Terzo Incontro Nazionale di Fisica Nucleare
INFN2016

Istituto Nazionale di Fisica Nucleare

The NUMEN Project:

$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ and $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ DCEX reactions preliminary results

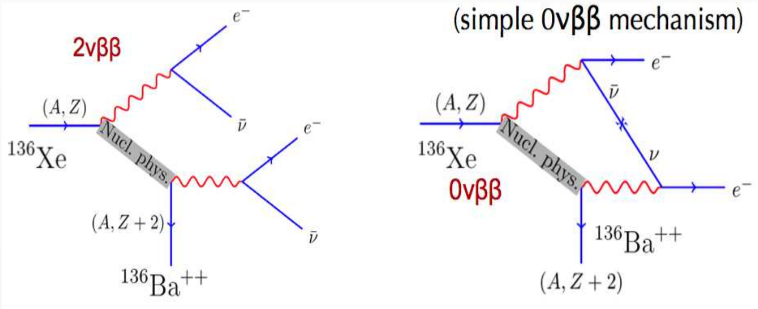
Gianluca Santagati for the NUMEN collaboration

NUMEN

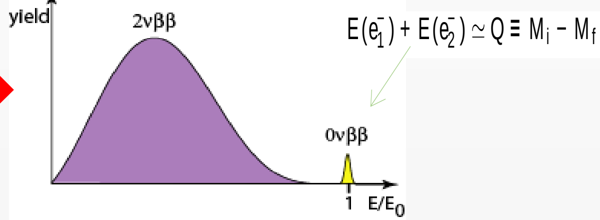
A basic question in modern Physics

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

What about the m_ν **absolute value** and the neutrino **nature**:
Dirac or Majorana particle?



Experimental signature for ββ



a) 2ν DBD: (A, Z) (A, Z+2) + 2e$^-$ + 2ν_e

$$T_{1/2} \approx 10^{19-21}\ y$$

Described for the first time
by Maria Goeppert-Mayer (1935)

- Respect the conservation law.
- Does not distinguish between Dirac and Majorana
- Experimentally observed in several nuclei

^{82}Se, ^{100}Mo, ^{48}Ca, ^{76}Ge, …

b) 0ν DBD: (A, Z) (A, Z+2) + 2e$^-$

$$T_{1/2} > 10^{24}\ y$$

- Neutrino has mass
- Neutrino is Majorana particle
- Violates the leptonic number conservation
- Experimentally not observed
- Forbidden in the Standard Model

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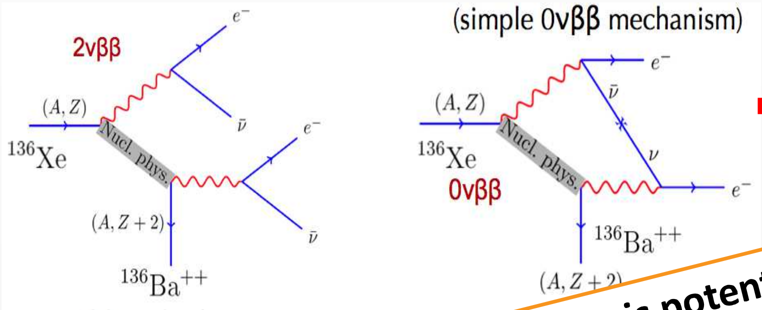

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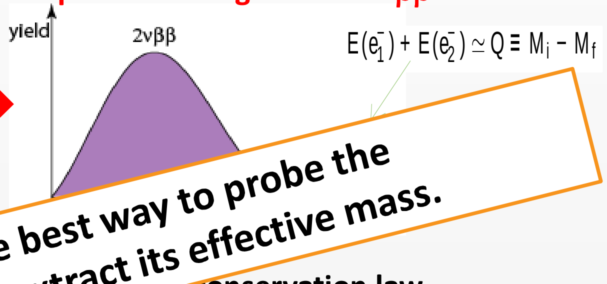

The very rare 0νββ decay is potentially the best way to probe the Majorana or Dirac nature of neutrino and to extract its effective mass.

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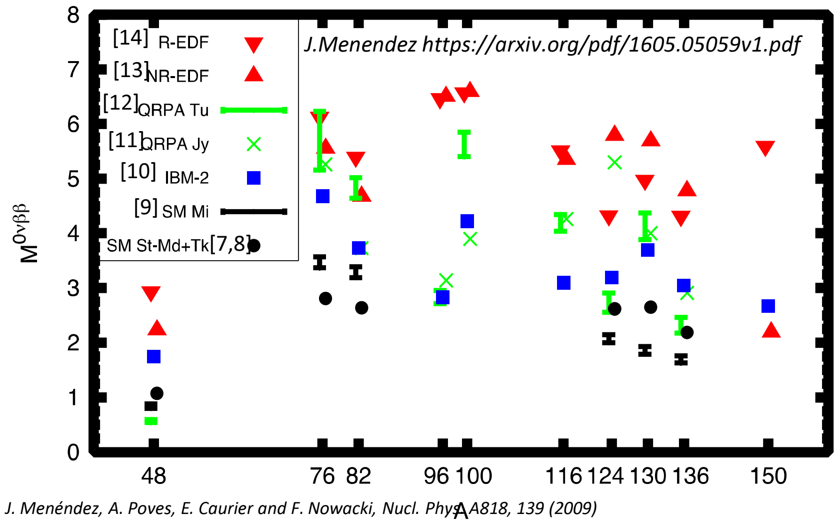
The role of nuclear physics

In the 0νββ the decay rate can be expressed as a product of independent factors, that also depends on a function containing physics beyond the Standard Model throught the masses and the mixing coefficients of the neutrinos species :

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

new physics inside !

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



The differences are about a factor of two to three, or three to four units.

[7] J. Menéndez, A. Poves, E. Caurier and F. Nowacki, Nucl. Phys. A818, 139 (2009)
[8] Y. Iwata, N. Shimizu, T. Otsuka, Y. Utsuno, J. Menéndez, M. Honma and T. Abe,Phys. Rev.Lett.116, 112502 (2016).
[9] A. Neacsu and M. Horoi, Phys. Rev. C93, 024308 (2016).
[10] J. Barea, J. Kotila and F. Iachello, Phys. Rev. C91, 034304 (2015).
[11] J. Hyvärinen and J. Suhonen, Phys. Rev. C87, 024613 (2015).
[12] F. Šimkovic, V. Rodin, A. Faessler and P. Vogel, Phys. Rev. C87, 045501 (2013).
[13] N. López Vaquero, T. R. Rodríguez and J. L. Egido, Phys. Rev. Lett.111, 142501(2013).
[14] J. Yao, L. Song, K. Hagino, P. Ring and J. Meng, Phys. Rev.C91, 024316 (2015).

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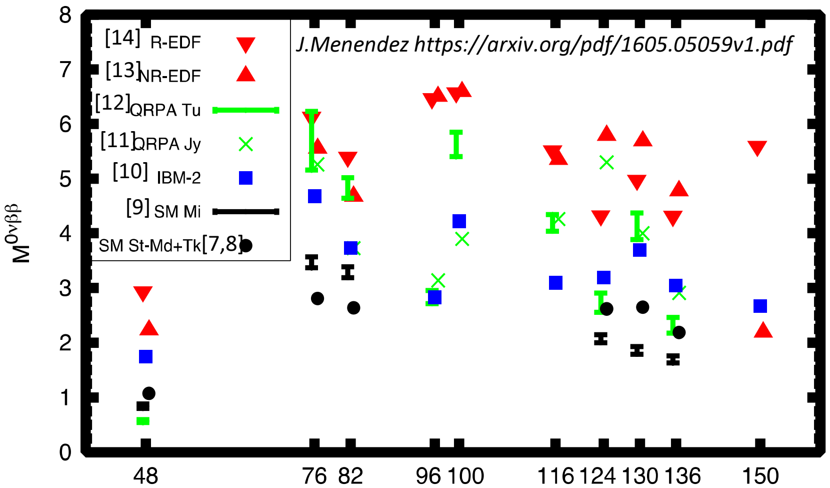

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Thus, if the *$M^{0\nu\beta\beta}$* nuclear matrix elements were known with sufficient precision, the neutrino mass could be established from *0νββ* decay rate measurements.

Heavy-ion DCE

- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order:

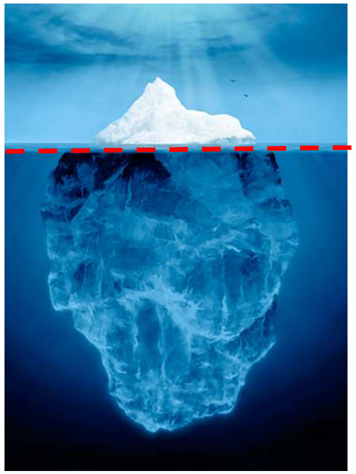
  Brink's Kinematical matching conditions *D.M.Brink, et al., Phys. Lett. B 40 (1972) 37*

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

NUMEN

RIKEN

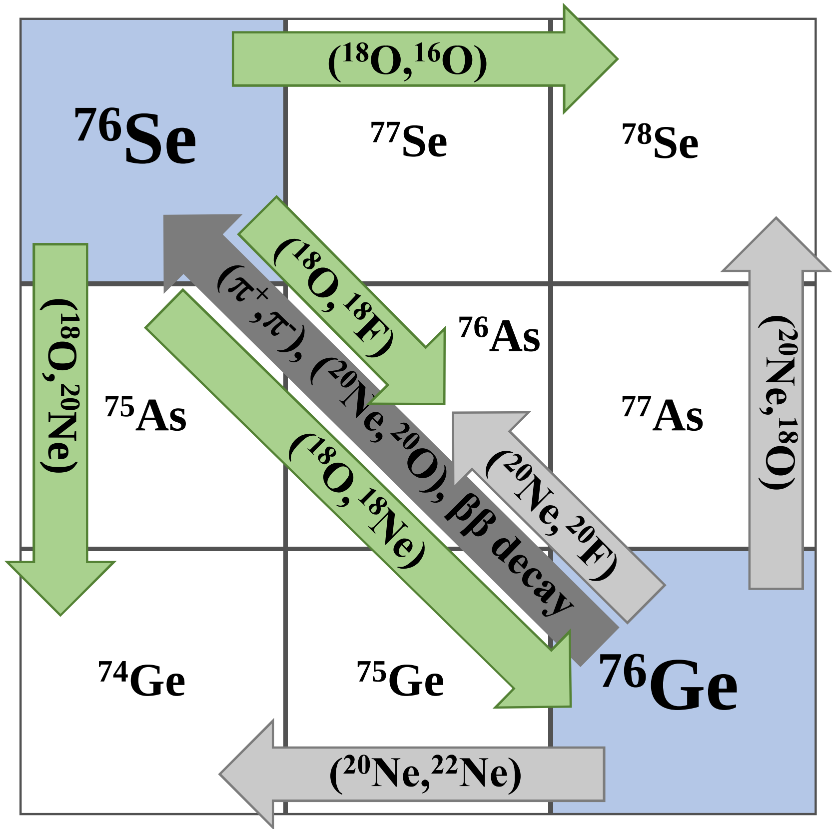
RCNP



Tiny amount of DGT strenght in low lying states

Sum rule almost exhausted by DGT Giant Mode

Takakiet al. JPS Conf. Proc. , 020038 (2015)



MAGNEX spectrometer @ LNS

Camera di scattering

$P_i = (x_i, y_i, \theta_i, \phi_i, \delta_i)$

Quadrupole

Dipole

Optical characteristics	Values
Maximum magnetic rigidity	1.8 T m
Solid angle	50 msr
Momentum acceptance	-14.3%, +10.3%

Focal Plane Detector (FPD)

$P_f = (x_f, y_f, \theta_f, \phi_f)$

Good compensation of the aberrations:
Trajectory reconstruction

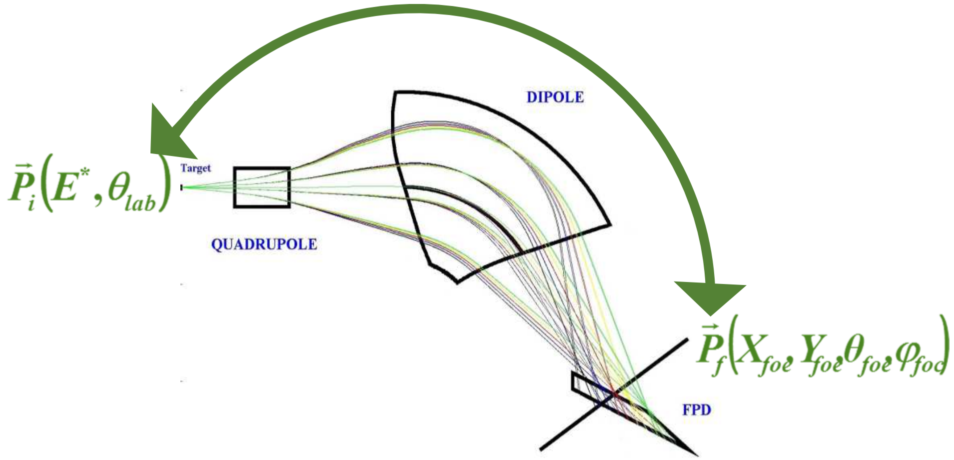
Measured resolutions:

- Energy $\Delta E/E \sim 1/1000$
- Angle $\Delta\theta \sim 0.3°$
- Mass $\Delta m/m \sim 1/160$

Transport Matrix

M: $P_i \rightarrow P_f$

M^{-1}: $P_f \rightarrow P_i$



Factorization of the charge exchange cross-section

For single CEX:

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

α = Fermi (F) or Gamow-Teller (GT)

unit cross-section $\hat{\sigma}(E_p, A) = K(E_p, 0)|J_\alpha|^2 N_\alpha^D$

T.N.Taddeucci, et al, Nucl. Phys. A 469 (1987) 125

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

C.J Guess,et al, PRC 83 064318 (2011)

β-decay transition strengths (reduced matrix elements)

B(GT;CEX)/B(GT;β-decay) ~ 1 within a few % especially for the strongest transitions

In the hypothesis of a surface localized process (for direct quasi elastic processes), in a simple model one can assume that the DCE process is just a second order charge exchange, where projectile and target exchange two uncorrelated isovector virtual mesons.

