F. Cappuzzello
Università di Catania and INFN LNS

The nuclear matrix elements of 0νββ decay and the NUMEN project at INFN-LNS

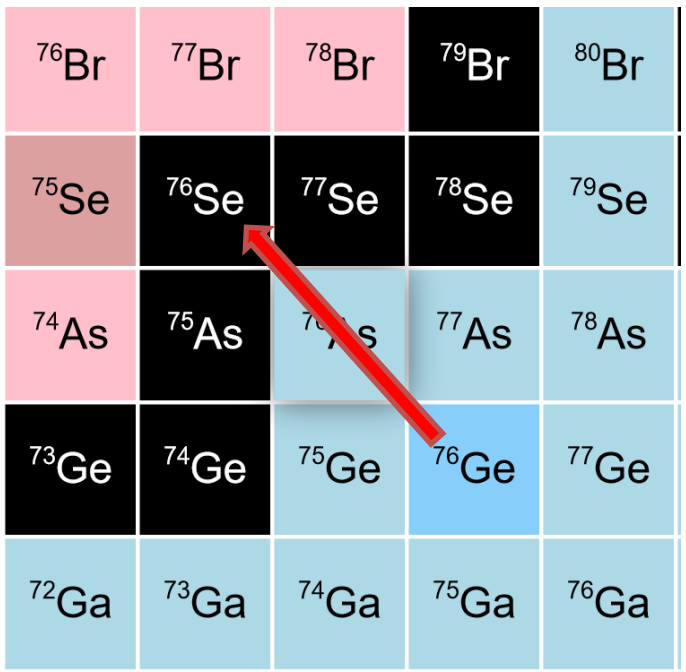
MEDEX'17 meeting "Matrix Elements for the Double beta decay EXperiments"

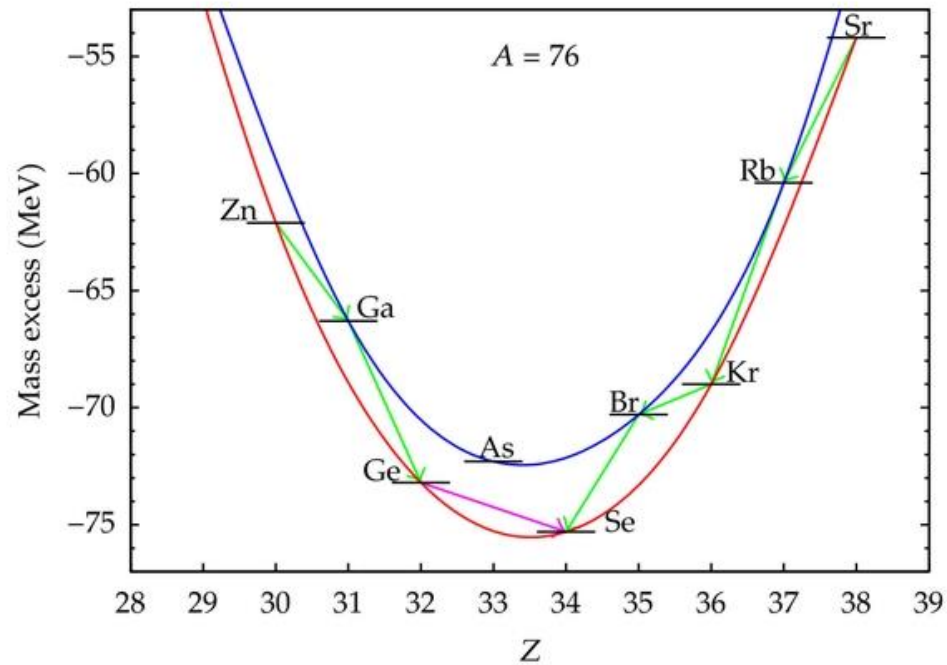
PRAGUE, May 29 - June 2, 2017

Physics case tutorial

Double β-decay

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



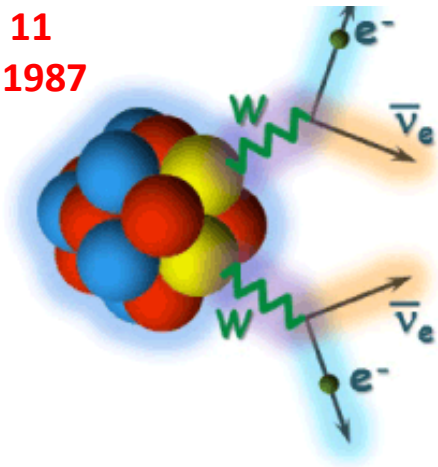


- ✓ Process mediated by the weak interaction observable in even-even nuclei where the single β-decay is energetically forbidden
- ✓ The role of the pairing force

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



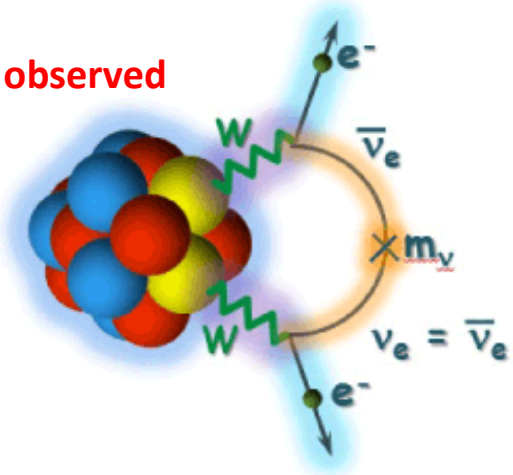
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

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

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

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**

$$1/T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2\left|\frac{\langle m_\nu \rangle}{m_e^4}\right|^2$$

Search for 0νββ decay. A worldwide challenge

List not complete…

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 (or others)	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	[China]

New physics for the next decades

but

requires

Nuclear Matrix Element (NME)!

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

- ✓ 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.

- ✓ Measurements (still not conclusive for $0\nu\beta\beta$):
  (π^+, π^-)
  single charge exchange (^{3}He,t), (d,^{2}He)
  electron capture
  transfer reactions
  muon nucleus scattering …

N. Auerbach, Ann. of Phys. 192 (1989) 77
S.J. Freeman and J.P. Schiffer JPG 39 (2012) 124004
D. Frekers, Prog. Part. Nucl. Phys. 64 (2010) 281
J.P. Schiffer, et al., PRL 100 (2008) 112501

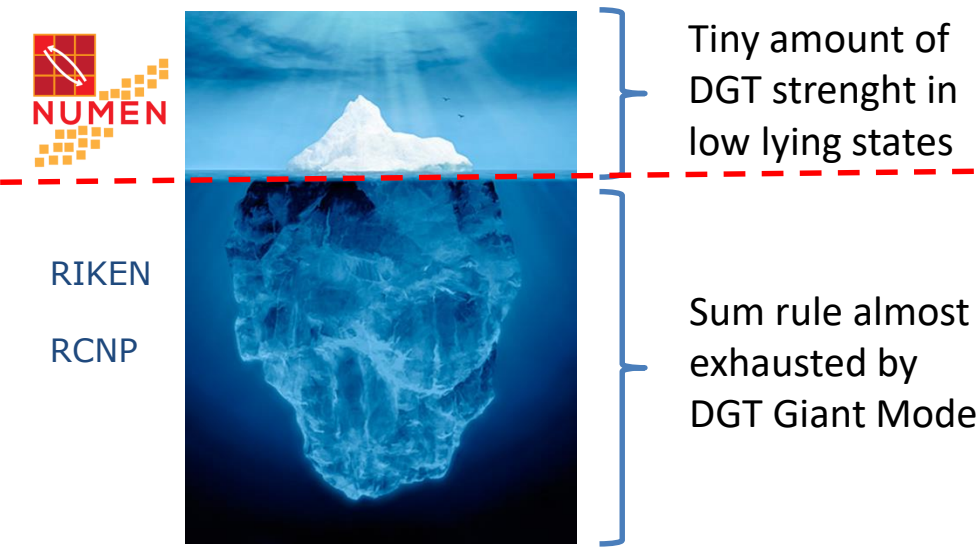
- ✓ A new experimental tool: heavy-ion Double Charge-Exchange (DCE)

