F. Cappuzzello
Università di Catania and INFN LNS

Recent Results from Heavy Ion induced DCE Reactions at the INFN-LNS

International Workshop on Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16)

September 29-30, 2016, RCNP, Osaka University

The NUMEN project

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

C. Agodi, J. Bellone, 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
INFN - Laboratori Nazionali del Sud, Catania, Italy
INFN - Sezione di Catania, Catania, Italy
Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
INFN - Sezione di Torino, Torino, Italy
Politecnico di Torino, Italy
INFN - Sezione di Genova, Genova, Italy
CNR-IMM, Sezione di Catania, Italy
Università degli Studi di Enna "Kore", Enna, Italy

T. Borello-Lewin, P. N. de Faria, J.L. Ferreira, R. Linares, J. Lubian, N.H. Medina, J.R.B. Oliveira, M.R.D. Rodrigues, D.R. Mendes Junior, V. Zagatto
Instituto de Física, Universidade Federal Fluminense, Niterói, RJ, Brazil
Instituto de Física, Universidade de São Paulo, São Paulo, SP, Brazil

X. Aslanoglou, A. Pakou, O. Sgouros, V. Soukeras, G. Souliotis,
Department of Physics and HINP, The University of Ioannina, Ioannina, Greece
Department of Chemistry and HINP, National and Kapodistrian University of Athens, Greece

E. Aciksoz, I. Boztosun, A. Hacisalihoglu, S.O. Solakcı,
Akdeniz University, Antalya, Turkey

L. Acosta, R. Bijker, E.R. Chávez Lomelí,
Universidad Nacional Autónoma de México

S. Boudhaim, M.L. Bouhssa, Z. Housni, A. Khouaja, J. Inchaou
Université Hassan II – Casablanca, Morocco

N. Auerbach,
School of Physics and Astronomy Tel Aviv University, Israel

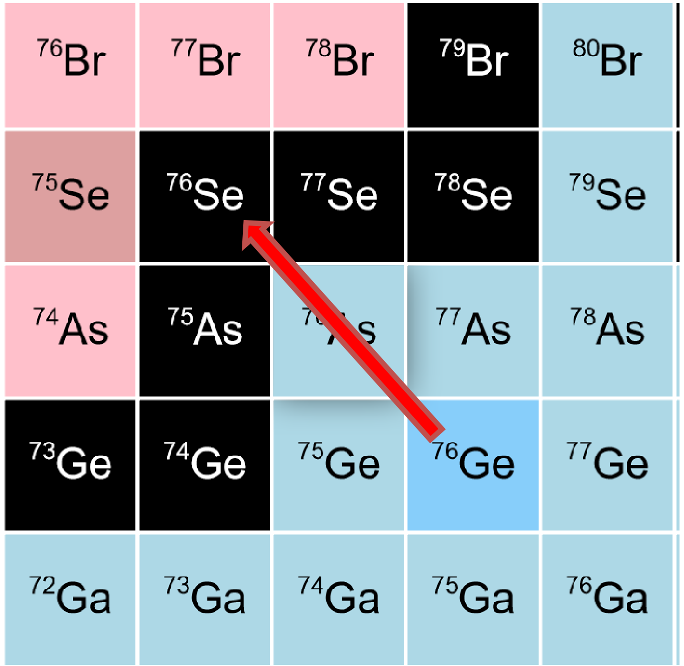
H. Lenske,
University of Giessen, Germany

J. Kotila
University of Jyvaskyla

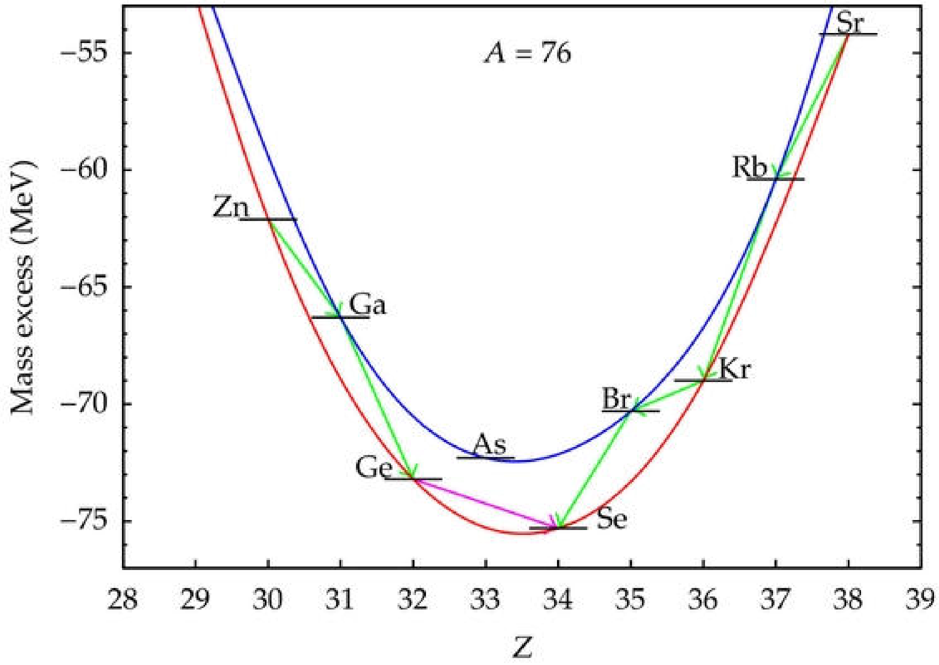
$$1/T^{0\nu}_{1/2}\left(0^+ \rightarrow 0^+\right) = G_{01}\boxed{\left|M^{\beta\beta 0\nu}\right|^2}\left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

Double β-decay

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



^{76}Br	^{77}Br	^{78}Br	^{79}Br	^{80}Br
^{75}Se	^{76}Se	^{77}Se	^{78}Se	^{79}Se
^{74}As	^{75}As	^{76}As	^{77}As	^{78}As
^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge
^{72}Ga	^{73}Ga	^{74}Ga	^{75}Ga	^{76}Ga



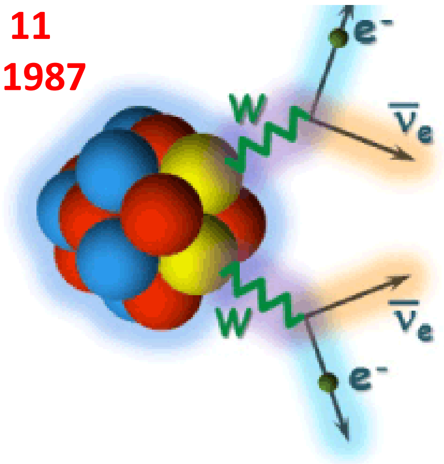
- ✓ Process mediated by the weak interaction occurring in even-even nuclei where the single β-decay is energetically forbidden

- ✓ The role of the pairing force

Double β-decay

Two-neutrino double beta decay

Observed in 11 nuclei since 1987



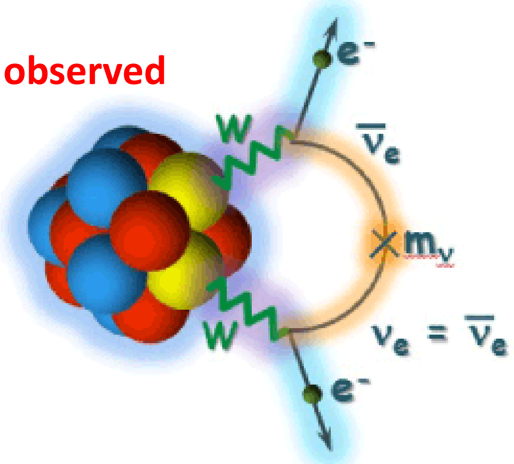
M. Goeppert-Mayer, Phys Rev. 48 (1935) 512

