THE NUCLEAR MATRIX ELEMENTS OF 0νββ DECAY AND THE NUMEN PROJECT AT INFN-LNS

F. Cappuzzello

The NUMEN collaboration

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

Collaborations

INFN LNF
INSTITUTO DE FISICA DA UNIVERSIDADE DE SAO PAULO, BRAZIL
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CICANUM, UNIVERSIDAD DE COSTA RICA, SAN JOSE, COSTA RICA
DEP. OF PHYSICS AND HINP, THE UNIV. OF IOANNINA, IOANNINA, GREECE
INSTITUT FÜR THEORETISCHE PHYSIK, GIESSEN UNIVERSITY, GERMANY
DÉPARTEMENT DE PHYSIQUE, UNIVERSITÉ HASSAN II – CASABLANCA, MOROCCO
CERN
BROKHAVEN NATIONAL LABORATORY
INSTITUTE OF MODERN PHYSICS, CHINESE ACADEMY OF SCIENCES, LANZHOU, CHINA
RCNP, OSAKA UNIVERSITY, OSAKA, JAPAN

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

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)!

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

- ✓ 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)

A new esperimental tool: DCE

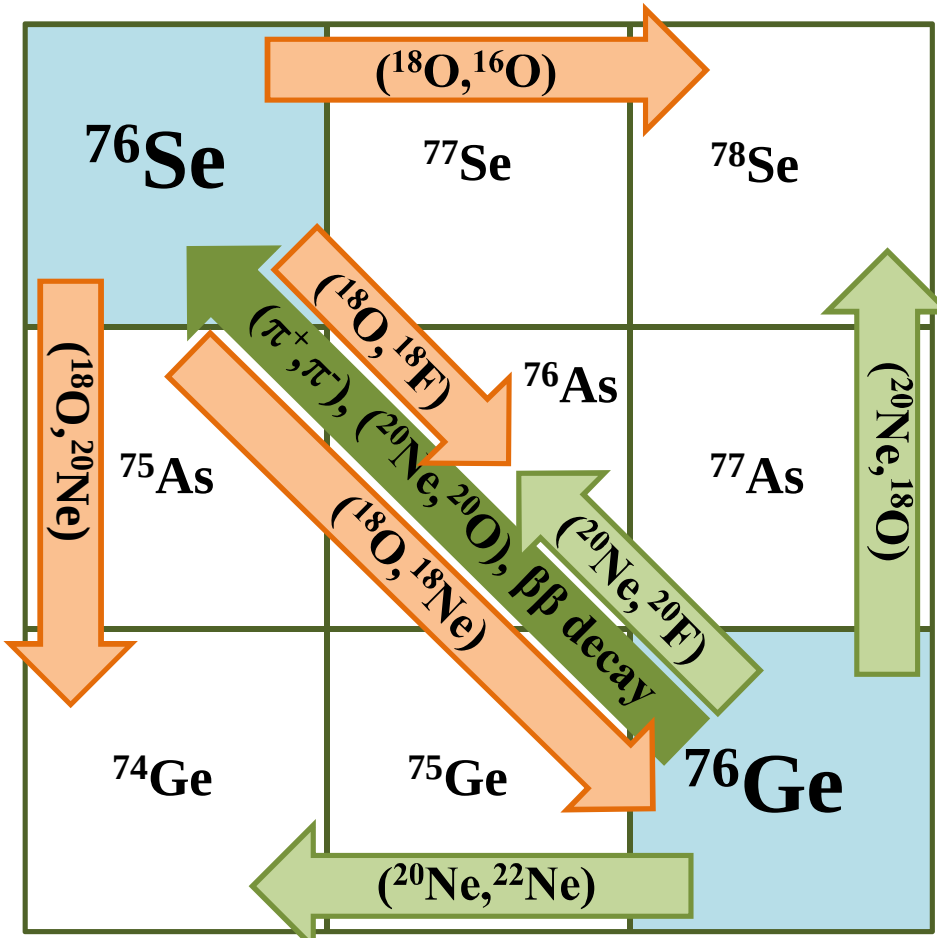
Heavy-ion DCE

1. **Induced by strong interaction**

2. **Sequential nucleon transfer mechanism 4th order:**
   - Brink's Kinematical matching conditions *D.M.Brink, et al., Phys. Lett. B 40 (1972) 37*

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

4. **Possibility to go in both directions**



$0\nu\beta\beta$ vs HI-DCE

1. **Initial and final states:** Parent/daughter states of the *0νββ* 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;

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

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

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

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

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-F competion** at low energy

