Double Charge-Exchange Reactions with SIB and the NUMEN Project

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

ECOS-EURISOL Joint Town Meeting

Institut de Physique Nucléaire, Orsay

ECOS EURISOL ENSAR October 28-31, 2014

A quick historical background

- ✓ 1986: first discovery of 2υββ decay predicted by Maria Goeppert Mayer in 1935 (today found in 12 nuclei)

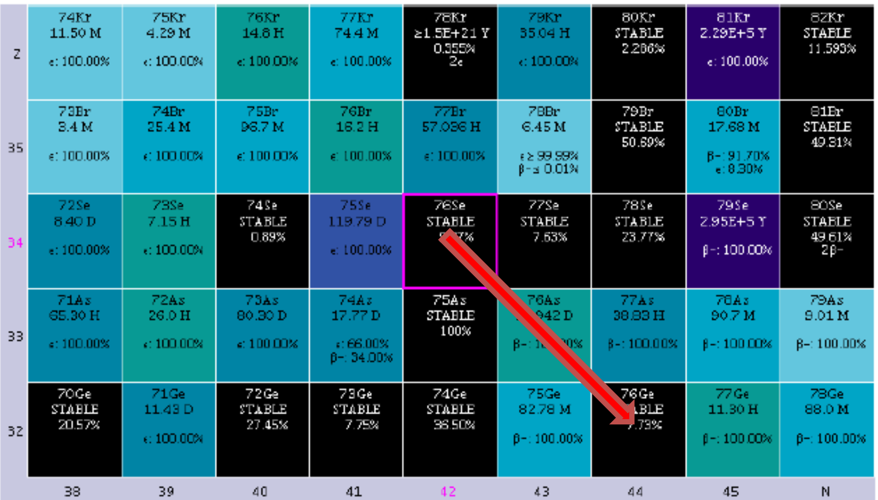
- ✓ 1998: discovery of neutrino oscillations and the non-zero mass of neutrinos, predicted by Pontecorvo in 1957

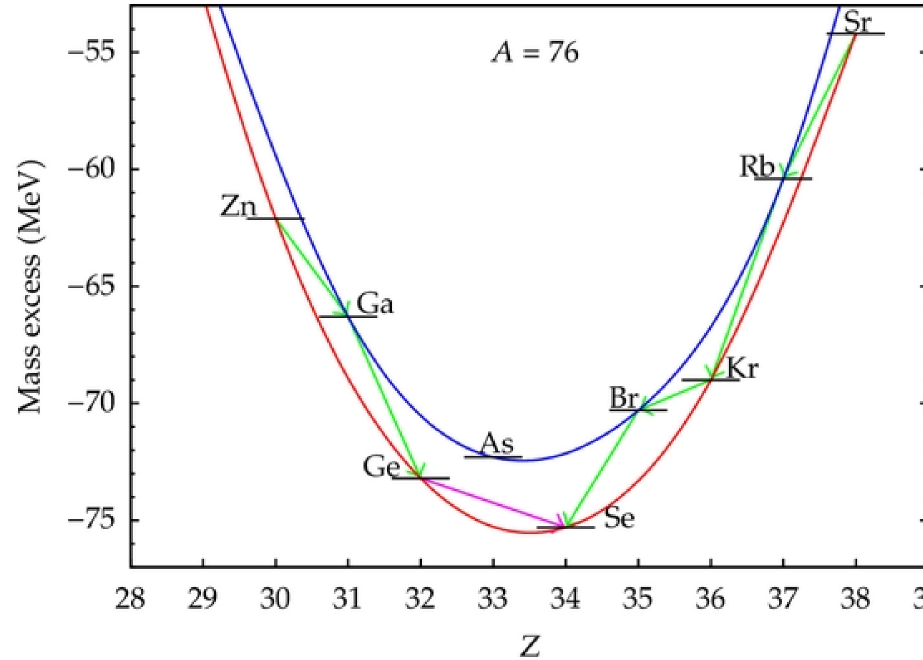
- ✓ 2013: discovery of Higgs boson and start of the era of research beyond the standard model

The Higgs mechanism cannot explain the mass of neutrinos

Double β-decay

$$ {}^{A}_{Z}X_{N} \rightarrow {}_{Z-2}^{\;\;A}Y_{N+2} + 2e^{-} + (2\bar{\nu}) $$



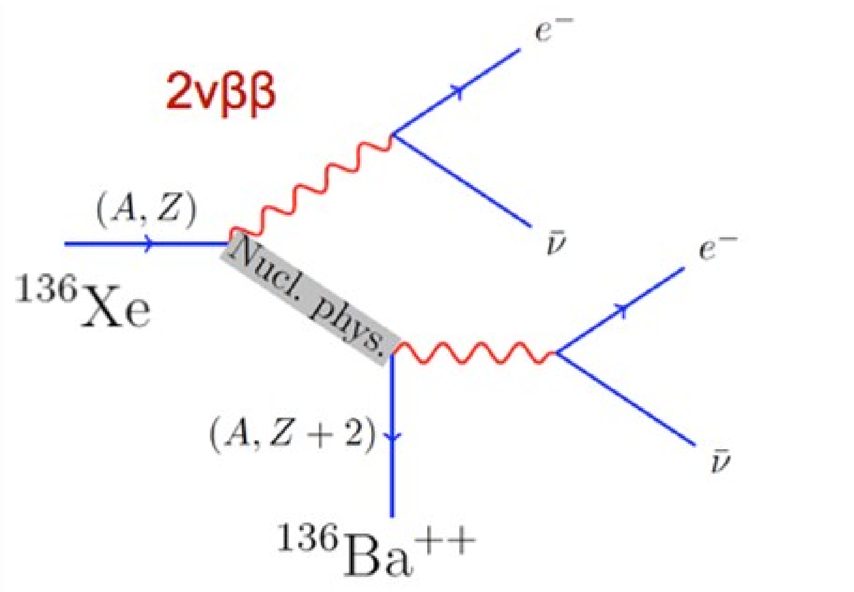


- ✓ Process mediated by the weak interaction occurring in even-even nuclei where the single β-decay is energetically forbidden

- ✓ The role of the pairing force

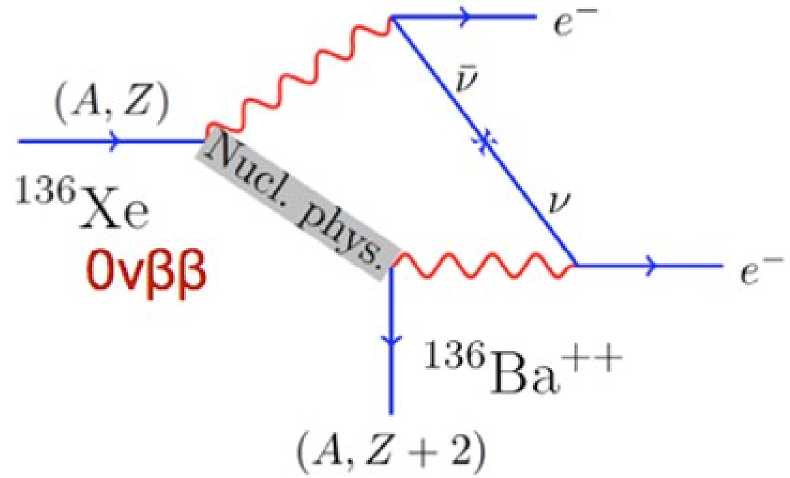
Double β-decay

Within standard model



Beyond standard model

(simple 0νββ mechanism)



$$1/T_{1/2}^{0\nu}(0^+ \to 0^+) = G_{01}\left|M^{\beta\beta0\nu}\right|^2 \left|\frac{\langle m_\nu\rangle}{m_e}\right|^2$$

Great new physics inside

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

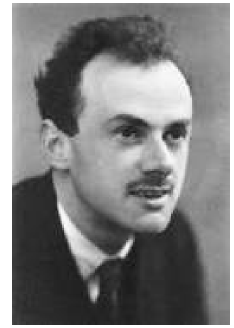
but one should know **Nuclear Matrix Element**

$$\left|M_\varepsilon^{\beta\beta0\nu}\right|^2 = \left|\left\langle \Psi_f \middle| \hat{O}_\varepsilon^{\beta\beta0\nu} \middle| \Psi_i \right\rangle\right|^2$$

ββ-decay

1) 2ν double β-decay

1) Does not distinguish between Dirac and Majorana
2) Experimentally observed in several nuclei since 1987