1. **Within standard model**
2. **$T_{1/2} \approx 10^{19}$ to $2*10^{21}$ yr**

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

Neutrinoless double beta decay

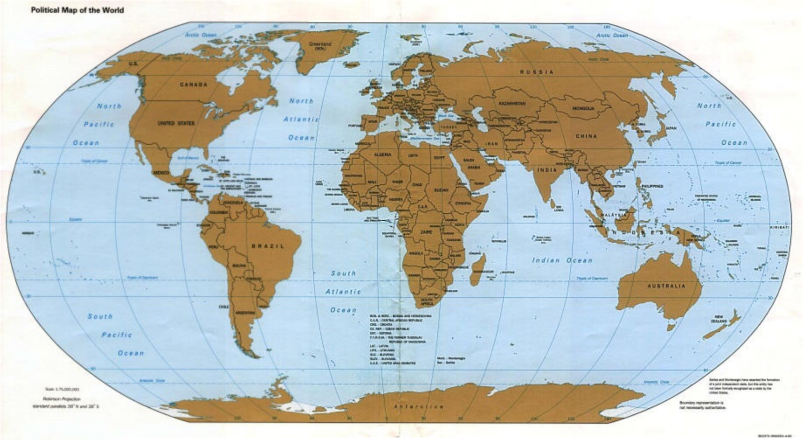
Still not observed



E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys Rev. 56 (1939) 1184

1. **Beyond standard model**
2. **Access to effective neutrino mass**
3. **Violation of lepton number conservation**
4. **CP violation in lepton sector**
5. **A way to leptogenesis and GUT**

$$1/T^{0\nu}_{1/2}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta\,0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e^4}\right|^2$$



Search for 0νββ decay. A worldwide race

$$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) > 10^{26}\,y$$

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)!

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

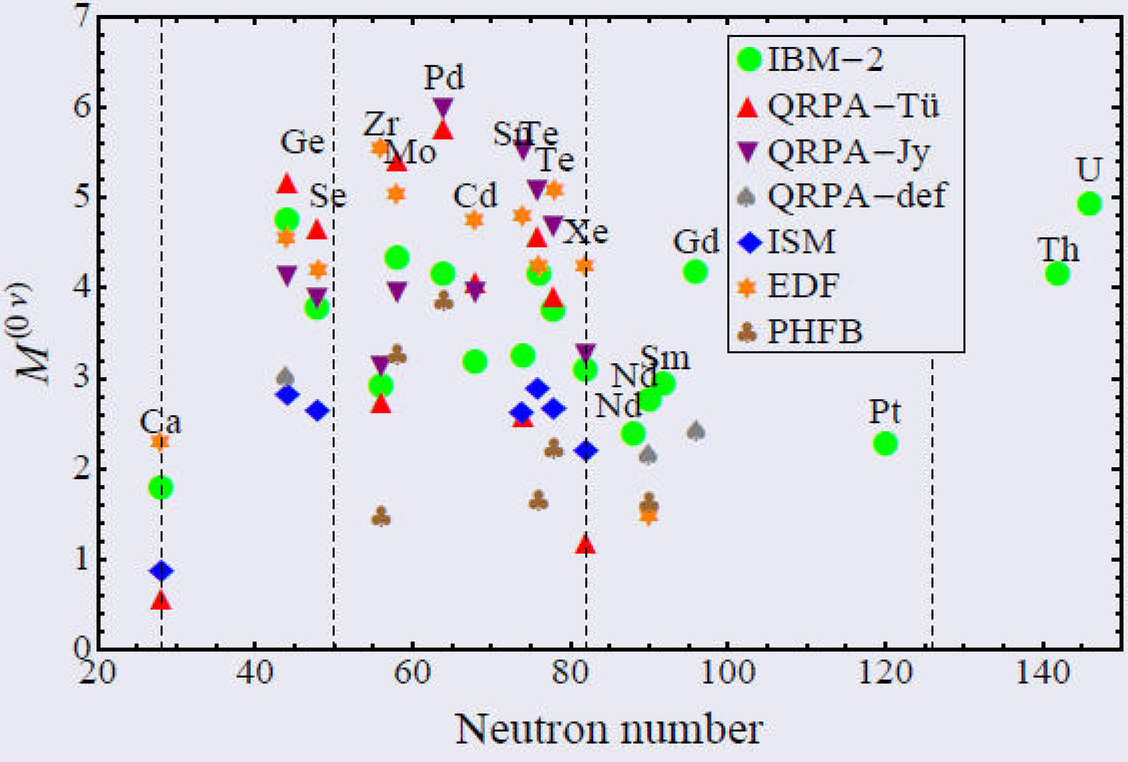
✓ Calculations (still sizeable uncertainties): QRPA, Large scale shell model, IBM, EDF, ab-initio …..

✓ Measurements (still not conclusive for $0\nu\beta\beta$):
(π^{+}, π^{-})
single charge exchange (^{3}He,t), (d,^{2}He)
electron capture
transfer reactions
muon capture …

