Recent results on heavy-ion induced reactions of interest for *$0\nu\beta\beta$* decay

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Women in Nuclear and Hadron Theoretical Physics: the last frontier - WTPLF 2018 10 – 11 December Genova

Outline

- Introduction: the framework
- DCE and $0\nu\beta\beta$: the NUMEN project
- Outlook and perspectives

Neutrinos :
90 years and we do not really know it yet !

***1930**: W.Pauli **hypothesis of existence of neutrino** to explain the energetic spectrum of electrons emitted in β decay*

From the papers:

E. Majorana, Nuovo Cimento 14, 171 (1937)
E. Fermi, Z. Phys. 88, 161 (1934)
B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968)

To the Nobel Prizes:

1988 – Muonic neutrinos discover, L.M.Lederman, M. Schwartz, J. Steinberger
1995 – Tau lepton discover, M. L. Perl and F. Reines
2002 – Cosmic neutrinos discover, R. Davi jr, M. Koshiba, R. Giacconi
2015 – Neutrino Oscillations, T. Kajita, A. Mc Donald

Introduction

Unanswered questions in neutrino physics:

- What is the absolute mass scale of neutrinos?
  E. Fermi, Z. Phys. 88, 161 (19
- Ar…
  … 171 (1937)
- … neutrino species are there?
  B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968)

An answer to all three questions can be obtained from neutrinoless double-beta decay (DBD) and related processes

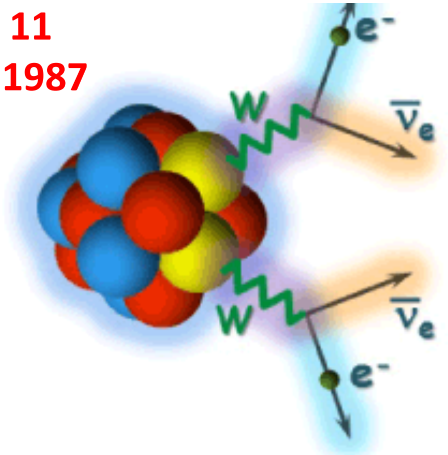
Indeed, if observed, neutrinoless DBD may provide evidence for physics beyond the Standard Model other than the mass mechanism.

Conversely, its non-observation will set stringent limits on other scenarios (sterile,…), and on non standard mechanisms

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



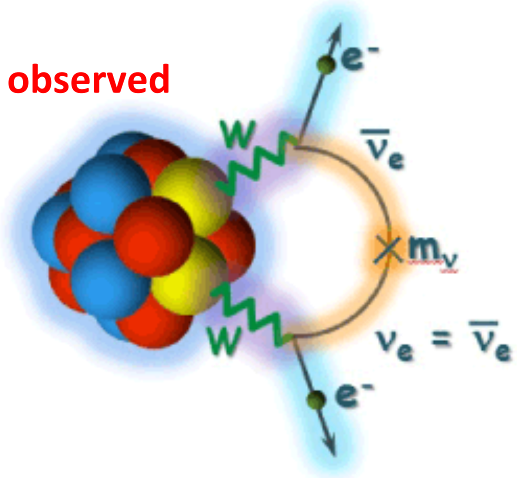
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. **Within standard model**
2. **$T_{1/2} \approx 10^{19}$ to $2*10^{21}$ yr**

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

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 lepto-genesis and GUT**

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

Neutrinoless DBD and the role of Nuclear Physics

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

Still not observed

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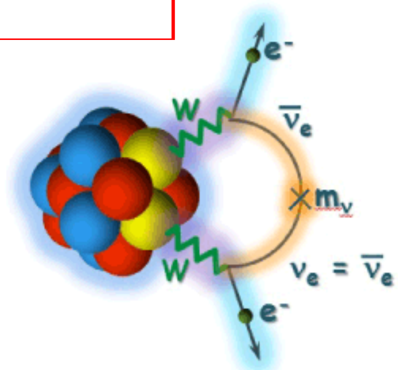
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**



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

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

Phase-space factor
(Atomic physics)
PSF

Matrix elements
(Nuclear physics)
NME

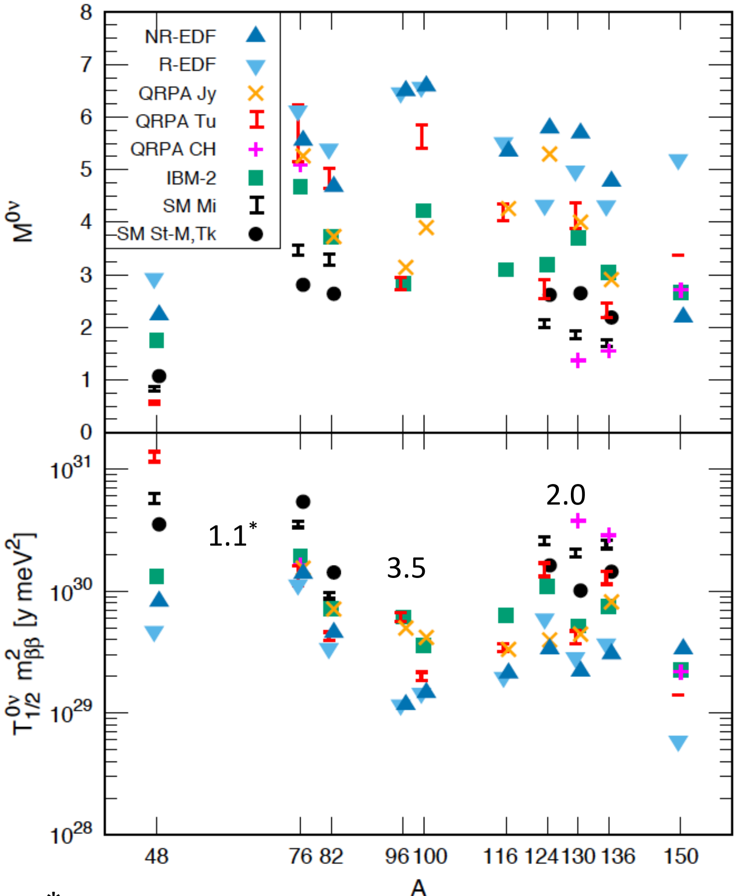
Beyond the standard model
(Particle physics)