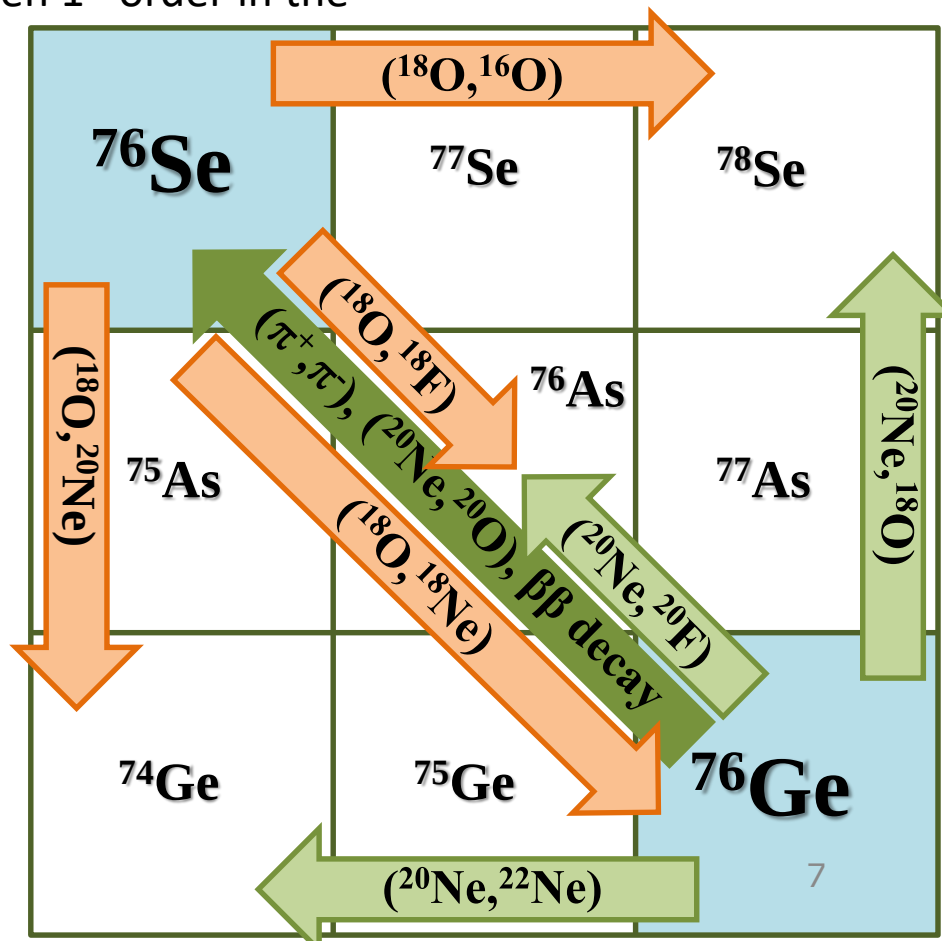
Heavy-ion DCE as surrogate processes

- ✓ 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 or even 1st order in the nucleus-nucleus potential
- ✓ Possibility to go in both directions





0νββ vs HI-DCE

Differences

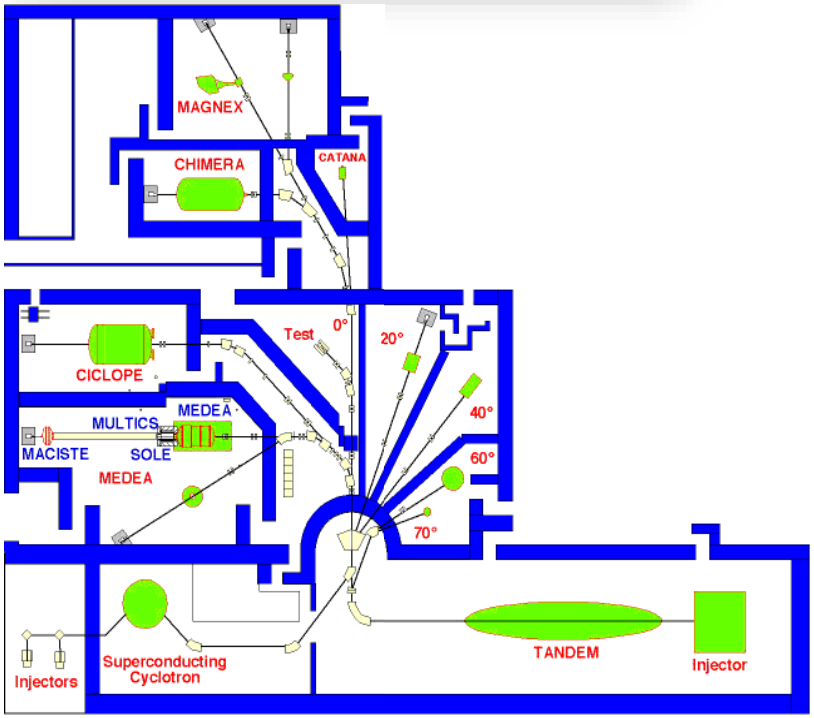
- DCE mediated by **strong interaction**, 0νββ by **weak interaction**
- DCE includes **sequential** transfer **mechanism**

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:** 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