Generalization to DCE:

In analogy to the single charge-exchange, the dependence of the cross-section from q is represented by a Bessel function.

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

unit cross-section $\hat{\sigma}_\alpha^{DCE}(E_p, A) = K(E_p, 0)|J_\alpha^{DCE}|^2 N_\alpha^D$

The NUMEN goals

1. ***The aim of the NUMEN Project*** **: Towards the access of the NME involved in the half-life of the *0νββ decay* by measuring the cross sections of HI induced DCE reactions with high accuracy.**

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

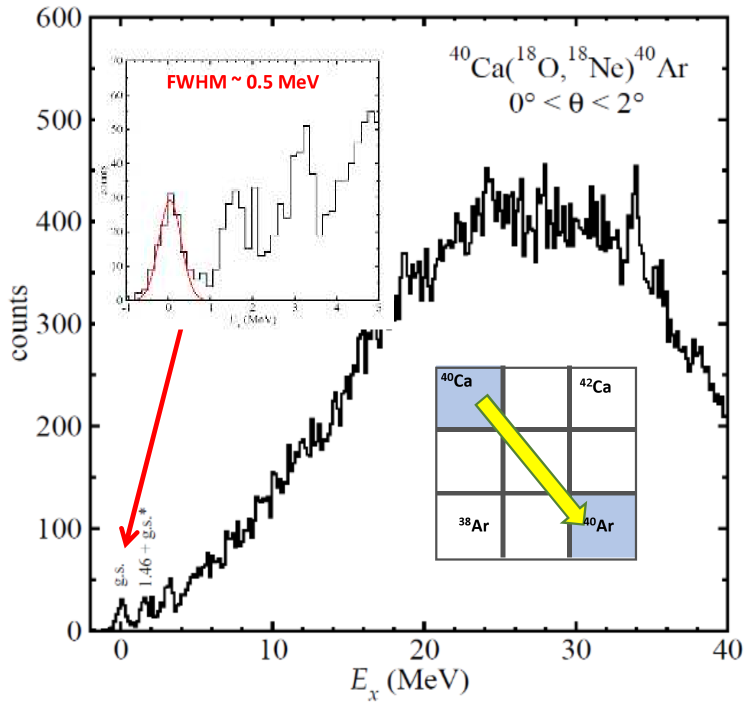
2. **A new generation of DCE constrained 0νββ NME theoretical calculations can emerge: the measured DCE cross sections provide a powerful tool for theory in order to give very stringent constraints in the NME estimation. The DCE processes can be artificially generated in the lab.**

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

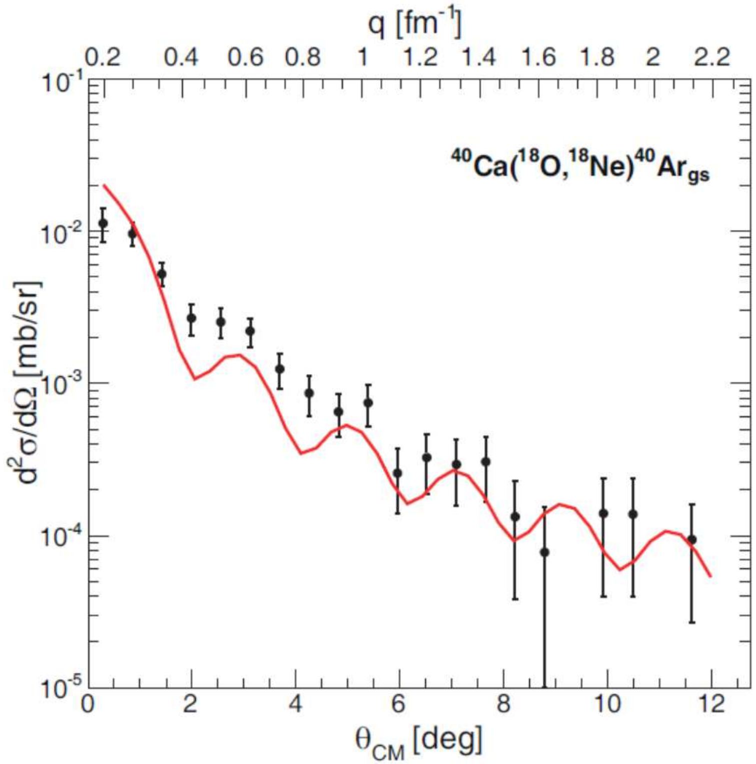
GERDA	CUORE	LUCIFER GOES UNDERGROUND	Enriched Xenon Observatory for double beta decay	
^{76}Ge	^{130}Te	^{82}Se	^{136}Xe	^{116}Cd

Strong impact in future development of the field, looking for a "golden isotope" …

The pilot experiment: $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ LNS



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



The position of the minima is well described by a Bessel function: such an oscillation pattern is not expected in complex multistep transfer reactions.

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

σ^{DCE} = 260 nb 0° < θ < 2°

NUMEN experimental runs

March 2016 ^{116}Cd + ^{20}Ne @ 15-22 MeV/u (test) at ϑ_{opt} = -3° (0° < θ_{lab} < 8°)

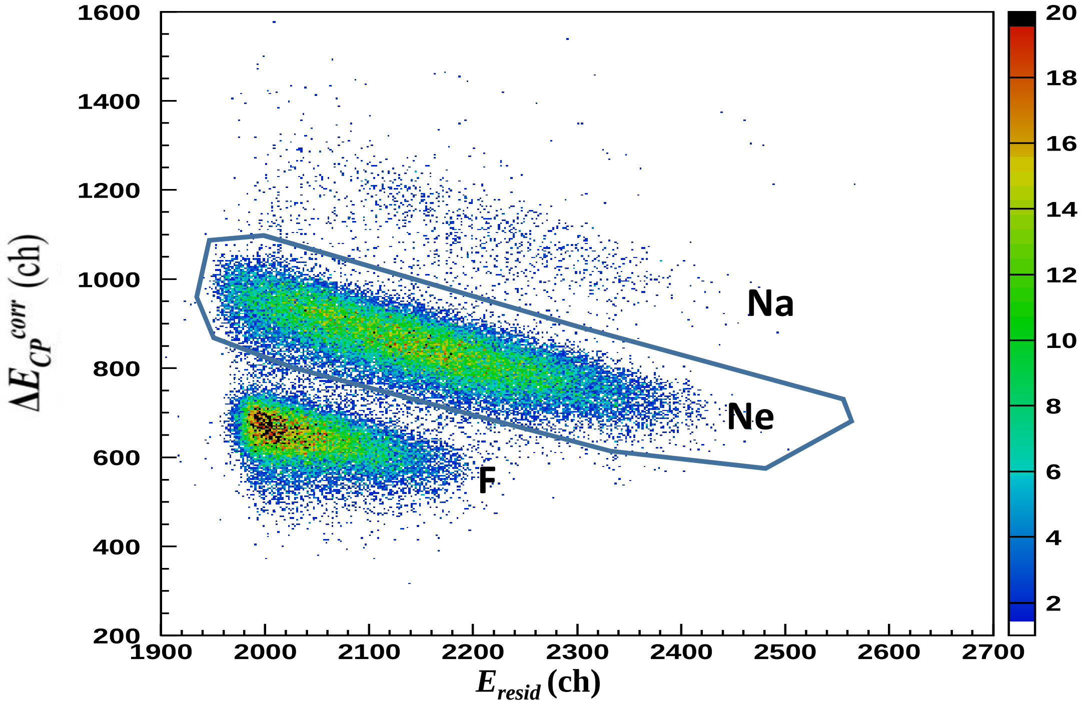
- DCEX reaction $^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$
- CEX reaction $^{116}Cd(^{20}Ne,^{20}F)^{116}In$
- 2p-transfer $^{116}Cd(^{20}Ne,^{18}O)^{118}Sn$
- 1p-transfer $^{116}Cd(^{20}Ne,^{19}F)^{117}In$

October 2015 - June 2016 ^{116}Sn + ^{18}O @ 15 MeV/u at ϑ_{opt} = 3° (0° < θ_{lab} < 9°)

- DCEX reaction $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$
- CEX reaction $^{116}Sn(^{18}O,^{18}F)^{116}In$
- 2p-transfer $^{116}Sn(^{18}O,^{20}Ne)^{114}Cd$
- 1p-transfer $^{116}Sn(^{18}O,^{19}F)^{115}In$
- 2n-transfer $^{116}Sn(^{18}O,^{16}O)^{118}Sn$

$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ DCEX data reduction

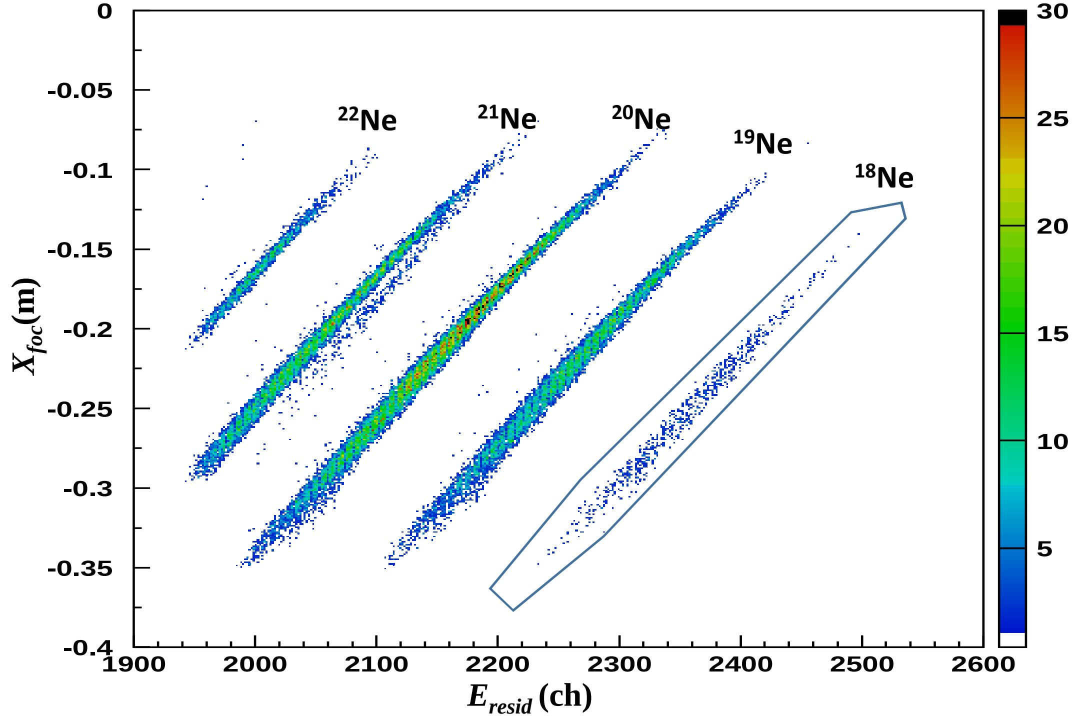
Z identification



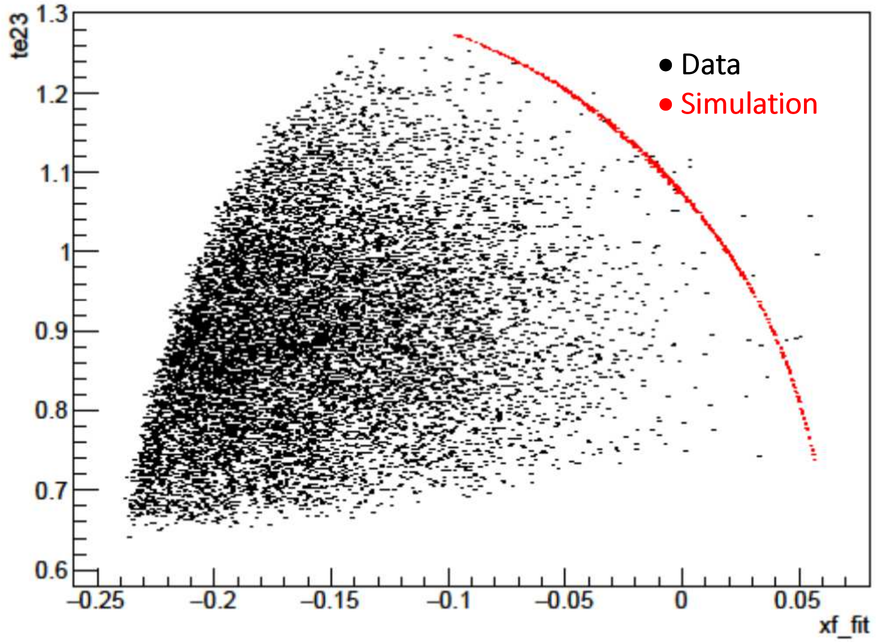
A. Cunsolo, et al., NIMA484 (2002) 56
A. Cunsolo, et al., NIMA481 (2002) 48
F. Cappuzzello et al., NIMA621 (2010) 419
F. Cappuzzello, et al. NIMA638 (2011) 74

