NUMEN: outlook towards high beam intensities experiments

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NUclear Matrix Elements for Neutrinoless double beta decay

MEN collaboration

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$$1/T^{0\nu}_{1/2}\,(0^+ \rightarrow 0^+) = G_{01}\boxed{\left|M^{\beta\beta\,0\nu}\right|^2}$$

ming collaborations

ctions
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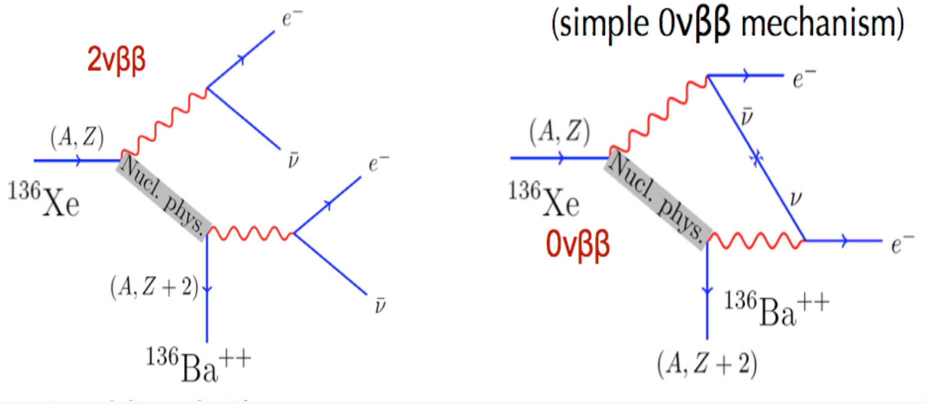
NATIONAL LABORATORY

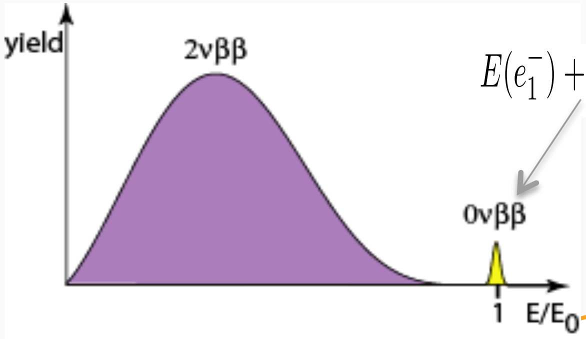
from **neutrino oscillations** we know → **neutrino mass ≠ 0**

What about the m_ν **absolute value** and the neutrino **nature** :

Dirac or Majorana particle?

Double β-decay





$E(e_1^-)+E(e_2^-)\simeq Q\equiv M_i-M_f$

DBD : (A, Z) (A, Z+2) + 2e⁻ + $2\nu_e$

- Respect the co

irac and Ma

$\approx 10^{19-21}\,y$

observed in several nuclei

^{82}Se, ^{100}Mo, ^{48}Ca,^{76}Ge, …

(1935)

The very rare **0νββ** decay is potentially the best way to probe the Majorana or Dirac nature of neutrino and to extract its effective mass.

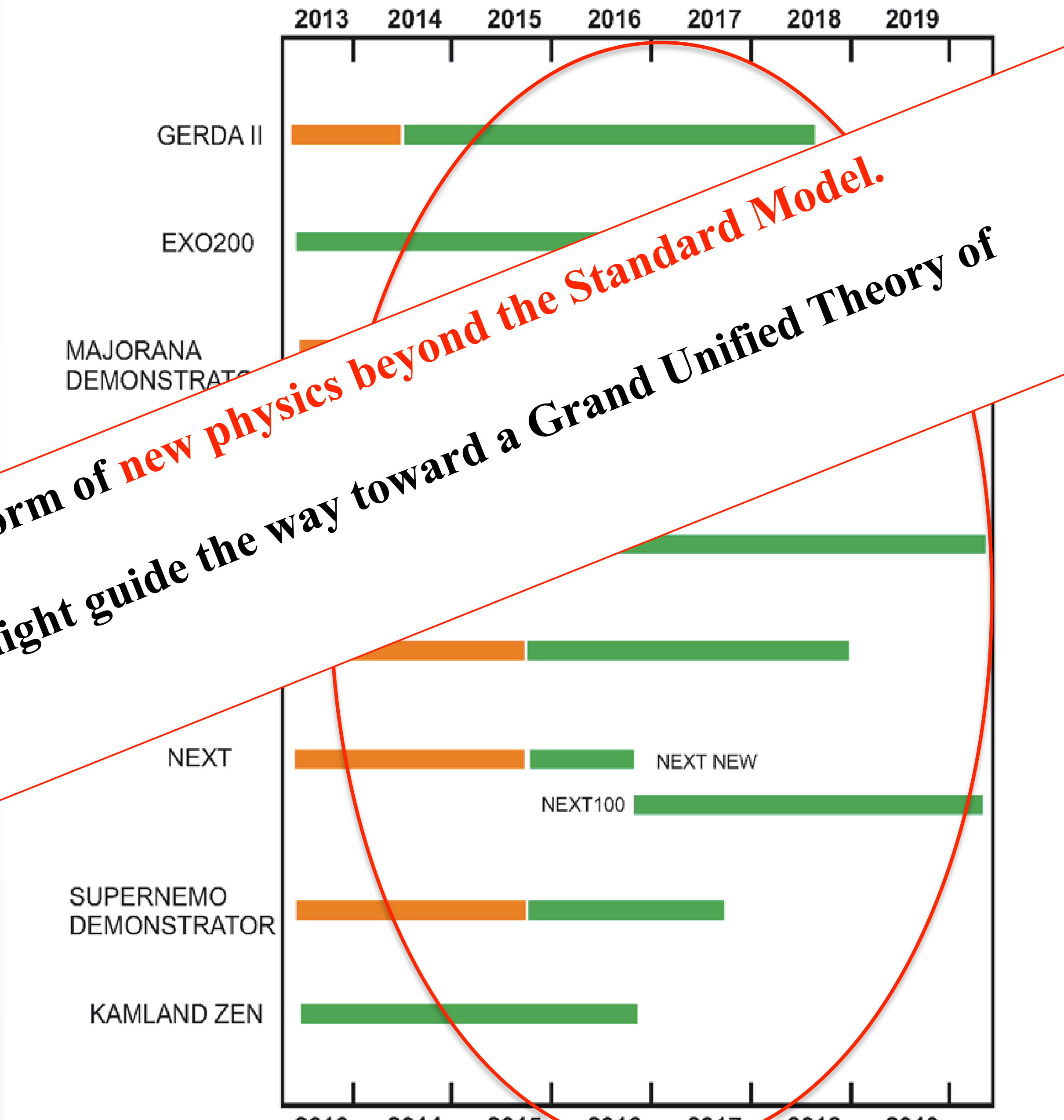
BD : (A, Z) (A, Z+2) + 2e⁻

- Neutrino has mass
- Neutrino is Majorana particle
- Violates the leptonic number conservatio

earch for $0\nu\beta\beta$ decay: a worldwide race

nt	Isotope	Lab	Status
	^{76}Ge	LNGS	Phase I completed Migration to Phase II
	^{130}Te	LNGS	Data taking / Construction
ator	^{76}Ge	SURF	Construction
	^{130}Te	SNOLAB	R&D / Construction
MO ator	^{82}Se (or others)	LSM	R&D / Constr
	^{48}C		
			&D
		apan]	R&D
	^{00}Mo	[Korea]	R&D

