INFN LNS
Istituto Nazionale
di Fisica Nucleare

NUMEN = Determining NME by

Heavy-Ion Double Charge Exchange

(What Next activity)

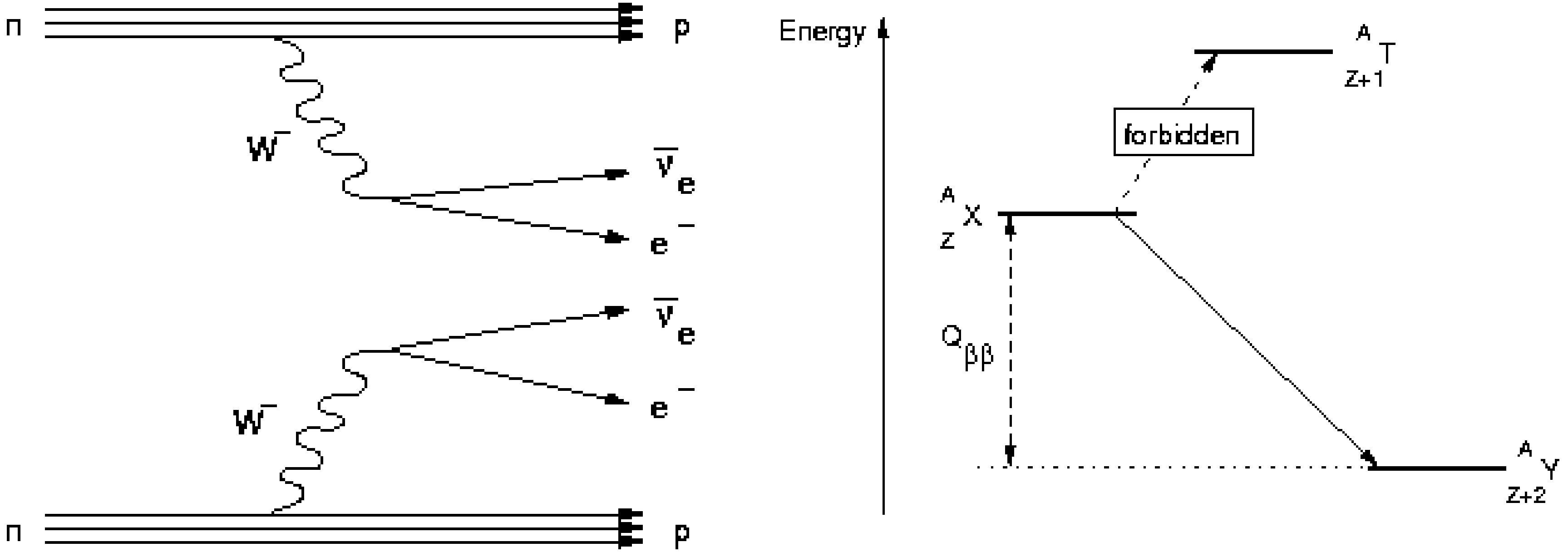
Theoretical activity only at Genoa

Santopinto– INFN - Italy

The $2\beta\beta$ decay

In 1935, Maria Goeppert-Mayer predicted the existence of the two neutrino double beta decay process $2\nu\beta\beta$ decay and was seen for first time in 1987 by Elliot et al. Phys. Rev. Lett. **59** 2020 **(1987)**

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} + 2\bar{\nu} \tag{1} $$

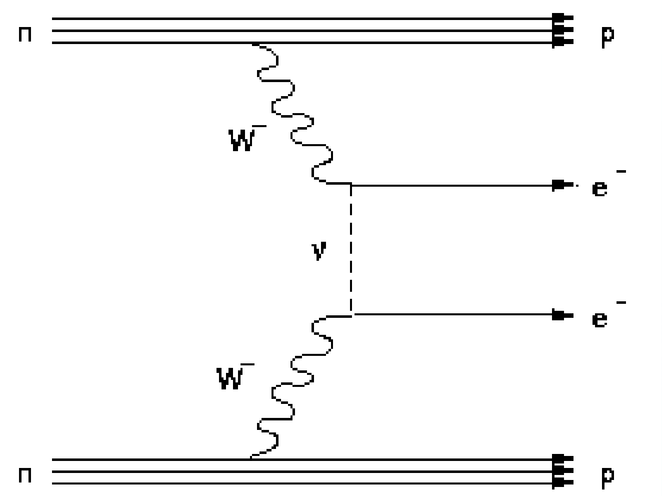


$2\nu\beta\beta$ process and energy scheme.