ν and anti-ν can be distinguished

ν and anti-ν are the same

2) 0ν double β-decay

Neutrino has mass

Neutrino is Majorana particle

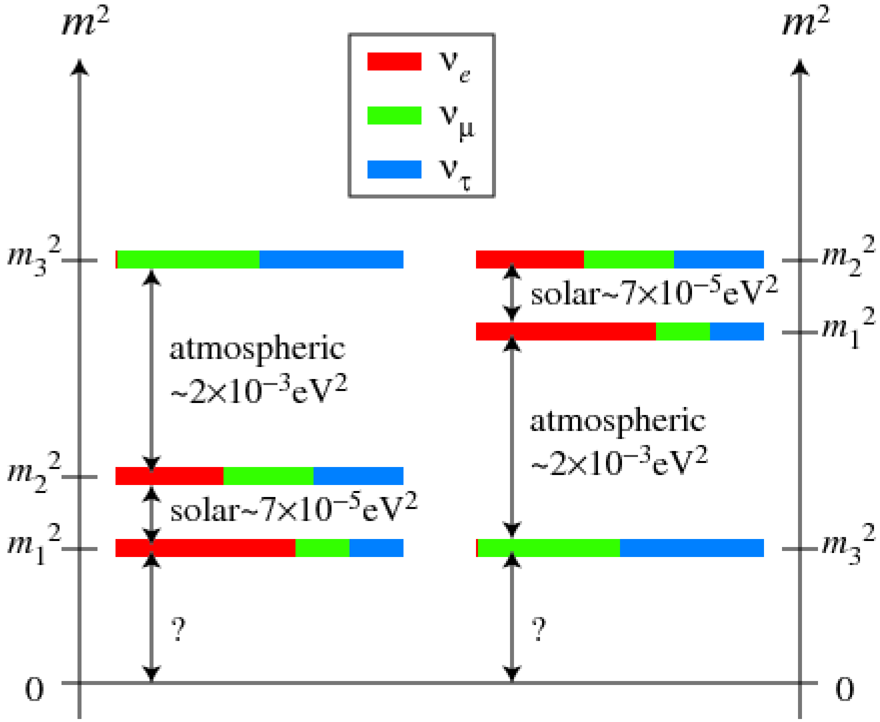
Violates the leptonic number conservation

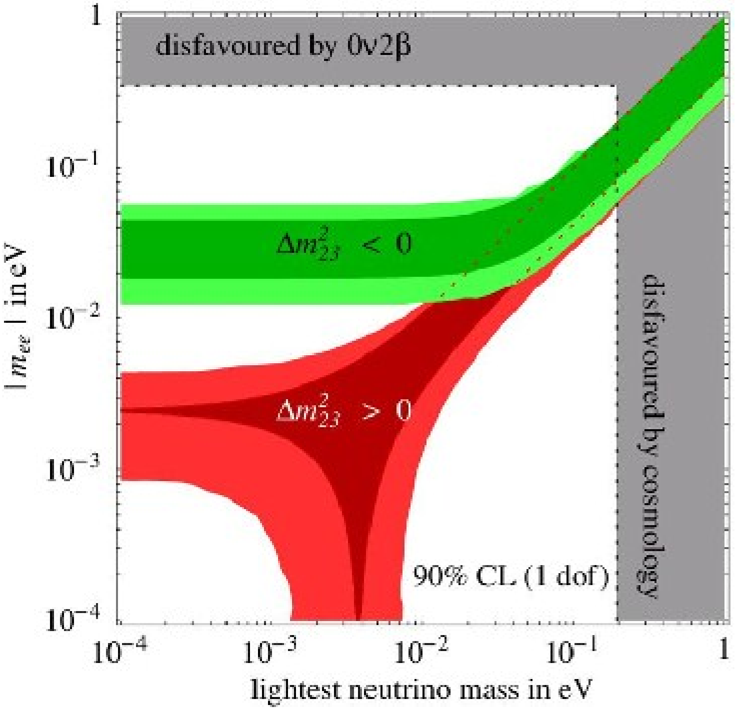
Experimentally not observed

Beyond the standard model

Normal *vs* inverted hierarchy

Neutrino oscillation experiments sensitive to Δm





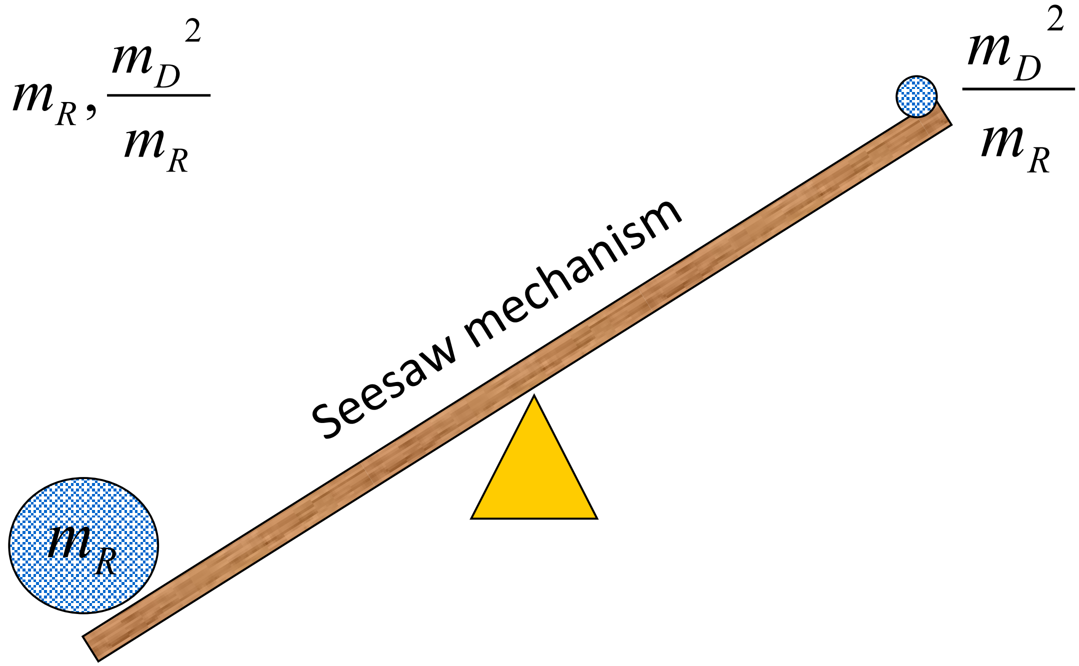
Matter *vs* Antimatter

- ✓ Leptonic number = 0 at Big Bang
- ✓ All the physics we know does conserve the leptonic number
- ✓ **Why the matter dominates over antimatter?**
- ✓ Majorana neutrinos can explain that since they do not conserve leptonic number!

Beyond the standard model

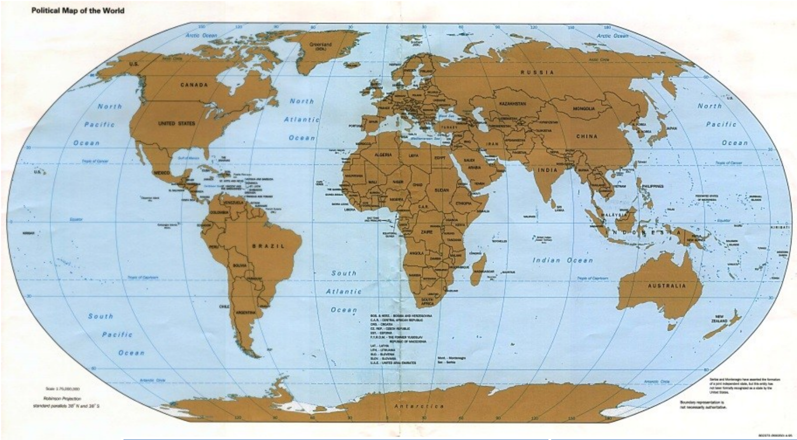
$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \qquad \det\begin{pmatrix} -\lambda & m_D \\ m_D & m_R-\lambda \end{pmatrix} = \lambda(\lambda - m_R) - m_D{}^2 = 0$$

$$\lambda = \frac{m_R \pm \sqrt{m_R{}^2 + 4m_D{}^2}}{2} \approx m_R, \frac{m_D{}^2}{m_R}$$



m_R Dirac mass will be the same order as the others. (0.1~10 GeV)

m_R Right handed Majorana mass will be at GUT scale **10^{15} GeV**



Search for 0νββ decay. A worldwide race

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)!

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

- ✓ 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.

