Nuclear Reactions for Neutrinoless Double Beta Decay

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(Italy)

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0νββ decay

Open problem in modern physics:

Neutrino absolute mass scale

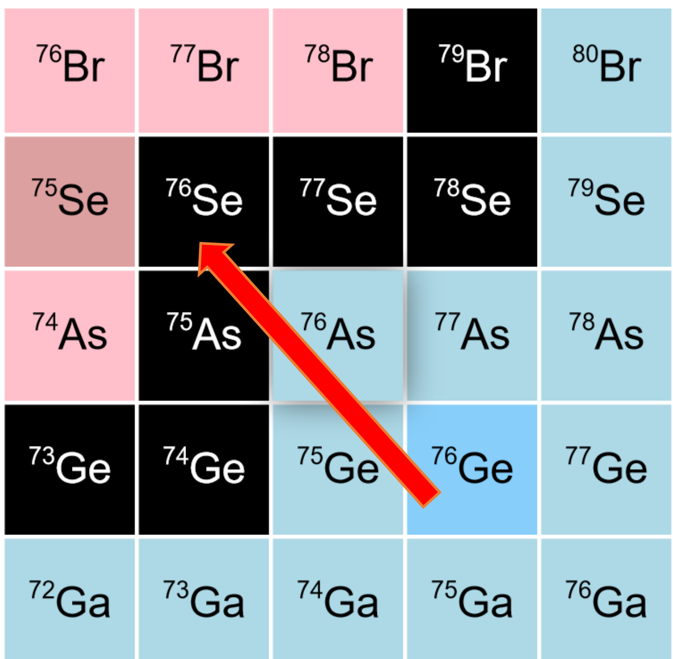
Neutrino nature

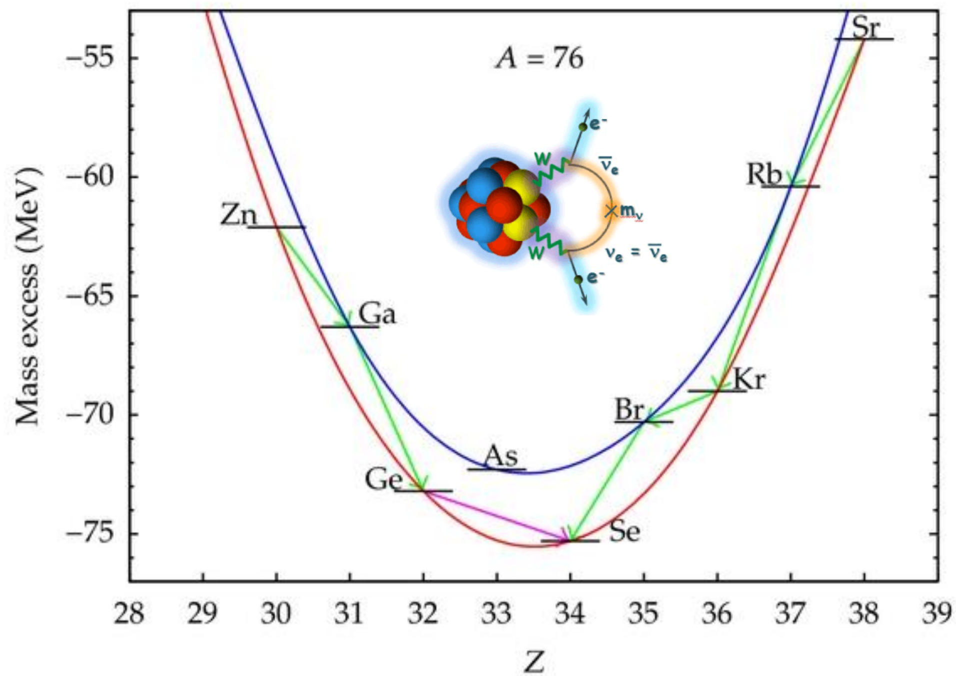
0νββ is considered the **most promising approach**

Still not observed

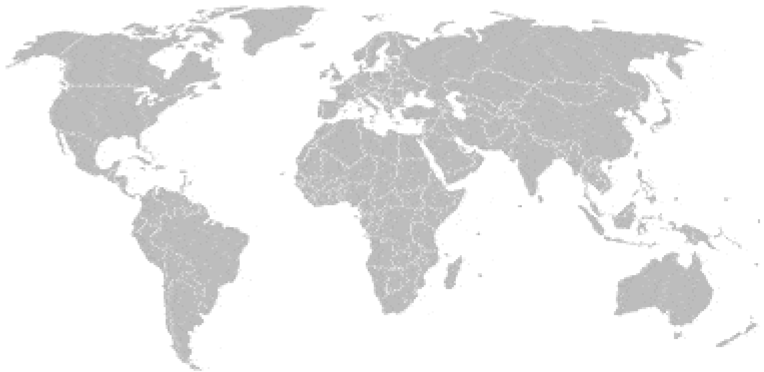
$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} + (2\bar{\nu}) $$

Beyond standard model





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



Search for $0\nu\beta\beta$ decay. A worldwide race

Experiment	Isotope	Lab	Status
GERDA	^{76}Ge	LNGS [Italy]	Operational
CUORE	^{130}Te	LNGS [Italy]	Construction
Majorana	^{76}Ge	SURF [USA]	Construction
KamLAND-Zen	^{136}Xe	Kamioka [Japan]	Operational
EXO/nEXO	^{136}Xe	WIPP [USA]	Operational
SNO+	^{130}Te	Sudbury [Canada]	Construction
SuperNEMO	^{82}Se (or others)	LSM [France]	R&D
CANDLES	^{48}Ca	Kamioka [Japan]	R&D
COBRA	^{116}Cd	LNGS [Italy]	R&D
Lucifer	^{82}Se	LNGS [Italy]	R&D
DCBA	many	[Japan]	R&D
AMoRe	^{100}Mo	[Korea]	R&D
MOON	^{100}Mo	[Japan]	R&D

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)

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

Transition probability of a **nuclear** process

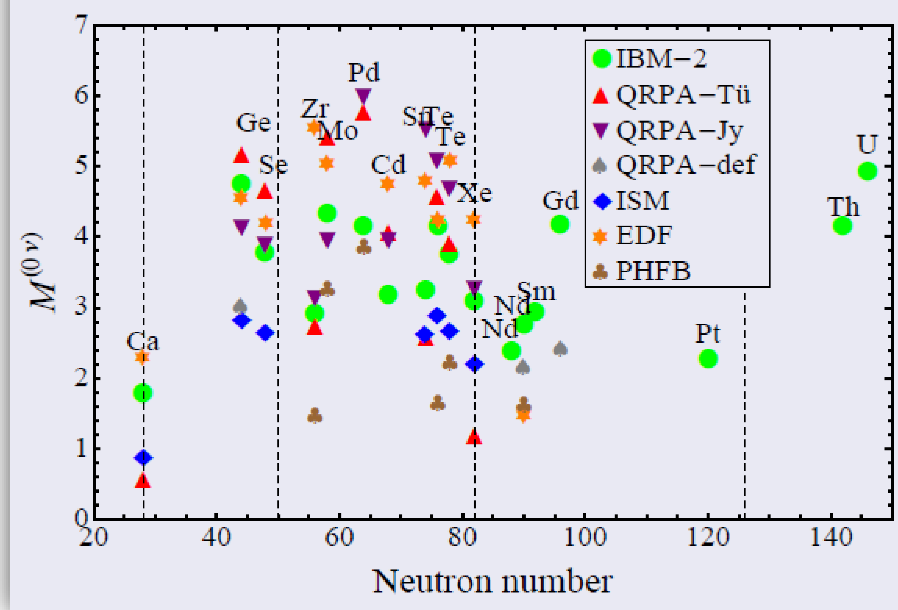
Nuclear physics plays a key role!