INFN LNS

Nuclear matrix elements

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

Comparison of the main NME calculations: spread about x2



*number = signal rate per 1000 kg yr exposure & for middle of NME values for For <m_{ee}> = 17.5 meV (‘bottom of IH’ for g_A=1.25, $\sin^2\theta_{12}$ = 0.318)

✓**Calculations (still sizeable uncertainties)**: QRPA, Large scale shell model, IBM-2 …..

✓**Measurements** (still not conclusive for 0νββ):

- (π^+, π^-)
- single charge exchange (^{3}He,t)
- electron capture
- transfer reactions …

No isotope significantly preferred when comparing decay rate per mass

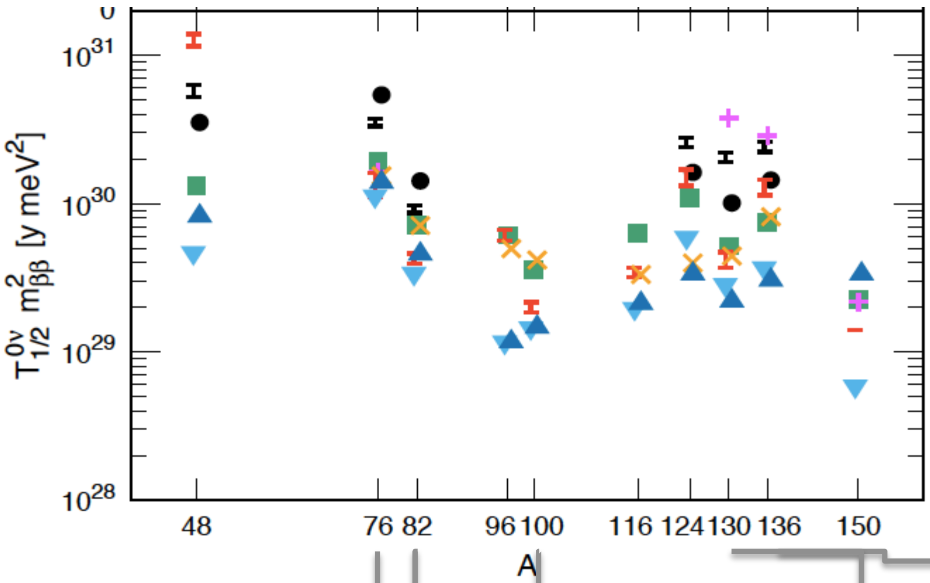
Choice mainly driven by experimental considerations

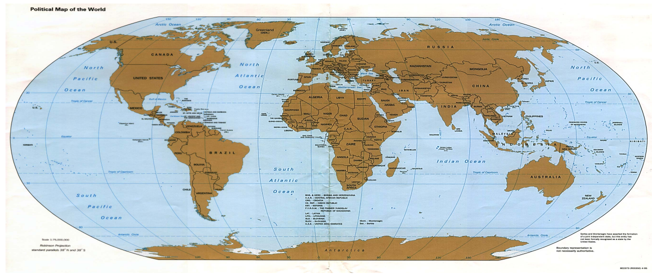
Engel & Menédez

arXiv:1610.06548v2

Courtesy of Stefan Schönert

Experiments: a worldwide race





LXe TPC: EXO-200 / nEXO
gas-Xe TPC: NEXT, PandaX-III
Xe-loaded LS: KamLAND-Zen

Te-loaded LS: SNO+
Te-bolometers: CUORE / CUPID-Te

Mo-bolometers: CUPID-Mo (ex Lumineu)
AMoRE

Se-bolometers: CUPID-0 (CUPID-Se)
Se-calo-tracko: SuperNEMO

Ge-semiconductor: GERDA, MJD, LEGEND

& other interesting, but less advanced R&D;
^{48}Ca, ^{150}Nd not available in large quantities

Courtesy of Stefan Schönert

The Idea:

HI-DCE as experimental tool

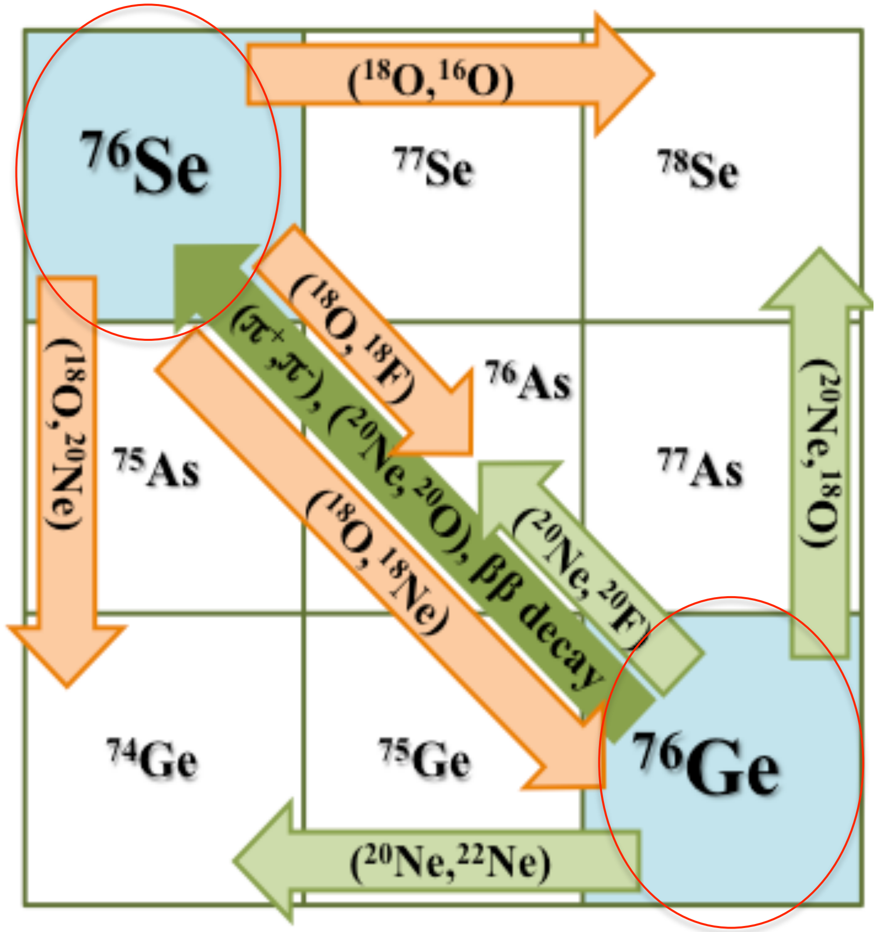
NUclear **M**atrix **E**lement towards **N**eutrinoless $\beta\beta$ decay

The challenge:

to access quantitative informations

Heavy Ion
Double Charge Exchange

1. Induced by strong interaction
2. Sequential nucleon transfer mechanism 4^{th} order:
   Brink's Kinematical matching conditions
   D.M.Brink, et al., Phys. Lett. B 40 (1972) 37
3. Meson exchange mechanism 2^{nd} order
4. Possibility to go in both directions



HI–DCE reactions vs $0\nu\beta\beta$ decay

Differences

- DCE mediated by **strong interaction**, 0νββ 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

A good linear correlation between double Gamow -Teller (DGT) transitions to the ground state of the final nucleus and *0νββ* decay NMEs is reported in ref.: *N. Shimizu, J. Menéndez and K. Yako, Phys. Rev. Lett. 120, 142502 (2018)*

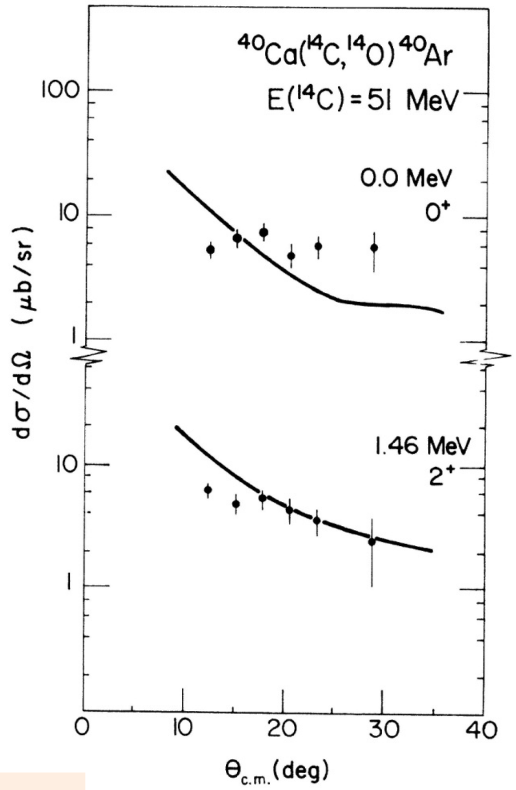
Past experimental attempts

Few experimental attempts:

- **not conclusive because** of the very poor yields in the measured energy spectra and the lack of angular distributions, due to the **very low cross-sections** involved.
- not easy to measure, in the same experimental conditions, the **different competitive reaction channels** (limit due to the prohibitive small cross-sections).

$^{40}Ca(^{14}C,^{14}O)^{40}Ar$ @ 51 MeV

$10° < \vartheta_{lab} < 30°$ Q = -4.8 MeV



D.M.Drake, et al., Phys. Rev. Lett. 45 (1980) 1765

C.H.Dasso, et al., Phys. Rev. C 34 (1986) 743

Recently at RIKEN and RCNP (80-200 MeV/u):

- (^{8}He,^{8}Be) was used to search for the tetra-neutron (4n) system, *K. Kisamori et al., Phys. Rev. Lett. 116, 052501 (2016).*
- (^{11}B,^{11}Li) and (^{12}C,^{12}Be) were used to find the DGT resonance, *H. Sagawa, T. Uesaka, Phys. Rev. C 94, 064325 (2016).*

DCE @ INFN - LNS

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

$0° < \vartheta_{lab} < 10°$ Q = -5.9 MeV

- ^{18}O and ^{18}Ne belong to the same multiplet in S and T
- Very low polarizability of core ^{16}O
- Sequential transfer processes very mismatched $Q_{opt} \sim 50$ MeV
- Doubly magic target

The facility: DCE @ LNS

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

crucial for the experimental challanges !

