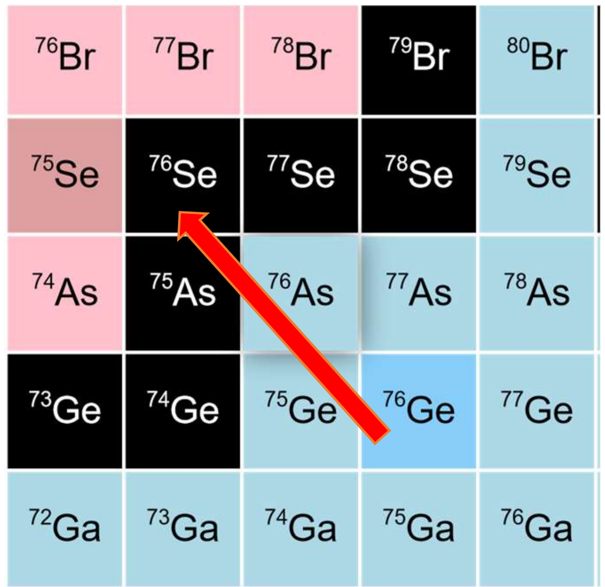
Double charge exchange reactions (DCE)

A Double Charge Exchange (DCE) reaction is a process induced by a projectile on a target

$$ {}^{A}_{Z}x_{N} + {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z\mp2}y_{N\pm2} + {}^{A}_{Z\pm2}Y_{N\mp2} $$

Two protons (neutrons) of the target are converted in two neutrons (protons), being the mass number *A* unchanged. The opposite transition occurs in the projectile

In the **isospin representation**, DCE reactions probe the **double isovector excitations** generated by combination of the **isospin rising and lowering operators** $\tau_x^{\pm}\tau_x^{\pm}$ $\tau_x^{\mp}\tau_x^{\mp}$ acting on two nucleons in the projectile and the target



Why to study DCE?

- Population of exotic nuclei from stable target and projectile
- Study of the response of nuclei to double isospin operator
- Possible connection with second order weak processes

Difficulties from experimental and theoretical side

Outline

- Past Double Charge Exchange exploration: achievements and limitations
- The interest for double beta decay and the idea of NUMEN
- The experimental apparatus
- The NUMEN pilot experiment
- The first results on the systems of interest for $0\nu\beta\beta$

Past Double Charge Exchange exploration: achievements and limitations

Pion-induced double charge exchange

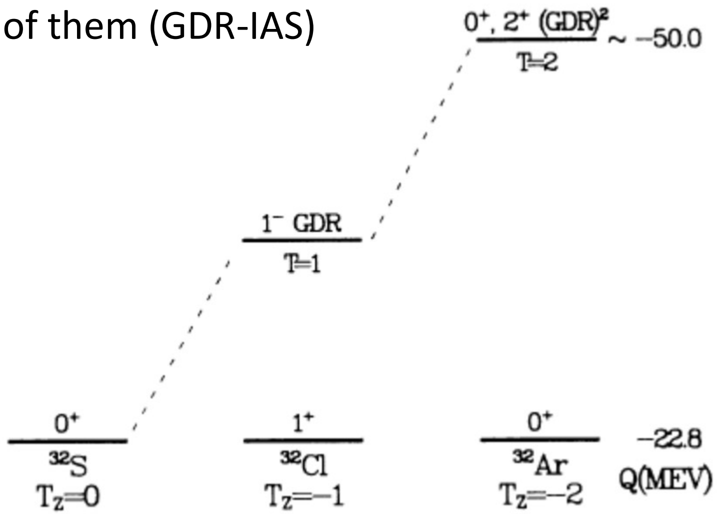
(π+, π-) or (π-, π+) cause a change of two units of charge in a nucleus

Experiments at Los Alamos Meson Physics Facility (LAMPF) in the 80's

Double Isovector Giant Dipole Resonance (GDR)^2 $J^\pi = 0^+, 2^+; T=2$

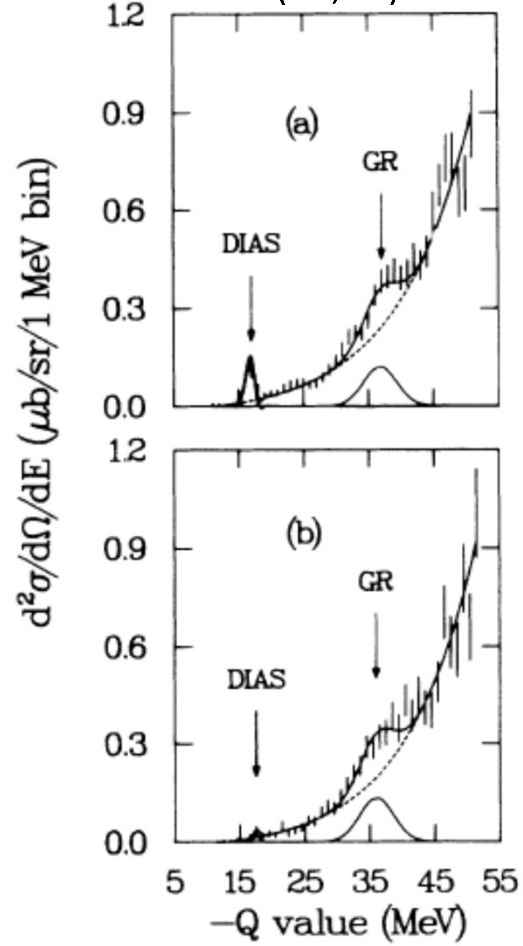
Double Isobaric Analog State (DIAS)

Combination of them (GDR-IAS)



S. Mordechai, C.F. Moore, Nature 352 (1991) 393

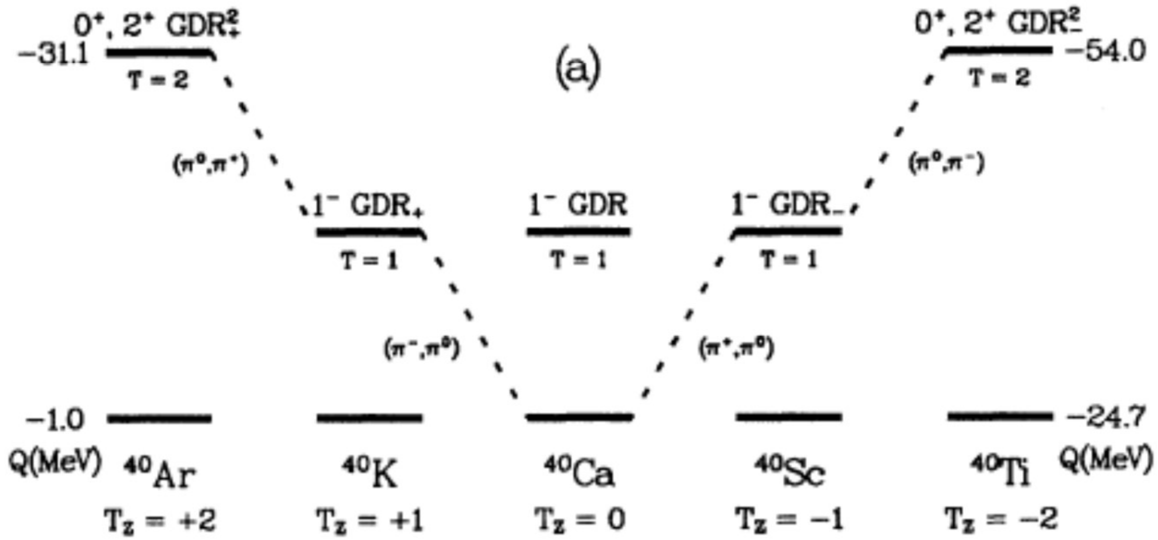
$^{56}Fe(\pi+, \pi-)\,^{56}Ni$



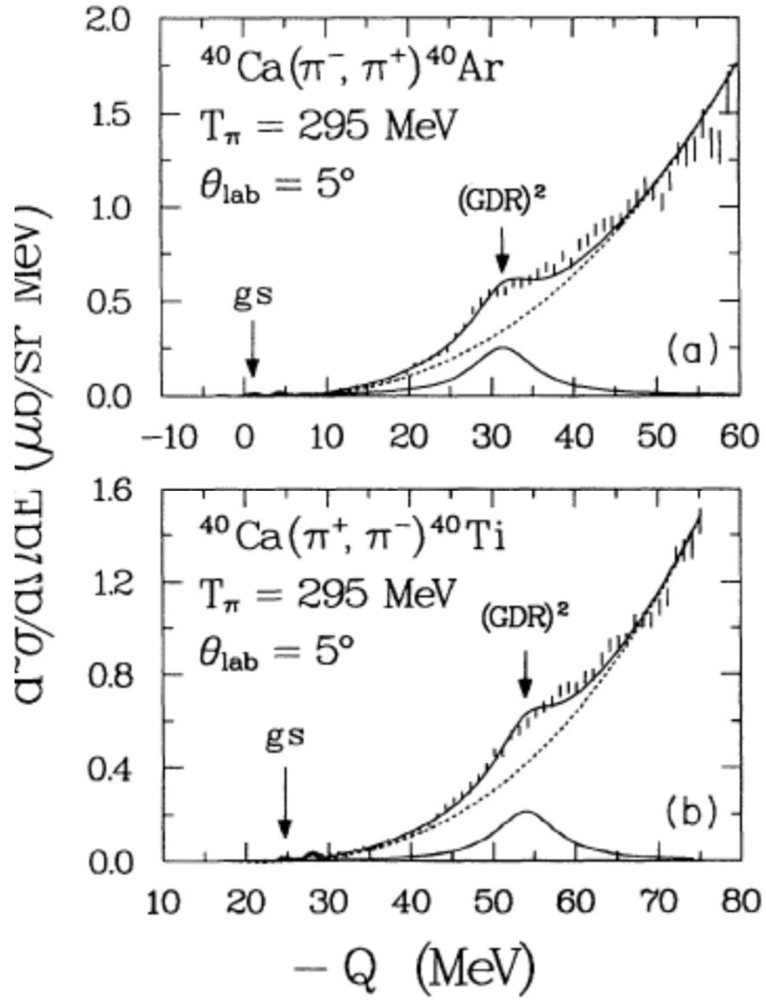
S. Mordechai et al., PRL 60 (1988)408

Pion-induced double charge exchange

$(GDR)^2$ observed also in the inverse reaction ($\Delta Tz=+2$) on the same target nucleus

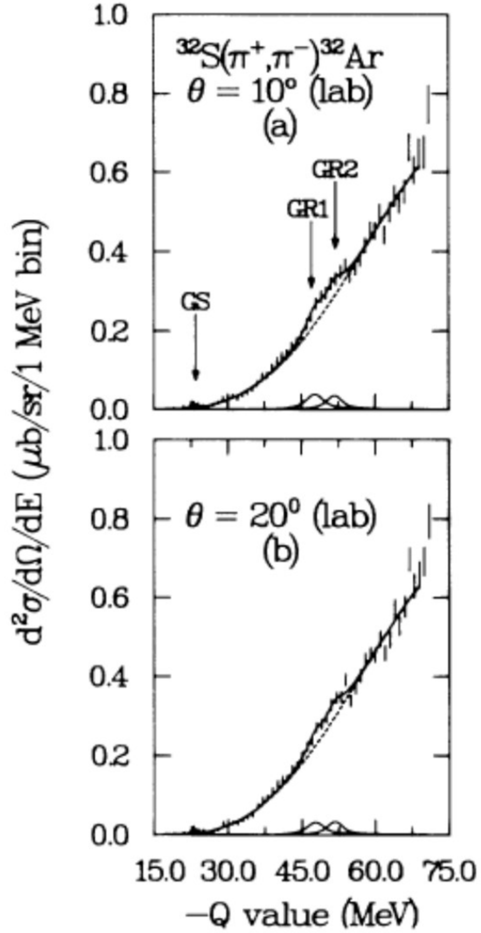


S.Mordechai et al., PRC 43 (1991) 1509

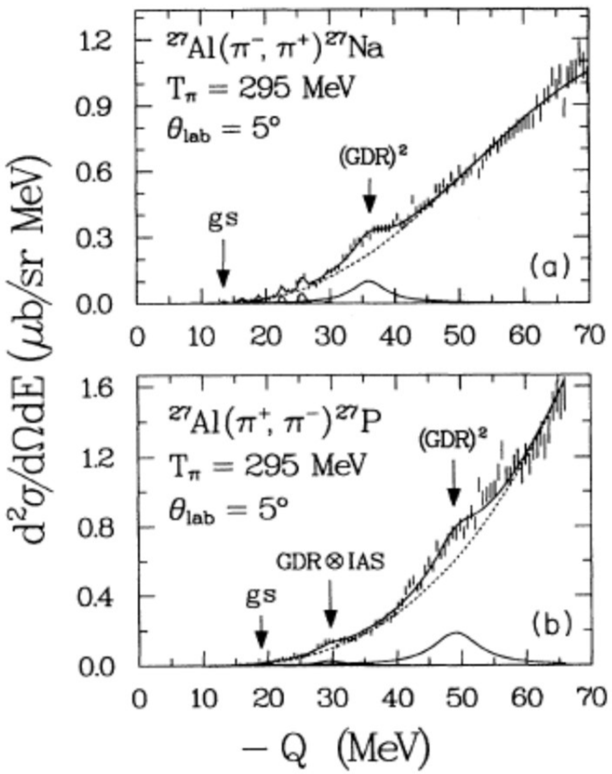


Pion-induced double charge exchange

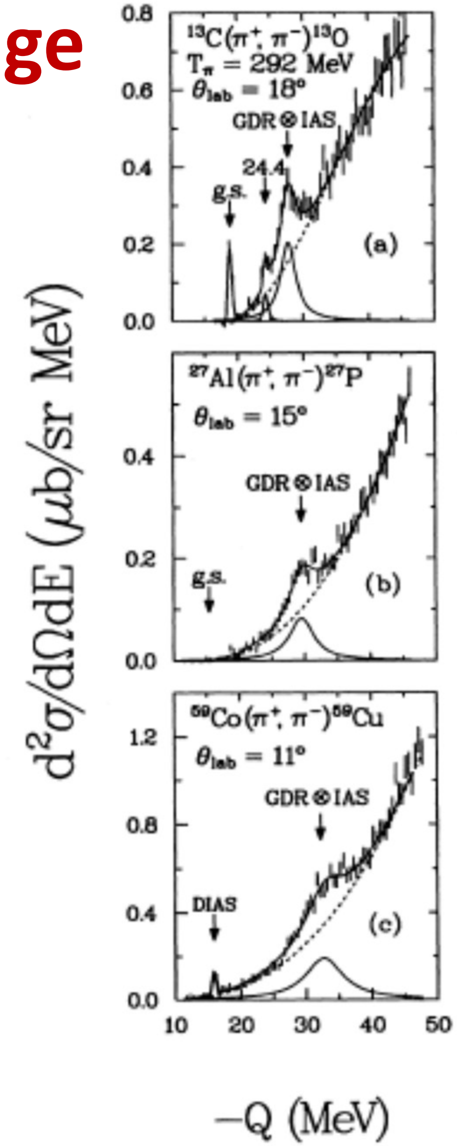
Systematic observation on a wide range of nuclei



S. Mordechai et al., PRL 61 (1988)531



S.Mordechai et al., PRC 43 (1991) 1509



S. Mordechai et al., PRC 43 (1991) 1111

Pion-induced double charge exchange

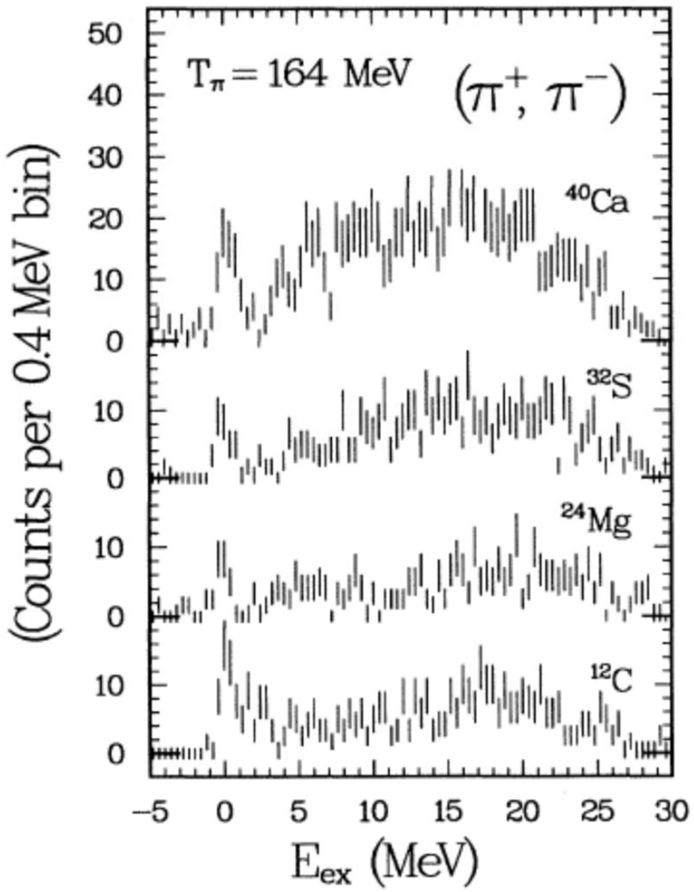
D.L. Watson et al., PRC 43 (1991) 43

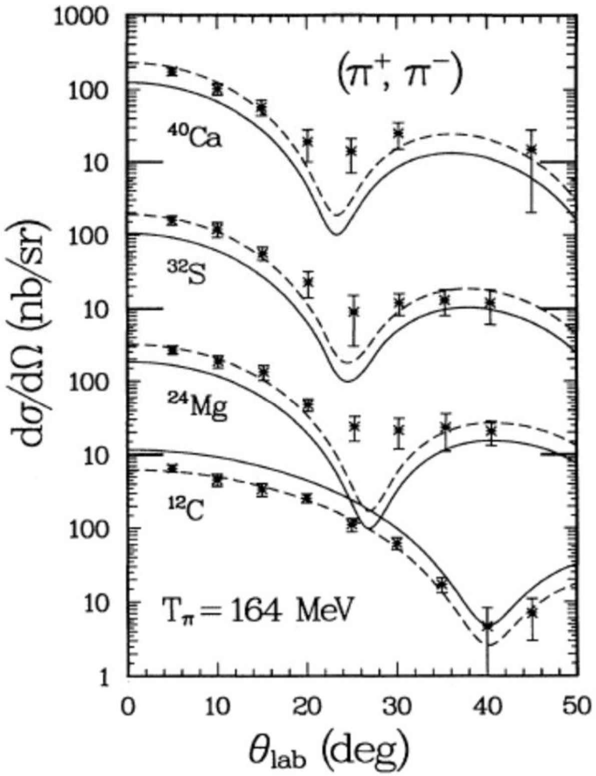
Interest in double giant resonances

BUT pions are spinless probe

Not ideal to populate Double GT (DGT)

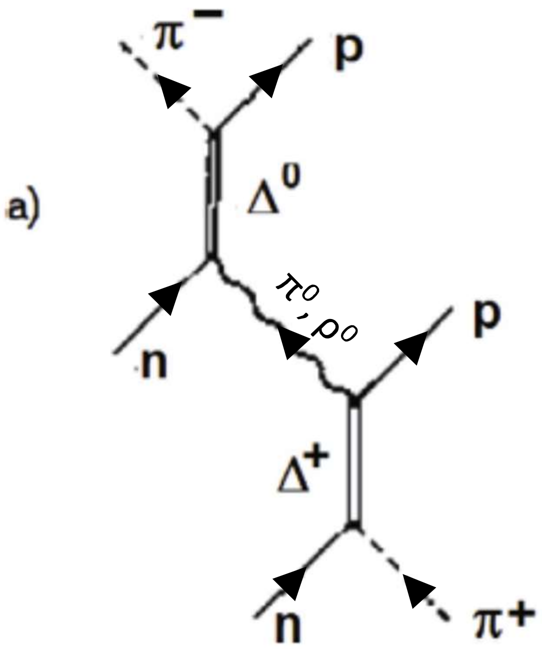
Scarce experimental information
about g.s. to g.s. transitions
low cross sections (nb/sr)