The $0\nu\beta\beta$ decay

In 1939, Wolfgang Furry proposed that a double beta decay without emission of neutrino

$$^A_ZX_N \rightarrow ^A_{Z+2} Y_{N-2} + 2e^- \tag{2}$$



Neutrinoless double beta decay exp. Tool to probe the Majorana or Dirac nature of neutrino and (eventually) to extract its effective mass.

Even-even nuclei where the single β- decay is energetically forbidden

The $0\nu\beta\beta$ decay

The half life time is given by the following formula for light neutrino mass :

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2|f(m_i, U_{ei})|^2$$

- The first term $G_{0\nu}(Q_{\beta\beta}, Z)$,i s a kinematical space factor (atomic physics).
- The second term $|M^{0\nu}|^2$ which depends on the nuclear structure .
- Third term contains physics beyond the standard model through the neutrino masses m_i and mixing matrix elements U_{ei} of neutrino species.

The role of nuclear physics

In the 0νββ double beta decay the decay rate can be expressed as

$$1/T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{01}\left|M^{\beta\beta\,0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2 \quad \Rightarrow \quad \boxed{\langle m_\nu \rangle = \sum_i \left|U_{ei}\right|^2 m_i e^{i\alpha_i}}$$

!

$$\Downarrow$$

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

•

The common operator for $0\nu\beta\beta$ is given by

$$M^{0\nu} = g_A^2 \left(M_{GT}^{0\nu} - \frac{1}{g_A^2} M_F^{0\nu} \right)$$

Fermi Matrix

$$M_F^{0\nu} = \langle \Psi_f | \sum_{mn} H(r_{nm}, \overline{E}) \tau_n^+ \tau_m^+ | \Psi_f \rangle$$

Gamow-Teller

$$M_{GT}^{0\nu} = \langle \Psi_f | \sum_{mn} H(r_{nm}, \overline{E}) \tau_n^+ \tau_m^+ \vec{\sigma}_n \vec{\sigma}_m | \Psi_f \rangle$$

for the $2\nu\beta\beta$ the neutrino potential is one. Iachello Phys. Rev. C 91 (2015)

Candidates of double beta decay

Different nuclear isotopes are necessary to minimize the impact of uncertainties in matrix element to extract information about neutrino and nuclear properties.

Table: $\beta\beta$ emitters with $Q_{\beta\beta} > 2$MeV

Transition	$Q_{\beta\beta}$(keV)	Abundance(%)
110Pd→110Cd	2013	12
76Ge→76Se	2040	8
124Sn→124Te	2288	6
136Xe→136Ba	2479	9
130Te→130Xe	2533	34
116Cd→116Sn	2802	7
82Se→82Kr	2995	9
100Mo→100Ru	3034	10
96Zr→96Mo	3350	3
150Nd→150Sm	3667	6
48Ca→48Ti	4271	0.2

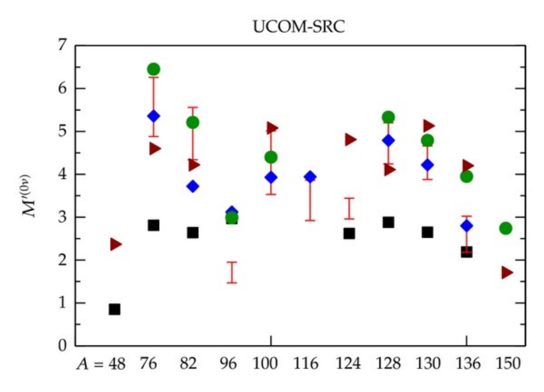
Giunti, Bilenky Int. Jour. Phys A. 30 **(2015)**

The state of the art

!