DCE @ INFN-LNS

The LNS laboratory in Catania



Superconducting Cyclotron and MAGNEX spectrometer @ LNS

crucial for the experimental challanges

K800 Superconducting Cyclotron

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

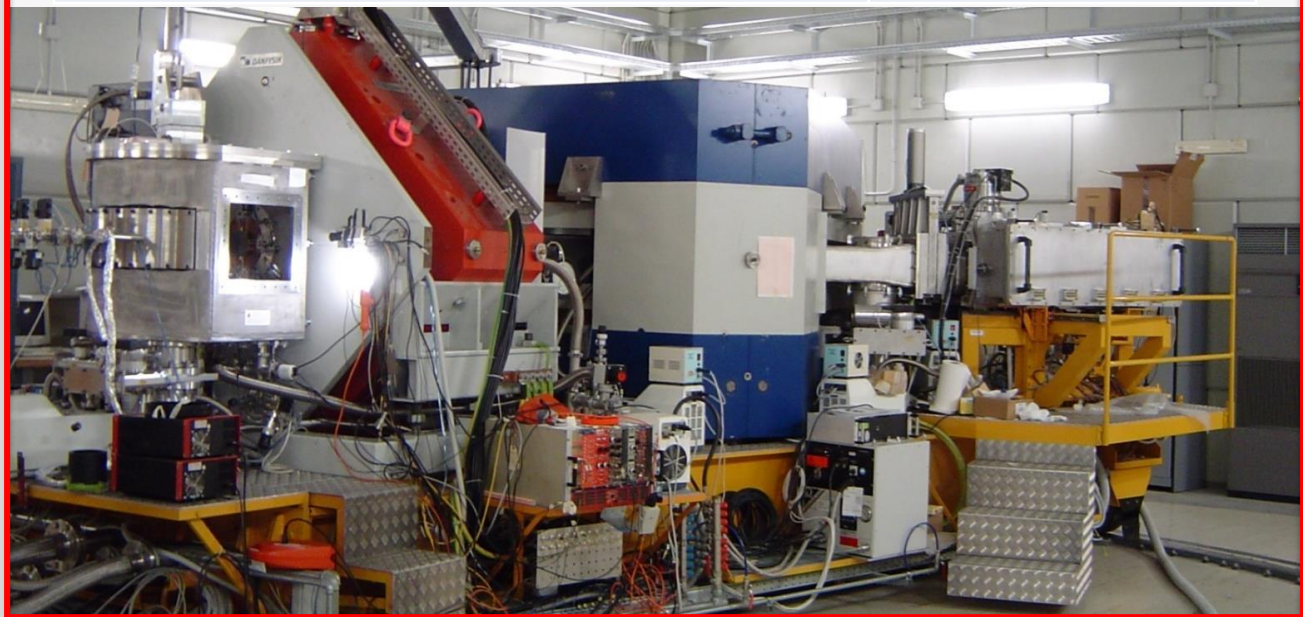
MAGNEX spectrometer

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

Achieved resolution

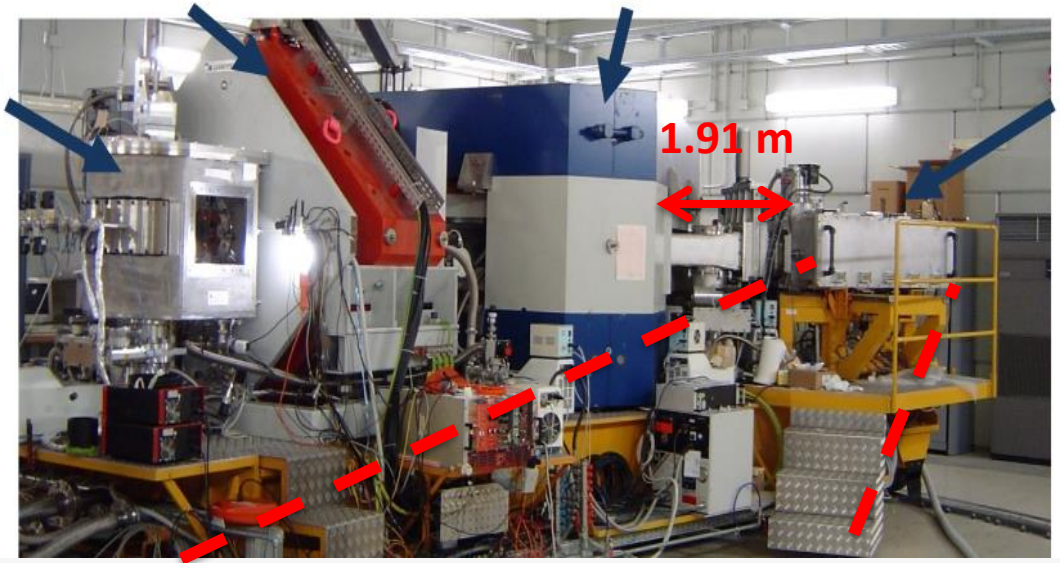
Energy **$\Delta E/E \sim 1/1000$**
Angle **$\Delta\theta \sim 0.2^\circ$**
Mass **$\Delta m/m \sim 1/160$**

Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68



The MAGNEX FPD

M. Cavallaro et al., Eur. Phys. J. A (2016) 48: 59

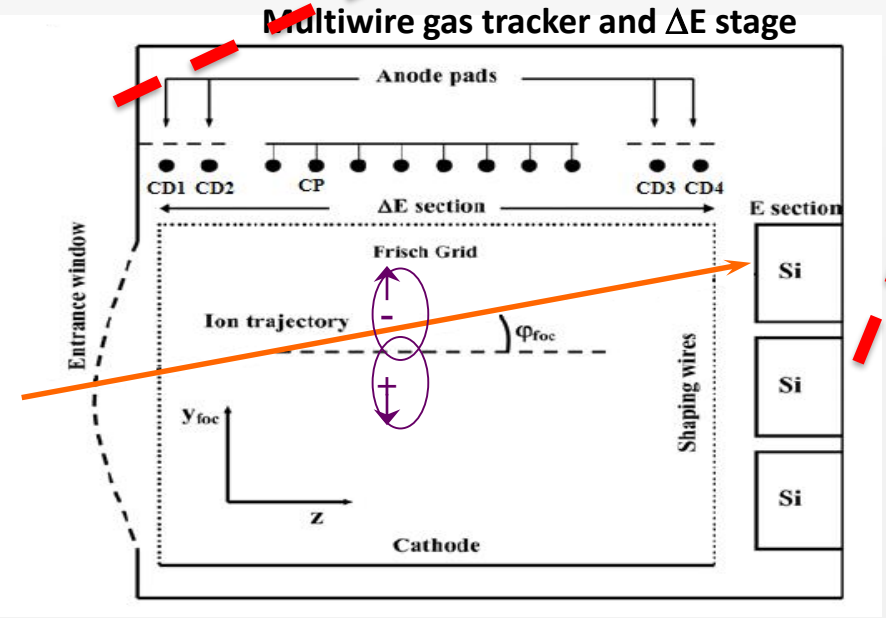


active area **140 x 20 cm²**

Ionization drift chamber, five independent proportional counters, four of which are position-sensitive and a **wall** of **stopping silicon detectors**

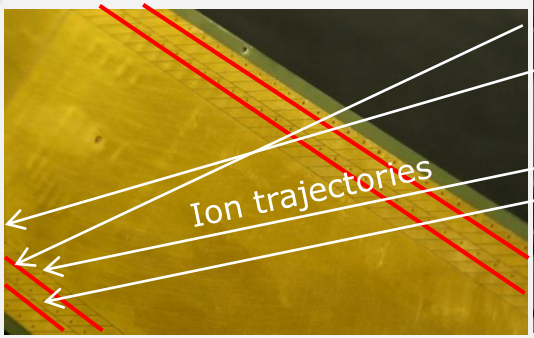
Pure isobutane; pressure range: 5-100 mbar; 600-800 V, wires ϕ =20 μm

Multiwire gas tracker and ΔE stage



Wall of 60 stopping 7 X 5 cm² Silicon detectors

View of the stripped anode

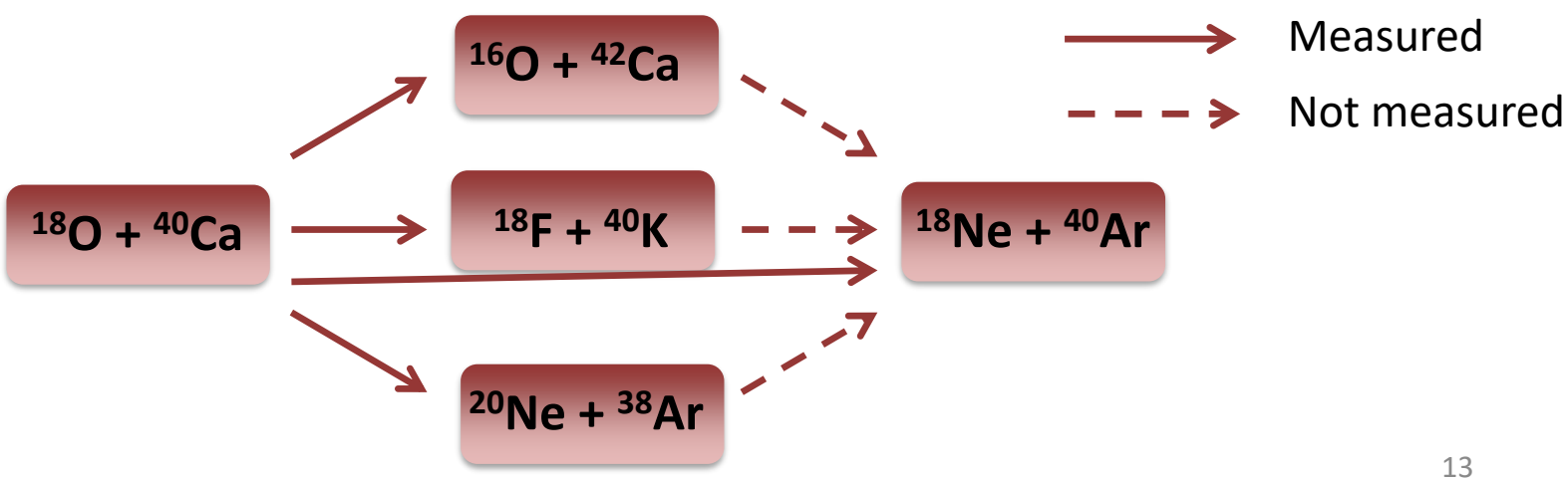


(^{18}O,^{18}Ne) DCE reactions at LNS

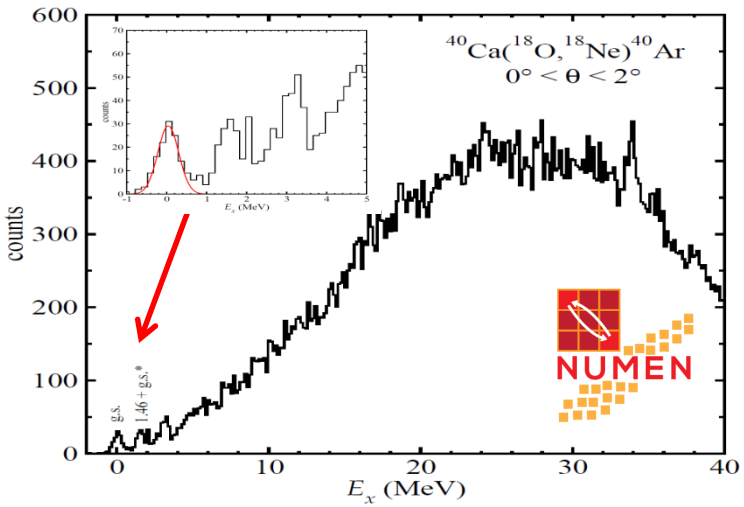
^{40}Ca(^{18}O,^{18}Ne)^{40}Ar @ 270 MeV

