Status of the NUMEN project

F. Cappuzzello
Università di Catania and INFN LNS

Quick historical background of NUMEN

The starting point

- ❖ In 2003 (^{14}C,^{14}O) and (^{18}O,^{18}Ne) reactions proposed for MAGNEX as a qualifying research program of exotic nuclei with Tandem beams

- ❖..the production of a ^{14}C beam is of paramount importance for the evolution of experiment at LNS ....

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Sud

Catania, 10.10.2003

Letter of intent for ^{14}C Tandem beam at the LNS

A.Cunsolo, F.Cappuzzello, A.Foti, A.Lazzaro, C.Nociforo, S.E.A.Orrigo, J.S.Winfield, M.Allia

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S.Gales, S.Fortier and IPN-Orsay collaborators

Institut de Physique Nucléaire, IN2P3-CNRS, Orsay Cedex, France

H.Lenske

Institut für Theoretische Physik, Universität Giessen, Giessen, Germany

Two-body reactions are essential tools to study the structure of nuclei [1]. Spectroscopic information regarding the ground as well as the excited states are accessed in a consistent manner, thus giving stringent conditions to nuclear structure theories. These information are better accomplished if highly monochromatic beams such as Tandem Van de Graaff ones are accelerated and magnetic spectrographs are used for the detection of the ejectiles. Unfortunately the drastic reduction of reaction cross sections with increasing number of transferred nucleons and, consequently, high negative reaction Q-values, limits this approach to the exploration of systems not too far from the stability. Nevertheless, for light nuclei it is still possible to investigate nuclei near the drip-line through multi nucleon transfer or double charge exchange (DCX) reactions. In particular reactions such as (^{14}C,^{14}O) (^{18}O,^{18}Ne) and (^{14}C,^{10}C) (^{18}O,^{14}O) could be used for this purpose, providing that the drawback of very small cross sections (less than 1 μb/sr at forward angles) is compensated by a proper upgrading of the detection system. Until now, in fact, no experimental devices could guarantee an acceptable compromise between the detection efficiency and the energy resolution in these extreme conditions. With the advent of the new ray-tracing spectrometer MAGNEX [2] at the LNS, which allows a large solid angle (~ 50 msr) and momentum byte (± 10%) still preserving a good energy and mass resolving power (~ 1000 and ~200 respectively over the full phase space) these exploration will become possible. Compare to the heavier even-even neutron rich stable beams, such as the ^{18}O, the ^{14}C one has the advantage to induce reactions less affected by energy straggling, which guarantees better energy resolution. In addition, the ^{14}C Tandem beam at 105 MeV is almost totally 6^+ charged, with negligible components of 5^+ and 4^+, differently form heavier beams, for which broader distributions of charge states are obtained. This allows to have higher intensities reachable for ^{14}C which turns out to be a key point when dealing with very low yields expected for the reactions mentioned above. Therefore we believe that the production of a ^{14}C Tandem beam is of paramount importance for the evolution of experiments at the LNS in the investigation of exotic nuclei with MAGNEX. In the following the application of MAGNEX to the ^{22}Ne(^{14}C,^{14}O)^{22}O, ^{18}O(^{14}C,^{10}C)^{22}O and ^{11}B(^{14}C,^{14}O)^{11}Li reactions is

Moving from ^{14}C to ^{18}O beam

❖ After a long survey of D.Rifuggiato we realized that ^{18}O beam much more reliable than ^{14}C

❖Still we considered ^{14}C better in terms of energy resolution and no real chance to do this physics with CS beams

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Catania, 01.02.2007

Proposal for ^{18}O Tandem beam at the LNS

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In the following we refer to the Letter of intent presented to the LNS Scientific Committee on 10.10.2003, attached to this document. In that Letter we presented a scientific program based on multi-nucleon transfer and Double Charge Exchange (DCX) reactions to explore the low energy spectra of neutron rich nuclei. This program requires the use of ^{14}C or ^{18}O LNS-Tandem beams and the MAGNEX spectrometer to detect ejectiles. The ^{14}C beam in particular presents the advantage to guarantee a smaller energy straggling and consequently a better energy resolution especially for the DCX reactions (about 140 KeV FWHM for the ^{11}B(^{14}C,^{14}O)^{11}Li reaction at 105 MeV incident energy on 100 μg/cm^2 target compared to about 250 KeV for the ^{11}B(^{18}O,^{18}Ne)^{11}Li at 120 MeV). On the other hand, for the multi-nucleon transfer, the simulated resolutions are similar for the two cases (^{18}O,^{14}O) and (^{14}C,^{10}C), for which values as good as 150 KeV can be reached for a ^{12}C target of 200 μg/cm^2. For the rest the use of ^{14}C or ^{18}O beam introduces similar experimental requirements, at least from the point of view of the detection of the ejectiles with MAGNEX. Taking this into account and considering that the ^{14}C beam will be less reliable than ^{18}O for obvious reasons, we consider the possibility to start our experimental program with ^{18}O beam and multi-nucleon transfer. In fact this was also suggested by the LNS Committee as appears in the attached

The DOCET experiment

- ❖ In 2012 (^{18}O,^{18}Ne) proposed as a tool for $0\nu\beta\beta$ nuclear matrix elements

- ❖ We propose to do this physics with CS beams

(^{18}O,^{18}Ne) Double Charge-Exchange with MAGNEX

Acronym: DoCET

C.Agodi[a], M. Bondi[a,b], F. Cappuzzello[a,b], D. Carbone[a,b], M. Cavallaro[a], A. Cunsolo[a], M. De Napoli[c], L. Fortunato[e], A. Foti[b,c], S.Lenzi[e],D. Nicolosi[a,b], C.Rea[e], G. Taranto[a,b], S. Tropea[a,b], A. Vitturi[e]
[a]*I.N.F.N. - Laboratori Nazionali del Sud, Catania, Italy;*
[b]*Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy*
[c]*I.N.F.N. - Sezione di Catania, Catania, Italy;*
[e]*Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy and I.N.F.N. - Sezione di Padova, Padova, Italy;*

Spokesperson: M. Cavallaro, **Co-Spokesperson**: F. Cappuzzello

Abstract: A request to perform the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar double charge-exchange (DCE) reaction at 270 MeV is presented. The MAGNEX spectrometer will be used at forward angles to detect the ^{18}Ne ejectiles. This experiment could represent a very challenging opportunity to explore the DCE reactions for the first time with good resolution in energy and angle and significant statistical sample.