The evaluation of NME: $$\left|M^{\beta\beta}_{0\nu\,\varepsilon}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}^{\beta\beta}_{0\nu\,\varepsilon} \middle| \Psi_i \right\rangle\right|^2$$

✓ **Calculations (still sizeable uncertainties)**: QRPA, Large scale shell 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

A. Giuliani and A. Poves, Adv. in High Energy Phys., **857016** (2012)

✓

N. Auerbach, Ann. Of Phys. 192 (1989) 77x

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
D.Frekers et al. NPA 916 (2013)219 - 240

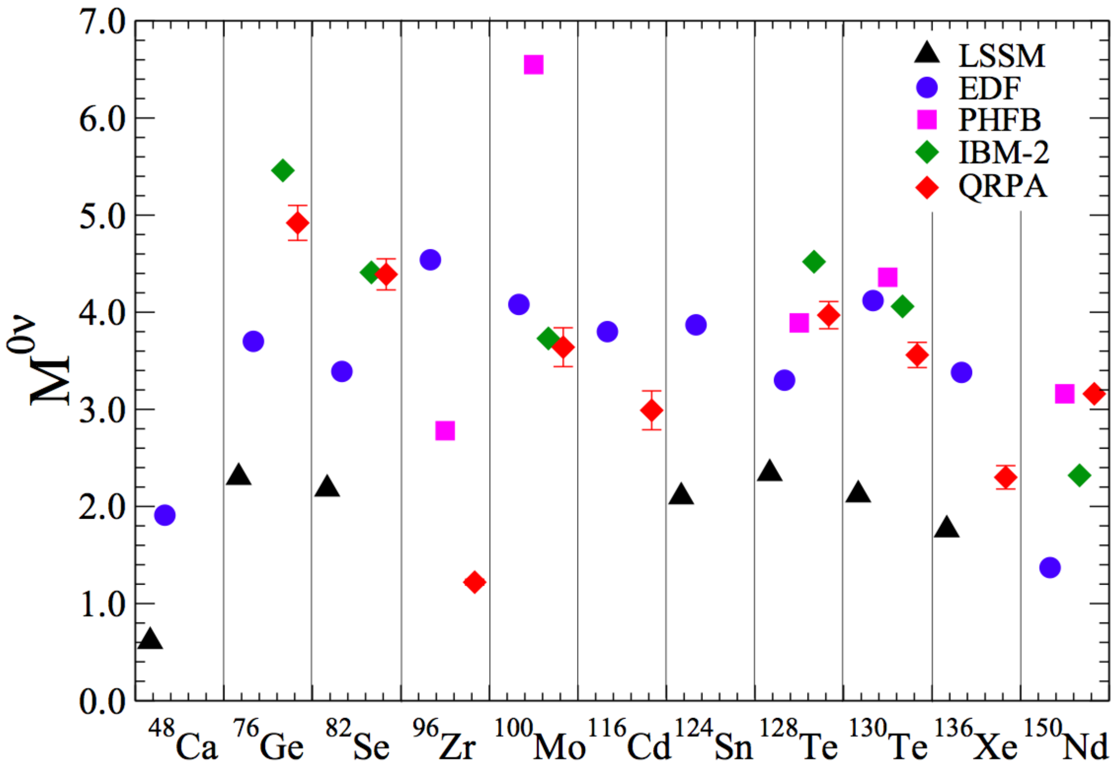
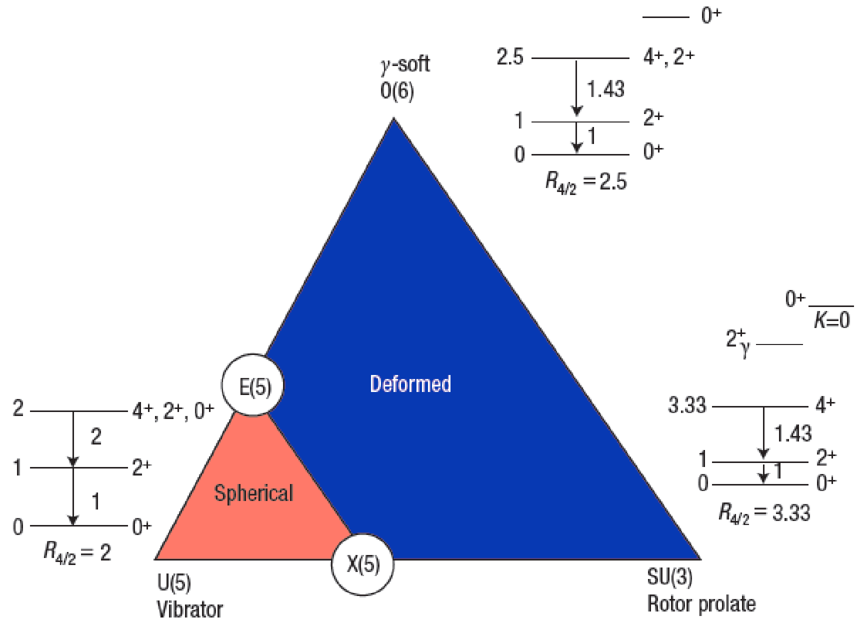


Figure: Matrix elements of the neutrinoless double beta decay for the different approaches.