A identification

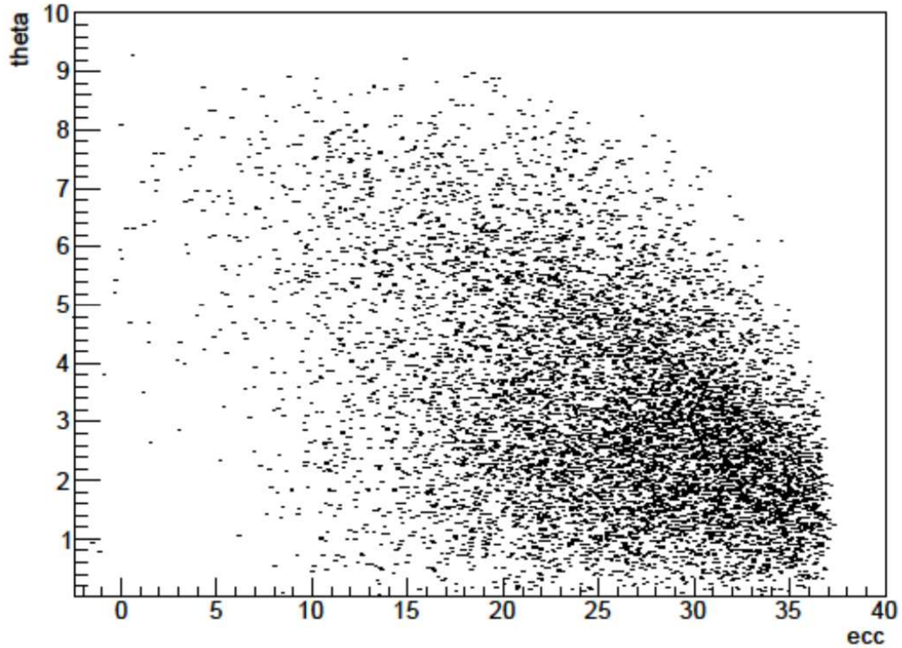
$$B\rho = \frac{p}{q} \rightarrow X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



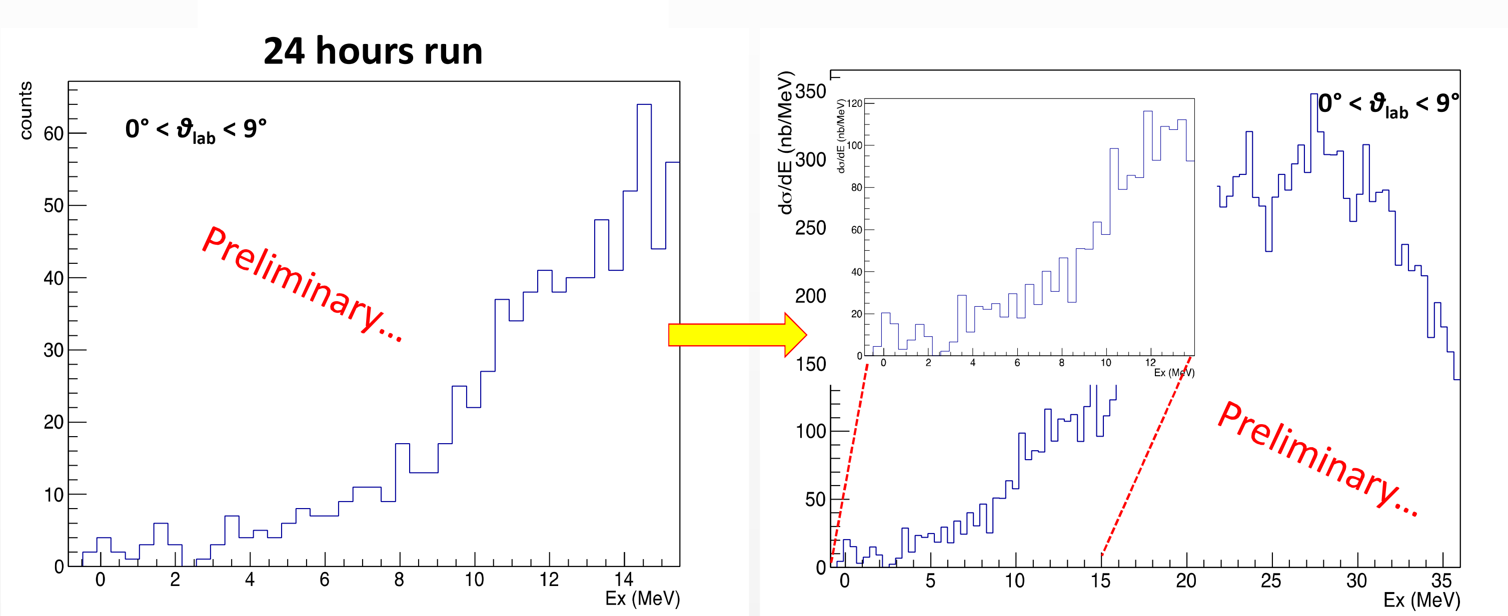
$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ DCEX reaction @ 15 MeV/A



After ray reconstruction



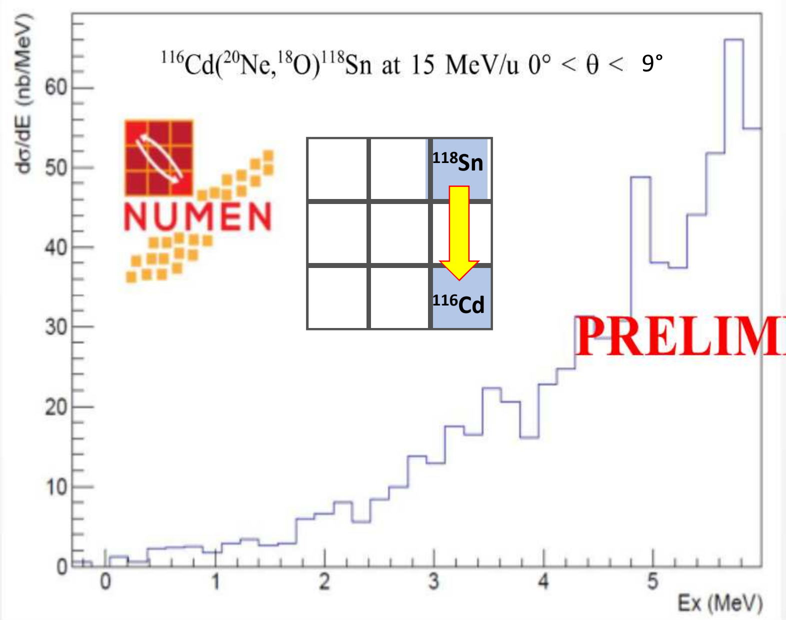
$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ DCEX reaction @ 15 MeV/A

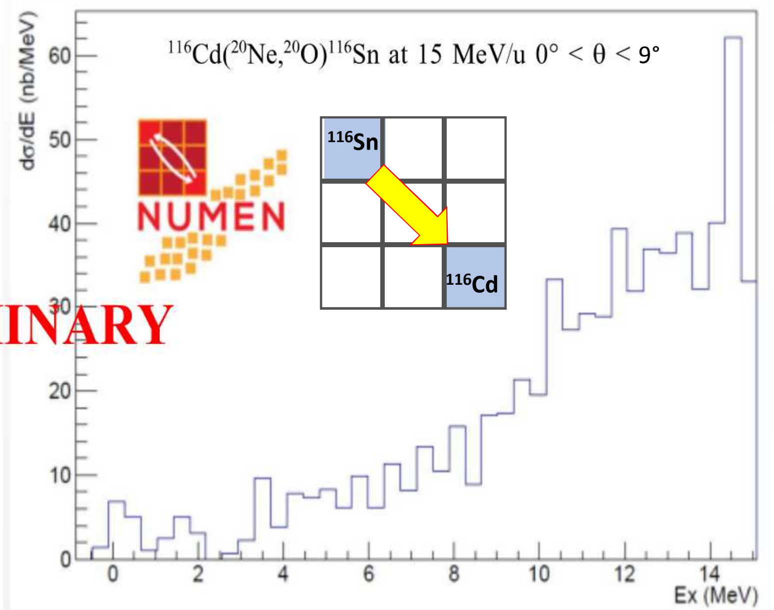


DCE transitions to $^{116}Sn_{gs}$ and first excited 2^+ state at 1.29 MeV are clearly separated (energy resolution ~ 0.75 MeV) and characterized by a remarkable cross section of about 66 nb and 38 nb, respectively.

The role of the competing processes

Multi nucleon transfer suppressed respect to DCE





Energy spectrum (Ex = $Q_0 - Q$) of the ^{116}Cd(^{20}Ne,^{18}O)^{118}Sn two-proton stripping reaction at 15 MeV/u 0° < ϑ_{lab} < 9°

Reconstructed energy spectrum of the ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn DCE reaction at 15 MeV/u 0° < ϑ_{lab} < 9°

Perspectives

1. **Theoretical upgrade → New Structure and Dynamic calculations**

2. **Present technology is not enough to measure at very high rates of heavy ions! → Cs and Magnex upgrade**

Magnex upgrade:

- FPD gas tracker → GEM - like tracker system
- Si detectors → SiC detectors
- new Front-End electronics
- array of detectors for measuring the coincident γ-rays
- enhancement of the maximum magnetic rigidity

NUMEN

NUclear Matrix Elements for Neutrinoless double beta decay

NUMEN

C. Agodi, J. Bellone, R. Bijker, D. Bonanno, D. Bongiovanni, V. Branchina, M.P. Bussa, L. Busso, L. Calabretta, A. Calanna, D. Calvo, F. Cappuzzello, D. Carbone, M. Cavallaro, M. Colonna, G. D'Agostino, N. Deshmukh, S. Ferrero, A. Foti, P. Finocchiaro, G. Giraudo, V. Greco, F. Iazzi, R. Introzzi, G. Lanzalone, A. Lavagno, F. La Via, J.A. Lay, G. Litrico, D. Lo Presti, F. Longhitano, A. Muoio, L. Pandola, F. Pinna, S. Reito, D. Rifuggiato, M.V. Ruslan, G. Santagati, E. Santopinto, L. Scaltrito, S. Tudisco

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Thank you !

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Back-up slides

$0\nu\beta\beta$ 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 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.

Planned experimental activity

NUclear REactions for neutrinoless double beta decay

Reactions	2017	2018	2019
^{20}Ne + ^{116}Cd at 15 MeV/u	~ 60 BTU		
^{18}O + ^{40}Ca at 25 MeV/u		~ 45 BTU	
^{18}O + ^{76}Se at 15 MeV/u		~ 75 BTU	
^{20}Ne + ^{76}Ge at 15 MeV/u		~ 60 BTU	
^{20}Ne + ^{116}Cd at 25 MeV/u			~ 60 BTU
^{20}Ne + ^{76}Ge at 25 MeV/u			~ 60 BTU

From the pilot experiment towards the "hot cases": The four phases of NUMEN project

- ***Phase1: the experiment feasibility***

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

- **Phase2: toward "few hot" cases optimizing experimental conditions and getting first result**

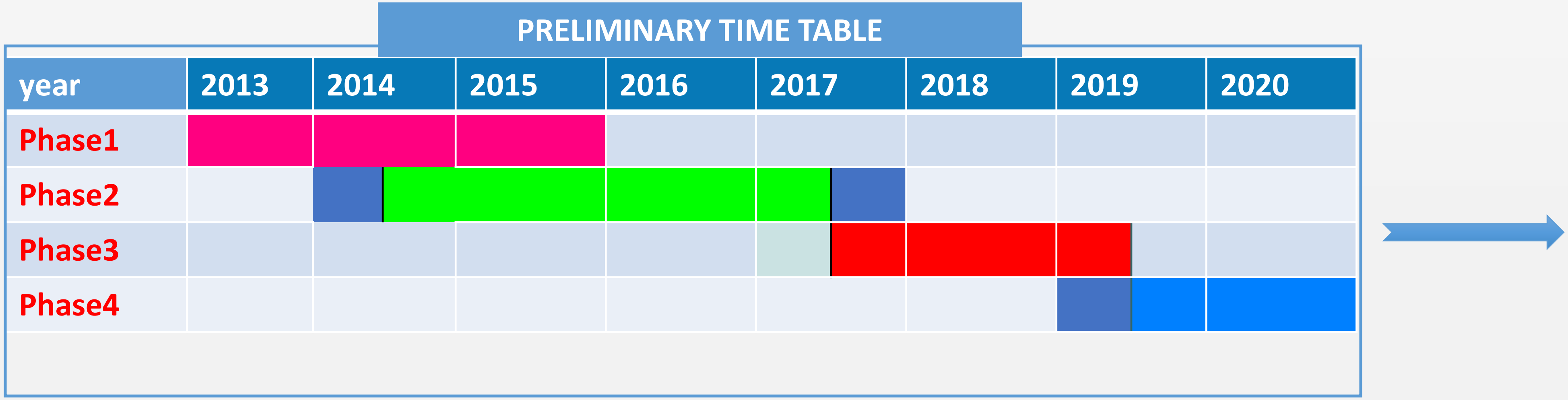
Upgrading of CS and MAGNEX, preserving the access to the present facility. Tests will be crucial.