NLDBD Report April 24, 2014



trino mass explanations: all are based on some form of new physics beyond the Standard Model.

easurement of the neutrino masses and mixing might guide the way toward a Grand Unified Theory of undamental interactions.

The role of nuclear physics

ne **$0\nu\beta\beta$** the decay rate can be expressed as a product of independent factors, that also de function containing **physics beyond the Standard Model** throught the **masses** and the **mixi ficients of the neutrinos species :**

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

$$\langle m_\nu\rangle = \sum_i \left|U_{ei}\right|^2 m_i$$

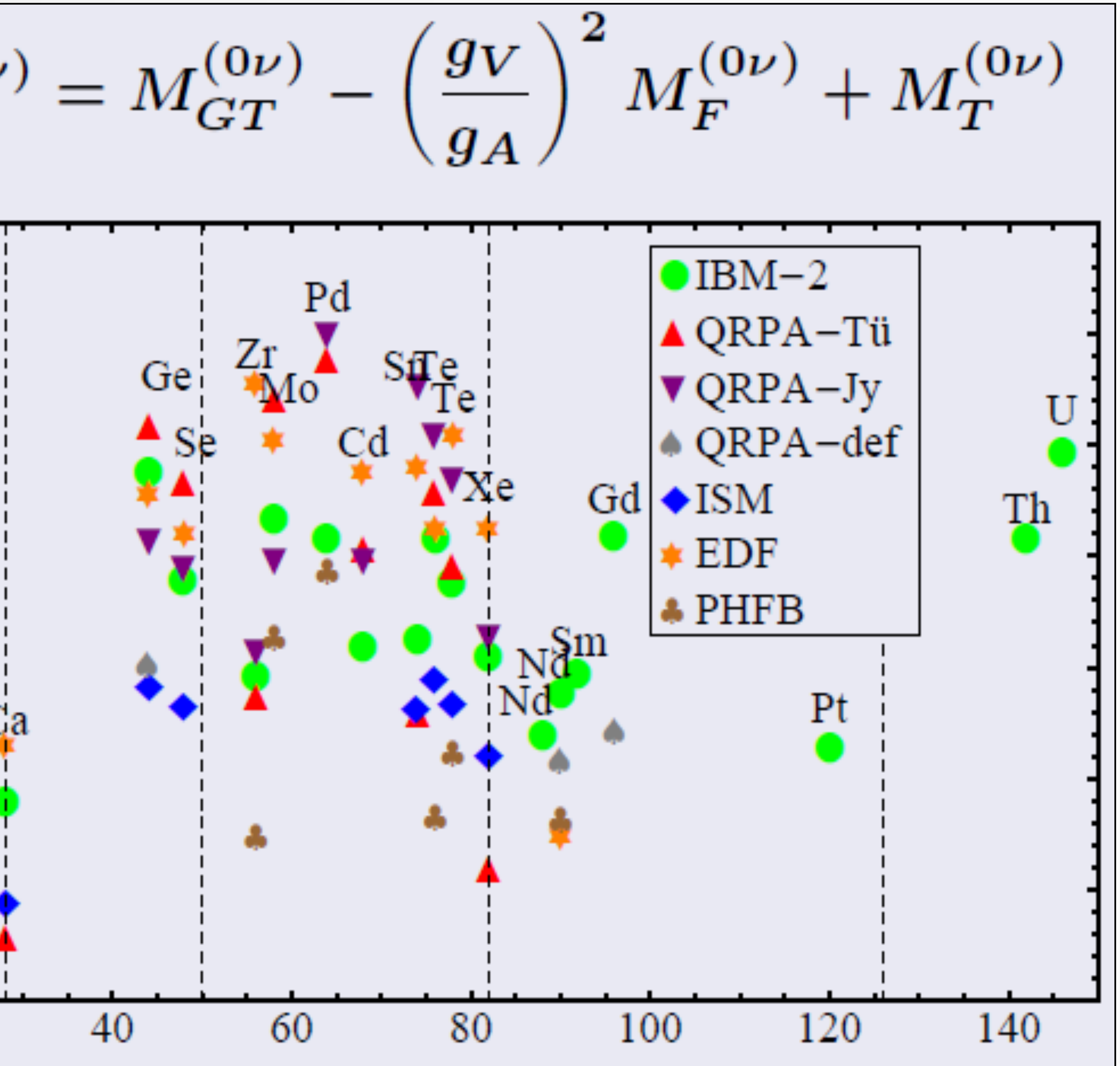
new physics inside !

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

hus, if the $M^{0\nu\beta\beta}$ nuclear matrix elements were known with sufficient precision, the eutrino mass could be established from $0\nu\beta\beta$ decay rate measurements

State of the art NME calculations

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



✓Calculations (still sizeable uncertainties): QRPA, Large scale sl model, IBM …..

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.
F.Iachello et al. NPB 237-238 (2013) 21 - 23

✓Measurements (still not conclusiv 0νββ):

(π^+, π^-)
single charge exchange (
electron capture
transfer reactions …

N. Auerbach, Ann. Of Phys. 192 (1989) 77
S.J. Freeman and J.P. Schiffer JPG 39 (2012) 124
D.Frekers, Prog. Part. Nucl. Phys. 64 (2010) 281
J.P. Schiffer, et al., PRL 100 (2008) 112501

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alitative is not enough…

The challange:

to access quantitative information !

