New results from the NUMEN experiment

Diana Carbone

for the NUMEN collaboration

Outline

Neutrinoless double beta decay

- The nuclear matrix elements involved
- The role of nuclear DCE reactions

The pilot experiment

- $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ DCE reaction
- The competing channels

The NUMEN project

- The idea
- The program

- NUMEN experimental runs
- The $^{20}Ne + ^{116}Cd$ reaction @ 15 AMeV
  - ✓ $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ DCE channel
  - ✓ $^{116}Cd(^{20}Ne,^{20}F)^{116}In$ SCE channel
  - ✓ $^{116}Cd(^{20}Ne,^{18}O)^{118}Sn$ 2p-transfer channel

0νββ decay

Open problem in modern physics:

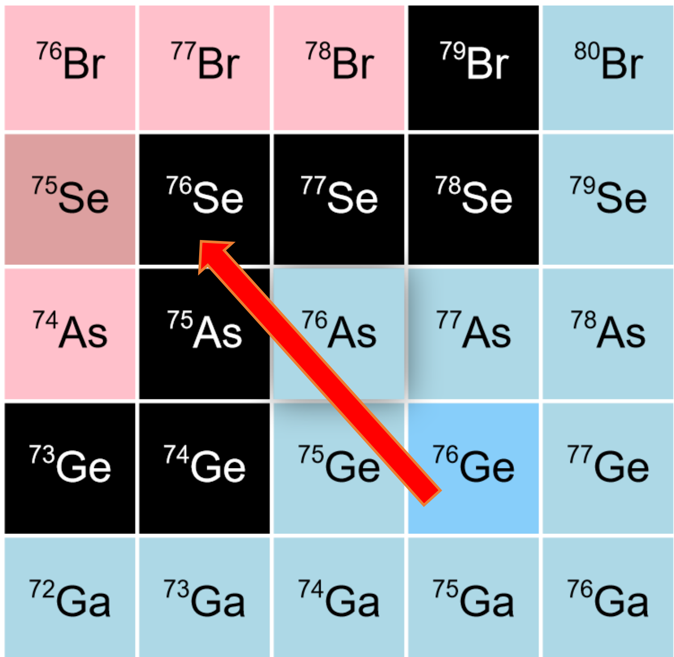
Neutrino absolute mass scale

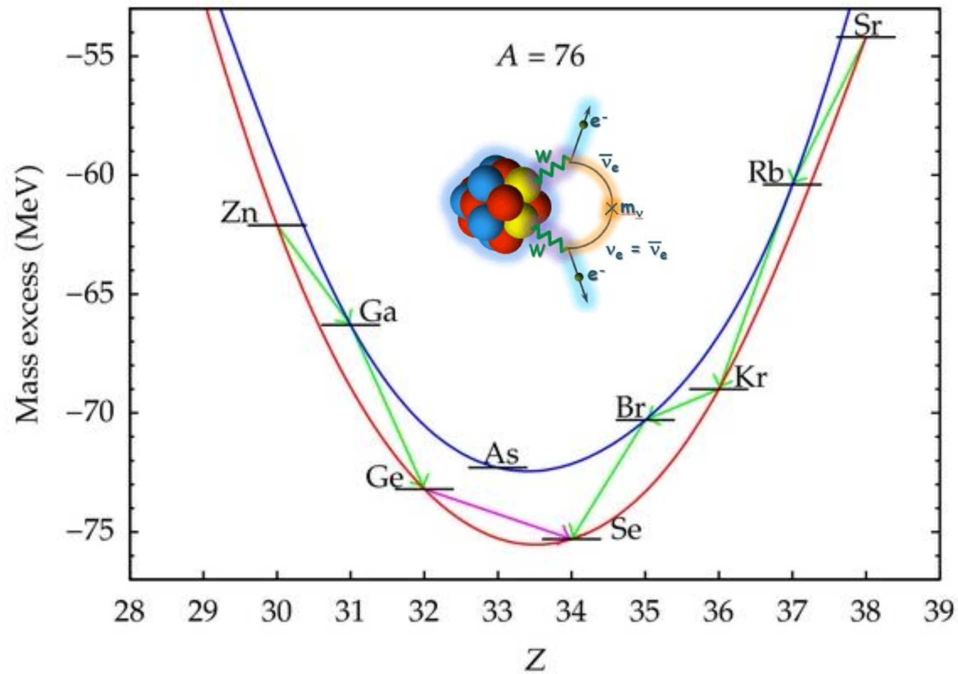
Neutrino nature → **0νββ** is considered the **most promising approach**

Still not observed

$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-}$$

Beyond standard model



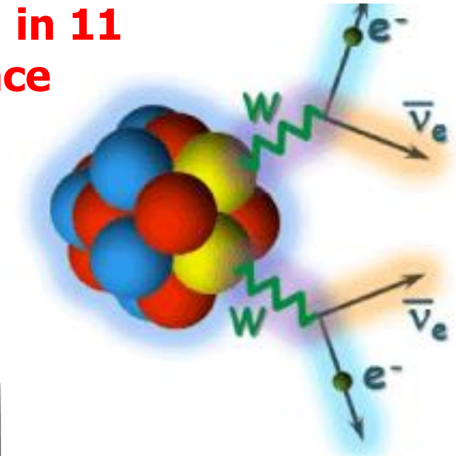


- ✓ Process mediated by the **weak interaction**
- ✓ Occurring in even-even nuclei where the **single β-decay** is energetically **forbidden**

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



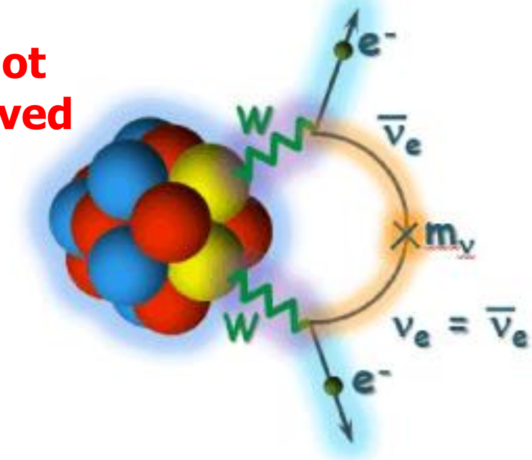
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. **Within standard model**
2. **$T_{1/2} \approx 10^{19}$ to 10^{24} yr**

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

Neutrinoless double beta decay

Still not observed



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

1. **Beyond standard model**
2. **Access to effective neutrino mass**
3. **Violation of lepton number conservation**
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**

$$1/T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2\left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

The idea

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)

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

Transition probability of a **nuclear** process

Nuclear physics plays a key role!

- Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF
- Measurements (still not conclusive for 0νββ):

  (π^+, π^-)
  single charge exchange (^{3}He,t), (d,^{2}He)
  electron capture
  transfer reactions
  muon nucleus scattering

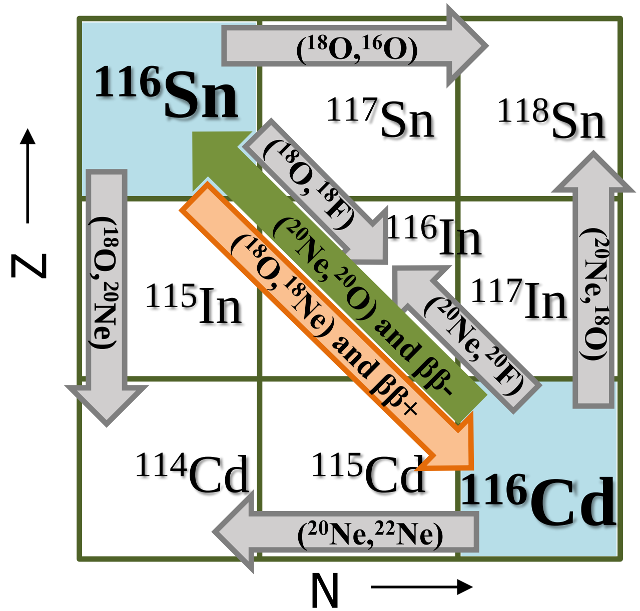
- A new experimental tool:
  heavy-ion Double Charge-Exchange (DCE)

Heavy-ion DCE reactions

As surrogate processes for 0νββ

- Induced by strong interaction
- Sequential nucleon transfer mechanism 4th order:

  Brink's Kinematical matching conditions *D.M.Brink, et al., Phys. Lett. B 40 (1972) 37*
- Meson exchange mechanism 2nd order in the nucleus-nucleus potential
- Possibility to go in both directions



$0\nu\beta\beta$ vs HI-DCE

Differences

- DCE mediated by **strong interaction**, $0\nu\beta\beta$ by **weak interaction**
- DCE includes **sequential** multinucleon 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
- **Non-local** processes: characterized by two vertices localized in a pair of valence nucleons
- **Same nuclear medium**: Constraint on the theoretical determination of quenching phenomena on $0\nu\beta\beta$
- **Off-shell propagation** through virtual intermediate channels