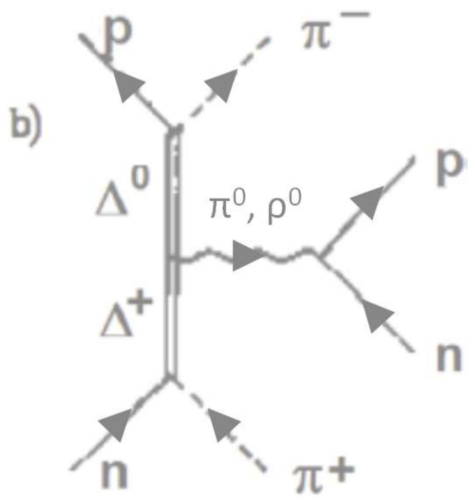




Δ-nucleon interaction: mechanism responsible for gs to gs non-analog transition

Pion-induced double charge exchange





M.B. Johnson et al., Phys. Rev. Lett. 52 (1984) 593
M.B. Johnson, C.L. Morris, Ann. Rev. Nucl. Part. Sci. 43 (1993) 165

Δ-nucleon interaction

Formation and decay of intermediate Δ resonances
(which plays the role of converter of hadronic charge)

Absorption of the incoming π^+ on a neutron into a Δ^+ which decays into a proton and a virtual neutral meson (π^0, ρ^0) which rescatters on a neutron into a Δ^0, which decays into a π^- and a second proton

Effective rank-2 isotensor interaction:

$$V^{(2)} \sim [\vec{\phi}_\pi \otimes \vec{\phi}_\pi]_2 \cdot [\boldsymbol{\tau}_i \otimes \boldsymbol{\tau}_j]_2$$

Pion isovector fields

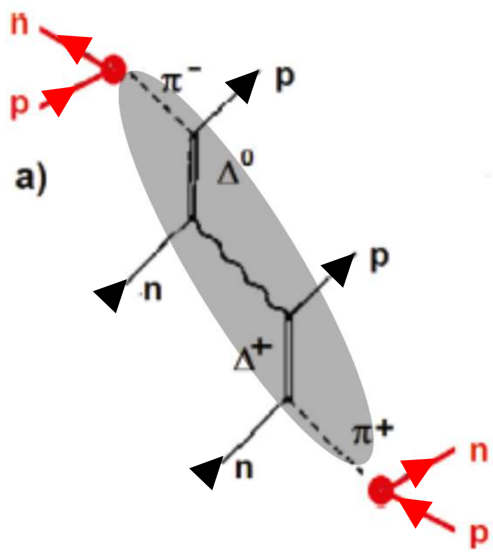
Nucleon isovector operators

Important role of nuclear structure in the description of (π^+,π^-)
→Nucleon-nucleon correlations

N. Auerbach et al., PRL 59 (1987) 1076
N. Auerbach et al., PRC 38 (1988) 1277

From Pion to Heavy-Ion induced Double Charge Exchange

H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716



These kinds of interactions are not specific for pion-induced DCE but can occur in similar form also in **other hadronic reactions**

Introduction of **projectile** (at least two nucleons involved for isospin flip)
Systems which support rank-2 isotensor processes

The **pion field** is **virtual**, being exchanged between projectile and target

e.g. in a reaction where in the target nn -> pp ($\Delta Z=+2$), the projectile acts as a source for the π^+ field and sink for the π^- field.

The lightest projectiles allowed are t or ^{3}He [(t, 3p) or the (^{3}He, 3n) reactions are very challenging from the experimental point of view]

If final ejectile particle-stable → **heavy-ion DCE** (HI-DCE) reactions (with ^{12}C or heavier projectiles)

Past HI-DCE experiments

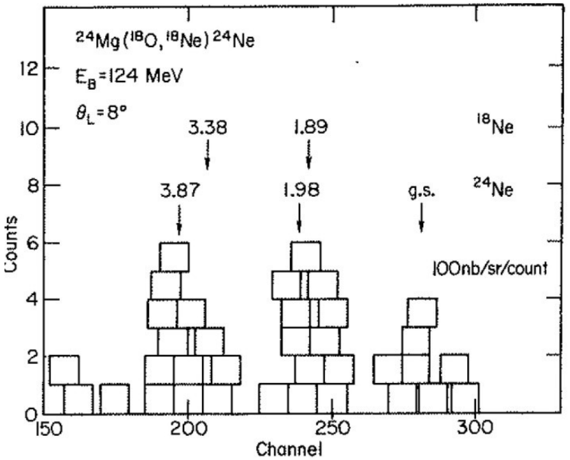
Main purposes:

-Populate nuclei far from stability
-Mass measurements by reaction Q-value measurements
-Search for DGT

Not conclusive for spectroscopic investigations due to poor statistical significance

J. Cerny, et al., Proc. 3° Int. Conf. on Nuclei Far from Stability, Cargese, 1976

$^{24}Mg(^{18}O,^{18}Ne)^{24}Ne$ @124 MeV

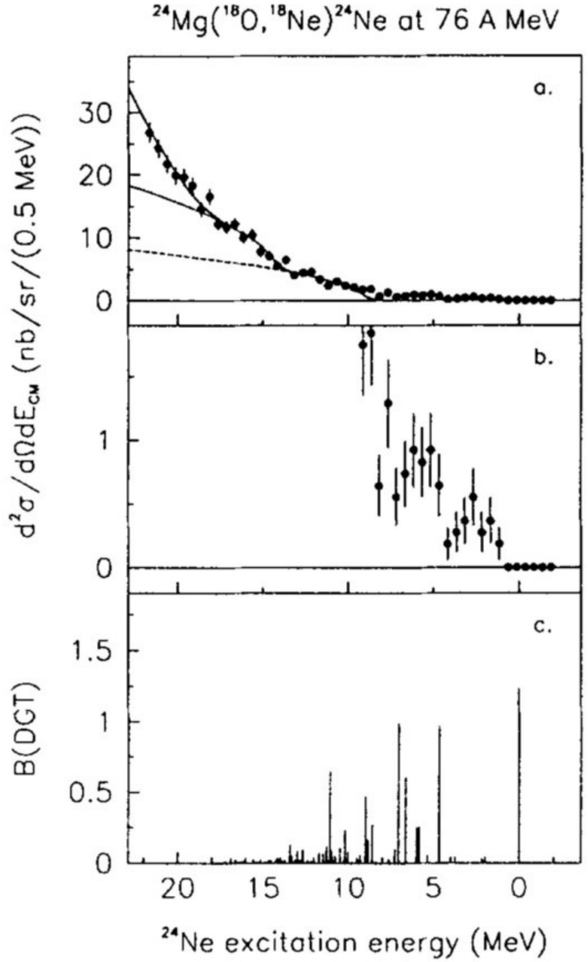


ϑ_{lab} = 8°

Q = -14.1 MeV

Small cross-section (100 nb/sr)

J.Blomgren, et al., Phys. Lett. B 362 (1995) 34



Q = -14.1 MeV

Very small cross-section (10 nb/sr)

Past HI-DCE experiments

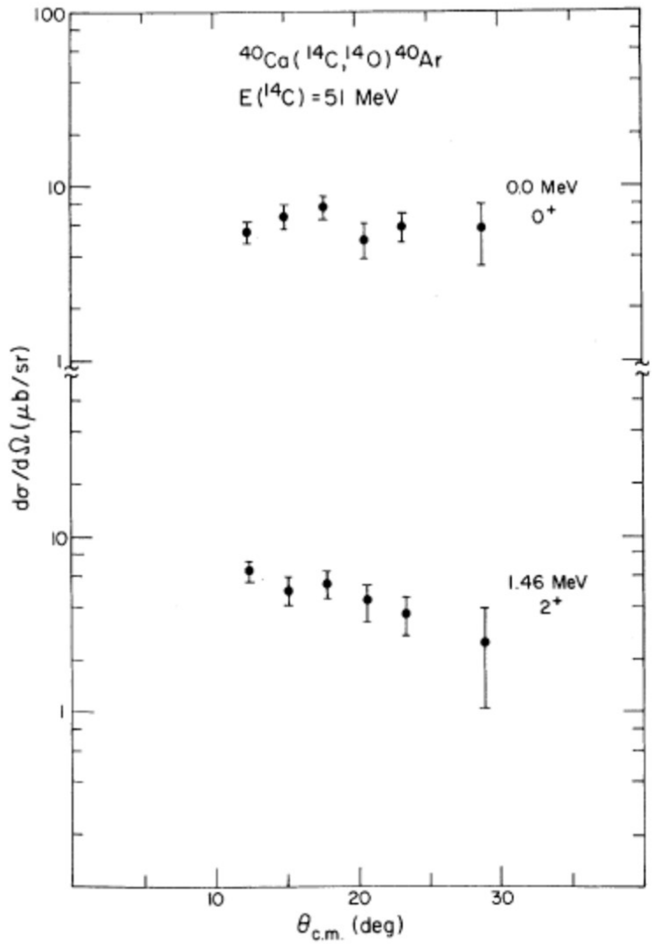
D.M. Drake et al., PRL 45 (1980) 1765

$^{40}Ca(^{14}C,^{14}O)^{40}Ar_{gs}$
$E(^{14}C)$=51 MeV

Barely above barrier

11 deg < θ_{cm} < 28 deg

Energy spectrum missing!

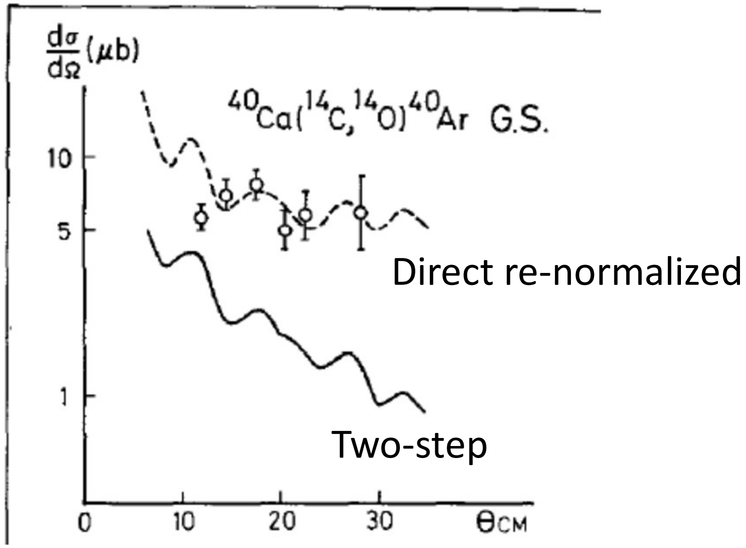


Interest in the study of the pair transfer modes

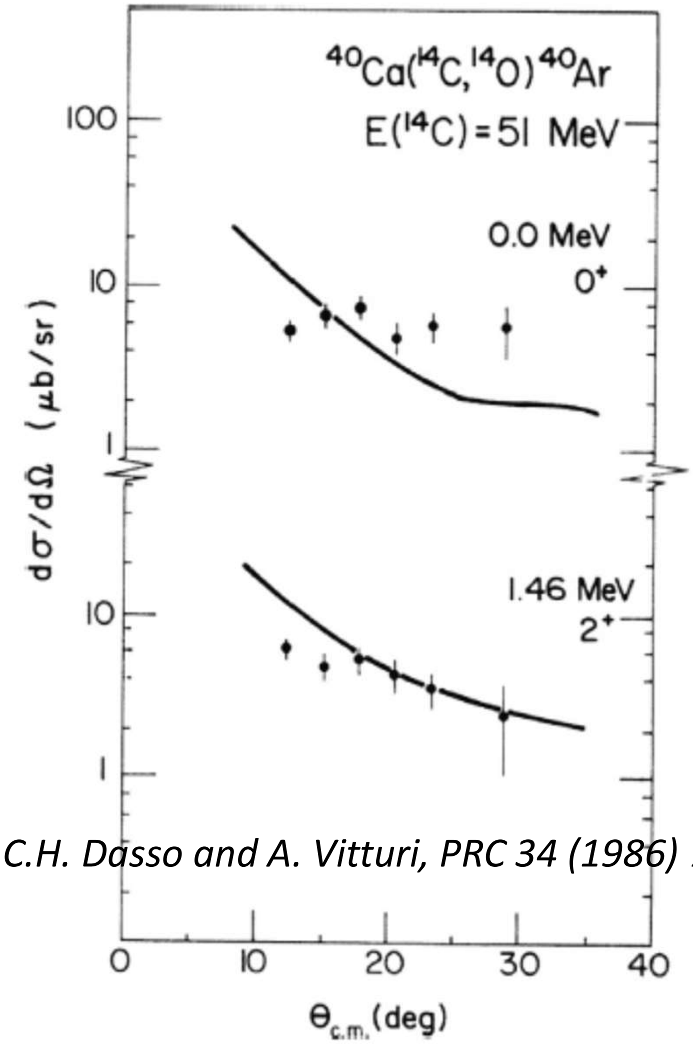
Spectroscopic tools to populate 2p-2h states (2-phonon states)

Past HI-DCE experiments

The (^{14}C,^{14}O) reaction
- Simultaneus pair-exchange (exchange of a di-neutron and a di-proton)
or
- Exhange of two units of charge between target and projectile



D.R.Bes et al., NPA 405 (1983) 313



C.H. Dasso and A. Vitturi, PRC 34 (1986) 743

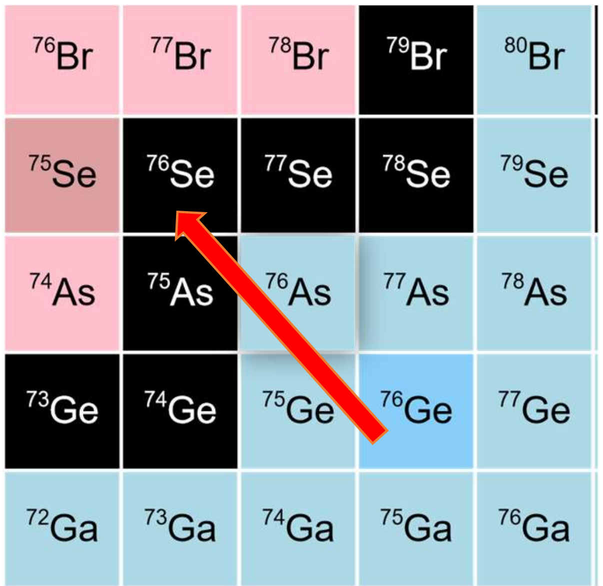
The interest for double beta decay and the idea of NUMEN

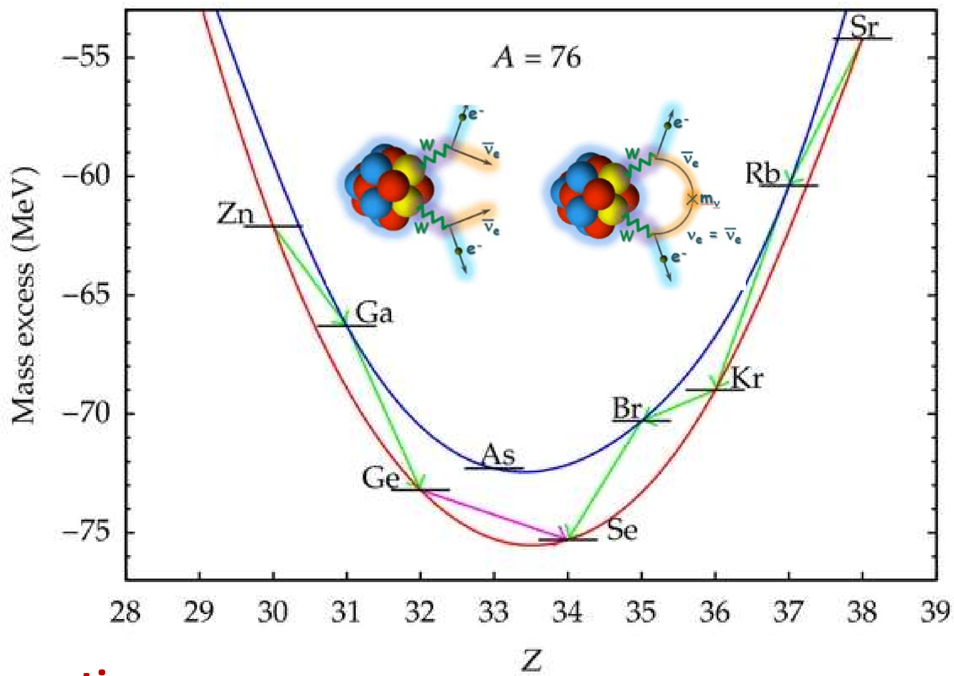
Recent HI-DCE experiments: connection with 0νββ decay

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**

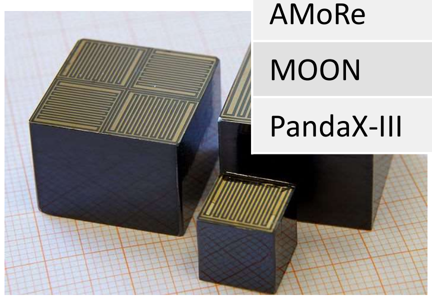
Search for 0νββ decay.
A worldwide race

Still not observed

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**

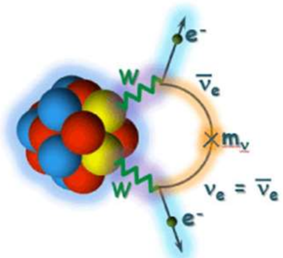
$$\left(T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)\right)^{-1} = G_{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

Nuclear Matrix Element (NME)

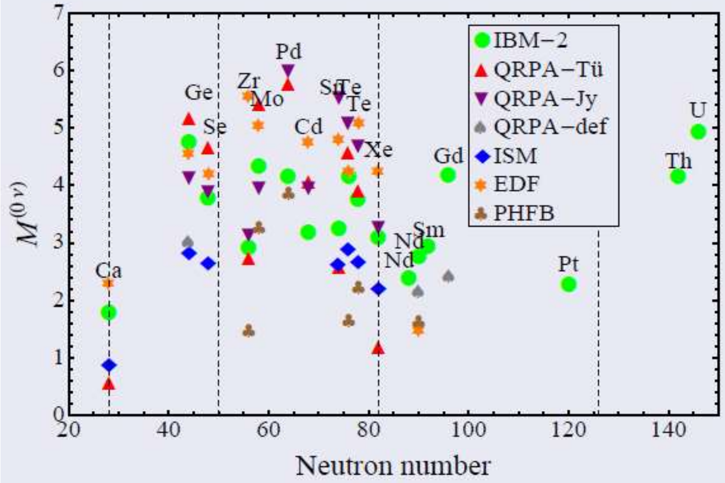
$$\left|M_{\varepsilon}^{0\nu\beta\beta}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}_{\varepsilon}^{0\nu\beta\beta} \middle| \Psi_i \right\rangle\right|^2$$

Transition probability of a **nuclear** process

Nuclear physics plays a key role!