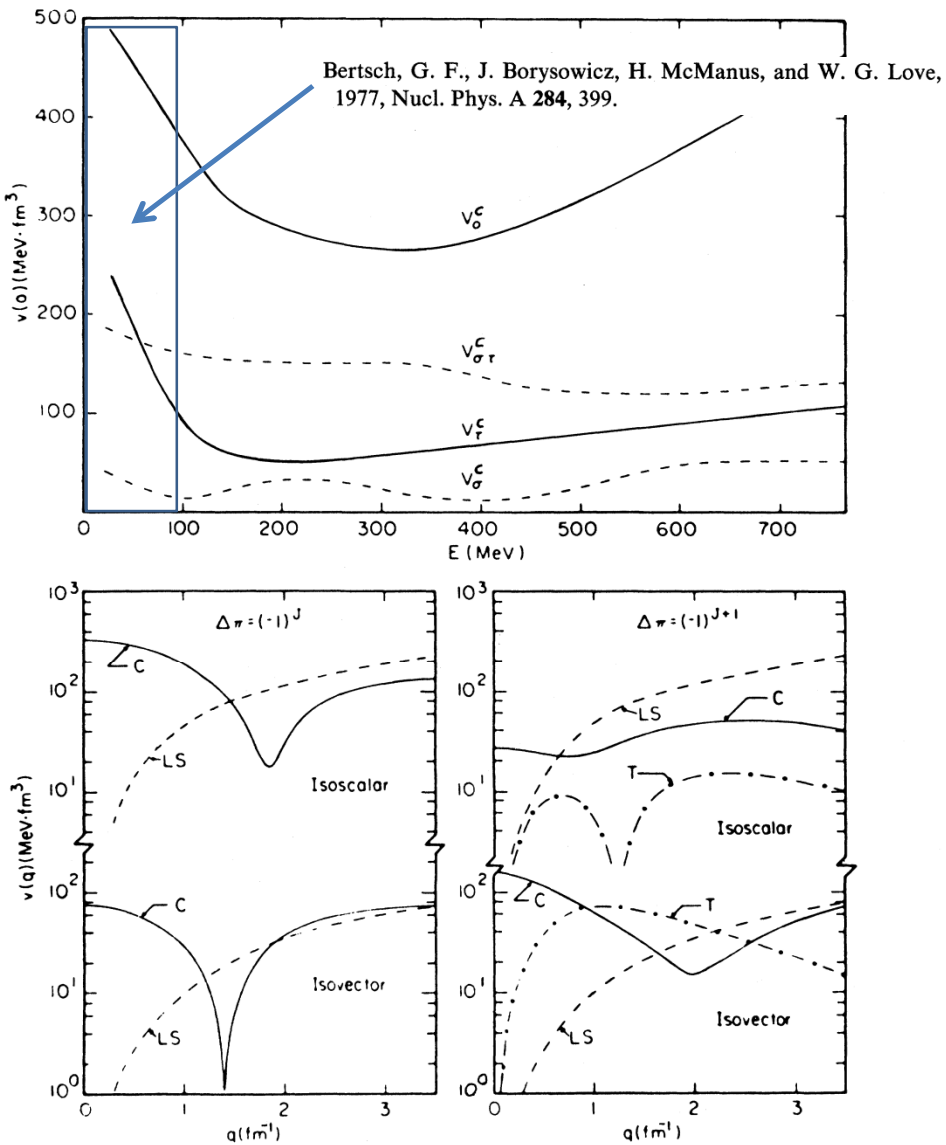
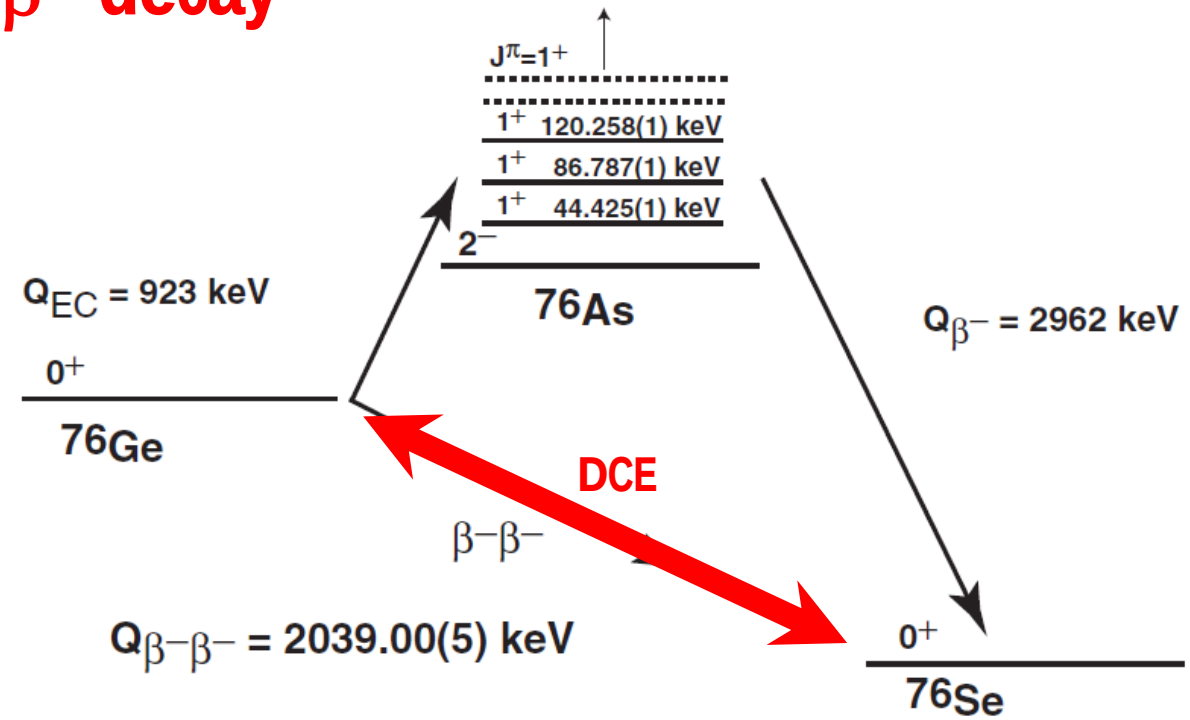
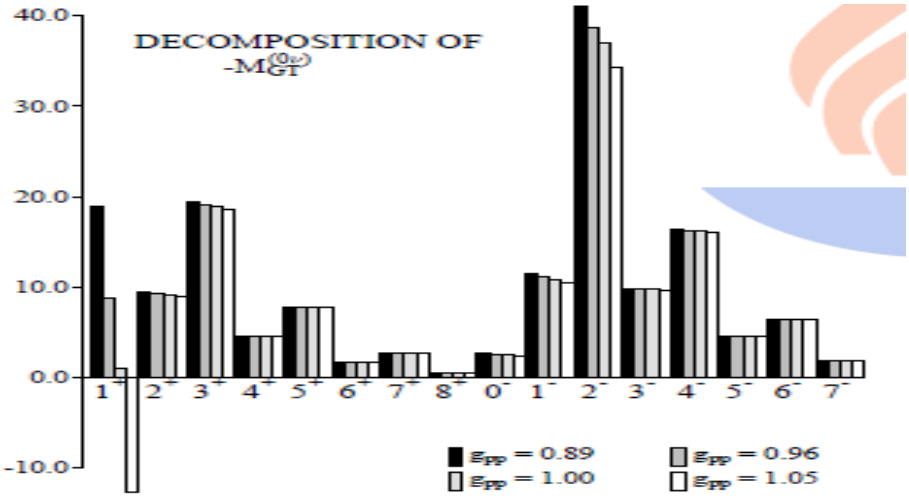


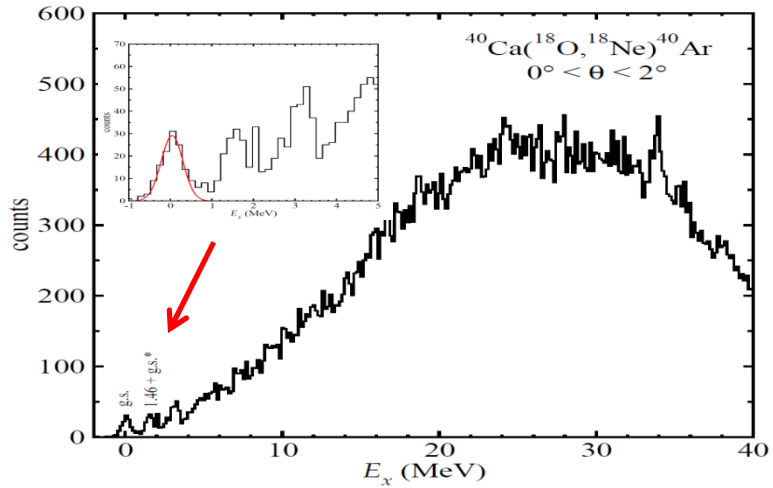
FIG. 15. Energy and momentum dependence of the free nucleon-nucleon t_F matrix. The upper part of the figure shows the energy dependence of the central components of the effective t_F matrix at zero-momentum transfer (including direct and exchange terms). The G-matrix interaction of Bertsch *et al.*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

Methodology for NME
0νββ - decay

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







J. Suhonen, Nucl. Phys. B 752, 53c(2005)

DCE @ INFN-LNS

The Superconducting Cyclotron (CS) at LNS

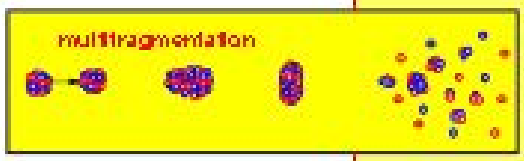
INFN LNS

The LNS K800 Superconducting Cyclotron

in operation since 1994

It can accelerate from Hydrogen to Uranium

Maximum nominal energy is 80 MeV/u



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.