- **Phase3: the facility upgrade**

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

- **Phase4: the experimental campaign**

High beam intensities (some pμA) and long experimental runs to reach integrated charge of hundreds of mC up to C, for the experiments in coincidences, for all the variety of isotopes for *0νββ* decay (^{48}Ca,^{82}Se,^{96}Zr,^{100}Mo,^{110}Pd,^{124}Sn,^{128}Te,^{136}Xe,^{148}Nd,^{150}Nd,^{154}Sm,^{160}Gd,^{198}Pt).

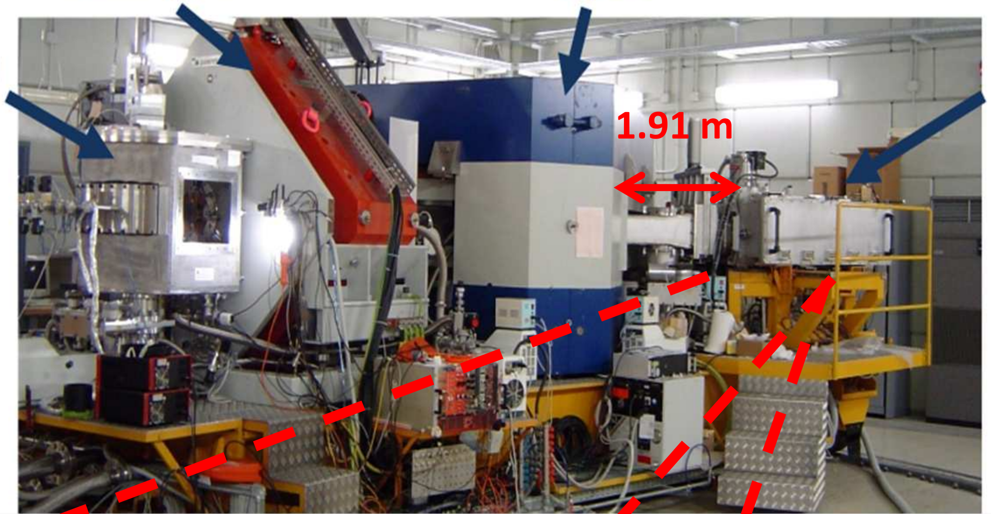


The MAGNEX FPD

Quadrupole

Dipole

Scattering Chamber



Focal Plane Detector

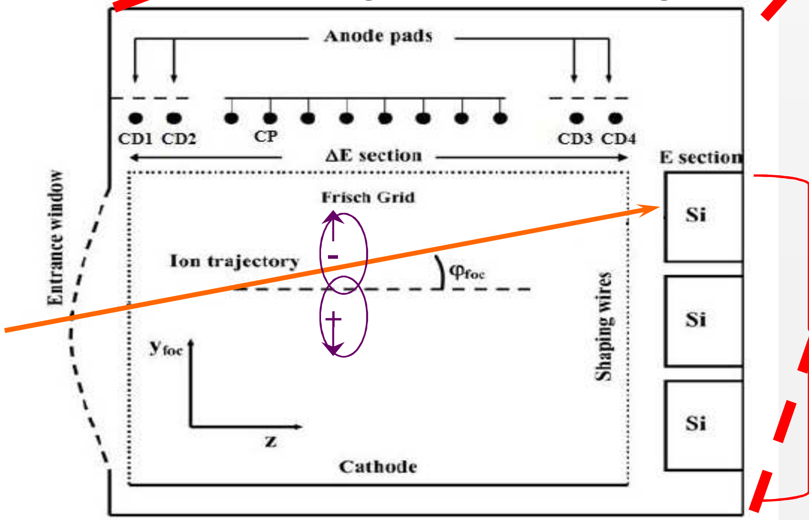
active area

140x20 cm²

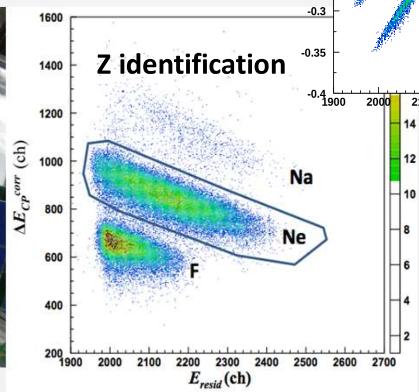
a ionization drift chamber, five independent proportional counters, four of which are position-sensitive and a wall of stopping silicon detectors.

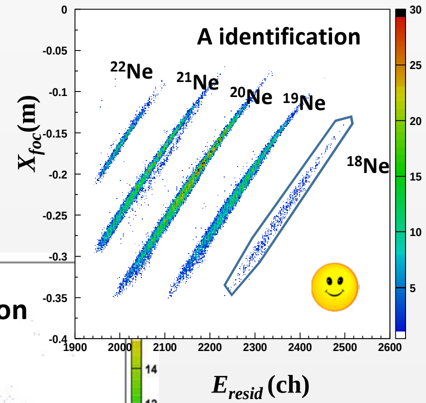
Pure isobutane pressure range: 5-100mbar; 600-800 Volt,wires 20 micron

Multiwire gas tracker and ΔE stage



Wall of 60 stopping 7 X 5 cm² Silicon detectors surface covered 100 X 21 cm²





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

$$X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$

MAGNEX Focal Plane Detector

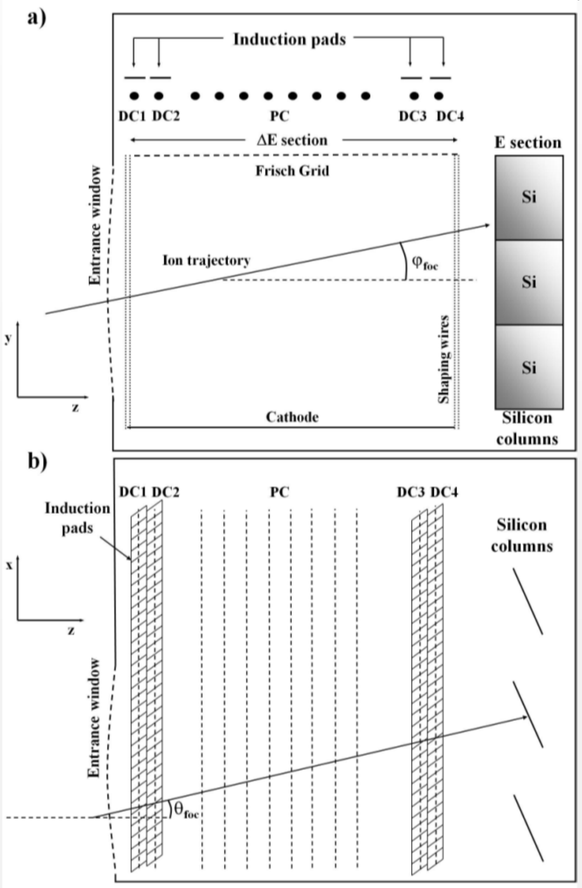
- Gas-filled hybrid detector

Drift chamber 1400mm x200mmx100mm
Pure isobutane pressure range: 5-100 mbar; 600-800 V,wires 20 micron

- Wall Si 500 μm

20 columns, 3 rows

Schematic view of the MAGNEX Focal Plane Detector: a) side view; b) top view.



60 Silicon Detectors
→ E_{res}

5 Proportional Wires
→ ΔE

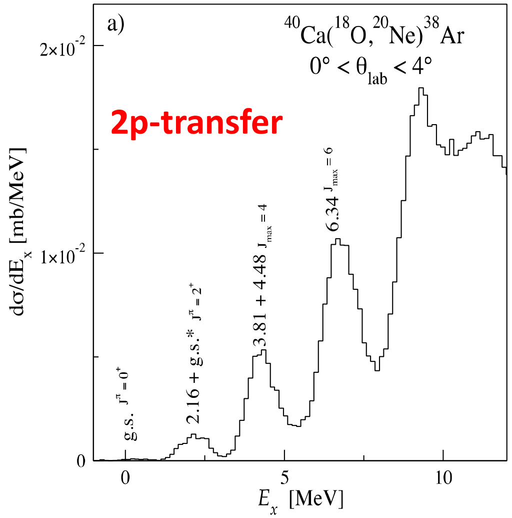
Ion identification

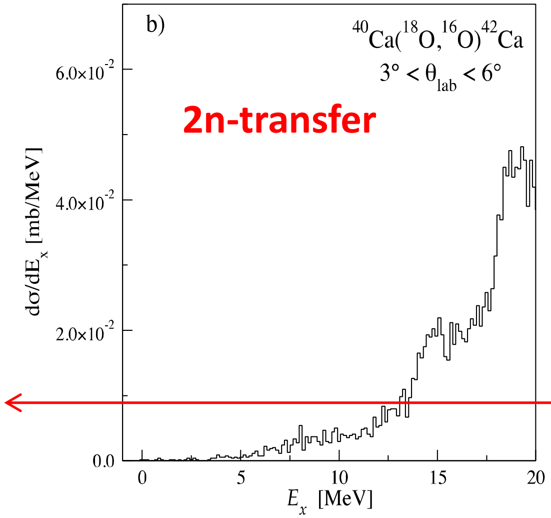
4 Induction Strip
→ X_1, X_2, X_3, X_4
→ X_{foc}, θ_{foc}

4 Drift Chamber (DC)
→ Y_1, Y_2, Y_3, Y_4
→ Y_{foc}, ϕ_{foc}

Ray-reconstruction

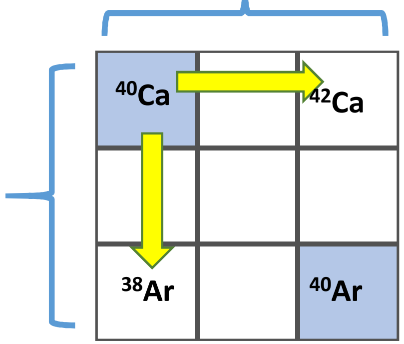
The role of the transfer reaction and the competing processes



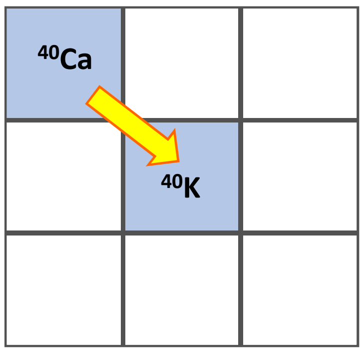


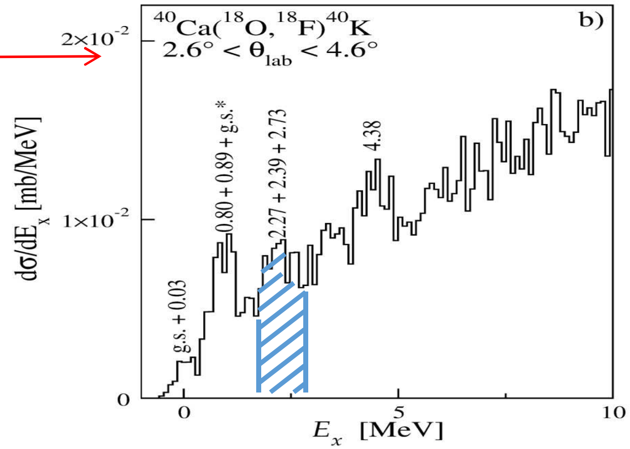
Less than 1% effect in the DCE cross section