$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



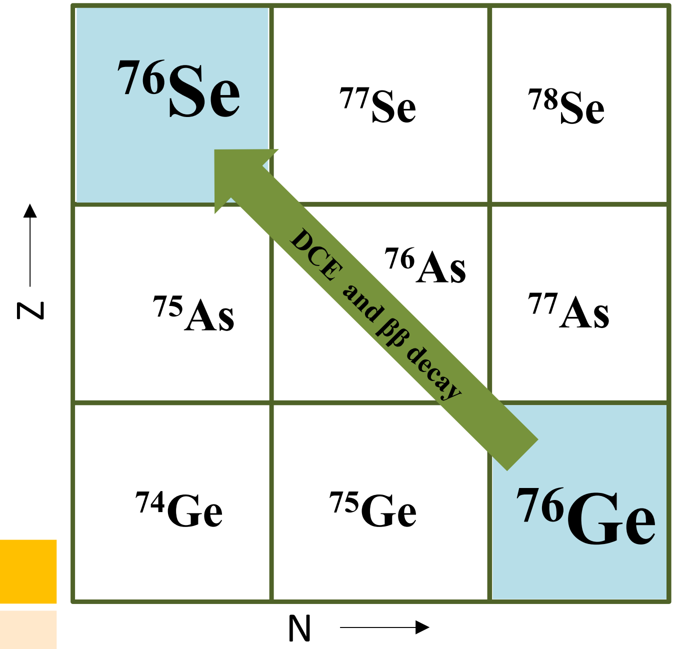
A new experimental tool

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

NUMEN

European Commission

erc NURE



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

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

0νββ vs DCE

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- Decay vs reaction **dynamics**
- DCE includes **sequential** transfer **mechanism**
- **Projectile and target** contributions in the NME

Similarities

- **Same initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ decay are the same as those of the target/residual nuclei in the DCE
- **Similar operator:** Short-range Fermi, Gamow-Teller and rank-2 tensor components are present in both the transition operators, with tunable weight in DCE
- **Large linear momentum** (~100 MeV/c) available in the virtual intermediate channel
- **Non-local** processes: characterized by two vertices localized in a pair of nucleons
- **Same nuclear medium**
- **Off-shell propagation** through virtual intermediate channels

The Goals of the Research Program

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

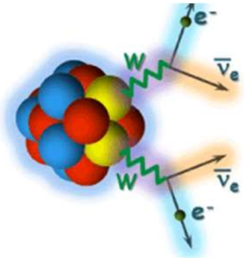
Mid term goals:

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

Double β-decay

Two-neutrino double beta decay

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

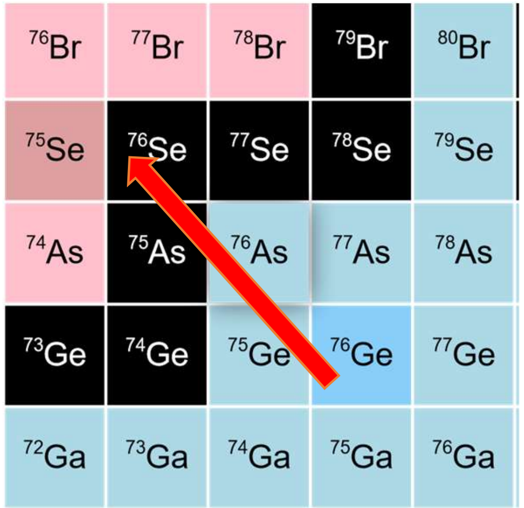


Observed in 11 isotopes since 1987

Ordinary 2° order β decay

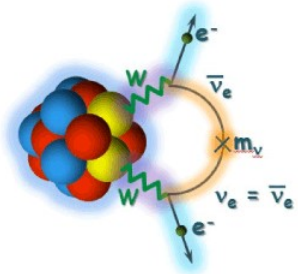
$$ {}^{A}_{Z}X_N \rightarrow {}_{Z+2}^{\;\;A}Y_{N-2} + 2e^- + (2\bar{\nu}) $$

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



Neutrinoless double beta decay

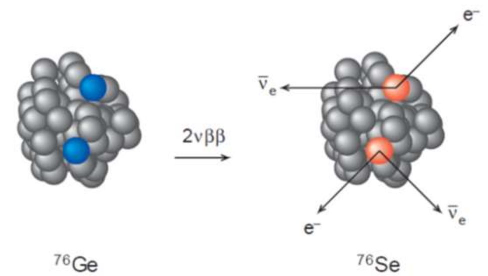
E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184



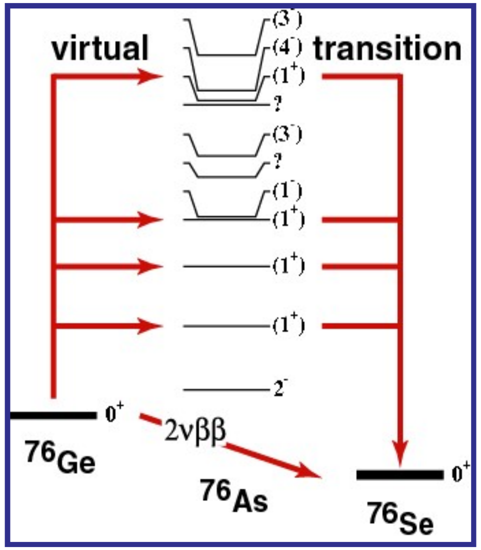
Still not observed

Beyond standard model

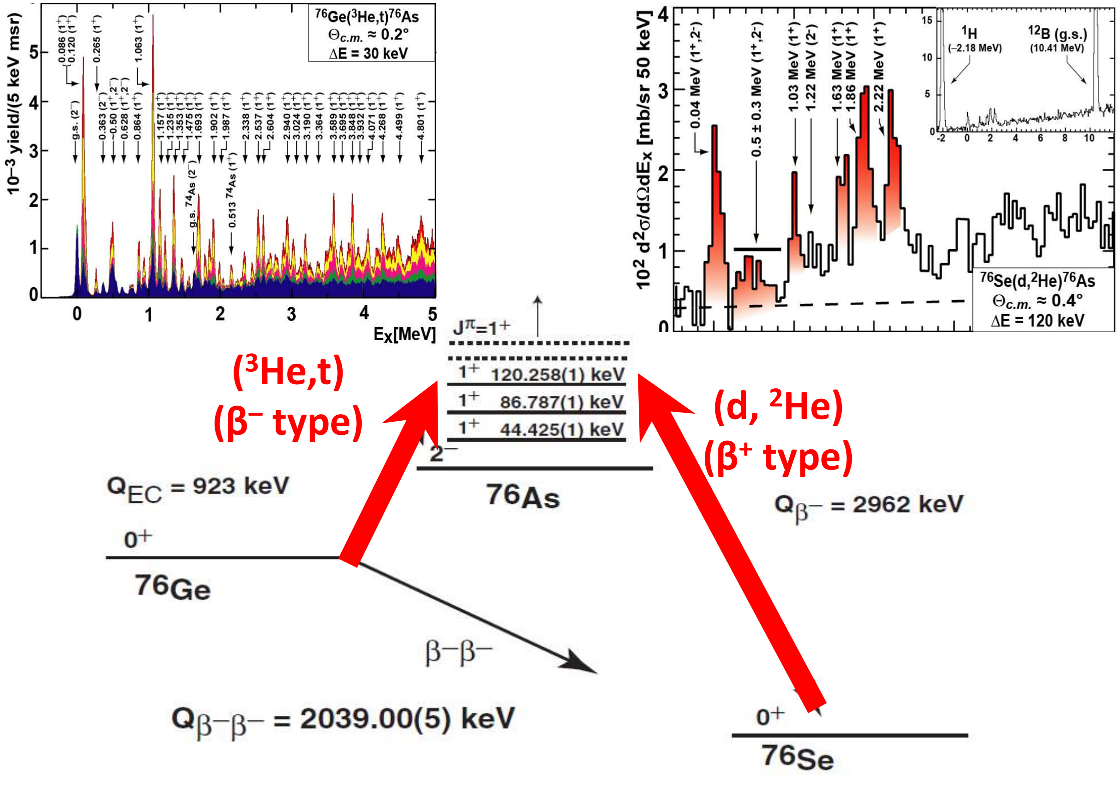
2νββ - decay



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

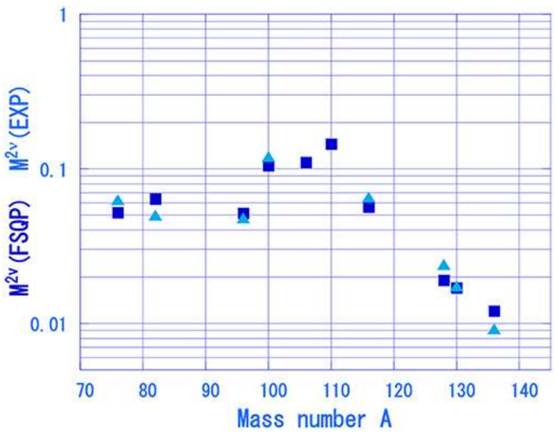


Methodology:
Single CEX to populate intermediate states



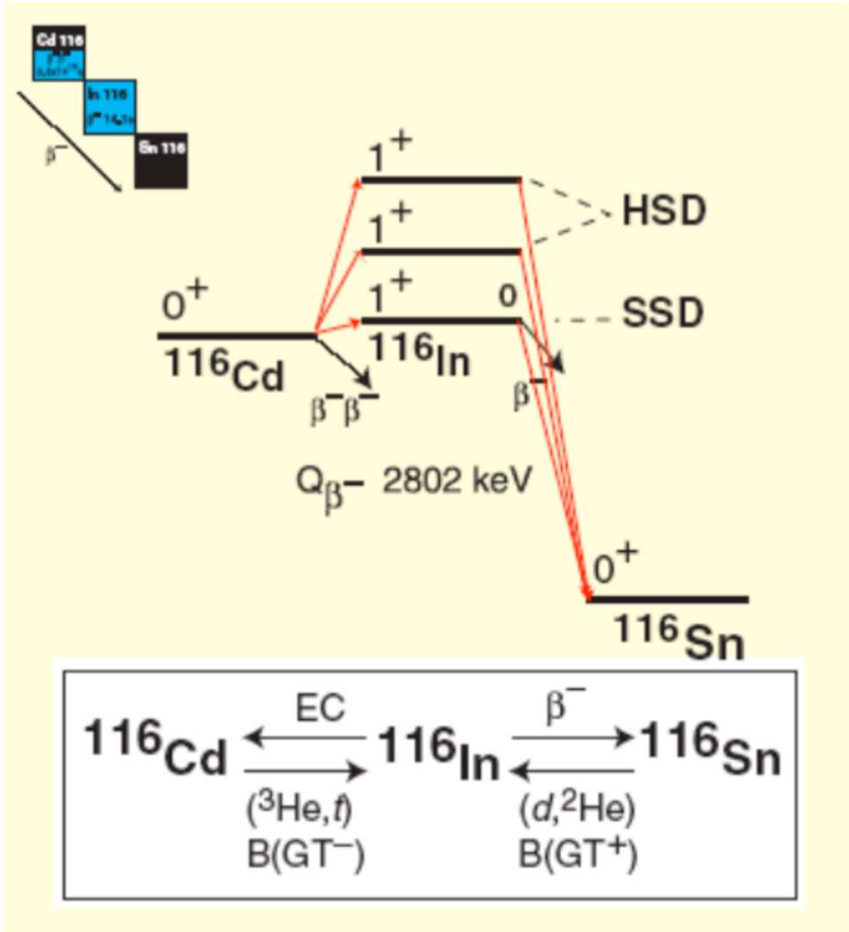
H. Ejiri Progr. Part. Nucl. Phys. 64 (2010) 249257

2νββ - decay



H.Ejiri, J.Suhonen, K.Zuber, Phys. Rep. 797 (2019) 1-102

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



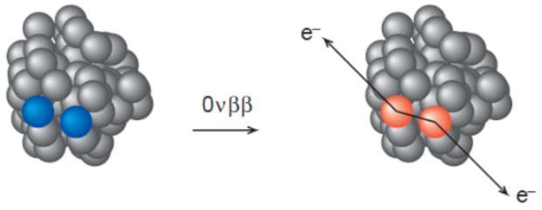
However

from CEX cross-sections -> **transition probabilities** are extracted

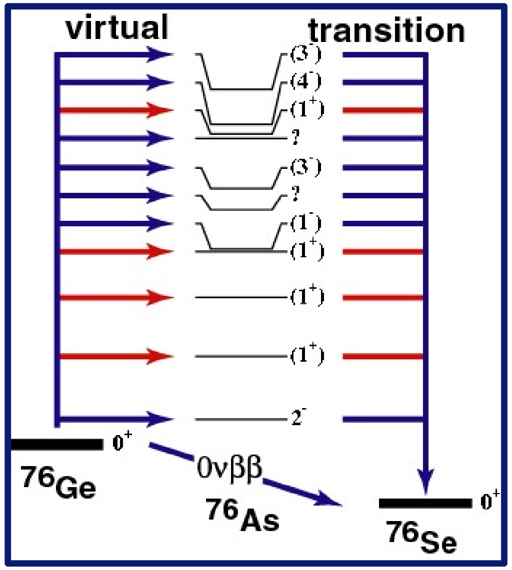
transition amplitudes are required, so phases are necessary

-> **Single State Dominance (SSD) approximation**
OR all positive signs in the coherent sum of the amplitudes

0νββ - decay



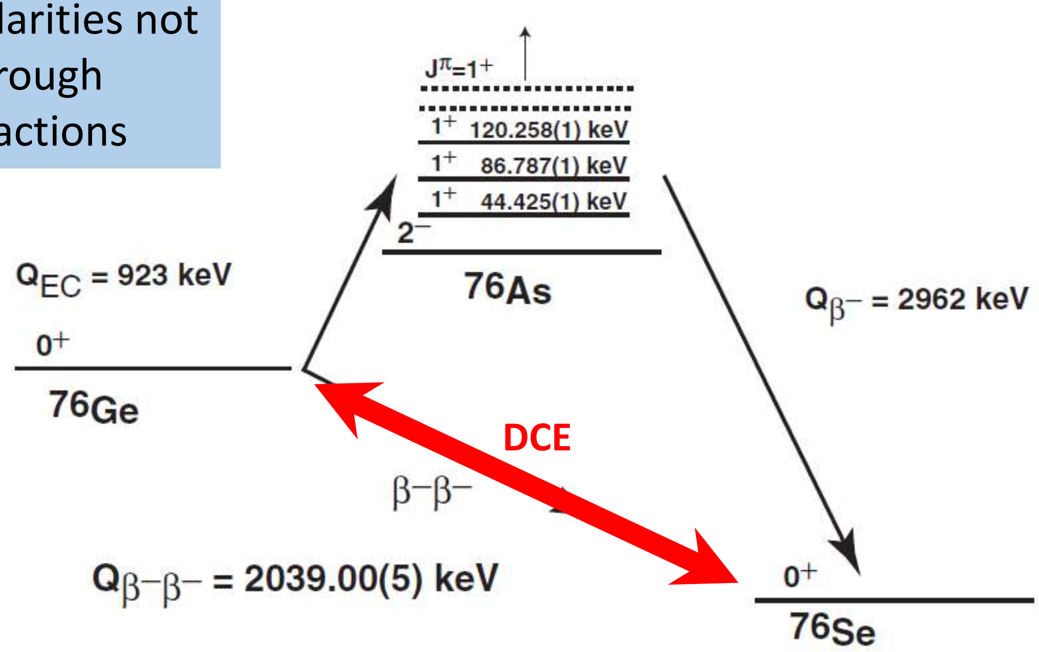
neutrino enters as virtual particle,
$q \sim 0.5 fm^{-1}$ (~ 100 MeV/c)
forbiddeness weakened L = 0, 1, 2…

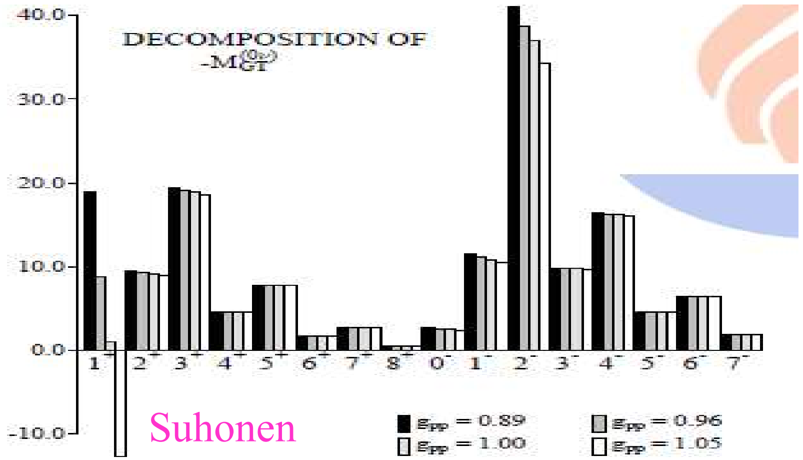


Closure approximation

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

High multipolarities not accessible through single CEX reactions





The experiments ai INFN-LNS

erc NURE

NUMEN

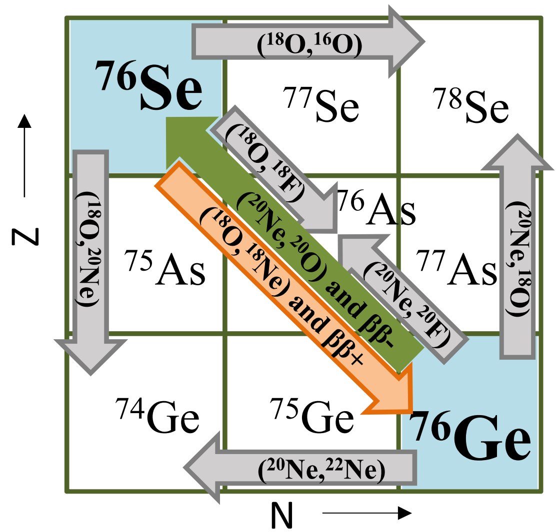
The experiments

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

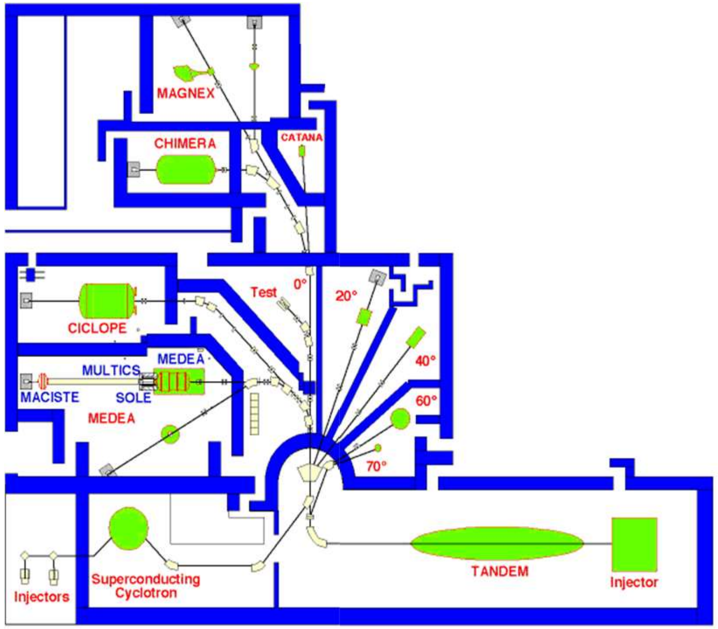
- **Two directions**:
  $\beta\beta^-$ via (^{20}Ne,^{20}O) and $\beta\beta^+$ via (^{18}O,^{18}Ne)

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

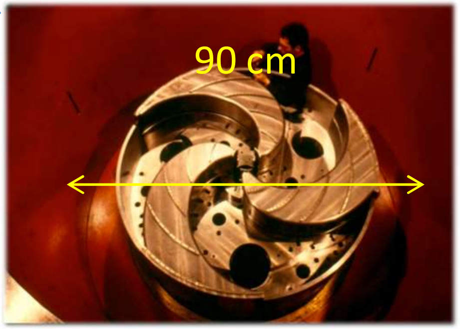
- **Two (or more) incident energies**
  to study the reaction mechanism