✓ 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

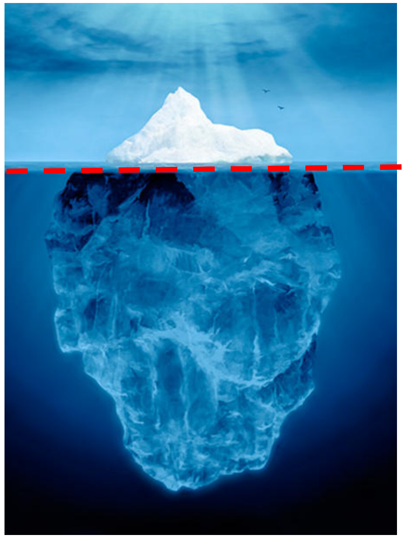
Heavy-ion DCE

- ✓ 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



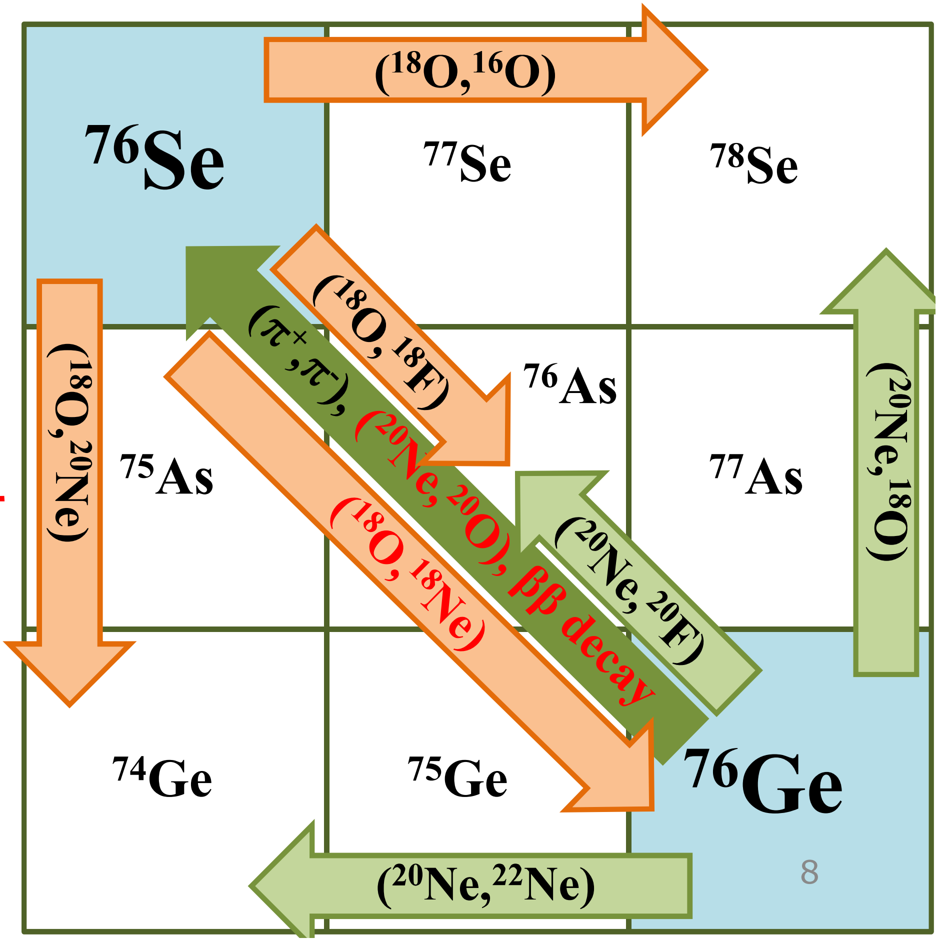
Tiny amount of DGT strenght in low lying states

Sum rule almost exhausted by DGT Giant Mode

RIKEN

RCNP

Takaki et al. JPS Conf. Proc., 020038 (2015)



0νββ 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 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.

Charge exchange cross-section and beta decay ME

for single CEX:

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

T.N. Taddeucci et al. Nucl. Phys. A469 (1987) 125

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

unit cross-section

β-decay transition strengths
(reduced matrix elements)

H. Lenske et al. Heavy Ion Single Charge Exchange Reactions and Beta Decay Matrix Elements

generalization to DCE (a simple approach):

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

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

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

H. Lenske et al. Heavy Ion Double Charge Exchange Reactions as a Probe for 2νββ Decay Matrix Elements

H. Lenske et al. Heavy Ion Double Charge Exchange Reactions as a Probe for 0νββ Decay Matrix Elements

The unit cross section

Single charge-exchange

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

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

Double charge-exchange

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

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)

$\hat{\sigma}_\alpha^{DCE}\left(E_p, A\right)$ is the Holy Graal

If known it would allow to determine the NME from DCE cross section measurement, whatever is the strenght fragmentation

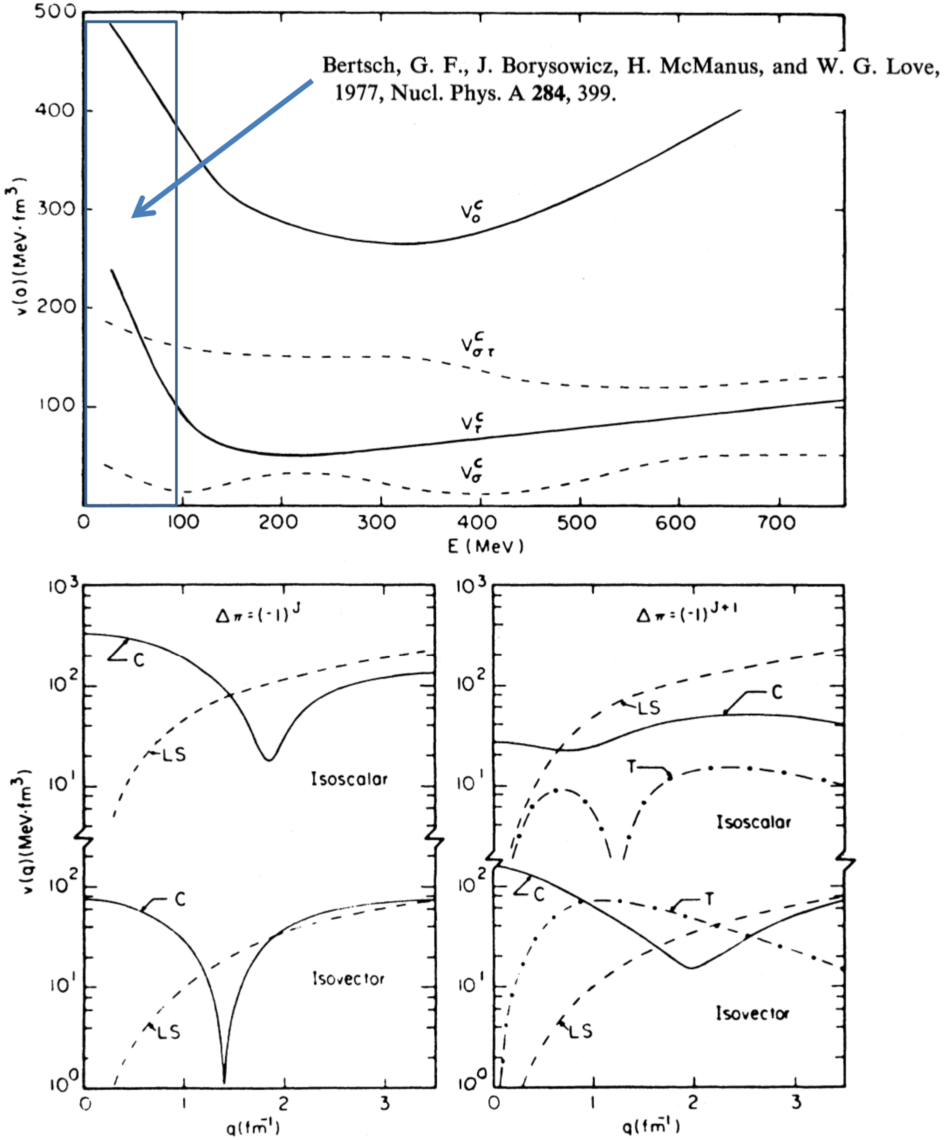
The volume integrals

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-like % F-like competion** at low energy



Bertsch, G. F., J. Borysowicz, H. McManus, and W. G. Love, 1977, Nucl. Phys. A **284**, 399.

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).