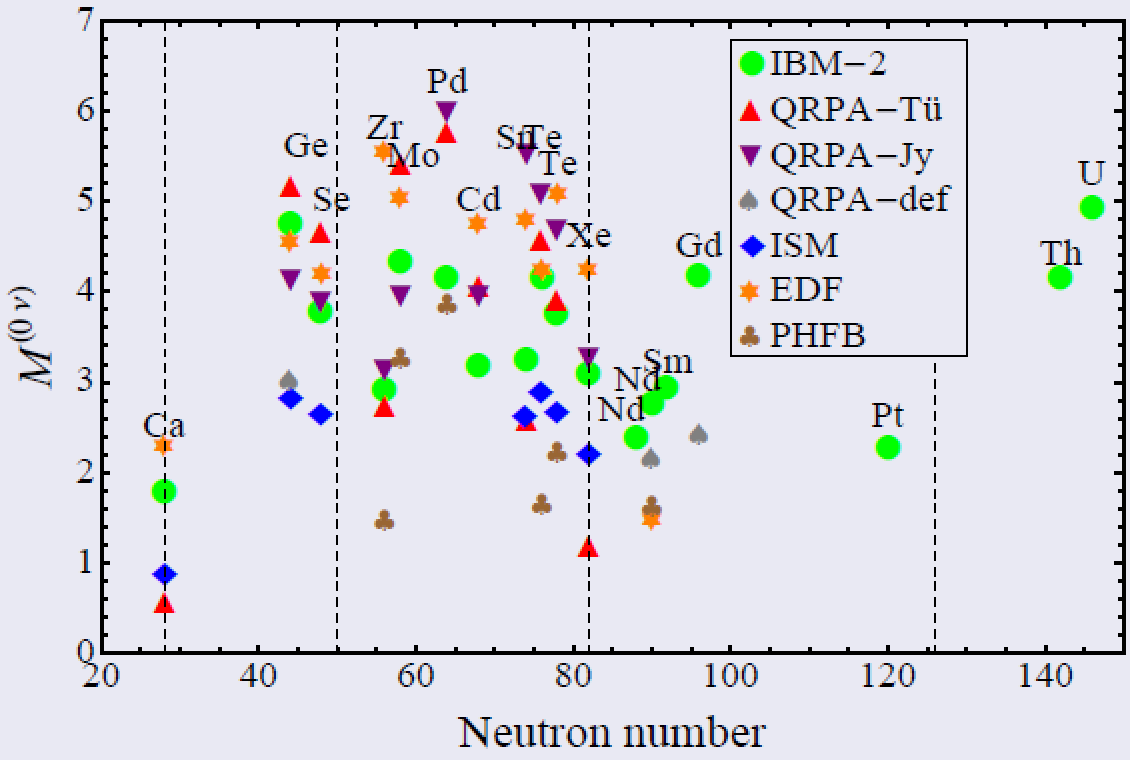
- ✓ Measurements (still not conclusive for $0\nu\beta\beta$):
  - (π^+, π^-)
  - single charge exchange (^{3}He,t)
  - electron capture
  - transfer reactions ...

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

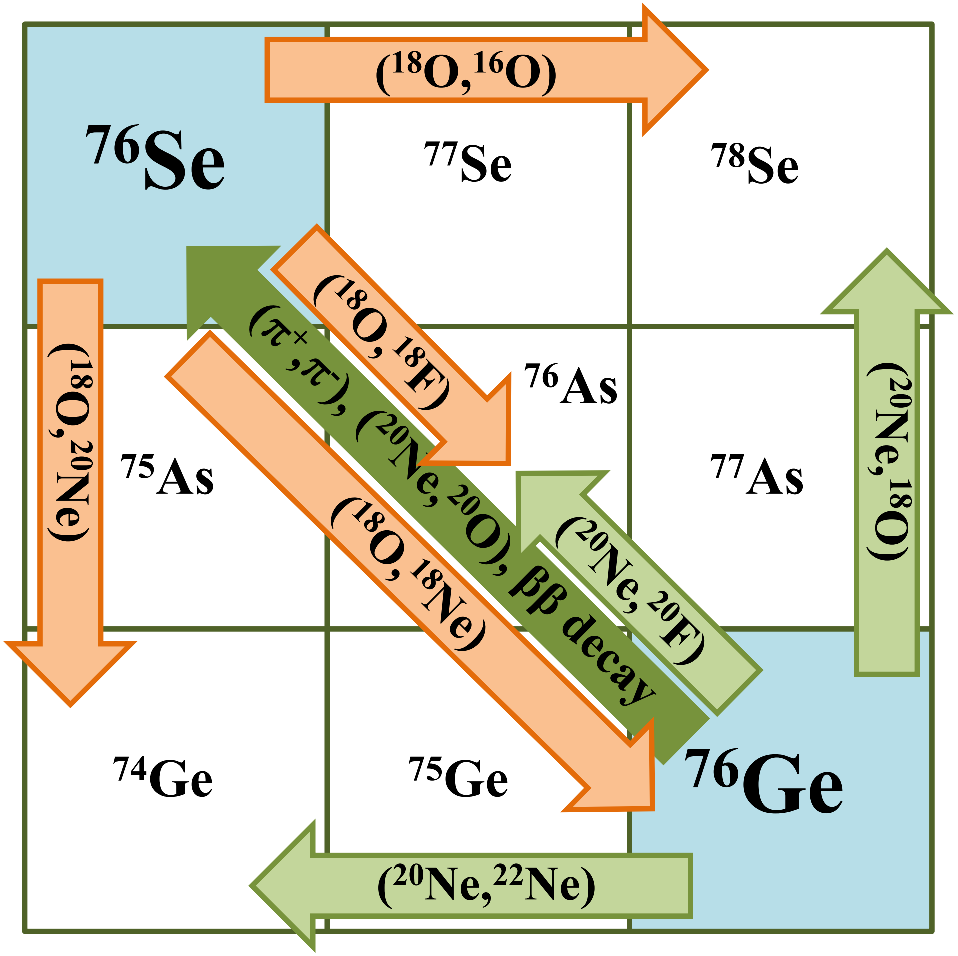
$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



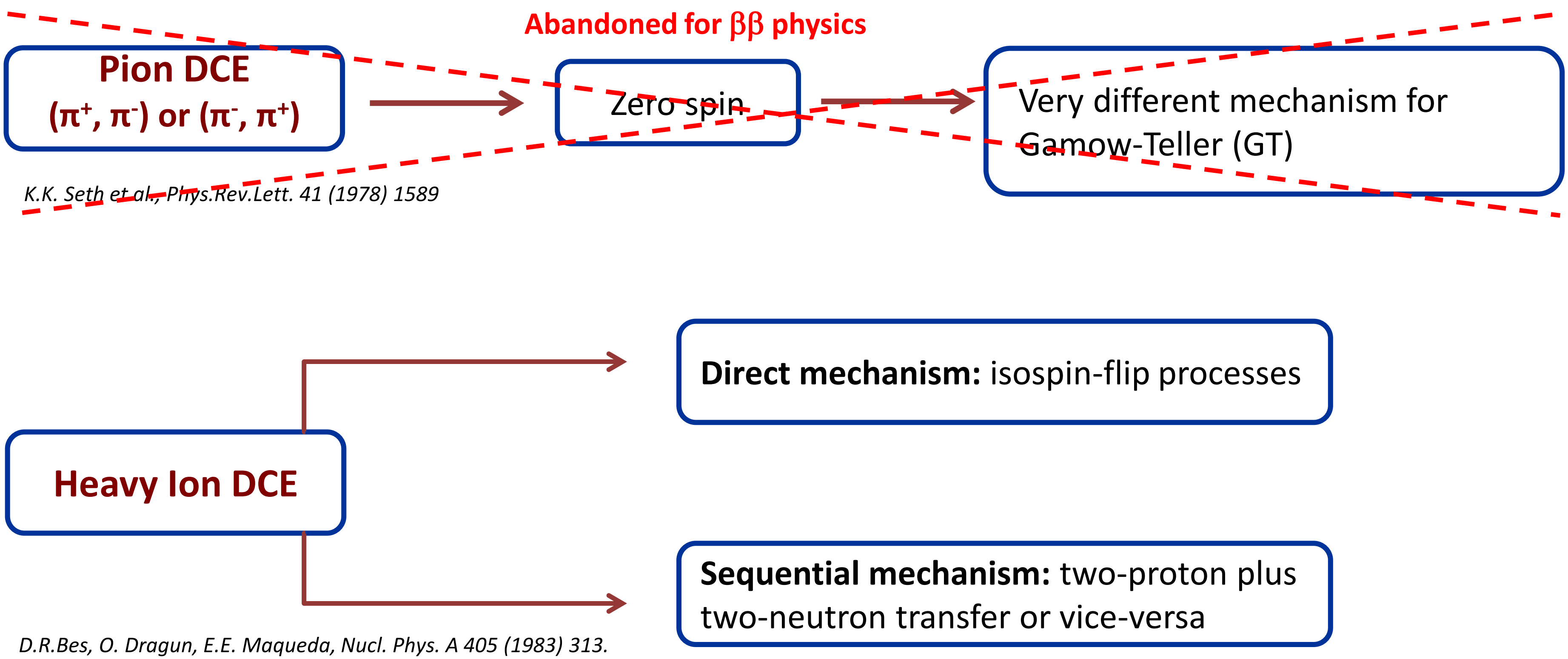
Courtesy of Prof. F.Iachello

A new esperimental tool: DCE

Double charge exchange reactions



Double charge exchange reactions



Heavy-ion DCE

1. **Sequential nucleon transfer mechanism 4th order:**

   - Brink's Kinematical matching conditions

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

2. **Meson exchange mechanism 2nd order:**

$0\nu\beta\beta$ 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 transfer:** 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.