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

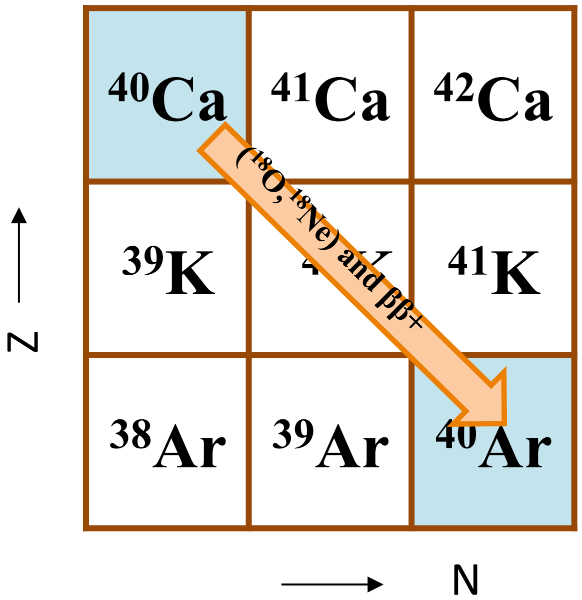
Good compensation of the aberrations: Trajectory reconstruction

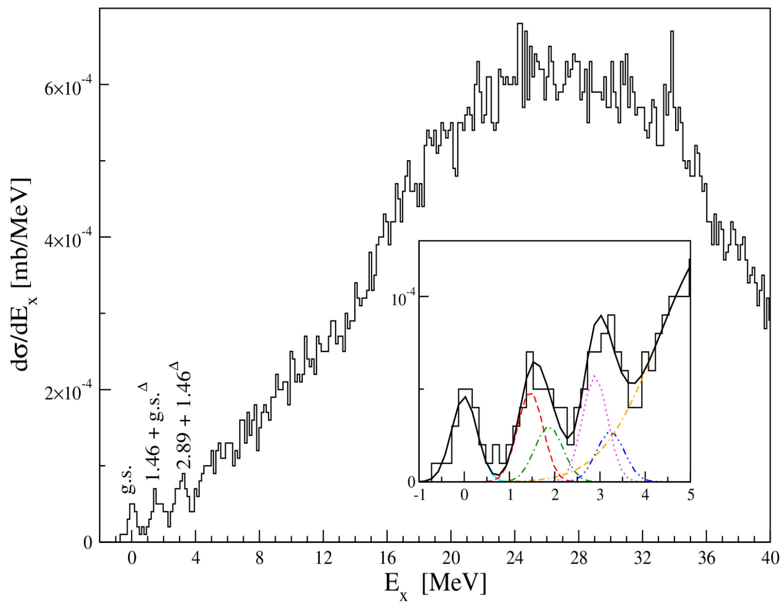
Measured resolutions:

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

DCE @ LNS

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV $0° < \vartheta_{lab} < 10°$ Q = -5.9 MeV





$d\sigma^{DCE}/d\Omega$= 11μb/sr at $\theta_{cm}=0^0$

- **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

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

$$\left|M_{\sigma\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 0.24 \pm 0.12$$

$$\left|M_{\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 0.22 \pm 0.11$$

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

- 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 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 is not enough to separate the g.s. from the excited states in the final nucleus → Detection of γ-rays

Much higher beam current is needed !

NUMEN experiment programs

- Beams intensity up to 10^{14} pps
- Energy range 15-70 MeV/u
- Beam power range 1-10 kW

(^{18}O , ^{18}Ne) → $\beta^+\beta^+$

(^{20}Ne, ^{20}O) → $\beta^-\beta^-$

The Phases of the NUMEN project

- Phase1: Experimental feasibility
- Phase2: **"hot" cases** optimizing the experimental conditions, getting first results, **R&D** for the upgrade, developement of **theoretical models**
- Phase3: Facility upgrade (Cyclotron, MAGNEX, beam lines, ...)
- Phase4: Systematic experimental campaign

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

	2016				2017				2018				2019			
PHASE 2	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$		Exp														
$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$	Test			Exp		Exp										
$^{130}Te(^{20}Ne,^{20}O)^{130}Xe$						Exp										
$^{76}Ge(^{20}Ne,^{20}O)^{76}Se$								Exp								
$^{76}Se(^{18}O,^{18}Ne)^{76}Ge$												Exp				
$^{106}Cd(^{18}O,^{18}Ne)^{106}Pd$																

The NUMEN goals

1. **Holy Graal:** sudying if **the σ^{DCE}** and in **turn NME_{DCE} are connected to *0νββ* NMEs as a smooth function of E_p and A** ⟶ require the development of the reaction and nuclear structure theory and a systematic set of data.

2. A new generation of **DCE constrained to 0νββ NME theoretical calculations** achievable in a short term with a reduced dataset

3. To provide **relative NME information on the different candidate isotopes** for the *0νββ* decay : the ratio of the σ^{DCE} can give **a model independent way** to compare the sensitivity of different half-life experiment

^{76}Ge ^{130}Te ^{82}Se ^{136}Xe ^{116}Cd

strong impact in future development of the field, looking for a "golden isotope" …

NUMEN phase 2

- R&D for upgrade @ LNS facilities

- Detector R&D : new MAGNEX focal plane detector for PID and tracker ;
  new target development
  electronic development ;

- Theoretical model developments.