Nuclear Matrix Elements

Nuclear Matrix Element (NME)

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

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



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

E. Caurier, et al., PRL 100 (2008) 052503
N. L. Vaquero, et al., PRL 111 (2013) 142501
J. Barea, PRC 87 (2013) 014315
T. R. Rodriguez, PLB 719 (2013) 174
F.Simkovic, PRC 77 (2008) 045503.
…

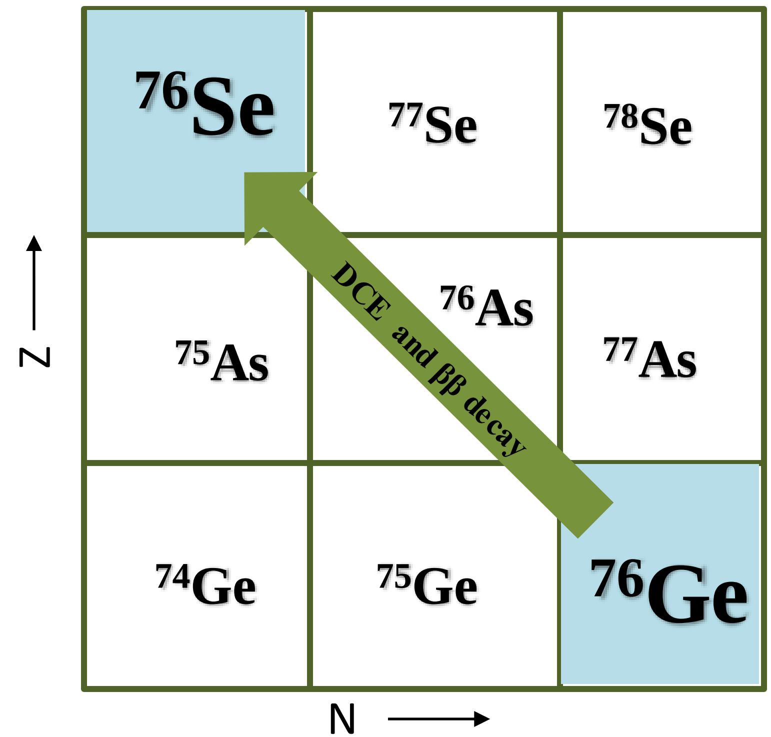
Warning: Many body WaveFunctions!

The idea

Is there an **experimental way** to access the NME?

The ERC project NURE:

Nuclear reactions
Double Charge Exchange reactions (DCE)
to stimulate in the laboratory the same nuclear transition occurring in $0\nu\beta\beta$



0νββ vs HI-DCE

Differences

- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- DCE includes **sequential** transfer **mechanism**

Similarities

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

NURE plans to measure the **absolute cross section** of **HI-DCE** reactions on **nuclei** candidates for $0\nu\beta\beta$ and to **extract «data-driven» NME**

the measured quantity is the **cross section**

details of the reaction

$$\frac{d\sigma}{d\Omega}(q,\omega) = f(NME)$$

The extraction of nuclear structure information from measured cross sections is **not trivial** but **feasible (result of decades of nuclear physics)**

e.g. for single charge-exchange: NME extracted within 2-5% accuracy by proportionality relation

$$\frac{d\sigma}{d\Omega}(q,\omega) = \hat{\sigma}(E_p, A) F(q,\omega) NME(\alpha)$$

- E_p incident energy
- q momentum transfer
- ω excitation energy

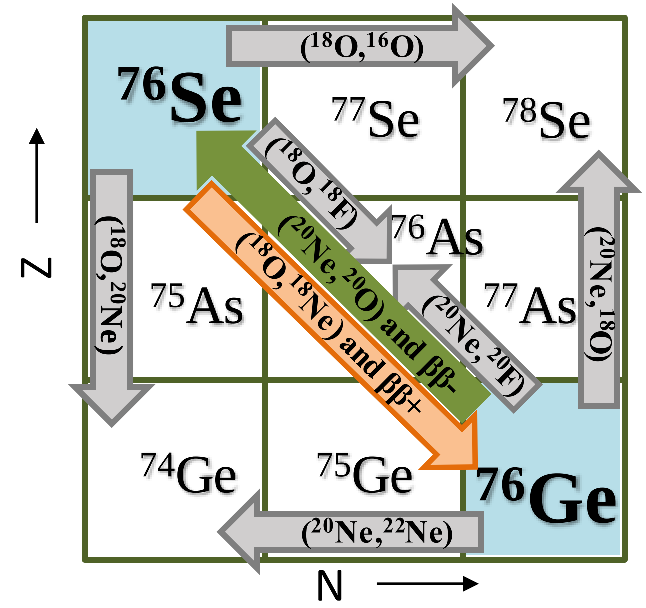
The project

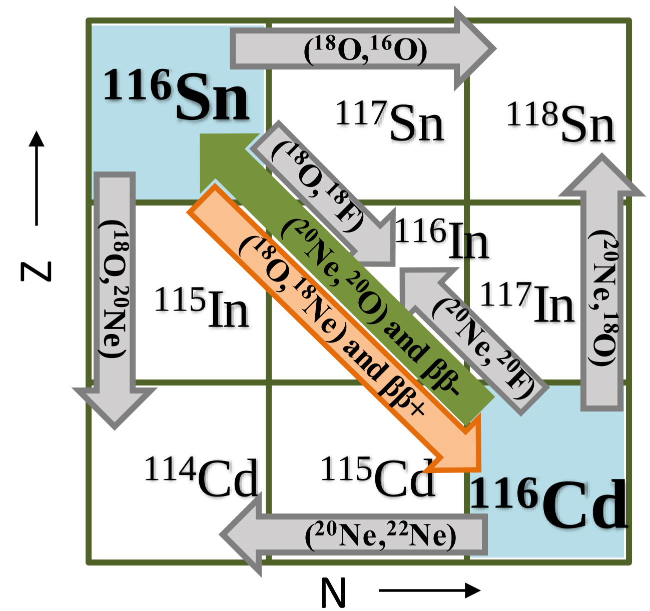
- **Only two transitions of interest for 0νββ:** ^{76}**Ge**↔^{76}**Se** and ^{116}**Cd**↔^{116}**Sn**
  GERDA, MAJORANA, COBRA

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

- **Complete net** of reactions which can contribute to the DCE cross-section:
  1p-, 2p-, 1n-, 2n-transfer, single cex, DCE

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





The context

Single charge-exchange reactions
induced by light ions (^{3}He,t), (d,^{2}He), …

Interesting for β-decay and 2νββ!