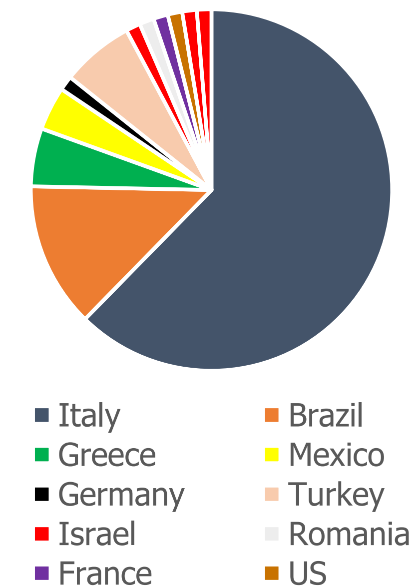
The NUMEN project

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

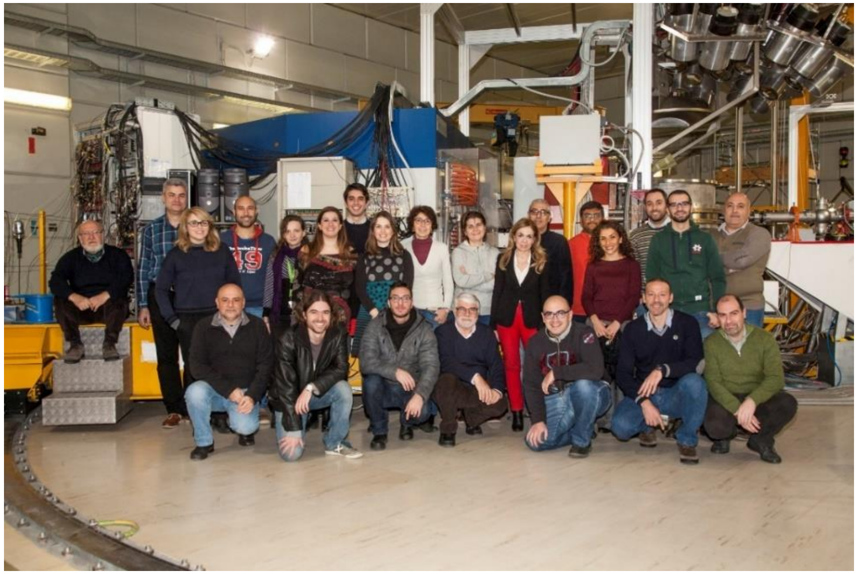
The collaboration

Spokespersons: F. Cappuzzello and C. Agodi

L. Acosta, C. Agodi, N. Auerbach, J. Bellone, S. Bianco, R. Bijker, D. Bonanno, D. Bongiovanni, T. Borello-Lewin, I. Boztosun, V. Branchina, S. Burrello, M.P. Bussa, S. Calabrese, L. Calabretta, A. Calanna, D. Calvo, F. Cappuzzello, D. Carbone, M. Cavallaro, E.R. Chávez Lomelí, A. Coban, M. Colonna, G. D'Agostino, G. De Geronimo, F. Delaunay, N. Deshmukh, P.N. de Faria, C. Ferraresi, J.L. Ferreira, P. Finocchiaro, M. Fisichella, A. Foti, G. Gallo, H. Garcia, G. Giraudo, V. Greco, A. Hacisalihoglu, J. Kotila, F. Iazzi, R. Introzzi, G. Lanzalone, A. Lavagno, F. La Via, J.A. Lay, H. Lenske, R. Linares, G. Litrico, F. Longhitano, D. Lo Presti, J. Lubian, N. Medina, D. R. Mendes, A. Muoio, J. R. B. Oliveira, A. Pakou, L. Pandola, H. Petrascu, F. Pinna, S. Reito, D. Rifuggiato, A. M.R.D. Rodrigues, A. D. Russo, G. Russo, G. Santagati, E. Santopinto, A. Spatafora, O. Sgouros, S.O. Solakcı, G. Souliotis, V. Soukeras, D. Torresi, S. Tudisco, R.I.M. Vsevolodovna, R. Wheadon, B. A. Yildirin, V. A. B. Zagatto

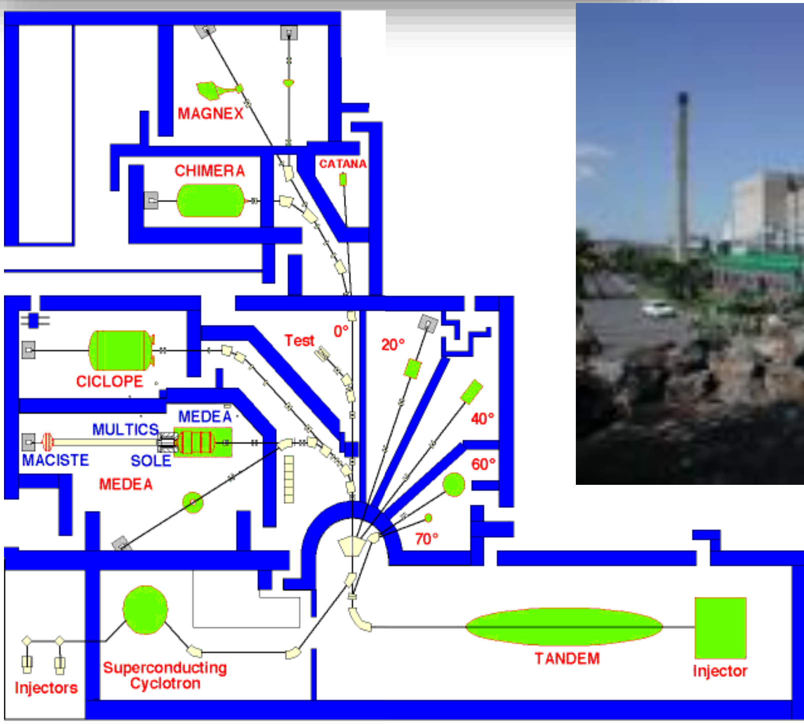


77 members
19 Institutions
12 countries



DCE @ INFN-LNS

The LNS laboratory in Catania

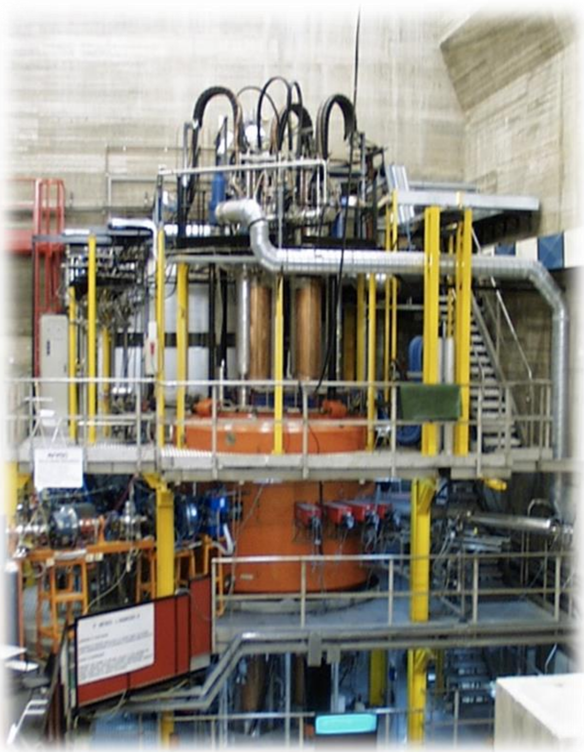


DCE @ INFN-LNS

Crucial for the experimental challenges

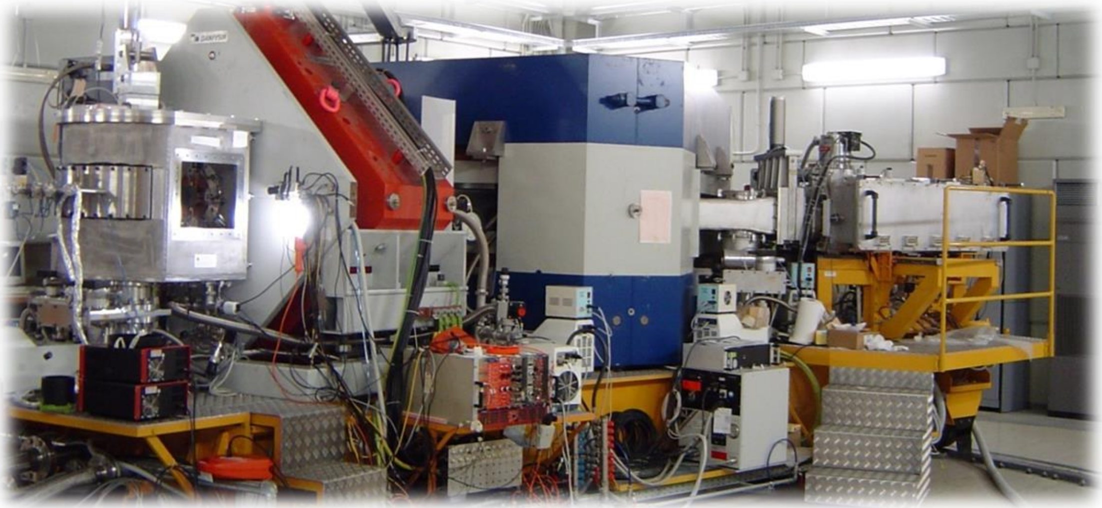
K800 Superconducting Cyclotron

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



MAGNEX spectrometer

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



Optical characteristics	Current values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	50
Momentum acceptance	-14%, +10%
Momentum dispersion (cm/%)	3.68