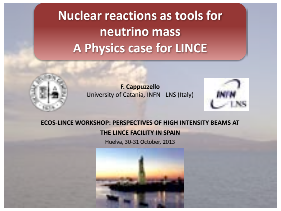
Double charge-exchange reactions (DCE) are processes characterized by the transfer of two units of the isospin third component ($\Delta T_z = \pm 2$), leaving the mass number unchanged.

Several features make the study of DCE interesting. One of these is the ability to reach nuclei far from the line of stability, especially for light systems, thus allowing challenging spectroscopic studies of neutron-rich or proton-rich nuclei (1) (2). Another, very ambitious goal is related to the connection to the double beta-decay and its implications for the neutrino mass (3). The nuclear matrix elements involved in the beta-decay are connected to the charge-exchange ones and consequently to the Fermi or Gamow-Teller (GT) transition strengths in the reactions. This aspect is the guide-line of our present proposal.

The last two years

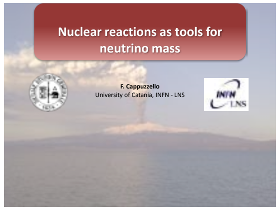
- Results of DOCET first presented at the ALTO workshop (Orsay) May 2013

- Proposal of the DOCET physics presented at ECOS-LINCE meeting as driving physics case for ECOS-LINCE project (October 2013)



- Proposal to ERC by M.Cavallaro (beginning 2014)

- NUMEN is proposed by F.C. and C.Agodi to INFN within the "What Next" initiative (February 2014). It includes the upgrade of MAGNEX and the CS accelerator



- NUMEN Phase 2 and CALL "SICILIA" approved in 2015

The NUMEN project

Proponents: C. Agodi, X. Aslanouglou, N. Auerbach, F. Balestra, R. Bijker, D. Bonanno, T. Borello, V. Branchina, L. Calabretta, A. Calanna, F. Cappuzzello, D. Carbone, M. Cavallaro, D. Calvo, M. Colonna, G. D'Agostino, N. Deshmuk, P. N. de Faria, A. Ferrero, A. Foti, P. Finocchiaro, P. R. S. Gomes, V. Greco, G. Lanzalone, H. Lenske, R. Linares, J. Lubian, F. Iazzi, R. Introzzi, A. Lavagno, D. Lo Presti, N. Medina, D. R. Mendes, A. Muoio, J. R. B. Oliveira, A. Pakou, L. Pandola, D. Rifuggiato, M. R. D. Rodrigues, G. Santagati, E. Santopinto, L. Scaltrito, O. Sgouros, V. Soukeras, S. Tudisco, R. I. M. Vsevolodovna, V. Zagatto

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

The NUMEN collaboration

INFN – LABORATORI NAZIONALI DEL SUD, CATANIA, ITALY
DIPARTIMENTO DI FISICA E ASTRONOMIA, UNIV. DI CATANIA, CATANIA, ITALY
INFN – SEZIONE DI CATANIA, CATANIA, ITALY
INFN – SEZIONE DI TORINO, TORINO, ITALY
POLITECNICO DI TORINO
UNIV. DEGLI STUDI DI ENNA "KORE", ENNA, ITALY
INFN – SEZIONE DI GENOVA, GENOVA, ITALY
INSTITUT FÜR THEORETISCHE PHYSIK, GIESSEN UNIVERSITY, GERMANY
DEP. OF PHYSICS AND HINP, THE UNIV. OF IOANNINA, IOANNINA, GREECE
INSTITUTO DE FISICA DA UNIVERSIDADE DE SAO PAULO, BRAZIL
INST. DE FISICA DA UNIV. FEDERAL FLUMINENSE, NITEROI, BRAZIL
AKDENIZ UNIVERSITY, ANTALYA, TURKEY
SCHOOL OF PHYSICS AND ASTRONOMY TEL AVIV UNIVERSITY

Forthcoming collaborations

OTHER INFN LOCAL SECTIONS
INSTITUTO DE CIENCIAS NUCLEARES, UNAM, MEXICO
CICANUM, UNIVERSIDAD DE COSTA RICA, SAN JOSE, COSTA RICA
DÉPARTEMENT DE PHYSIQUE, UNIVERSITÉ HASSAN II – CASABLANCA, MOROCCO
CERN
BROKHAVEN NATIONAL LABORATORY
INSTITUTE OF MODERN PHYSICS, CHINESE ACADEMY OF SCIENCES, LANZHOU, CHINA
RCNP, OSAKA UNIVERSITY, OSAKA, JAPAN
NIELS BOHR INSTITUTE, DENMARK
UNIVERSITY OF LA PLATA, ARGENTINA

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

The NUMEN project

Project presented to....

- LNS community
- What Next initiative
- International Evaluation Committee (F.Iachello, M.Harakeh, D.Frekers)
- INFN CSN2, CSN3, CSN4 and CSN5
- INFN CVI, INFN Direttivo, INFN Review Committee
- INFN-LNS Scientific Committee

Project refereed by....

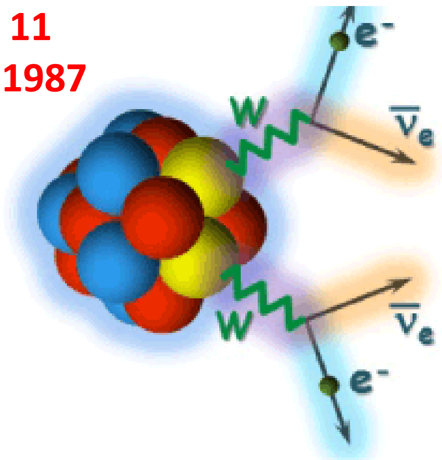
- International Evaluation Committee evaluated the whole project (F.Iachello, M.Harakeh, D.Frekers)
- INFN CSN3 evaluated experiments and MAGNEX tracker upgrade (A.Fantini, E.Fioretto, S.Leoni, A.Vitturi)
- INFN CSN5 evaluated the SiC proposal within CALL SICILIA
- INFN MAC evaluates the proposed machine upgrade within the project of upgrade of LNS CS accelerator
- INFN-LNS Scientific Comittee evaluates the beam time requests
- ......