Weak interaction probes
β, 2νββ,
μ-capture,
ν-nucleus scattering, …

Transfer reactions
for constraining Ψ_i, Ψ_f

Other researches
to extract information on NME from experimental data and/or constrain the theory

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

Heavy-ion induced **double charge-exchange**
limited in the past due to low cross-sections

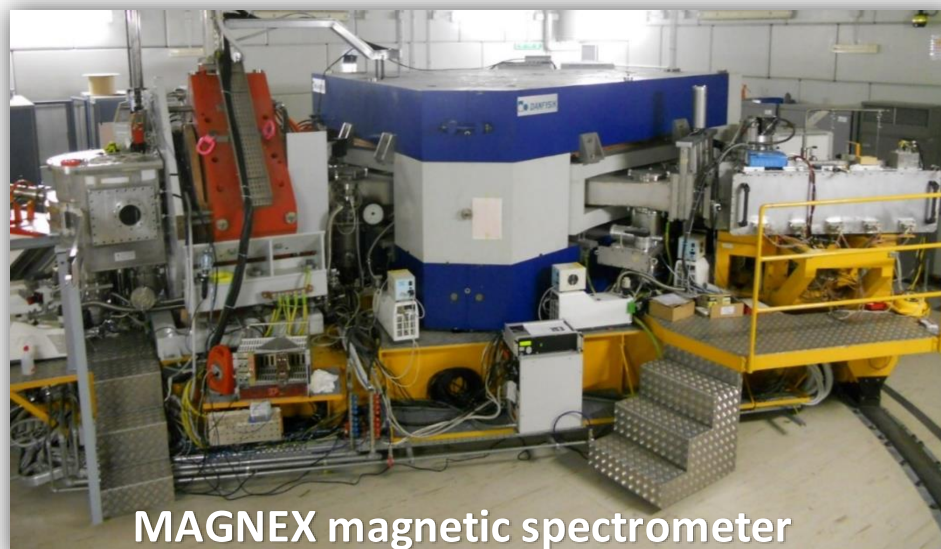
Renewed interest (RIKEN, Osaka) but low resolution (~1.5 MeV)

The pilot experiment

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

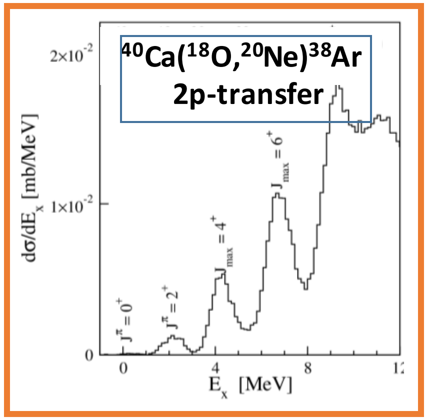
INFN LNS
Catania

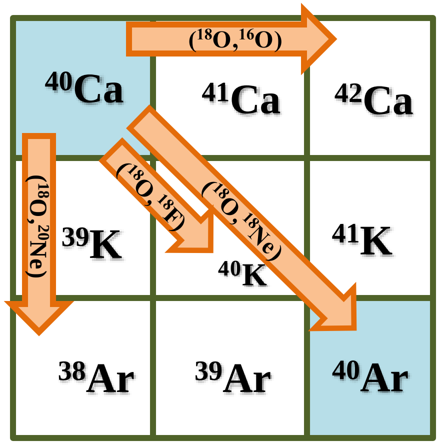
- $^{18}O^{7+}$ beam from Cyclotron at **270 MeV** (10 pnA, 3300 μC in 10 days)
- ^{40}**Ca** target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer 0° < ϑ_{lab} < 10°
  corresponding to a momentum transfer ranging **from 0.17 fm^{-1} to 2.2 fm^{-1}**