The recent NUMEN workshop

"Challenges in the investigation of double charge-exchange nuclear reactions: towards neutrino-less double beta decay"

✓More than 80 worldwide participants

✓Researchers for all the communities (nuclear physics, astro-particle, particle physics, theory, accelerators, detectors)

✓Alive discussions

✓New collaborations for NUMEN

✓Decisive step on the theoretical side

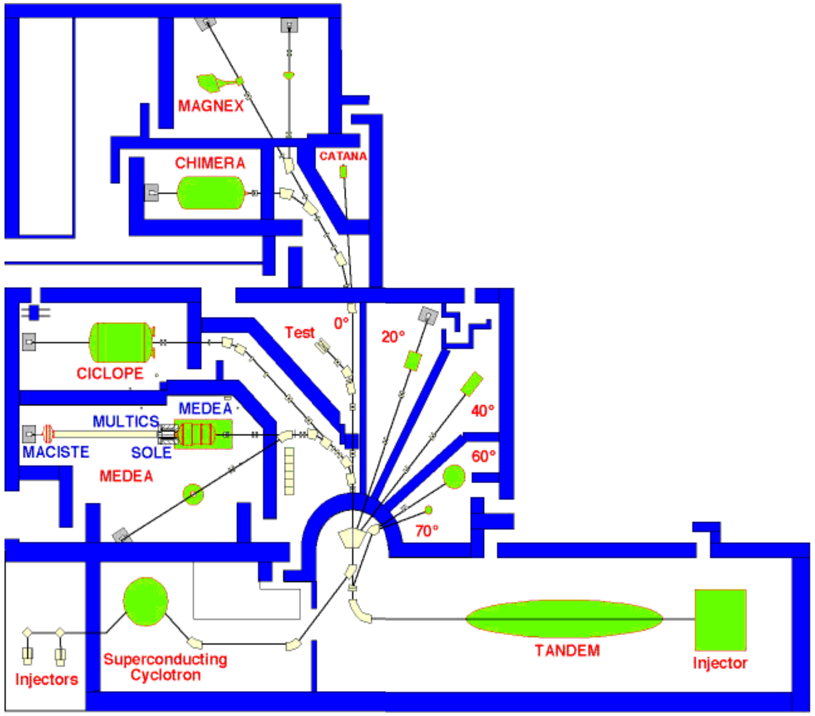
https://agenda.infn.it/event/NUMEN2015

NUMEN 2015 Workshop - LNS 1-2 dicembre 2015

Fallout: a theoretical group working on DCE reactions and connections with ββ was set with appropriate manpower and financial resources within NUMEN

DCE @ INFN-LNS

The LNS laboratory in Catania

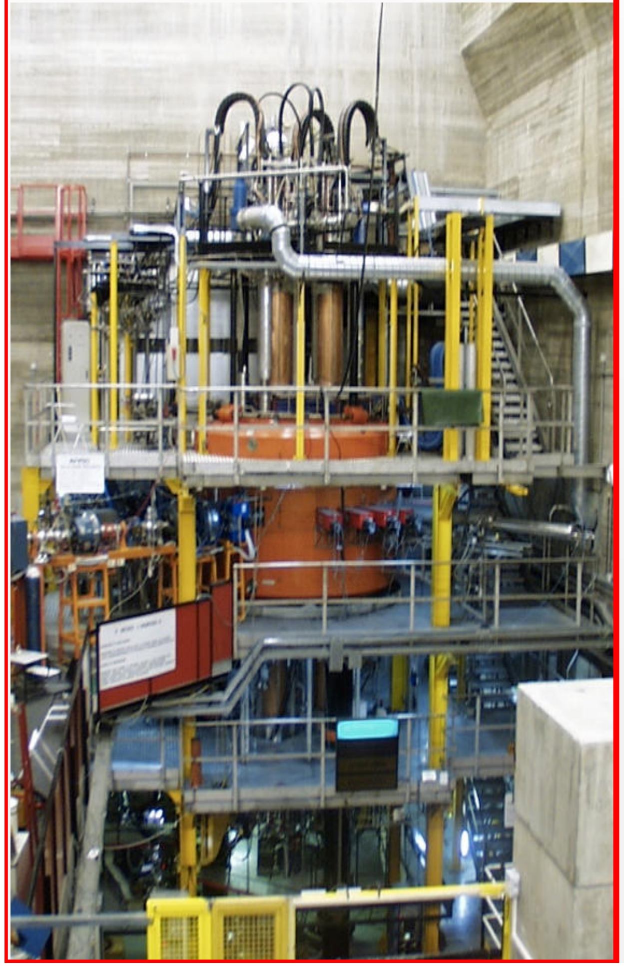


Superconducting Cyclotron and MAGNEX spectrometer @ LNS

crucial for the experimental challanges

K800 Superconducting Cyclotron

- **In operation since 1996**
- **Accelerates from ^{1}H to ^{238}U**
- **Maximum energy is 80 MeV/u**



MAGNEX spectrometer

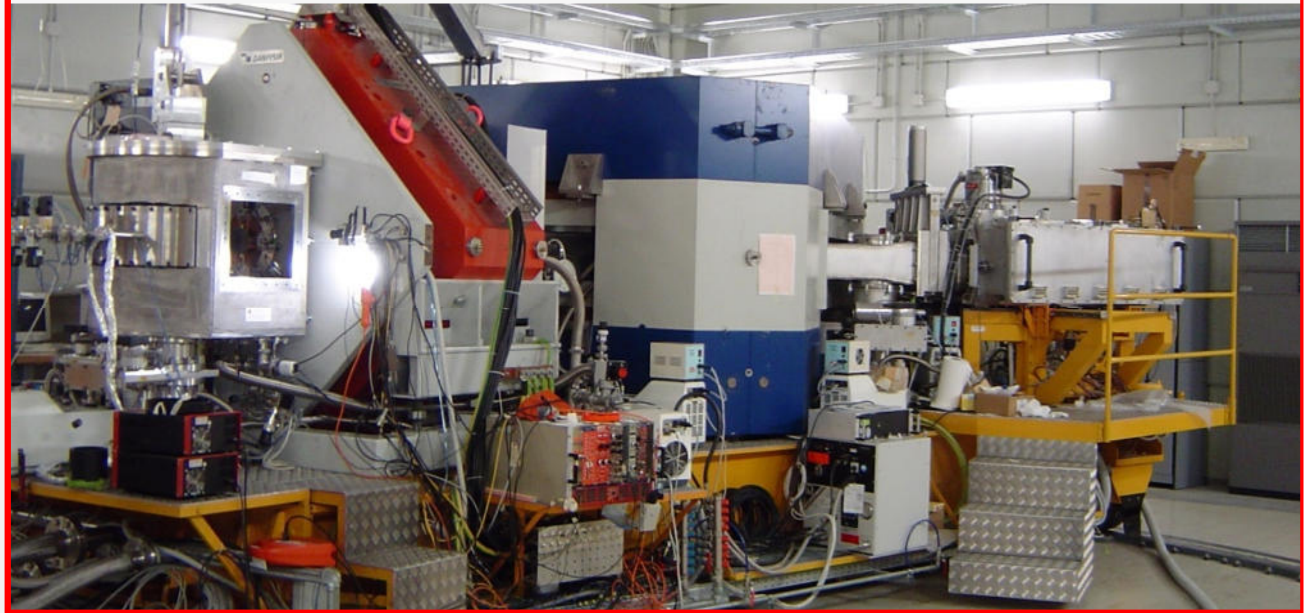
F. Cappuzzello et al., Eur. Phys. J. A (2016) 52: 167

F. Cappuzzello et al., Nature Comm. 6, 6743 (2015)

Achieved resolution

Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.2^{\circ}$
Mass $\Delta m/m \sim 1/160$