About the reaction mechanism

A fundamental property

The complicated many-body heavy-ion scattering problem is largely simplified for direct quasi-elastic reactions

$$V_\alpha(r_\alpha, \chi_\alpha) = U_\alpha(r_\alpha) + W_\alpha(r_\alpha, \chi_\alpha)$$

Optical potential (U_α) — Residual interaction (W_α)

Factorization of the charge exchange cross-section

for single CEX:

β-decay transition strengths (reduced matrix elements)

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

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

unit cross-section

For small q

$$F(q,\omega) = \frac{K(E_p,\omega)}{K(E_p,0)} e^{-\frac{1}{3}q^2\langle r^2\rangle} e^{[p(\omega)-a_0]}$$

generalization to DCE:

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

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

For small q

$$F_\alpha^{DCE}(q,\omega) = \frac{K(E_p,\omega)}{K(E_p,0)} e^{-\frac{1}{3}{q_1}^2\langle {r_1}^2\rangle} e^{-\frac{1}{3}(\vec{q}-\vec{q}_1)^2\langle {r_2}^2\rangle} e^{[p(\omega)-a_0]}$$

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

This is what happens in single charge exchange
As an example the B(GT;CEX)/B(GT;β-decay) ~ 1 within a few % especially for the strongest transitions

The volume integrals

Nuclear spin and isospin excitati

Franz Osterfeld

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

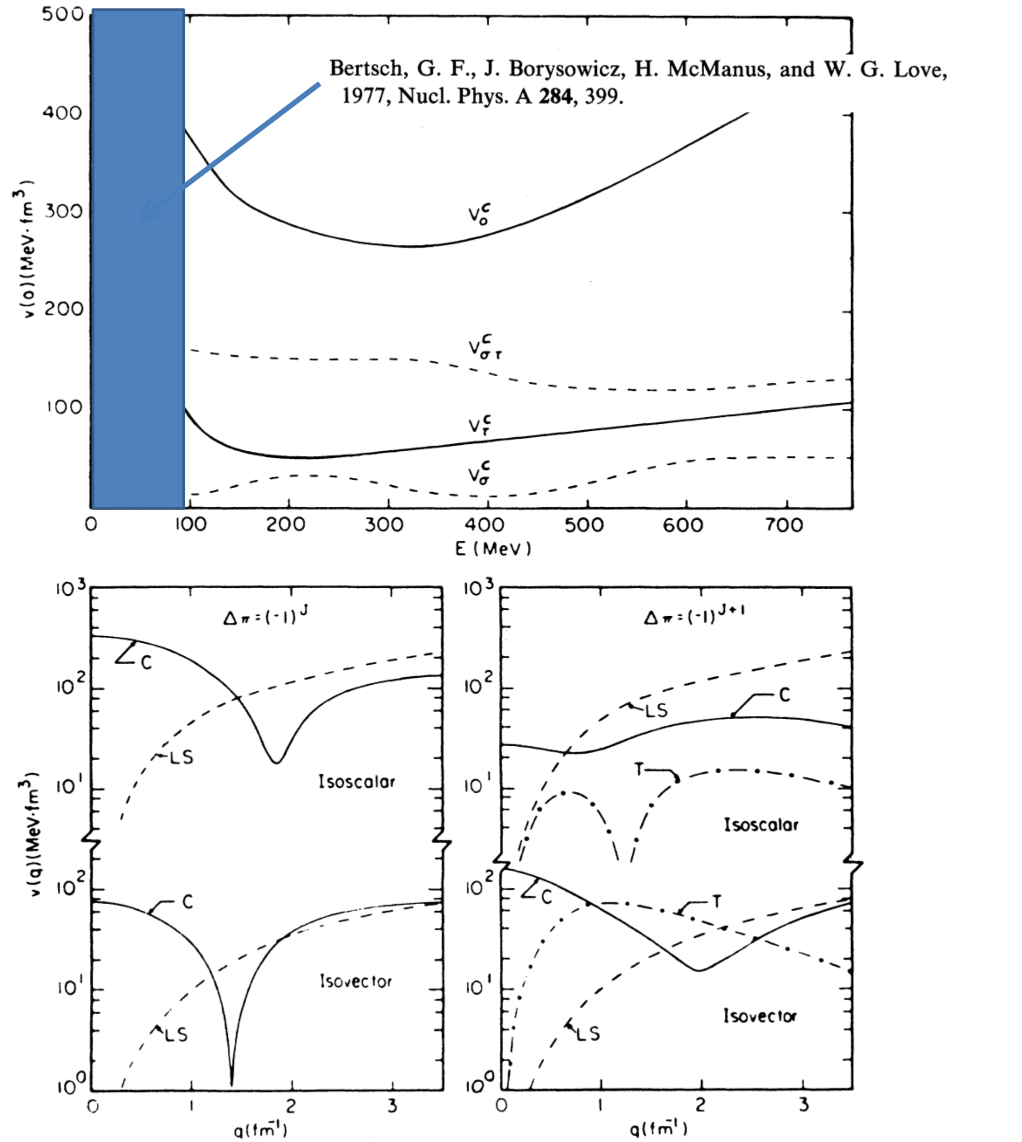
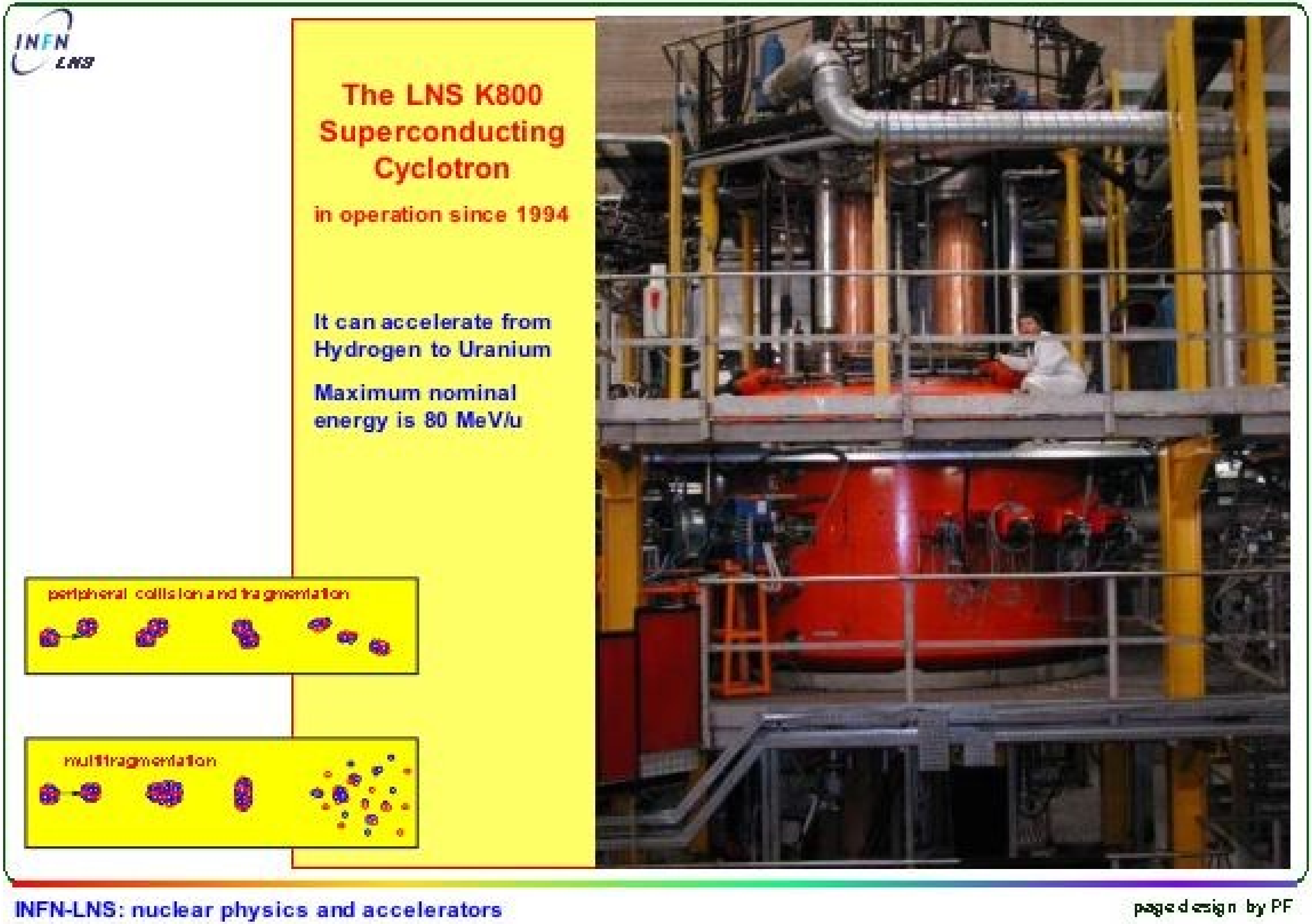