The LNS laboratory in Catania



Superconducting cyclotron K800



- **176 Tons**
- **Max magnetic field: 4.8 T**

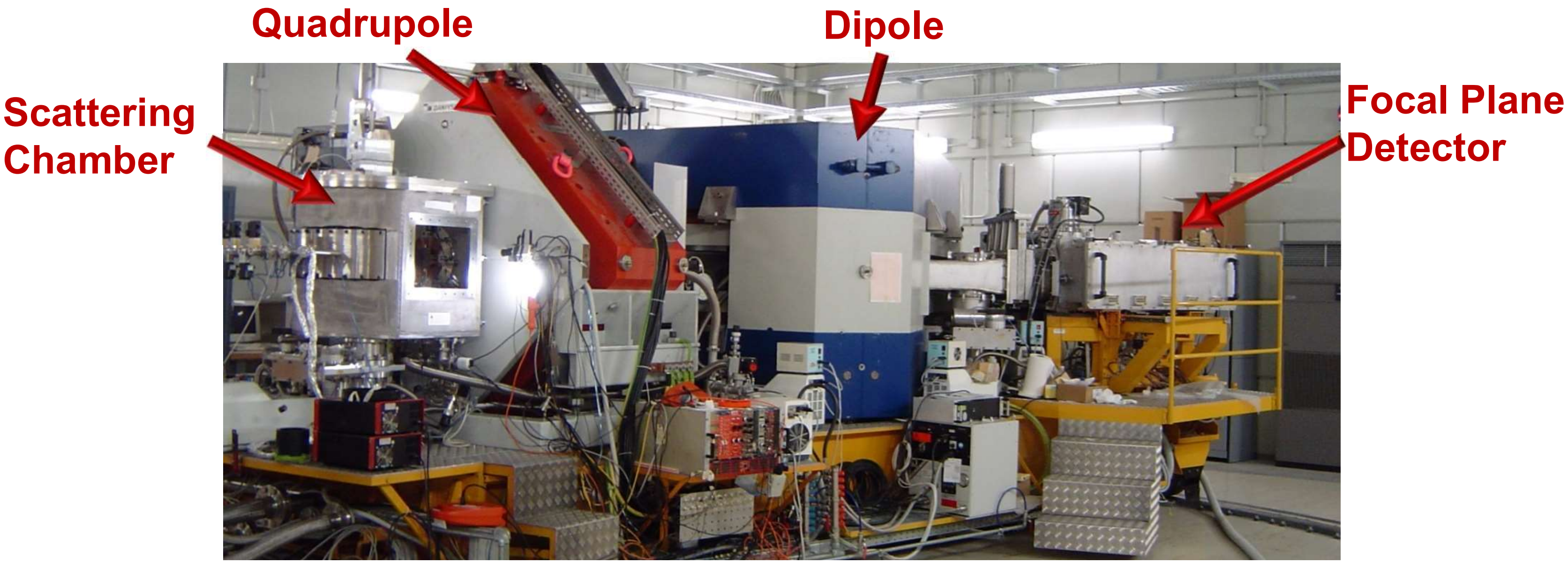
- Accelerating ion beams from proton to Uranium at energy up to 80 AMeV
- Superconducting magnets with Niobium-Titanium coils in liquid Helium at 4.2 K

MAGNEX: a large acceptance QD spectrometer

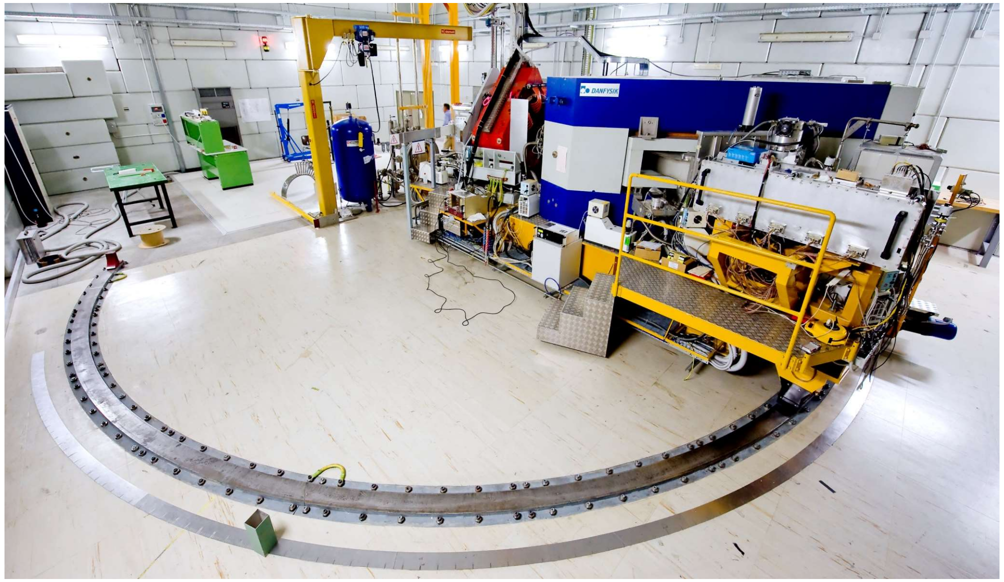
F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167

- **The Quadrupole**: vertically focusing
  (Aperture radius 20 cm, effective length 58 cm. Maximum field strength 5 T/m)

- **The Dipole**: momentum dispersion (and horizontal focus)
  (Mean bend angle 55°, radius 1.60 m. Maximum field ~ 1.15 T)



MAGNEX characteristics



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

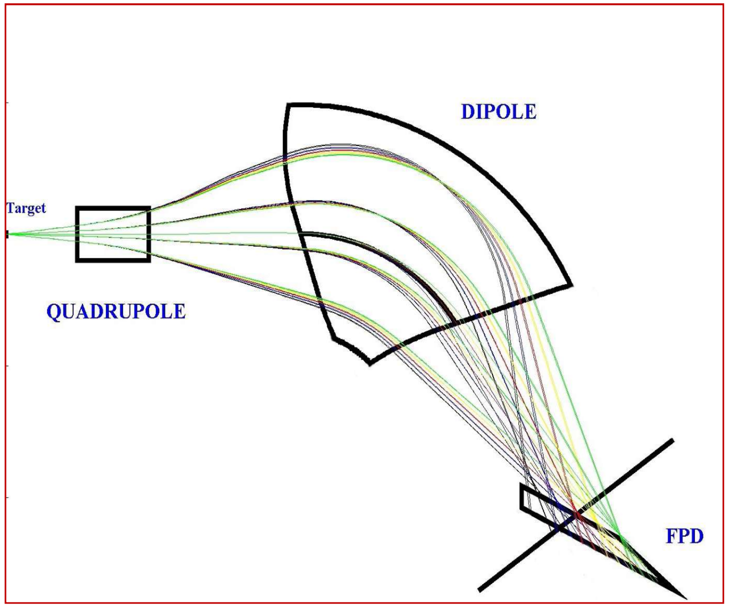
We have measured in a **wide mass range** (from protons to medium-mass nuclei)

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

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

Needs to go to large acceptance to study rare processes

The large acceptance problem



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

F transport matrix

Large acceptance

Aberrations

$$x_i(f) = \sum_j R_{ij} x_j(i) + \sum_{j,k} T_{ijk} x_j(i) x_k(i) + ...$$

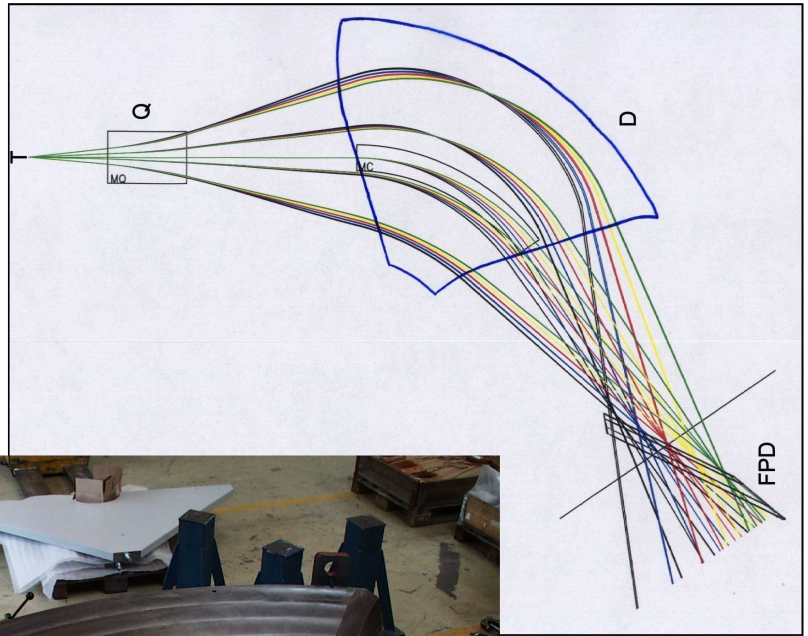
Up to 10° order

Careful hardware design
(to minimize the aberrations)

Software ray-reconstruction
(to know the aberrations)

Hardware minimisation of aberrations

- Rotation of the focal plane detector of 59°
- Shift of the focal plane detector
- Introduction of surface coils located between the dipole pole faces and the inner high vacuum chamber, giving tunable quadrupolar and sextupolar corrections
- Shaping of dipole entrance and exit boundaries (8th order polynomial)



Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

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

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

Inversion of the transport matrix

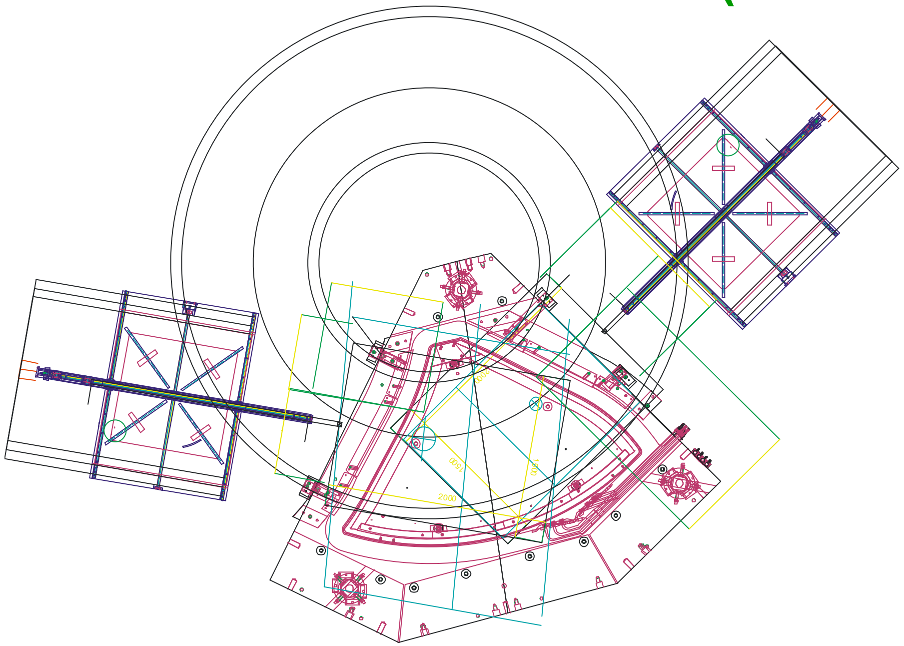
$$F^{-1} : \vec{\mathbf{X}}_{\mathbf{f}} \rightarrow \vec{\mathbf{X}}_{\mathbf{i}}$$

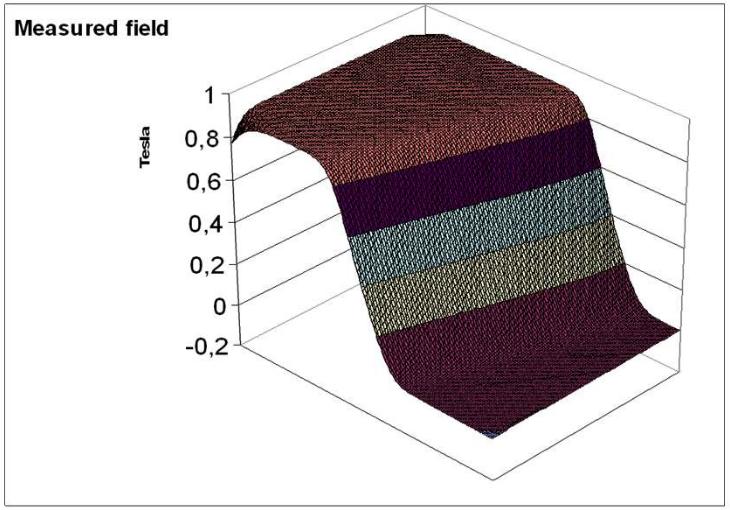
1) Detailed knowledge of the geometry and magnetic field

1) Detailed knowledge of the magnetic field

Measurement of the field (3D map)

Measurements at Danfysik
240000 points
2 months (night and day)





Interpolation of the field

Regular function up to 10° order

A.Lazzaro et al., NIMA 570 (2007) 192

A.Lazzaro et al., NIMA 585 (2008) 136

A.Lazzaro et al., NIMA 591 (2008) 394

A.Lazzaro et al., NIMA 602 (2009) 494

Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

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

$$F : \vec{\mathbf{X}}_i \rightarrow \vec{\mathbf{X}}_f$$

Inversion of the transport matrix

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

1) Detailed knowledge of the geometry and magnetic field

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

2) MAGNEX Focal Plane Detector

Two tasks to accomplish:

1) High resolution measurement at the focal plane of the phase space parameters (X_{foc}, Y_{foc}, θ_{foc}, ϕ_{foc})

2) Identification of the reaction ejectiles (Z, A) - crucial aspect for heavy ions

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

FPD characteristics

Horizontal and vertical position resolution (FWHM)	0.6 mm
Horizontal and vertical angular resolution (FWHM)	0.3°
Mass resolution[(a)]	0.6%
Explored ion mass range	from $A = 1$ to $A = 48$
Energy loss resolution[(b)]	6.3%
Maximum incident ion rate (uniform distribution)	5 kHz
Maximum incident ion rate (localized in ~ 1 cm)	2 kHz

For O at 300 MeV
10^4 Hz/mm^2

Software ray-reconstruction

ALGEBRIC RAY-RECONSTRUCTION

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

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

Inversion of the transport matrix

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

1) Detailed knowledge of the geometry and magnetic field

3) Algorithm to transport and invert

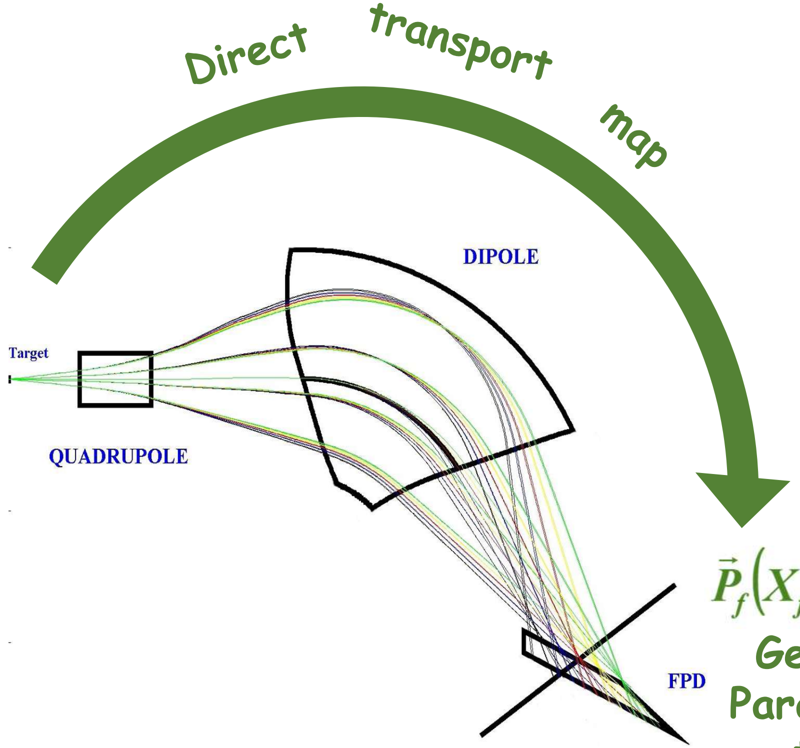
2) High resolution measurement at the focal plane (highly performing detectors)

3) Algorithm to transport and invert

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

Solution of the equation of motion for each detected particle

$$F \quad : \vec{X}_i \rightarrow \vec{X}_f$$



$\vec{P}_i(E^*, \theta_{lab})$
Physical Parameters at the target

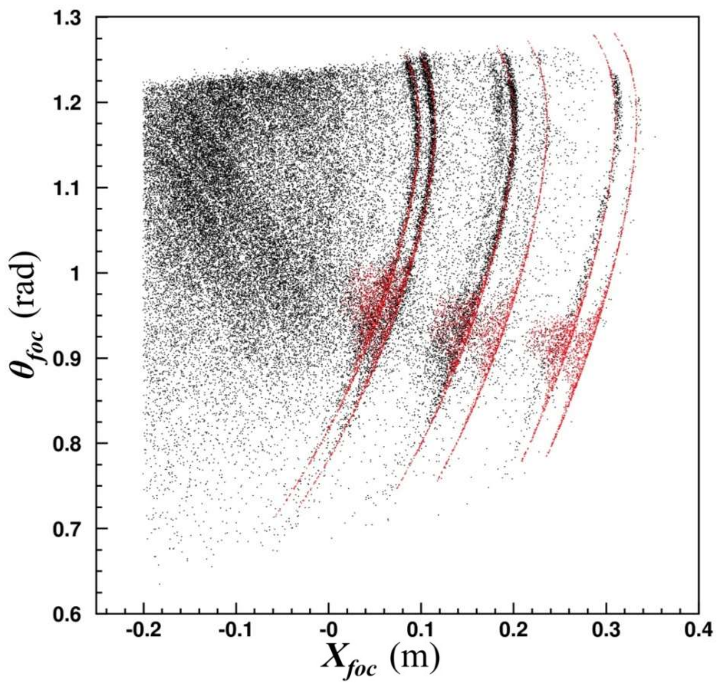
$\vec{P}_f(X_{foc}, Y_{foc}, \theta_{foc}, \varphi_{foc})$
Geometrical Parameters at the FPD

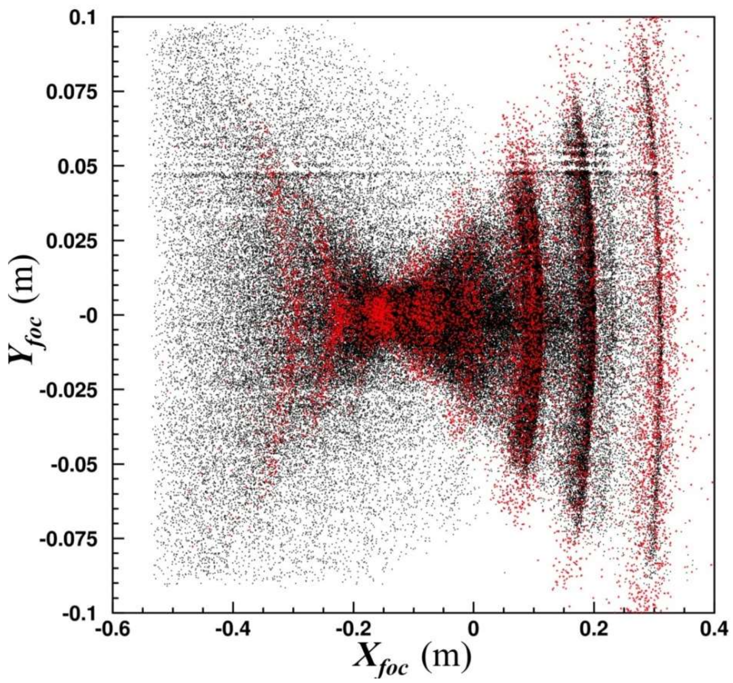
F. Cappuzzello, et al., NIM A 638, (2011) 74