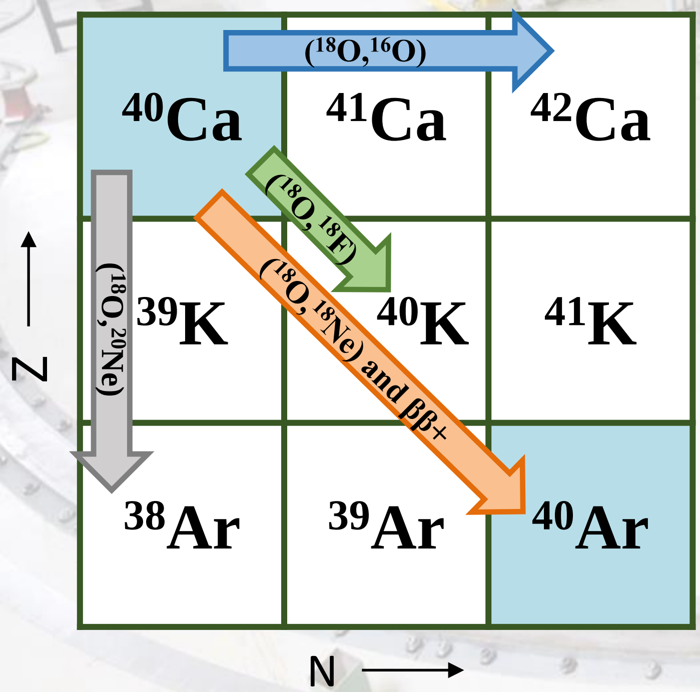
Good compensation of the aberrations: Trajectory reconstruction → Measured resolutions:

- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.2°$
- Mass $\Delta m/m \sim 1/160$

The pilot experiment

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

- $^{18}O^{7+}$ beam from Cyclotron at 270 MeV (10 pnA, 3300 μC in 10 days)
- ^{40}Ca target 300 μg/cm²
- Ejectiles detected by the MAGNEX spectrometer $0° \leq \theta_{lab} \leq 10°$ corresponding to a momentum transfer ranging from 0.17 fm^{-1} to 2.2 fm^{-1}

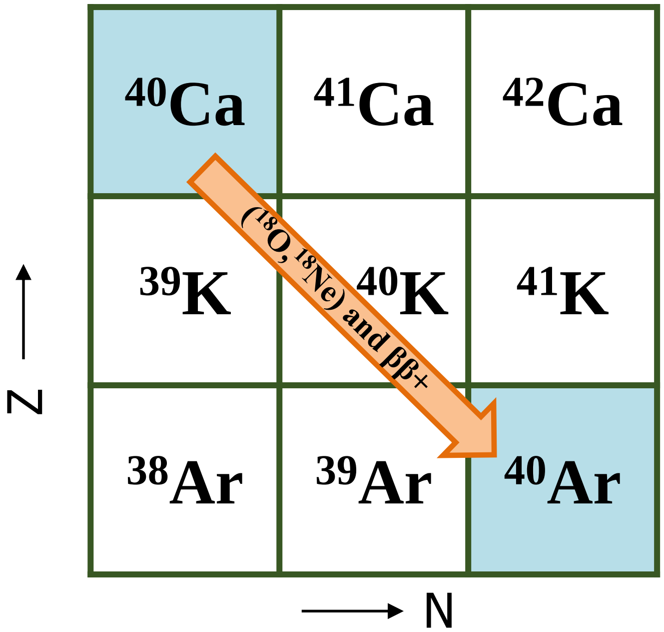


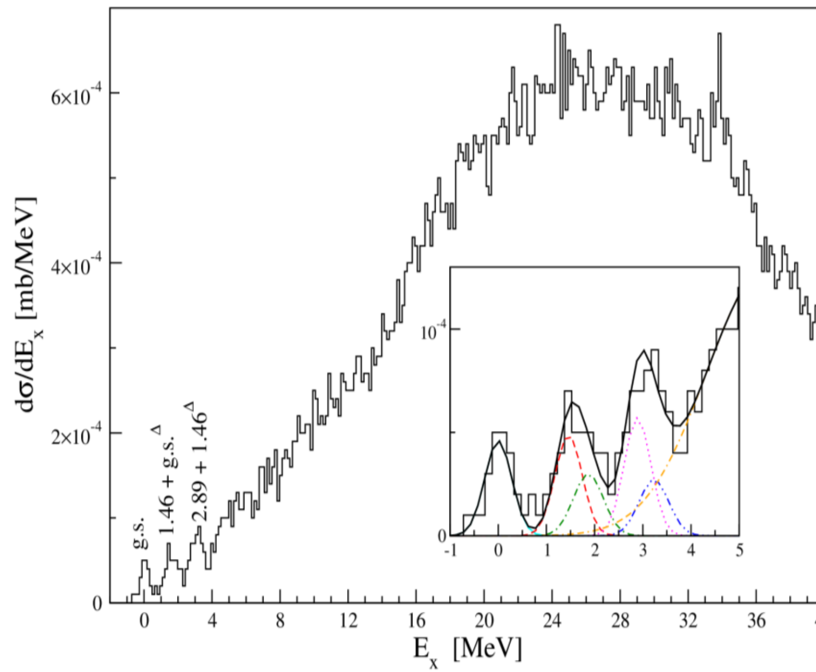
Measured channels

- DCE reaction $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$
- SCE reaction $^{40}Ca(^{18}O,^{18}F)^{40}K$
- 2p-transfer $^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$
- 2n-transfer $^{40}Ca(^{18}O,^{16}O)^{42}Ca$

The pilot experiment

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





- **Experimental feasibility:** zero-deg, resolution (500 keV), low cross-section (μb/sr)
  Limitations of the past HI-DCE experiments are overcome!