- Long run @ LNS with MAGNEX with few isotopes, candidates for $0\nu\beta\beta$ already at our reach in terms of energy resolution and availability of thin targets

European Commission
Horizon 2020
European Union funding
for Research & Innovation
erc
ERC Starting Grant 2016

enhance the project discovery potential already in NUMEN phase 2

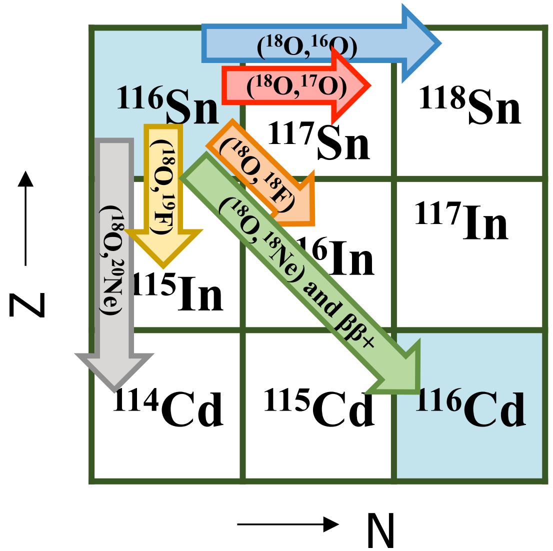
NUMEN:
some recent results

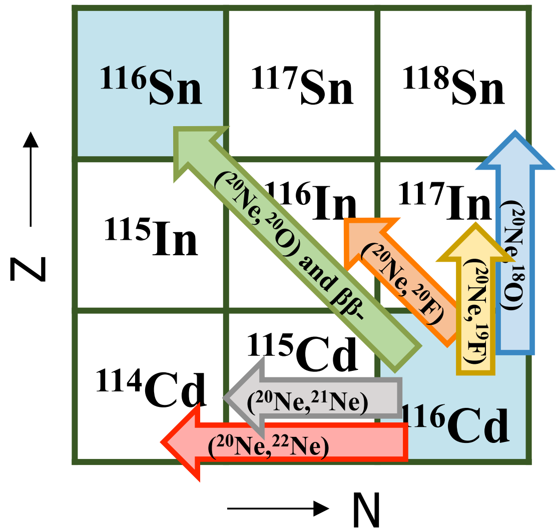
Women in Nuclear and Hadron Theoretical Physics:
the last frontier - WTPLF 2018 10 – 11 December Genova

NUMEN runs - Phase 2

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

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



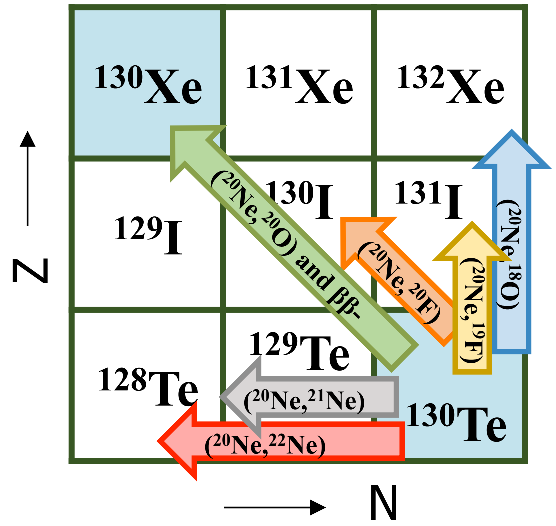


^{130}Te – ^{130}Xe case

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

^{76}Ge – ^{76}Se case

- Two experiment @ 15 MeV
- ^{20}Ne + ^{76}Ge
- ^{18}O + ^{76}Se

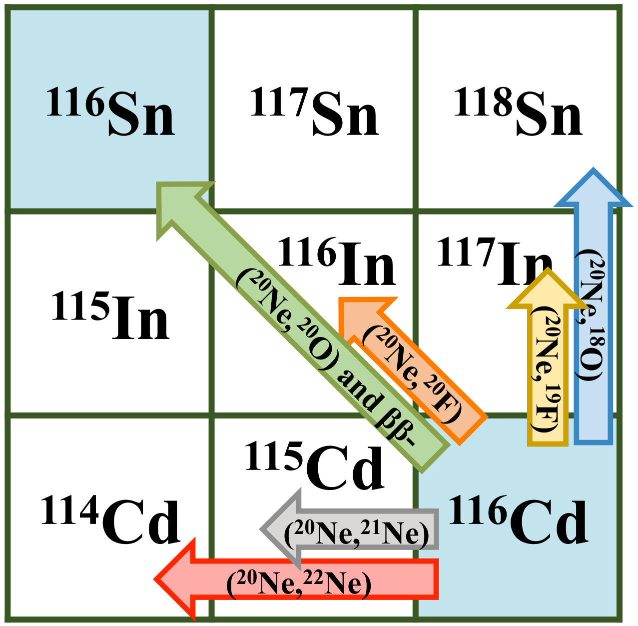


The $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ reaction

- $^{20}Ne^{10+}$ beam at 15 AMeV incident energy delivered by CS accelerator
- ^{116}Cd rolled target, 1370 μg/cm² thickness
- Ejectiles detected by the MAGNEX large acceptance spectrometer
- Angular acceptance 3° < θ < 14°