Very weak



single charge exchange





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

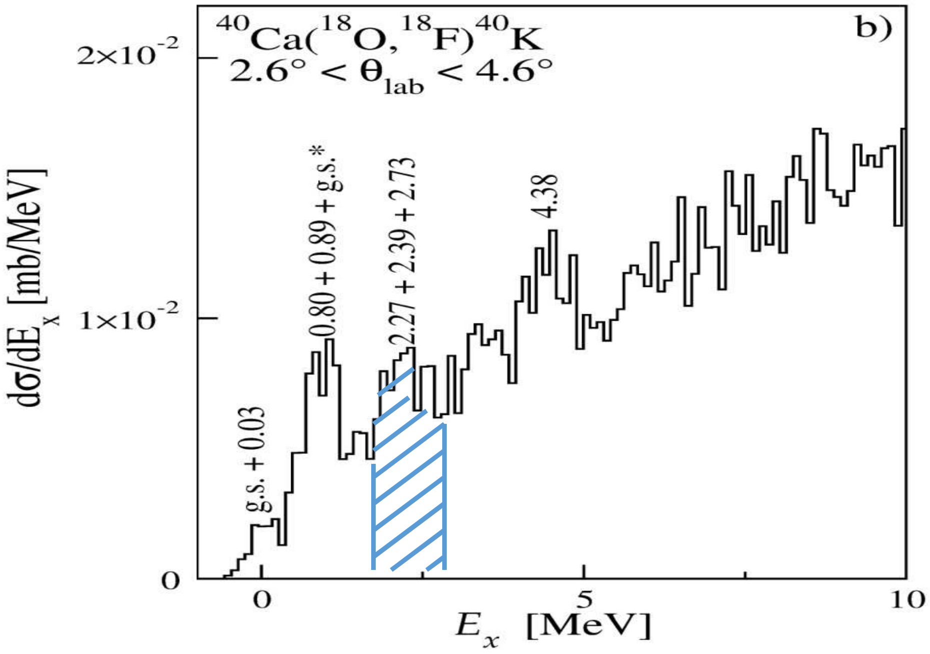
Extracted B(GT) = 0.087

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

HI Single CEX @ LNS

INFN LNS
Istituto Nazionale di Fisica Nucleare

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

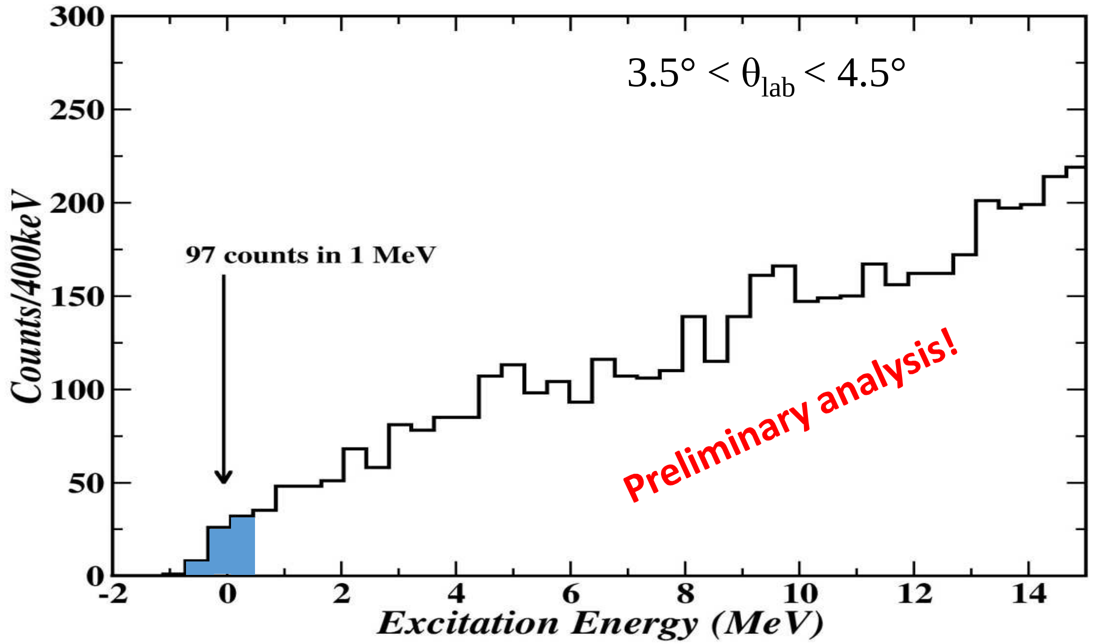


x-section (2MeV < E_x < 3MeV)
≈ 0.5 mb/sr

Extracted B(GT) = 0.087

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

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



x-section (within 1 MeV)
≈ 0.17 mb/sr

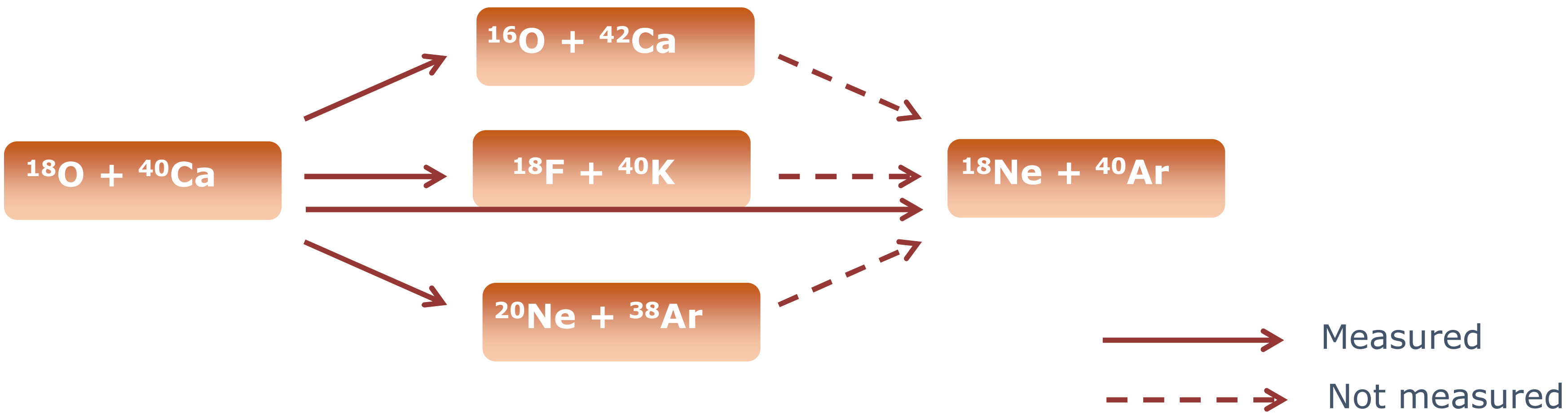
Extracted upper limit for B(GT) < 0.8

B(GT) from (d,^{2}He) = 0.4
S.Rakers, et al., PRC 71 (2005) 054313

The pilot experiment: $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$@LNS

LNS
INFN Istituto Nazionale di Fisica Nucleare

- $^{18}O^{7+}$ 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 $\theta_{opt} = 4°$ → $-2° < \theta_{lab} < 10°$



Analogia con il decadimento β

L'interazione forte nucleone-nucleone V_{NN} presenta

isoscalari — isovettoriali

$$V_{NN} \equiv V_{ij}(r_{ij}) = \underbrace{V_O + V_\sigma(\vec{\sigma_i}\cdot\vec{\sigma_j}) + V_{SO}(\vec{S}\cdot\vec{L}) + V_T S_T}_{\text{isoscalari}} + \underbrace{\tau_i\cdot\tau_j[V_\tau + V_{\sigma\tau}(\vec{\sigma_i}\cdot\vec{\sigma_j}) + V_{SO}^\tau(\vec{S}\cdot\vec{L}) + V_T^\tau S_T]}_{\text{isovettoriali}}$$

Fermi-like (V_τ)   *Gamow Teller-like* ($V_{\sigma\tau}$)

→ ampiezze di transizioni hanno struttura molto simile a quelle del decadimento β essendo tali transizioni permesse (L=0) distinte in:

- Fermi, S=0 → ΔJ=0 e $O_F=\tau^\pm$
- Gamow-Teller, S=1 → ΔJ=1 e $O_{GT}= \sigma\tau^\pm$

Connessione tra decadimento β e reazioni di scambio di carica notata alla fine degli anni '50 [1]. Formalizzata[3] per sistemi leggeri, sotto opportune condizioni (q ~0, L=0) vale la fattorizzazione:

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

Espressione che vale anche per ioni pesanti entro un 20-30% di precisione

1) Bloom et al, Phys. Rev. Lett. 3 (1959).

2) C.D. Goodman et al, Phys. Rev. Lett. 44 (1980).

3) T. Taddeucci et al, Phys. Rev. C 28 (1983).

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-F competion** at low energy

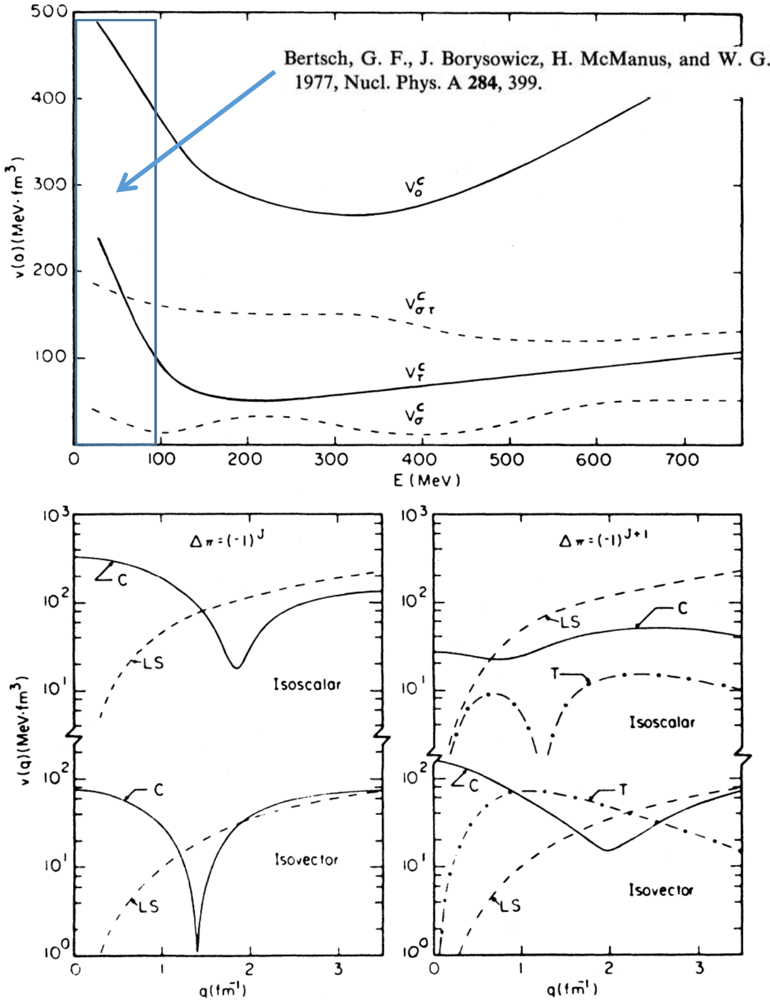


FIG. 15. Energy and momentum dependence of the free nucleon-nucleon t_F matrix. The upper part of the figure shows the energy dependence of the central components of the effective t_F matrix at zero-momentum transfer (including direct and exchange terms). The *G*-matrix interaction of Bertsch *et al.* (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).

Factorization of the double charge exchange cross-section

Under the hypotesis of surface localization, one can assume that the DCE process is just a second order charge exchange: DCE cross sections can be factorized in a nuclear structure term, containing the matrix element, and a nuclear reaction factor.

generalization to DCE:

In analogy to the single charge-exchange, the dependence of the cross-section from *q* is represented by a Bessel function.

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

unit cross-section

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

A wide range of DCE cross sections has never been accurately measured due to :

- The difficult to perform zero degrees measurements.
- The poor yields in the measured energy spectra and angular distributions, due to the very low cross sections.
- The difficulty to disentangle possible contributions of multi-nucleon transfer reactions leading to the same final state.

Factorization of the charge exchange cross-section

for single CEX:

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

β-decay transition strengths (reduced matrix elements)

α= Fermi (F)
or Gamow Teller (GT)

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

C.J Guess,et al, PRC 83 064318 (2011)

unit cross-section

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

T.N.Taddeucci, et al, Nucl. Phys. A 469 (1987) 125

The factor $F_\alpha(q,\omega)$ describes the shape of the cross-section distribution as a function of the linear momentum transfer and the excitation energy.

(d,^{2}He)

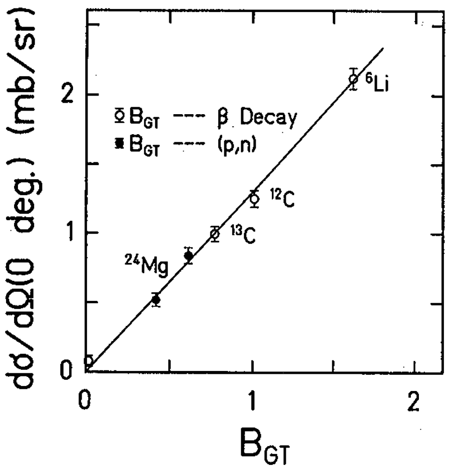


Fig. 12. The measured cm cross-sections of the (d, ^{2}He) reactions at 03 as a function of the G1 strengths deduced from β-decay or (p,n) reaction studies. The solid line is a linear "t to the data [244].

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

(^{7}Li,^{7}Be) S. Nakayama PRC 60 (1999) 047303

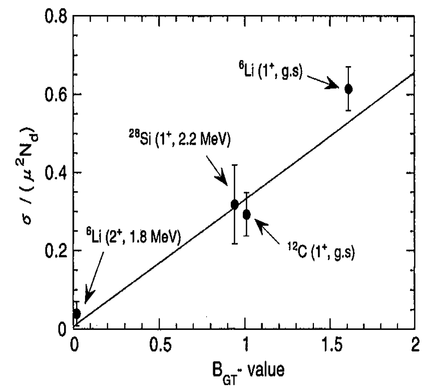


Fig. 18. Cross-sections σ/(μN") for G1 transitions in the (^{7}Li, ^{7}Be) reactions at 03 and B(G1) values. μ and N" are the reduced mass and the distortion factor, respectively [197].