- **Data analysis feasibility**: the analysis of the DCE cross-section has lead to NME compatible with the existing calculations

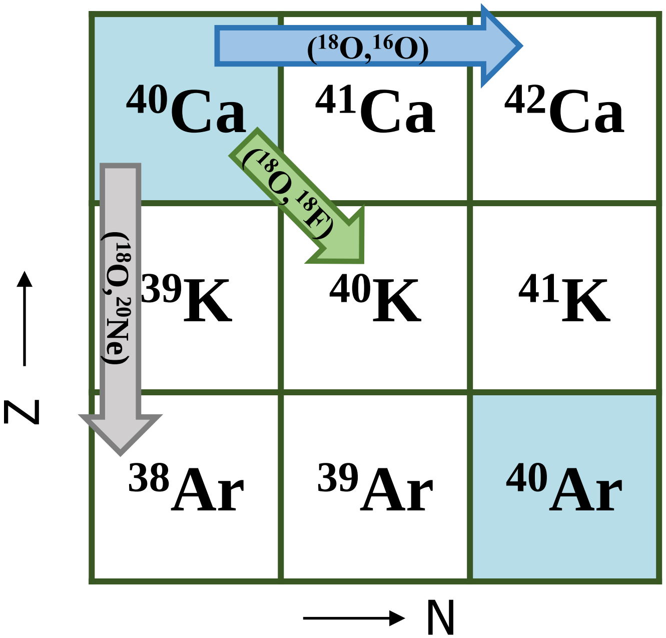
$$\left|M^{DCE}_{\sigma\tau}\left(^{40}Ca\right)\right|^2 = 1.2 \pm 0.6$$

$$\left|M^{DCE}_{\tau}\left(^{40}Ca\right)\right|^2 = 1.1 \pm 0.5$$

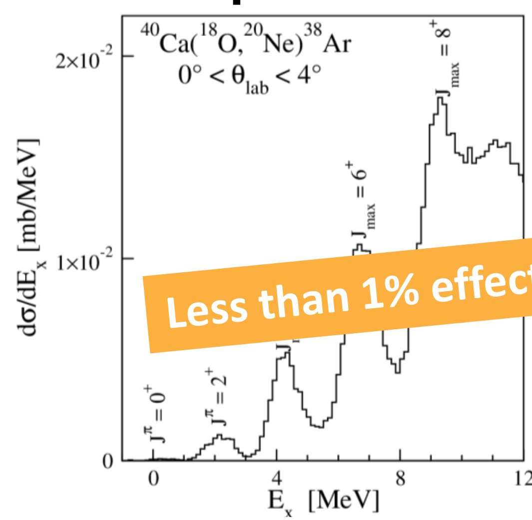
F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145

The pilot experiment

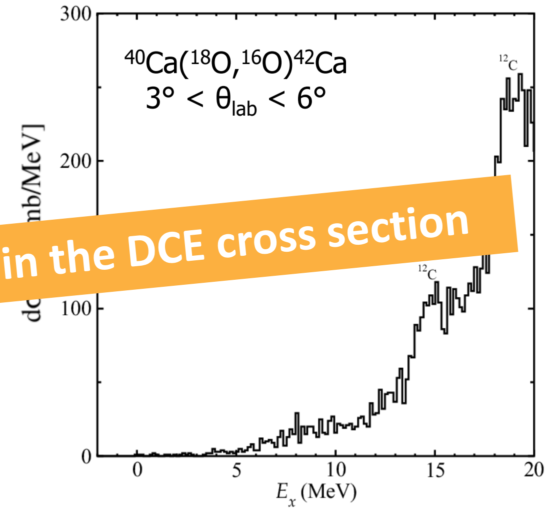
The role of the competing processes



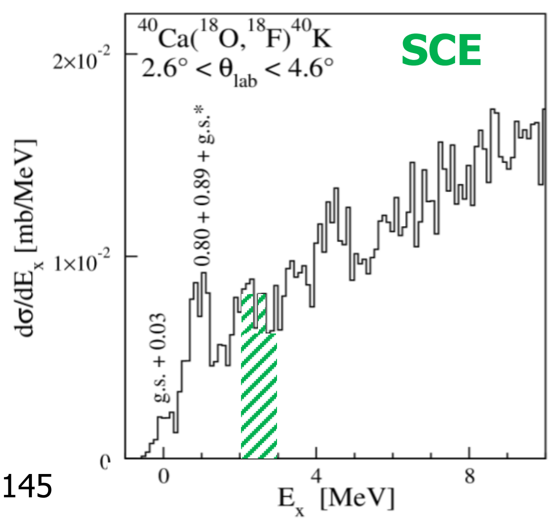
2p-transfer



2n-transfer



Less than 1% effect in the DCE cross section



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

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

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

NUMEN

Moving towards hot-cases
(^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe, …)

Caveat

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

(talk J. De Oliveira)

Much higher beam current is needed

The NUMEN project

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

F. Cappuzzello et al., J. Phys.: Conf. Ser. 630 (2015) 12018

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

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

- **Phase2**: **Experimental exploration** of few cases (NURE) and **work on theory** (running until 2021)

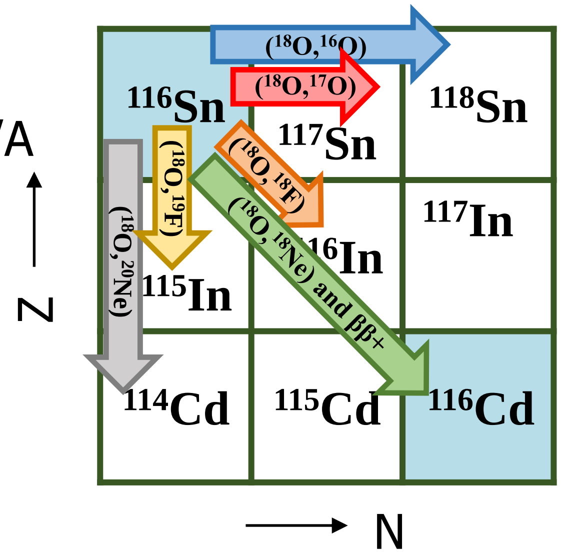
- **Phase3**: **Facility upgrade** (Cyclotron, MAGNEX, beam line, …) to work with two orders of magnitude more intense beam **(talk D. Lo Presti)**