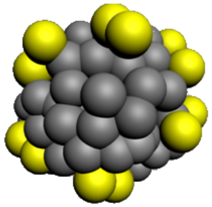
F. Šimkovic Nucl. Phys. B **229-232 (2012)**

Interacting Boson Model (IBM)

- $U(5)$ for vibrational symmetry
- $SU(3)$ for rotational symmetry
- $O(6)$ for collective symmetry (γ -unstable)



Interacting Boson Model (IBM)



Creation and anihilation operators for bosons

$$b_i^\dagger, b_i \quad i = l, m \quad (l = 0, 2 \quad -l \leq l)$$

$$[b_i, b_j^\dagger] = \delta_{ij}, \quad [b_i^\dagger, b_j^\dagger] = [b_i, b_j] = 0$$

Generators of $U(6)$

$$G_i^j = b_i^\dagger b_j \quad i, j = 1, ...6$$

there are 36 bilineal products

$$[G_i^j, G_l^k] = G_i^j \delta_{j,k} - G_l^k \delta_{i,l}$$

where $i, j, j, l = 1, .., 6$

A. Arima y F. Iachello Phys. Rev. Lett. 35 1069 **(1975)**

Problem:

we want to arrive to measure in an independent way the NMEs: DCE?

The NMCs from DCE (strong nuclear interaction) will be proportional to the weak ones for zero neutrino double beta, but not equal. Anyway, since the geometrical structure of the operators involved (F , GT) is the same, and also the initial and final nuclear states, very important information can be extracted from DCE -NMCs

Factorization of the charge exchange cross-section

for singlecharge exchange SCE well proved:

β-decay transition strengths
(reduced matrix elements)

α= Fermi (F)
or Gamow Teller (GT)

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

$$\boxed{|M_j(\alpha)|^2 = |B(\alpha)|}$$

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

unit cross-section

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

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.

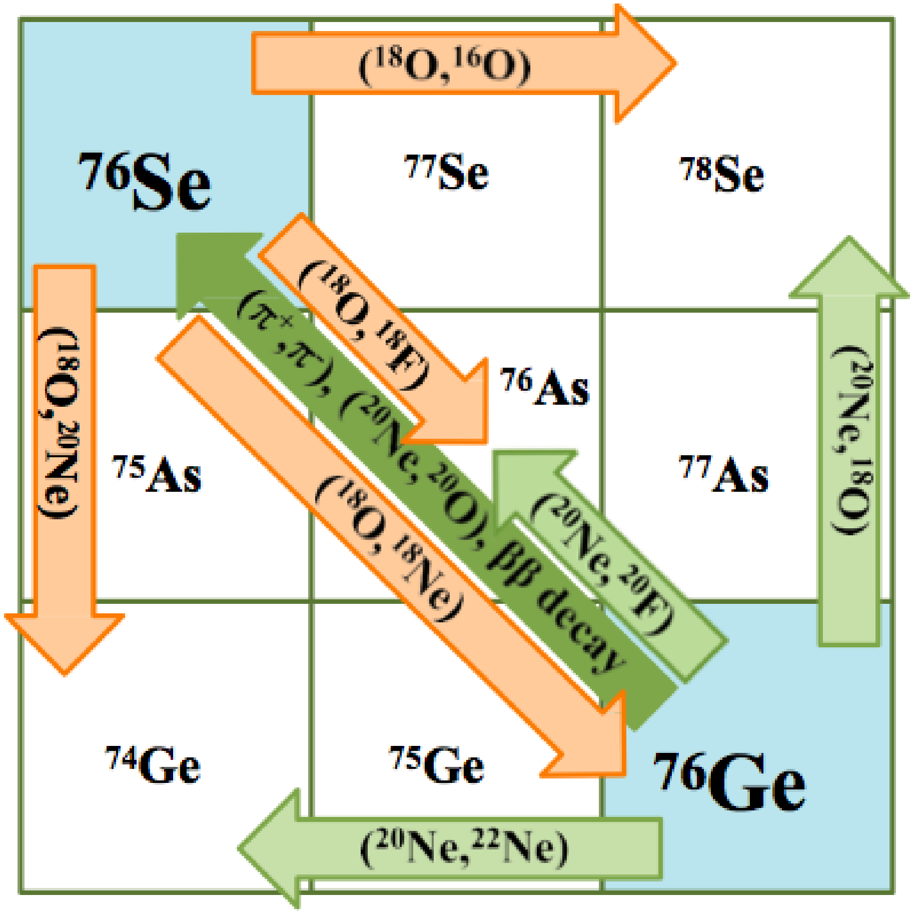
In the hypothesis of a surface localized process :