B(GT;CEX)/B(GT;β-decay) ~ 1 within a few % especially for the strongest transitions

More about NME

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

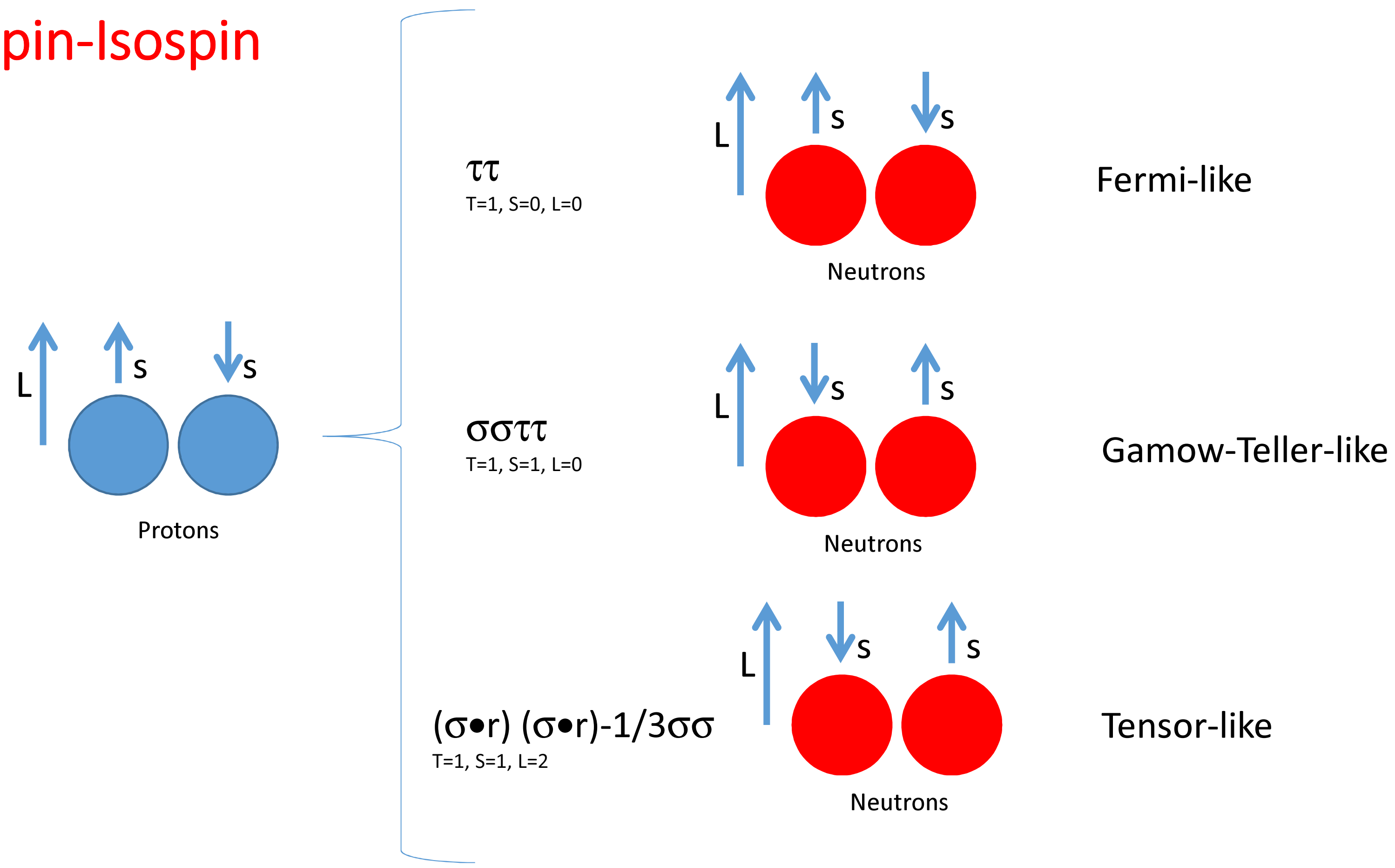
For L = 0 decays

$$\hat{O}_{\varepsilon}^{\beta\beta 0\nu} = \begin{cases} g_A^2 \sum_{i,j} \sigma_i \sigma_j \tau_i \tau_j & \text{Gamow-Teller like} \\ g_V^2 \sum_{i,j} \tau_i \tau_j & \text{Fermi like} \end{cases}$$

Warning: Normally the coupling constants g_A and g_V are kept out form the matrix element and we talk of reduced matrix elements

$$\left|M_{\alpha}^{\beta\beta 0\nu}\right|^2 = \left|M_{\alpha}\right|^2 = B_{\alpha}$$

Spin-Isospin



The 3 operators are both present in weak and strong interaction

Radial dependence

$\Delta r \Delta p \sim h/2\pi$

$\Delta r \sim 2fm$ ⟶ $\Delta p \sim 0.5 fm^{-1} \sim 100$ MeV/c

All the L are possible and as a consequence the operator behaves as the Coulomb potential

$f(r) \propto 1/r$ neutrino potential

Similarly for the DCE!

NME: 2νββ vs 0νββ

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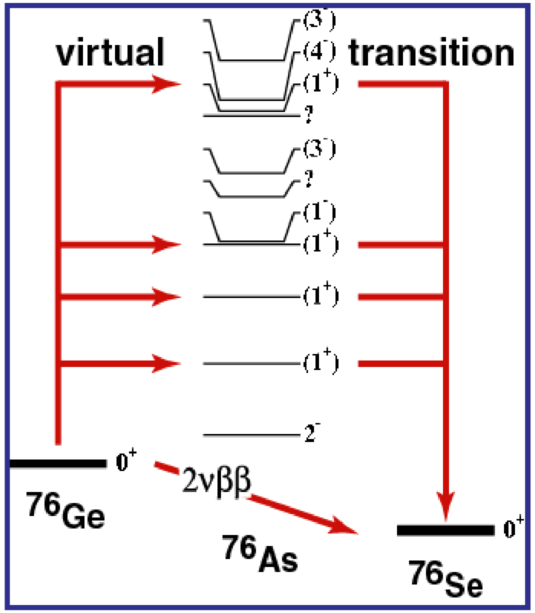
NME 2νββ - decay

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

q-transfer like ordinary β-decay
(q ~ 0.01 fm^{-1} ~ 2 MeV/c)
only allowed decays possible

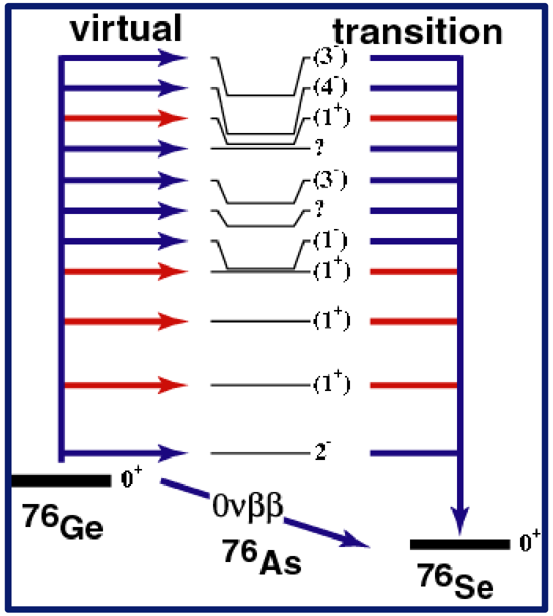


Can be determined via charge-exchange reactions in the (n,p) and (p,n) direction (e.g. (d,^{2}He) or (^{3}He,t))

NME 0νββ - decay

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

neutrino enters as virtual particle,
q~0.5fm^{-1} (~ 100 MeV/c)
degree of forbiddeness weakened



NOT (easily) accessible via charge-exchange reactions

Single state dominance

$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

Closure approximation

The unit cross section

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In the σ(E_p,A) the specificity of the single or double charge exchange is express through the volume integrals of the potentials: the other factors are general features of the scattering.

Single charge-exchange

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

Double charge-exchange

J_{ST} Volume integral of the $V_{ST}GV_{ST}$ potential, where G is the intermediate channel propagator:

$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

where $E_{i,n,f}$ indicate the energies of the initial, intermediate and final channels, respectively

E_n is a complex number whose imaginary component represents the off-shell propagation through the virtual intermediate states

The unit cross section

In the $\sigma(E_p,A)$ **the specificity** of the single or double charge exchange is express through the **volume integrals of the potentials**: the other factors are general features of the scattering.

Single charge-exchange

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

Double charge-exchange

J_{ST} Volume integral of the $V_{ST}GV_{ST}$ potential, where G is the intermediate channel propagator:

$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

E_n is a complex number whose imaginary component represents the off-shell propagation through the virtual intermediate states

If known $\sigma(E_p,A)$ would allow to determine the NME from DCE cross section measurement, whatever is the strenght fragmentation

In single charge exchange reactions

(d,^{2}He)

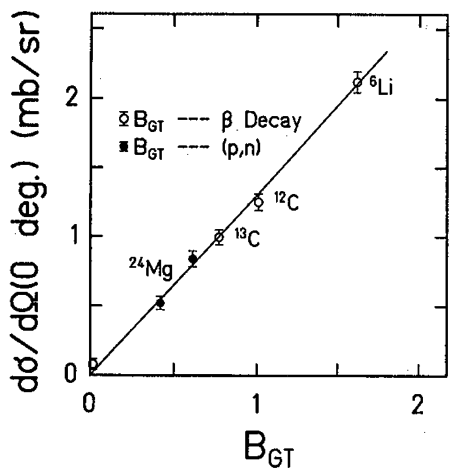

Fig. 12. The measured cm cross-sections of the (d,^{2}He) reactions at 0° as a function of the GT strengths deduced from β-decay or (p,n) reaction studies. The solid line is a linear fit to the data [244].

Y. Fujita Prog. Part. Nuc. Phys. 66 (2011) 549
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T.N. Taddeucci Nucl. Phys. A 469 (1997) 125

(^{7}Li,^{7}Be) S. Nakayama PRC 60 (1999) 047303

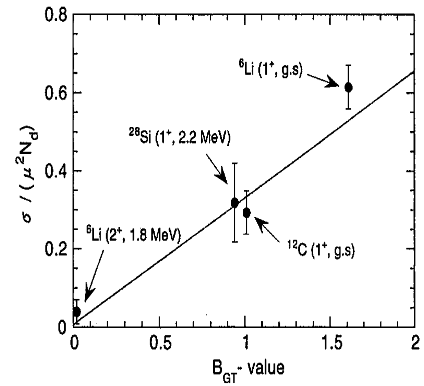


Fig. 18. Cross-sections $\sigma/(\mu N'')$ for GT transitions in the (^{7}Li,^{7}Be) reactions at 0° and B(GT) values. μ and N'' are the reduced mass and the distortion factor, respectively [197].

B(GT;CEX)/B(GT;β-decay) ~ 1 within a few % especially for the strongest transitions

Search for 0νββ decay: a worldwide race

NLDBD Report April 24, 2014

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 (o… others)		
Candles	^{48}Ca		
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

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

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

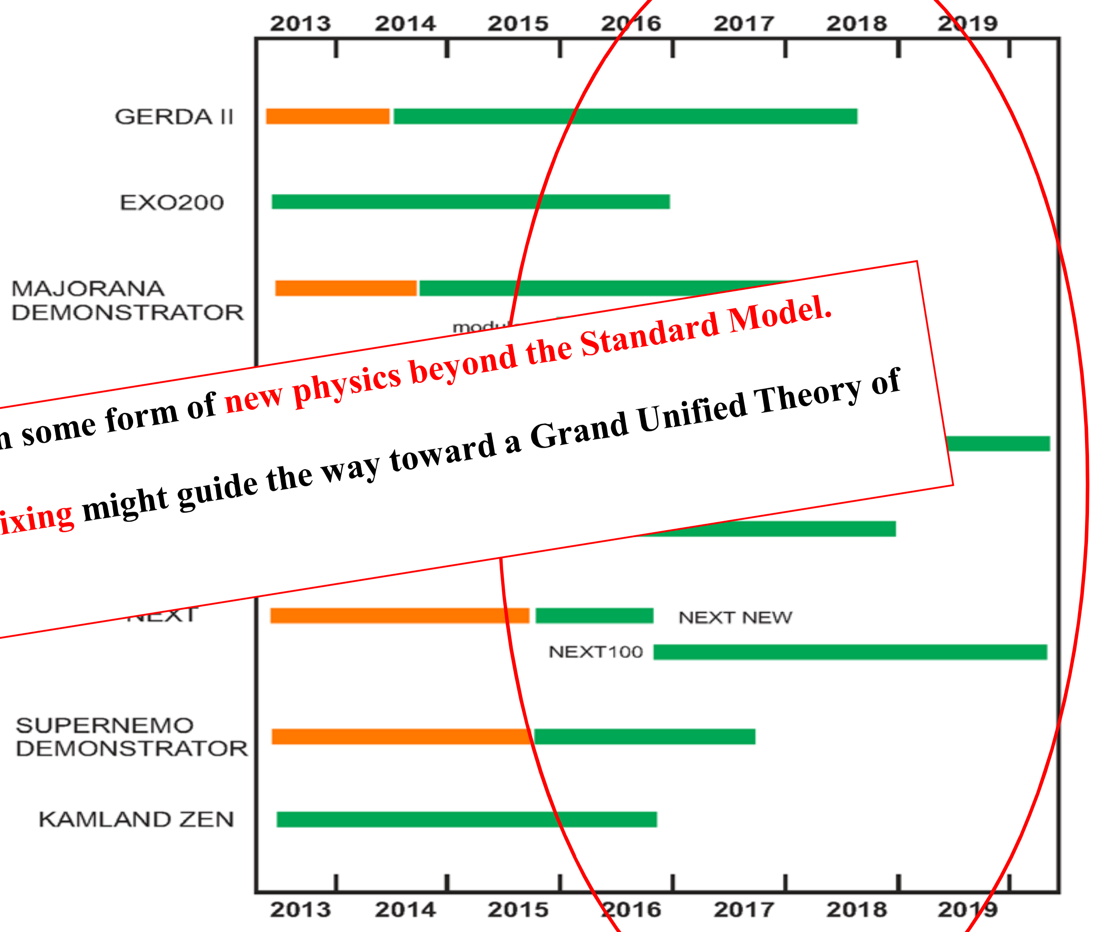
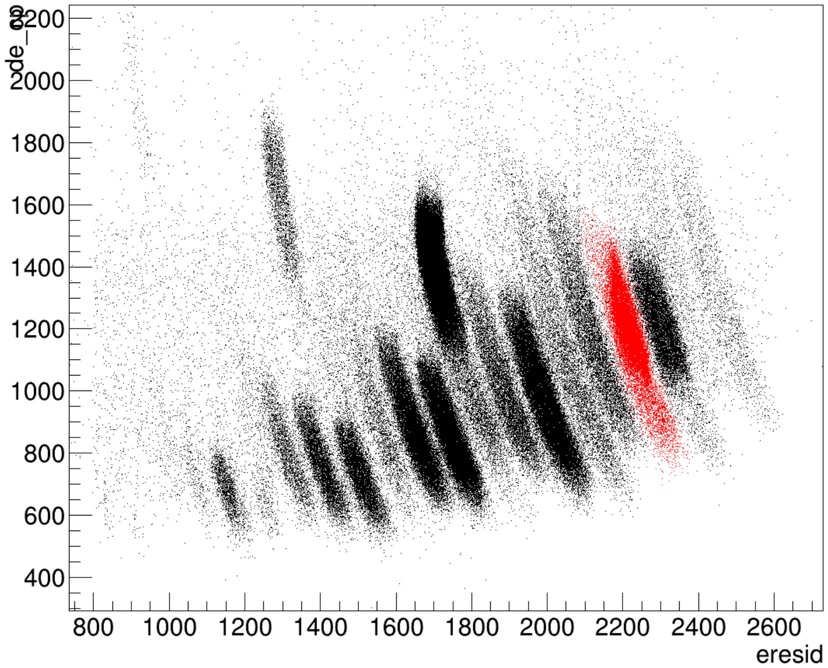
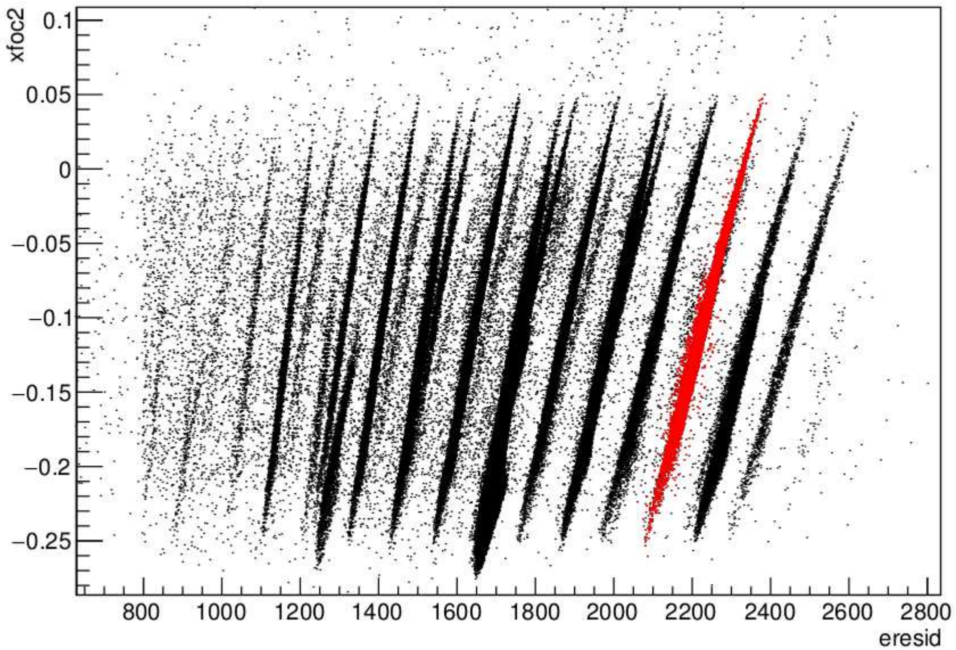