FIG. 15. Energy and momentum dependence of the free nucleon-nucleon t_F matrix. The upper part of the figure shows the energy dependence of the central components of the effective t_F matrix at zero-momentum transfer (including direct and exchange terms). The *G*-matrix interaction of Bertsch *et al.*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

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

DCE @ INFN-LNS

The Superconducting Cyclotron (CS) at LNS



MAGNEX

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.

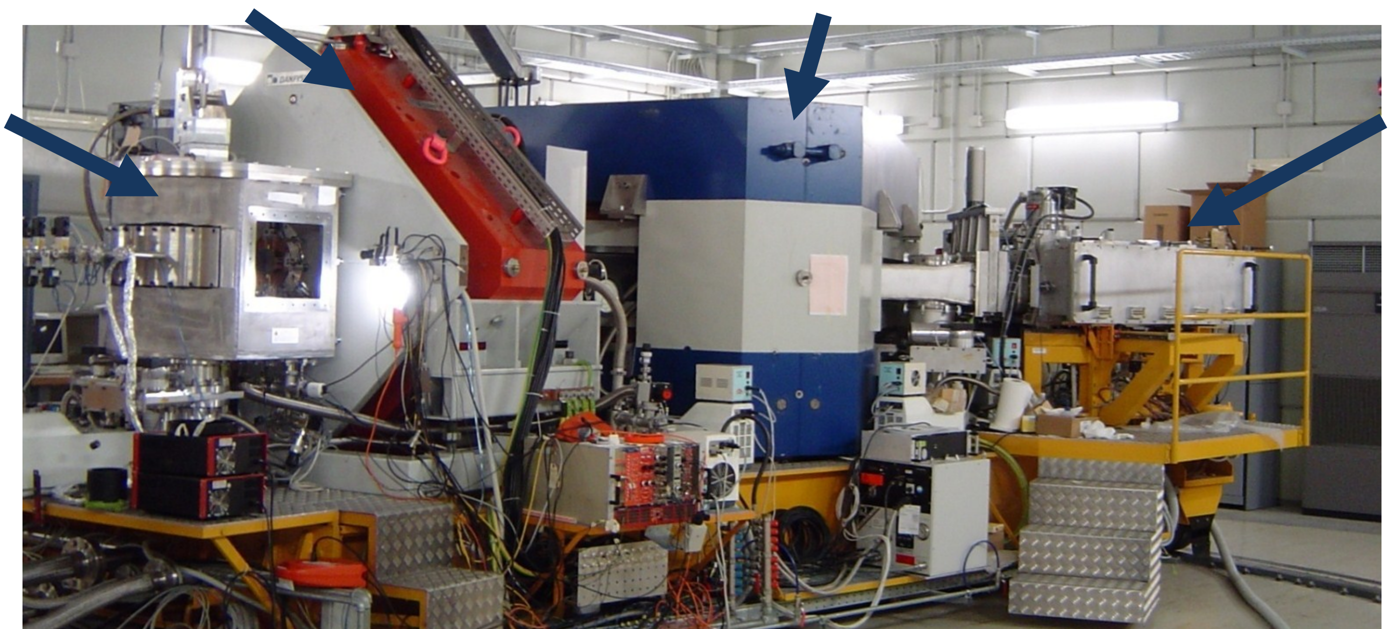
Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68

Achieved resolution

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

Angle $\Delta\theta \sim 0.2°$

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



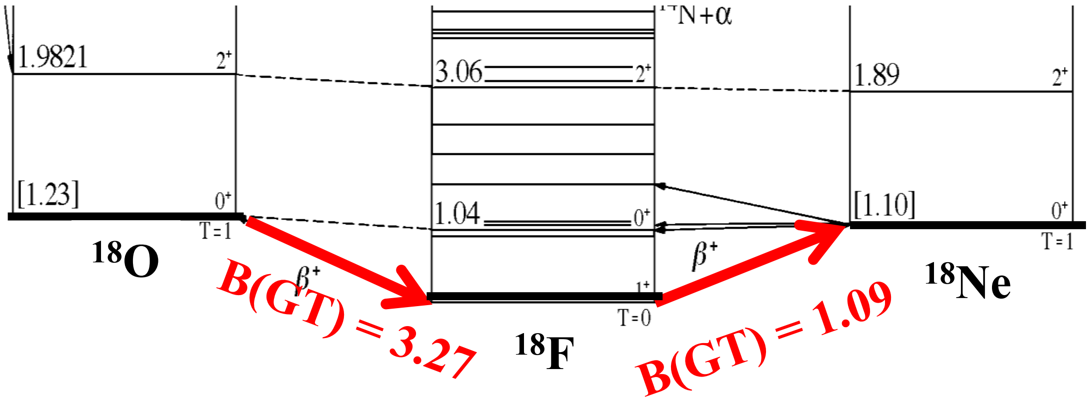
(^{18}O,^{18}Ne) DCE reactions at LNS

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

$0° < \vartheta_{lab} < 10°$ $Q = -5.9$ 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
- Target $T = 0$ ⟶ only $T = 2$ states of the residual

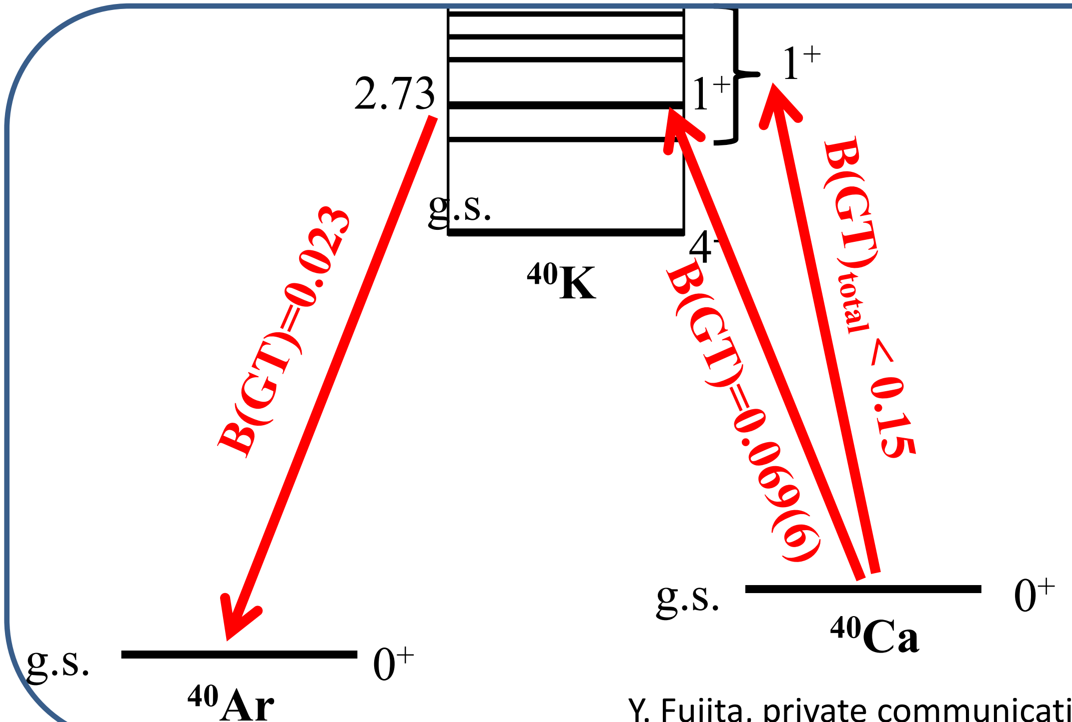
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$