Physics case tutorial

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



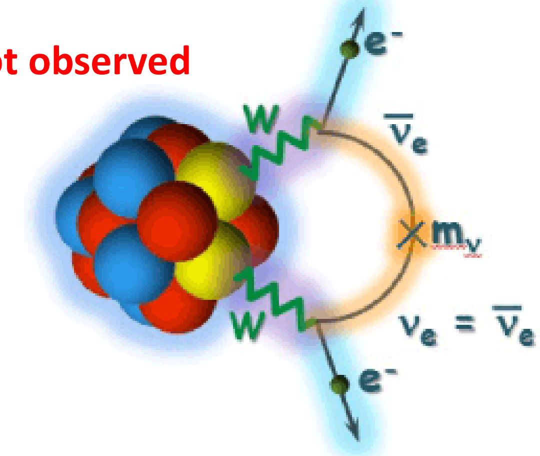
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

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

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

Neutrinoless double beta decay

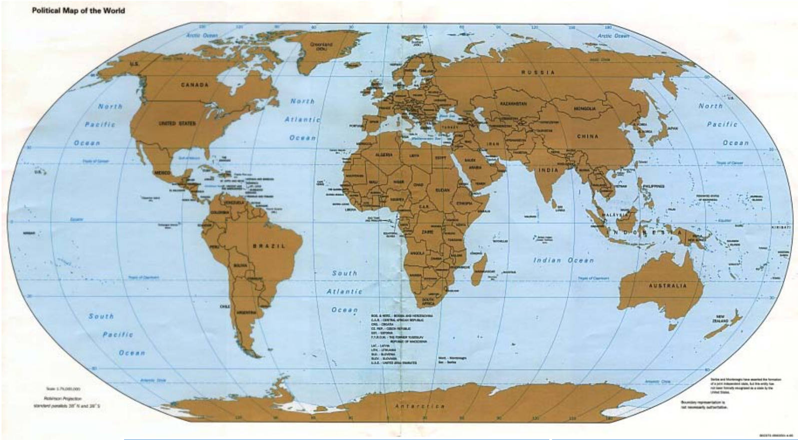
Still not observed



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**

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



Search for 0νββ decay. A worldwide race

$$T^{0\nu}_{1/2}(0^+ \to 0^+) > 10^{26}\,y$$

Experiment	Isotope	Lab	Status
GERDA	^{76}Ge	LNGS	Phase I completed Migration to Phase II
CUORE0 /CUORE	^{130}Te	LNGS	Data taking / Construction
Majorana Demonstrator	^{76}Ge	SURF	Construction
SNO+	^{130}Te	SNOLAB	R&D / Construction
SuperNEMO demonstrator	^{82}Se (or others)	LSM	R&D / Construction
Candles	^{48}Ca	Kamioka	R&D / Construction
COBRA	^{116}Cd	LNGS	R&D
Lucifer	^{82}Se	LNGS	R&D
DCBA	many	[Japan]	R&D
AMoRe	^{100}Mo	[Korea]	R&D
MOON	^{100}Mo	[Japan]	R&D

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.

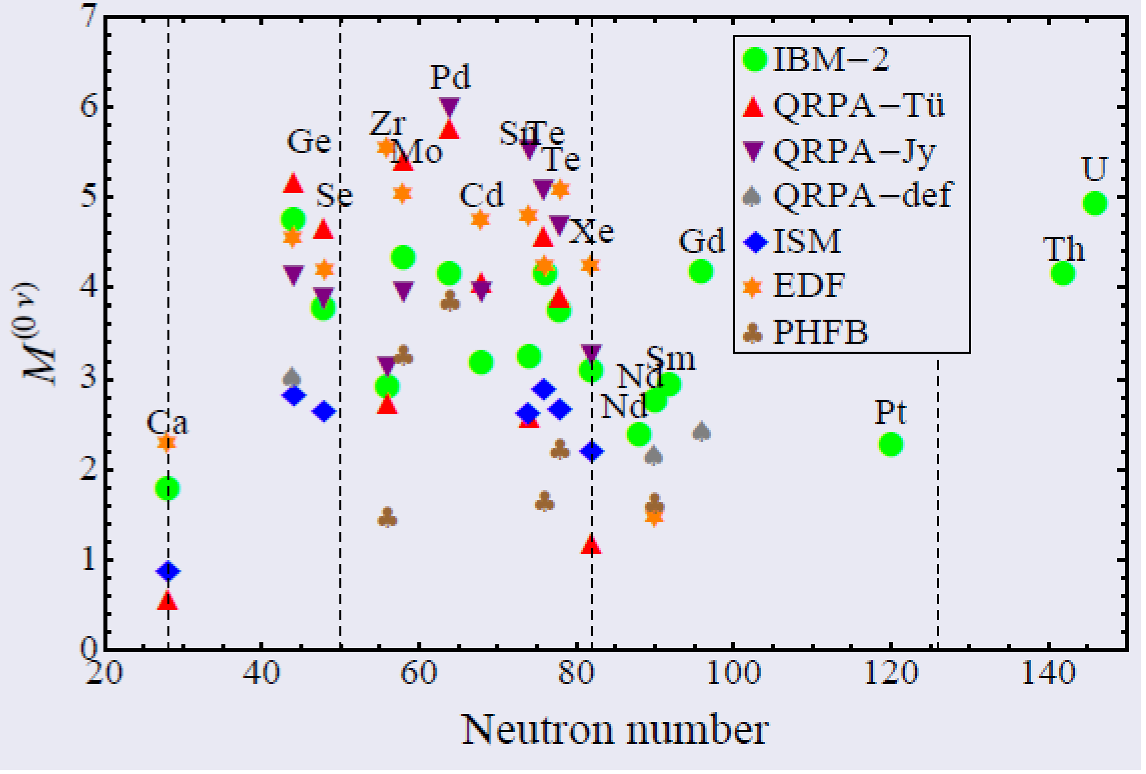
- ✓ Measurements (still not conclusive for $0\nu\beta\beta$):
  (π^+, π^-)
  single charge exchange $(^3He,t)$, $(d,^2He)$
  electron capture
  transfer reactions …

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)