FACTORIZATION for DCE? A factorization formula has to be worked out, if possible. Otherwise also all the other competive processes will be calculated.

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

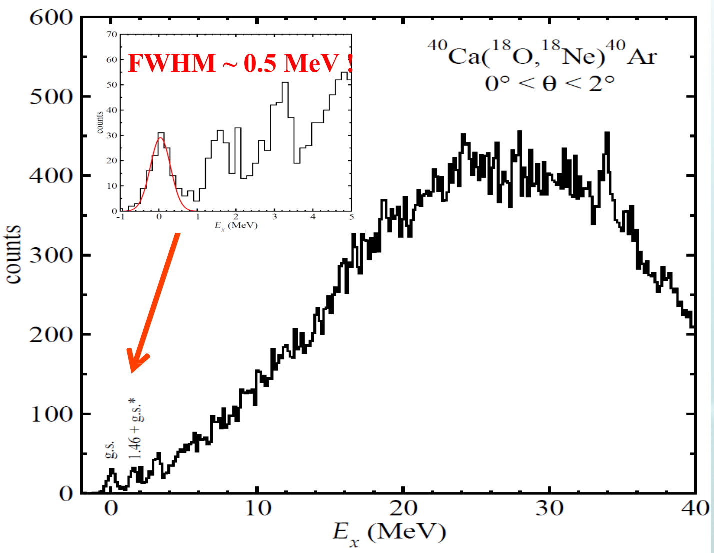
$$\frac{d\sigma^{DCE}}{d\Omega}(q,\omega) = \hat{\sigma}_\alpha^{DCE}\left(E_p, A\right)F_\alpha^{DCE}(q,\omega)B_T^{DCE}(\alpha)B_P^{DCE}(\alpha)$$

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


$(^{18}\mathrm{O},^{16}\mathrm{O})$
$^{76}\mathrm{Se}$
$^{77}\mathrm{Se}$
$^{78}\mathrm{Se}$
$(^{18}\mathrm{O},^{18}\mathrm{F})$
(π^{+},π^{-}), $(^{20}\mathrm{Ne},^{20}\mathrm{O})$, ββ decay
$(^{18}\mathrm{O},^{20}\mathrm{Ne})$
$^{76}\mathrm{As}$
$^{75}\mathrm{As}$
$^{77}\mathrm{As}$
$(^{20}\mathrm{Ne},^{18}\mathrm{O})$
$(^{18}\mathrm{O},^{18}\mathrm{Ne})$
$(^{20}\mathrm{Ne},^{20}\mathrm{F})$
$^{74}\mathrm{Ge}$
$^{75}\mathrm{Ge}$
$^{76}\mathrm{Ge}$
$(^{20}\mathrm{Ne},^{22}\mathrm{Ne})$