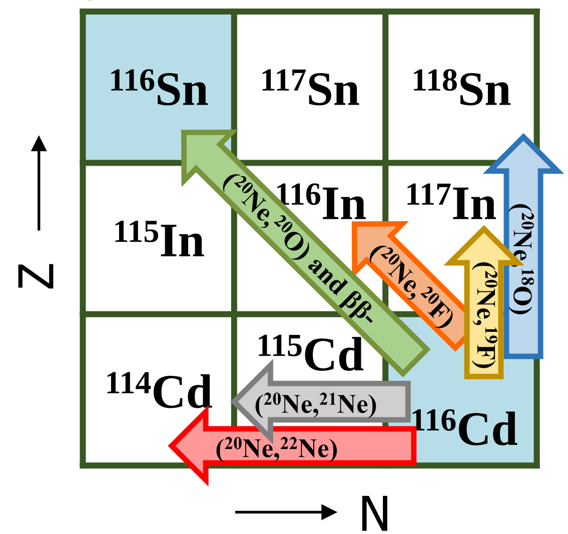
- **Phase4**: **Systematic experimental campaign** on all the systems with the upgraded facility

NUMEN runs – Phase 2

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

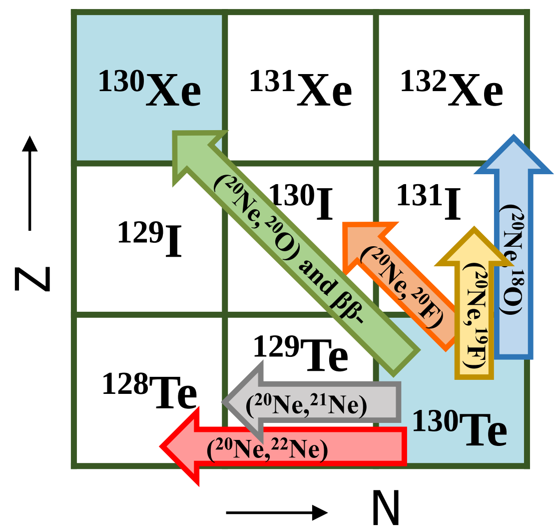
- Two experiments @ 15 MeV/A
- ^{18}O + ^{116}Sn
- ^{20}Ne + ^{116}Cd





^{130}Te – ^{130}Xe case

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



^{76}Ge – ^{76}Se case

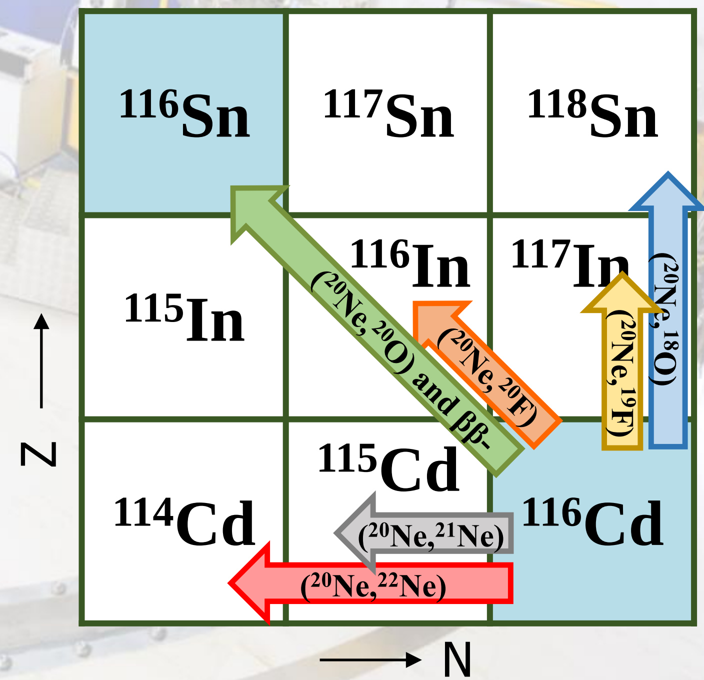
- Experiment in November 2017

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

- $^{20}Ne^{10+}$ beam at 15 AMeV incident energy delivered by CS accelerator
- ^{116}Cd rolled target, 1370 μg/cm^2 thickness
- Ejectiles detected by the MAGNEX large acceptance spectrometer
- Angular acceptance 3° < θ_{lab} < 14°

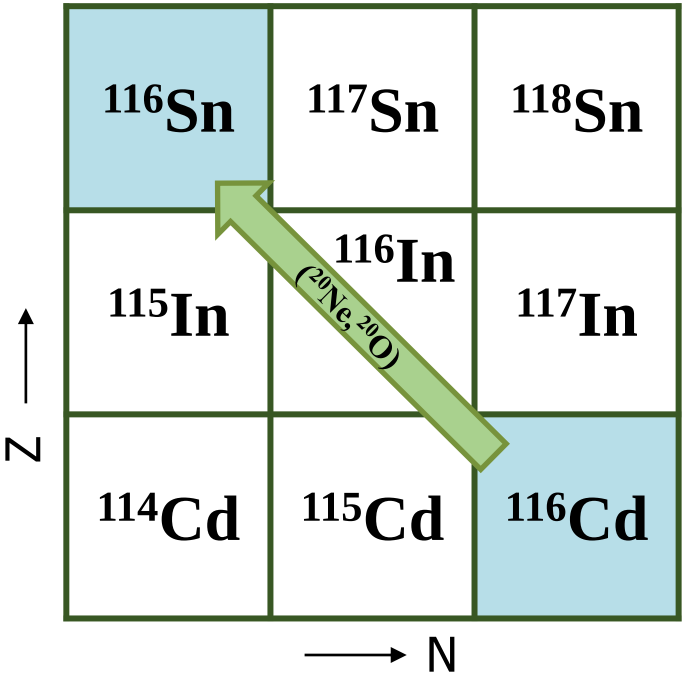
Measured channels

- DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$
- SCE reaction $^{116}Cd(^{20}Ne,^{20}F)^{116}In$
- 2p-transfer $^{116}Cd(^{20}Ne,^{18}O)^{118}Sn$
- 2n-transfer $^{116}Cd(^{20}Ne,^{22}Ne)^{114}Cd$
- 1p-transfer $^{116}Cd(^{20}Ne,^{19}F)^{117}In$
- 1n-transfer $^{116}Cd(^{20}Ne,^{21}Ne)^{115}Cd$