Double charge exchange reactions

uble charge exchange reactions are characterized by the transfer of isospin $\Delta T_Z = \pm$
g the mass number unchanged

duced by strong interaction

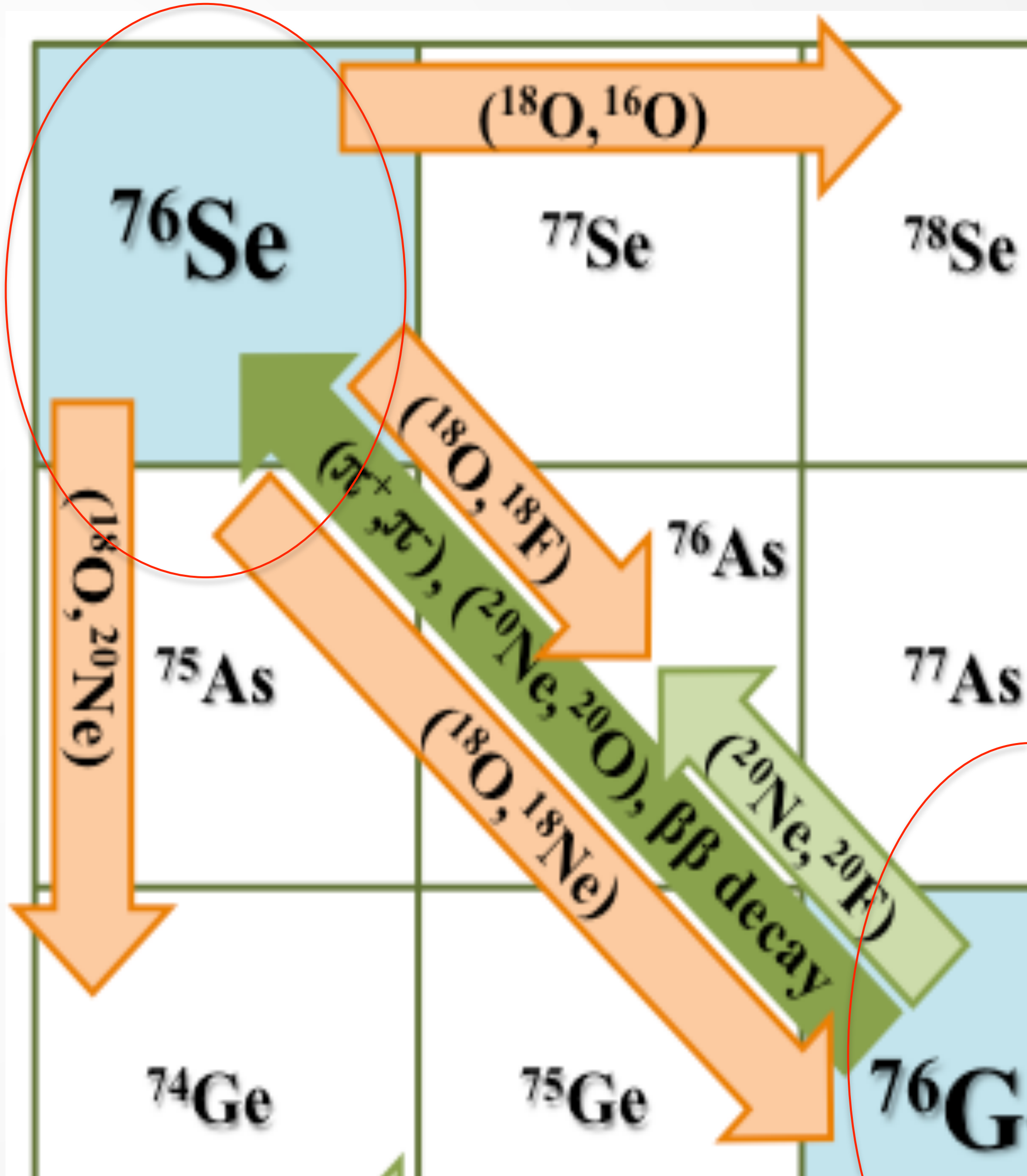
quential nucleon transfer mechanism
order:

- Brink's Kinematical matching conditions

D.M.Brink, et al., Phys. Lett. B 40 (1972) 37

eson exchange mechanism 2nd order

Possibility to go in both directions



Initial and final states: Parent/daughter states of the *0νββ* **are the same** as those of target/residual nuclei in the DCE;

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

Connection between β-decay and Single Charge Exchange

rization of the charge exchange
cross-section

$$\boxed{B(\alpha) = \frac{1}{2J_i + 1}|M(\alpha)|^2}$$

or single CEX:

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

$$\frac{B(GT)[(^3He,t);q=0]}{B(GT)[\beta_{decay}]} =$$

In the hypothesis of a surface localized process (for direct quasi elastic processes).

ple model one can assume that the DCE process is just a second order charge exchange, where projectile ar ge two uncorrelated isovector virtual mesons.

eralization
o DCE:

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

conducting Cyclotron

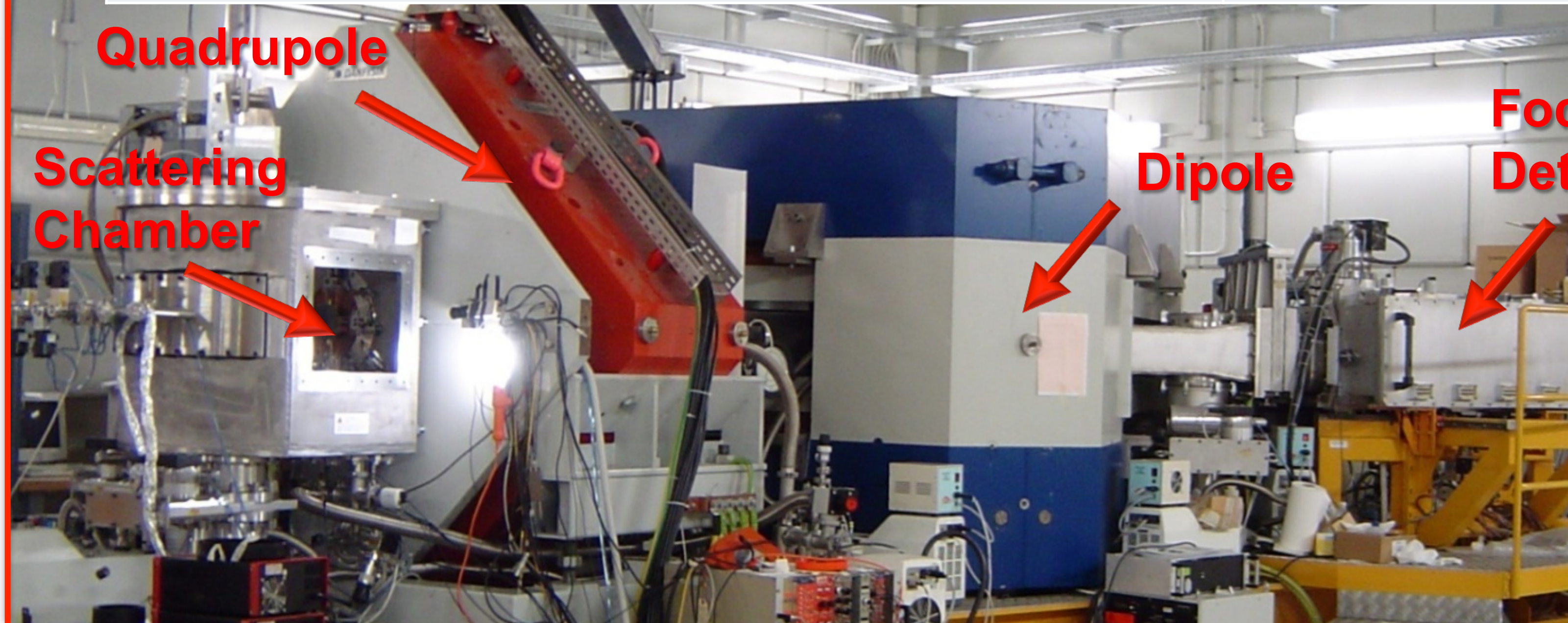
perconducting Cyclotron in full
on since 1996.
ccelerate from Hydrogen to
n.
um nominal energy is 80 MeV/u.