Measured channels

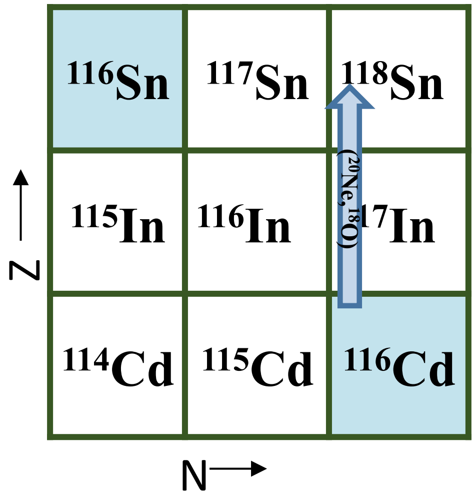
- DCE reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$
- CEX reaction $^{116}Cd(^{20}Ne,^{20}F)^{116}In$
- 2p-transfer $^{116}Cd(^{20}Ne,^{18}O)^{118}Sn$
- 2n-transfer $^{116}Cd(^{20}Ne,^{22}Ne)^{114}Cd$
- 1p-transfer $^{116}Cd(^{20}Ne,^{19}F)^{117}In$
- 1n-transfer $^{116}Cd(^{20}Ne,^{21}Ne)^{115}Cd$



Calculation for multi-nucleon transfer

Cross section calculations
(DWBA + IBM)

2p-transfer

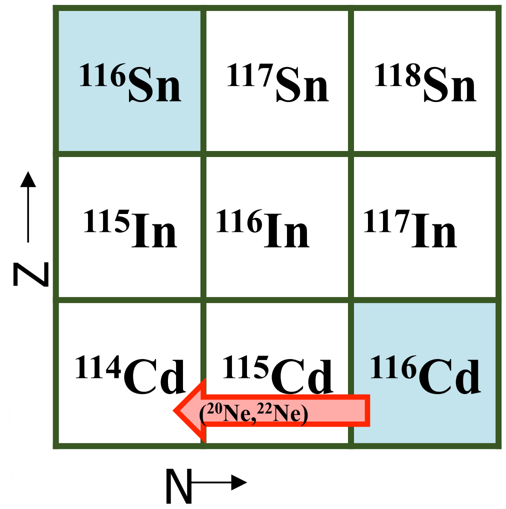


EXP. DATA:
33 ± 10 nb

CALCULATIONS:
~ 26 nb

Agreement!

2n-transfer



EXP. DATA:
450 ± 200 nb

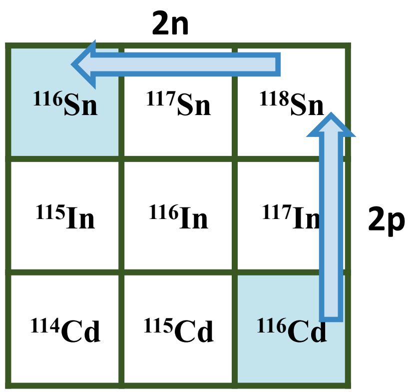
CALCULATIONS:
~ 340 nb

Calculation for multi-nucleon transfer

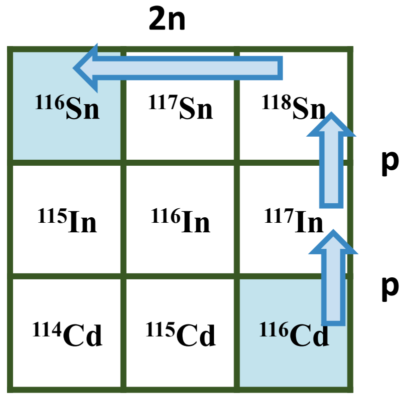
The role of multi-nucleon transfer routes

vs

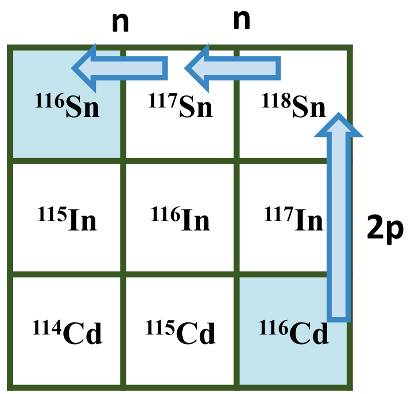
The diagonal process (experimental cross section 12 ± 2 nb)