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



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

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

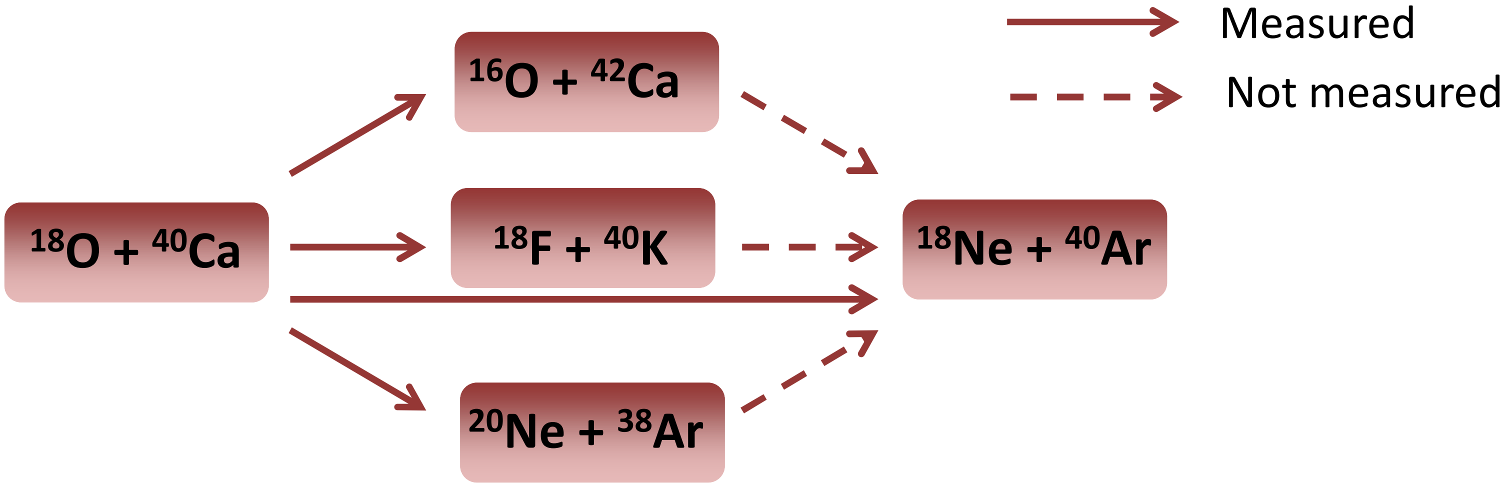
First pilot experiment 2013

$0^{\circ} < \vartheta_{lab} < 10^{\circ}$ 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
- Doubly magic target
- Low reaction Q-value Q_0=-2.9 MeV

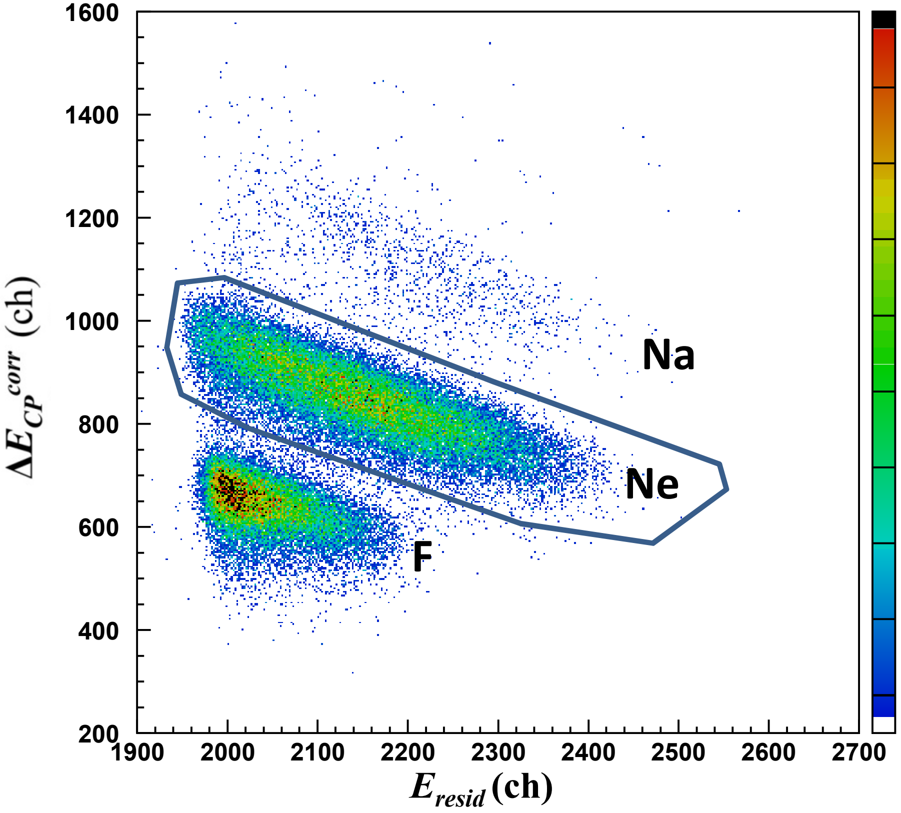
Experimental Set-up

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



F. Cappuzzello et al., NIMA621 (2010) 419

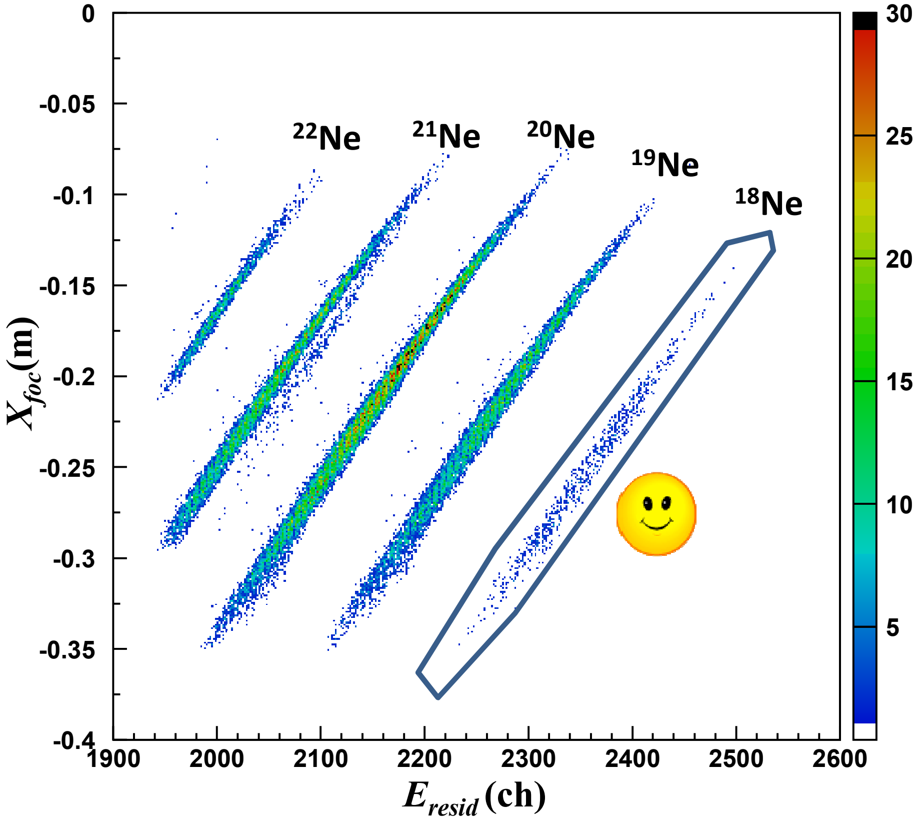
F. Cappuzzello, et al. NIMA638 (2011) 74

M.Cavallaro et al. EPJ A 48: 59 (2012)