State of the art NME calculations

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



Courtesy of Prof. F.Iachello

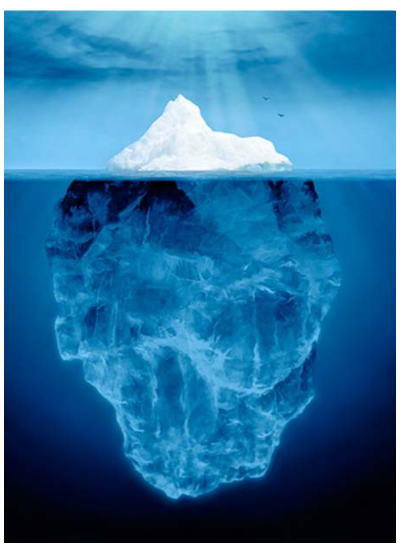
Heavy-ion DCE

- ✓ 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*

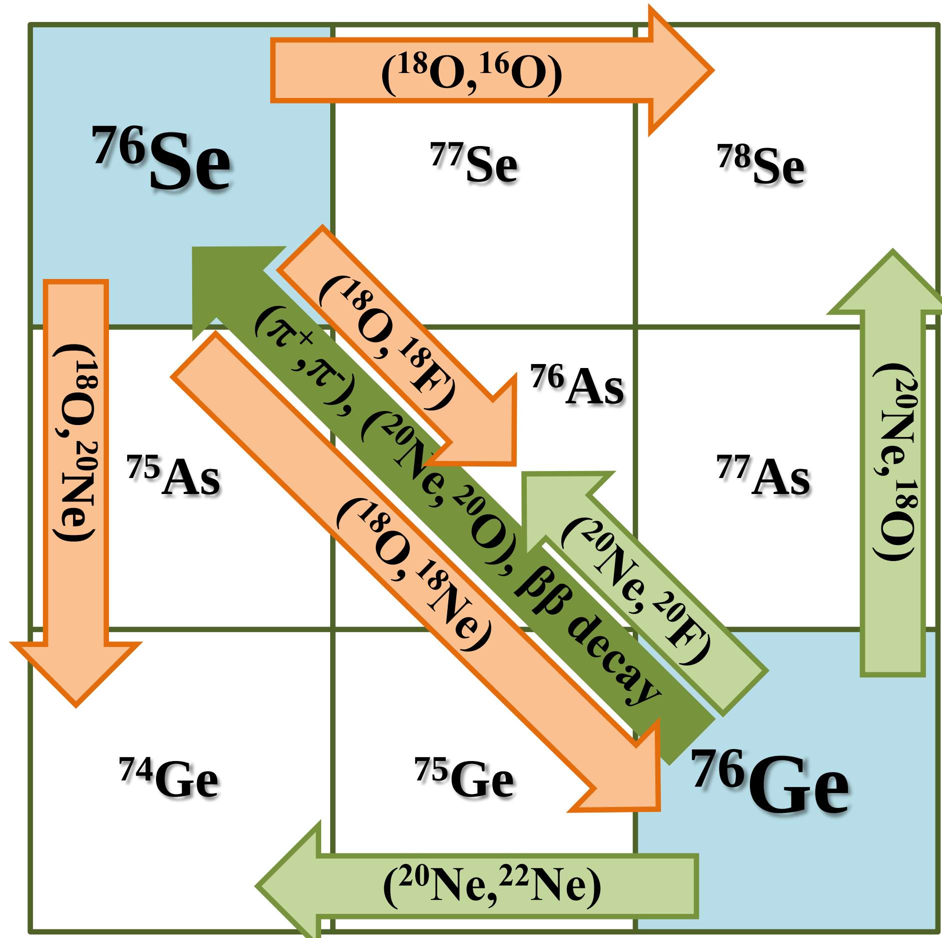
- ✓ Meson exchange mechanism 2nd order
- ✓ Possibility to go in both directions

From T. Uesaka talk at NN2015



Tiny amount of DGT strenght in low lying states

Sum rule almost exhausted by DGT Giant Mode



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

1. **Initial and final states:** Parent/daughter states of the $0\nu\beta\beta$ are the same as those of the target/residual nuclei in the DCE;

2. **Spin-Isospin mathematical structure** of the transition operator: Fermi, Gamow-Teller and rank-2 tensor together with higher L components are present in both cases;

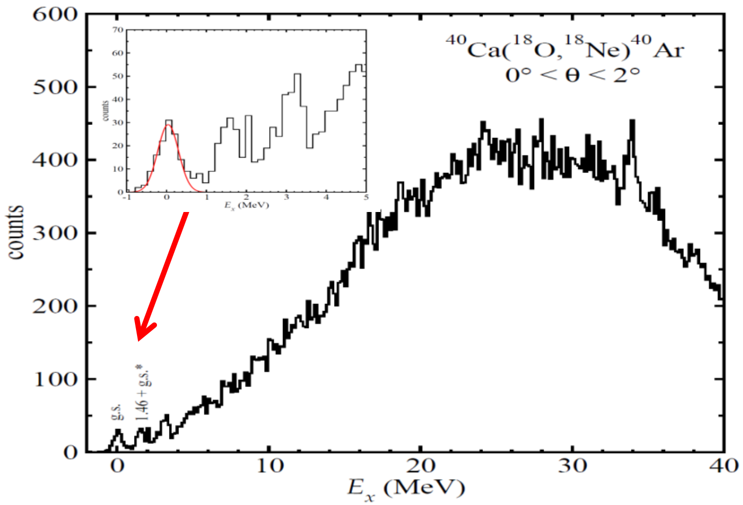
3. **Large momentum available:** A linear momentum transfer as high as 100 MeV/c or so is characteristic of both processes;

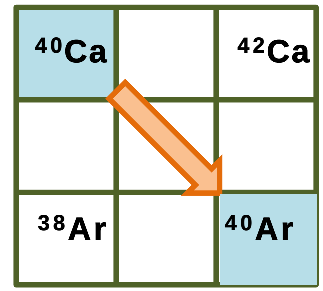
4. **Non-locality**: both processes are characterized by two vertices localized in two valence nucleons. In the ground to ground state transitions in particular a pair of protons/neutrons is converted in a pair of neutrons/protons so the non-locality is affected by basic pairing correlation length;

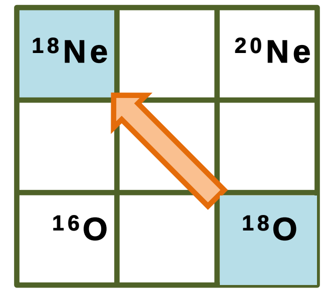
5. **In-medium** processes: both processes happen in the same nuclear medium, thus **quenching** phenomena are expected to be similar;

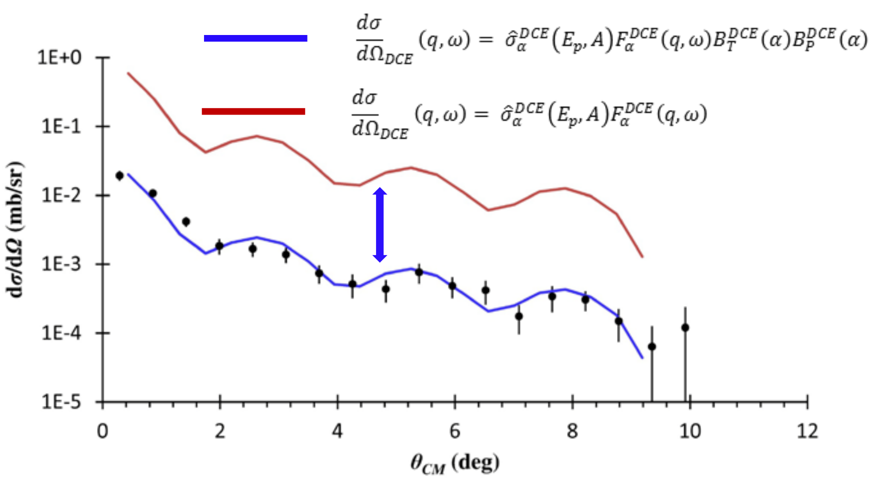
6. Relevant **off-shell propagation** in the intermediate channel: both processes proceed via the same intermediate nuclei off-energy-shell even up to 100 MeV.