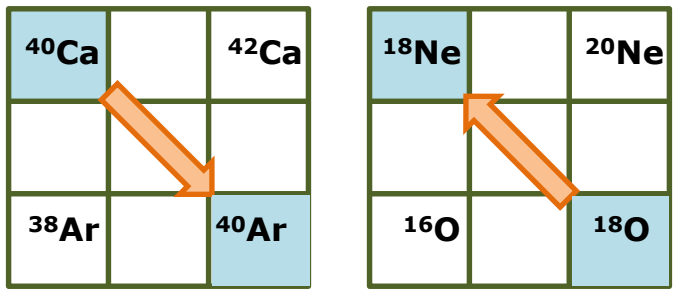
First pilot experiment

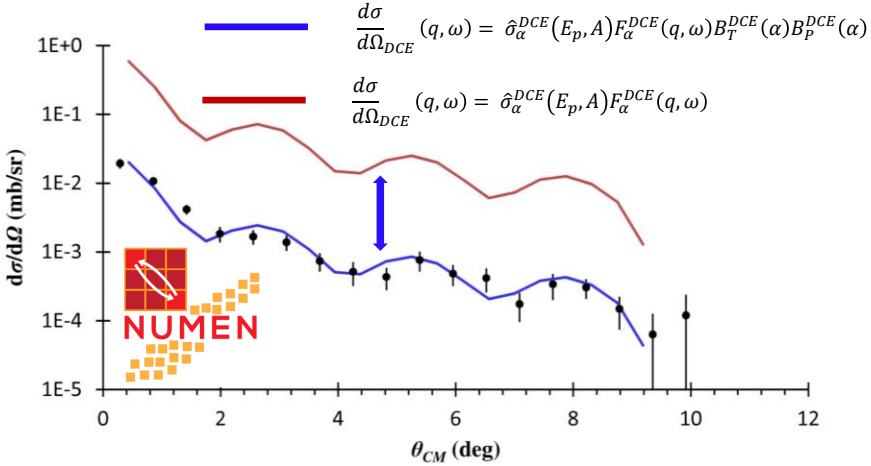
- $^{18}O^{7+}$ beam from Cyclotron at **270 MeV (10 pnA, 3300 μC in 10 days)**
- **^{40}Ca** solid target 300 μg/cm^2
- Ejectiles detected by the MAGNEX spectrometer ($0° < \vartheta_{lab} < 10°$)
- Unique angular setting: $-2° < \theta_{lab} < 10°$ corresponding to a momentum transfer range **from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

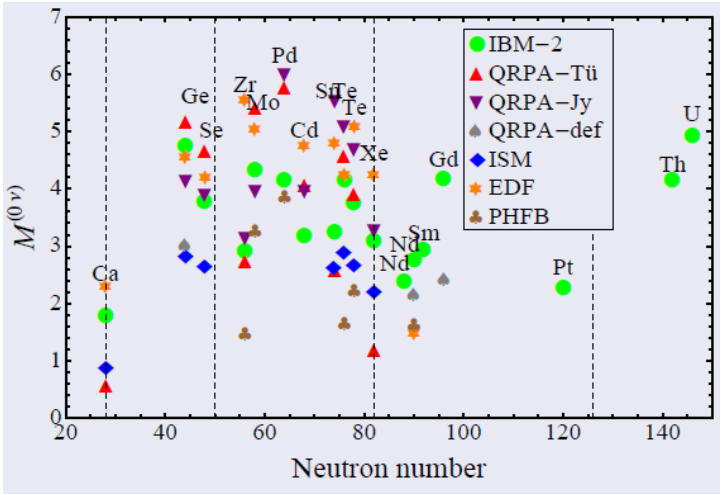


$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV









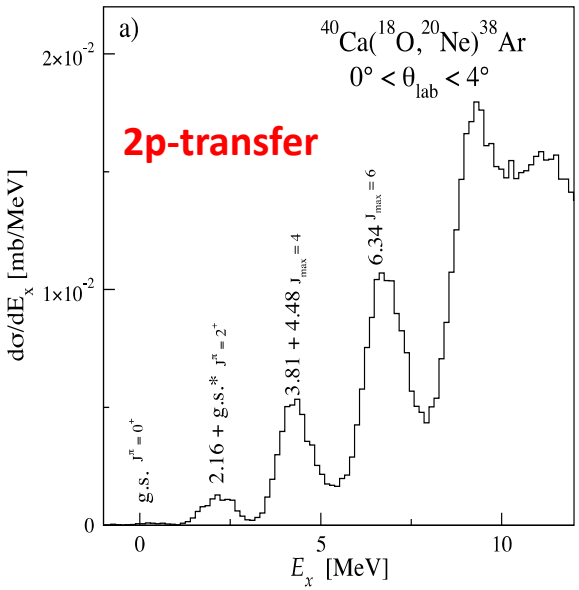
$$\left|M_{\sigma\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 0.24 \pm 0.12$$

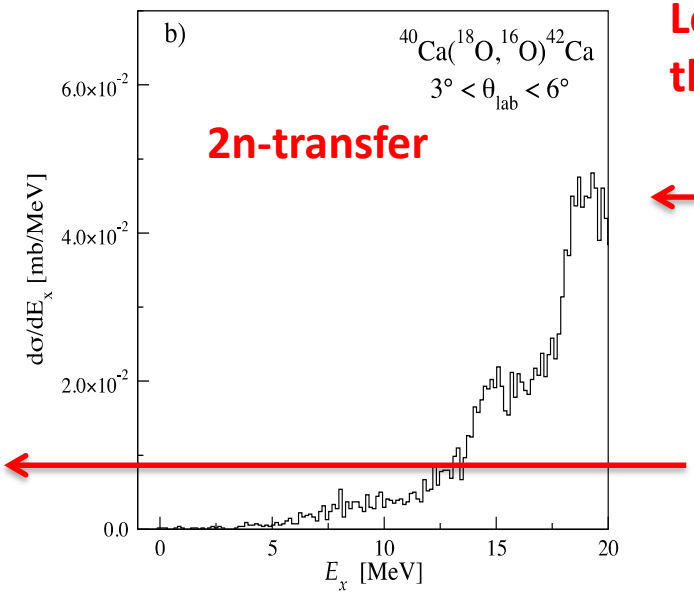
$$\left|M_{\tau}^{DCE}\left(^{40}Ca\right)\right|^2 = 0.22 \pm 0.11$$

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

Pauli blocking about 0.14 for F and GT

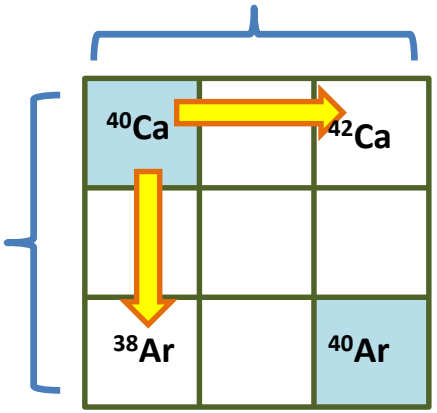
The role of the transfer reaction and the competing processes