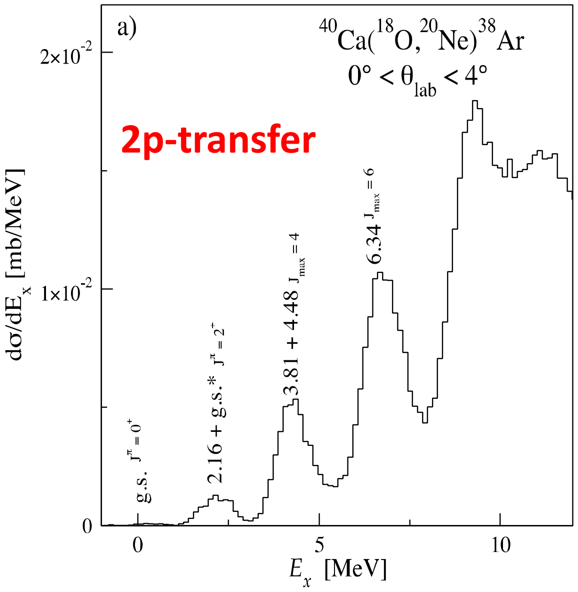
D.Carbone et al. EPJ A 48: 60 (2012)

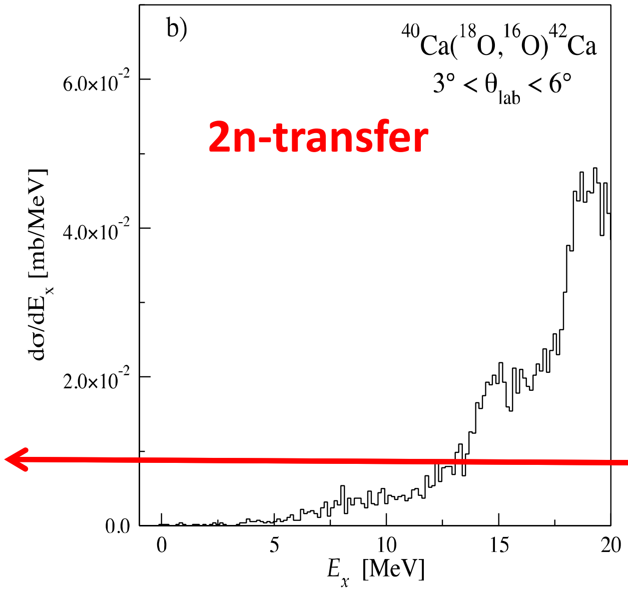
A identification

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



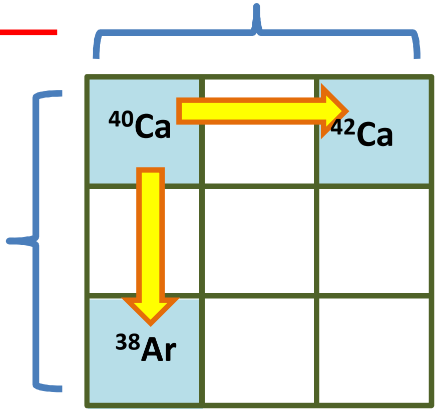
The role of the transfer reaction and the competing processes



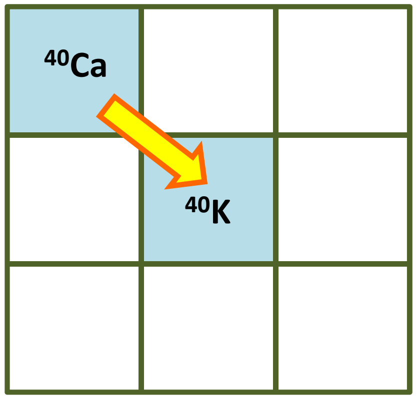


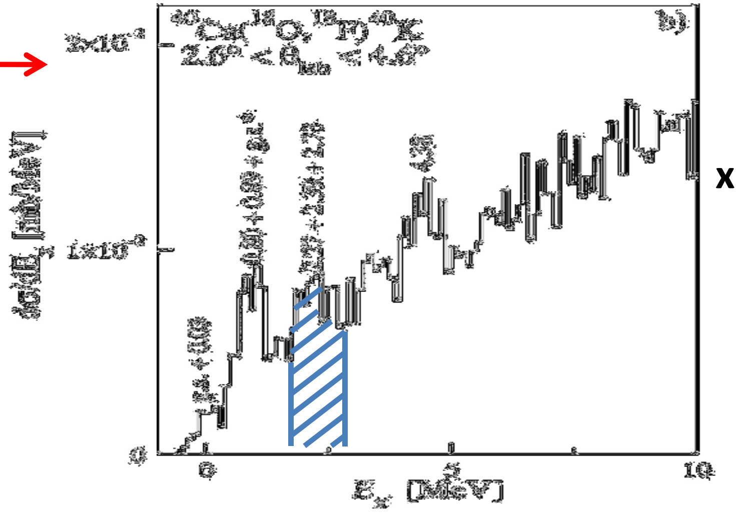
Less than 1% effect in the DCE cross section

Very weak



single charge exchange



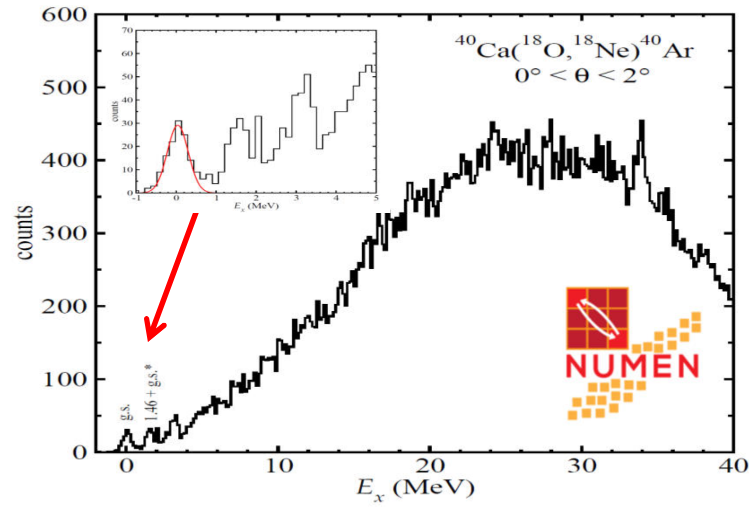


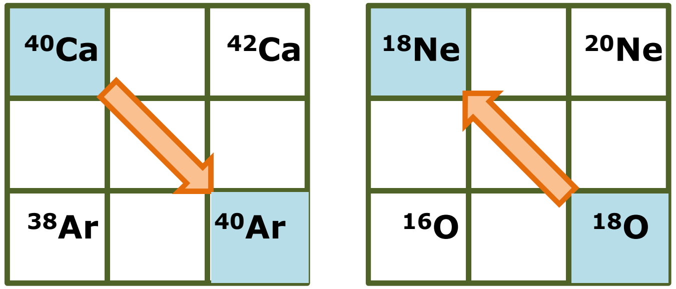
x-section (2MeV < E_x < 3MeV)
≈ 0.5 mb/sr