Preliminary results

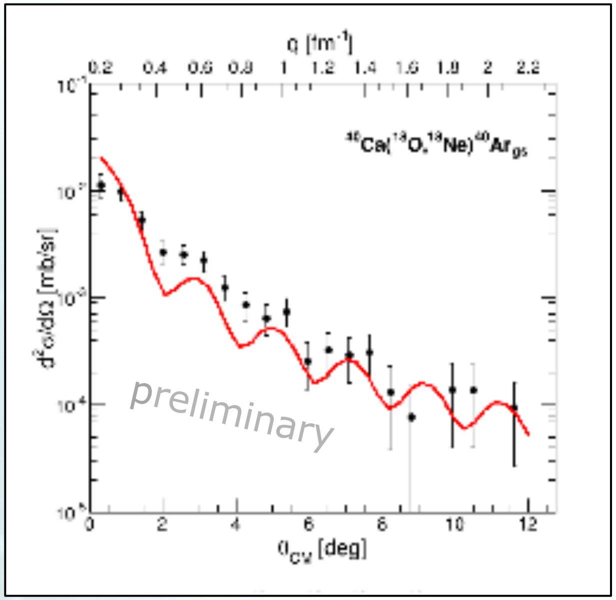
Measured energy spectrum of ^{40}Ar at very forward angles with an energy resolution of FWHM ~ 0.5 MeV .



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

Differential cross-section of the transition

^{0}Ca$_{g.s.}$(^{18}O,^{18}Ne)^{40}Ar$_{g.s.}$ @ 270 Mev



The position of the minima is well described by a Bessel function : such an oscillation pattern is not expectd in complex multistep transfer reactions.This gives hope about the possibility of a factorization formula

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

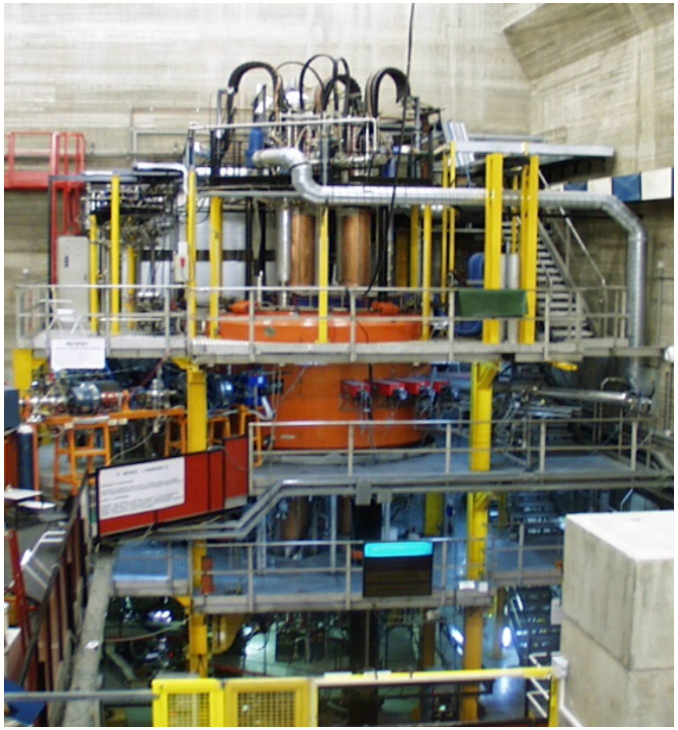
Double Charge Exchange Experiment NUMEN

INFN Laboratori Nazionali del Sud – Catania

- Canditates isotopes:^{198}**Pt**, ^{48}**Ca**, ^{82}**Se**, ^{100}**Mo**, ^{124}**Sn**, ^{128}**Te**, ^{130}**Te**, ^{136}**Xe**, ^{148}**Nd**, ^{150}**Nd**, ^{154}**Sm**, ^{160}**Gd** .

Double Charge Exchange Experiments Set-up

- The Superconducting Cyclotron (CS) at LNS.
- K800 Superconducting Cyclotron in full operation since 1996. It can accelerate from Hydrogen to Uranium.
- Maximum nominal energy is 80 MeV/u.
- The pilot experiment: ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar@LNS.
- $^{18}O_7{}^+$ beam from Cyclotron at 270 MeV .
- ^{40}Ca solid target 300 $\sim$ g/cm^2.