Projectile

Super-allowed transition

GT strength not fragmented



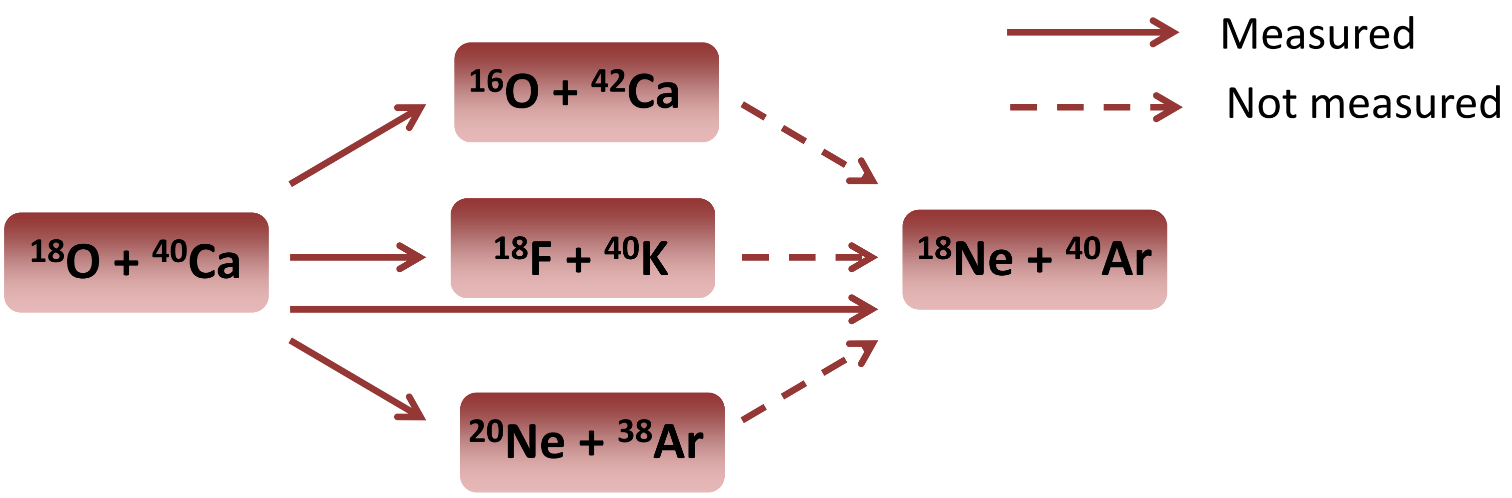
Target

GT strength not much fragmented

Y. Fujita, private communication

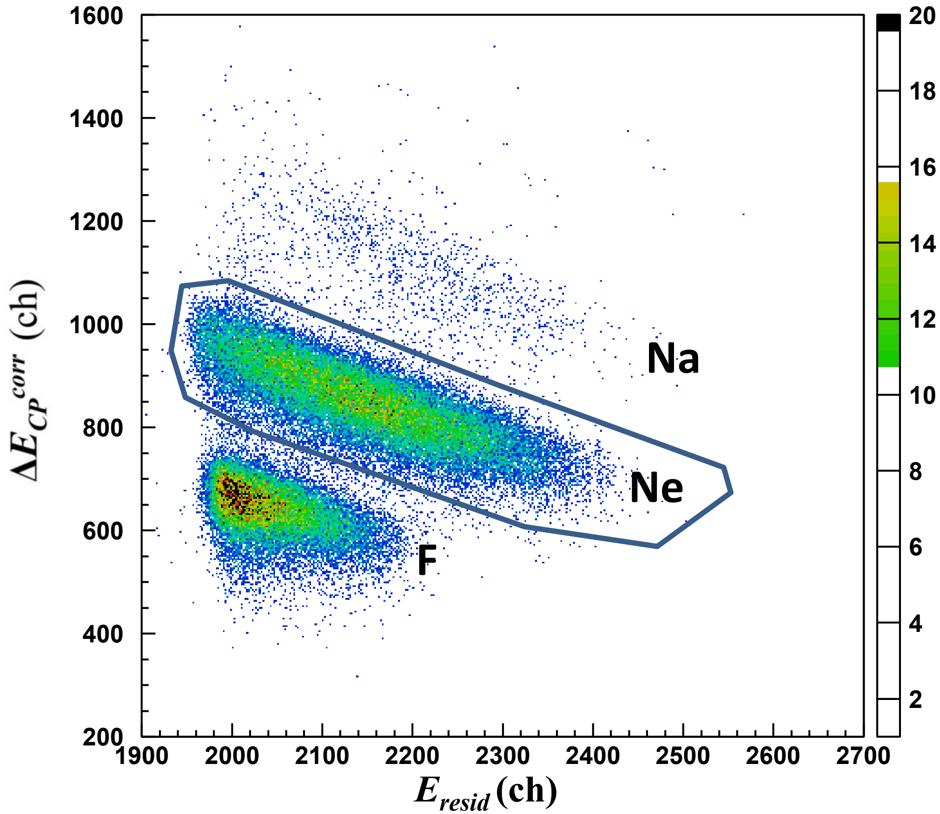
Experimental Set-up

- $^{18}O^{7+}$ 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}**



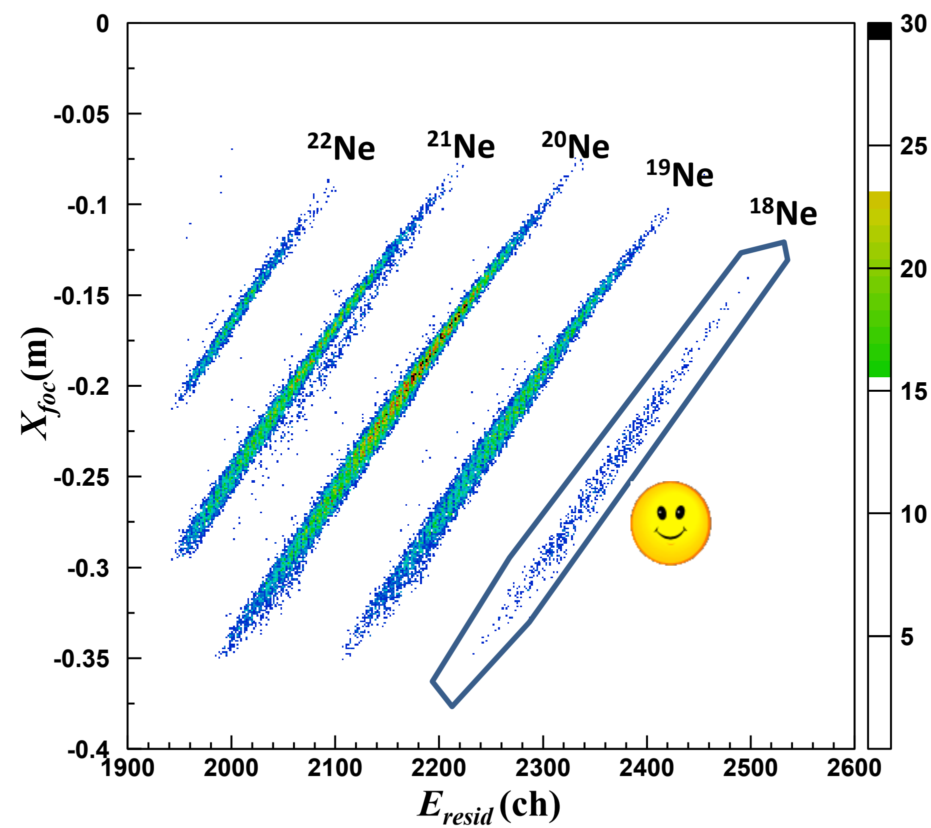
Particle Identification

Z identification



A identification

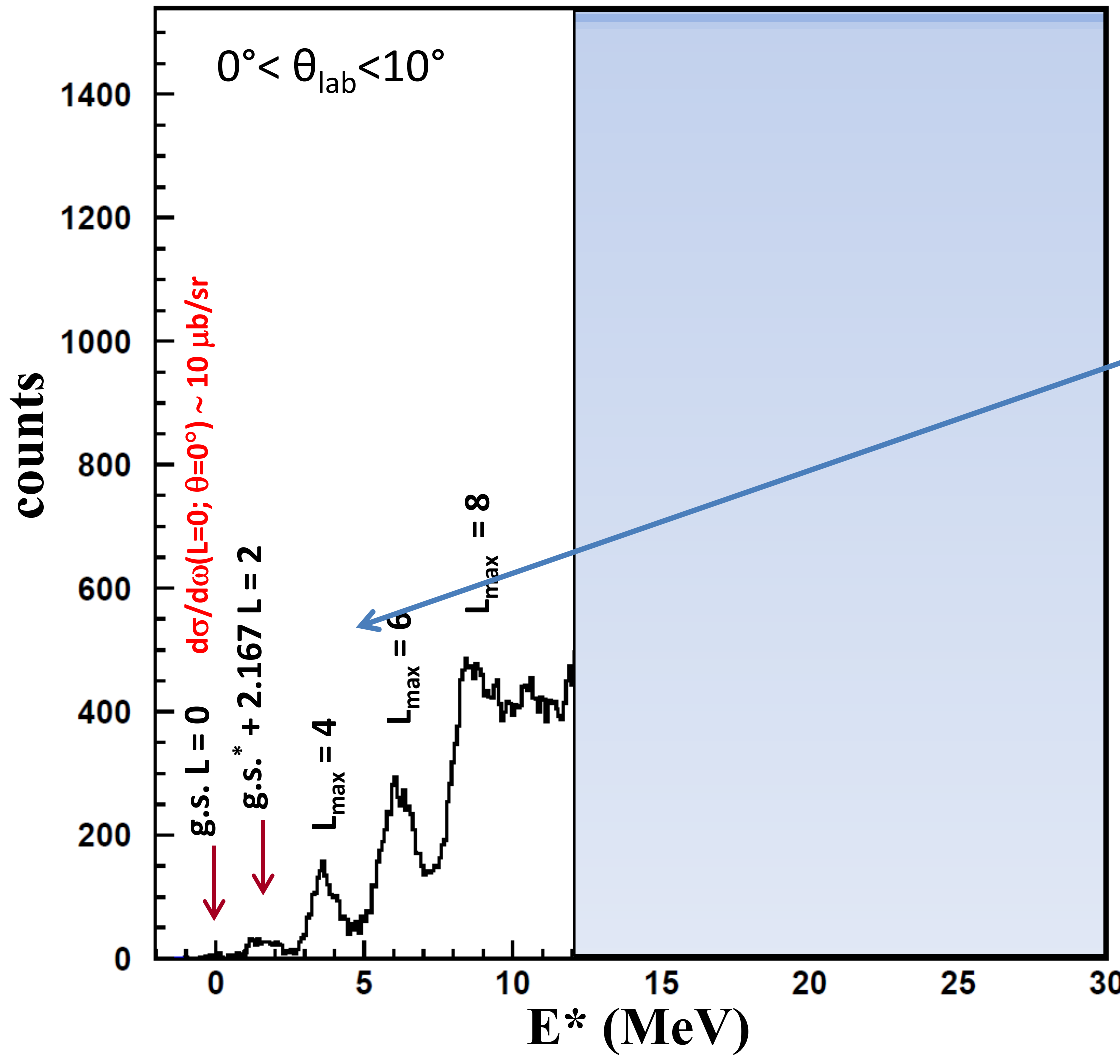