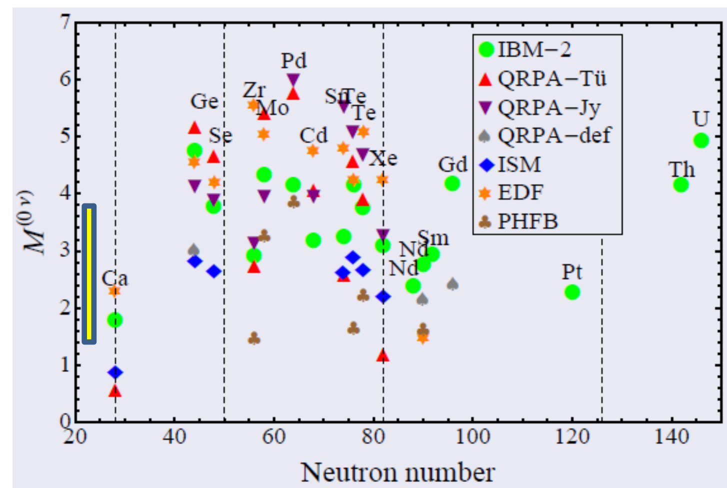
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV











$$\left|M^{0\nu\beta\beta}\left({}^{40}Ca\right)\right|^2 = 0.37 \pm 0.18$$

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

Pauli blocking about 0.14 for F and GT

Status and perspectives of NUMEN

The recent NUMEN workshop

"Challenges in the investigation of double charge-exchange nuclear reactions: towards neutrino-less double beta decay"

✓More than 80 worldwide participants

✓Researchers for all the communities (INFN GR 1-2-3-4-5)

✓Alive discussions

✓New collaborations for NUMEN

✓Decisive step on the theoretical side

List of speakers:
N. Auerback Tel Aviv University (Israel)
R. Broglia Università di Milano (Italy) and Niels Bohr Inst., Copenhagen (Denmark)
O. Civitarese Dept. Phys., University of La Plata, Buenos Aires (Argentina)
H. Ejiri RCNP, Osaka University (Japan)
A. Faessler University of Tuebingen (Germany)
D. Frekers University of Muenster (Germany)
M. Horoi Dept. Phys., Central Michigan University (USA)
J. Kotila Dept. Phys., University of Jyvaskyla (Finland)
F. La Via CNR - IMM (Italy)
D. Lo Presti INFN - Catania (Italy)
L.Calabretta INFN - LNS (Italy)
H. Lenske University of Giessen (Germany)
G. Potel Lawrence Livermore National Laboratory (USA)
M. Takaki Center for Nuclear Study, Univ. of Tokyo (Japan)
K. Zuber Technische Universität Dresden (Germany)

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S. Tudisco (tudisco@lns.infn.it)

agenda.infn.it/event/NUMEN2015

Moving towards hot-cases:

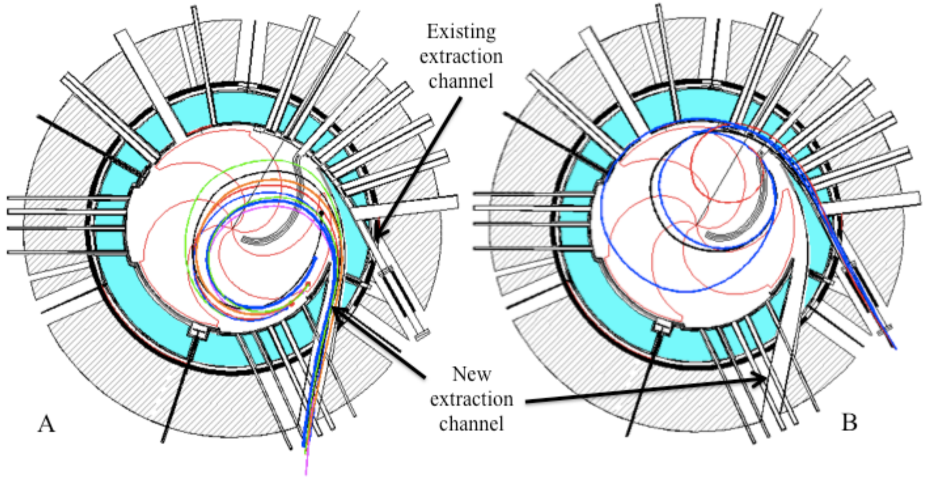
Caveat

- 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)
- The reaction Q-values are normally more negative than in the ^{40}Ca case
- 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

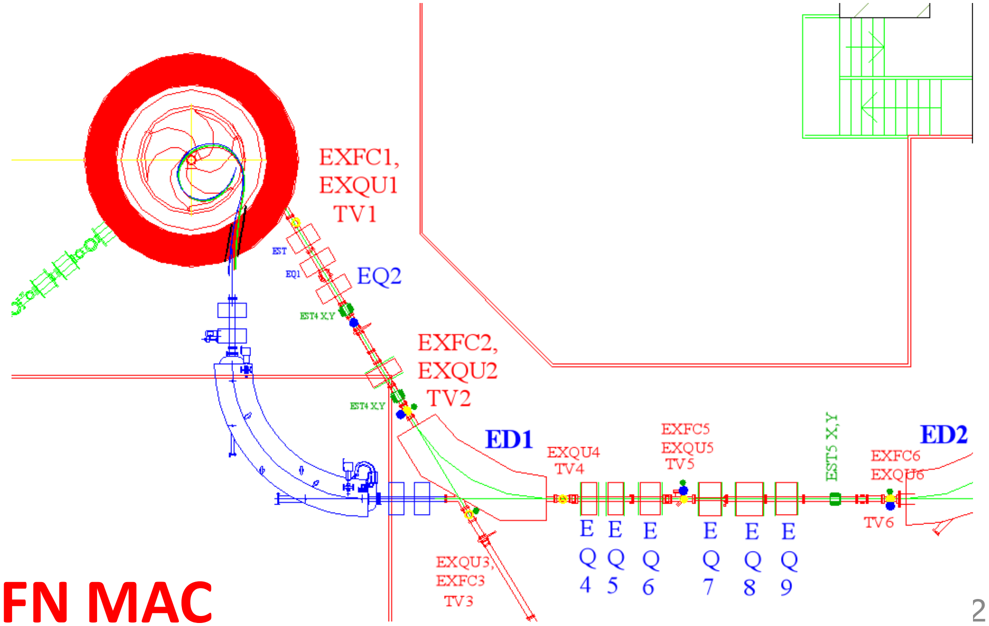
Major upgrade of LNS facilities: The CS accelerator