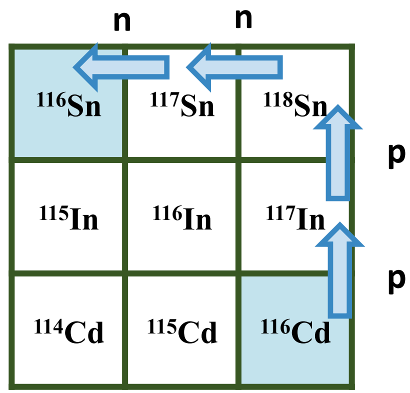
3×10^{-5} nb



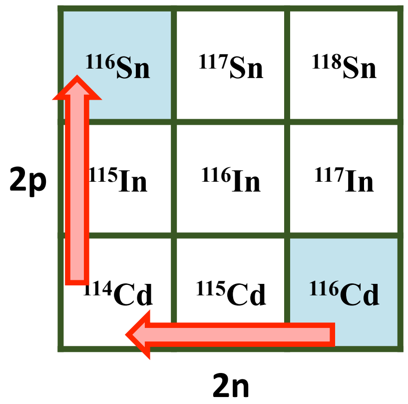
6.6×10^{-5} nb



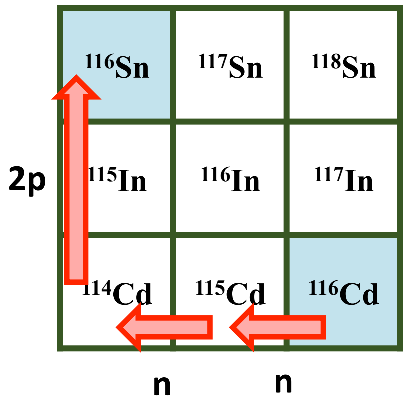
1.1×10^{-5} nb



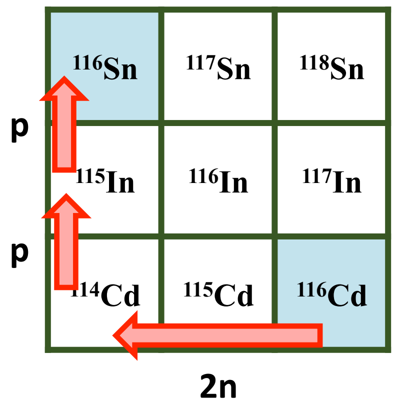
1.7×10^{-5} nb



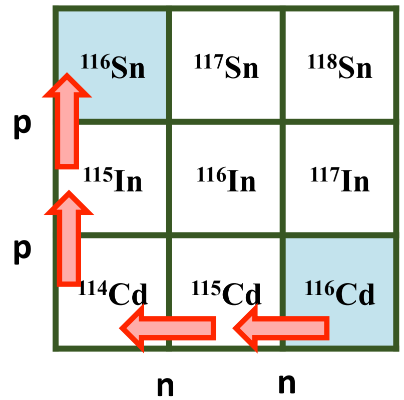
6.9×10^{-4} nb



4.0×10^{-5} nb



3.0×10^{-4} nb



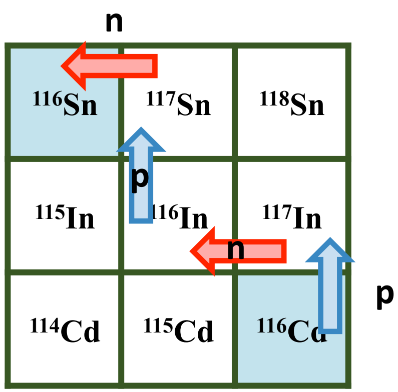
8.3×10^{-5} nb

Calculation for multi-nucleon transfer

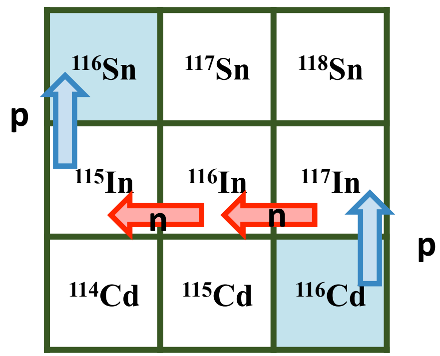
The role of multi-nucleon transfer routes

vs

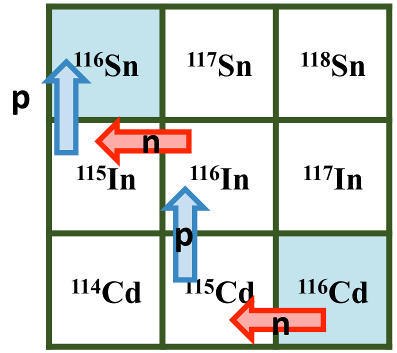
The diagonal process (experimental cross section 12 ± 2 nb)



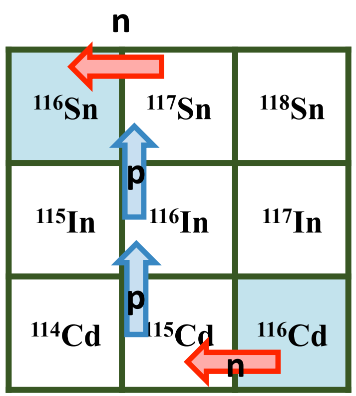
9.4×10^{-8} nb



1.5×10^{-6} nb



3.2×10^{-7} nb



1.1×10^{-7} nb

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

Present technology is not enough…

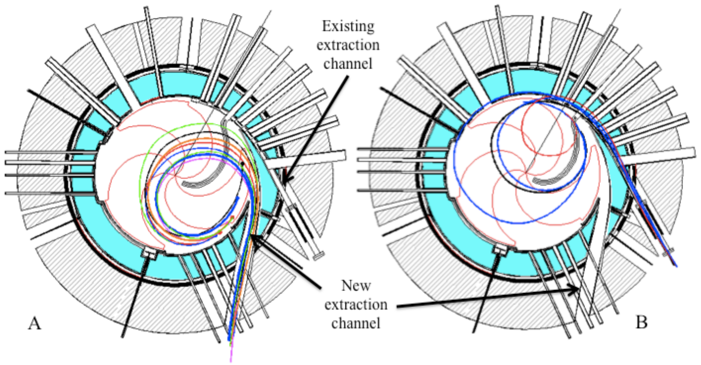
The challenge: to detect with good energy, mass and angular resolutions rare events at very high rates of heavy ions!