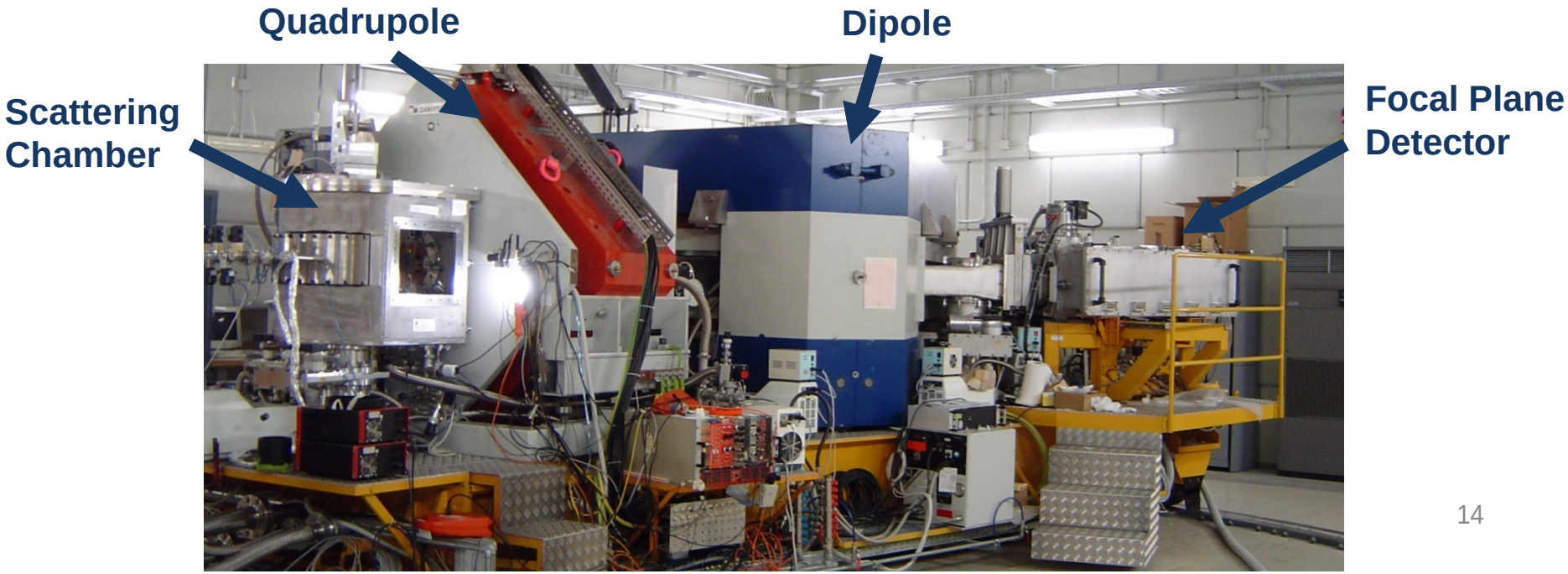
Optical characteristics	Measured values
Maximum magnetic rigidity	1.8 T m
Solid angle	**50 msr**
Momentum acceptance	**-14.3%, +10.3%**
Momentum dispersion for k= - 0.104 (cm/%)	3.68

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

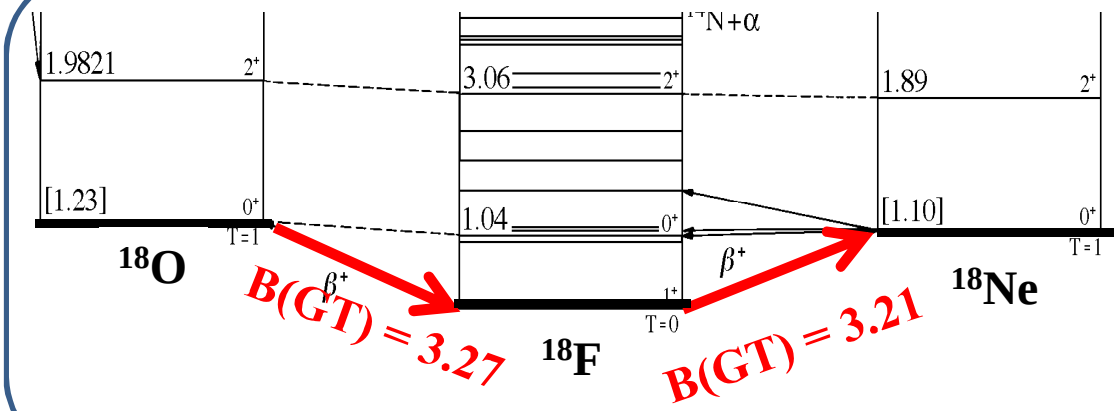
^{40}Ca(^{18}O,^{18}Ne)^{40}Ar @ 270 MeV

$0° < \vartheta_{lab} < 10°$ Q = -5.9 MeV

First pilot experiment

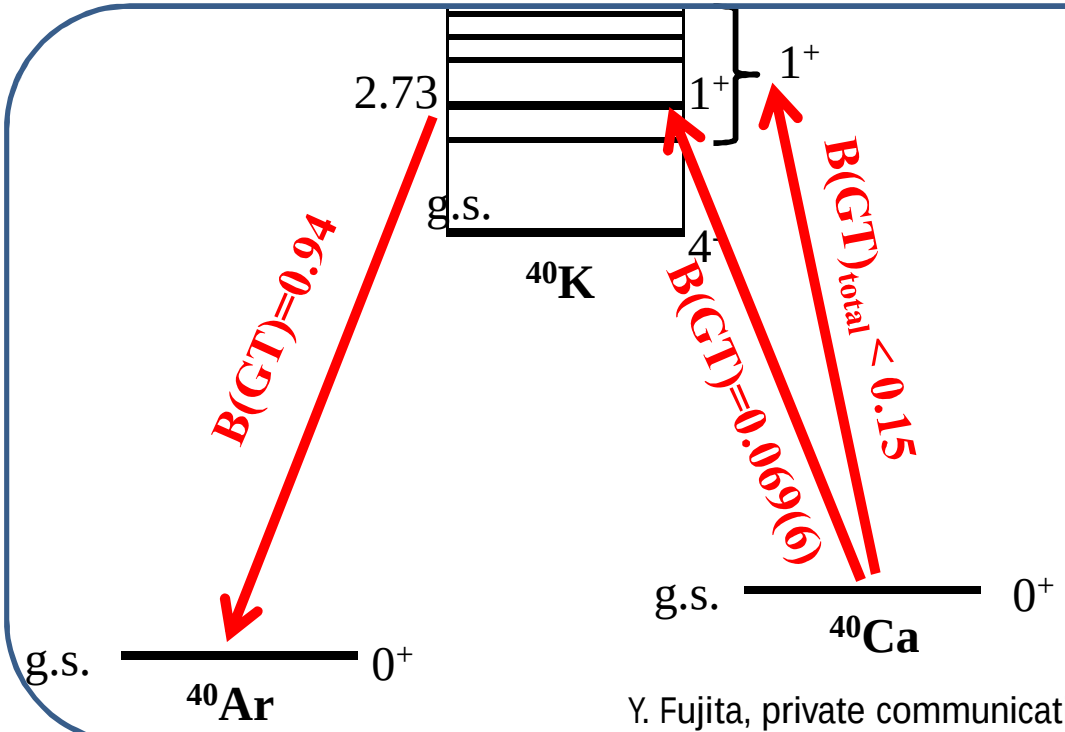
- ^{18}O and ^{18}Ne belong to the same multiplet in S and T
- Very low polarizability of core ^{16}O
- Sequential transfer processes very mismatched $Q_{opt} \sim 50$ MeV
- Doubly magic target

