NUMEN project @ LNS: Status and perspectives

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on behalf of C. Agodi

The NUMEN project

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Institutions

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3. Istituto Nazionale di Fisica Nucleare, Sezione di Torino
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5. Dipartimento di Fisica e Astronomia, Università di Catania, Italy
6. Politecnico di Torino, Italy
7. Università degli Studi di Enna "Kore", Enna, Italy
8. Universidade de Sao Paulo, Brazil
9. Universidade Federal Fluminense, Niteroi, Brazil
10. University of Ioannina, Ioannina, Greece
11. Universidad Nacional Autónoma de México
12. CNR-IMM, Sezione di Catania, Italy
13. University of Giessen, Germany
14. Akdeniz University, Antalya, Turkey
15. Université Hassan II – Casablanca, Morocco
16. School of Physics and Astronomy Tel Aviv University, Israel

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

Heavy-ion DCE

✓ Induced by strong interaction

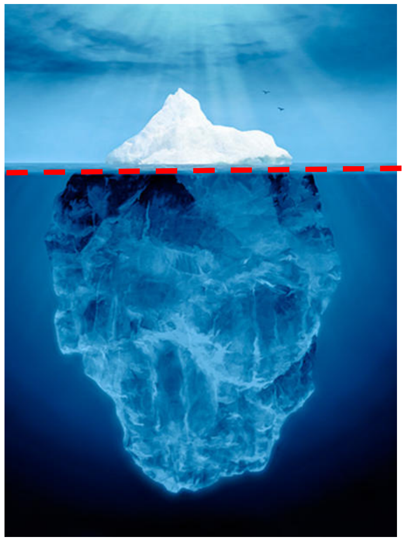
✓ Sequential nucleon transfer mechanism 4th order:

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

NUMEN

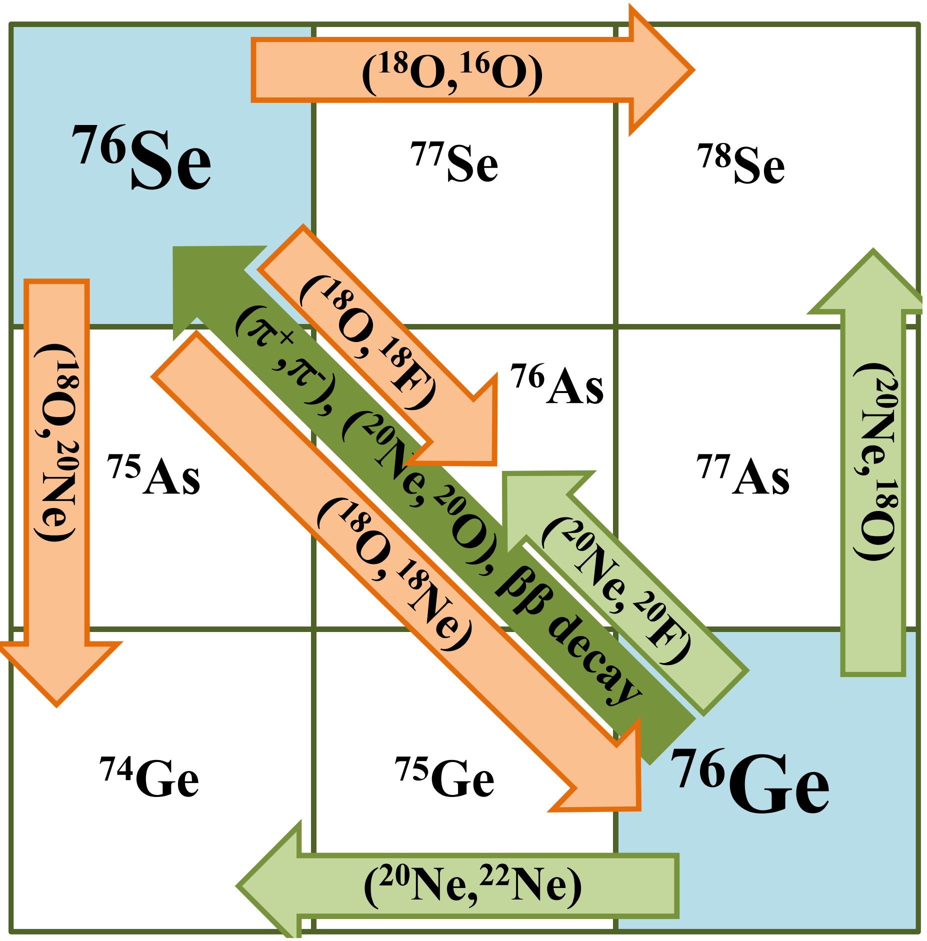


Tiny amount of DGT strenght in low lying states

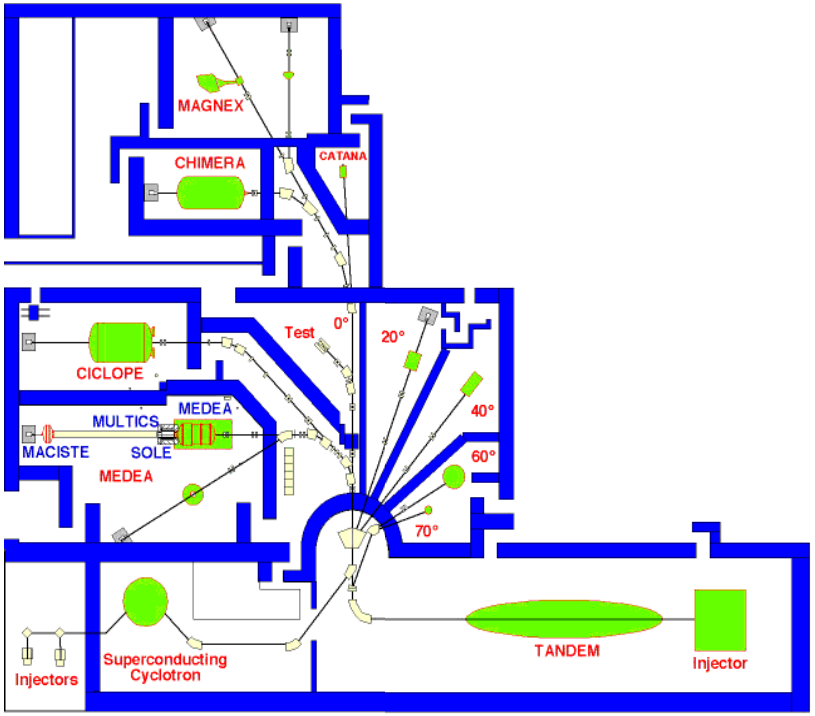
Sum rule almost exhausted by DGT Giant Mode