S. Calabrese and G. Santagati posters

Experimental results



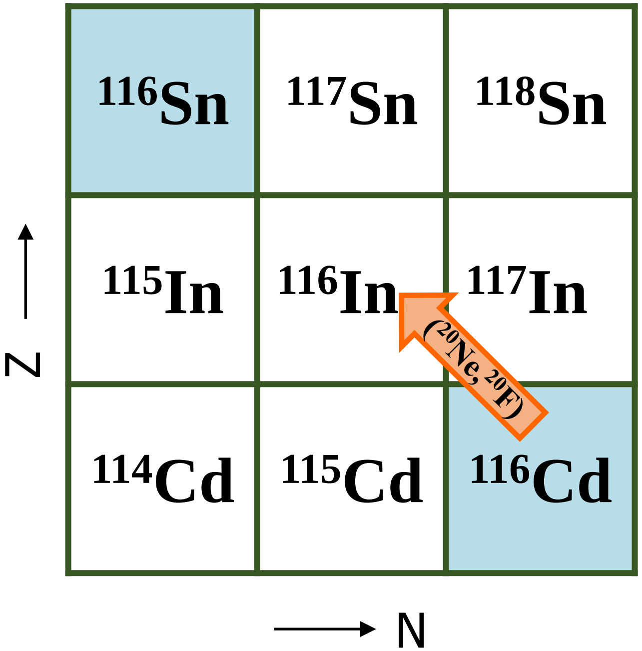
DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$

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

Resolution ~ 800 keV FWHM

Experimental results

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



^{116}In

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

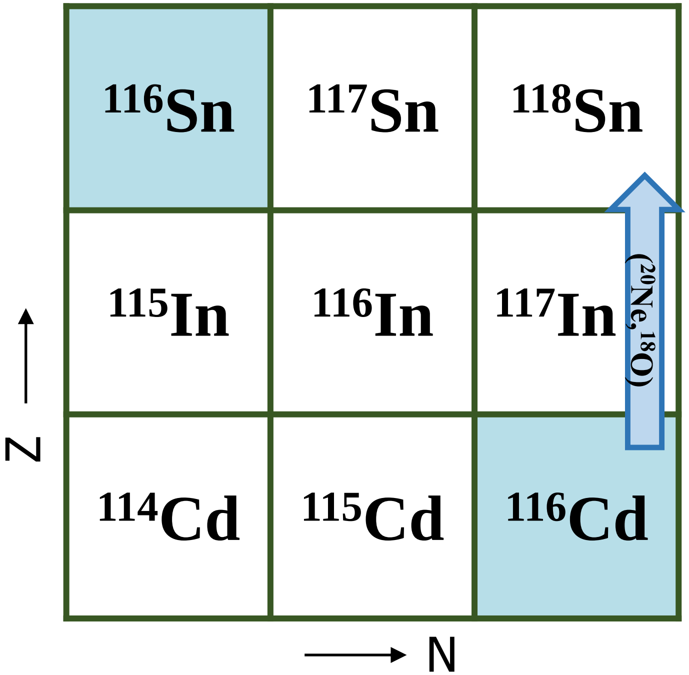
^{20}F

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

High level density in residual and ejectile

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

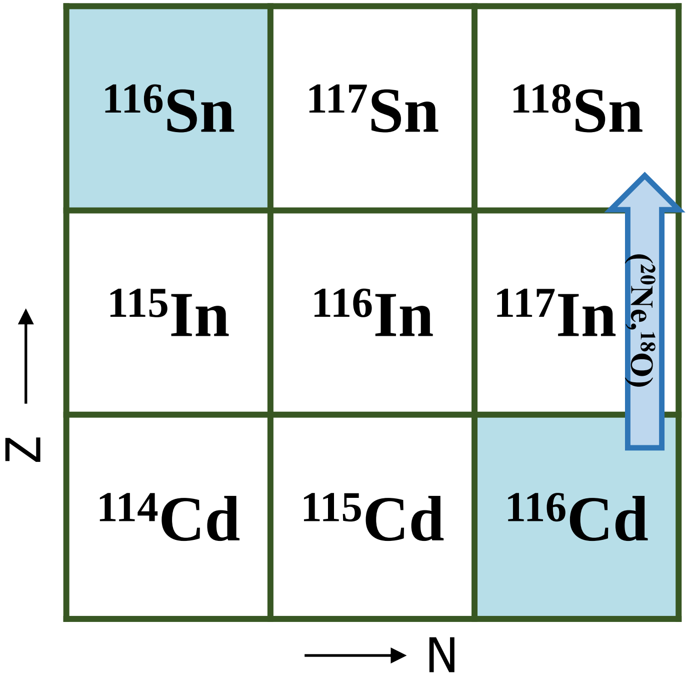
Experimental results



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

cross section towards g.s. comparable with the DCE channel similar to the ^{40}Ca experiment