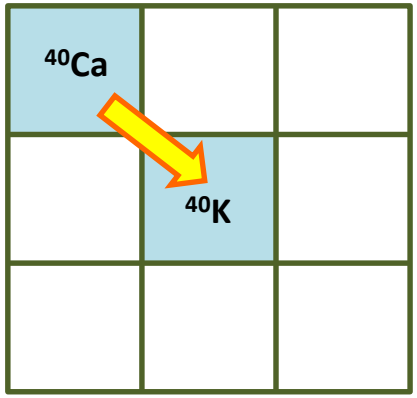


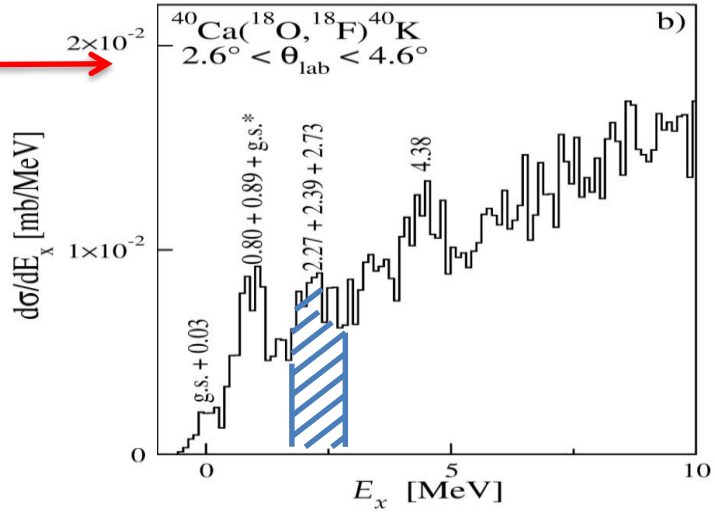
Less than 1% effect in the DCE cross section

Very weak



single charge exchange





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

Extracted B(GT) = 0.087

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

Moving towards hot-cases:

Caveat

- The reaction Q-values are normally more negative than in the ^{40}Ca case
- The (^{18}O,^{18}Ne) reaction is particularly advantageous, but it is of $\beta^+\beta^+$ kind;
- None of the reactions of $\beta^-\beta^-$ kind looks like 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 will be necessary, e.g. ^{136}Xe or ^{130}Xe
- In some cases the energy resolution is not enough to separate the g.s. from the excited states in the final nucleus $\rightarrow$ Coincident detection of γ-rays

Much higher beam current is needed

The NUMEN project

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

Proponents: C. Agodi, J. Bellone, S. Bianco, D. Bonanno, D. Bongiovanni, V. Branchina, M.P. Bussa, L. Busso, S. Calabrese, L. Calabretta, A. Calanna, D. Calvo, F. Cappuzzello, D. Carbone, M. Cavallaro, M. Colonna, G. D'Agostino, N. Deshmukh, C. Ferraresi, P. Finocchiaro, M. Fisichella, A. Foti, G. Gallo, U. Garcia, G. Giraudo, V. Greco, Z.J. Kotila, F. Iazzi, R. Introzzi, G. Lanzalone, A. Lavagno, F. La Via, J.A. Lay, G. Litrico, F. Longhitano, D. Lo Presti, A. Muoio, L. Pandola, F. Pinna, F. Pirri, S. Reito, D. Rifuggiato, A.D. Russo, G. Russo, G. Santagati, E. Santopinto, D. Torresi, S. Tudisco, R.I.M. Vsevolodovna, R.J. Wheadon

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Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
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University of Giessen, Germany

E. Aciksoz, I. Boztosun, A. Hacisalihoglu, S.O. Solakcı

Akdeniz University, Antalya, Turkey

N. Auerbach

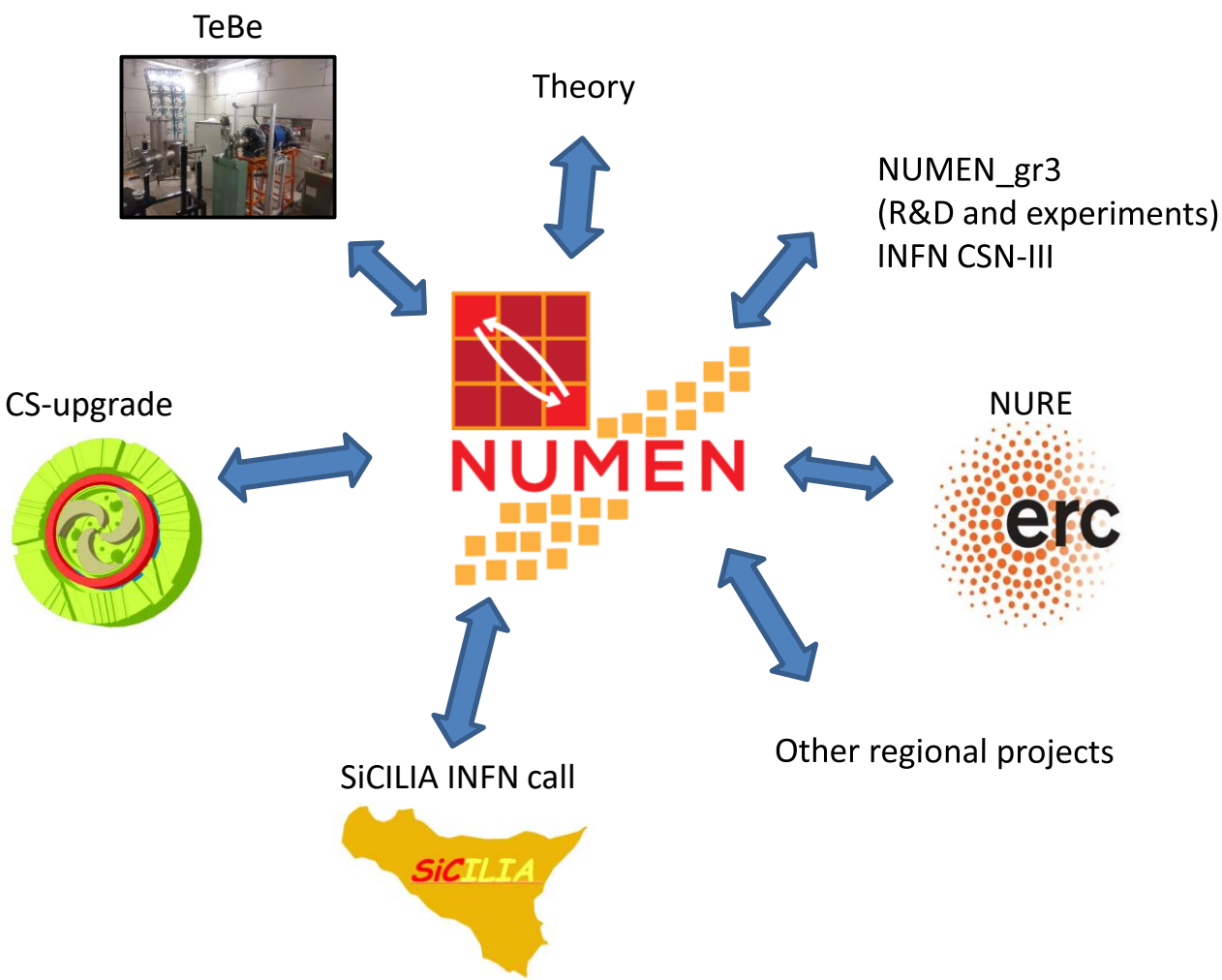
School of Physics and Astronomy Tel Aviv University, Israel

H. Petrascu,

IFIN-HH, Bucarest, Romania

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

A broad view


TeBe
Theory
NUMEN_gr3
(R&D and experiments)
INFN CSN-III
CS-upgrade
NUMEN
NURE
erc
Other regional projects
SiCILIA INFN call
SiCILIA

NUMEN

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**

The Goals of the Research Program

Main goal (Holy Grail):

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
- Model-independent comparative information on the sensitivity of half-life experiments
- Complete study of the reaction mechanism