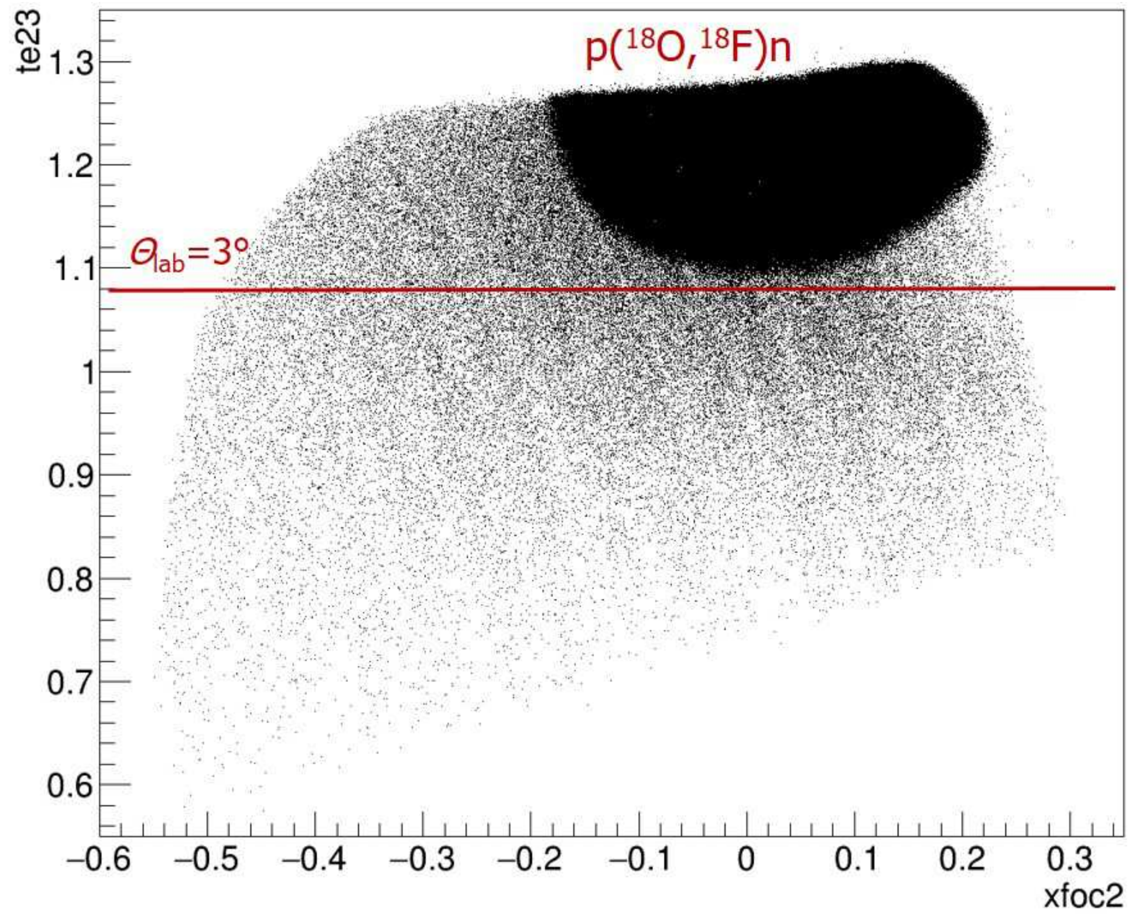
Figure 2.2. Approximate timelines for the presented projects. The orange bars represent nominal construction periods and green illustrates actual or intended running.

$^{116}Sn(^{18}O,^{18}F)^{116}In$ CEX data reduction



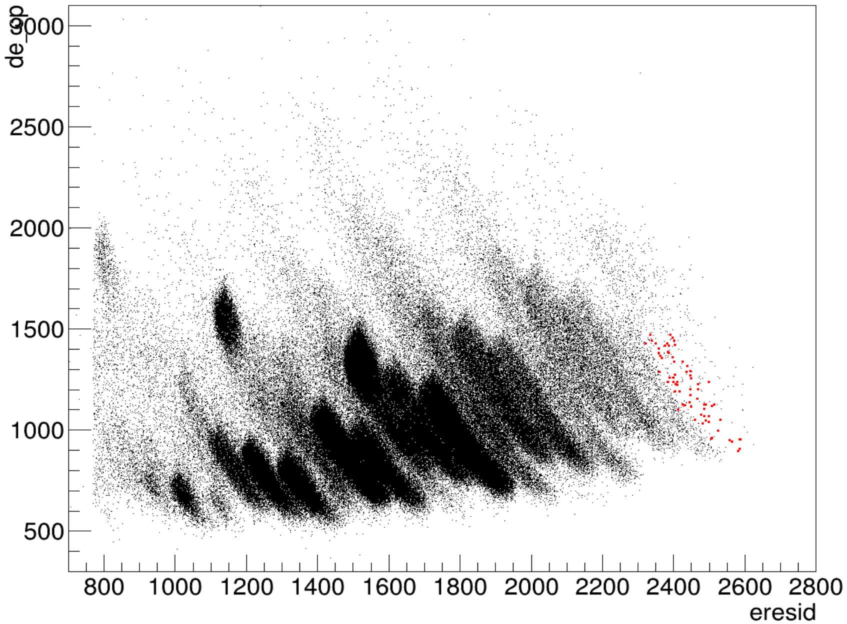
$^{18}F^{9+}$



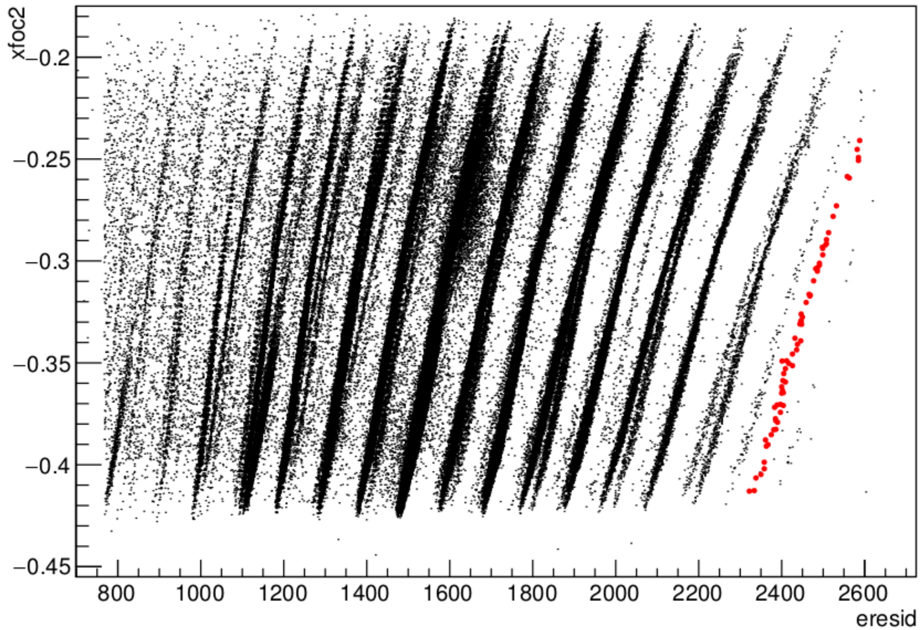


te23
xfoc2
p(^{18}O,^{18}F)n
Θ_{lab}=3°

$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ DCEX data reduction

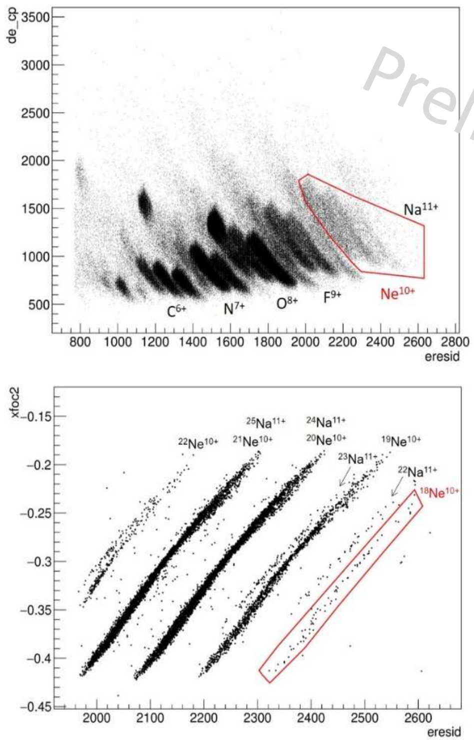


$^{18}Ne^{10+}$

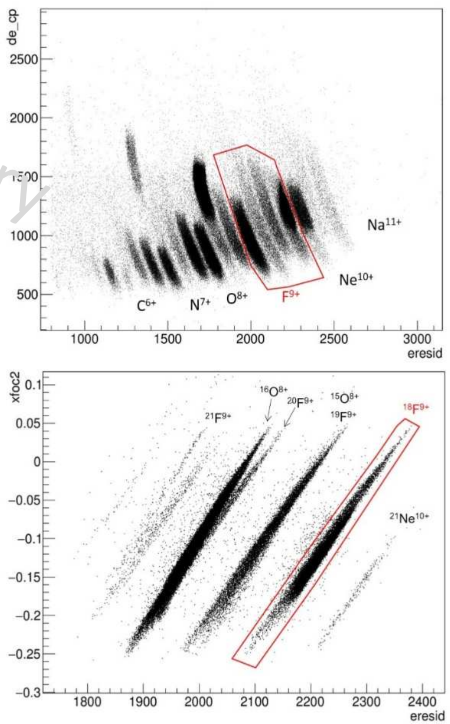


The experiment
$^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ @ 15 MeV/u

- ✓ **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)