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



Projectile

Super-allowed transition
GT strength not fragmented

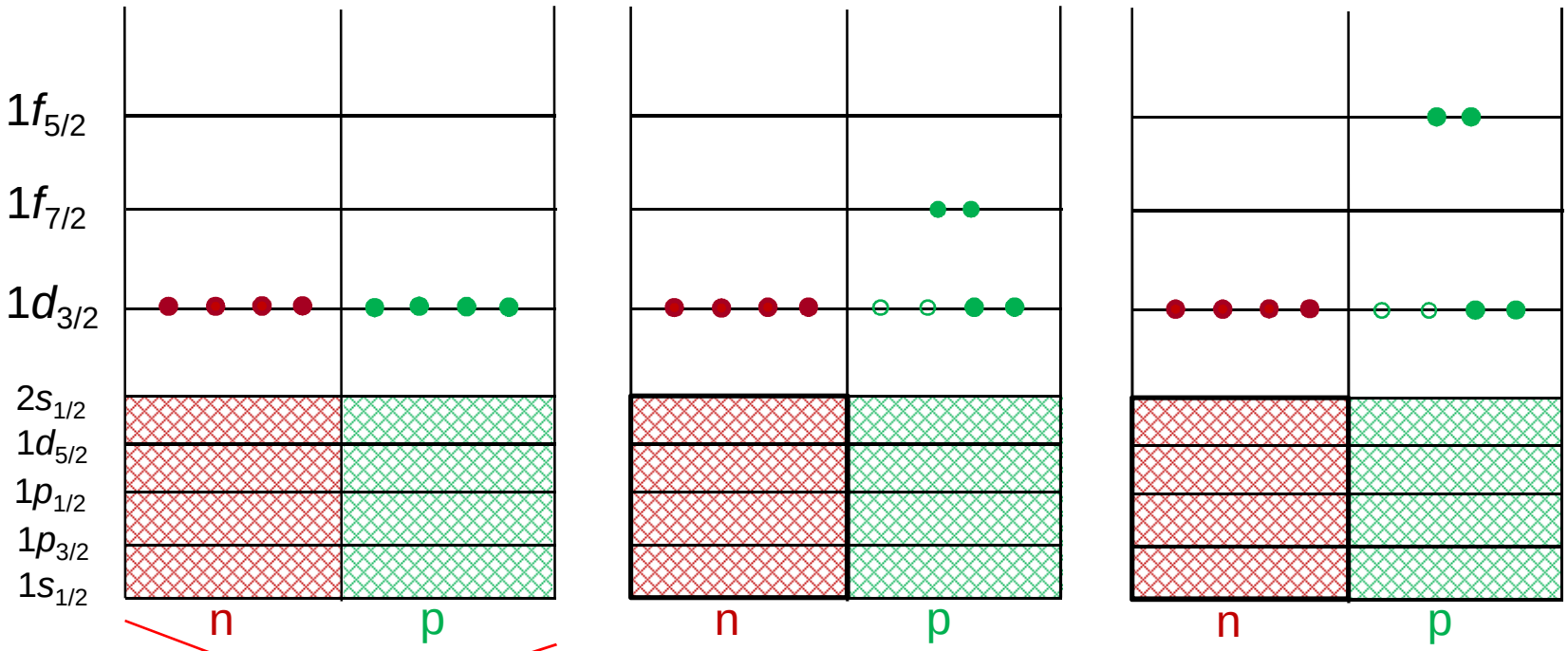


Y. Fujita, private communication

Target

GT strength not much fragmented

About ^{40}Ca ground state

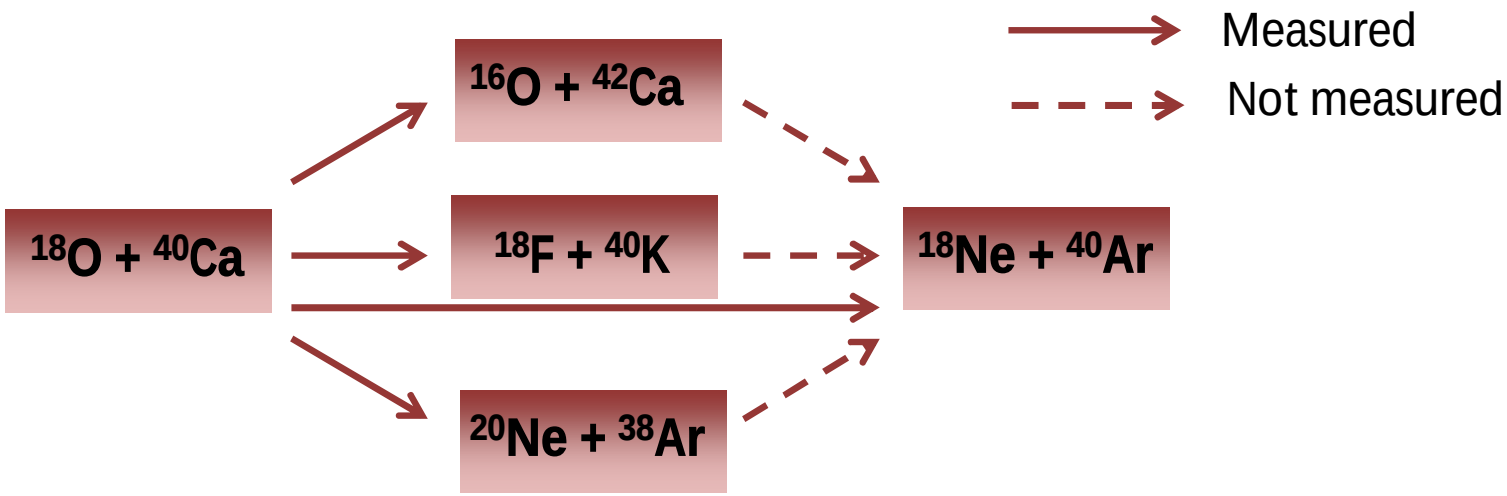


$$|^{40}Ca_{g.s.}\rangle = 0.86\,|[1d_{3/2}\otimes 1d_{3/2}]^{0+}\rangle + 0.06\,|[1f_{7/2}\otimes 1f_{7/2}]^{0+}\rangle + 0.06\,|[1f_{5/2}\otimes 1f_{5/2}]^{0+}\rangle + \ldots$$