MAGNEX magnetic spectrometer

Achieved resolution
Energy ΔE/E ~ 1/1000
Angle Δθ ~ 0.2°
Mass Δm/m ~ 1/160

F. Cappuzzello et al., *MAGNEX: an innovative large acceptance spectrometer for nuclear reaction studies*, i Types, Uses and Safety (Nova Publisher Inc., NY, 2011) pp. 1–63.

Optical characteristics	Measured valu
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10**
Momentum dispersion for k= - 0.104 (cm/%)	3.68



Ca(O, Ne) Ar@LNS

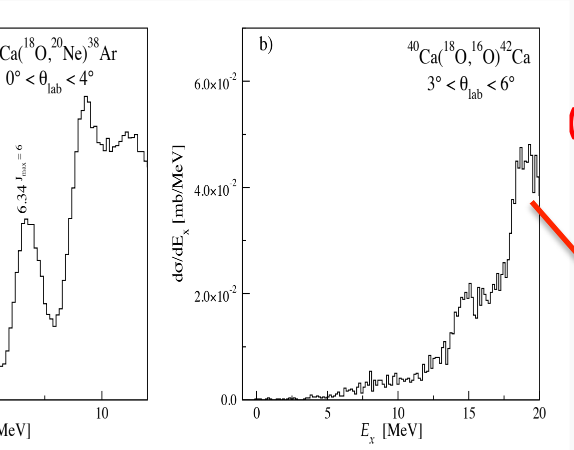
$^{18}O^{7+}$ beam from LNS Cyclotron at 270 MeV (10 pnA)

^{40}Ca solid target of 300 µg/cm²

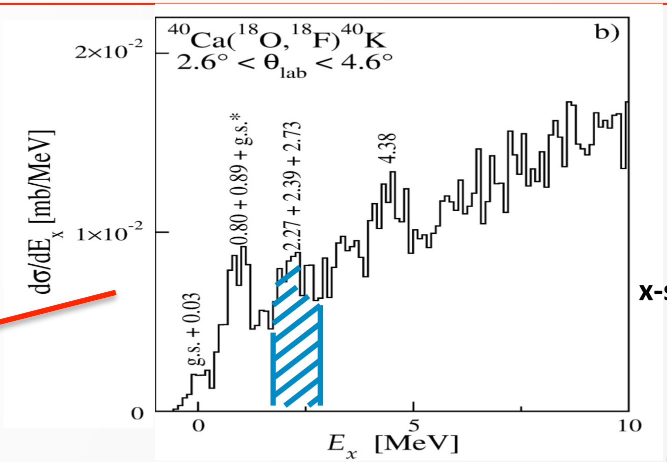
Ejectiles detected by the MAGNEX spectrometer