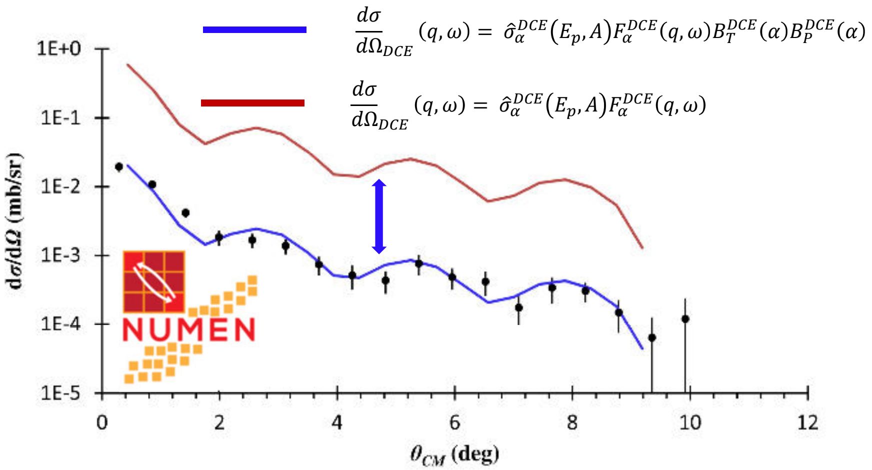
Extracted B(GT) = 0.087

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

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

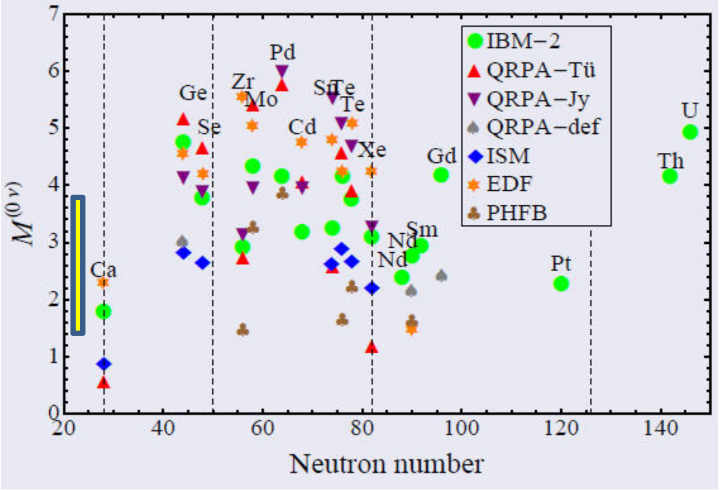






$$\frac{d\sigma}{d\Omega_{DCE}}(q,\omega) = \hat{\sigma}_\alpha^{DCE}(E_p,A)F_\alpha^{DCE}(q,\omega)B_T^{DCE}(\alpha)B_P^{DCE}(\alpha)$$

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



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

Pauli blocking about 0.14 for F and GT

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

Recent experiments

Isotopes selected for NUMEN 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	🟥 **Performed experiment at 15 MeV/u**											
^{116}Cd (^{20}Ne,^{20}O) ^{116}Sn	15-25	🟦 **Performed test**											
^{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											🟨	🟨

NUMEN Experimental runs

test 2015 → **Experiment 2016**

^{116}Sn + ^{18}O @ 15 MeV/A (one week test)

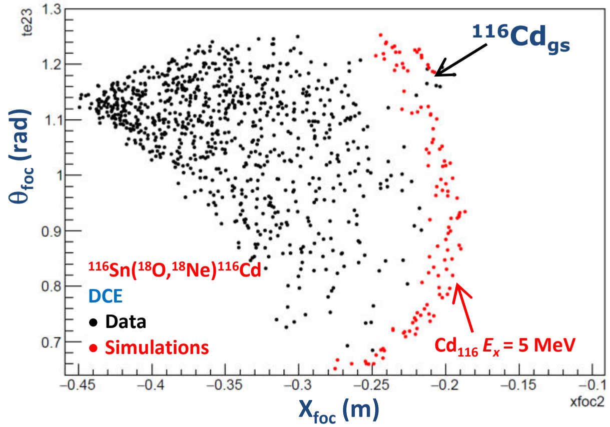
We measured at 0° < θ_{lab} < 10° (zero-degree measurement):

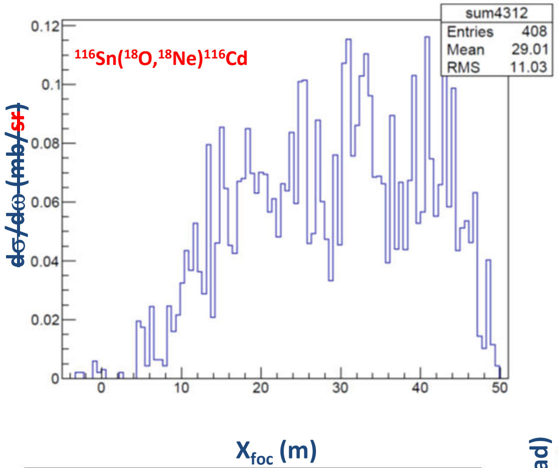
- DCEX reaction ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd
- CEX reaction ^{116}Sn(^{18}O,^{18}F)^{116}In
- 2p-transfer ^{116}Sn(^{18}O,^{20}Ne)^{114}Cd
- 1p-transfer ^{116}Sn(^{18}O,^{19}F)^{115}In

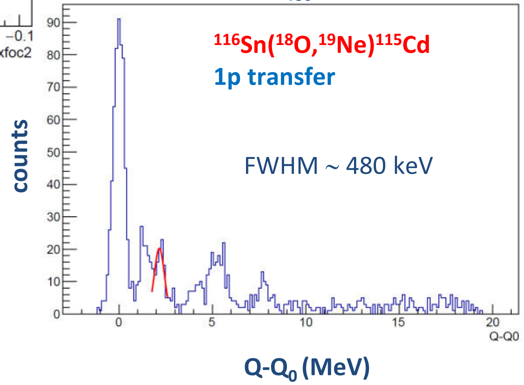
Results from a test run on ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd October 2015

- ✓ 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

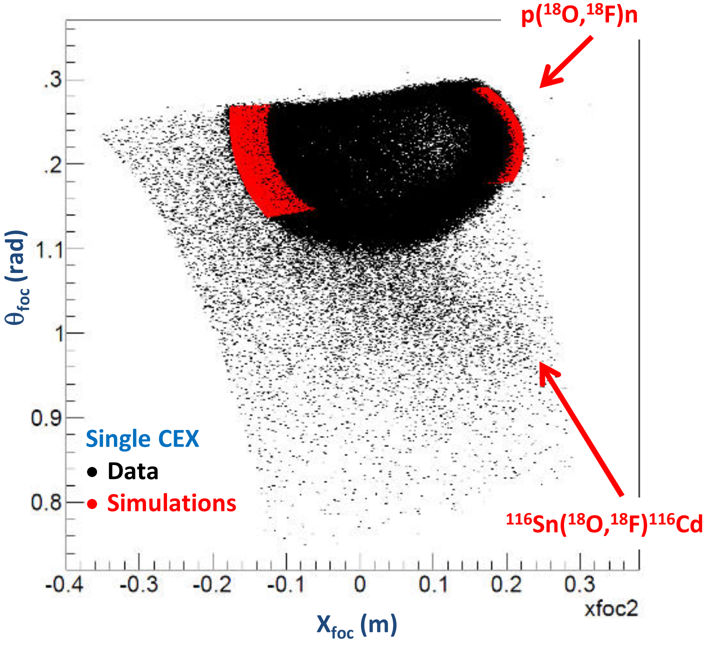
Good sensitivity for DCE







Good energy resolution and accuracy



Perhaps 4 counts for

^{116}Sn$_{gs}$→^{116}Cd$_{gs}$

Experiment at 15 MeV/u
finished in July 2016

NUMEN Experimental runs

^{116}Cd + ^{20}Ne @ 15 MeV/A and 22 MeV/A
(one week test)