3) Algorithm to transport and invert

Examples of parameters at the focal plane

Black: measured parameters
Red: Simulated parameters



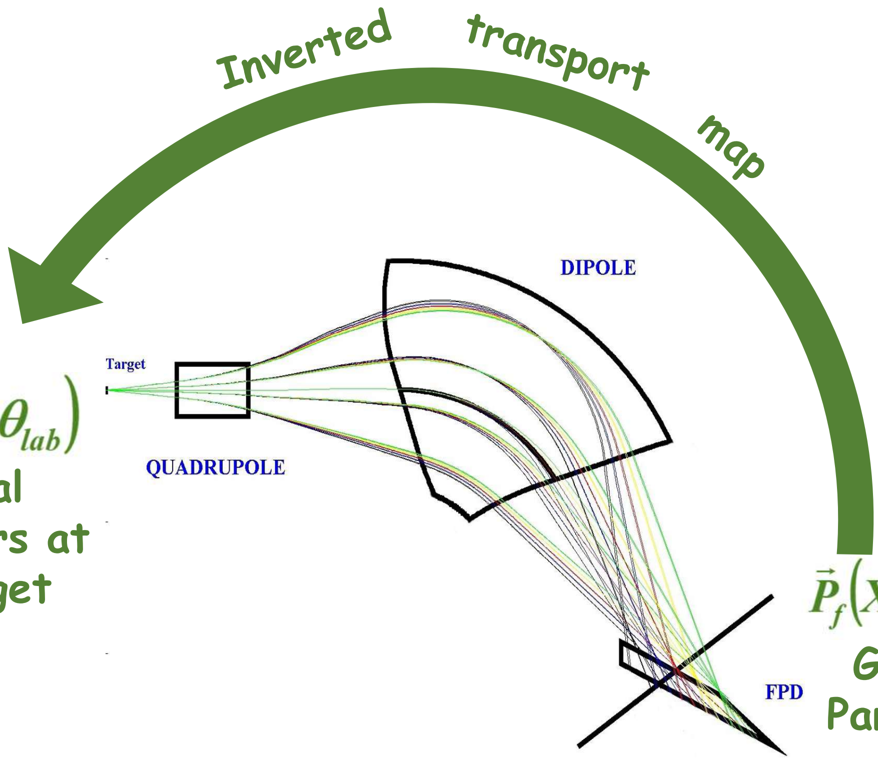


3) Algorithm to transport and invert

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

Solution of the equation of motion for each detected particle

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



$\vec{P}_i(E^*, \theta_{lab})$
Physical Parameters at the target

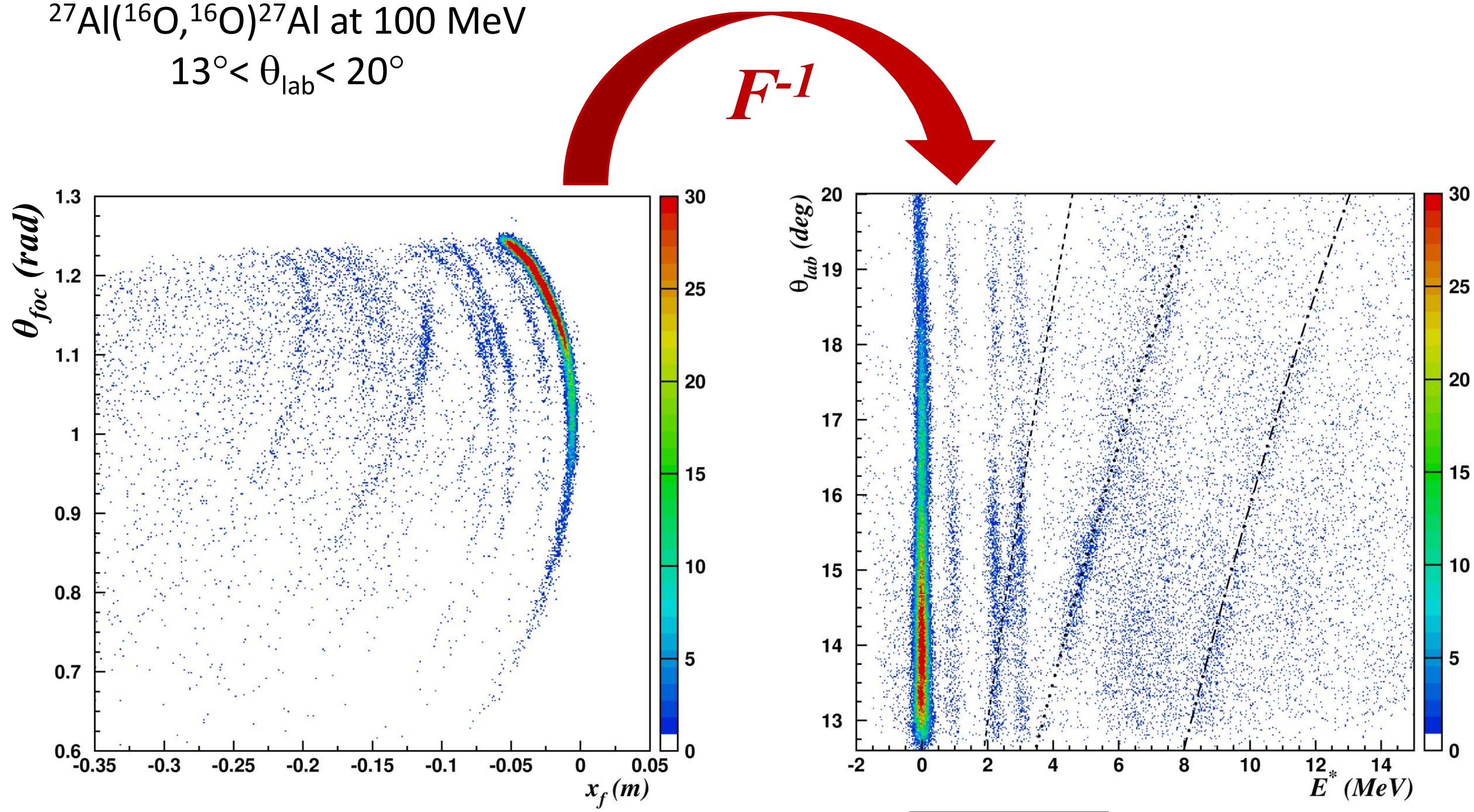
$\vec{P}_f(X_{foc}, Y_{foc}, \theta_{foc}, \varphi_{foc})$
Geometrical Parameters at the FPD

F. Cappuzzello, et al., NIM A 638, (2011) 74

3) Algorithm to transport and invert

$^{27}Al(^{16}O,^{16}O)^{27}Al$ at 100 MeV

$13° < \theta_{lab} < 20°$



$$E^* = Q - K\left(1 + \frac{M_{ejectile}}{M_{residual}}\right) + E_{beam}\left(1 - \frac{M_{beam}}{M_{residual}}\right) + 2\frac{\sqrt{M_{beam}M_{ejectile}}}{M_{residual}}\sqrt{E_{beam}K}\cos\theta_{lab}$$

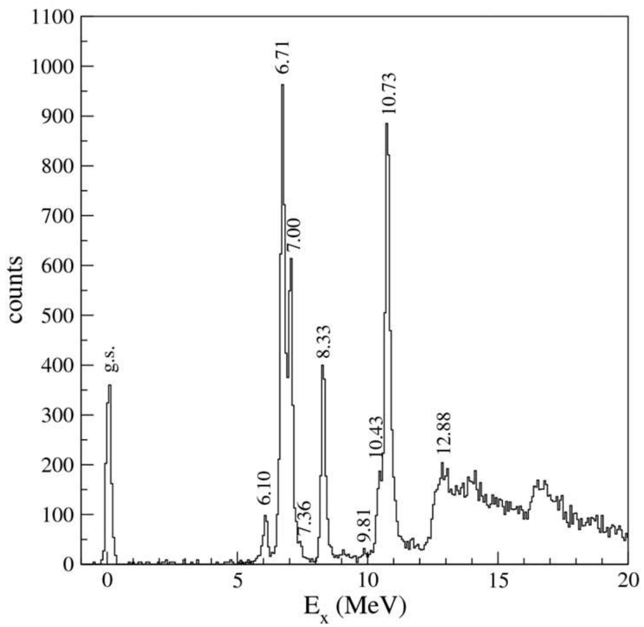
M. Cavallaro et al., NIMA 648 (2011) 46-51

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

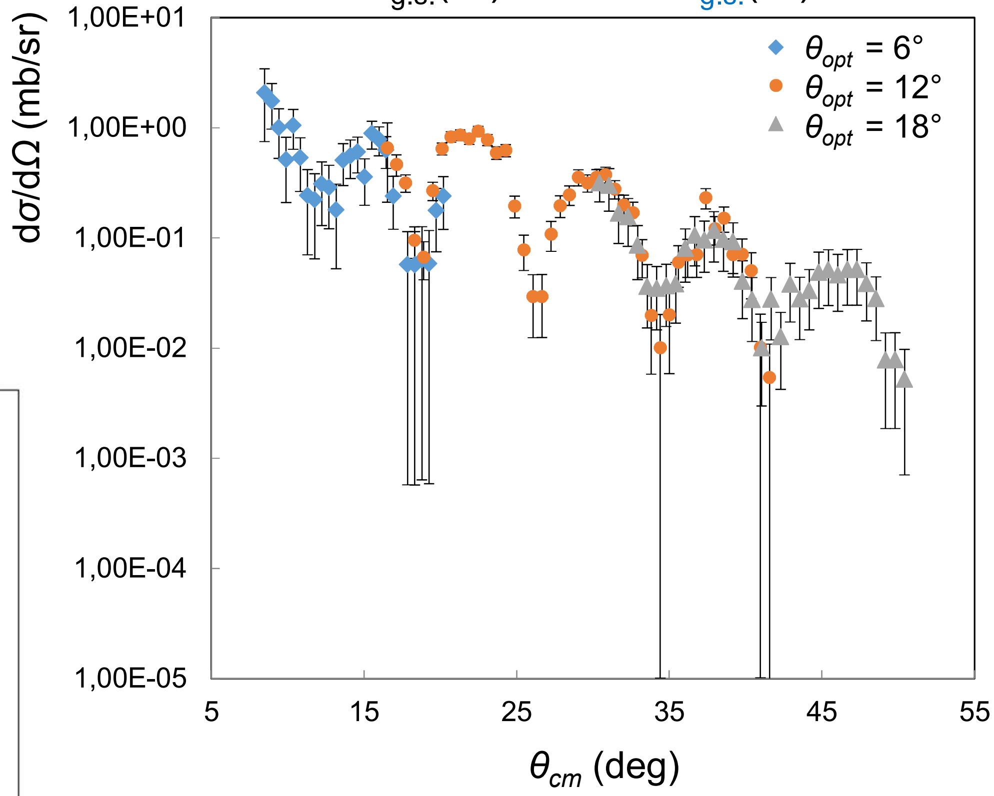
Typical energy spectra and angular distributions

$^{12}C(^{18}O,^{16}O)^{14}C$

E = 84 MeV



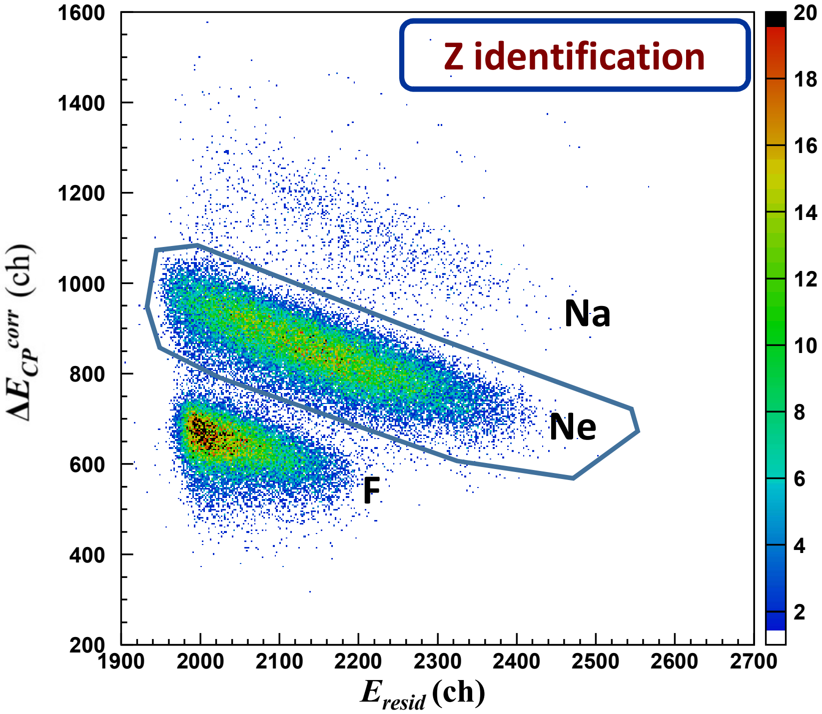
$^{18}O + ^{12}C_{g.s.}(0^+) \rightarrow ^{18}O + ^{14}C_{g.s.}(0^+)$ ***L* = 0**



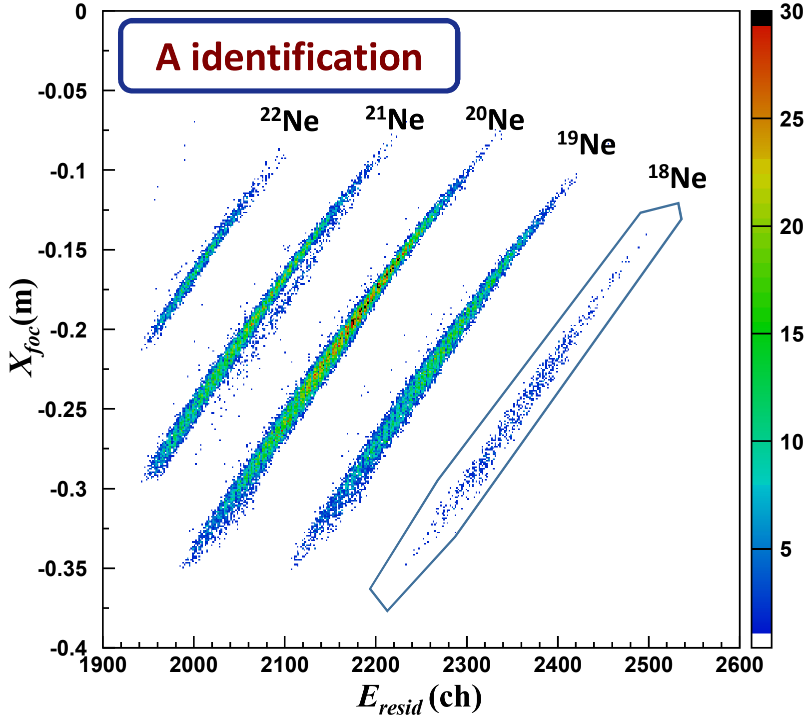
M. Cavallaro et al., Phys Rev C 88 (2013) 054601

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

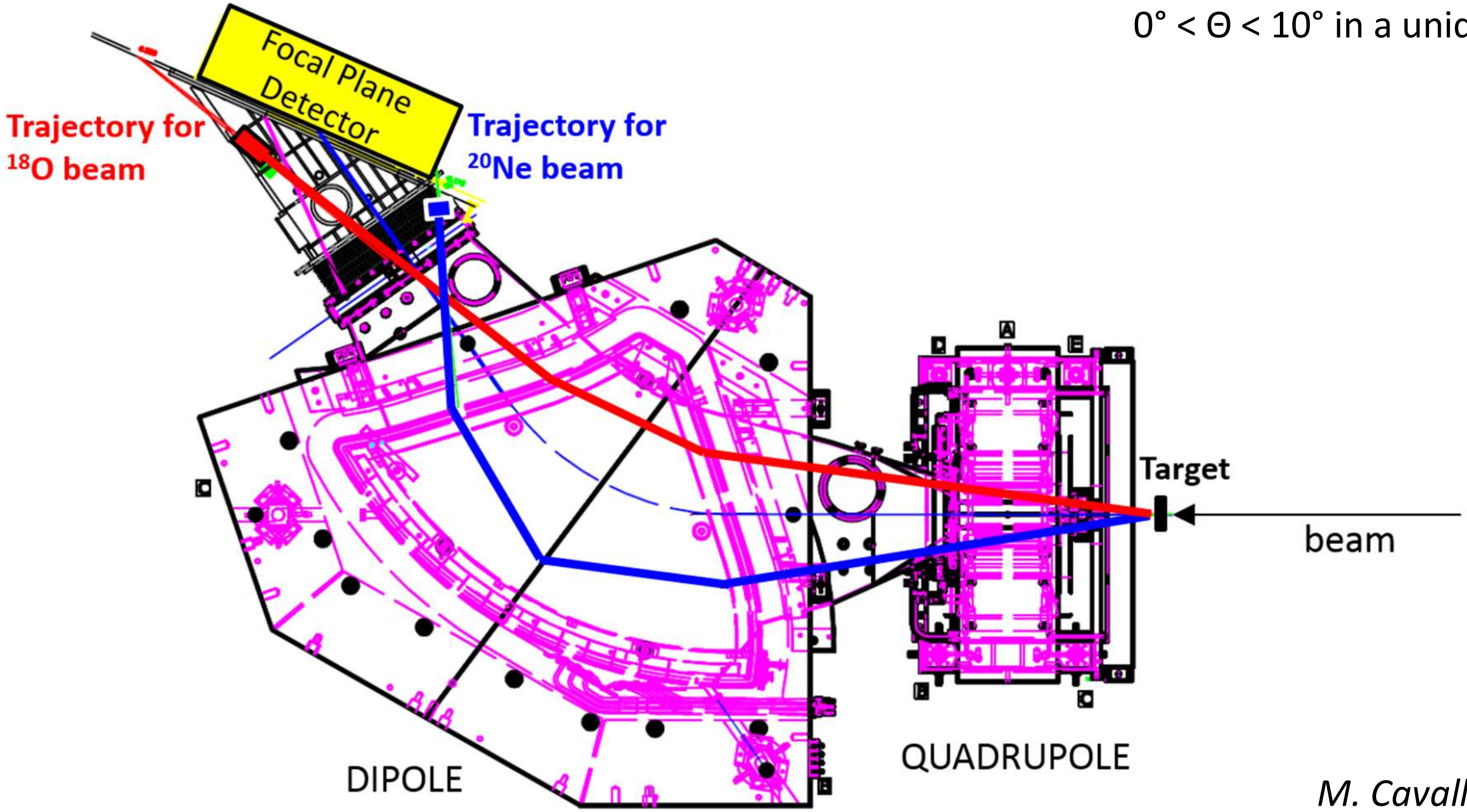
M.Cavallaro et al. EPJ A 48: 59 (2012)