Angular setting

$$\theta_{opt} = 4° \longrightarrow \boxed{-2° < \theta_{lab} < 10°}$$



2n-transfer:
(^{18}O,^{16}O)^{42}Ca @ 270 MeV



x-section (2M
≈ 0.5

Extracted E

B(GT) from (
Y. I

^{16}O + ^{42}Ca

^{18}O + ^{40}Ca

^{40}Ca(^{18}O,^{18}F)^{40}K

^{18}F + ^{40}K

^{18}Ne + ^{40}Ar

^{20}Ne + ^{38}Ar

2p-transfer:
^{40}Ca(^{18}O,^{20}Ne)^{38}Ar @ 270 MeV

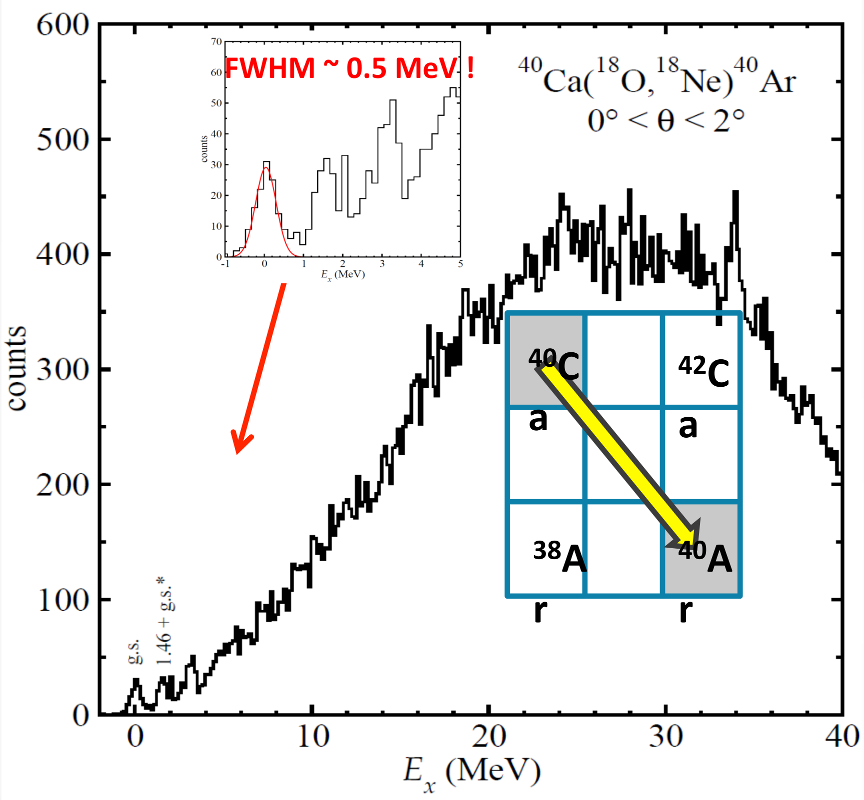
⟶ Measured

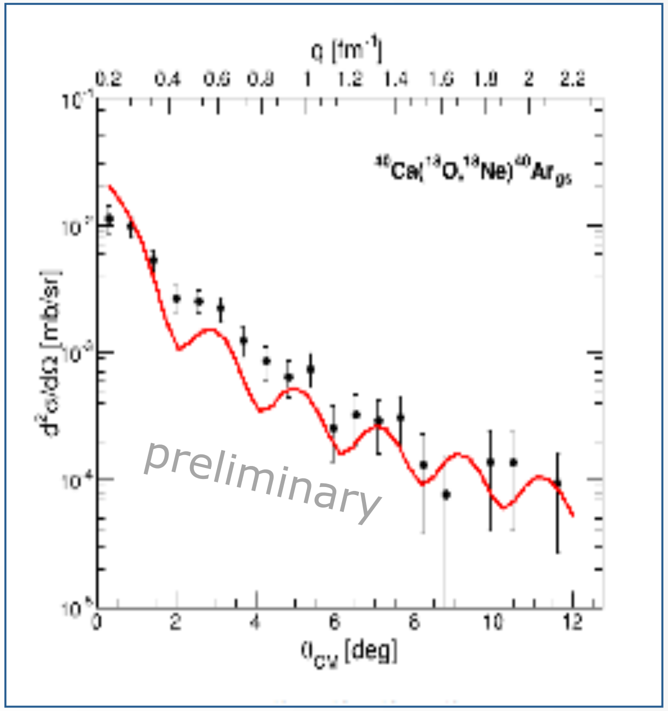
- - → Not measur

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

sured energy spectrum of ^{40}Ar at very forward angles
with an energy resolution of FWHM ~ 0.5 MeV .

Differential cross-section of the transition
$^{40}Ca_{g.s.}(^{18}O,^{18}Ne)^{40}Ar_{g.s.}$ @ 270 Mev





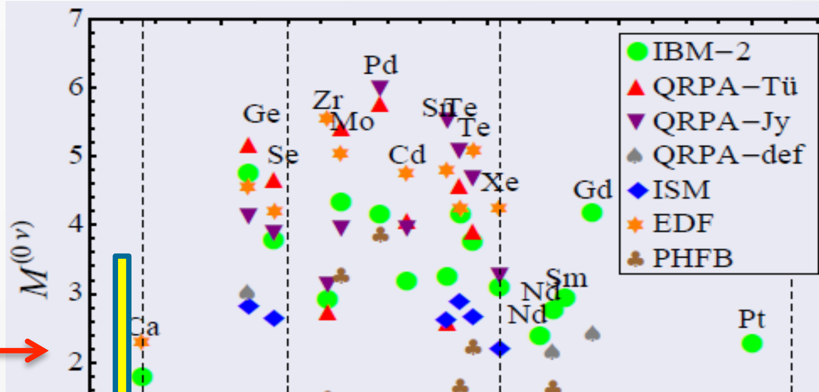
^{40}Ar 0$^+$ ground state is well separated from both the first excited
e ^{40}Ar 2$^+$ at 1.46 MeV and the ^{18}Ne excited state at 1.887 MeV

The position of the minima is well described by a Bessel function
oscillation pattern is not expectd in complex multistep transfer rea

$$d\sigma^{DCE}/d\Omega = 11 \mu b/sr \quad \text{at } \theta_{cm} = 0^0$$

speculate: a comparison between ^{48}Ca and ^{40}Ca

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



Experimental limits
moving towards "hot-cases" :

Determination of nuclear matrix elements seems to be at
our reach… but :

The (^{18}O,^{18}Ne) reaction is particularly advantageous, but it is of $\beta^+\beta^+$ kin

None of the reactions of $\beta^-\beta^-$ kind looks like as favourable as the (^{18}O,^{18}

(^{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 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. f
the excited states in the final nucleus → Coincident detection of γ-rays

Much higher beam current is needed !

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sent technology is not enough…

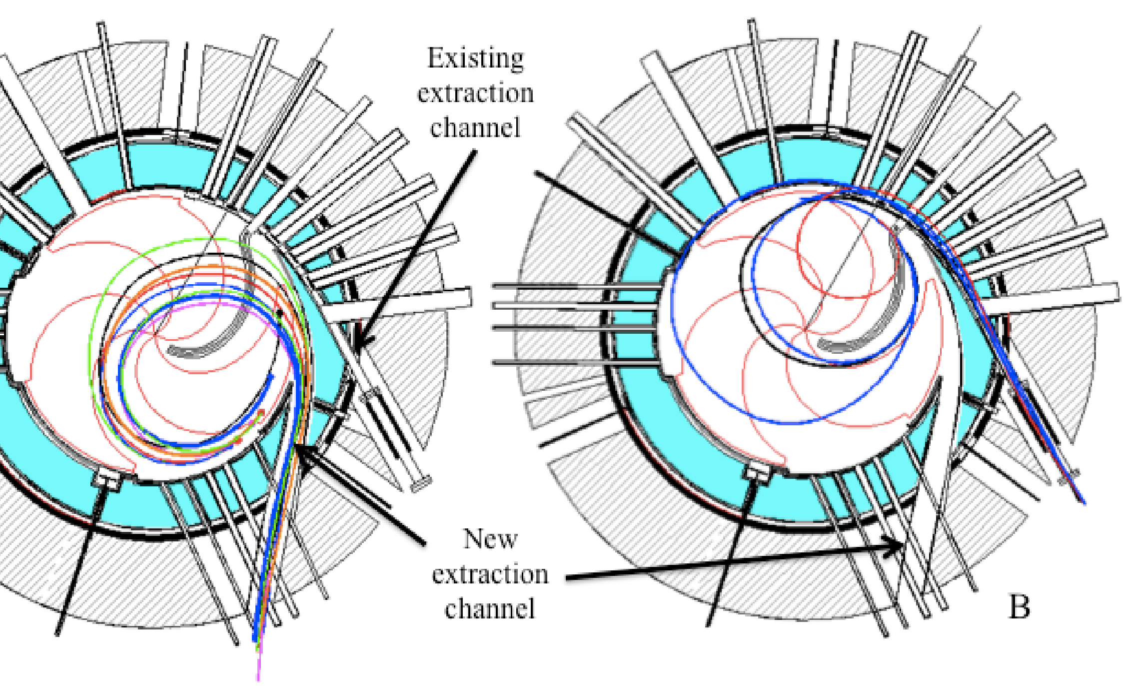
The challange:
to measure at very high rates of heavy ions!