- **Upgraded set-up to match about 1000 times more beam current than the present**

- **Substantial change in the technologies used in CS and in the MAGNEX detector**

Upgrade @ LNS facilities

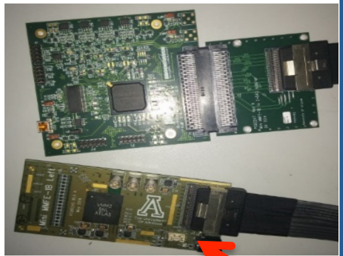
- **Upgrade of the LNS accelerator and beam lines**



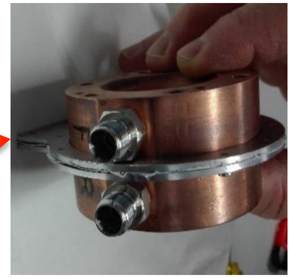
- **CS** accelerator current (from 100 W to 5-10 kW); from elecrostatic to extraction by stripping
- **beam transport line** transmission efficiency to nearly 100%. The new beam transport line corresponds with the FRAgment Ion Separation line.

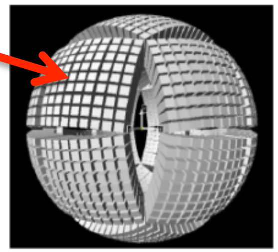
Project approved by INFN
(~19M€ from PON/MIUR-ESI H2020 UE)

- **Upgrade of the experimental setup**



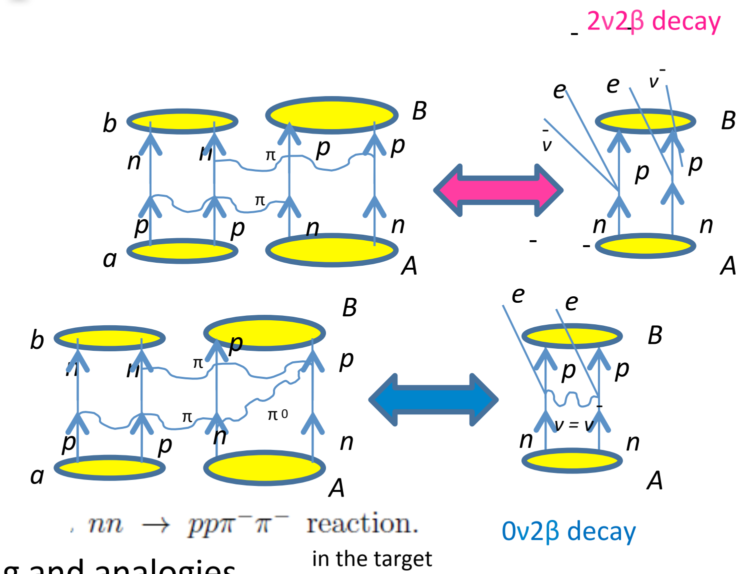
The upgraded magnetic system for MAGNEX
The new beam dump . . . .
Design of the targets . . . .
NUMEN focal plane detector tracker . . . . .
Particle identification . . . .
The gamma calorimeter for NUMEN . . . . .
Front-end and read-out electronics . . . .
Data handling and data processing . . . .





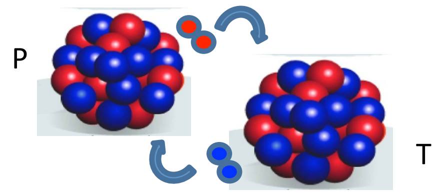
Theoretical developments

1. Two-step (uncorrelated) process (1bDCE) : two consecutive SCE
-- Analogies with 2ν2β decay
2. One-step (correlated) process (2bDCE) :
-- Analogies with 0ν2β decay
3. Study of competing processes:
-- Multinucleon transfer



- Double Charge Exchange (DCE) : modeling and analogies with double β decay
  -- calculations with HIDEX and FRESCO codes

- Double Charge Exchange (DCE) : modeling of the correlated one-step process
  → upgrade on structure inputs – IBM models



- Competing channels: (multi) nucleon transfer FRESCO code

- **Lenske et al. Phys. Rev. C 98, 044620 (2018).**
- **J.I.Bellone et al. (NUMEN coll.), Journal of Physics: Conference Series 1056, 012004 (2018).**
- **E.Santopinto et al. Phys. Rev. C 98, 061601 (R) (2018)**

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

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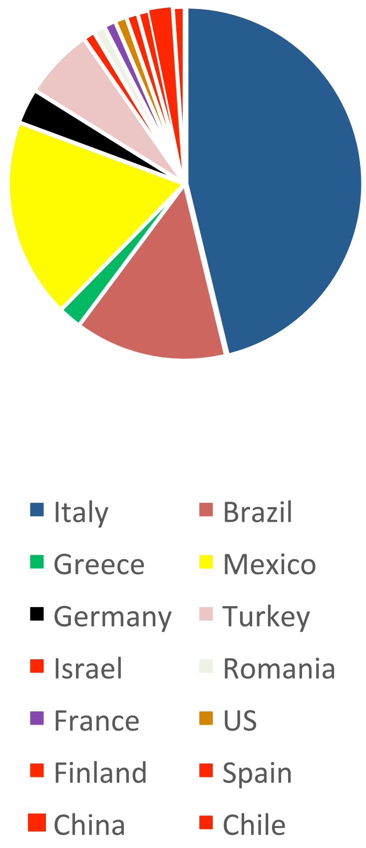
30 Institutions
14 Countries



Perspectives

➢ **NUMEN main goal** is the extraction from measured cross-sections of "data-driven" information on Nuclear Matrix Elements for all the systems candidate for $0\nu\beta\beta$

➢ A big challenge for **nuclear technology** and **nuclear theory**

➢ Strong sinergy between **experimental** and **theoretical physicists**

High intensity beams are the new frontier for

these challenging studies !

The Fifth Solvay Conference - 1927

Thank you!

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