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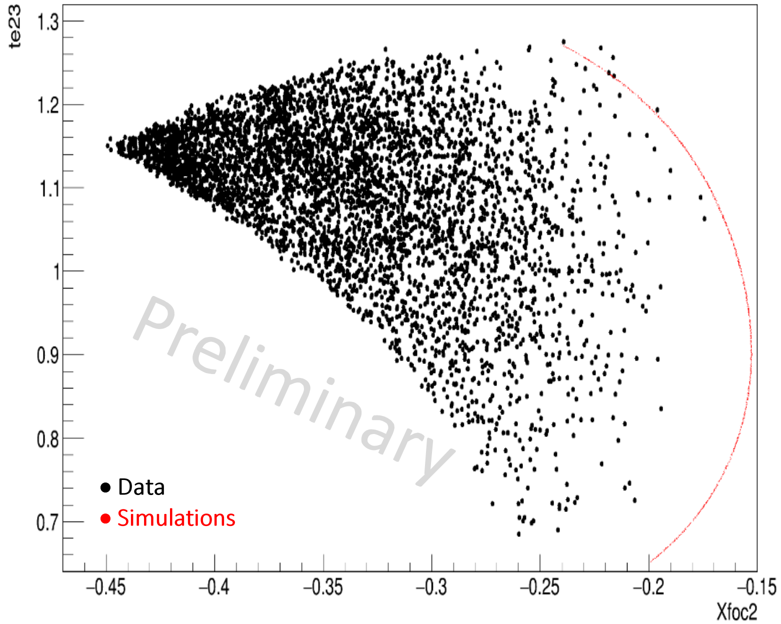
Study of the ^{18}O + ^{116}Sn at 15 MeV/u

Partial data-set in the case of identified ^{18}Ne ejectiles : DCE channel

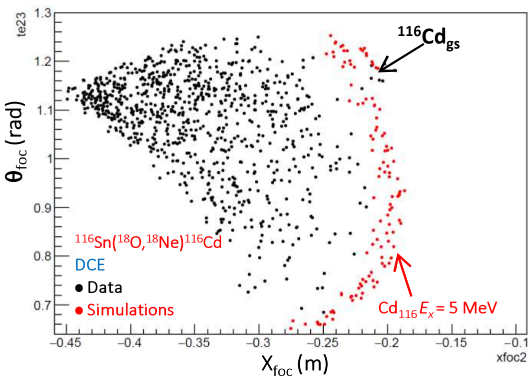


θ_{foc} - X_{foc} correlation for the identified DCE channel: $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$ at 15 MeV/u.
The red line is the result of simulation with a narrow cut in the vertical phase space for the transition to the $^{116}Cd_{gs}$.

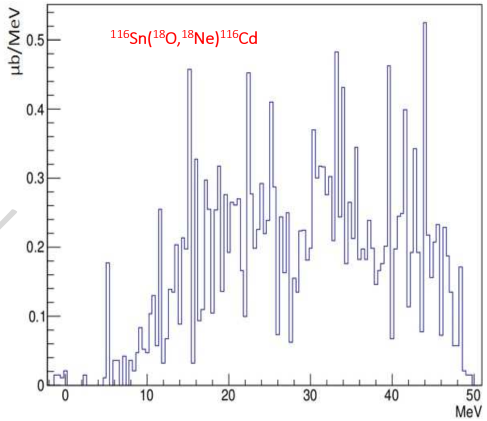
n on $^{116}Sn(^{18}O,^{18}Ne)^{116}Cd$

- ✓ 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

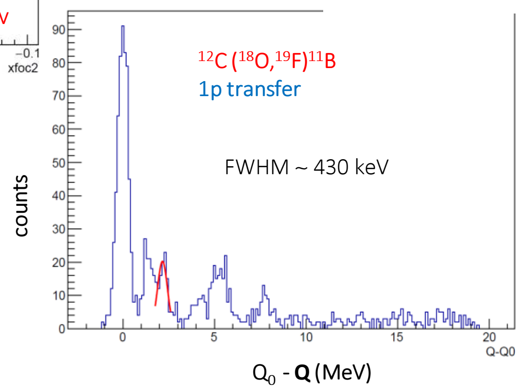
Good sensitivity for DCE



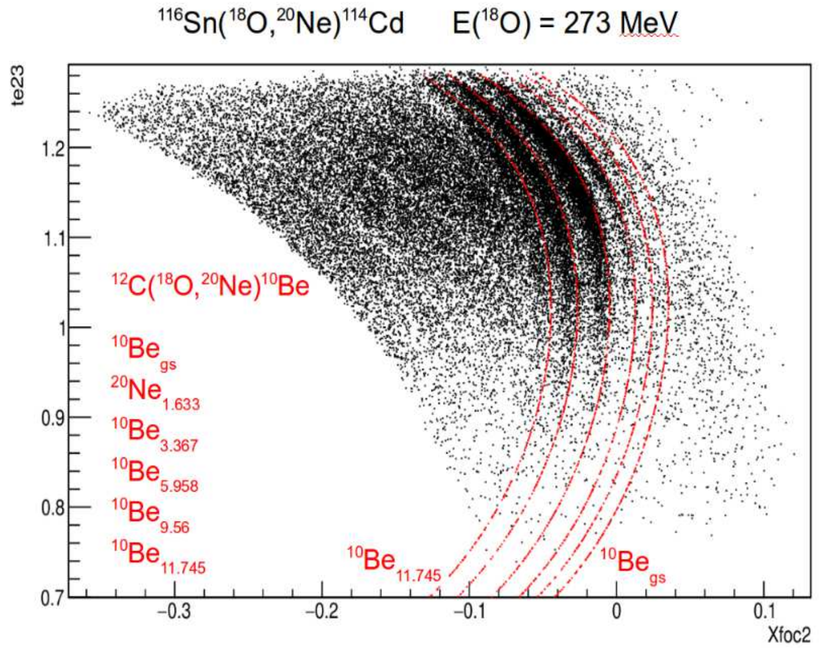
Preliminary



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

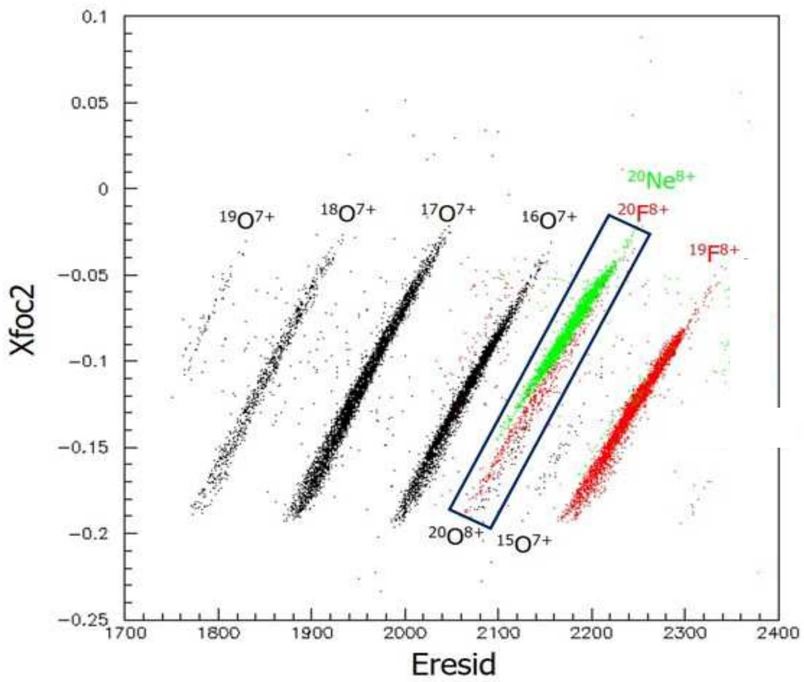


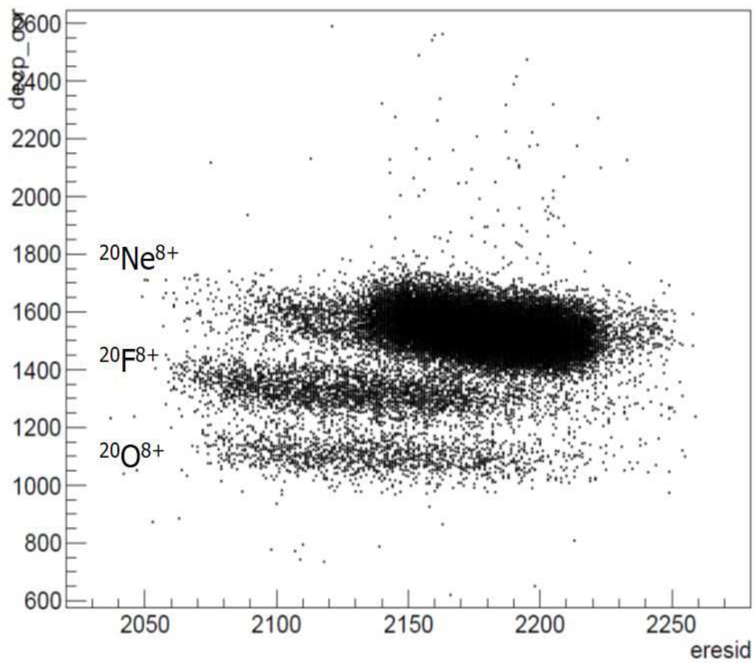
^{12}C contaminant in the target



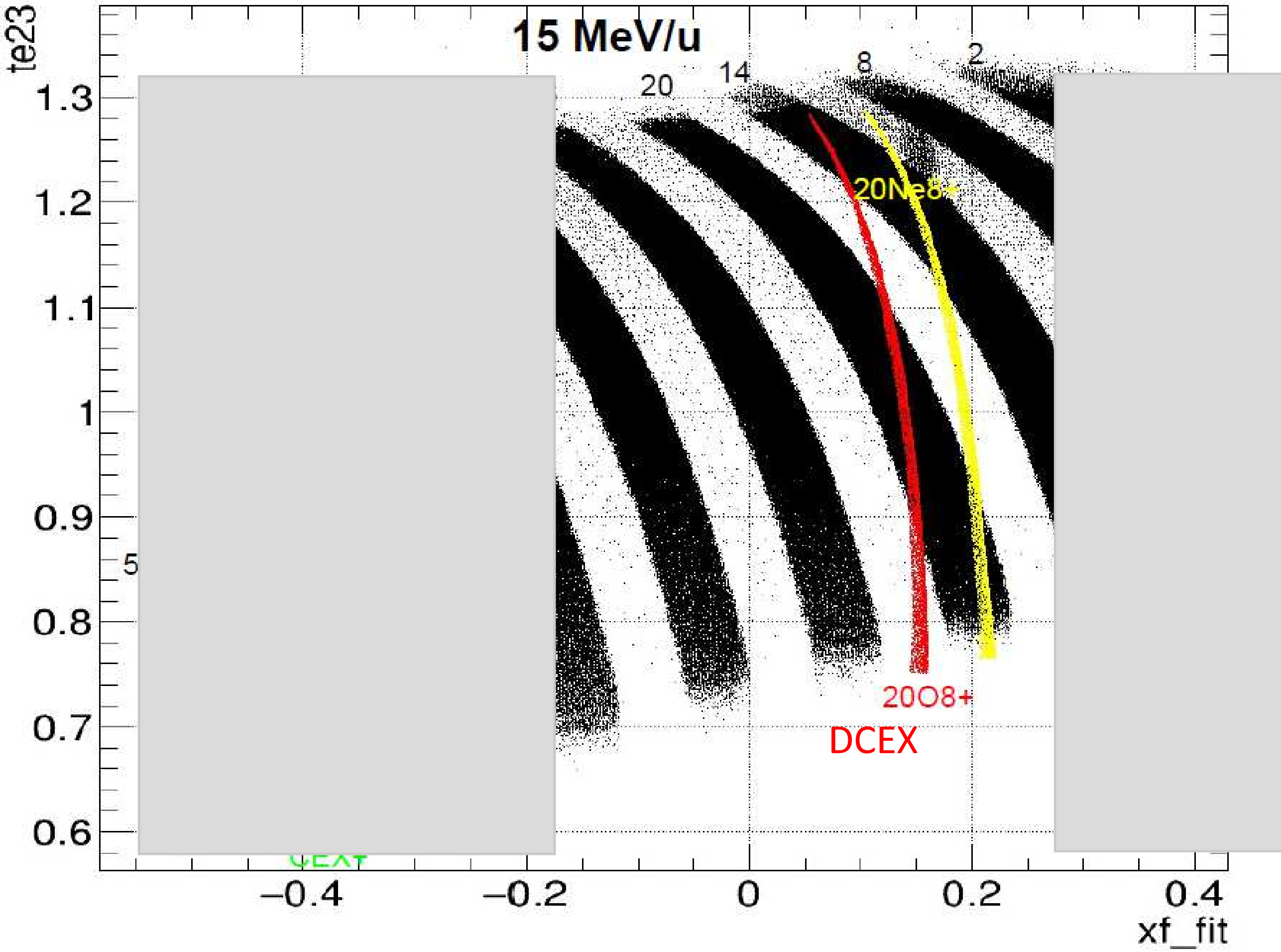
Preliminary plot of the parameters θ_{foc} (horizontal angle) and X_{foc} (horizontal position), measured at the focal plane for the selected ^{20}Ne ejectiles (two-proton transfer channel). The red points in the figure represent the simulated events of the transitions due to ^{12}C contaminant in the target. The events which are at the right side of the transition to the $^{12}C(^{18}O,^{20}Ne)^{10}Be_{g.s.}$ are due to the ^{116}Sn and are free from contamination. A supplementary run on carbon target was also performed for background subtraction.

$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$ DCEX reaction @ 15 MeV/A





Experiment at 15 MeV/A



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