Upgraded set-up to work with two orders of magnitude more current than the presen

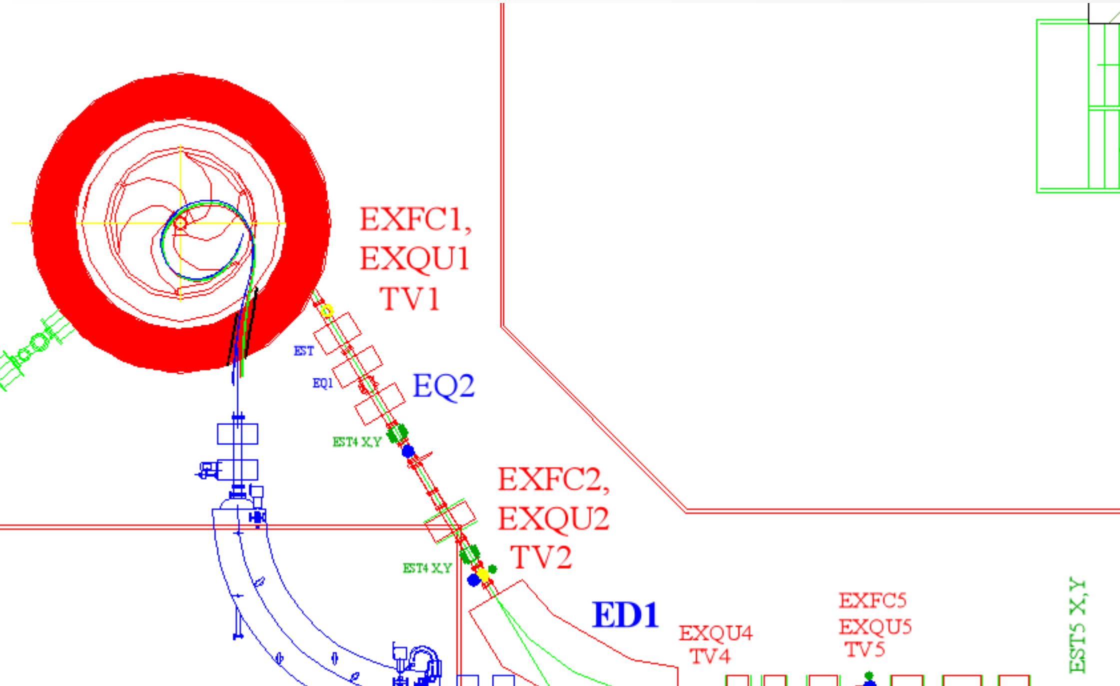
Substantial change in the technologies used in CS and in the MAGNEX detector

Major upgrade of LNS facilities: The CS accelerator

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



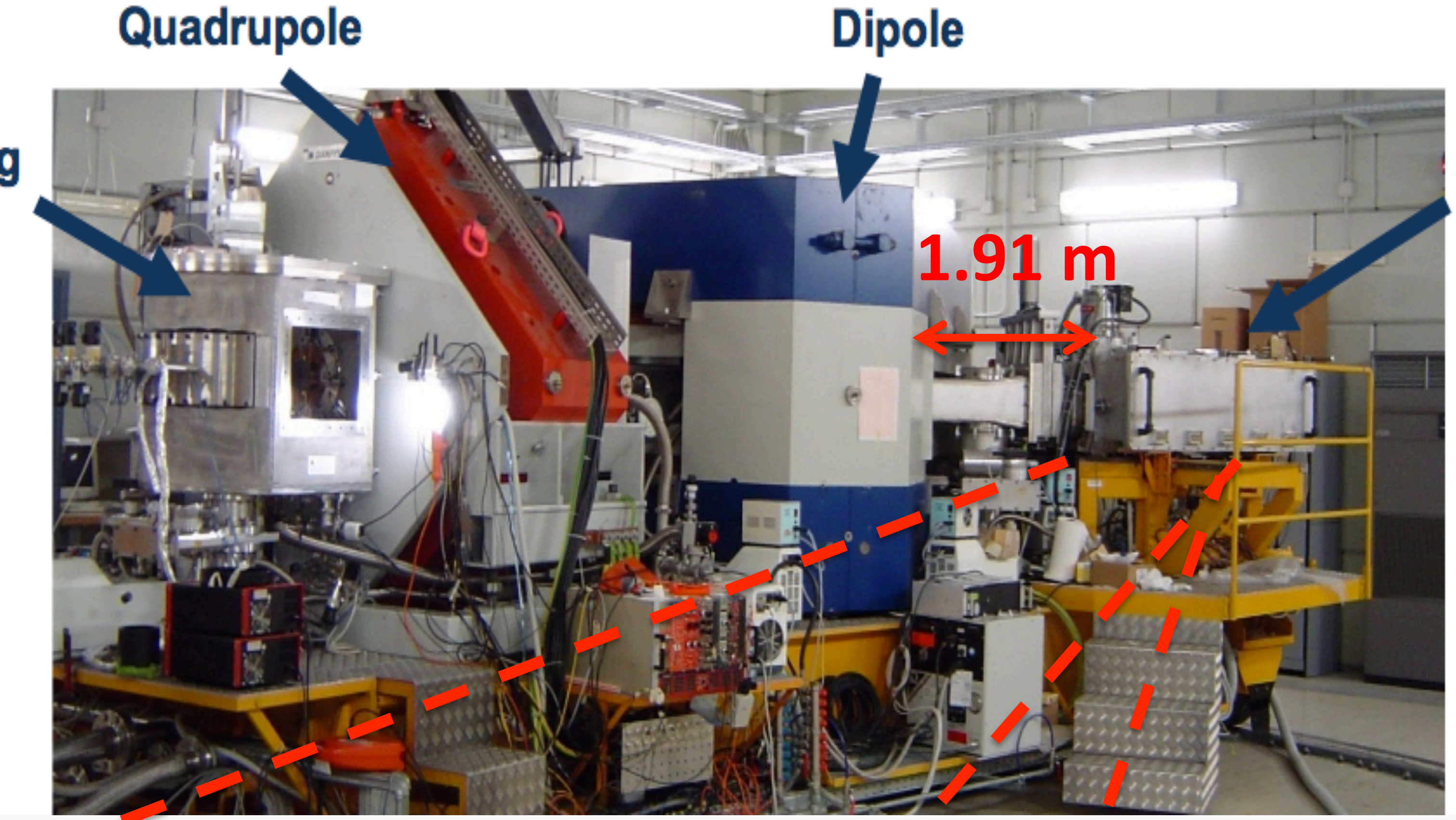
From electrostatic extraction to extraction by stripping