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

Cross-section measurement at zero-degrees

Measurement of the beam current at Faraday Cup

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

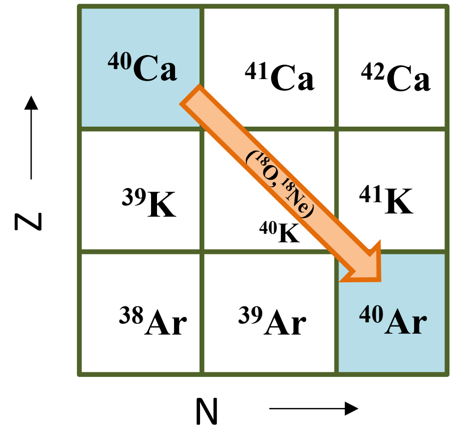


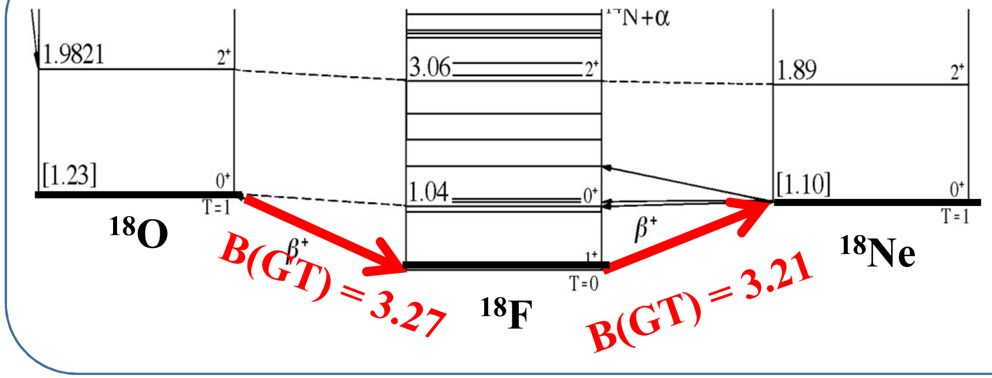
M. Cavallaro et al., NIMB (2019) in press

The NUMEN pilot experiment

The pilot experiment

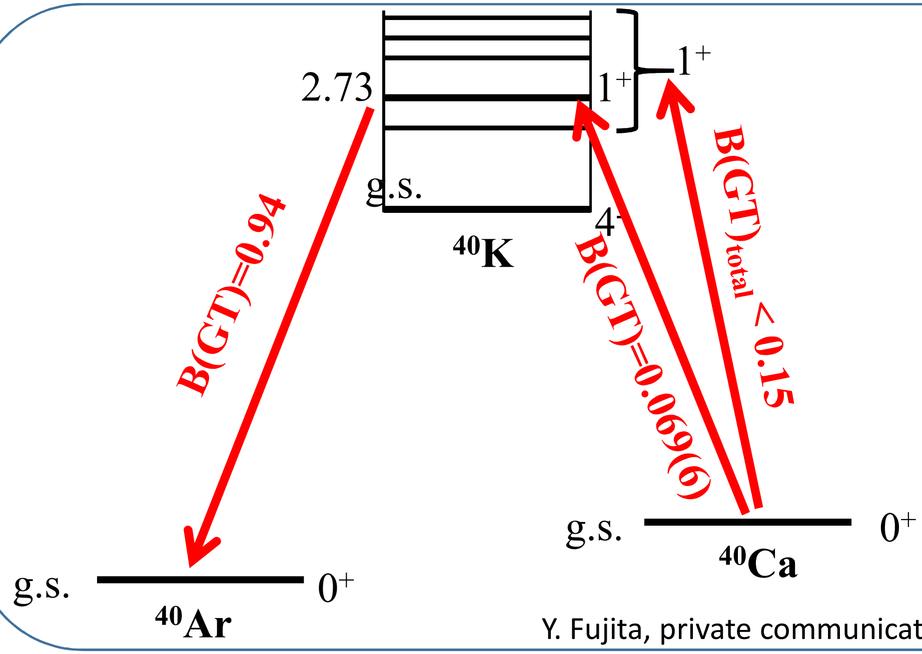
^{40}Ca (^{18}O,^{18}Ne) ^{40}Ar at 270 MeV





Projectile

^{18}O and ^{18}Ne belong to the same multiplet in *S* and *T*
Super-allowed transition
GT strength not fragmented

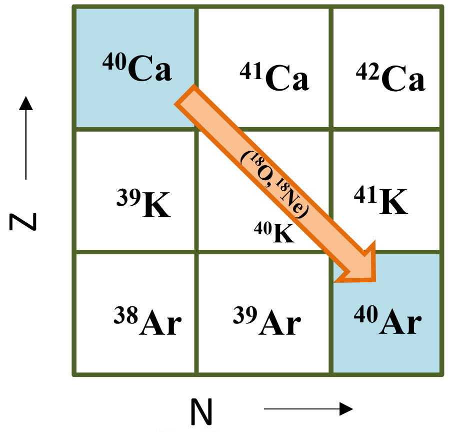


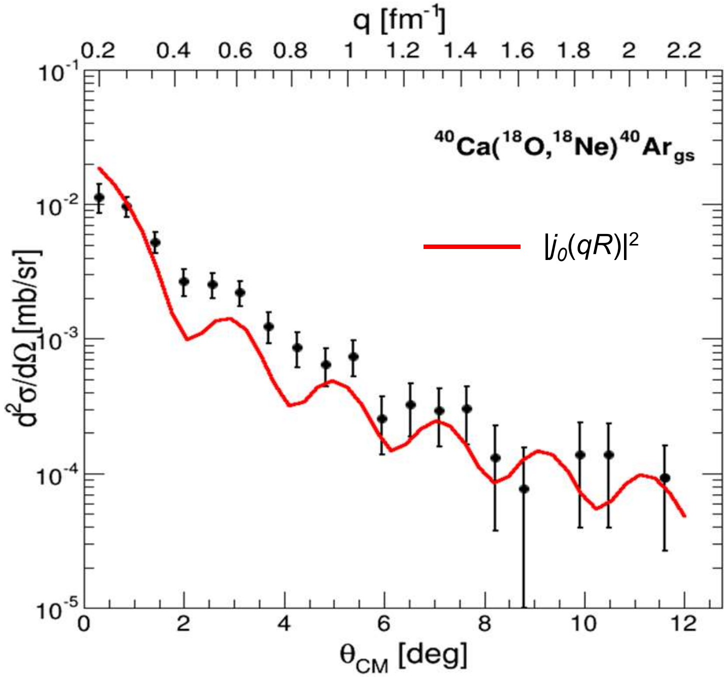
Target

GT strength not much fragmented

Y. Fujita, private communication

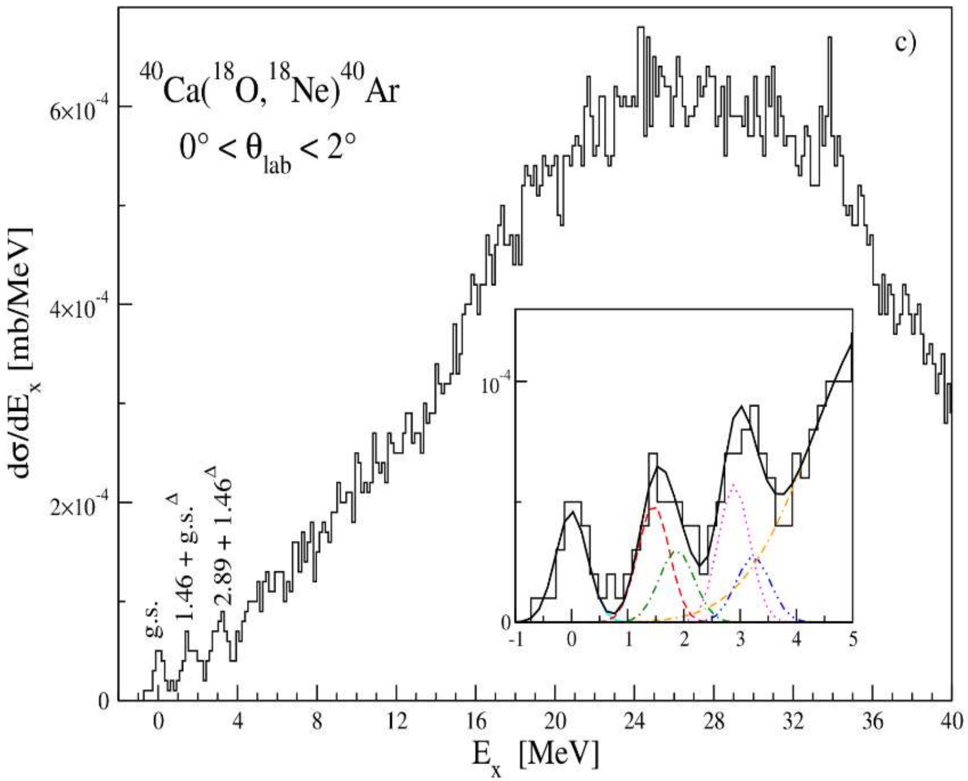
The pilot experiment





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

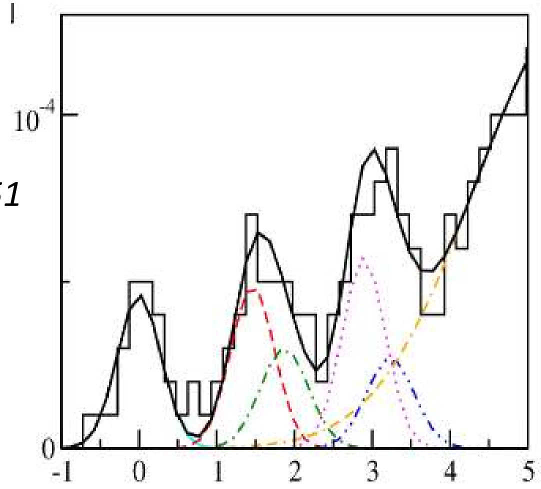
Limitations of the past HI-DCE experiments are overcome!

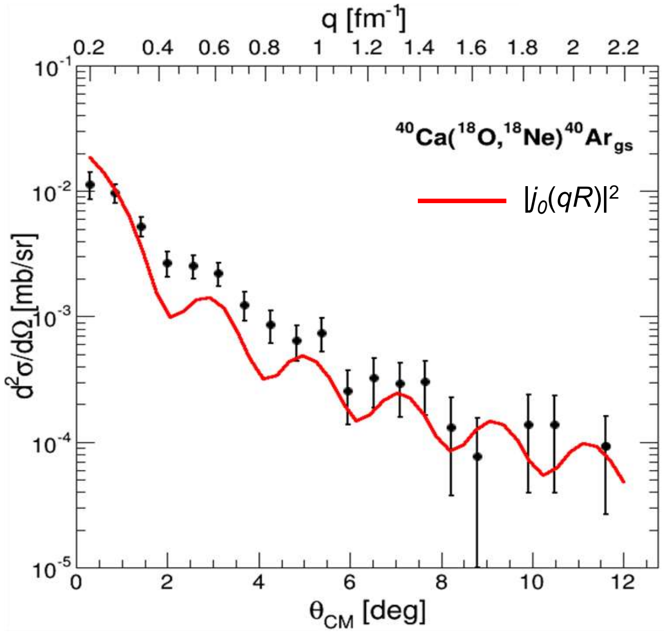
The pilot experiment: comparison with litterature

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar_{gs}$
$E(^{18}O)$=270 MeV

F. Cappuzzello, et al., EPJA (2015) 51

0 deg < θ_{cm} < 12 deg



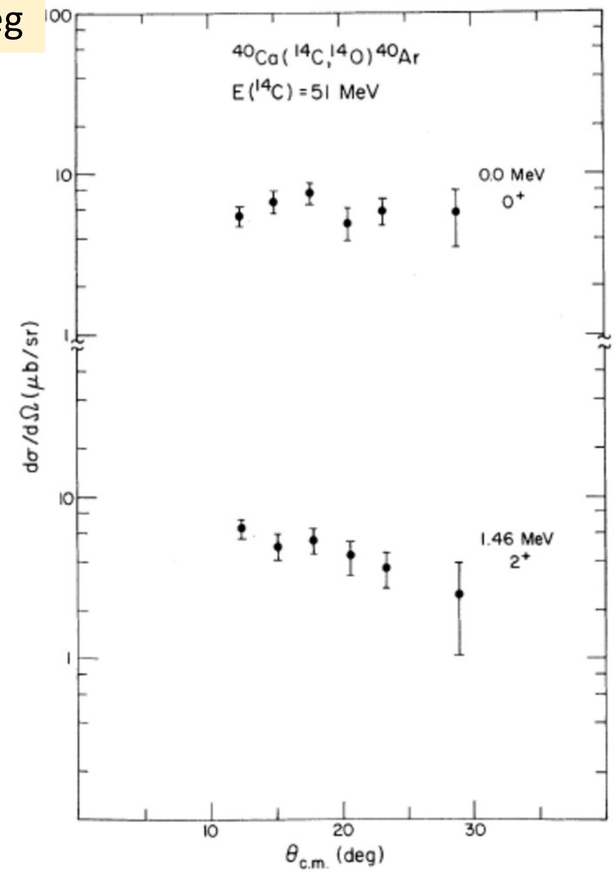


Barely above barrier

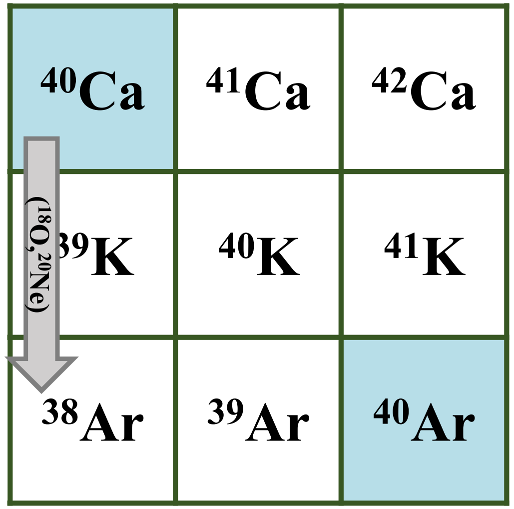
$^{40}Ca(^{14}C,^{14}O)^{40}Ar_{gs}$
$E(^{14}C)$=51 MeV

D.M. Drake et al., PRL 45 (1980) 1765

11 deg < θ_{cm} < 28 deg

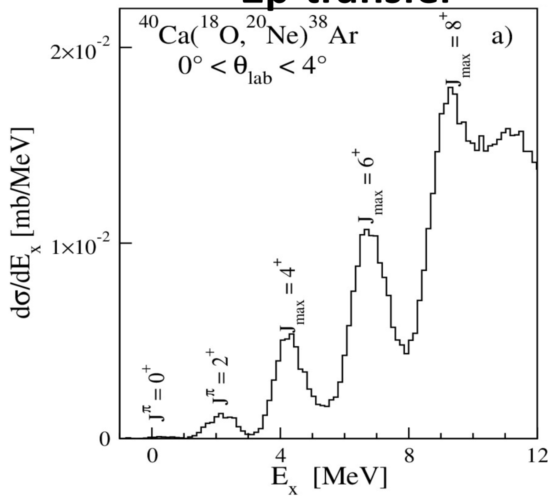


The pilot experiment: comparison with litterature



The role of the competing processes

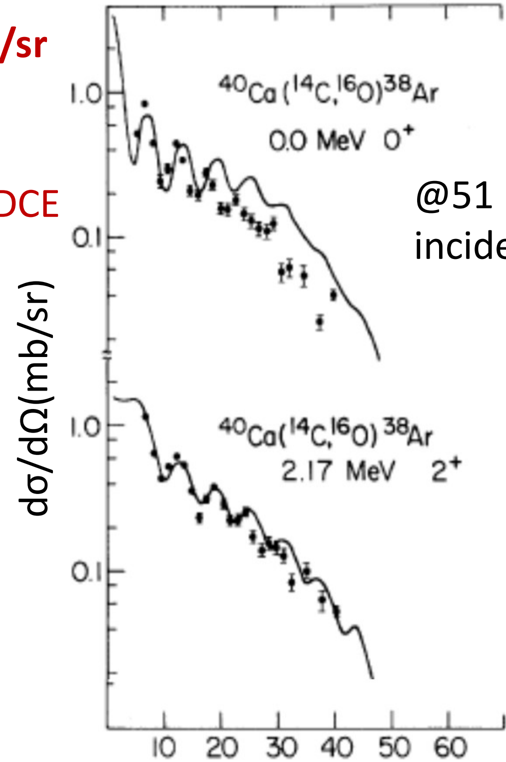
2p-transfer



1 order of magnitude lower than DCE

1 mb/sr

2 orders of magnitude higher than DCE



@51 MeV incident energy

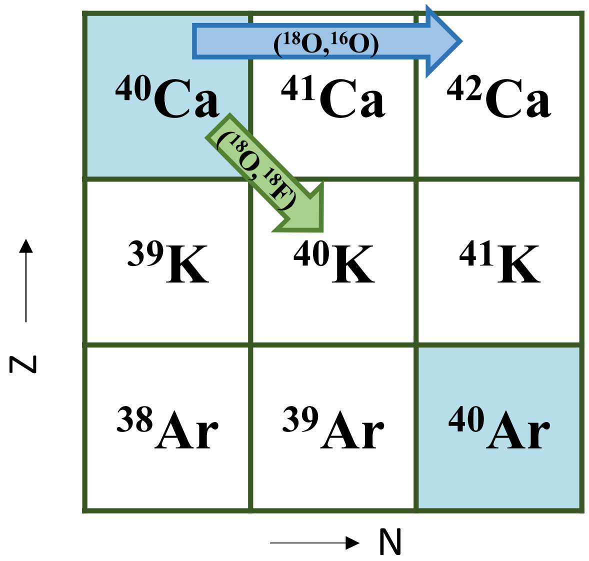
Good energy matching of the sequential pick-up and stripping process

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

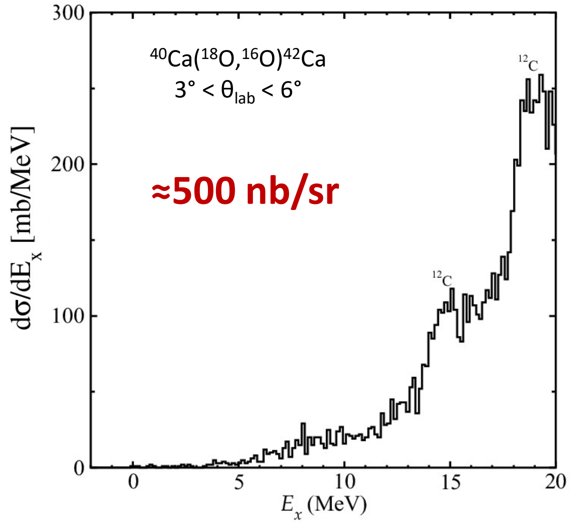
D.M. Drake et al., PRL 45 (1980) 1765

The pilot experiment

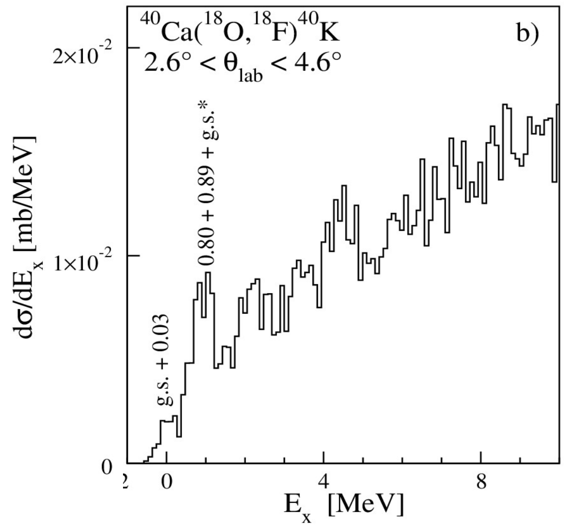
The role of the competing processes



2n-transfer



SCE



First model-independent conclusions:
Competing transfer channels (involving same target and projectile) are much smaller than DCE