RIKEN

RCNP



The LNS laboratory in Catania



The Superconducting Cyclotron (CS) at LNS

The LNS K800 Superconducting Cyclotron

in operation since 1994

It can accelerate from Hydrogen to Uranium

Maximum nominal energy is 80 MeV/u

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

MAGNEX

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

Achieved resolution

Energy $\Delta E/E \sim 1/1000$

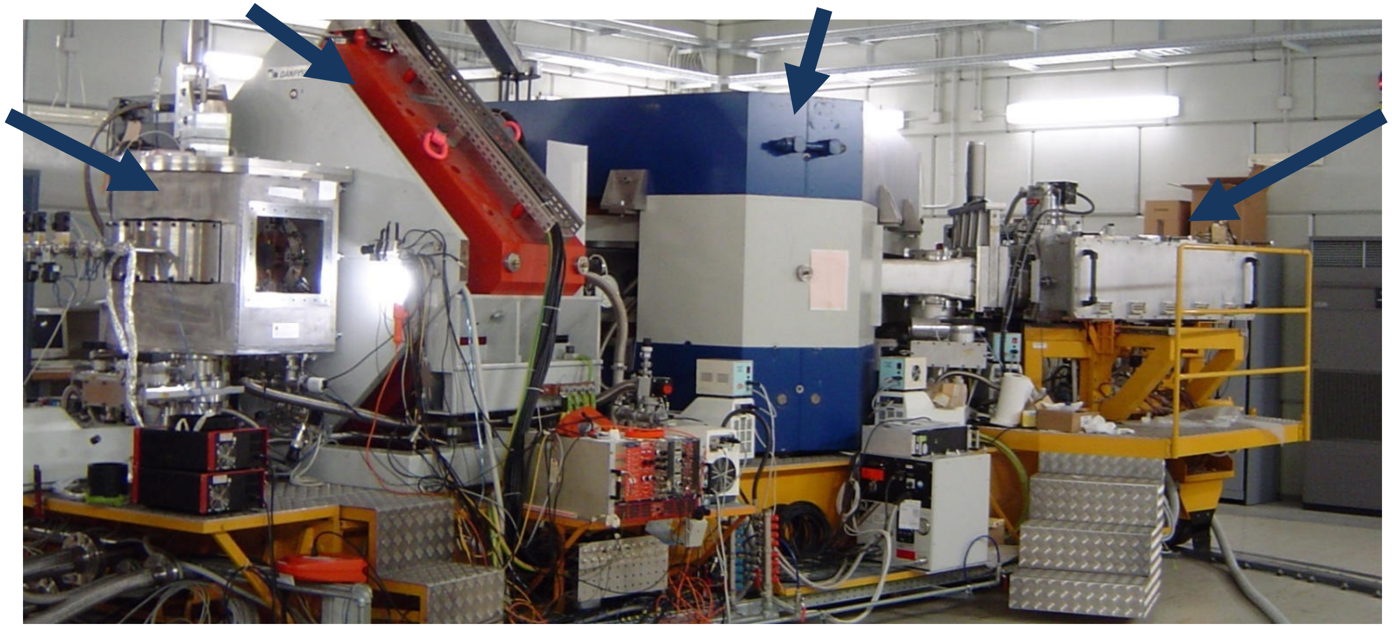
Angle $\Delta\theta \sim 0.2^{\circ}$

Mass $\Delta m/m \sim 1/160$

Quadrupole

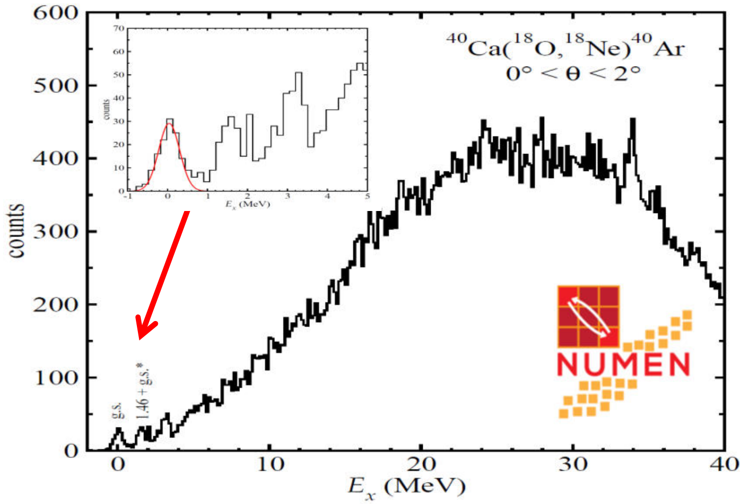
Dipole

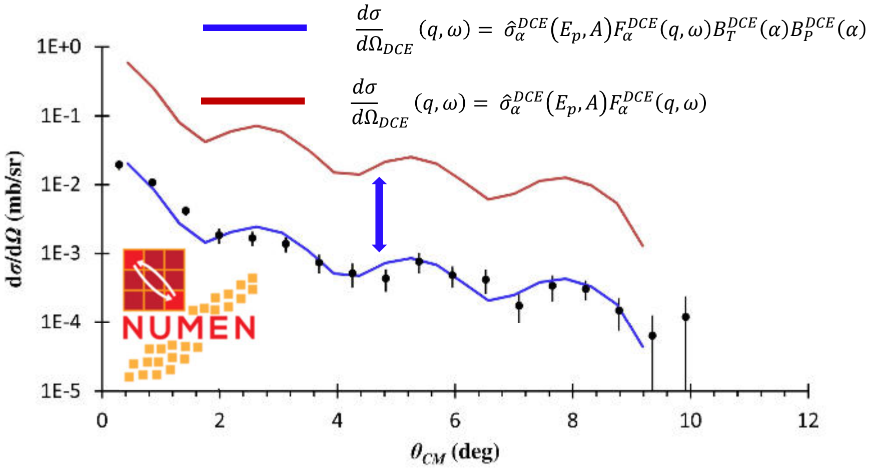
Scattering Chamber



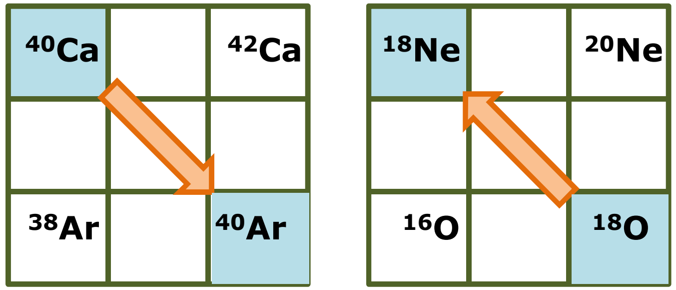
Focal Plane Detector

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



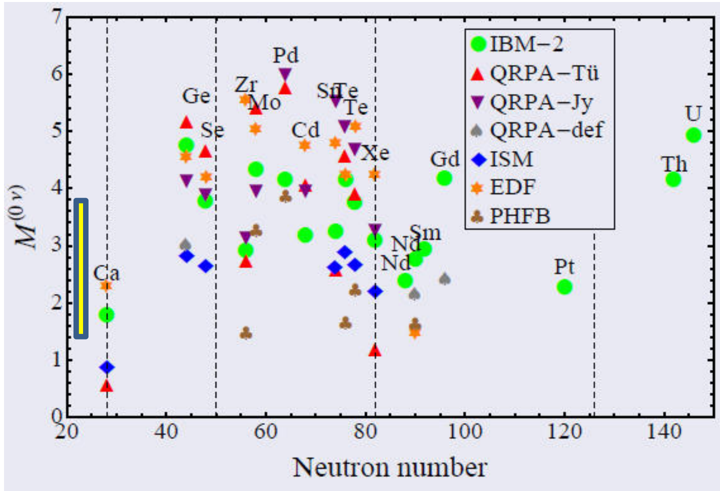


F. Cappuzzello et al. Eur. Phys. J. A (2015) 51: 145



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

First experimentally driven NME



Pauli blocking about 0.14 for F and GT

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

NUMEN

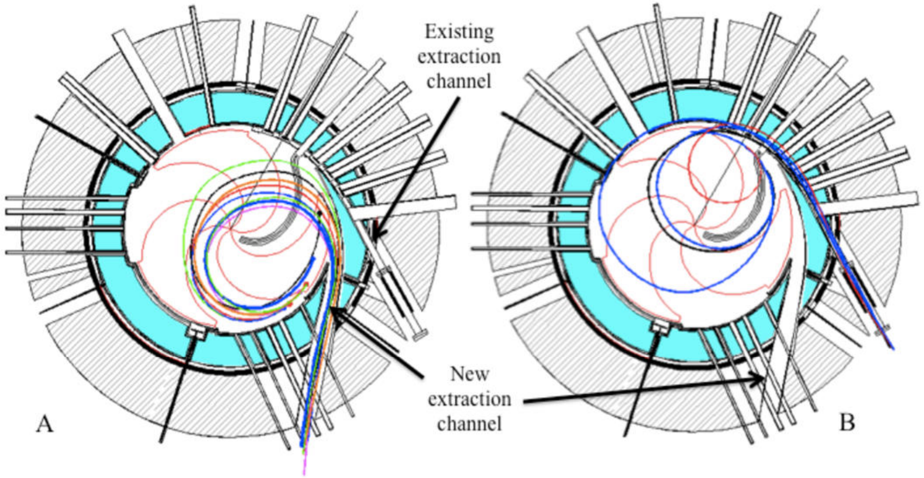
Present technology is not enough…

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

- **Upgraded set-up** to work with two orders of magnitude more beam current than the present
- **Substantial change in the technologies** used in **CS** and in the **MAGNEX** detector

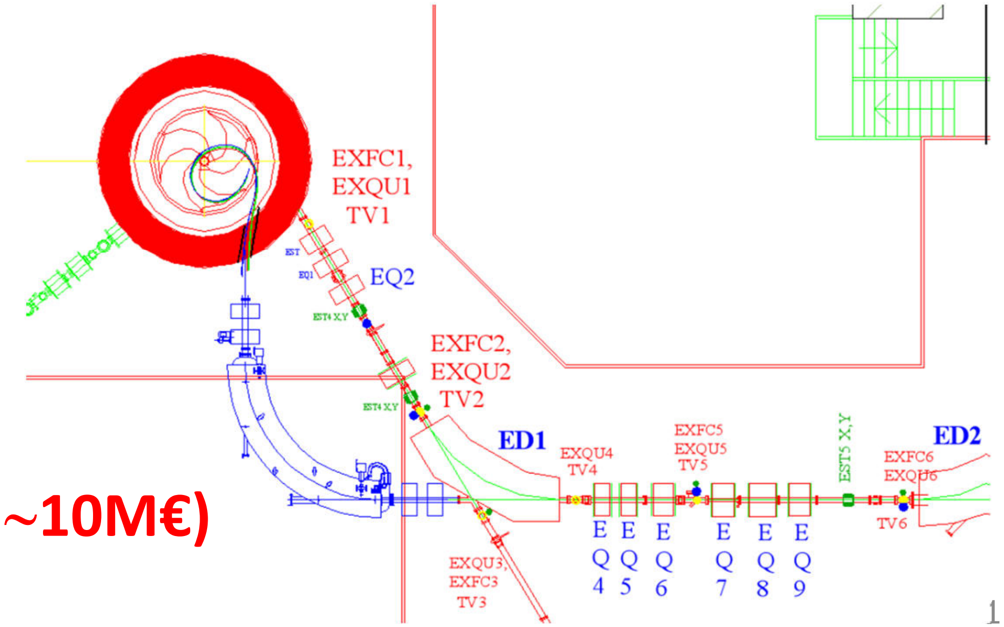
Major upgrade of LNS facilities: The CS accelerator

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



Extraction by stripping

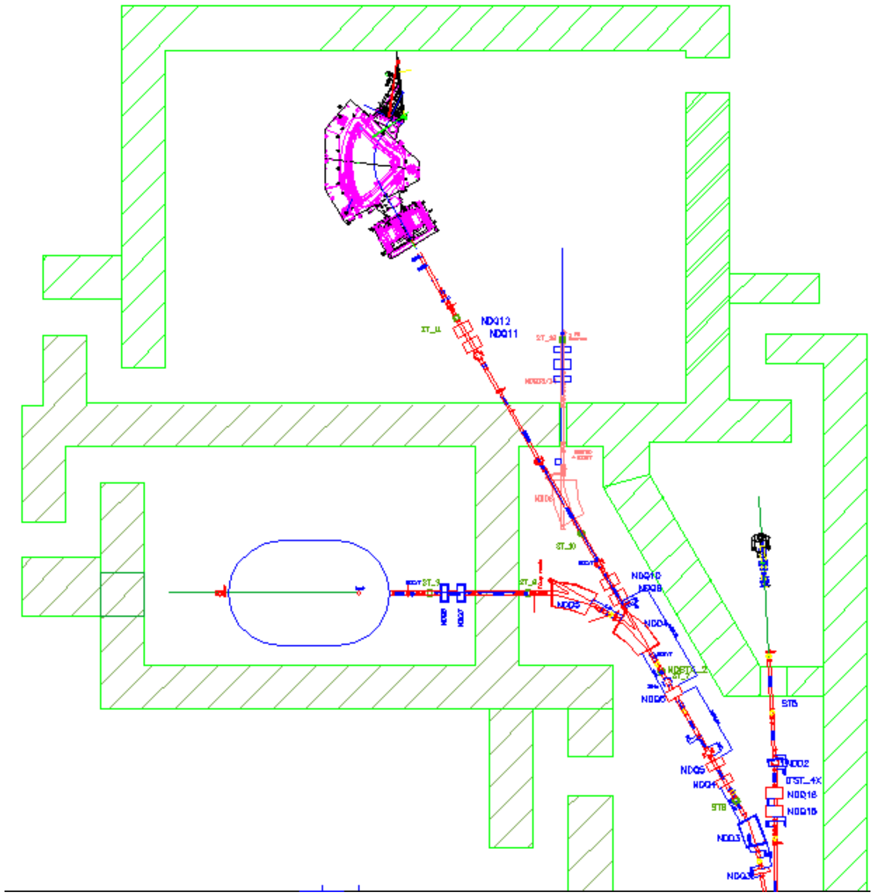
- The **beam transport line** transmission efficiency to nearly 100%