The **beam transport line**

ansmission efficiency to

early 100%



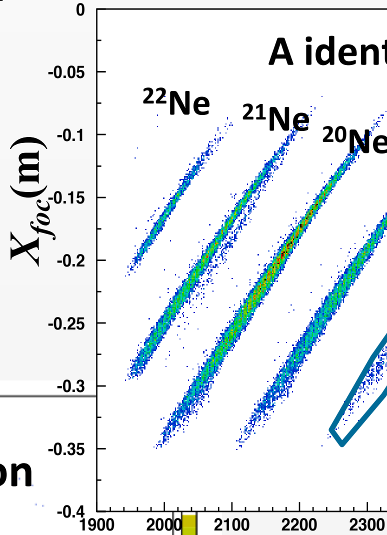
Focal Plane Detector

active area

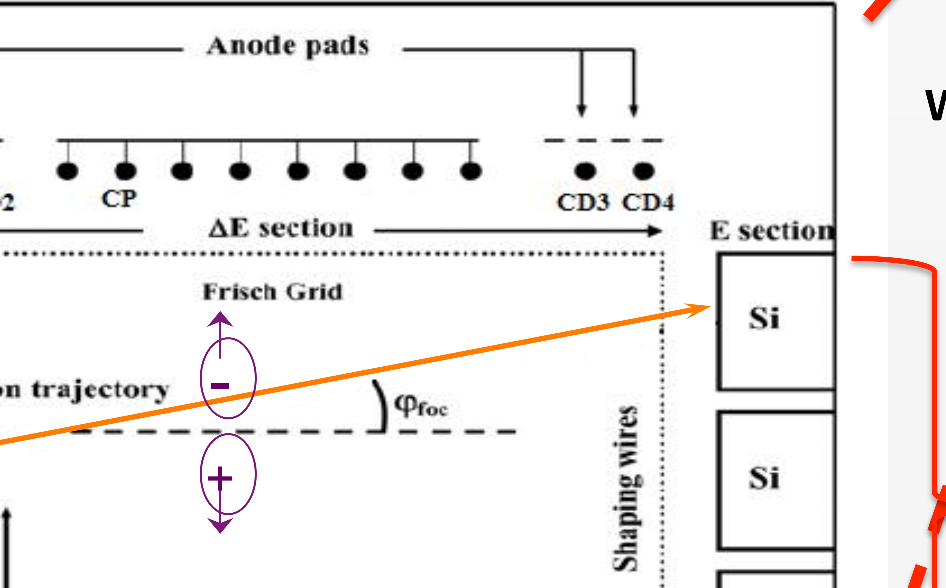
140x20 cm^2

a **ionization drift chamber**, five independent proportional counte of which are position-sensitive an of stopping **silicon detectors.**

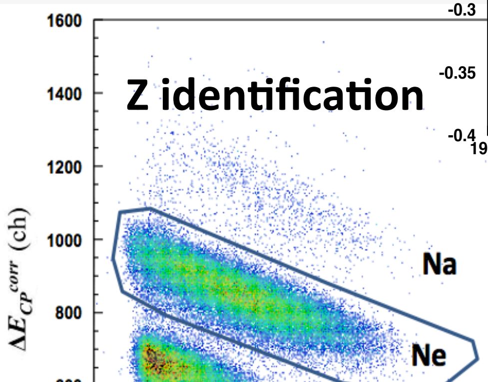
Pure isobutane pressure range: 5-100mbar; 600-800 Volt,wires 20 micron

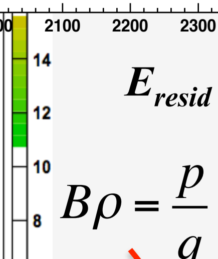


Multiwire gas tracker and ΔE stage



Wall of 60 stopping 7 X 5 cm^2 Silicon detectors surface covered 100 X 21 cm^2



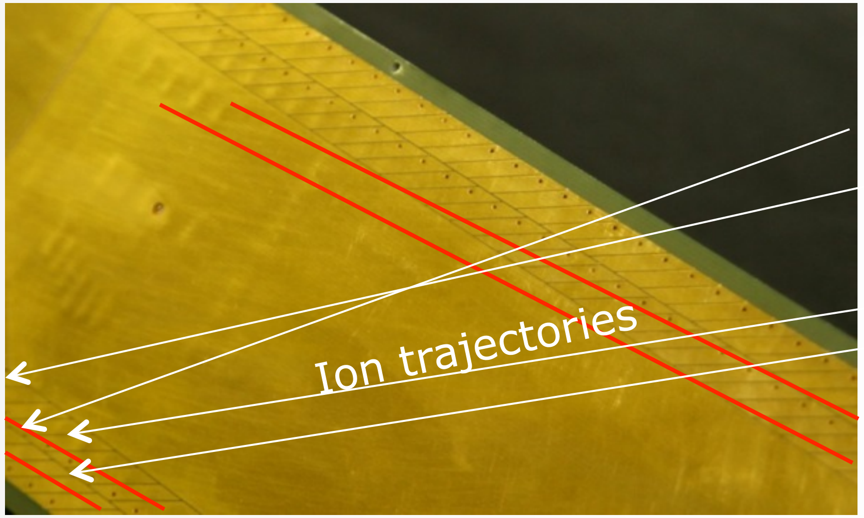


$B\rho = \frac{p}{q}$

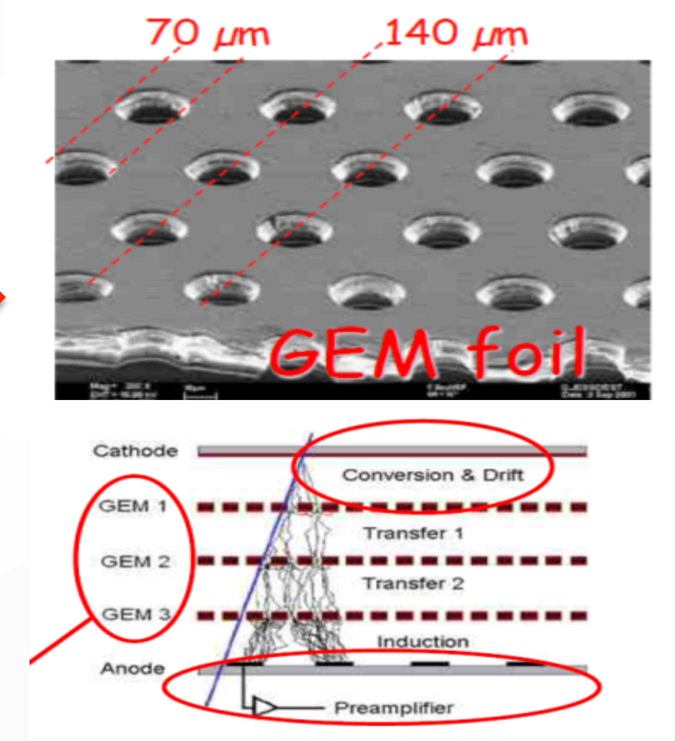
from ≈ 2 kHz → to several MHz

1. *A new gas tracker*

v limited to ~ 5 kHz due to the slow drift of positive ions from the multiplication wires to the Frish grid