Heavy-Ion induced Double Charge Exchange

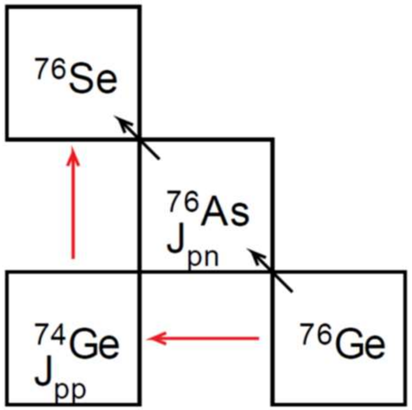
Heavy ion DCE can proceed in principle:

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

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

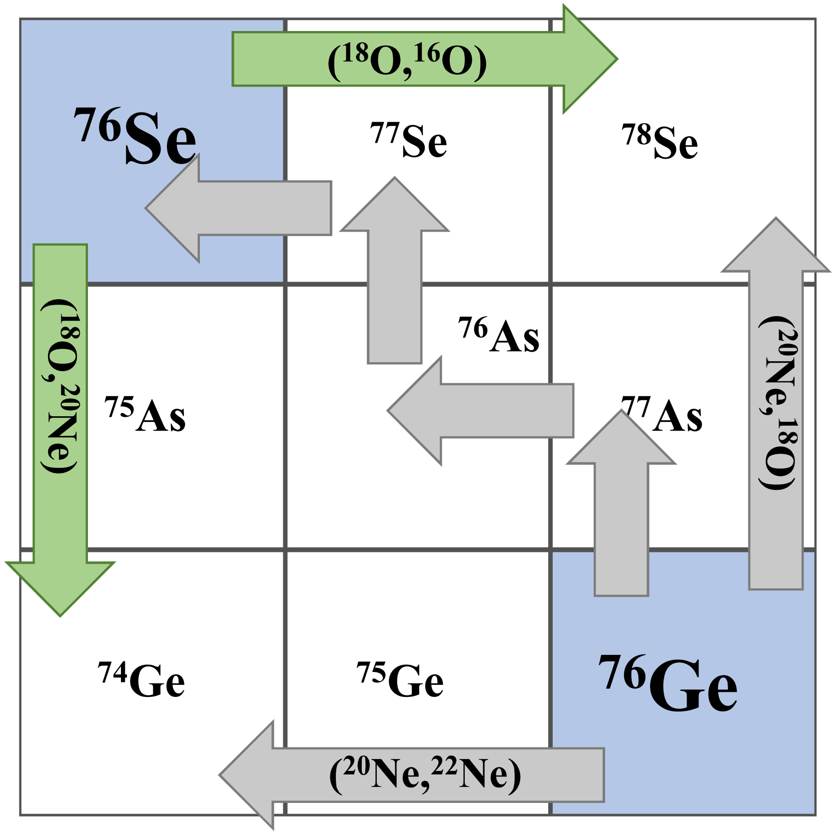
1. Multi-nucleon transfer (proton pick-up/stripping followed by neutron stripping/pick-up)

- ✓ **Probing at least twice** nucleus-nucleus Initial (**ISI**) and Final (**FSI**) State interaction (at least 2° order)
- ✓ **mean field driven**
- ✓ **Single-nucleon transfer of 4° order**
- ✓ **Sequential transfer of 2p/2n pairs is of 2° 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)



Expansion of NME in terms of summation over states of the (A-2) nucleus.

Role of pairing



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

2. Double Single Charge Exchange (DSCE)

The existence of pion-induced DCE proves that there is a reaction mechanism (other that sequential transfer) mediated by an interaction of more direct character

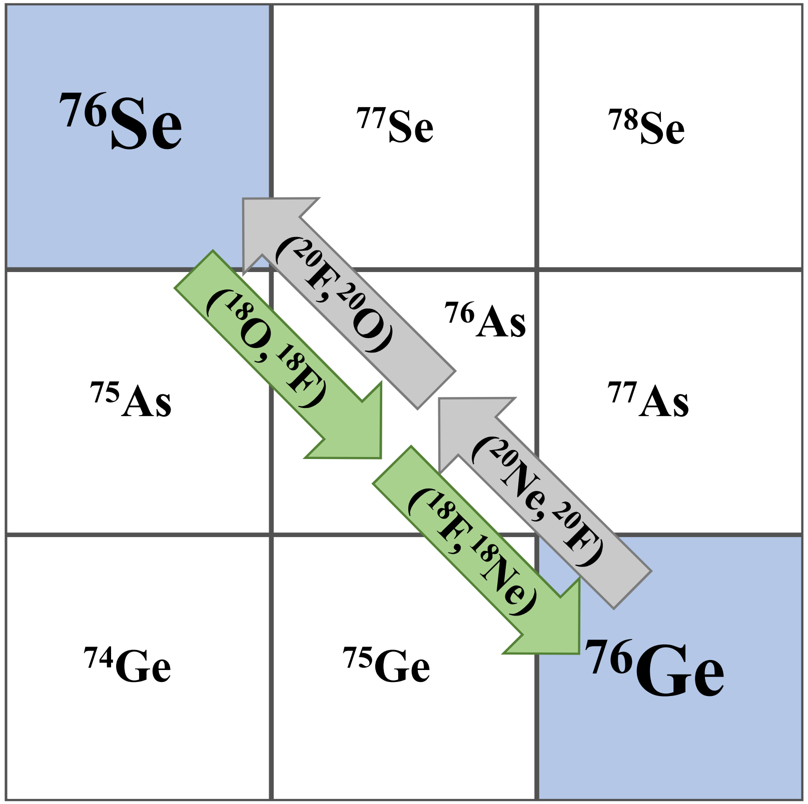
- ✓ **Two-step process (two consecutive SCE occur in an uncorrelated manner), no correlation between vertices**
- ✓ **Probing twice** nucleus nucleus Initial (**ISI**) and Final (**FSI**) State Interaction

DSCE reaction amplitude

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

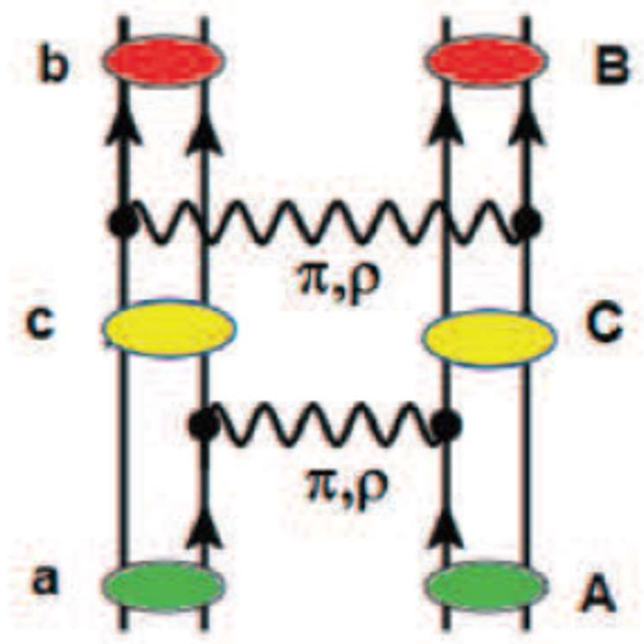
$$\mathcal{G} = \sum_{cC} |cC\rangle G_{cC} \langle cC|$$

Effects of SSD and closure studied



2. Double Single Charge Exchange (DSCE)

- ✓ **Analogies with 2νββ** decay which is a sequential decay process where the leptons are emitted subsequently in an uncorrelated manner
- ✓ **but sum over products of projectile and target** NME's

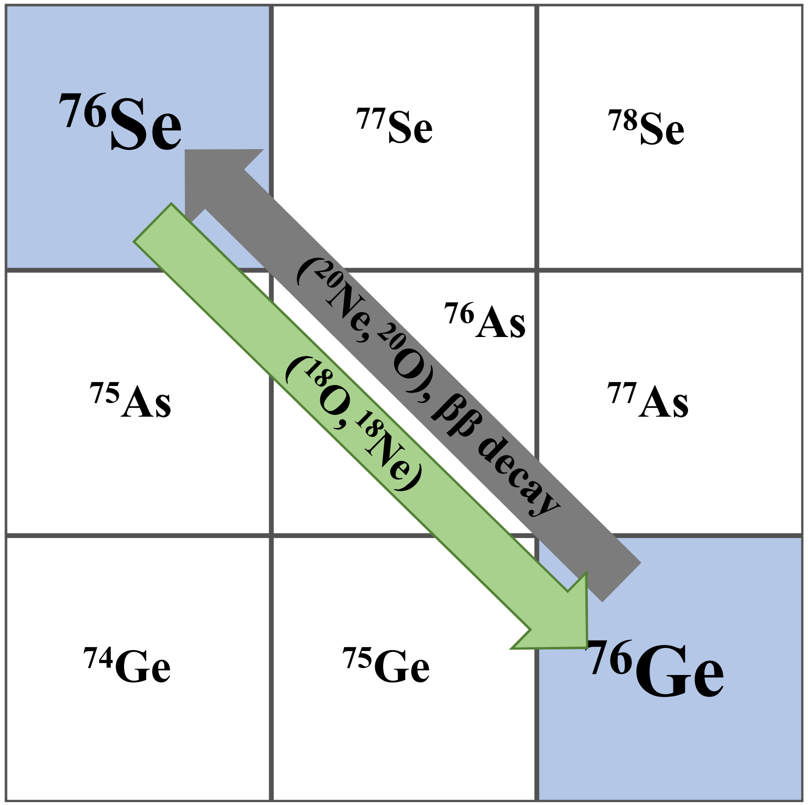


- ✓ The transition operator will be **dependent** on the **projectile/target combination** and on **incident energy**. These dependencies may be taken advantage of, in principle, for selecting suitable conditions such that the DSCE amplitudes are either suppressed or enhanced.

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

Independent on the projectile/target combination because rely on **nucleonic short-range correlations** (universal phenomena of nuclear matter)

- ✓ **Probing once** nucleus nucleus Initial (**ISI**) and Final (**FSI**) State Interaction
- ✓ **Correspondence with 0νββ ?**

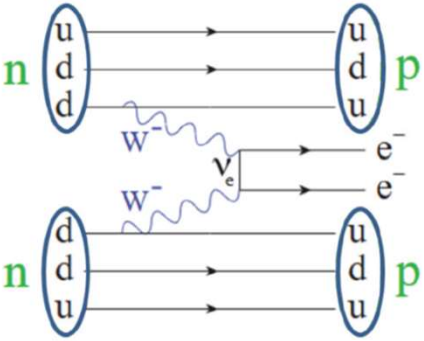


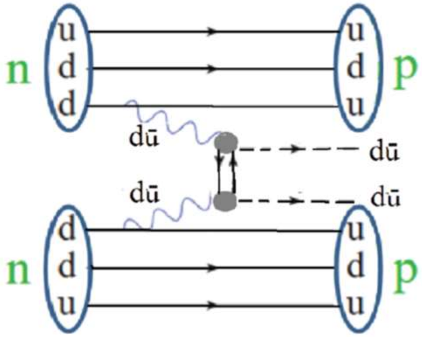
H. Lenske et al. Progr. Part. and Nucl. Physics 109 (2019) 103716
H. Lenske, CERN Proceedings 2019-001 (2019)

The “*Majorana*” hadron mechanism for HI-DCE

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

Elementary **weak interaction** process mediating 0νββ





Similar diagrammatic structure

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

Can occur, in principle, in an isolated nucleus

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 $q\bar{q}$

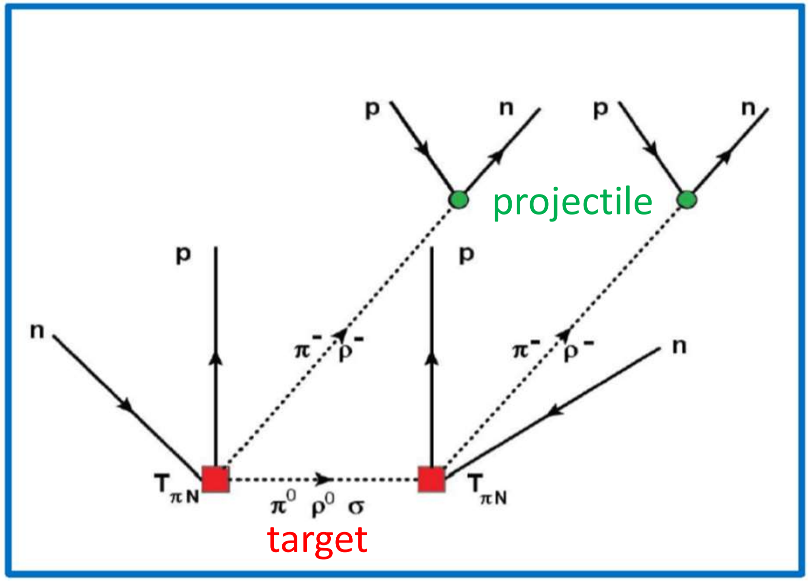
Inhibited by energy conservation, it requires a reaction partner which take care of the virtuality of the process by absorbing the two charged virtual mesons

The "*Majorana*" hadron mechanism for HI-DCE

Diagrammatic structure

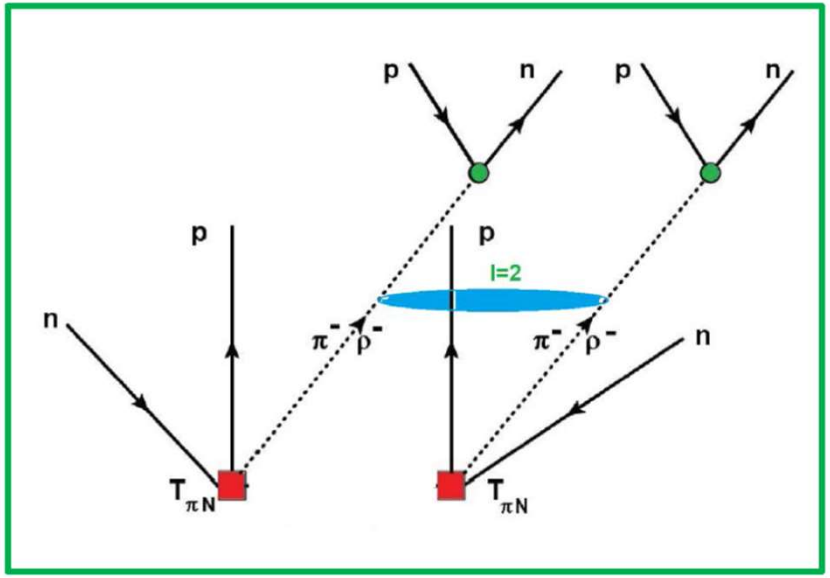
The target undergoes a correlated double meson pair decay and the projectile absorbs the pions

Correlation between nucleons



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

The nucleons emit the charged mesons independetly and the mesons correlate

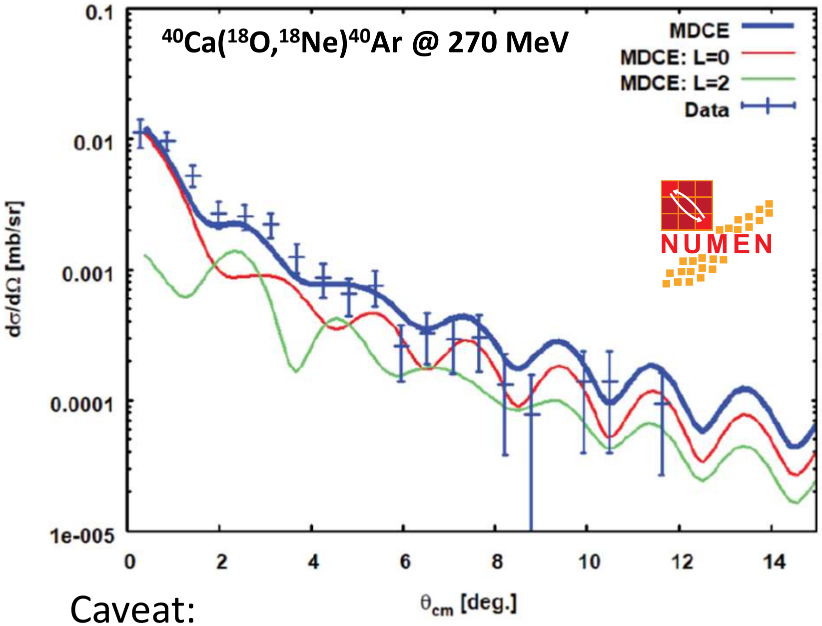


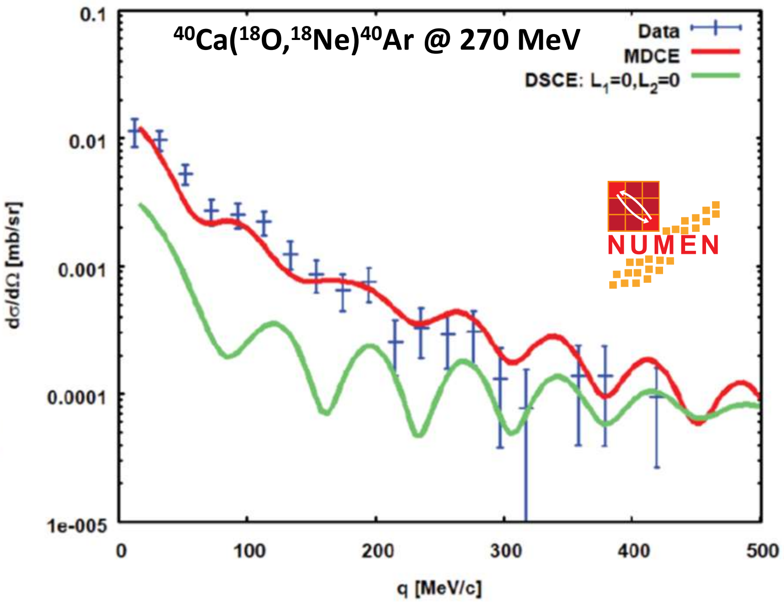
Universal because of generic **meson** dynamics

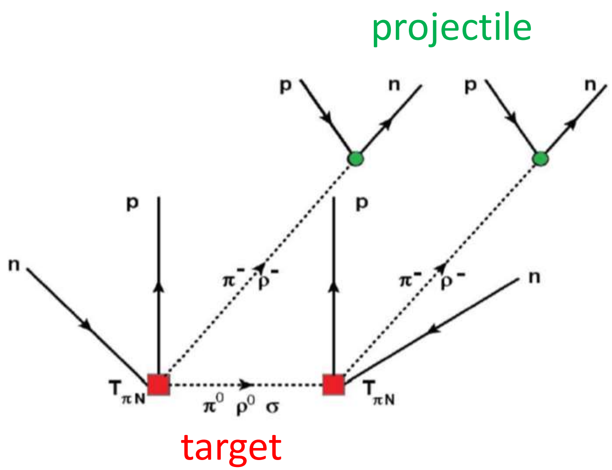
The “*Majorana*” mechanism for HI-DCE

H. Lenske, CERN Proceedings 2019-001 (2019) [49]

- ✓ ISI and FSI ion-ion interaction from double folding (available new elastic and inelastic data)
- ✓ QRPA transition densities for microscopic form factors
- ✓ One-step DWBA for the MDCE amplitudes and two-step DWBA for DSCE







Caveat:

- ✓ Only Nπ-correlations included
- ✓ Off-shell momentum structure approximated with on-shell component (T-matrix instead of G-matrix)

→ **Scaling factor**

Encouraging results, but still room for improvements

Progress in Particle and Nuclear Physics 109 (2019) 103716

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journal homepage: www.elsevier.com/locate/ppnp

Review

Heavy ion charge exchange reactions as probes for nuclear β-decay

Horst Lenske [a,d,*], Francesco Cappuzzello [b,c,d], Manuela Cavallaro [b,d], Maria Colonna [b,d]