Status and perspectives of NUMEN

The Phases of NUMEN project

- **Phase1**: The experimental feasibility
- **Phase2**: "hot" cases optimizing the experimental conditions and getting first results (approved)
- **Phase3**: The facility Upgrade (Cyclotron, MAGNEX, beam lines, ...)
- **Phase4** : The systematic experimental campaign

Time table

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

Recent NUMEN experiments

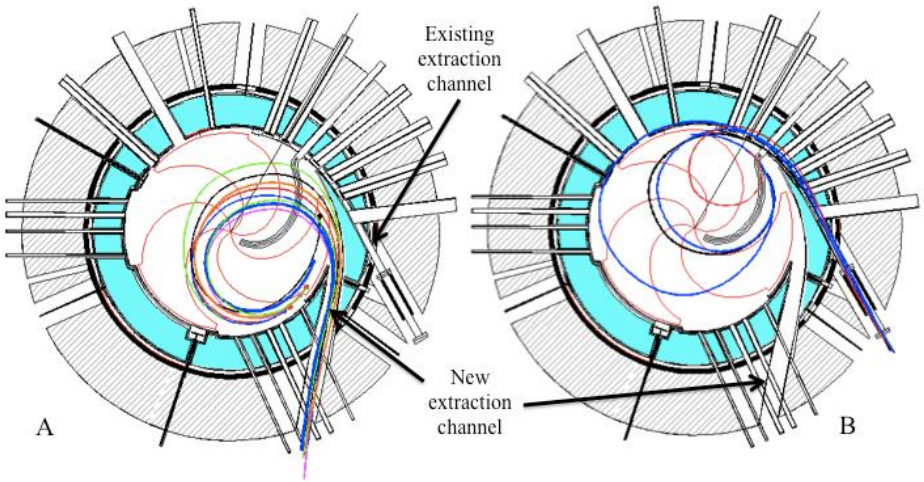
Facing some hot cases in Phase 2

		2016				2017				2018			
Reaction	**Energy (MeV/u)**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
^{116}Sn (^{18}O,^{18}Ne) ^{116}Cd	15-30	**Exp**											
^{116}Cd (^{20}Ne,^{20}O) ^{116}Sn	15-25		**Test**		**Exp**		**Running**						
^{130}Te (^{20}Ne,^{20}O) ^{130}Xe	15-25						**Running**		**Exp**				
^{76}Ge (^{20}Ne,^{20}O) ^{76}Se	15-25												
^{76}Se (^{18}O,^{18}Ne) ^{76}Ge	15-30												
^{106}Cd(^{18}O,^{18}Ne) ^{106}Pd	15-30												

Recent NUMEN R&D

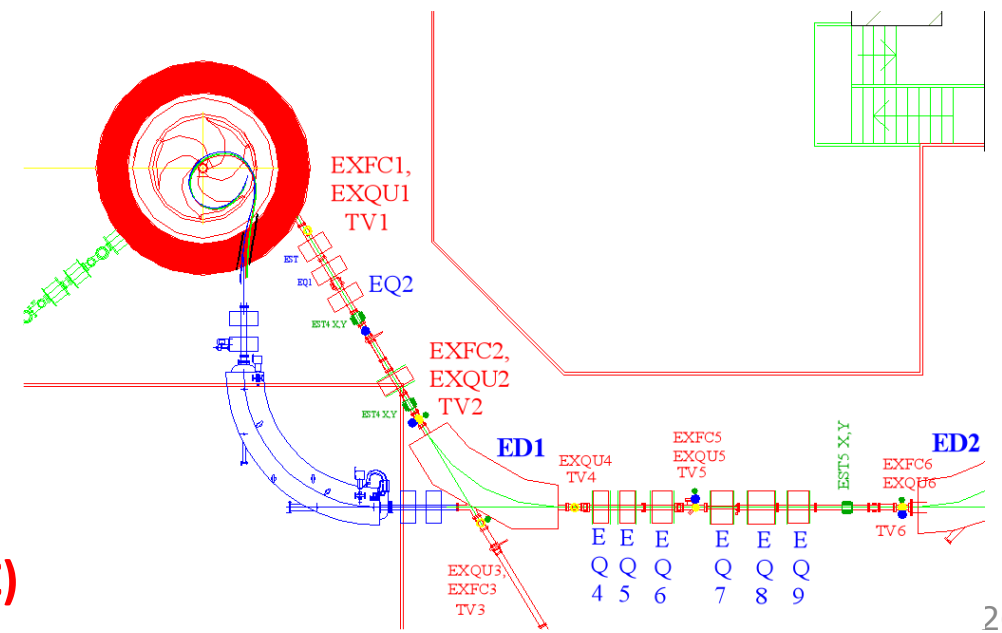
Major upgrade of LNS facilities: The CS accelerator

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



Extraction by stripping

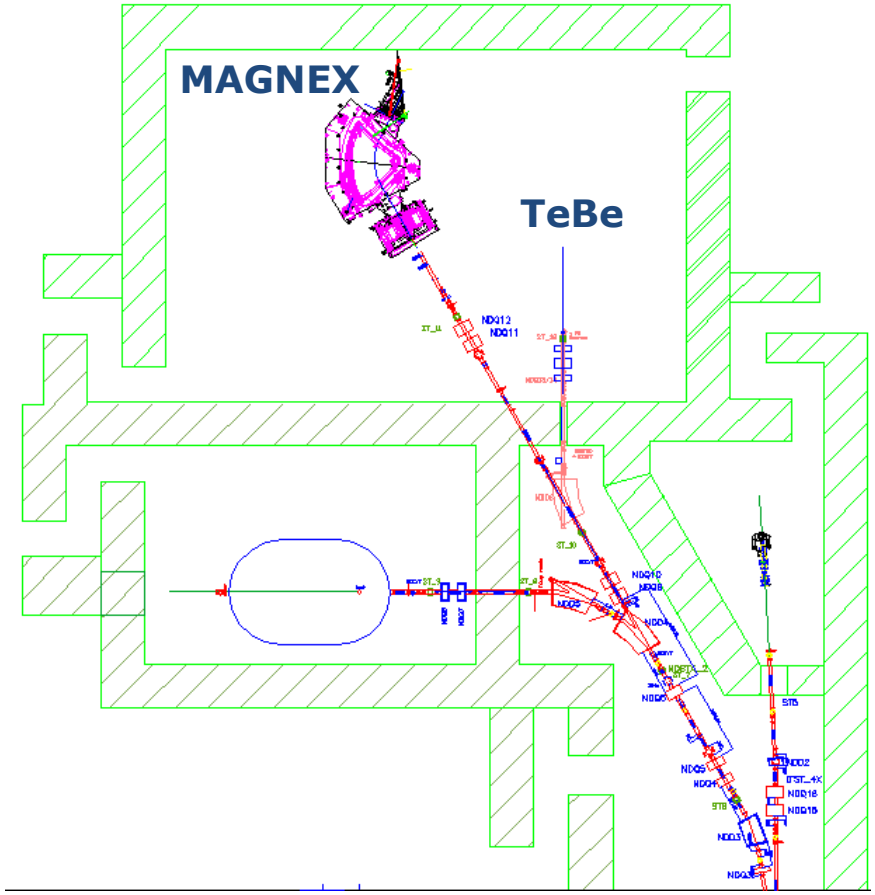
- The **beam transport line** transmission efficiency to nearly 100%



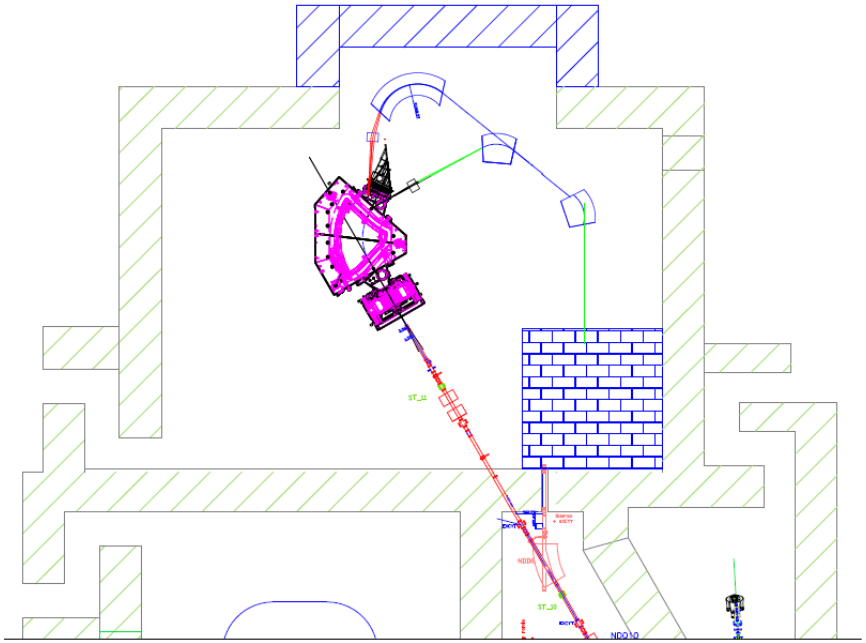
TDR of the project approved
Cryostat tender started (~4.1M€)