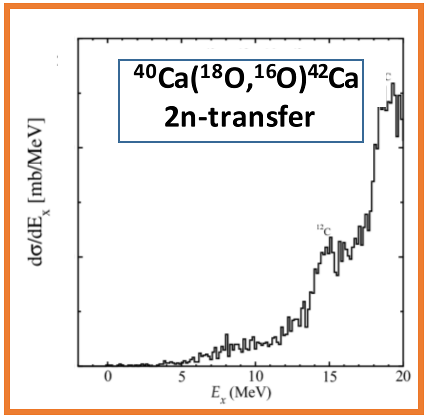


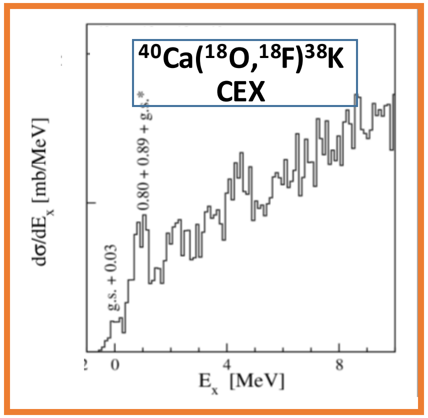
The pilot experiment

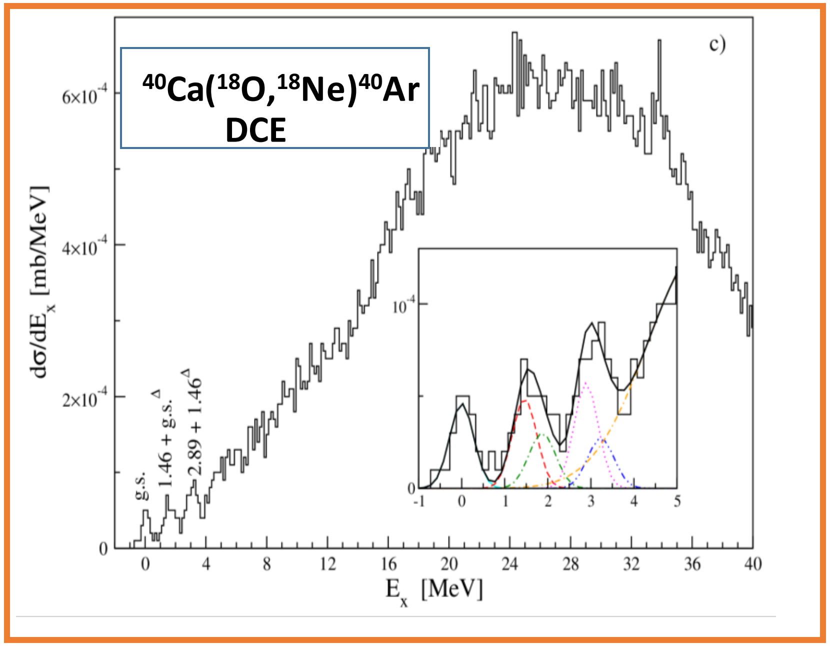
$^{18}O + ^{40}Ca$ at 270 MeV











- **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

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

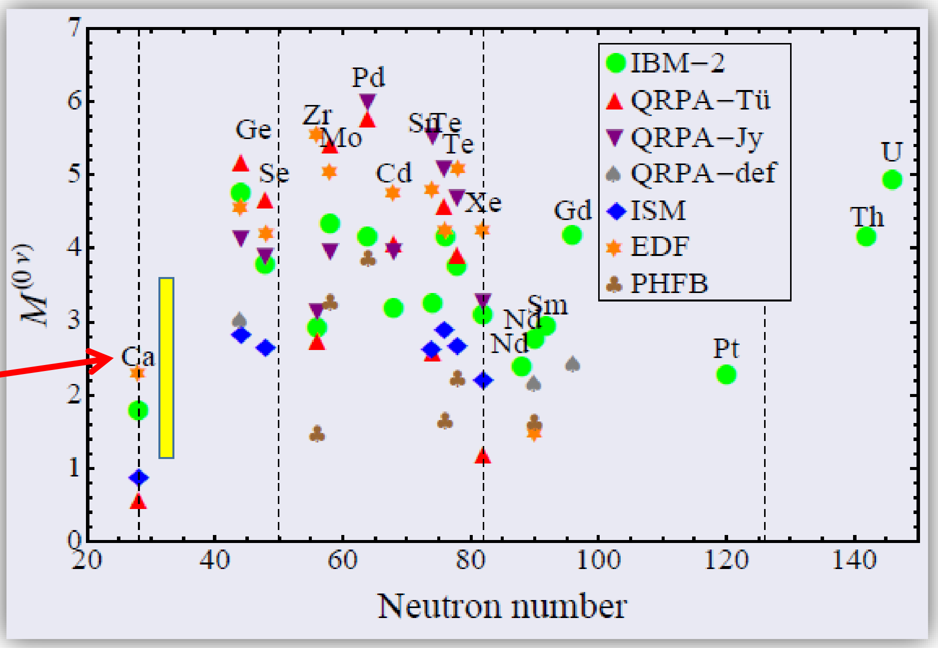
Preliminary NME extraction

In the lack of «real» theory…

Under the hypothesis of validity of the factorization

$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_{\alpha}^{DCE}(E_p, A)\, F_{\alpha}^{DCE}(q,\omega)\, B_{T}^{DCE}(\alpha)\, B_{P}^{DCE}(\alpha)$$

$$\left| M\left({}^{40}Ca\right)\right|^2 = 0.37 \pm 0.18$$



Just to speculate:
removing Pauli blocking one can roughly estimate

$$\left| M^{0\nu\beta\beta}\left({}^{48}Ca\right)\right|^2 = 2.6 \pm 1.3$$

Pauli blocking about 0.14 for F and GT

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

A broader view

Limitations of NURE:

- Only two systems can be studied in 5 years (due to the **low cross-sections**)
- A more accurate job on the **theory** is needed

A broader view

The NUMEN project

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

The collaboration

Spokespersons: F. Cappuzzello and C. Agodi

E. Aciksoz, L. Acosta, C. Agodi, X. Aslanouglou, N. Auerbach,
J. Bellone, R. Bijker, S. Bianco, D. Bonanno, D. Bongiovanni,
T. Borello, I. Boztosun, V. Branchina, M.P. Bussa, L. Busso,
S. Calabrese, L. Calabretta, A. Calanna, D. Calvo,
F. Cappuzzello, D. Carbone, M. Cavallaro, E.R. Chávez Lomelí,
M. Colonna, G. D'Agostino, N. Deshmuk, P.N. de Faria, C. Ferraresi,
J.L. Ferreira, P. Finocchiaro, A. Foti, G. Gallo, U. 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, F. Pirri, S. Reito,
D. Rifuggiato, M.R.D. Rodrigues, A. Russo, G. Russo,
G. Santagati, E. Santopinto, O. Sgouros, S.O. Solakcı,
G. Souliotis, V. Soukeras, S. Tudisco, R.I.M. Vsevolodovna,
R. Wheadon, V. Zagatto

Italy, Brazil, Greece, México, Germany, Turkey, Israel, Romany

Operating in a wider context, in a wider time scale (10-15 yr), in close synergy with NURE

A broader view

The **NUMEN** project

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

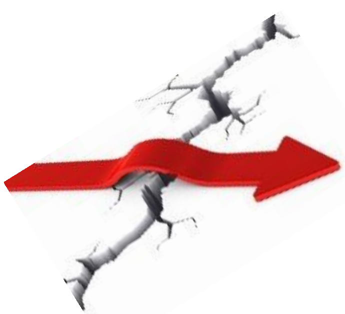
- **Phase1**: The experimental **feasibility** (completed)
- **Phase2**: **experimental exploration** of few cases (NURE) and **work on theory** (running until 2021)
- **Phase3**: **Facility upgrade** (Cyclotron, MAGNEX, beam line, …) to work with two orders of magnitude more intense beam
- **Phase4**: **Systematic experimental campaign** on all the systems with the upgraded facility

The Goals of the Research Program

Main goal (Holy Graal):

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

Secondary goals:



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

BY-PRODUCTS

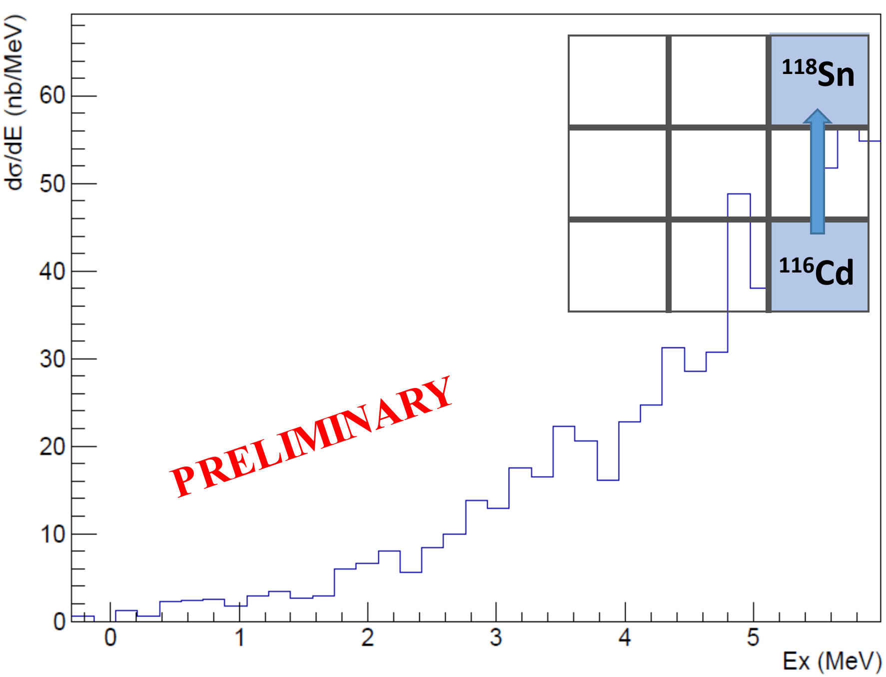
Results from a test run on ^{116}Cd (^{20}Ne,^{20}O)^{116}Sn