From multi-wire tracker



To micro-pattern electron multipliers tracker

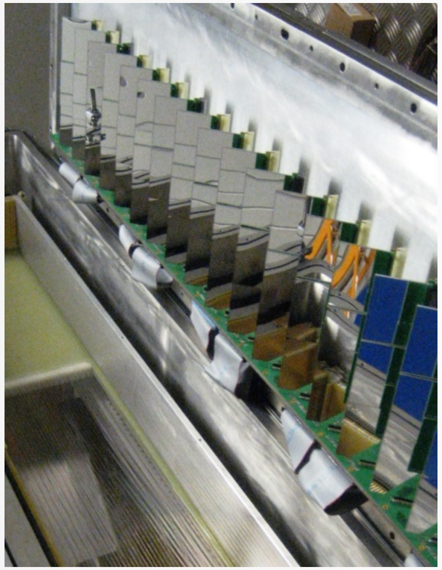
- **R&D key issue : GEM-based tracker at low pressure and wide dynamic range**

from ≈ 2 kHz → to several MHz

A new particle identification wall

From

of 7 X 5 cm^2 silicon pad detectors



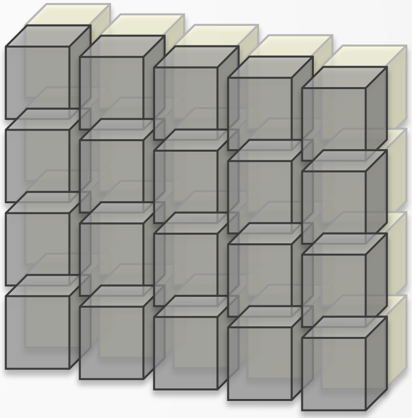
ble-hit probability at 100 kHz > 30%

n-cost for breaking with localized exposure

ts to deteriorate at about 10^8-10^9 ions/cm^2

To

A wall of 1 X 1 cm^2 telescopes of SiC
detectors



- PID function decoupled from gas tracker
- Double-hit probability at 100 kHz < 1%
- Much smaller maintenance cost
- First irradiation tests successfully performe
collaboration with CNR
- Radiation hard material (10^{13} ions/cm^2

A wide dynamical range

hickness of the telescope must be chosen in order to permit the detection of the eject
wide dynamical range of incident energies (10 to 60 MeV/A)

(^{18}O,^{18}Ne) DCE reaction:

In order to have a good signal in **the first stage** of the telescope :

$\Delta E_1 \approx$ 100 μm for 10 to 30 MeV/A
$\Delta E_2 \approx$ 1000 μm for 30 to 60 MeV/A

For the **second stage**

$E \approx$ 1000 μm for 10 to 60 MeV/A

od solution would be **a triple stage telescope** to cover the whole energy range for the
EN experimental campaign guarantying an unambiguos identification of the ion mass
ic number and charge state.

A technological challenge !

To mantain the actual performances at high rates:

NUMEN requirements
1 cm^2 three-stage telescope
thickness of ΔE_1 stage 100 μm
thickness of ΔE_2 stage 1000 μm
thickness of E stage 1000 μm
high geometrical efficiency (~ 80%)
good energy resolution (1%)
good time resolution (1-2 ns)
hard to radiation damage (>10^{13} ions/cm^2)
capacitance ~ 100 pF
implementation of the pulse-shape analysis

kness of the
e must be chosen in
permit the
n of the ejectiles in
dynamical range of
energies (10 to 60

a high degree o
segmentation is
in order to limit
hit events proba
below 10% in th
FPD.

To obtain accura
measurement of
absolute cross se

Diamond	GaN	4H SiC	Si
5.5	**3.39**	**3.26**	**1.12**
10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
1800	1000	800	1450
1200	30	115	450
$2.2\cdot10^7$		$2\cdot10^7$	$0.8\cdot10^7$

① substitution of the present Focal Plane Detector (FPD) gas tracker with a micro-patterned electron multipliers foils for a tracker system;

② substitution of the wall of silicon pad stopping detectors with a wall of telescopes based on SiC-SiC detectors ;

③ introduction of an array of detectors for measuring the coincident γ-rays;

④ enhancement of the maximum magnetic rigidity

The four phases of NUMEN project

e1: *the experiment feasibility*

O,^{18}Ne)^{40}Ar @ 270 MeV **already done**: the results demostrate the technique feasibility.

e2: toward "few hot" cases optimizing experimental conditions and getting first result

ding of CS and MAGNEX, preserving the access to the present facility. Tests will be crucial.

ase3: the facility upgrade

mbling of the old set-up and re-assembling of the new ones will start: about 18-24 months

e4: the experimental campaign

eam intensities (some pμA) and long experimental runs to reach integrated charge of hundreds of mC up

eriments in coincidences, for all the variety of isotopes for *0νββ* decay (^{48}Ca,^{82}Se,^{96}Zr,^{100}Mo,^{110}Pd,^{124}

Nd,^{150}Nd,^{154}Sm,^{160}Gd,^{198}Pt).

Preliminary time table

	2013	2014	2015	2016	2017	2018	2019	2020	2021
e1	done								
e2				Approved					

Outlook

The NUMEN goals

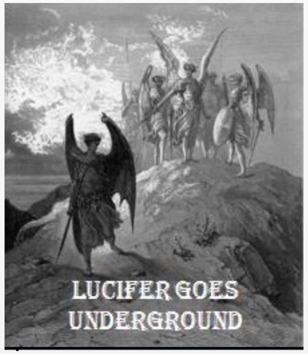
. The NUMEN Holy Graal: the unit cross section

. A new generation of DCE constrained 0νββ NME theoretical calculation

. The ratio of measured cross sections can give a model independent wa compare the sensitivity of different half-life experiments.

^{76}Ge

^{130}Te



^{82}Se

^{136}Xe

^{116}Cd

strong impact in future development of the field.

"...non è facile fare fisica molto innovativa se questa non è sorretta da tecnologie altrettanto innovative"