A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

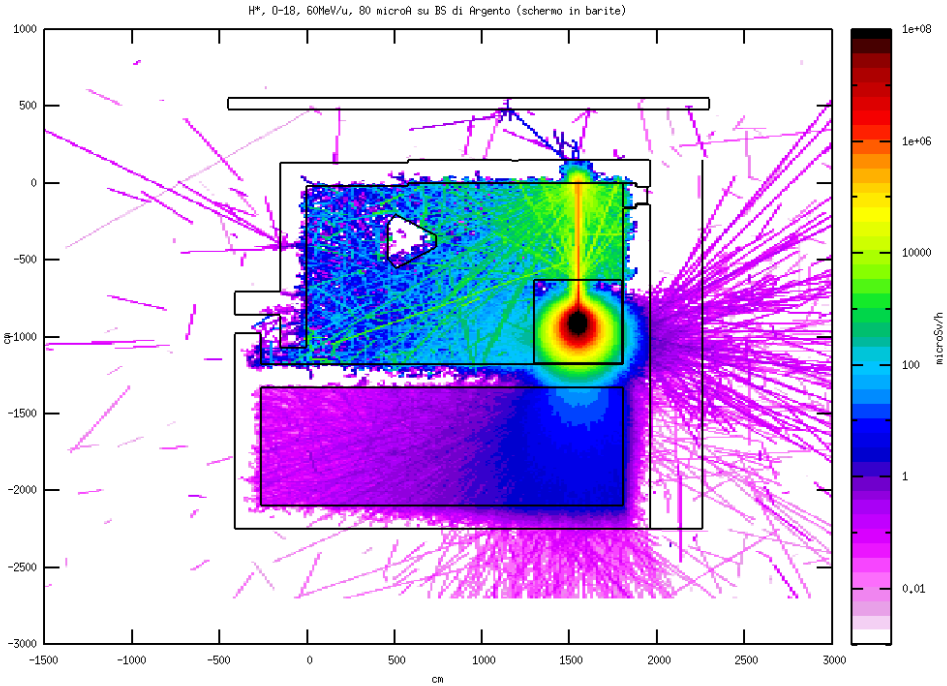


Future MAGNEX hall

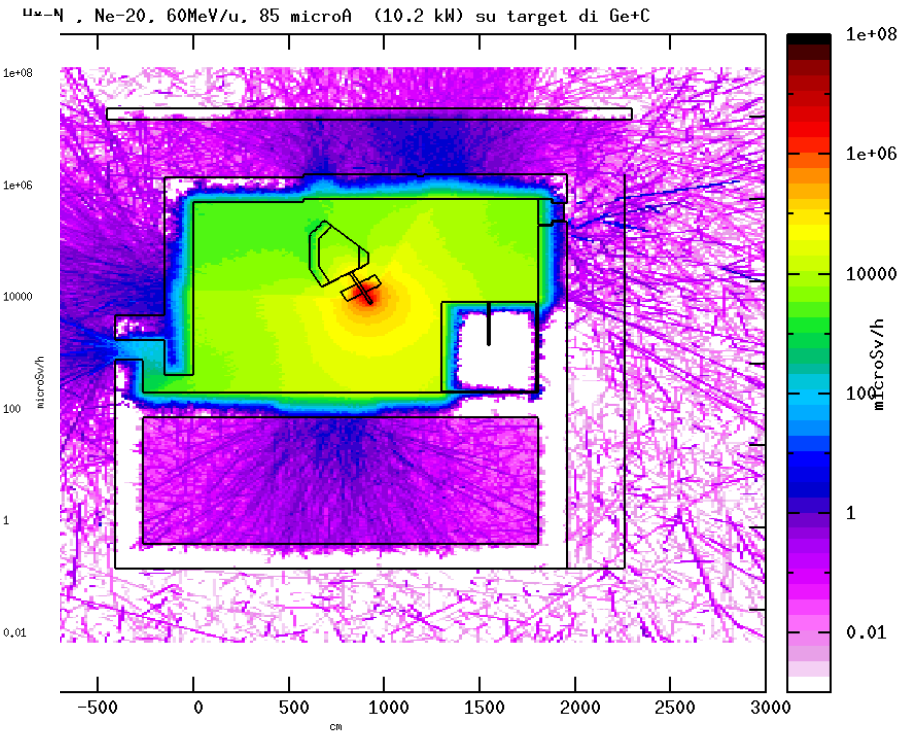


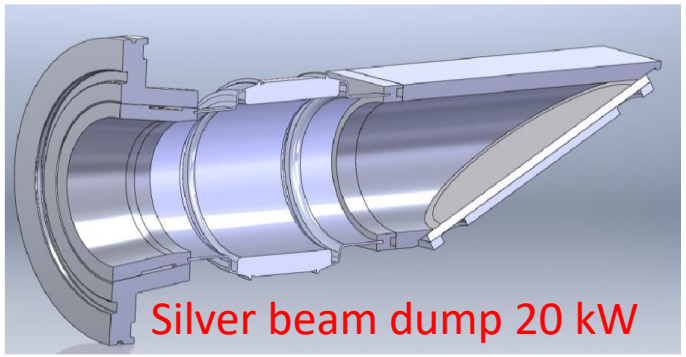
A challenging beam dump inside the MAGNEX hall

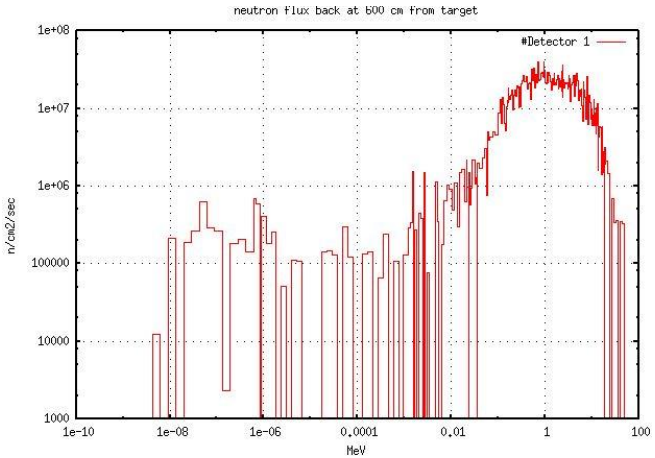
85 μA beam of ^{18}O on Ag



85 μA beam of ^{20}Ne on $^{76}Ge+C$







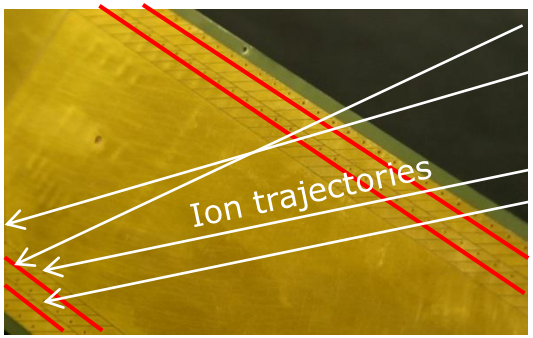
From S.Russo (LNS radioprotection service)