$\beta^-\beta^-$ direction

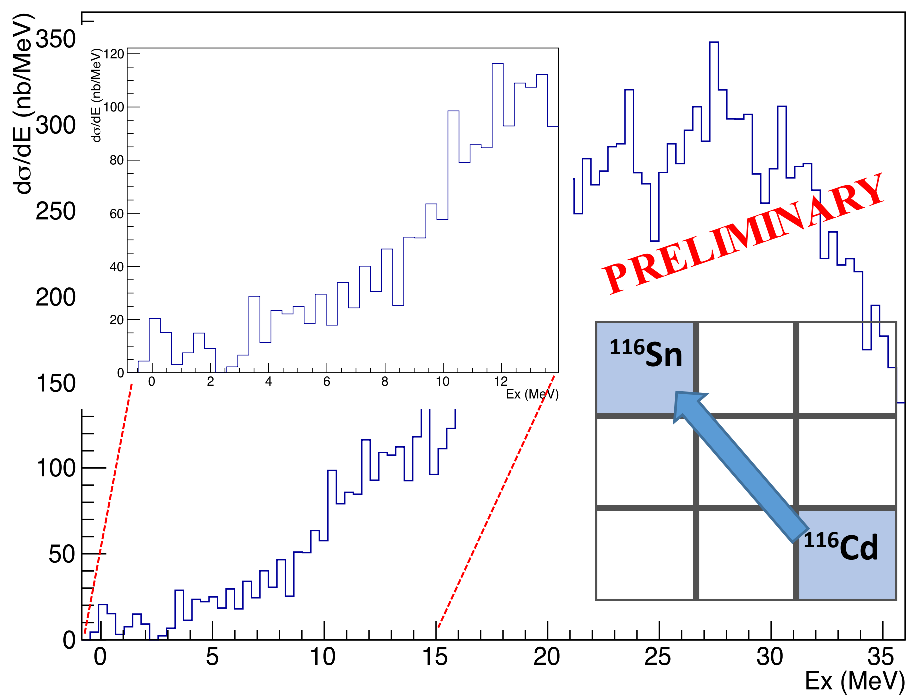
^{116}Cd, candidate nucleus for 0νββ

Multi-nucleon transfer suppressed compared to DCE (similarly to ^{40}Ca case)

^{116}Cd(^{20}Ne,^{18}O)^{118}Sn 15 MeV/u 0° < θ < 8°



^{116}Cd(^{20}Ne,^{20}O)^{116}Sn 15 MeV/u 0° < θ < 8°



Conclusions and Outlooks

- Many **experimental facilities** for $0\nu\beta\beta$ half-life, but not for the **NME**
- Pioneering experiments shown that **DCE cross sections can be suitably measured**
- First results for the (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) are encouraging, showing that **quantitative information on $0\nu\beta\beta$ NME** are not precluded
- **Experimental campaign** on nuclei candidates for $0\nu\beta\beta$ and work on the **theory** in the next 5 years
- The **upgrade** foreseen 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 $0\nu\beta\beta$