Pauli blocked for
F and GT

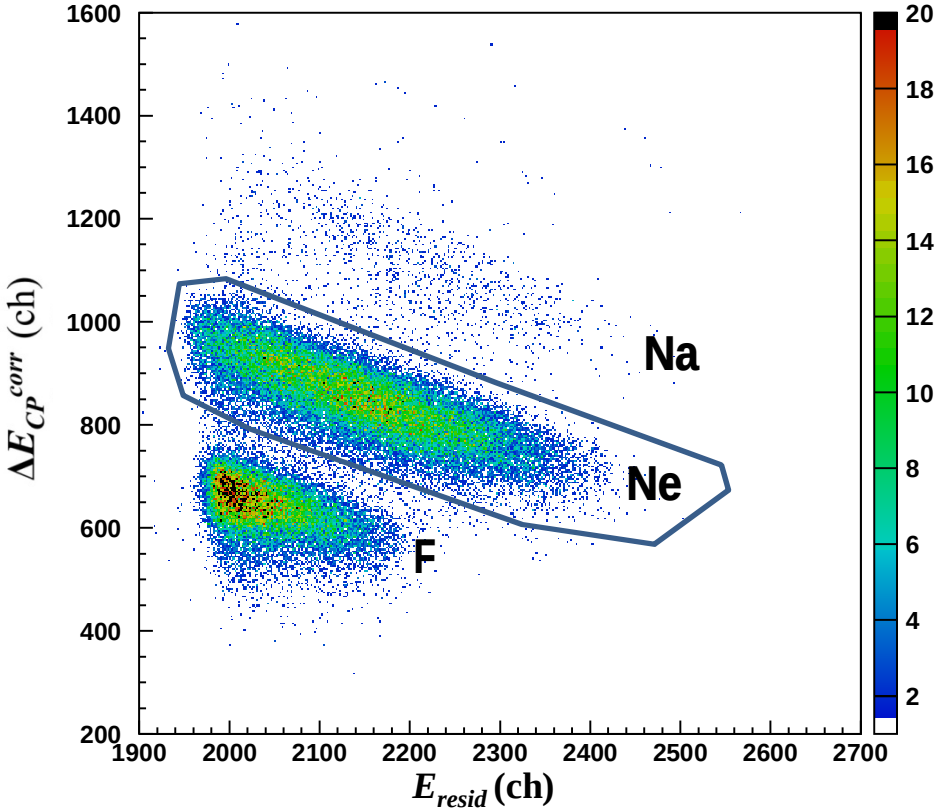
Experimental Set-up

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



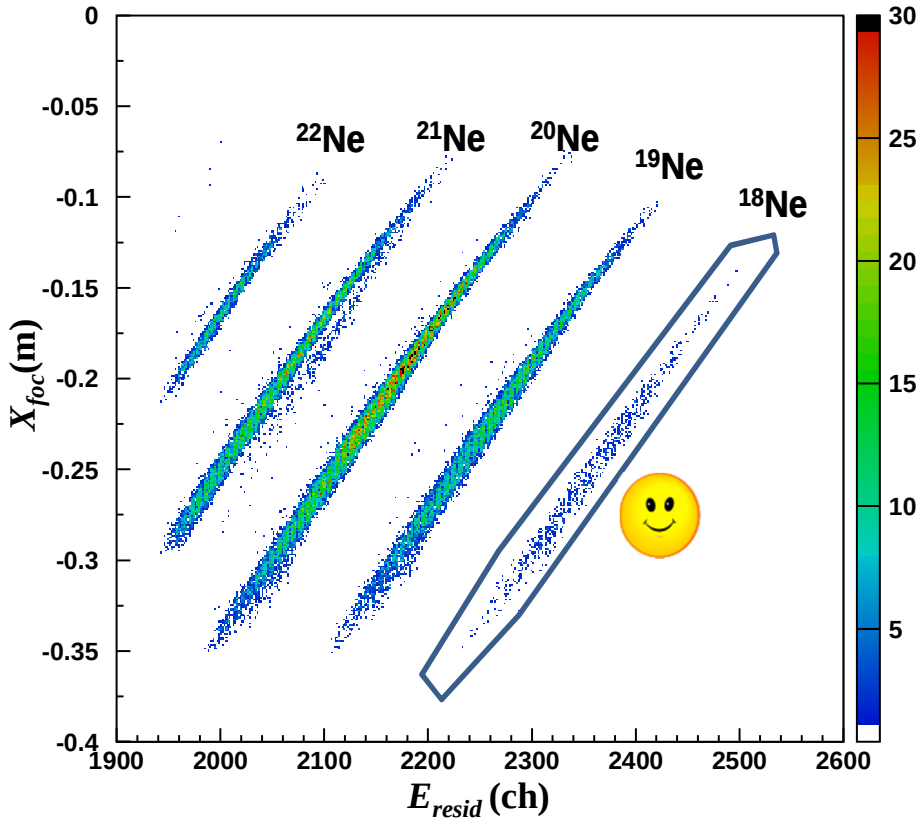
Particle Identification

Z identification



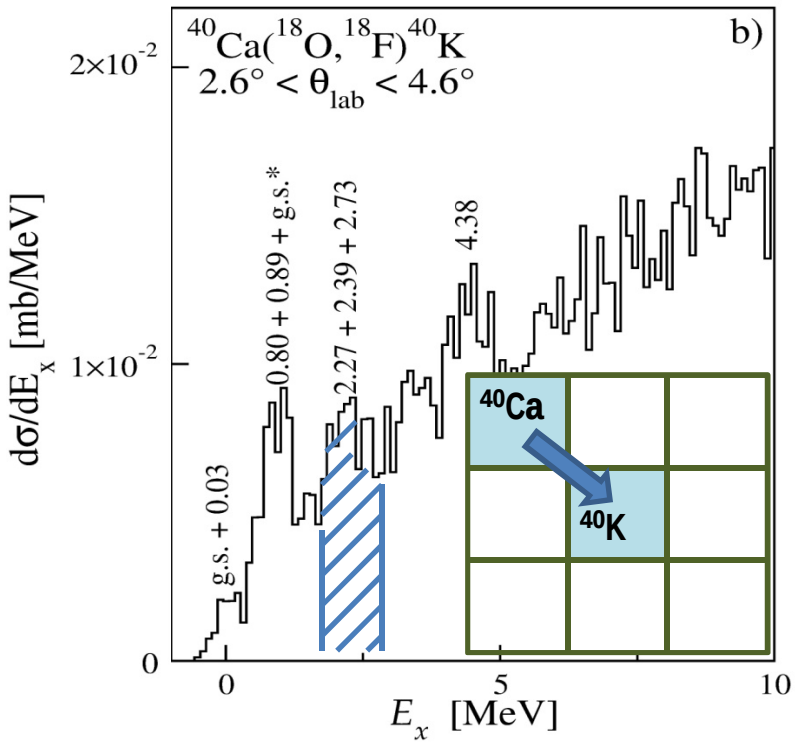
A identification

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



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)