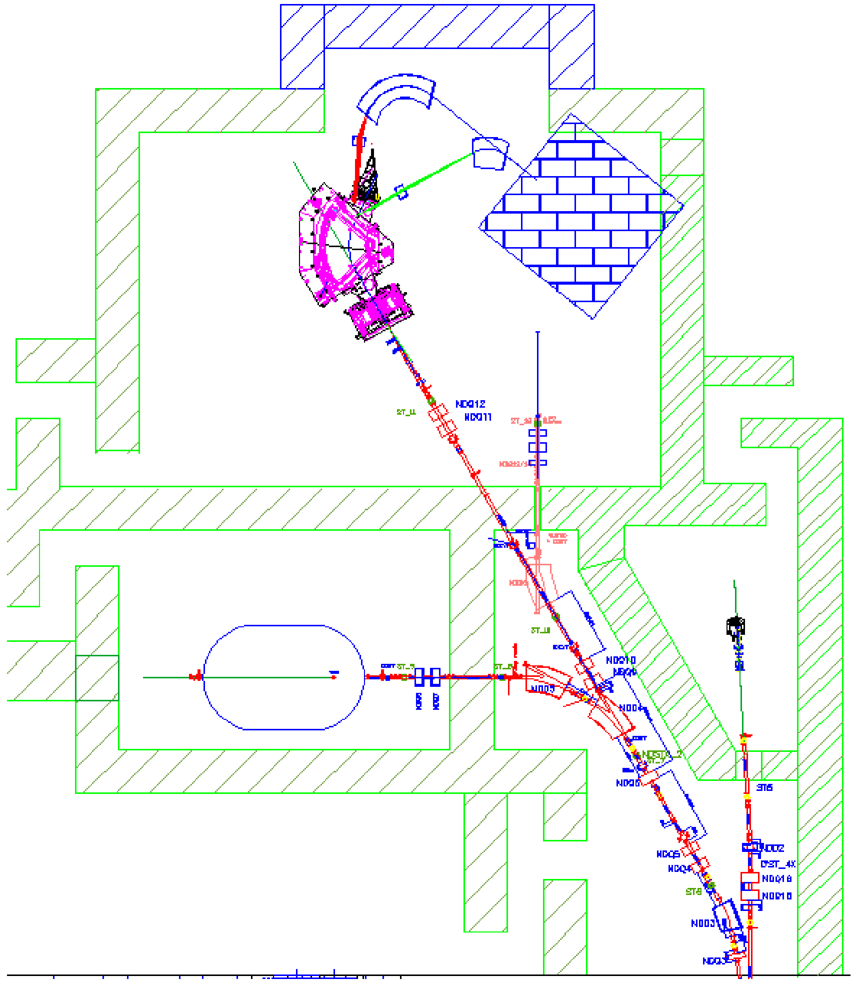
Project approved by INFN (~10M€)

A challenging beam dump inside the MAGNEX hall

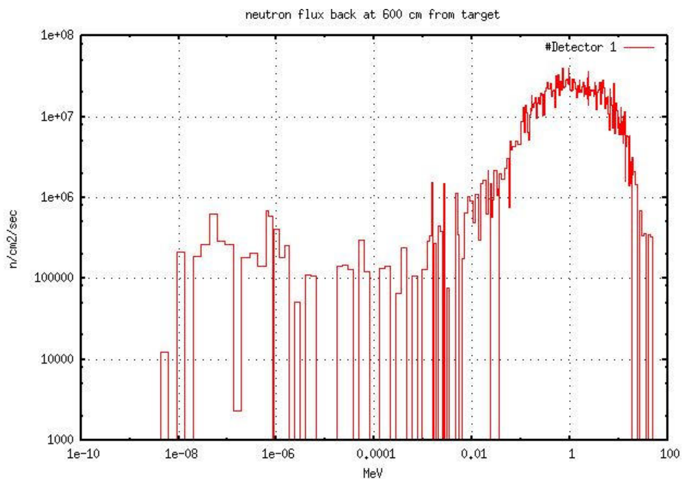
Present MAGNEX hall



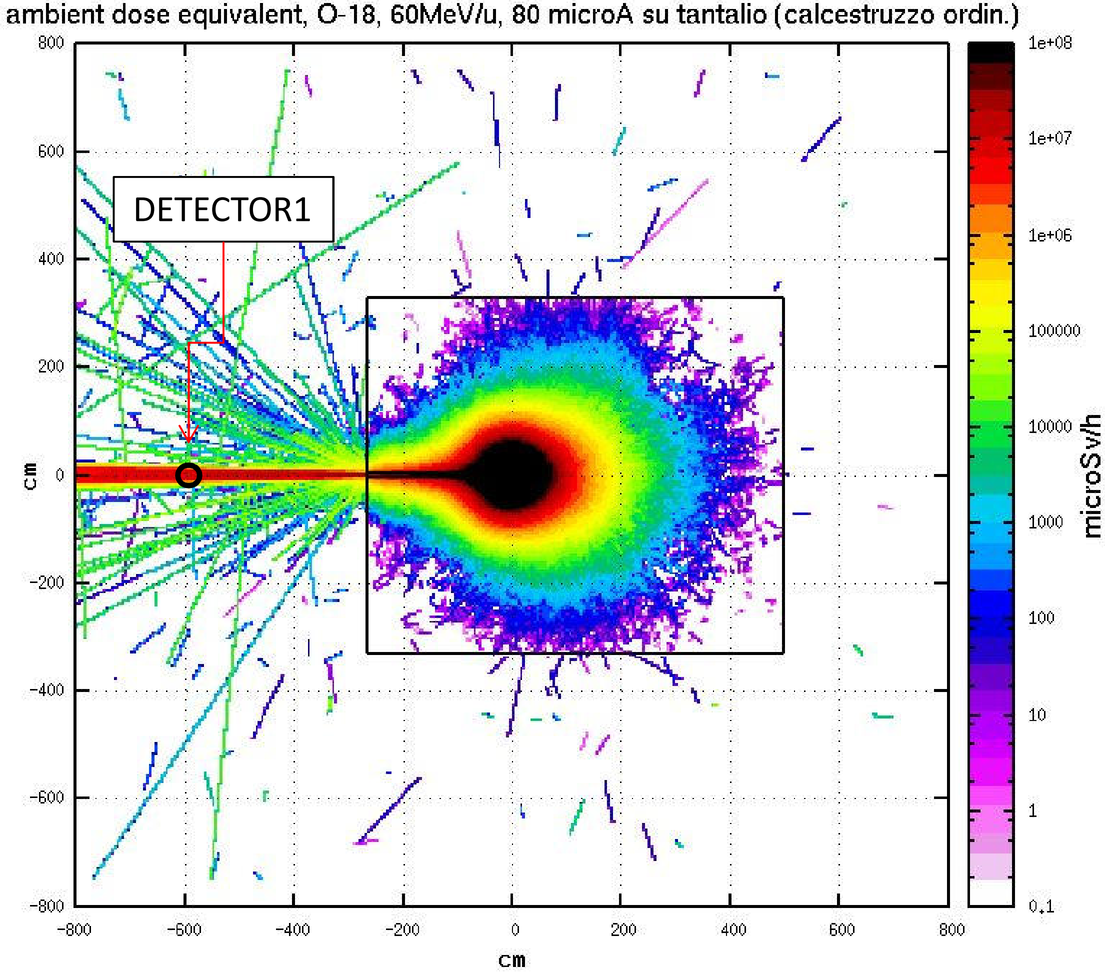
Possible MAGNEX hall



A challenging beam dump inside the MAGNEX hall



(6,25 E+13 pps)

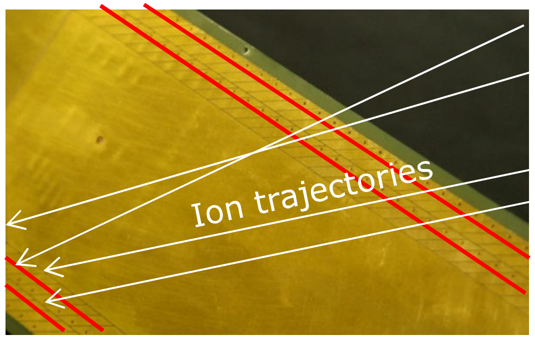


From S.Russo (LNS radioprotection service)

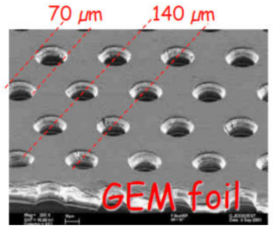
Major upgrade of LNS facilities: the MAGNEX spectrometer

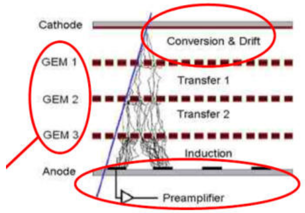
- The **MAGNEX focal plane** detector rate (from few kHz to several MHz)

From multi-wire tracker



To micro-pattern tracker

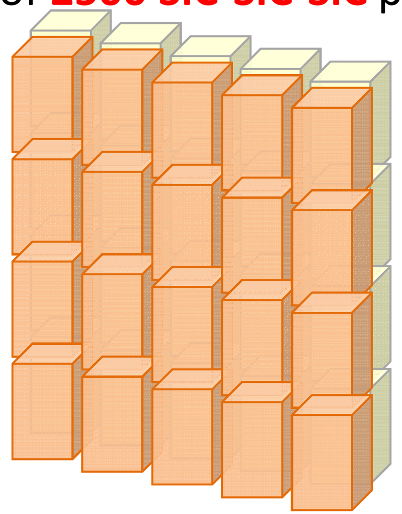




- **R&D key issue : GEM-based tracker at low pressure and wide dynamic range**
- **INFN-LNS (M. Cavallaro), collaboration with INFN-CT, UNAM**

From wall of **60** Si pad

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

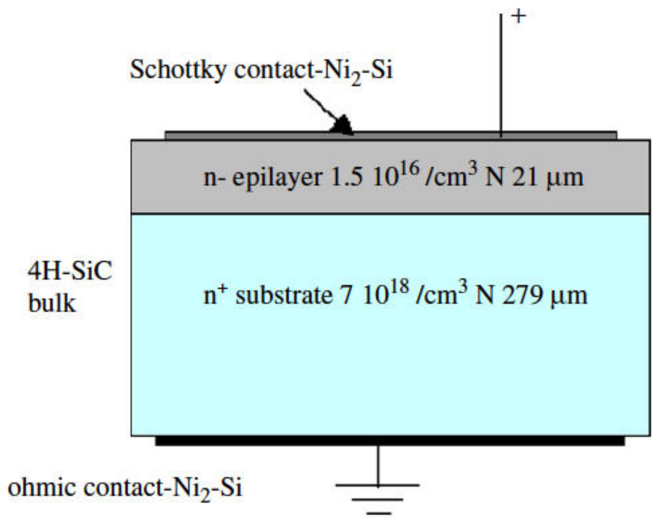


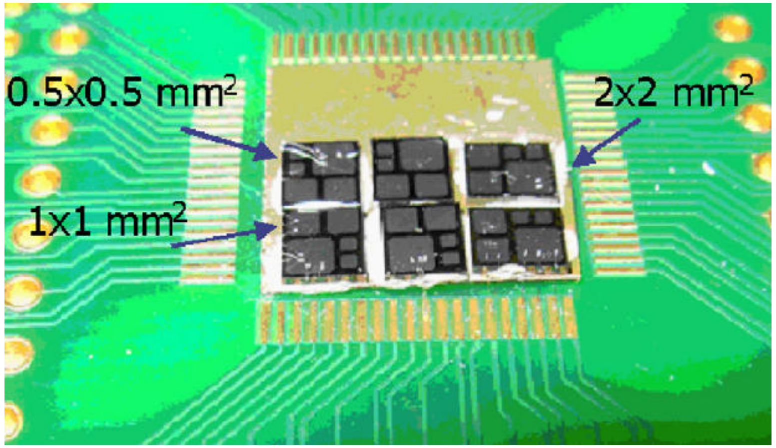
A big challenge!