The new focal plane detector

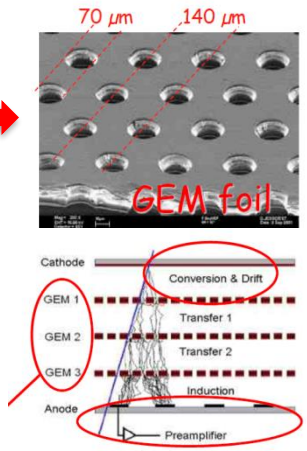
Major upgrade of LNS facilities: MAGNEX

- The **MAGNEX focal plane** detector rate (from 2 kHz to several MHz)

From multi-wire tracker



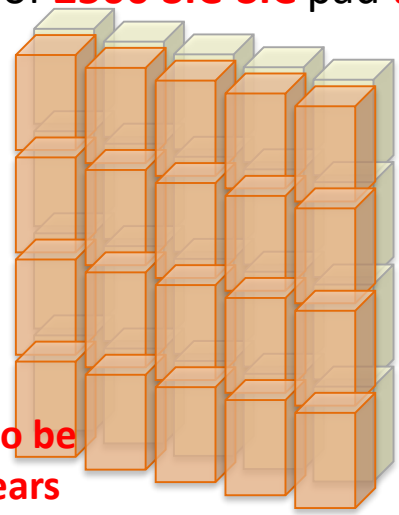
To micro-pattern tracker



- **R&D key issue : MPGD-based tracker at low pressure and wide dynamic range**
- **INFN-LNS, collaboration with INFN-CT, UNAM, MSU**

From wall of **60** Si pad

To wall of **2500 SiC-SiC** pad **telescopes**



About 10^{14} ions to be collected in 10 years

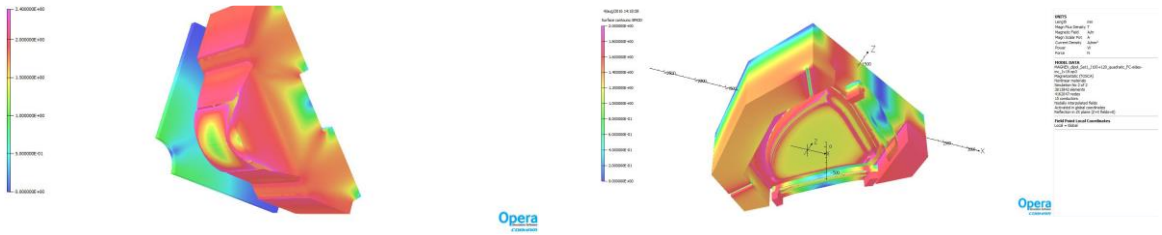
A big challenge!

Call approved by INFN CSN5 (SICILIA)

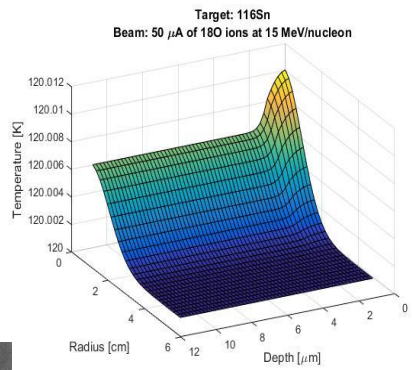
collaboration with CNR, STM, FBK

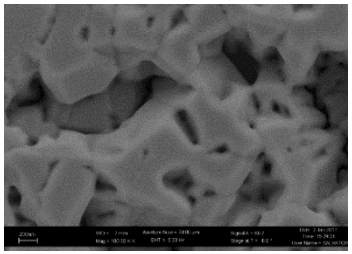
Other upgrades

- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)



- The **target** technology for intense heavy-ion beams





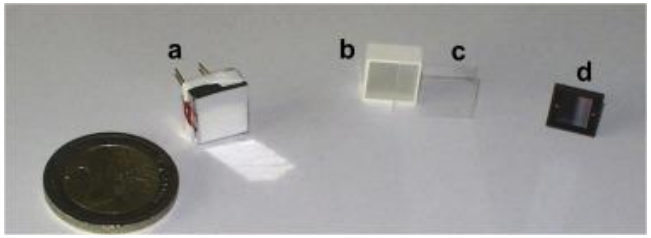
- An **array of scintillators for γ-rays** measurement in coincidence with MAGNEX

Other upgrades

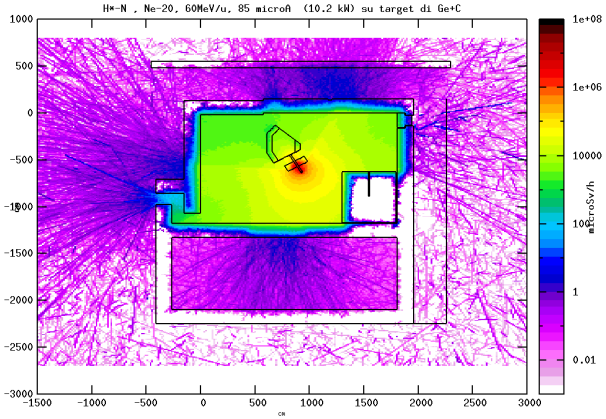
Electronics for very high rate

A new test bench facility for detector developments

Plan_B for particle identification



Simulations



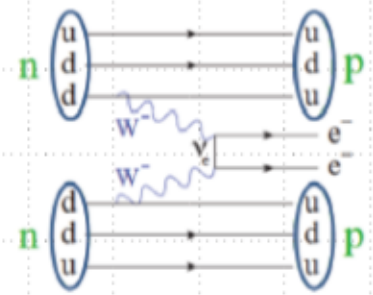
- Data Acquisition
- Irradiation tests
- Data Reduction

Development of theory

- **One of the three pillars of NUMEN** (formal development and calculations)

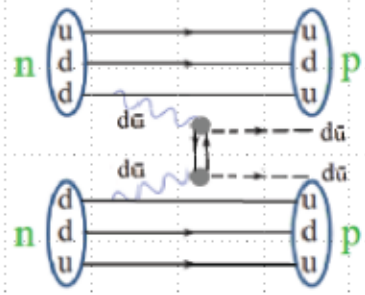
Weak Interaction 0ν2β decay and Strong Interaction Analogue

weak 0ν2β decay



- simultaneous d→u Δq=+1 transitions by emission of a virtual weak gauge boson W^-
- $W^- \rightarrow e^- + \bar{\nu}_e / \nu_e$: decay into electron and Majorana neutrino
- Correlation of the two events by exchange of the virtual $\nu_e \bar{\nu}_e$ pair
- Emission of two electrons ON their mass-shell: $p^2_e = m^2_e$
- Direct observation (GERDA@LNGS...)

Hadronic analogue



- simultaneous d→u Δq=+1 transitions by emission of a virtual $d\bar{u}$ vector pair ↔ ρ^- meson
- $\rho^- \rightarrow \pi^- + \pi^0$: decay into a pair of pions
- Heavy vector mesons ρ^{-*}
- Correlation of the two events by exchange of the virtual $q\bar{q}$ pair as contained in $\pi^0 \cong (d\bar{d}+u\bar{u})/\sqrt{2}$
- Emission of two π^- OFF their mass-shell: $p^2_\pi \neq m^2_\pi$
- No direct observation

H. Lenske, Genova, May, 2017 30

Conclusions and Outlooks

- **NUMEN represents a challenging perspective** for the future of LNS in nuclear science
- **The project** turns around the MAGNEX and the Cyclotron upgrade toward high intensity
- **Results** of relevance for $0\nu\beta\beta$ physics already got in **the initial campaigns**
- **A big challenge for nuclear technology and nuclear theory**

Conference on Neutrinos and Nuclear Physics (CNNP2017)

15-21 October 2017
Catania (Italy)

http://agenda.infn.it/event/CNNP2017

Registration open

Scientific topics:

- Nuclear double β decays
- Nuclear structure in connection with ν physics
- Nuclear reactions as a probe for weak decays
- Neutrino-nucleus interactions at low and high energy
- Supernova models and detection of supernova ν
- Solar models and detection of solar ν
- Direct and indirect dark-matter searches
- Rare β decays for neutrino-mass measurements
- Neutrino oscillations and matter effects
- Anomalies in reactor ν
- New related detection technologies

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