[a] Institut für Theoretische Physik, JLU Gießen, Gießen, Germany
[b] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy
[c] Dipartimento di Fisica e Astronomia "E. Majorana", Università di Catania, Catania, Italy
[d] The NUMEN Collaboration, LNS Catania, Catania, Italy

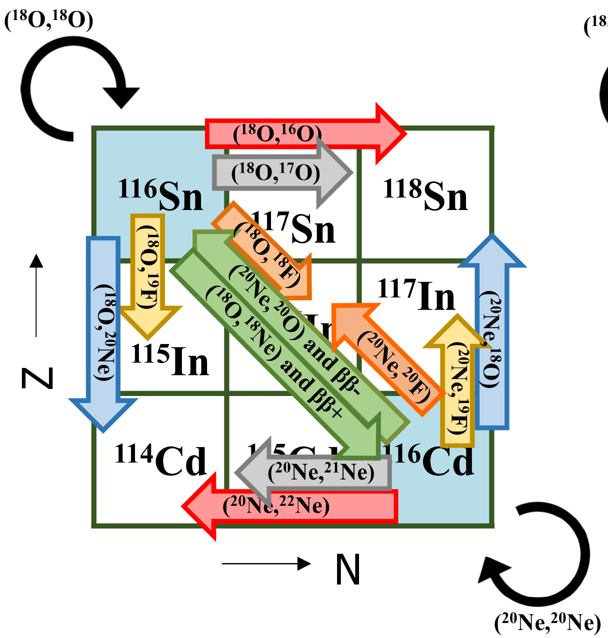
The systems of interest for 0νββ

NUMEN runs – Phase 2

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

@ 15 MeV/A

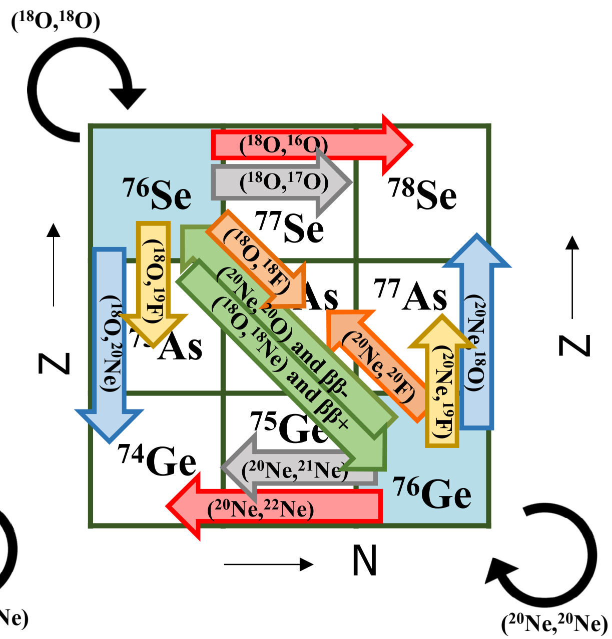
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd



^{76}Ge – ^{76}Se case

@ 15 MeV/A

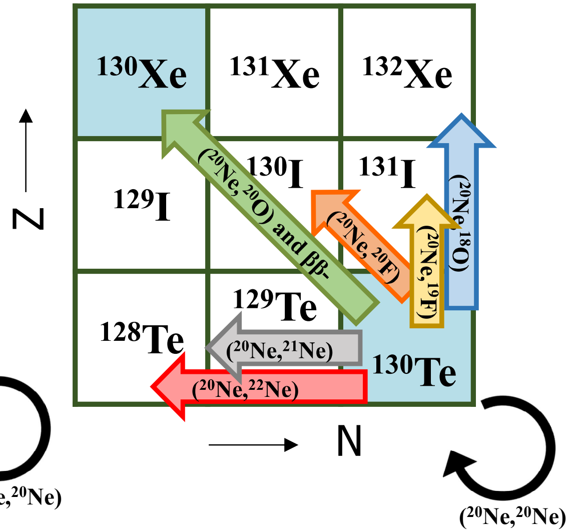
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se



^{130}Te – ^{130}Xe case

@ 15 MeV/A

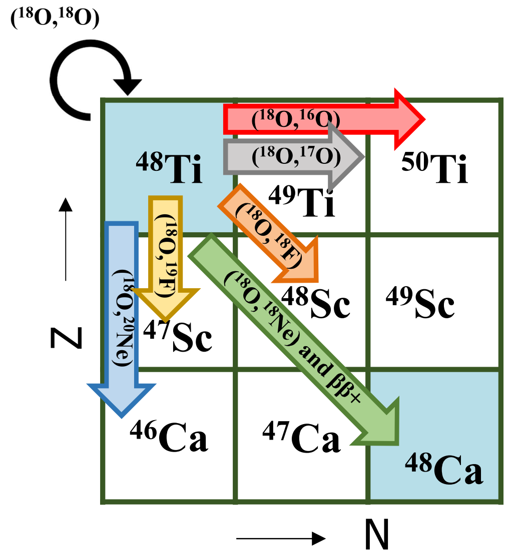
- ^{20}Ne + ^{130}Te



^{48}Ti – ^{48}Ca case

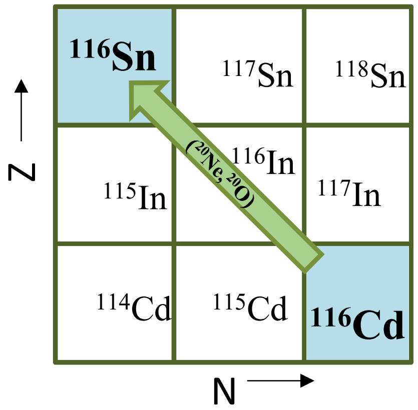
@ 15 MeV/A

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



Experimental results

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



- g.s. → g.s. transition isolated (FWHM 800keV)
- Absolute cross section measured
- Angular distribution
- 0 deg < θ_{cm} < 14 deg

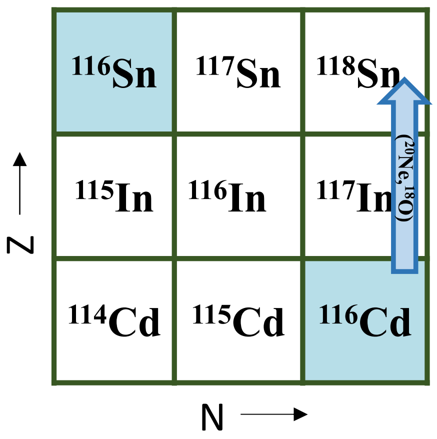
Experimental results

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

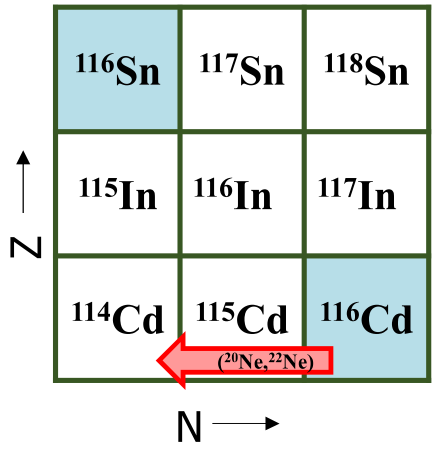
Analysis of cross-section sensitivity
<0.2 nb in the Region Of Interest

Multi-nucleon transfer

2p-transfer



2n-transfer



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

Agreement!

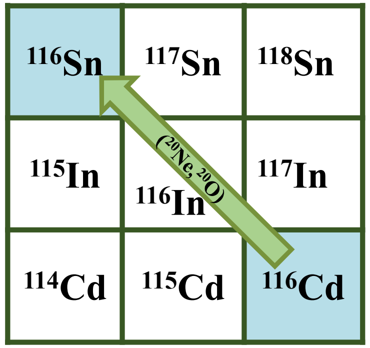
Multi-nucleon transfer routes

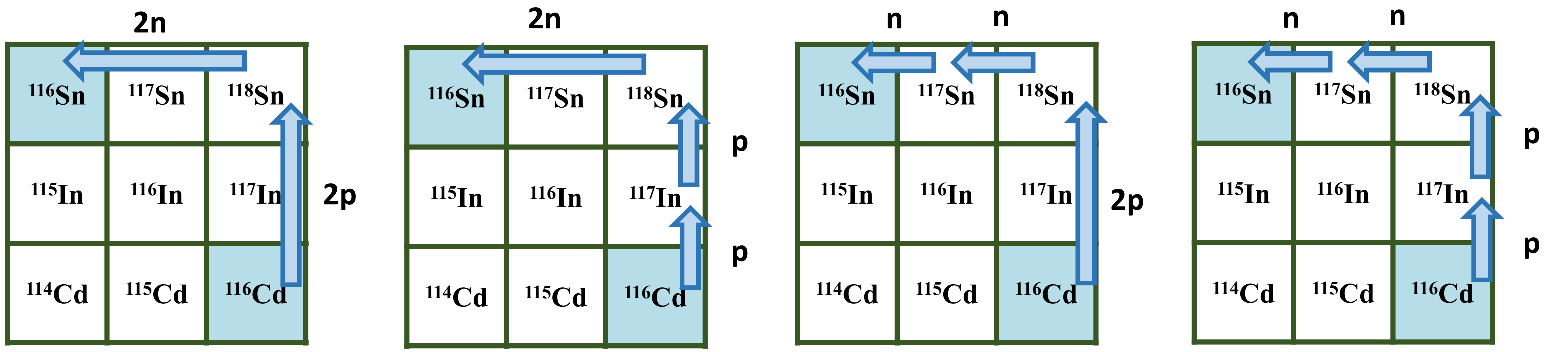
J. Lubian, J.Ferreira et al.,

vs

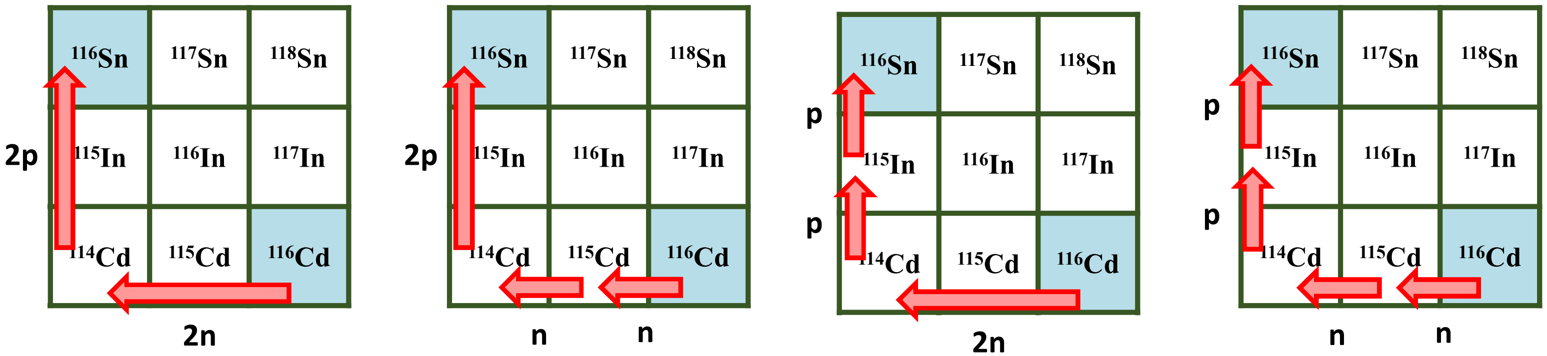
Diagonal process

(exp. cross section **12 ± 2 nb**)





3 x 10^{-5} nb | **6.6 x 10^{-5} nb** | **1.1 x 10^{-5} nb** | **1.7 x 10^{-5} nb**

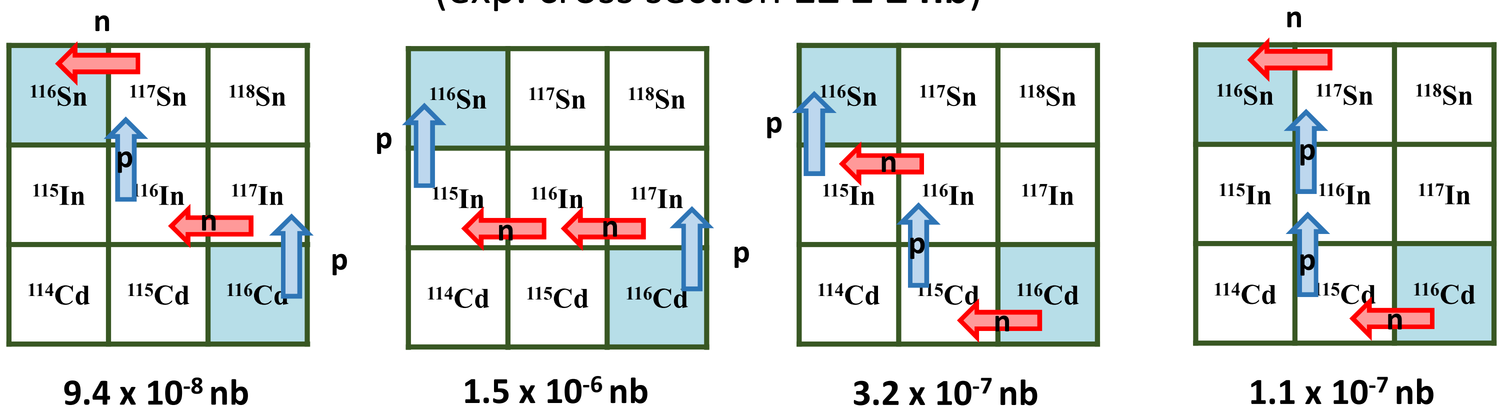


6.9 x 10^{-4} nb | **4.0 x 10^{-5} nb** | **3.0 x 10^{-4} nb** | **8.3 x 10^{-5} nb**

Multi-nucleon transfer routes
vs
Diagonal process

J. Lubian, J.Ferreira et al.

(exp. cross section **12 ± 2 nb**)



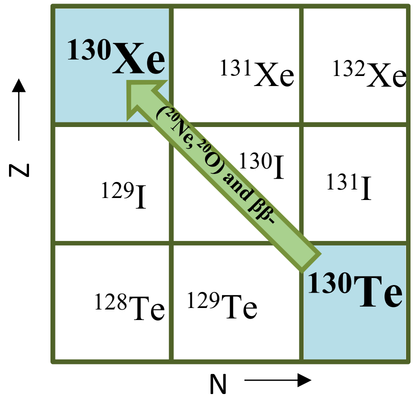
Negligible contribution of multi-nucleon transfer on the diagonal DCE process

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

J.A.Lay et al., Journ. Of Phys. Conf. Series 1056 (2018) 012029

Experimental results

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



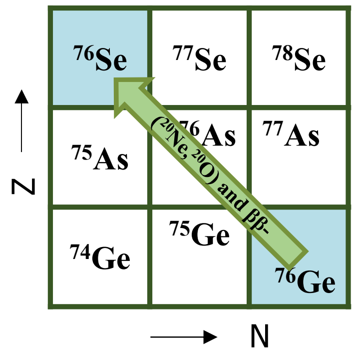
- g.s. → g.s. transition maybe isolated
- Absolute cross section measured

Resolution ~ 500 keV FWHM

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

Experimental results

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



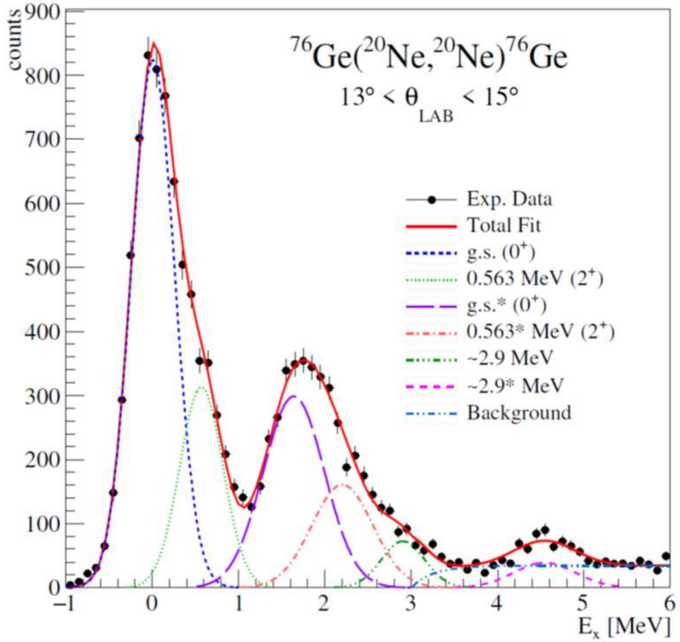
Still very preliminary!

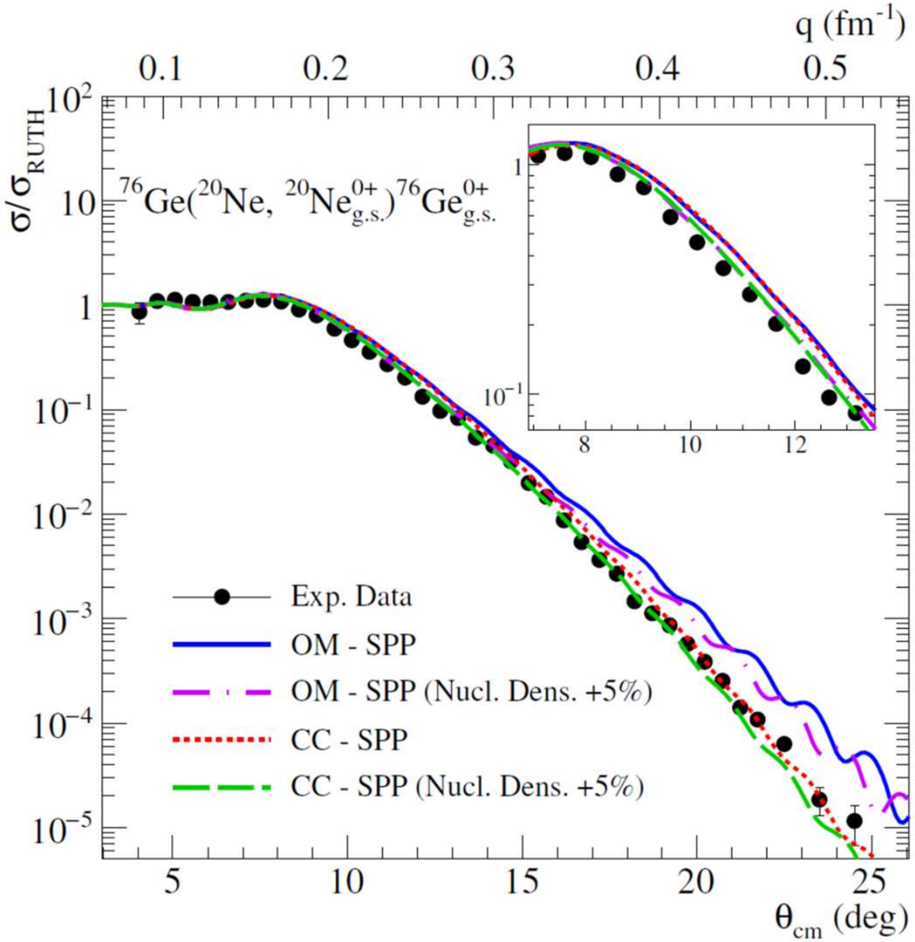
About 50 counts in the ^{76}Se ground state region

Experimental results

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

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





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

Outline

- Past Double Charge Exchange exploration: achievements and limitations
- The interest for double beta decay and the idea of NUMEN
- The experimental apparatus
- The NUMEN pilot experiment
- The first results on the systems of interest for $0\nu\beta\beta$