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



Extraction by stripping

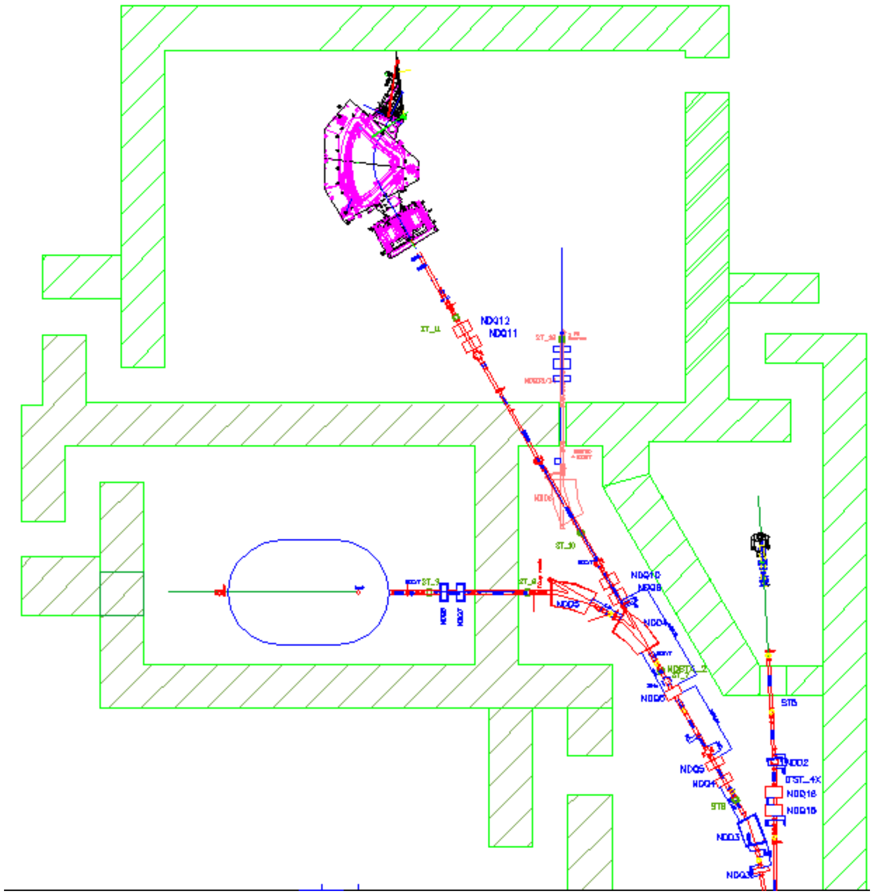
- The **beam transport line** transmission efficiency to nearly 100%