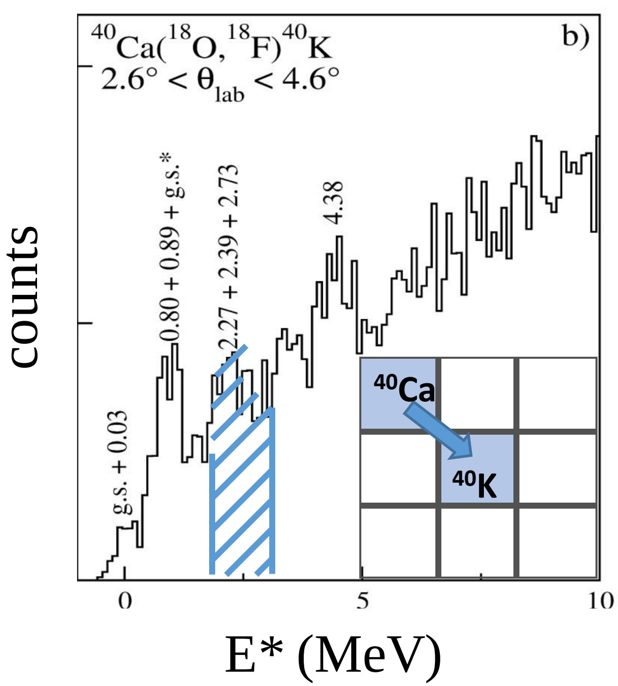

Thank you

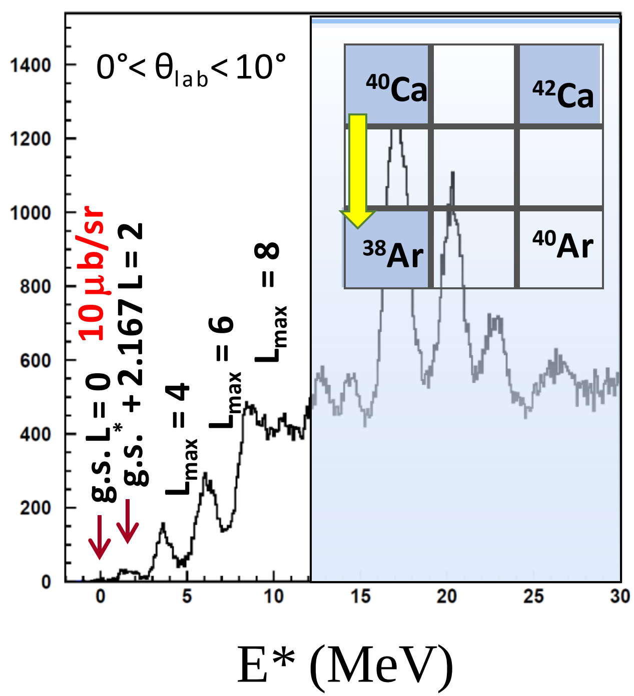
Measurement of the competing channels

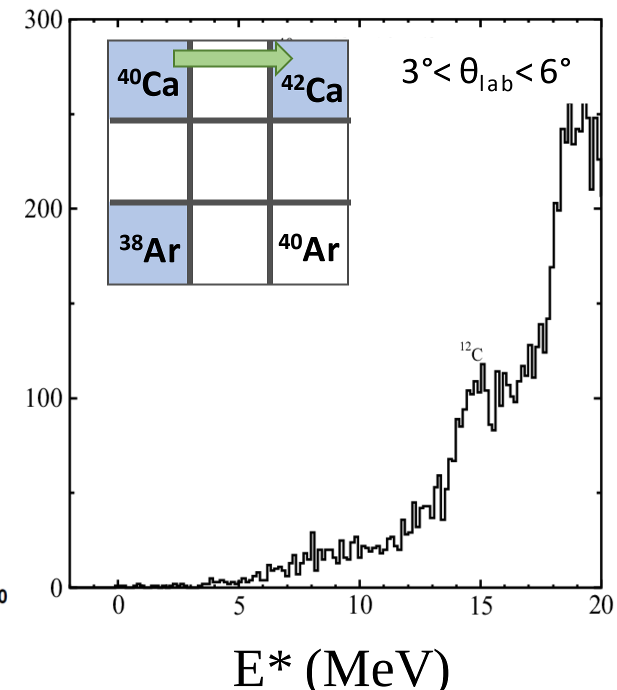
- Suppression of $L = 0$ (mismatch)
- The 2n-transfer from the high spin intermediate states to the 0^+ $^{40}Ar_{g.s.}$ is further reduced due to the vanishing Clebsch-Gordan

Less than 1% contribution to the DCE cross section

Single CEX	2p transfer	2n transfer
$^{40}Ca(^{18}O,^{18}F)^{38}K$	$^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$	$^{40}Ca(^{18}O,^{16}O)^{42}Ca$







Factorization of the charge exchange cross-section

for single CEX:

$$\frac{d\sigma}{d\Omega}(q,\omega) = \hat{\sigma}_\alpha(E_p, A) F_\alpha(q,\omega) B_T(\alpha) B_P(\alpha)$$

unit cross-section

universal property of nuclear response to F and GT probes

$$\hat{\sigma}(E_p, A) = K(E_p, 0)|J_{ST}|^2 N_{ST}^D$$

J_{ST} Volume integral of the V_{ST} potential

β-decay transition strengths (reduced matrix elements)

dependence on q and energy

generalization to DCE:

$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_\alpha^{DCE}(E_p, A) F_\alpha^{DCE}(q,\omega) B_T^{DCE}(\alpha) B_P^{DCE}(\alpha)$$

$$\hat{\sigma}_\alpha^{DCE}(E_p, A) = K(E_p, 0)\left|J'_{ST}\right|^2 N_{ST}^D$$

J'_{ST} Volume integral of the $V_{ST}GV_{ST}$ potential, where $G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$ is the intermediate channel propagator (including off-shell)

If the DCE factorization is valid and $\hat{\sigma}_\alpha^{DCE}$ is known, it would allow to determine the NME from DCE cross section measurement, whatever is the strenght fragmentation

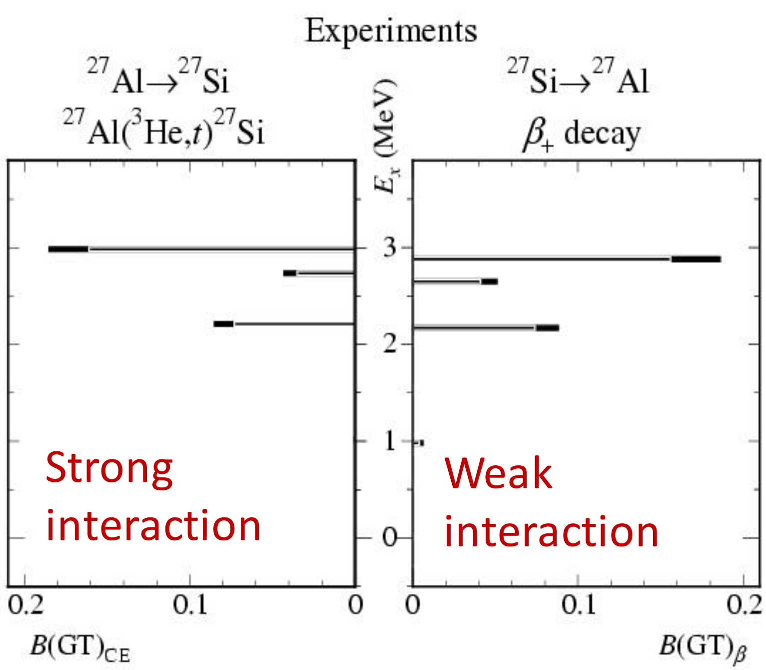
Connection between β-decay and Single CEX

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

- **For (p,n), (n,p), (d, ^{2}He)**

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

- **(^{3}He,t)** *Y. Fujita Prog. Part. Nuc. Phys. 66 (2011)*

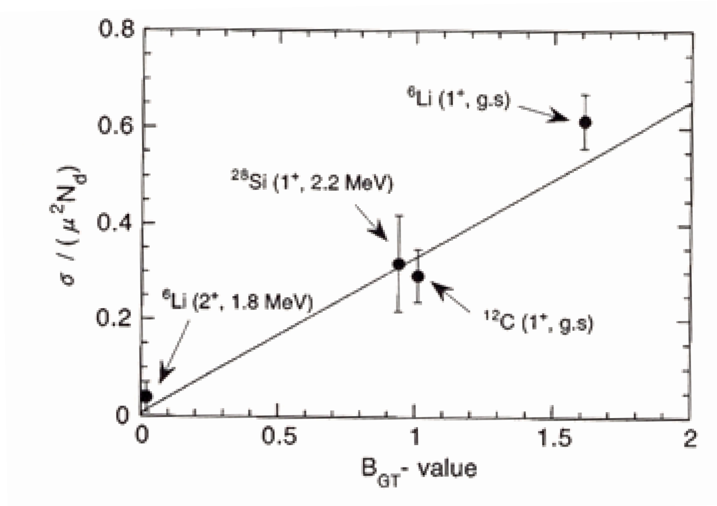


$$\frac{B(GT)_{[(3He,t);q=0]}}{B(GT)_{[\beta-decay]}} = 1 \pm 0.05$$

(In general for B(GT)>0.05)