$$B\rho = \frac{p}{q} \rightarrow X_{foc}^2 \propto \frac{m}{q^2} E_{resid}$$



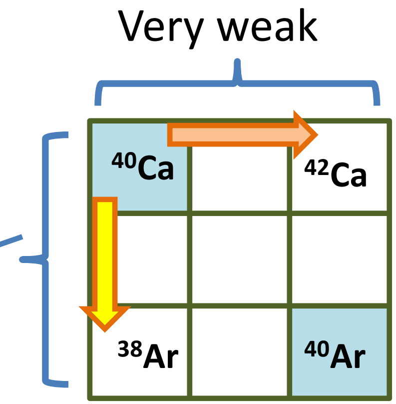
A. Cunsolo, et al., NIMA484 (2002) 56
A. Cunsolo, et al., NIMA481 (2002) 48
F. Cappuzzello et al., NIMA621 (2010) 419
F. Cappuzzello, et al. NIMA638 (2011) 74

The role of the transfer reactions

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



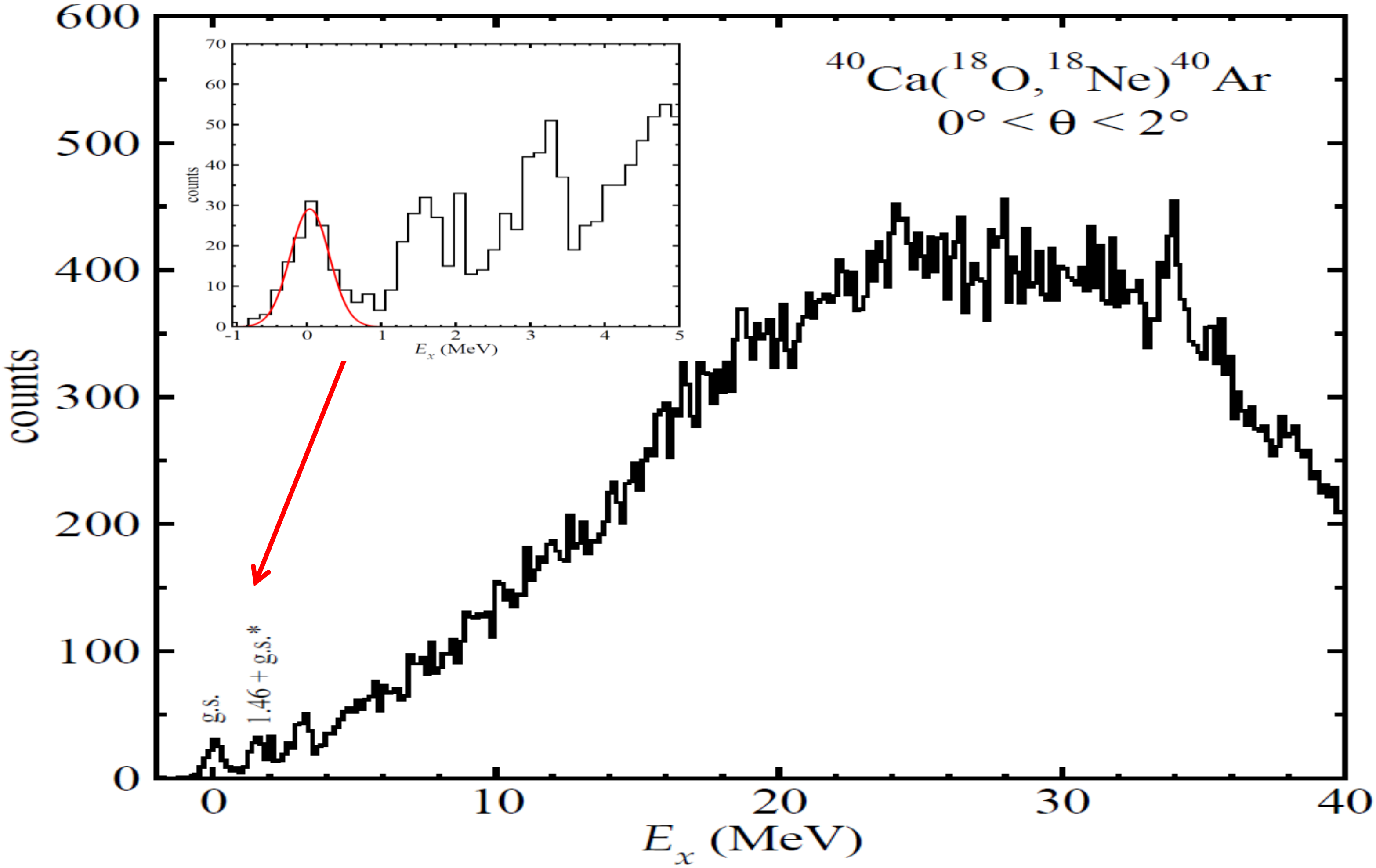
Suppression of the $^{40}Ca(^{18}O,^{16}O)^{42}C$ channel