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

SiC detectors: state of art

The Schottky diodes are fabricated by epitaxy onto high-purity 4H–SiC n-type substrate.





Limits
- ✓ Thickness of EPI-Layer ≈ 80 μm
- ✓ Detection surface
- ✓ Substracte Thickness ≈ 200 μm

Major upgrade required by NUMEN

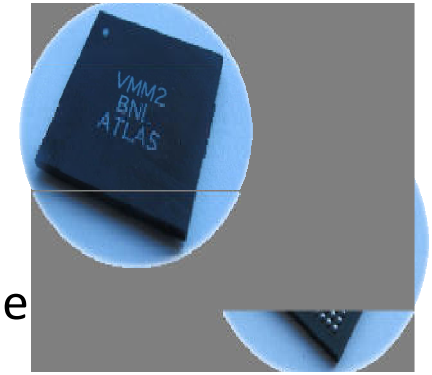
Target
- ✓ p-n junctions
- ✓ Schottky diodes

- ✓ 1x1 cm^2 ΔE-E telescope
- ✓ thickness of ΔE stage 100 μm
- ✓ thickness of E stage 500-1000 μm

First prototypes ready for the end of this year

Front-end and read-out electronics

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)

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

3) Demanding radiation hardness required

Number of channels

- Gas tracker ~ 2000 ch
- SiC-SiC ~ 7500 ch
- γ-ray calorimeter ~ 2500 ch

Tot ~ 12000 ch

Other upgrades

- The **MAGNEX** maximum magnetic **rigidity** (from 1.8 Tm to 2.2 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 H. Lenske.
- **Data Acquisition** (L. Pandola)
- **Data Reduction** (D. Carbone)

The Phases of NUMEN project

- **Phase1**: The experimental feasibility
- **Phase2**: "hot" cases optimizing the experimental conditions, getting first results and complete the tender for the new accelerator and detector (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									

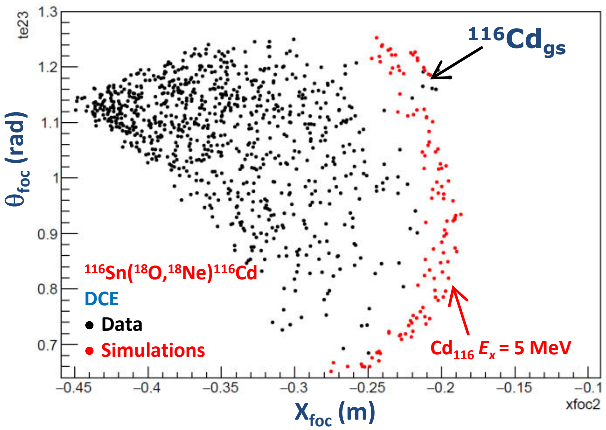
Results from a test run on $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ October 2015

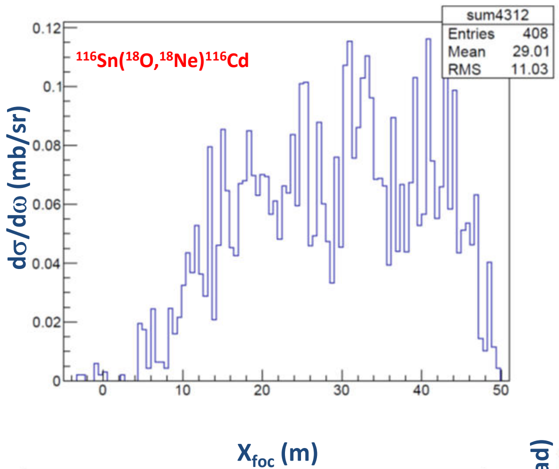
Valuable job from our young collaborators

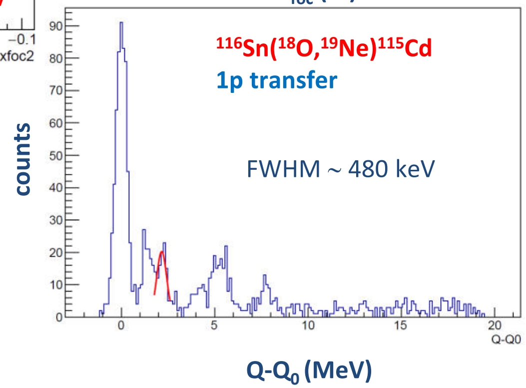
- ✓ E_{beam}=15MeV/u, target thickness 400 μg/cm^2
- ✓ 150μC integrated charge in 50 hours at 1 enA (including dead time 50%)
- ✓ Detector and beam transport performances studied up to 6 enA
- ✓ Realistic cross section estimate for DCE

Preliminary

Good sensitivity for DCE



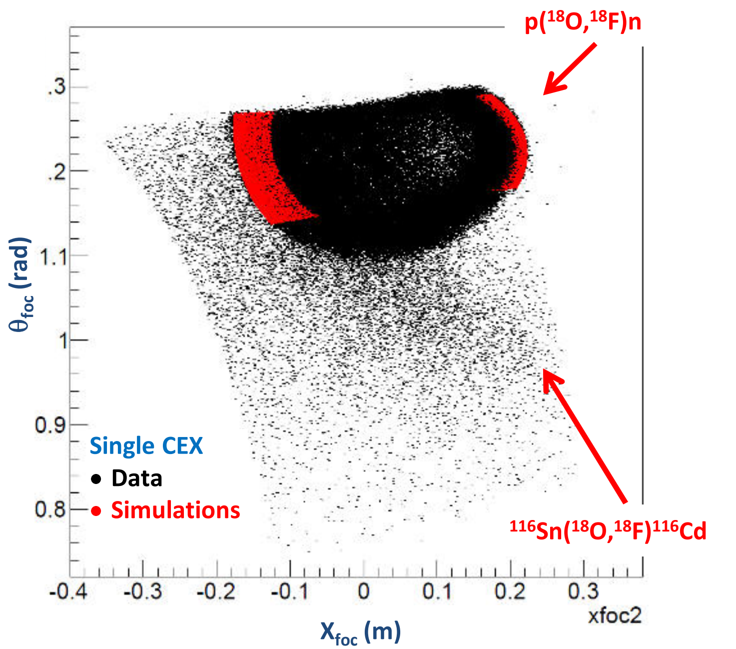




Perhaps 4 counts for $^{116}Sn_{gs} \rightarrow {}^{116}Cd_{gs}$

Experiment at 15 MeV/u just finished

Good energy resolution and accuracy



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	**Performed experiment at 15 MeV/u**											
$^{116}Cd\ (^{20}Ne,^{20}O)\ ^{116}Sn$	15-25	**Performed 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												

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
- It is playing an important role for **attracting worldwide researchers at the LNS,** (more than 50 in 2015)
- It is playing a key role for nuclear physics in Italy. **INFN-LNS was recently included** in the restricted list of **italian strategical reserach projects**
- **Results** of relevance for $0\nu\beta\beta$ physics are expected **soon**

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

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

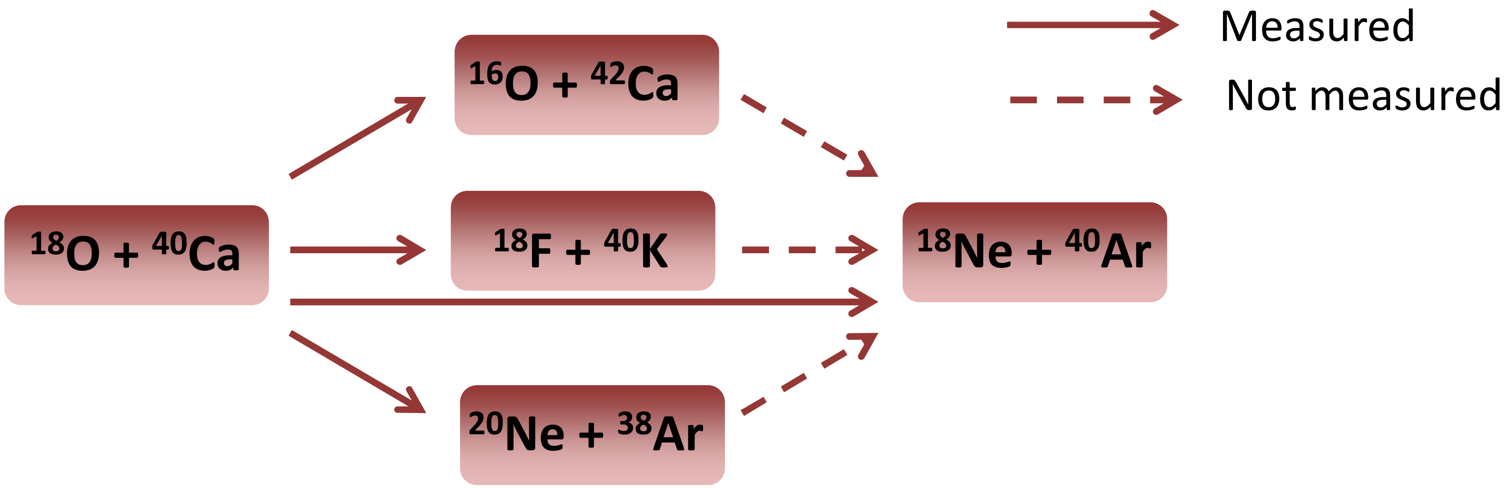
First pilot experiment

$0^{\circ} < \vartheta_{lab} < 10^{\circ}$ 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

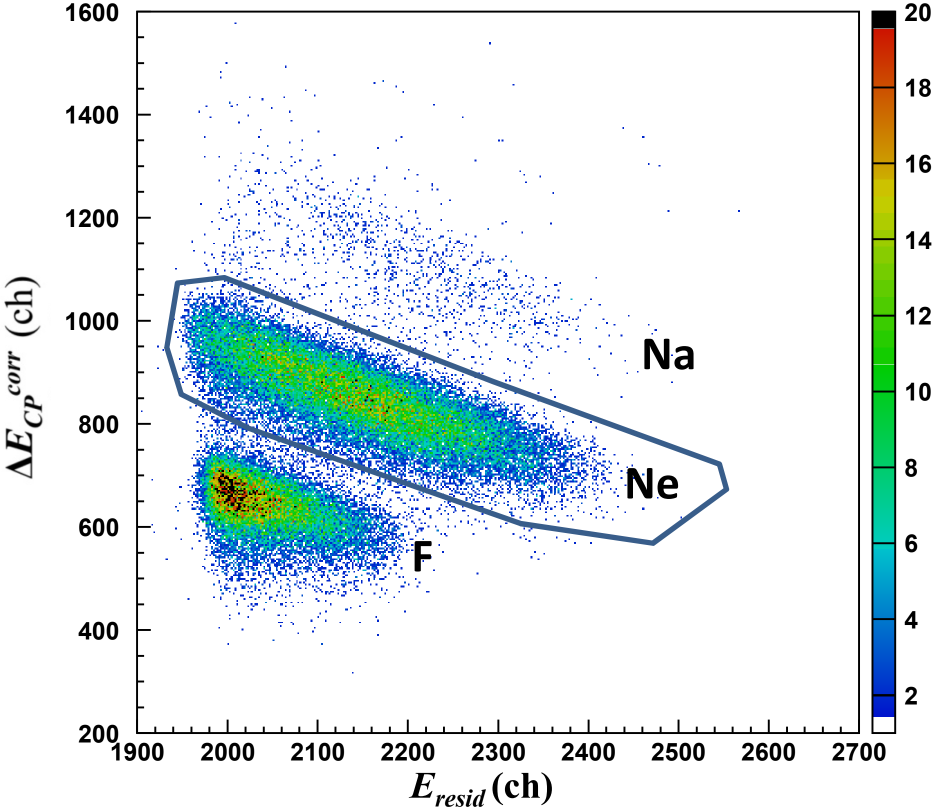
Experimental Set-up

- $^{18}O^{7+}$ 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
- Unique angular setting: $-2° < \theta_{lab} < 10°$ corresponding to a momentum transfer range **from 0.17 fm^{-1} to about 2.2 fm^{-1}**