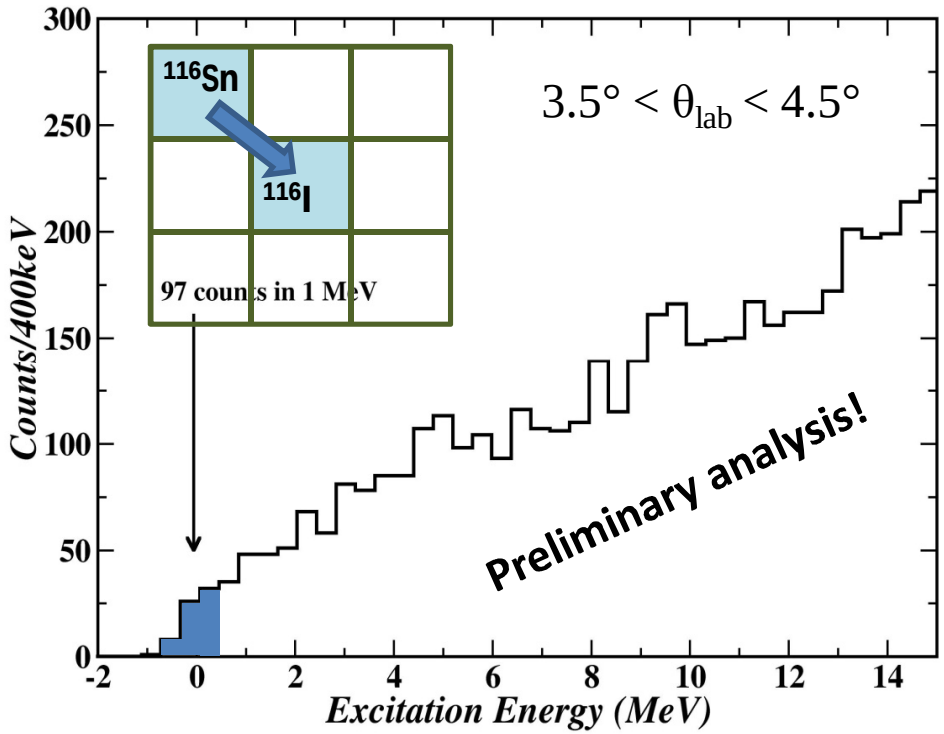
≈ 0.5 mb/sr

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

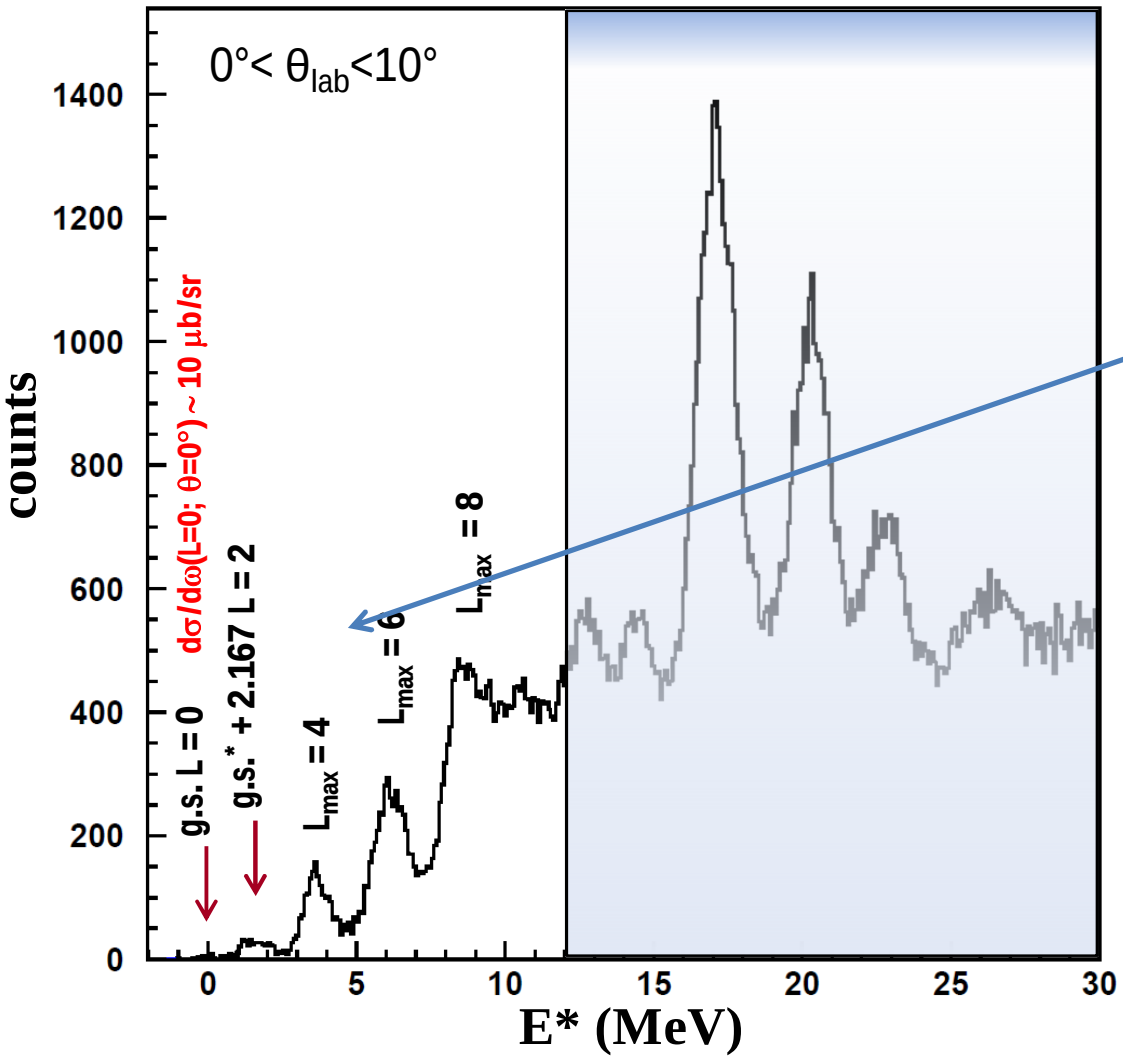
Extracted upper limit for B(GT) < 0.8

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

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

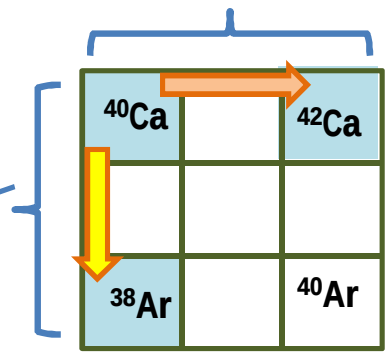
The role of the transfer reactions