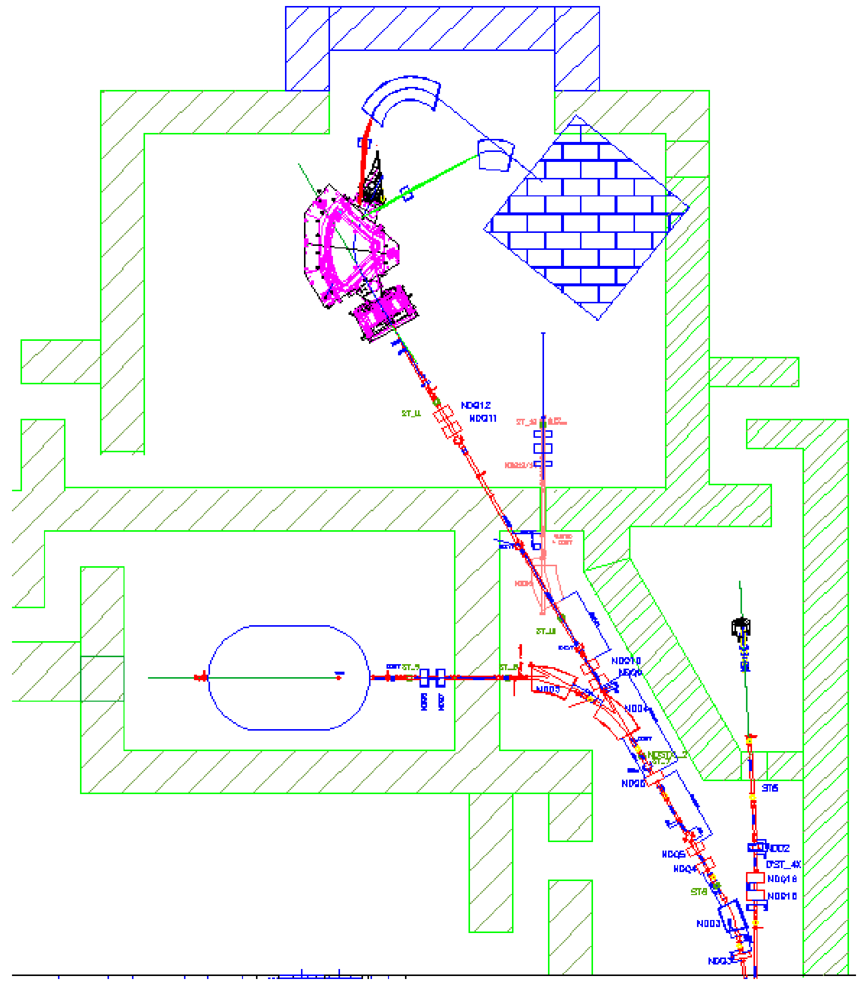
Project submitted to INFN MAC

A challenging beam dump inside the MAGNEX hall

Present MAGNEX hall

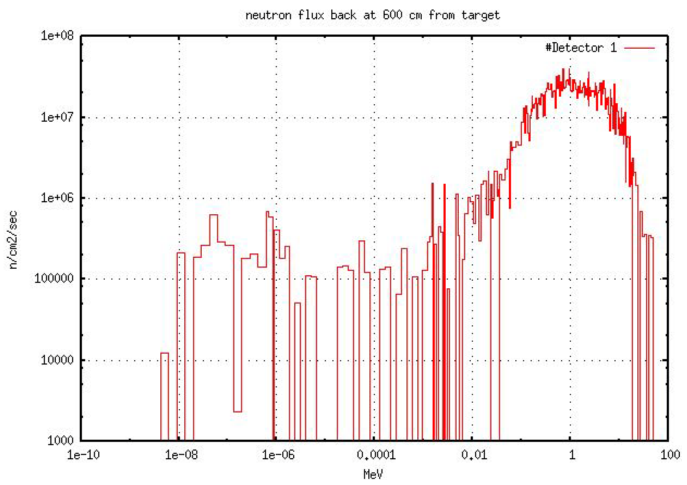


Possible MAGNEX hall

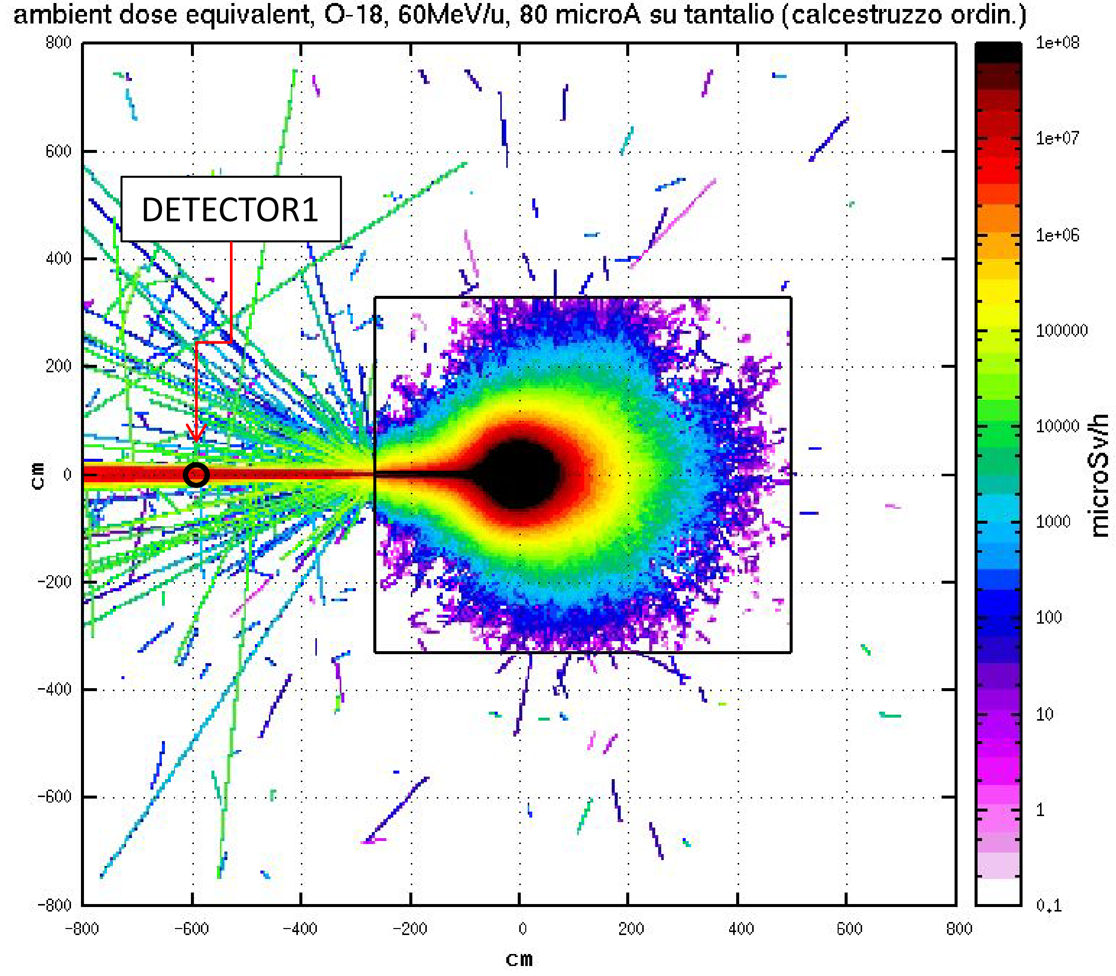


From L.Calabretta

A challenging beam dump inside the MAGNEX hall



(6,25 E+13 pps)

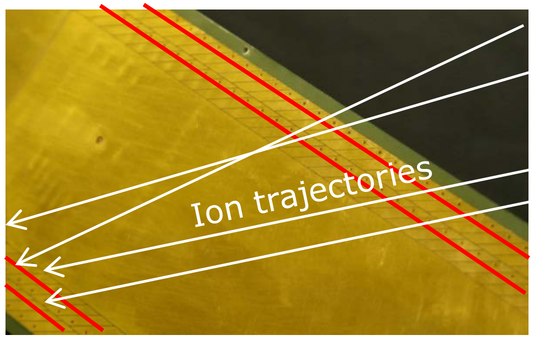


From S.Russo (LNS radioprotection service)

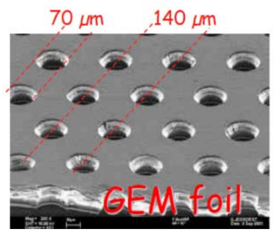
Major upgrade of LNS facilities: the MAGNEX spectrometer

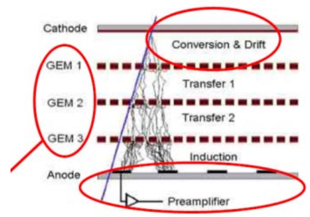
- The **MAGNEX focal plane** detector rate (from 2 kHz to several MHz)

From multi-wire tracker



To micro-pattern tracker

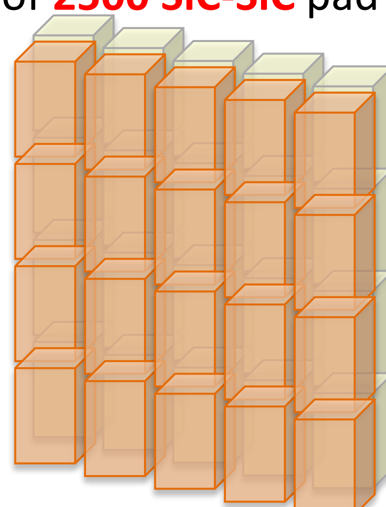




- **R&D key issue : GEM-based tracker at low pressure and wide dynamic range**
- **INFN-LNS (M. Cavallaro), collaboration with INFN-LNF, CERN, INFN-BA**

From wall of **60** Si pad

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

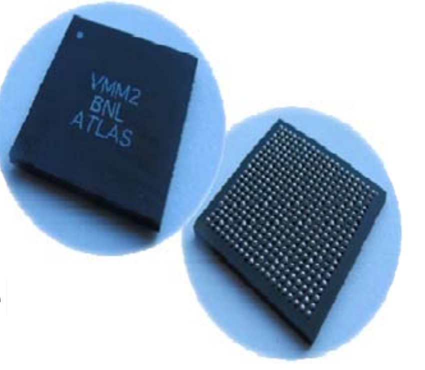


A big challenge!