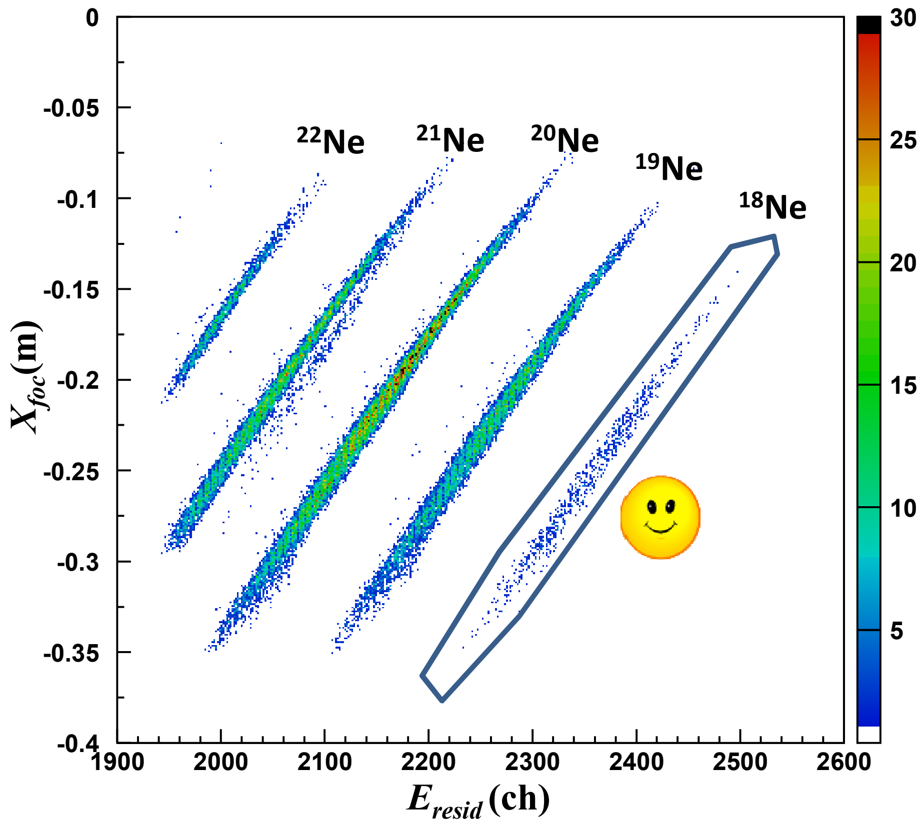
Particle Identification

Z identification



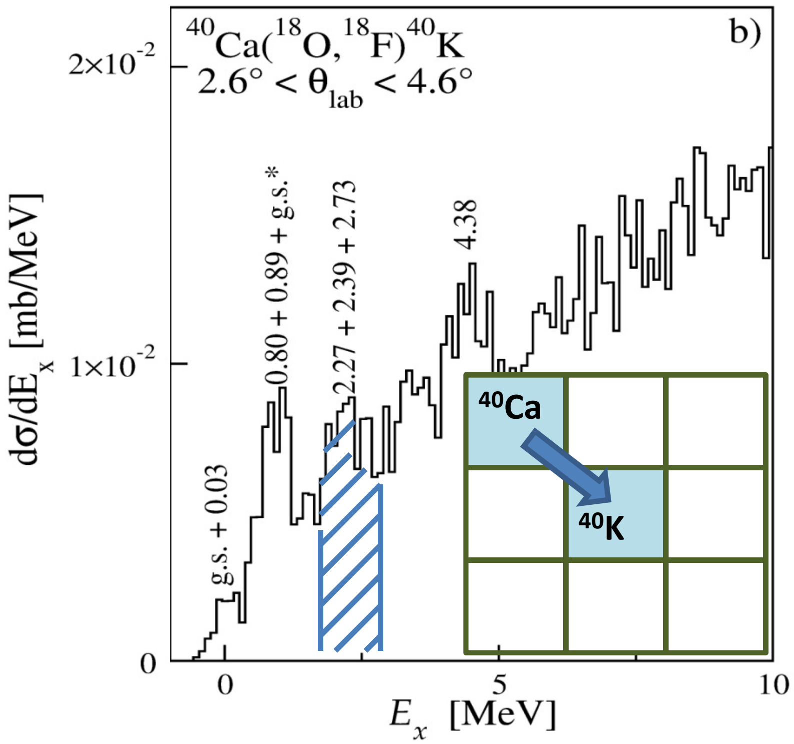
A identification

$$B\rho = \frac{p}{q} \rightarrow X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



A. Cunsolo, et al., NIMA484 (2002) 56
A. Cunsolo, et al., NIMA481 (2002) 48
F. Cappuzzello et al., NIMA621 (2010) 419
F. Cappuzzello, et al. NIMA638 (2011) 74

Single CEX $^{40}Ca(^{18}O,^{18}F)^{40}K$ at 15 MeV/u



x-section (2MeV < E_x < 3MeV)

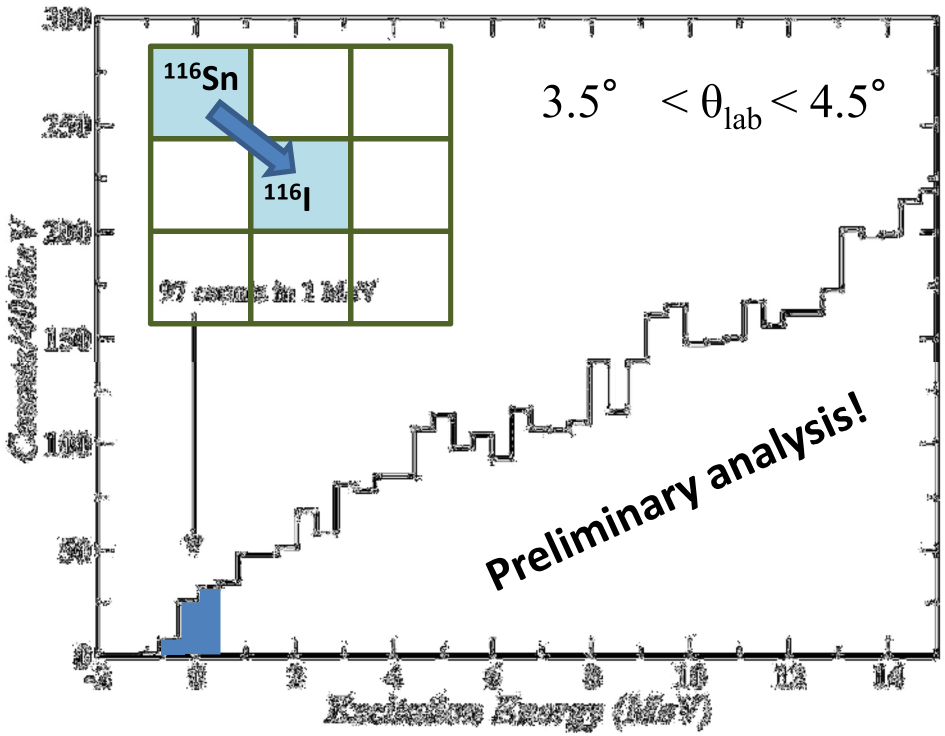
≈ 0.5 mb/sr

Extracted B(GT) = 0.087±0.01

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

Y. Fujita

Single CEX $^{116}Sn(^{18}O,^{18}F)^{116}In$ at 25 MeV/u



x-section (within 1 MeV)