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



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

Very weak

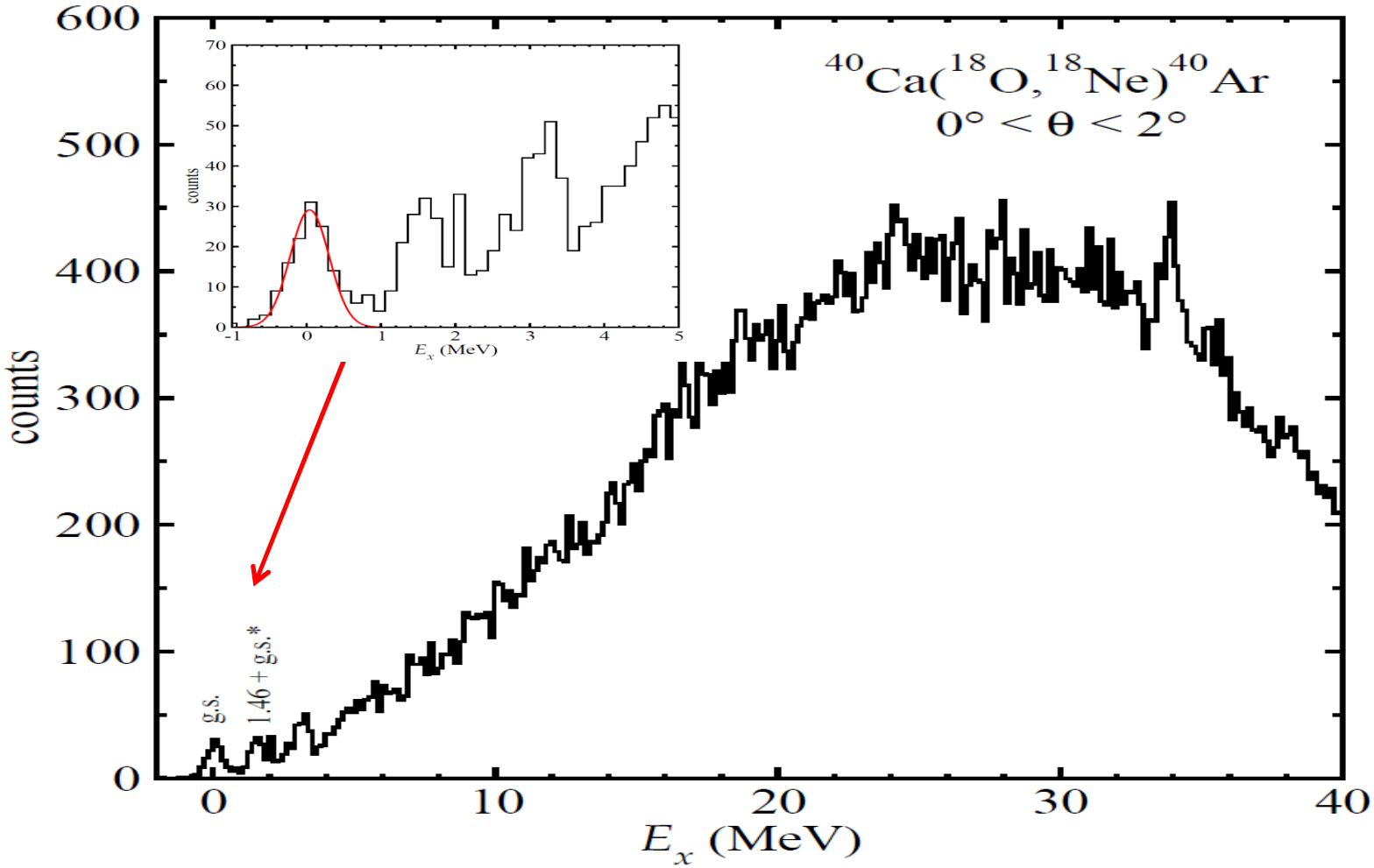


Suppression of L = 0 in the pair transfer

Suppression of L > 0 in the double pair transfer

Less than 1% effect in the DCE cross section

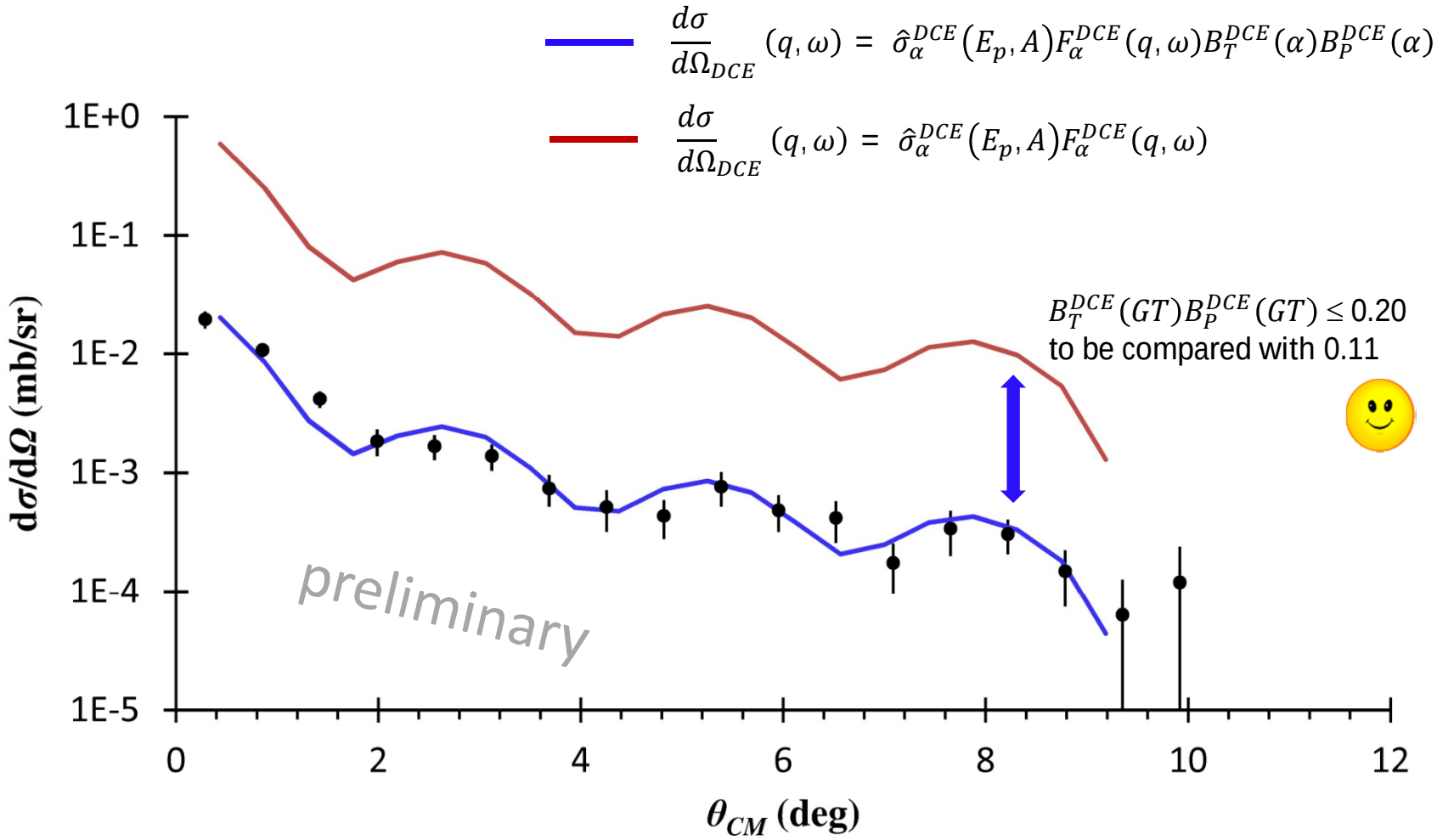
$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV



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



Preliminary matrix elements

Pure GT → $\left|M^{DCE}_{40Ca\to 40Ar}(GT)\right|^2 = 0.42 \pm 0.21$

Pure F → $\left|M^{DCE}_{40Ca\to 40Ar}(F)\right|^2 = 0.28 \pm 0.14$

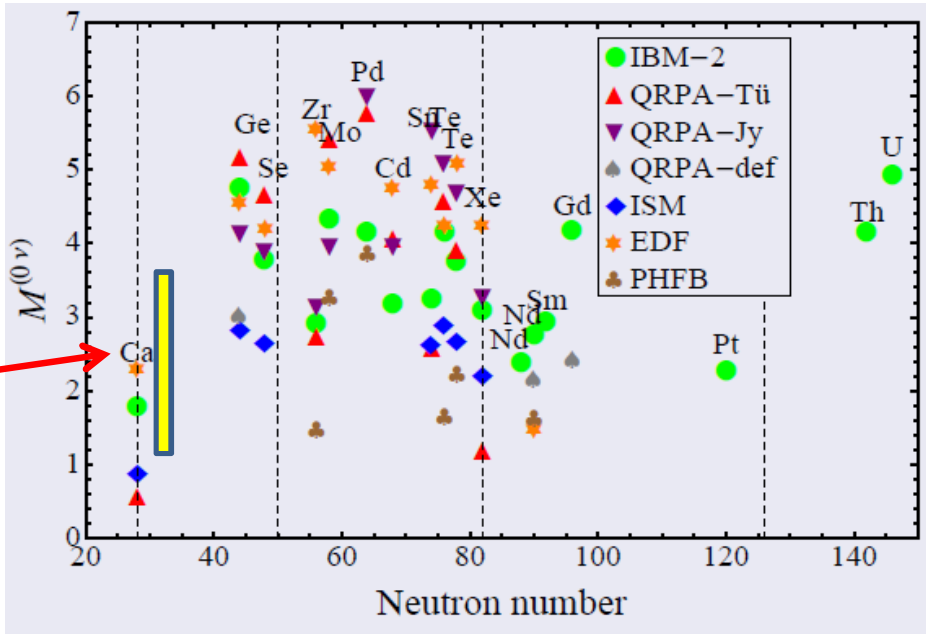
$$\left|M^{0\nu\beta\beta}\left({}^{40}Ca\right)\right|^2 = 0.37 \pm 0.18$$

Assuming a closure approximation for all multipolarities we get an uncertainty of 20% by changing the closure energy from 0 to 50 MeV

Pauli blocking about 0.14 for F and GT

Just to speculate:
removing Pauli blocking one can roughly estimate

$$\left|M^{0\nu\beta\beta}\left({}^{48}Ca\right)\right|^2 = 2.6 \pm 1.3$$



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)

- 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 $\rightarrow$ 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: NUMEN

- The **CS** accelerator current upgrade (from 100 W to 5-10 kW);
- The **MAGNEX focal plane** detector will be upgraded from 2 khz to 500 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
- **Nuclear reaction theory** upgrading

The NUMEN goals

The NUMEN goals

Compare sensitivity

Sensitivity of different half-life experiments

- ✓ Requires factorisation
- ✓ Sizeable inaccuracies reduced in the ratio
- ✓ Does not require systematics

NUMEN Holy Graal

Getting σ^{DCE} as a predictable function of E_p and A

- ✓ Requires cross section factorisation
- ✓ Experimentally requires large systematics

Constraints to theory

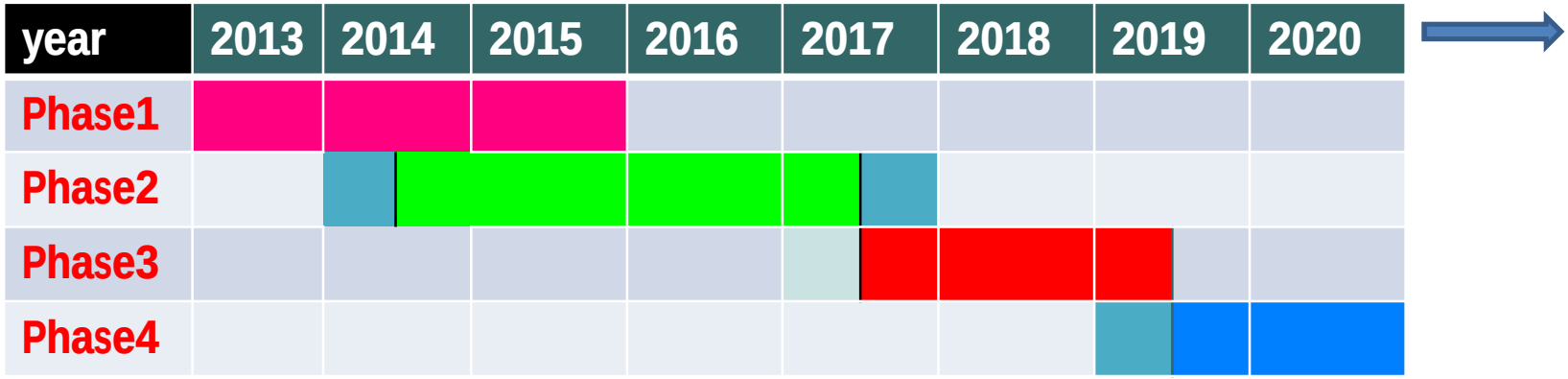
A new generation of DCE constrained $0\nu\beta\beta$ NME theoretical calculations can emerge

- ✓ Does not require factorisation
- ✓ Does not require systematics
- ✓ Requires reaction theory

The Phases of NUMEN project

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

Preliminary time table



An intense experimental activity 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												
$^{116}Cd\,(^{20}Ne,^{20}O)\,^{116}Sn$	15-25												
$^{130}Te\,(^{20}Ne,^{20}O)\,^{130}Xe$	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												

An intense R&D activity in phase 2

		2016				2017				2018			
R&D item	**Activity**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
Ion Tracker	Low pressure tests												
	Electric field simulations												
	Study of positive ions backflow												
	Development of read-out system												
	Construction of a prototype												
	Tests with radioactive-sources and beam												
	Design of the final detector												
	Design of the final segmented read-out electrode												
	Construction of the final detector												
PID-wall	Radiation hardness test of SiC e CsI												
	Prototyping different thicknesses and area SiC detectors												
	Building a SiC-CsI PID module												
	Developing read-out electronics												
	Design of the final PID-wall												
	Construction of the final detector												
Magnetic rigidity	Magnetic field simulations												
	Installation of new power supplies												
γ-ray calorimeter	Prototyping different detector solutions												
	Radio-active source and in-beam tests												
	Design of the final detector assembly												

Conclusions and Outlooks

- Many facilities for $0\nu\beta\beta$ half life, but not for the NME
- Pioneering experiments at RCNP (Osaka) and LNS (Catania) are showing that the **(^{18}O,^{18}Ne)** cross section can be suitably measured
- First results for the (^{18}O,^{18}Ne) are encouraging, showing that **quantitative information on $0\nu\beta\beta$ NME are not precluded**
- Good to have NME calculations also for (^{40}Ca,^{40}Ar)