Suppression of L = 0 in the pair transfer

Suppression of L > 0 in the double pair transfer

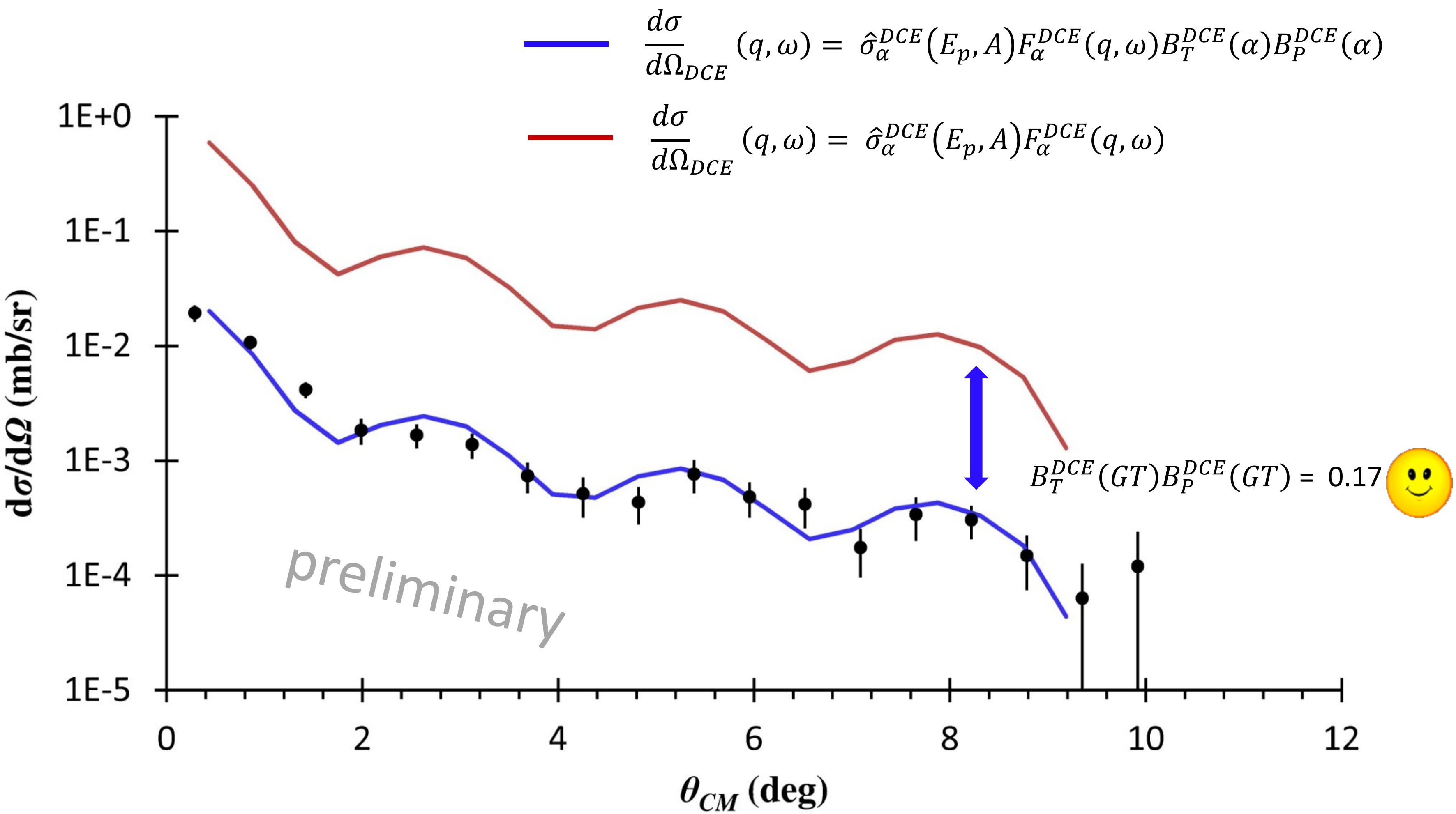
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV



FWHM ~ 0.5 MeV

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

$^{40}Ca_{g.s.}(0^+)(^{18}O,^{18}Ne)^{40}Ar_{g.s.}(0^+)$ @ 270 MeV



Assuming pure GT

The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ case:

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

87 μb/sr   0.72   **0.17**

To be compared to:

$$B^2[\mathrm{GT};{}^{18}\mathrm{O}_{gs}(0^+) \rightarrow {}^{18}\mathrm{F}_{gs}(1^+)] = 3.56 \; * \; B^2[\mathrm{GT};{}^{40}\mathrm{Ca}_{gs}(0^+) \rightarrow {}^{40}\mathrm{K}_{0\text{-}6MeV}(1^+)] = 0.0075$$

0.098

Y. Fujita private communication

D.J.Mercer et al. Phys. Rev. C 49 (1994) 3104

Assuming pure F

The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ case:

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

39 μb/sr

0.77

0.36

To be compared to:

$$B^2[F; {}^{18}O_{gs}(0^+) \rightarrow {}^{18}F_{gs}(1^+)] = 4.00$$

*

$$B^2[F; {}^{40}Ca_{gs}(0^+) \rightarrow {}^{40}K_{0\text{-}6MeV}(1^+)] = 0.138$$

0.55

Y. Fujita private communication

D.J.Mercer et al. Phys. Rev. C 49 (1994) 3104

The NUMEN project

Determining the Nuclear Matrix Elements of Neutrinoless Double Beta Decays by Heavy-Ion Double Charge Exchange Reactions

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

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

Moving towards hot-cases

Caveat

- The (^{18}O,^{18}Ne) reaction is particularly advantageous, but it is of *β⁺β⁺* kind;
- None of the reactions of *β⁻β⁻* 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)
- 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. from the excited states in the final nucleus → Coincident detection of γ-rays
- A strong fragmentation of the double GT strength is known in the nuclei of interest compared to the ^{40}Ca.

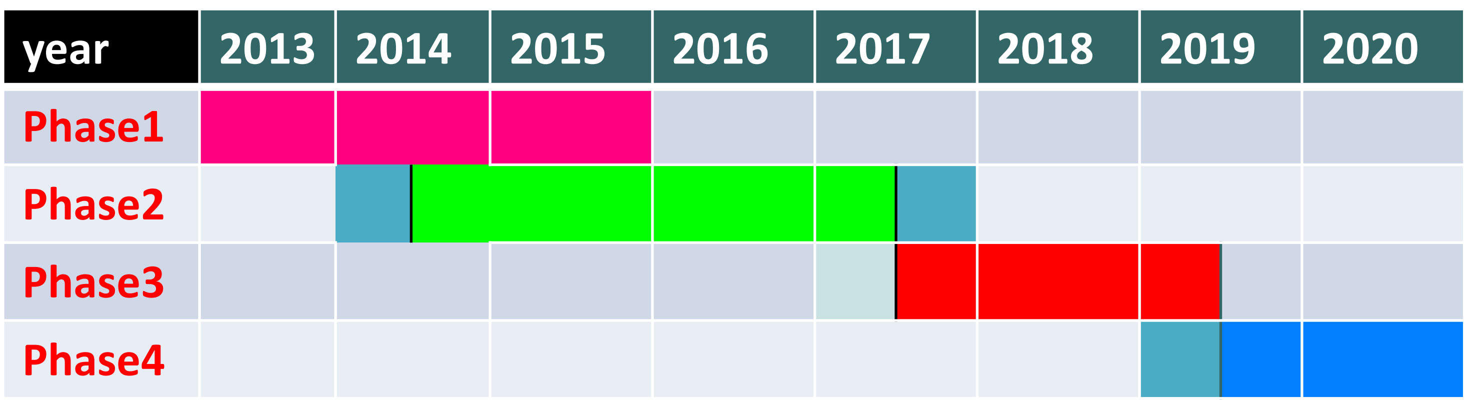
Major upgrade of LNS facilities

- The **CS** accelerator current upgrade (from **100 W to 5-10 kW**);
- The **MAGNEX focal plane** detector will be upgraded from 1 khz to 100 khz
- The **MAGNEX** maximum magnetic **rigidity** will be increased
- An **array of detectors for γ-rays** measurement in coincidence with MAGNEX will be built
- The **beam transport line** transmission efficiency will be upgraded from about 70% to nearly 100%
- The **target** technology for intense heavy-ion beams will be developed

The Phases of NUMEN project

- **Phase1**: The experimental feasibility
- **Phase2**: "hot" cases optimizing the set-up and getting first results
- **Phase3**: The facility Upgrade (Cyclotron, MAGNEX, beam line, …..):
- **Phase4** : The systematic experimental campaign

Preliminary time table



Conclusions and Outlooks

- The factorization of DCE cross sections is potentially a major source of information about NME for $0\nu\beta\beta$
- Pioneering experiments at RCNP (Osaka) and LNS (Catania) are showing that the (^{18}O,^{18}Ne) cross section can be suitably measured
- Magnetic spectrometers are essential, especially with large acceptance
- Severe limitation from present available beam current
- High beam intensity is the new frontier for these studies
- A natural research item for ECOS perspectives
- Strong synergy between heavy-ion and neutrino community