≈ 0.17 mb/sr

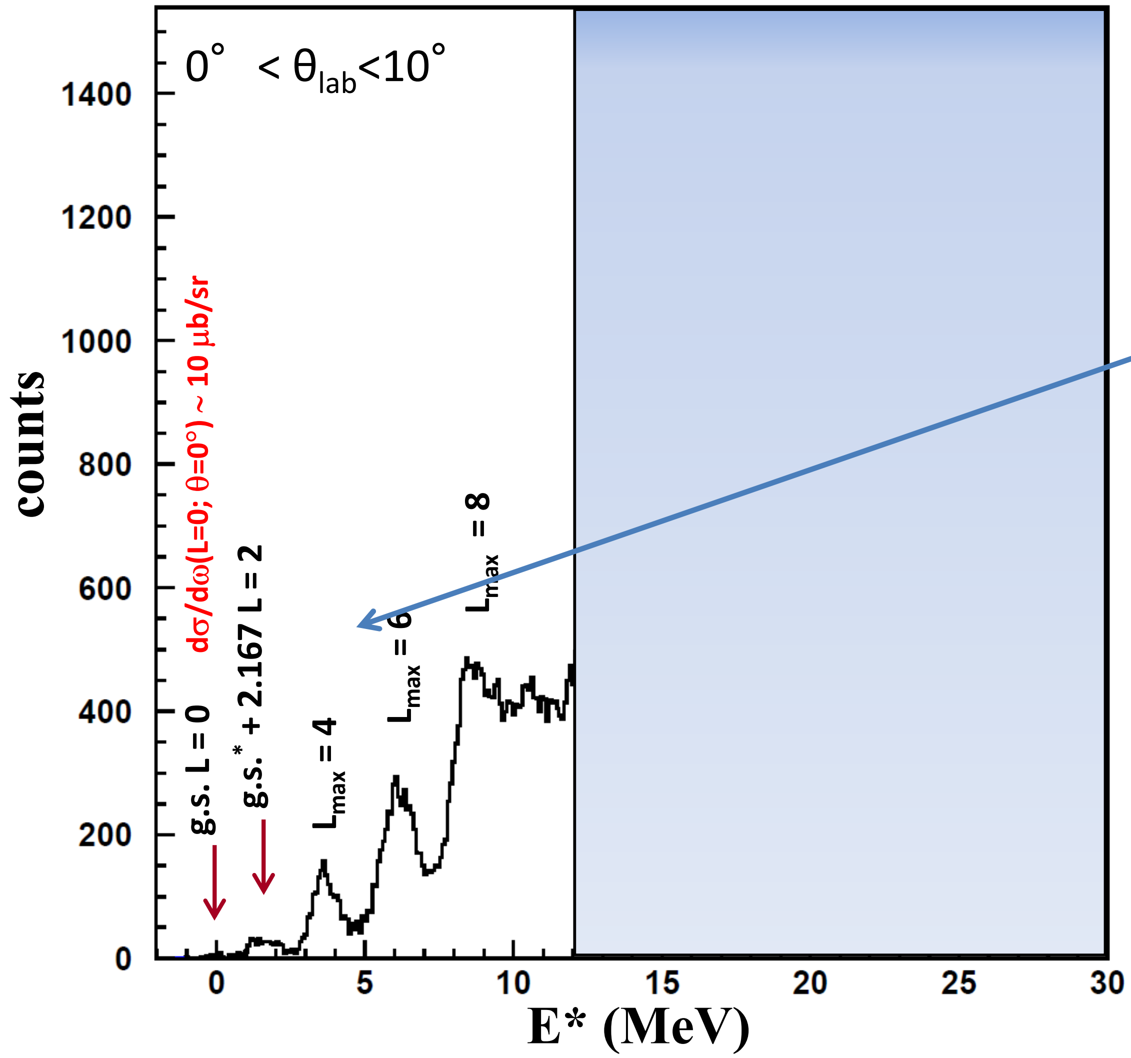
Extracted upper limit for B(GT) < 0.8

B(GT) from (d,^{2}He) = 0.4

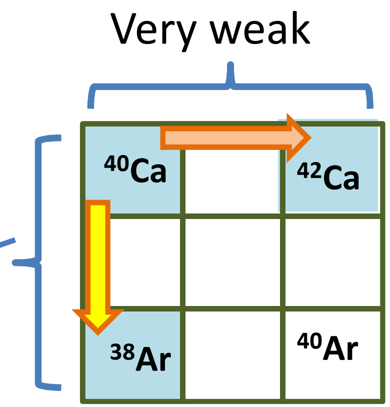
S.Rakers, et al., PRC 71 (2005) 054313

The role of the transfer reactions

$^{40}Ca(^{18}O,^{20}Ne)^{38}Ar$ @ 270 MeV



Suppression of the $^{40}Ca(^{18}O,^{16}O)^{42}C$ channel



Suppression of L = 0 in the pair transfer

Suppression of L > 0 in the double pair transfer

Less than 1% effect in the DCE cross section

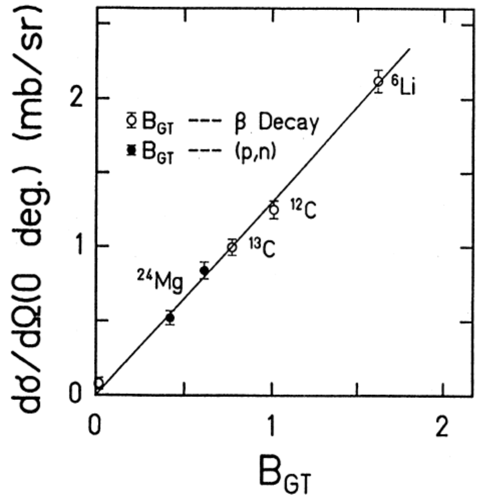
Connection between β-decay and Single Charge Exchange

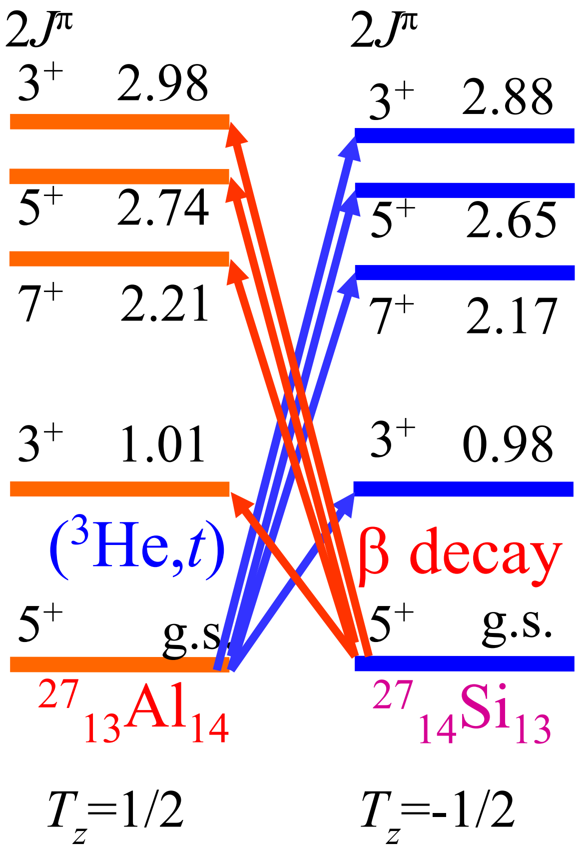
Y. Fujita Prog. Part. Nuc. Phys. 66 (2011) 549
H. Ejiri Phys. Rep. 338 (2000) 256
F. Osterfeld Rev. Mod. Phys. 64 (1992) 491
T.N. Taddeucci Nucl. Phys. A 469 (1997) 125

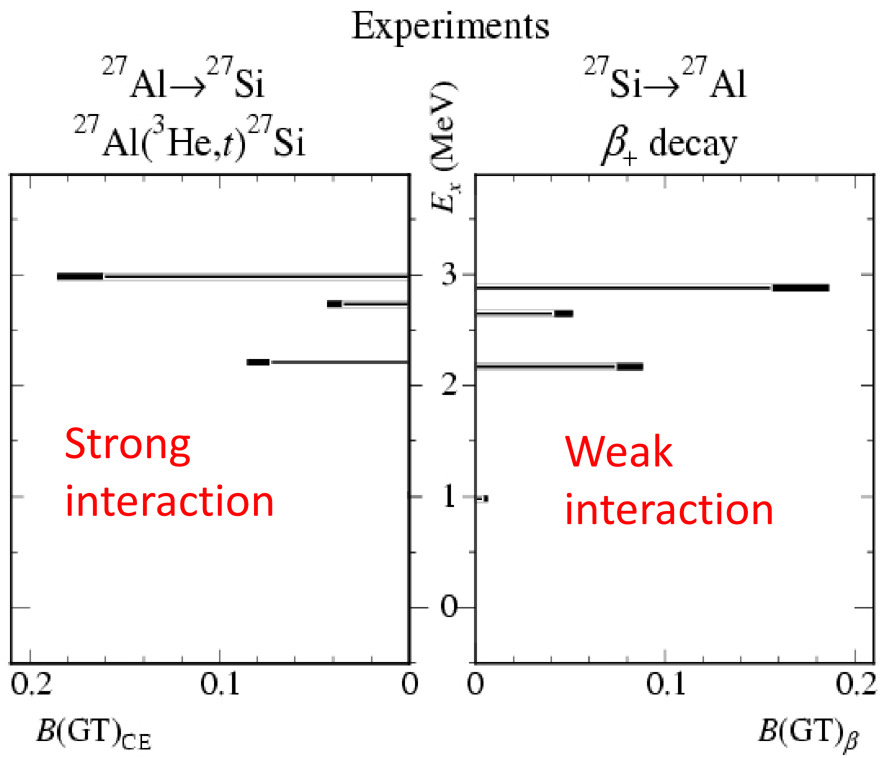
- (^{3}He,t): In general for B(GT)>0.05

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

- Similar results for the (d,^{2}He)







For heavier projectiles

(^{7}Li,^{7}Be)

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

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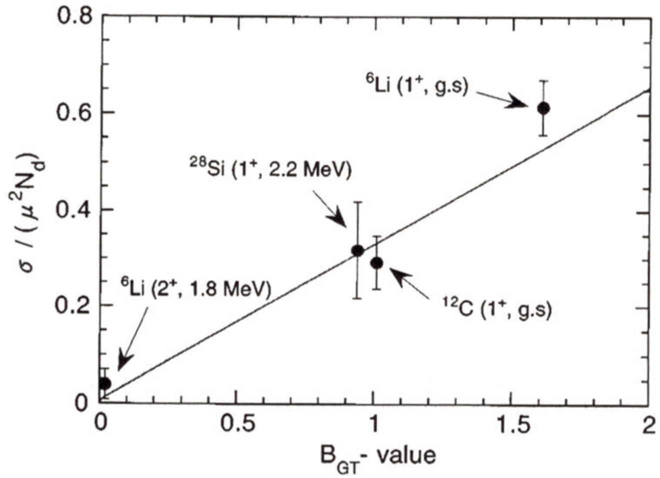
Available online at www.sciencedirect.com
SCIENCE DIRECT
Nuclear Physics A 739 (2004) 30–56
NUCLEAR PHYSICS A
www.elsevier.com/locate/npe

Analysis of the ^{11}B(^{7}Li, ^{7}Be)^{11}Be reaction at 57 MeV in a microscopic approach

F. Cappuzzello [a,*], H. Lenske [b], A. Cunsolo [a,c], D. Beaumel [d], S. Fortier [d], A. Foti [c,e], A. Lazzaro [a,c], C. Nociforo [a], S.E.A. Orrigo [a,c], J.S. Winfield [a]

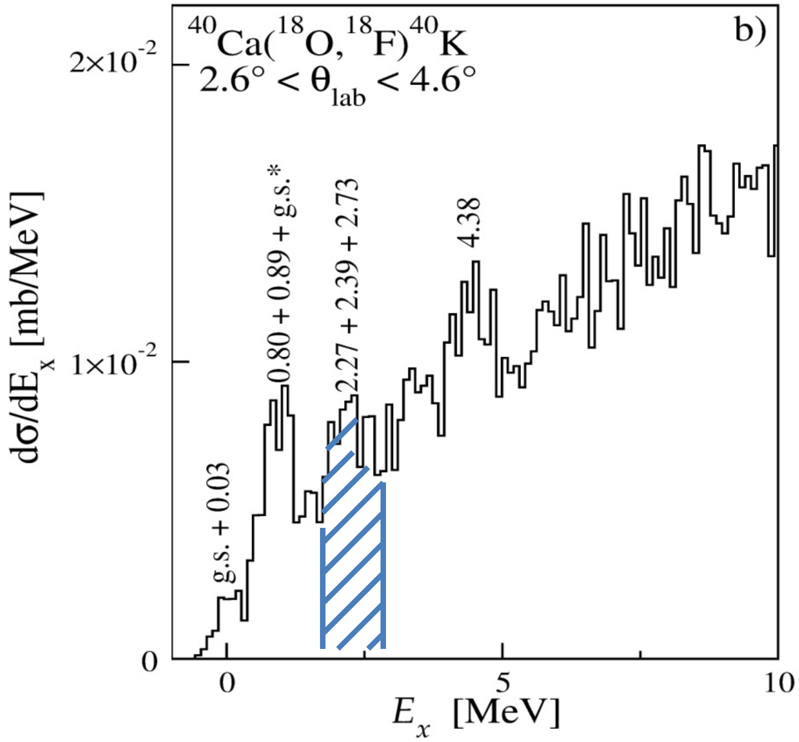
See also
F.Cappuzzello et al. *Phys.Lett B* 516 (2001) 21-26
F.Cappuzzello et al. EuroPhys.Lett 65 (2004) 766-772
S.E.A.Orrigo, et al. *Phys.Lett. B* 633 (2006) 469-473
C.Nociforo et al. *Eur.Phys.J. A* 27 (2006) 283-288
M.Cavallaro Nuovo Cimento C 34 (2011) 1