Connection between β-decay and Single CEX

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



S. Nakayama PRC 60 (1999) 047303

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

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

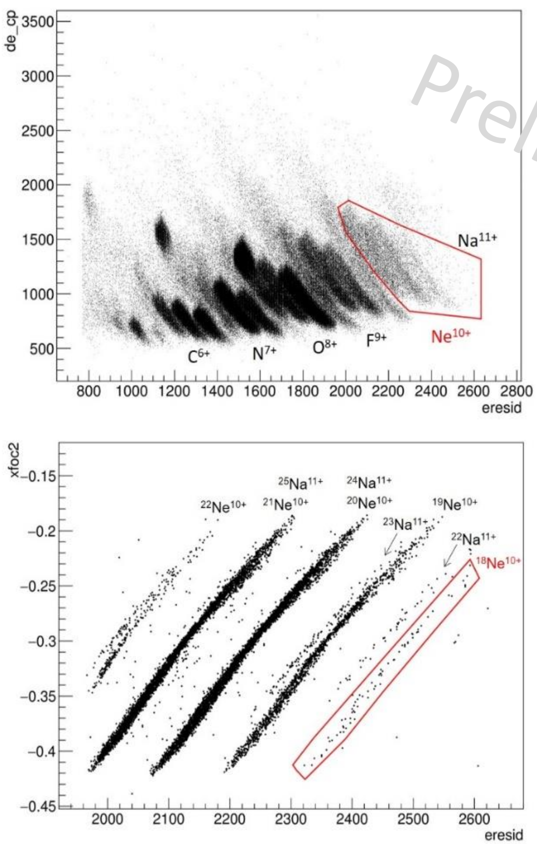
✓ **Microscopic and unified theory** of reaction and structure is mandatory for quantitative analyses

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

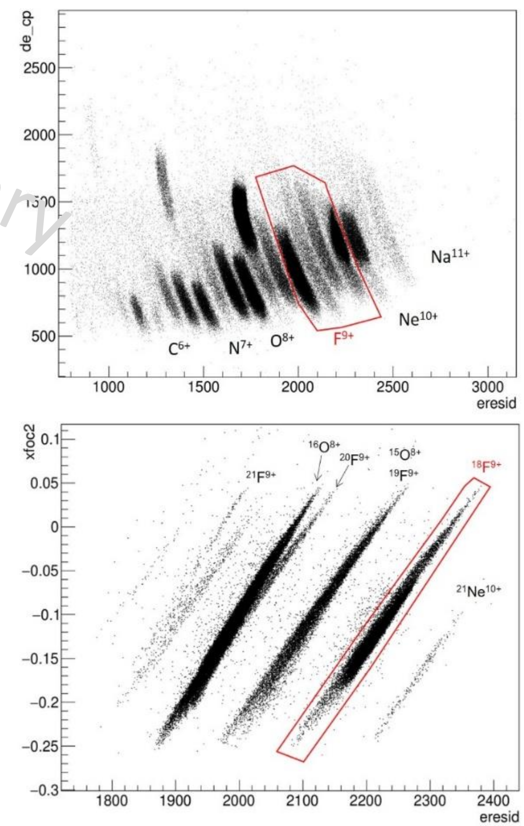
The experiment

$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ @ 15 MeV/u

- ✓ E_{beam}=15MeV/u, ^{116}Sn target thickness 323 μg/cm^2
- ✓ 2.7 mC integrated charge in 45 BTU
- ✓ Detector and beam transport performances studied up to 8 enA



Identification of the Ne Isotopes: ^{20}Ne(2p channel) and ^{18}Ne (DCEX)

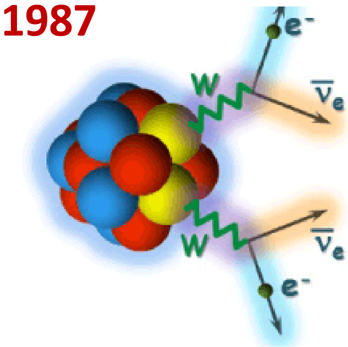


Identification of ^{18}F (CEX)

Double β-decay

Two-neutrino double beta decay

Observed in 11 isotopes since 1987

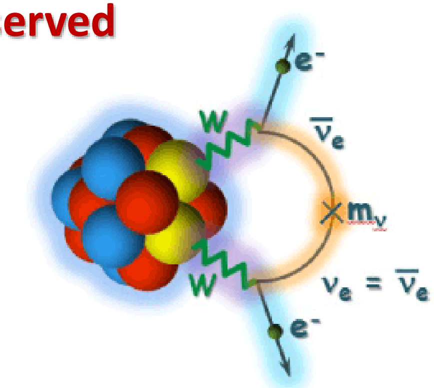


M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

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

Neutrinoless double beta decay

Still not observed



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

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

0νββ in case of process mediated by mass mechanism

(light neutrino exchange)
$m_{light} << 1$ keV

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

Effective neutrino Majorana mass

$$\langle m_k \rangle = \left|\sum_k |U_{ek}|^2 m_k e^{i\alpha k}\right|$$

Neutrino mixing matrix elements

neutrino masses

CP-violating Majorana phases

Cancellation of terms possible, so $\langle m_k \rangle$ could be smaller than m_k

0νββ in case of heavy neutrino exchange:

$$\left(\frac{m_p}{\langle m_{\nu(heavy)} \rangle}\right)$$

Cosmology: $M = \sum_k m_k = m_1 + m_2 + m_3$

β decay : $m_\nu = \sqrt{\sum_k |U_{ek}|^2 m_k}$

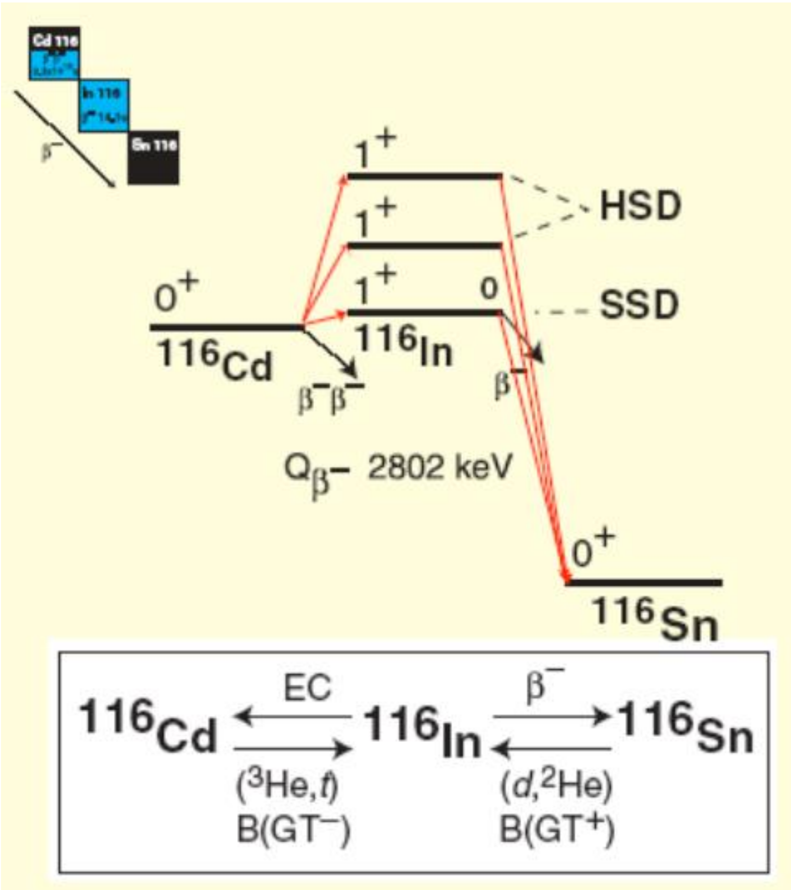
2νββ NMEs and experimental data

Transition amplitudes from single charge exchange (CEX) data

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

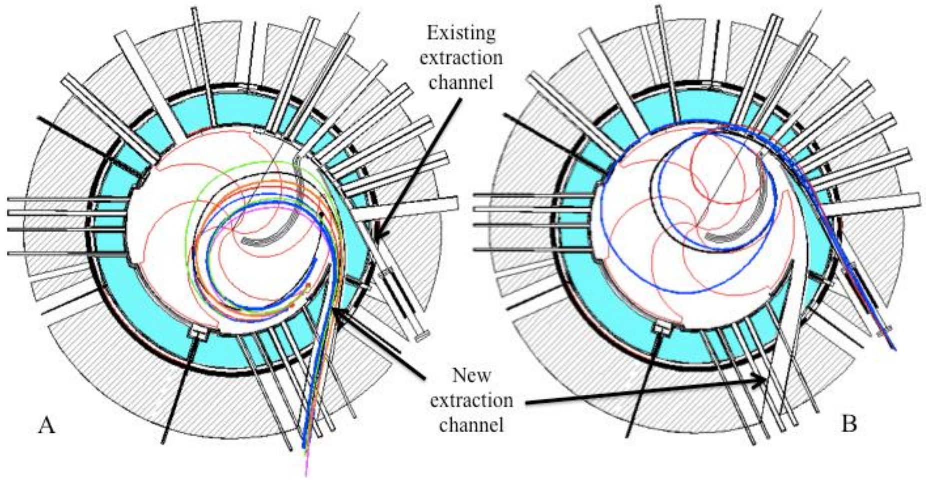
From CEX cross-sections, **transition probabilities** are extracted but **transition amplitudes** are required, so phases are necessary -> **single state dominance approximation** used

This is not possible in 0νββ



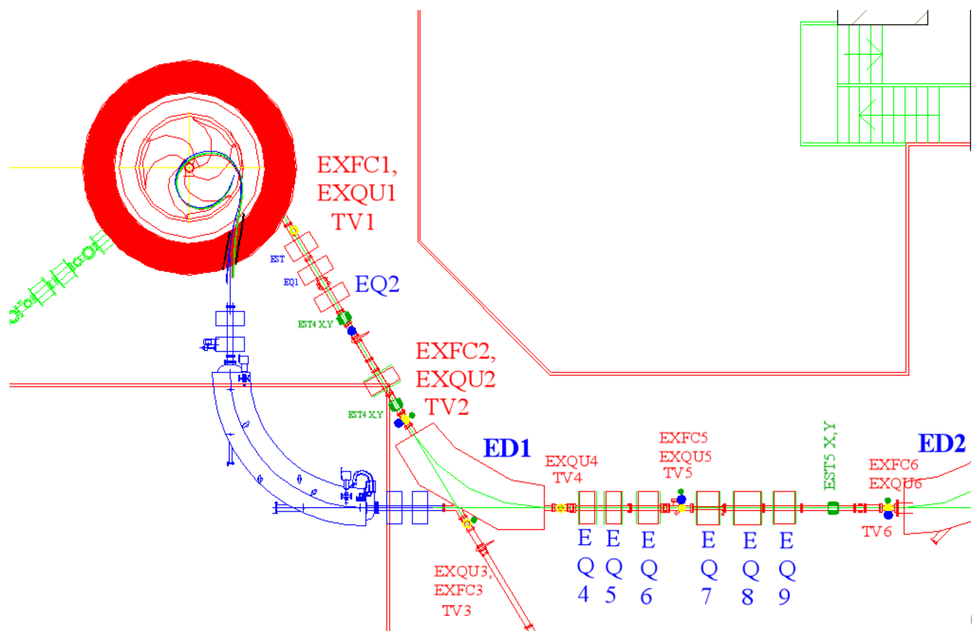
Major upgrade of LNS facilities: The CS accelerator

- The CS accelerator current (from 100 W to 5-10 kW);



From electrostatic extraction to Extraction by stripping

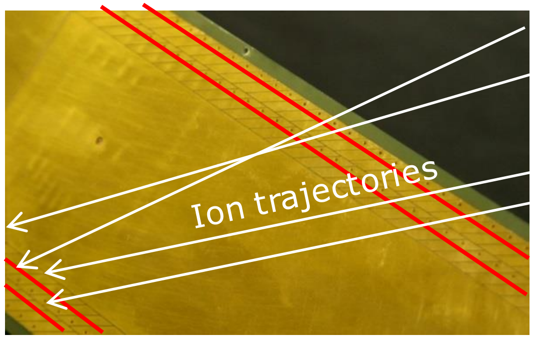
- The beam transport line transmission efficiency to nearly 100%



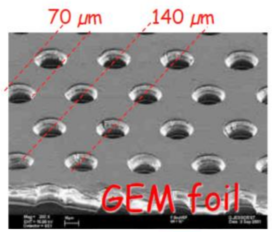
Major upgrade of LNS facilities: the MAGNEX spectrometer

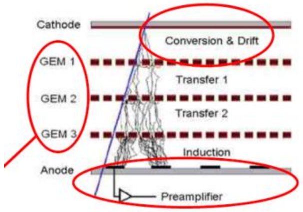
- The MAGNEX focal plane detector rate (from few kHz to MHz)

From multi-wire tracker



To micro-pattern tracker

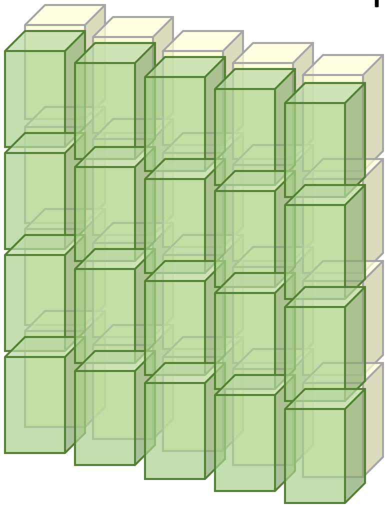




- R&D key issue : GEM-based tracker at low pressure and wide dynamic range
- INFN-LNS (M. Cavallaro), collaboration with INFN-CT, UNAM

From wall of 60 Si pad

To wall of 2500 SiC-SiC-SiC pad telescopes



A big challenge!

0.9 M€ call approved by INFN CSN5 (SICILIA)
P.I. S.Tudisco,
collaboration with
CNR, STM, FBK