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

Front-end and read-out electronics (See talk D.Bonanno)

ELECTRONICS PROTOTYPES (D. LoPresti)



1) ASIC front–end chip:

for FPD chip **VMM2(3)** in collaboration with Brookhaven National Laboratory ($8x10^4$ transistor/channe for 64 channels)

for PM and PM-like signal chip **DRS4** commercial chip delivered by PSI

2) Read – out: new generation of **FPGA** and System On Module (**SOM**)

Number of channels

- Gas tracker ~ 30000 ch
- SiC-SiC ~ 7500 ch
- Gamma array ~ 2500 ch

Tot ~ 40000 ch

Other upgrades

- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.5 Tm)
- An **array of detectors for γ-rays** measurement in coincidence with MAGNEX (in collaboration with IFUSP and IFUFF (J. de Oliveira))
- The **target** technology for intense heavy-ion beams (developed by Poli Torino and INFN (D.Calvo))
- **Nuclear reaction theory** (formal development and calculations)

  coordinated by INFN CSN-IV (M. Colonna) in collaboration with Prof. H. Lenske. Recent interest from Prof. N. Auerbach, Prof. O. Civitarese and Prof. R. Broglia
- **Data Acquisition** (L. Pandola)
- **Data Reduction** (D. Carbone)

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
Phase1	done								
Phase2				Approved					
Phase3									
Phase4									

Challenging 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	**Approved experiment**											
^{116}Cd (^{20}Ne,^{20}O) ^{116}Sn	15-25	**Approved test**											
^{130}Te (^{20}Ne,^{20}O) ^{130}Xe	15-25												
^{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												

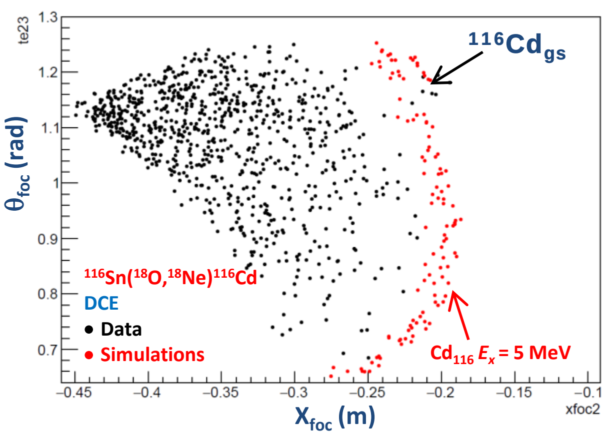
Results from a test run on $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ October 2015

Valuable job from our young collaborators

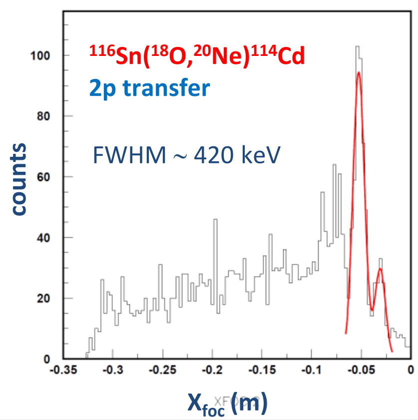
- ✓ E_{beam}=15MeV/u, target thickness 400 μg/cm^2
- ✓ 150μC integrated charge in 50 hours at 1 enA (including dead time 50%)
- ✓ Detector and beam transport performances studied up to 6 enA
- ✓ Realistic cross section estimate for DCE

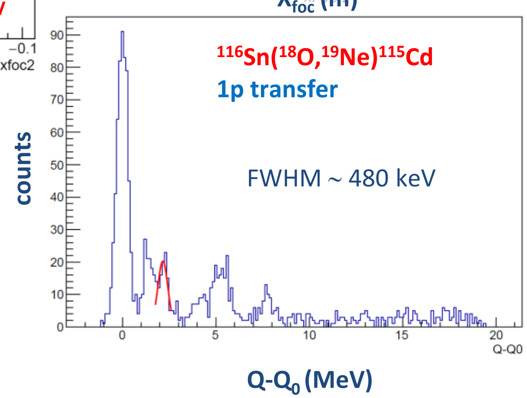
Preliminary

Good sensitivity for DCE

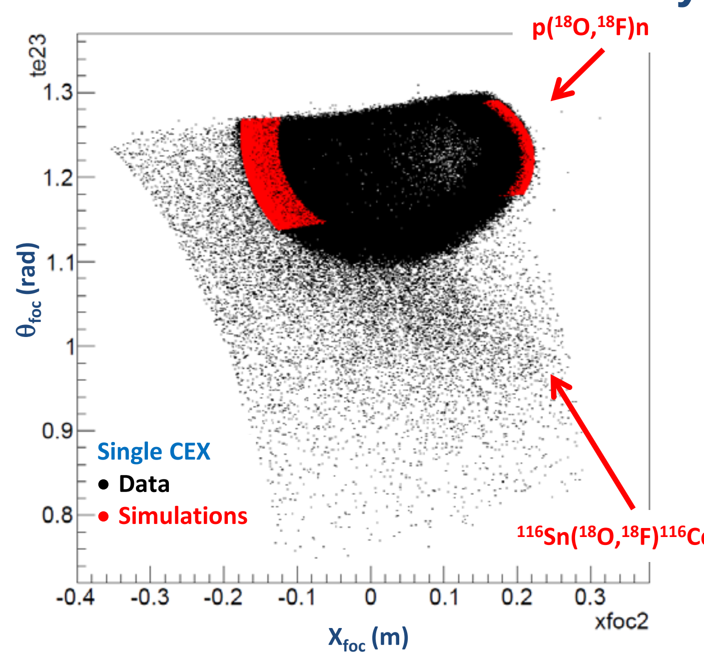


Perhaps 3 counts for $^{116}Sn_{gs} \rightarrow ^{116}Cd_{gs}$





Good energy resolution and accuracy



Conclusions and Outlooks

- **NUMEN represents a challenging perspective** for the future of LNS in nuclear science, in the spirit of ECOS
- **The project** turns around the MAGNEX and the Cyclotron upgrade toward high intensity
- It is playing an important role for **attracting worldwide researchers at the LNS,** (more than 50 in 2015)
- Results of relevance for $0\nu\beta\beta$ physics are expected from 2016