S. Nakayama PRC 60 (1999) 047303



- ✓ Confirmed by us on different nuclei: ^{11}Be, ^{12}B, ^{15}C, ^{19}O
- ✓ Microscopic and unified theory of reaction and structure is mandatory for quantitative analyses
- ✓ Best results for transitions among isospin multiplets in the projectiles as (^{7}Li$_{gs(3/2-)}$,^{7}Be$_{gs(3/2-)}$)
- ✓ (^{18}O$_{gs(0+)}$,^{18}F$_{gs(1+)}$) should be better than (^{7}Li,^{7}Be) even if not really explored to now

Single CEX $^{40}Ca(^{18}O,^{18}F)^{40}K$ at 15 MeV/u



x-section ($2MeV < E_x < 3MeV$)

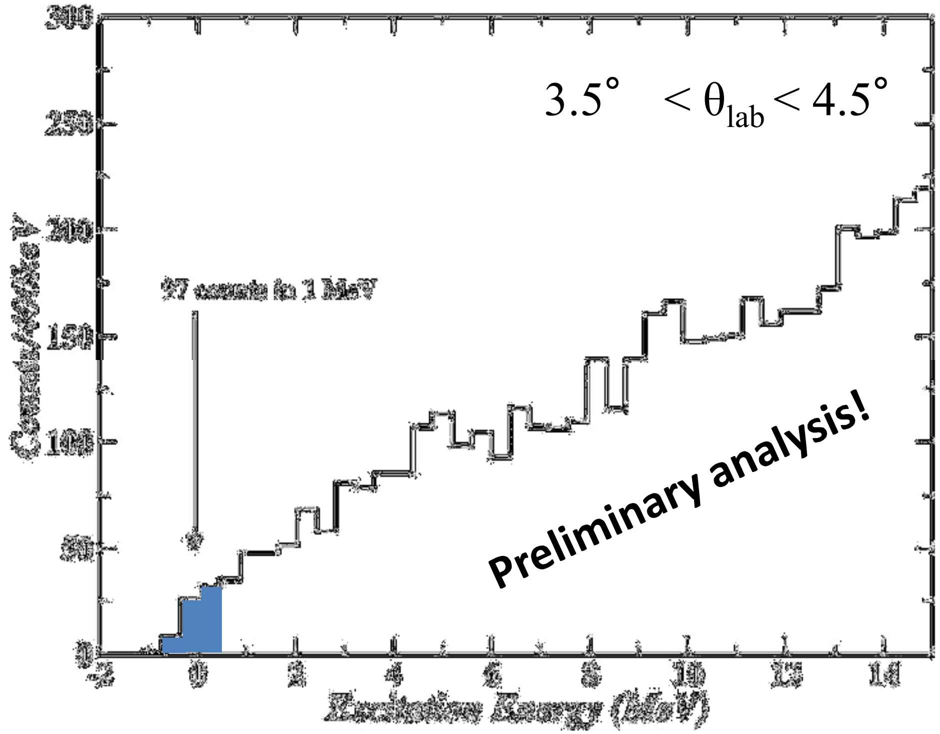
≈ 0.5 mb/sr

Extracted B(GT) = 0.087

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

Y. Fujita

Single CEX $^{116}Sn(^{18}O,^{18}F)^{116}In$ at 25 MeV/u



x-section (within 1 MeV)

≈ 0.17 mb/sr

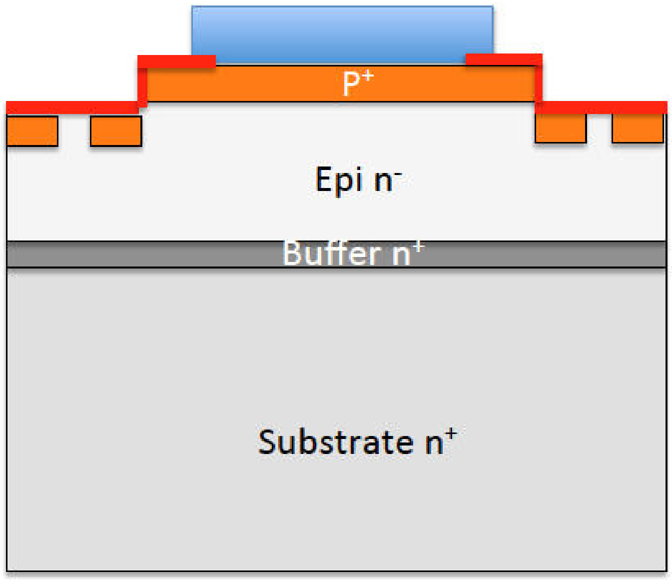
Extracted upper limit for B(GT) < 0.8

B(GT) from (d,^{2}He) = 0.4

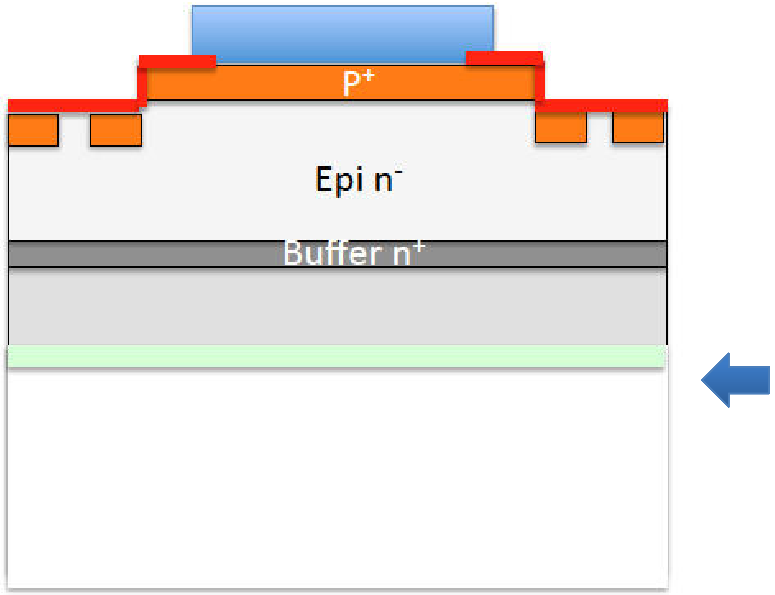
S.Rakers, et al., PRC 71 (2005) 054313

Epi Th= 100 μm
N=5-8e13 /cm^3

Rivelatore ΔE

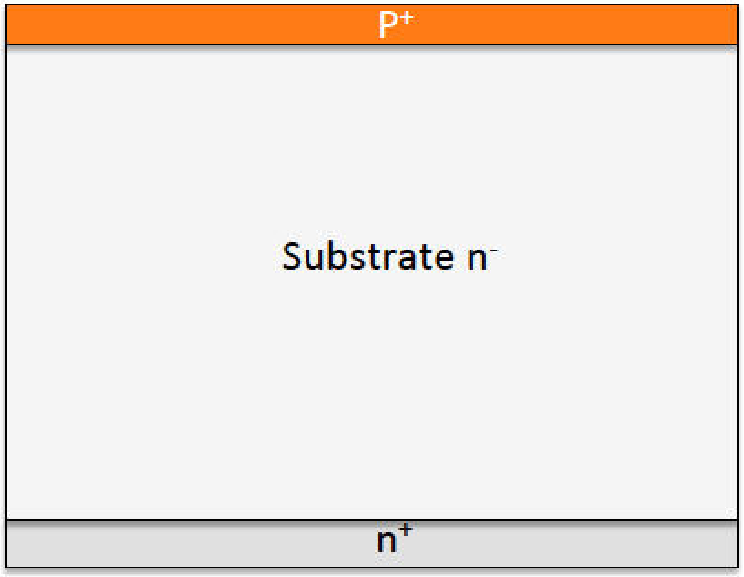


Ossidazione e metallizzazione fronte

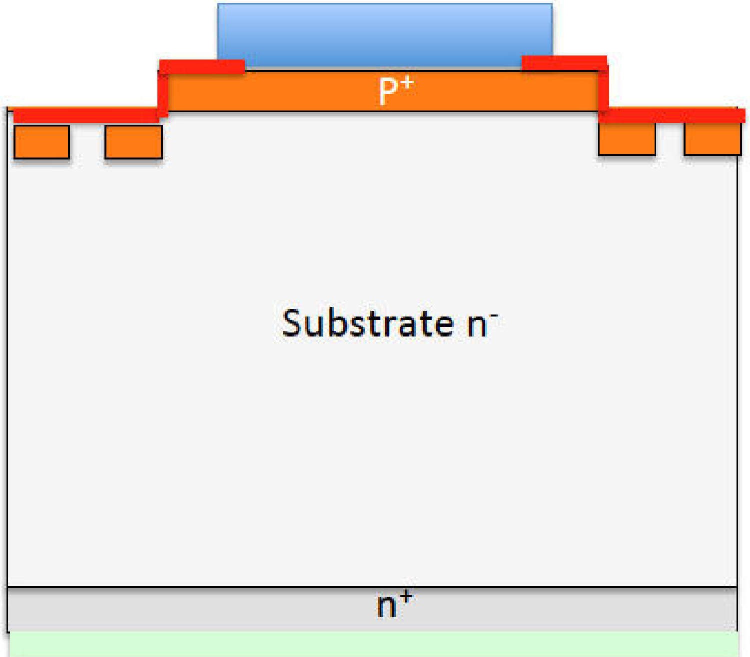


Riduzione spessore e metallizzazione retro

Rivelatore E



Epitassia di anodo e catodo su substrato intrinseco (ETC)



Stesso processo dell'altro rivelatore

About the reaction mechanism

Factorization of the charge exchange cross-section

β-decay transition strengths
(reduced matrix elements)

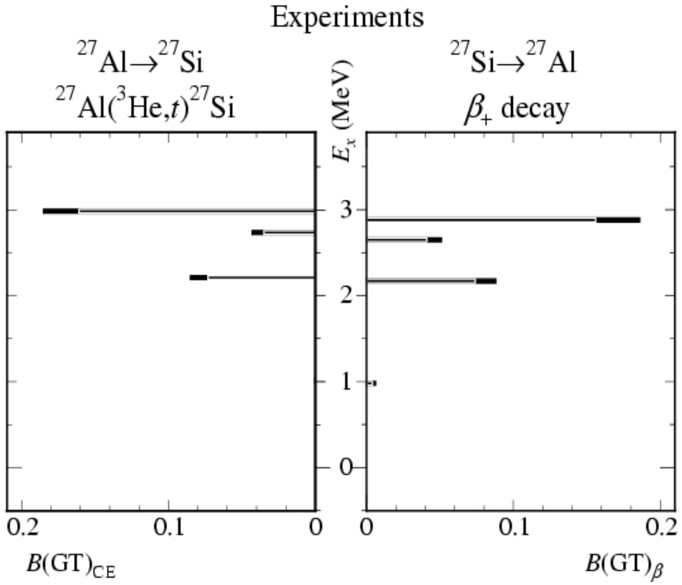
for single CEX:

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

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

unit cross-section

Talk of S.E.A. Orrigo



generalization to DCE:

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

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

The unit cross section

Single charge-exchange

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

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

Double charge-exchange

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

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)

$\hat{\sigma}_\alpha^{DCE}(E_p, A)$ is the Holy Graal

If known it would allow to determine the NME from DCE cross section measurement, whatever is the strenght fragmentation

The volume integrals

Nuclear spin and isospin excitations

Franz Osterfeld

Reviews of Modern Physics, Vol. 64, No. 2, April 1992

- ✓ Volume integrals are **larger at smaller energies**
- ✓ They enter to the **fourth power** in the unit cross section!
- ✓ **GT-like % F-like competion** at low energy

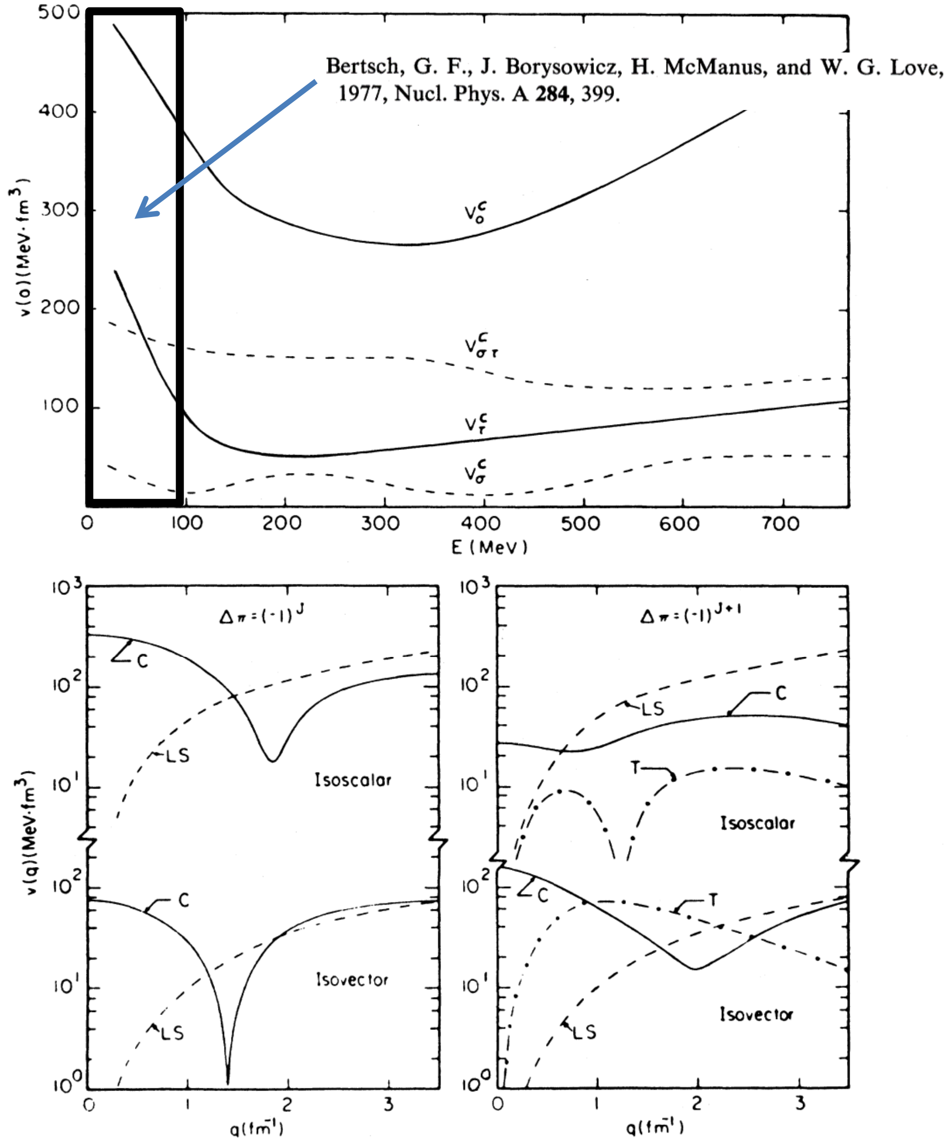
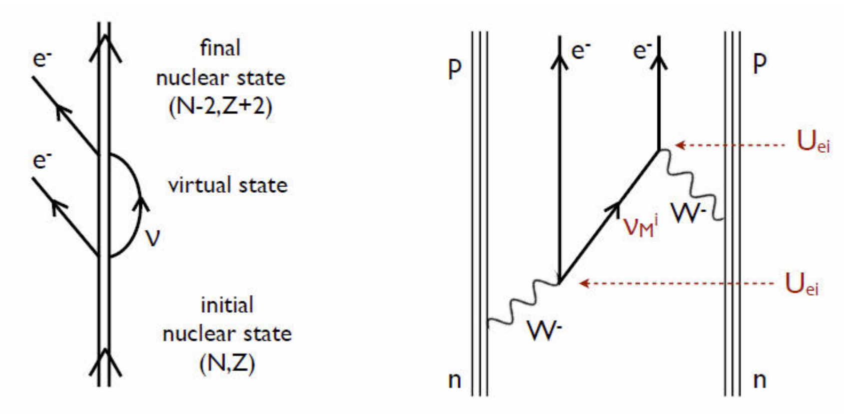
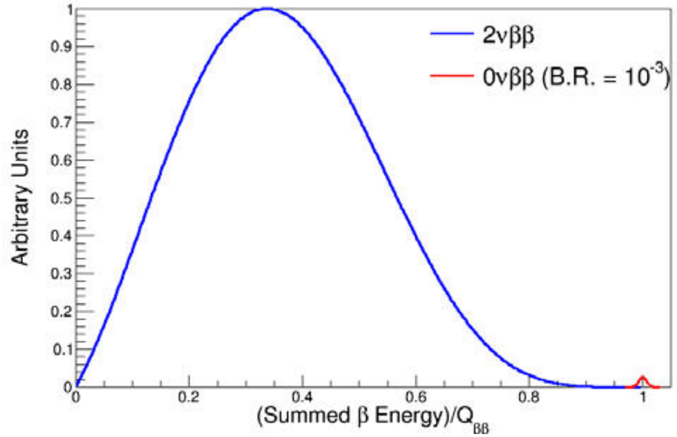
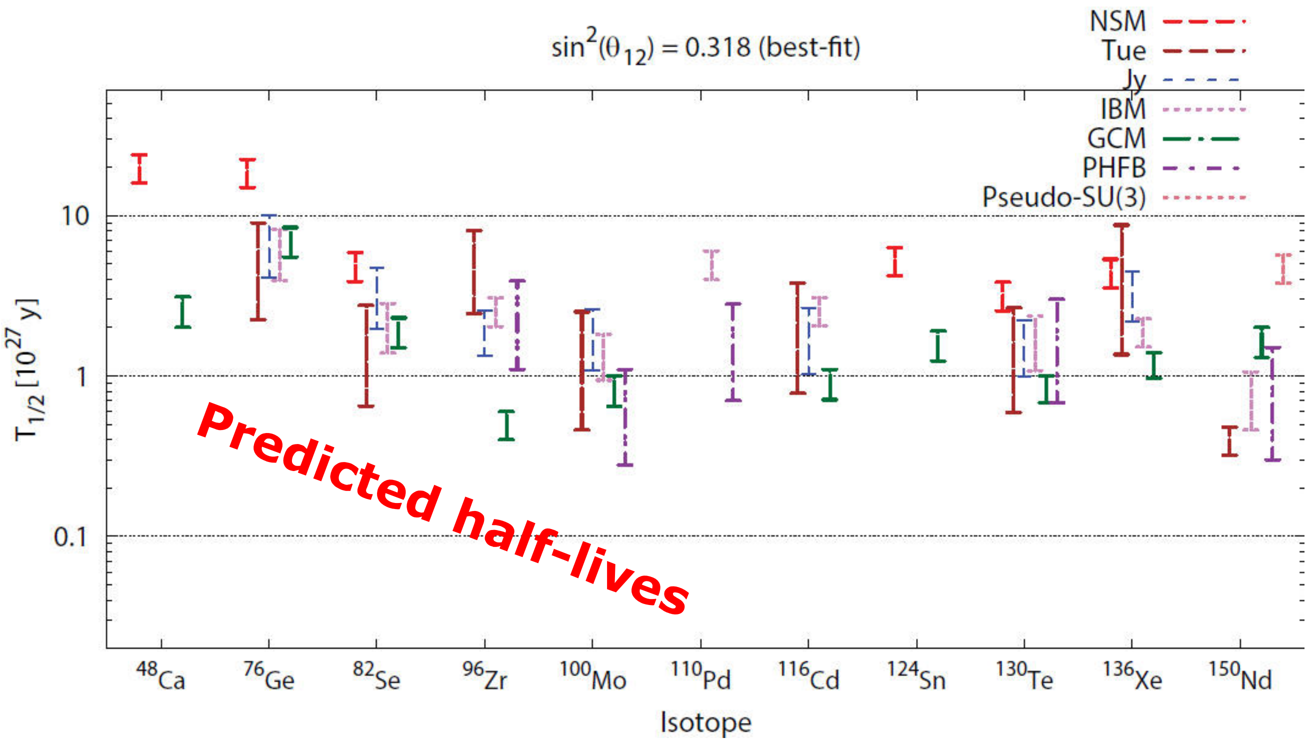


FIG. 15. Energy and momentum dependence of the free nucleon-nucleon t_F matrix. The upper part of the figure shows the energy dependence of the central components of the effective t_F matrix at zero-momentum transfer (including direct and exchange terms). The *G*-matrix interaction of Bertsch *et al.* (1977) was used below 100 MeV and joined smoothly to the t_F matrix above 100 MeV. The lower figures show the momentum dependence of the 135-MeV t_F matrix for natural-(left figure) and unnatural-(right figure) parity transitions. Isoscalar and isovector central (*C*), spin-orbit (*LS*), and tensor (*T*) components are shown. From Petrovich and Love (1981).

Neutrino-less double β-decay







The NUMEN goals

3

Compare sensitivity

Sensitivity of different half-life experiments

1

NUMEN Holy Graal

Studying if the σ^{DCE} is a smooth function of E_p and A

2

Calculations constraints

A new generation of DCE constrained $0\nu\beta\beta$ NME theoretical calculations can emerge