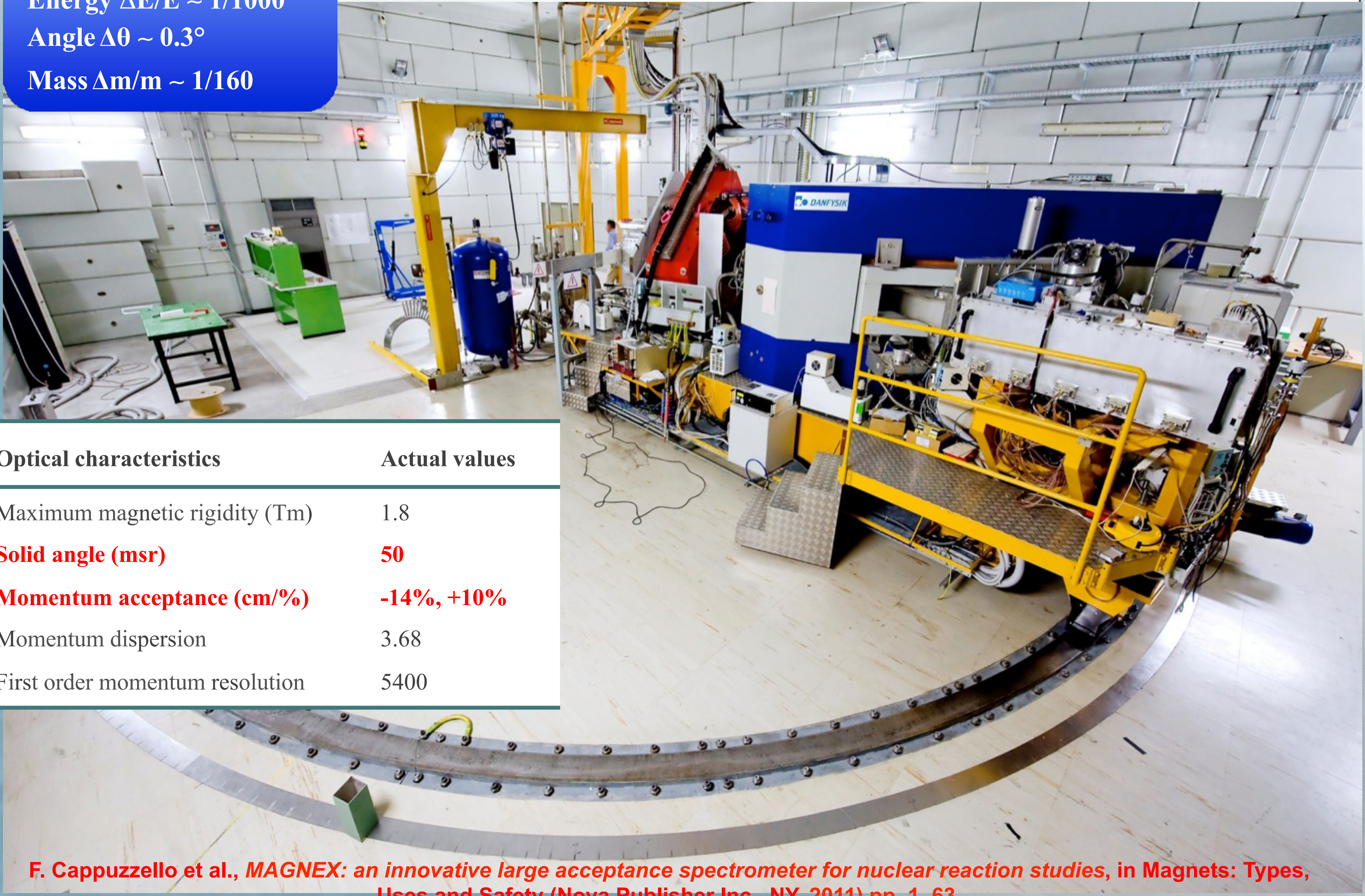
The experimental SET-UP@ LNS: MAGNEX

Measured Resolution:

Energy ΔE/E ~ 1/1000

Angle Δθ ~ 0.3°

Mass Δm/m ~ 1/160



Optical characteristics	Actual values
Maximum magnetic rigidity (Tm)	1.8
Solid angle (msr)	**50**
Momentum acceptance (cm/%)	**-14%, +10%**
Momentum dispersion	3.68
First order momentum resolution	5400

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

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The NUMEN Project

C. Agodi, F. Cappuzzello, M. Bondì, L. Calabretta, D. Carbone, M. Cavallaro, M. Colonna, A. Cunsolo, G. Cuttone, A. Foti, P. Finocchiaro, V. Greco, L. Pandola, D. Rifuggiato,E. Santopinto, S. Tudisco

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