Calculations for multi-nucleon transfer

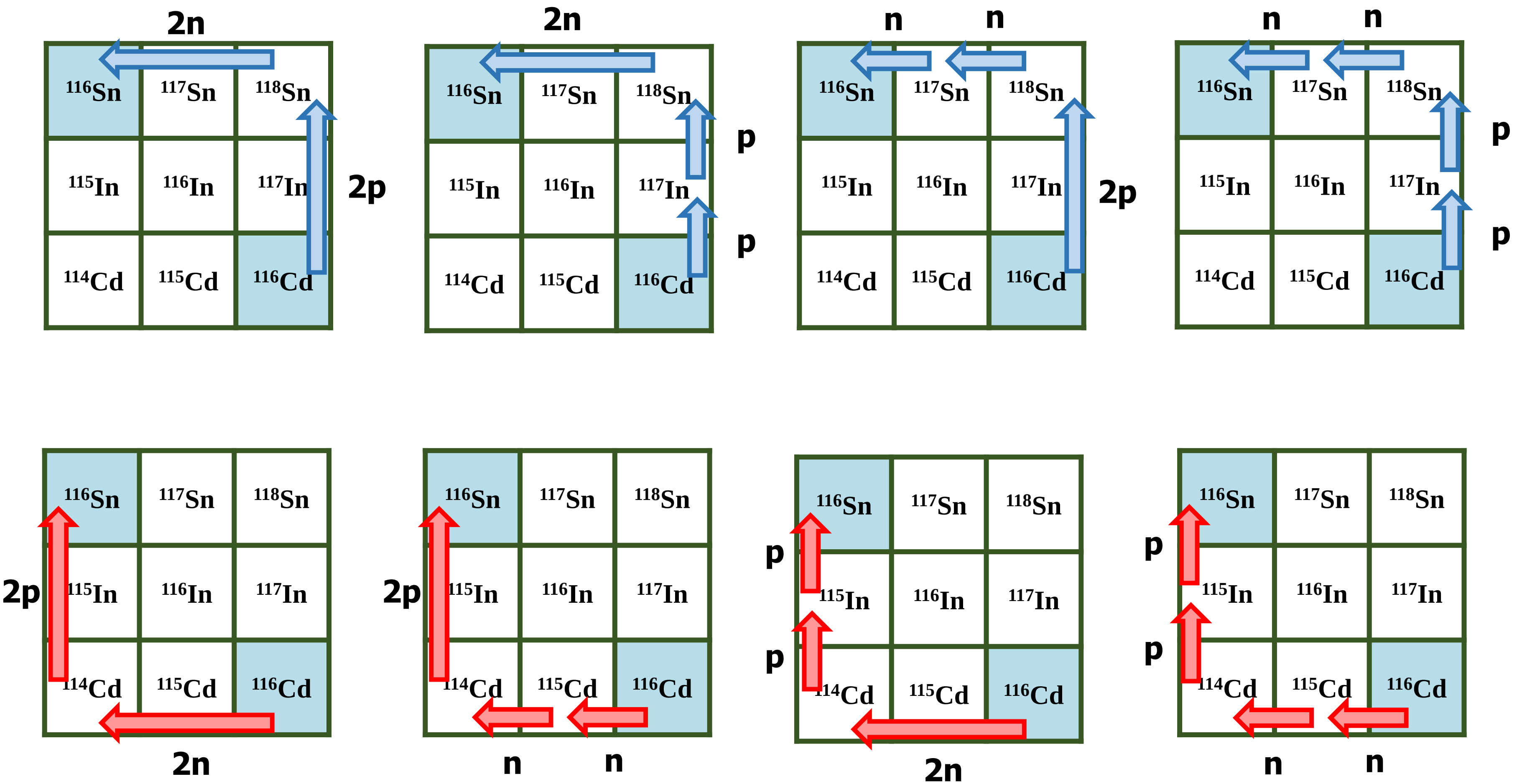


Fully microscopic approach

(J. Lubian talk)
(R. Vsevolodovna poster)

Calculations for multi-nucleon transfer

The role of multi-nucleon transfer routes
vs
The diagonal process (experimental cross section)

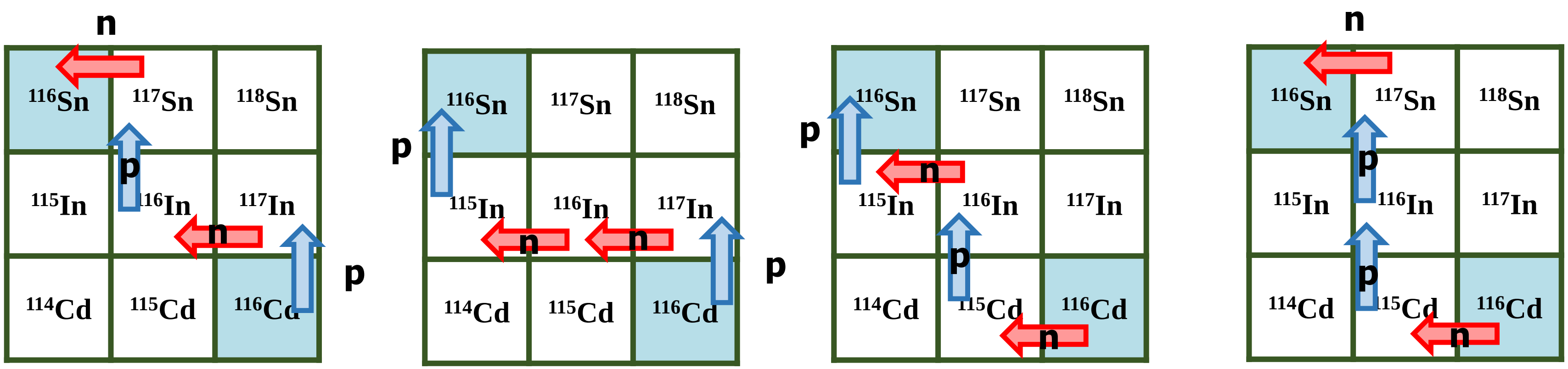


Calculations for multi-nucleon transfer

The role of multi-nucleon transfer routes

vs

The diagonal process (experimental cross section)



We can rule out the contribution of multi-nucleon transfer on the diagonal DCE process

Conclusions and Outlooks

Use of HI-DCE reaction for 0νββ decay

- Relevant results achieved in the pilot experiment
- Promising results from the first experiments on "hot" cases
- **$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$** measured for the first time together with all the competing channels
  - ✓ Good energy resolution to isolate the g.s. → g.s. transition
  - ✓ Absolute cross section measured
- Role of multi-nucleon transfer routes negligible with respect to the diagonal DCE

Outlooks

- Complete the data reduction for all the measured channels
- Measurement on other targets of interest
- Theoretical developments for DCE and SCE on the way
- CS and MAGNEX FPD upgrade for reaching high intensity

Thank you