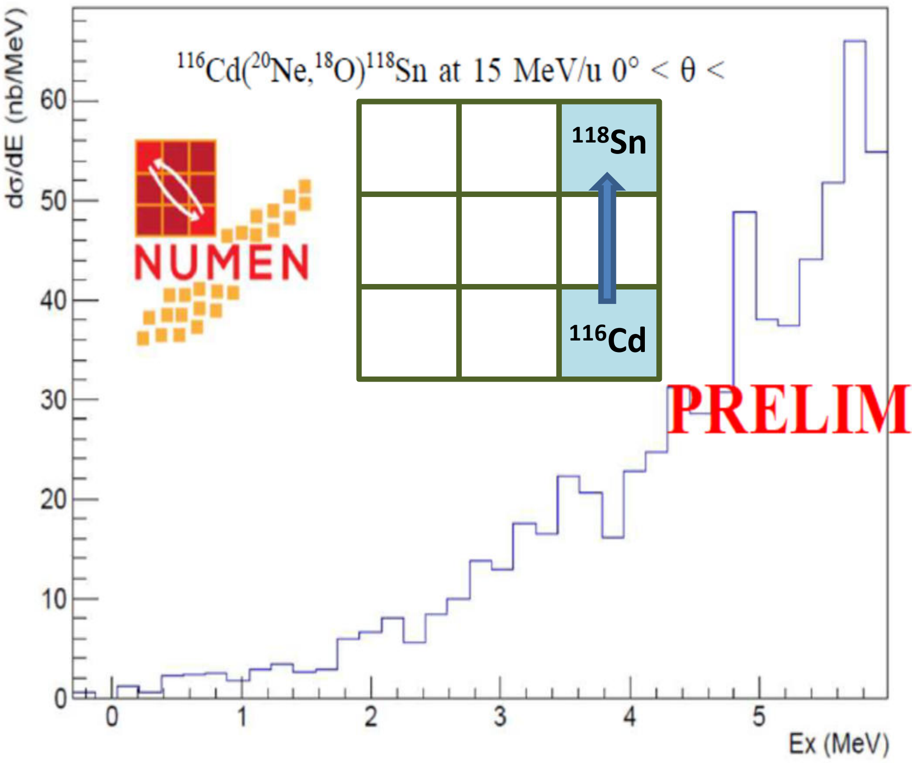
We measured at 0° < θ_{lab} < 8° (zero-degree measurement):

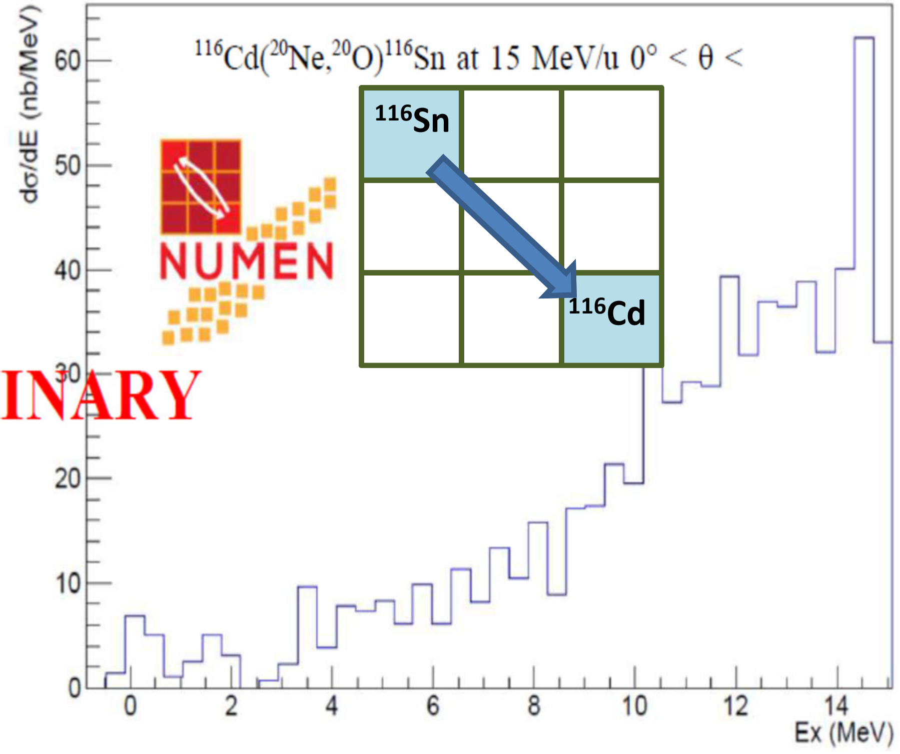
- DCEX reaction ^{116}Cd(^{20}Ne,^{20}O)^{116}Sn
- CEX reaction ^{116}Cd(^{20}Ne,^{20}F)^{116}In
- 2p-transfer ^{116}Cd(^{20}Ne,^{18}O)^{118}Sn
- 1p-transfer ^{116}Cd(^{20}Ne,^{19}F)^{117}In

Data reduction in progress...

Results from a test run on ^{116}Sn(^{18}O,^{18}Ne)^{116}Cd March 2016

Again multi-nucleon transfer suppressed compared to DCE



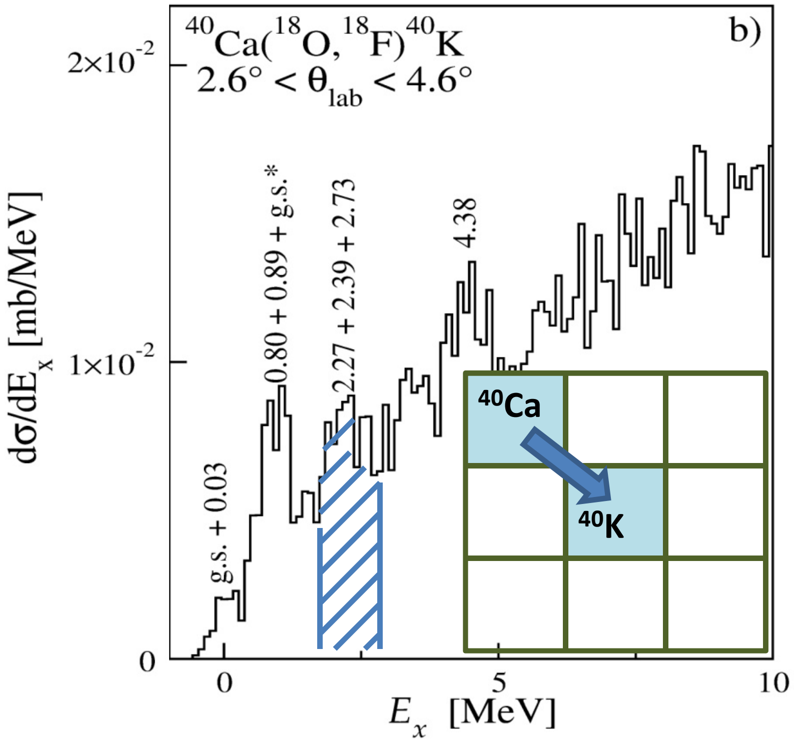


PRELIMINARY

Conclusions and Outlooks

- Cross sections of **heavy-ion induced charge exchange reactions are approachable** by present detection technology
- **They can potentially give an almost unique experimental access to many key aspects of present and future research of** 0νββ physics
- **Results** of relevance for 0νββ physics are expected **soon**

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



x-section (2MeV < E_x < 3MeV)

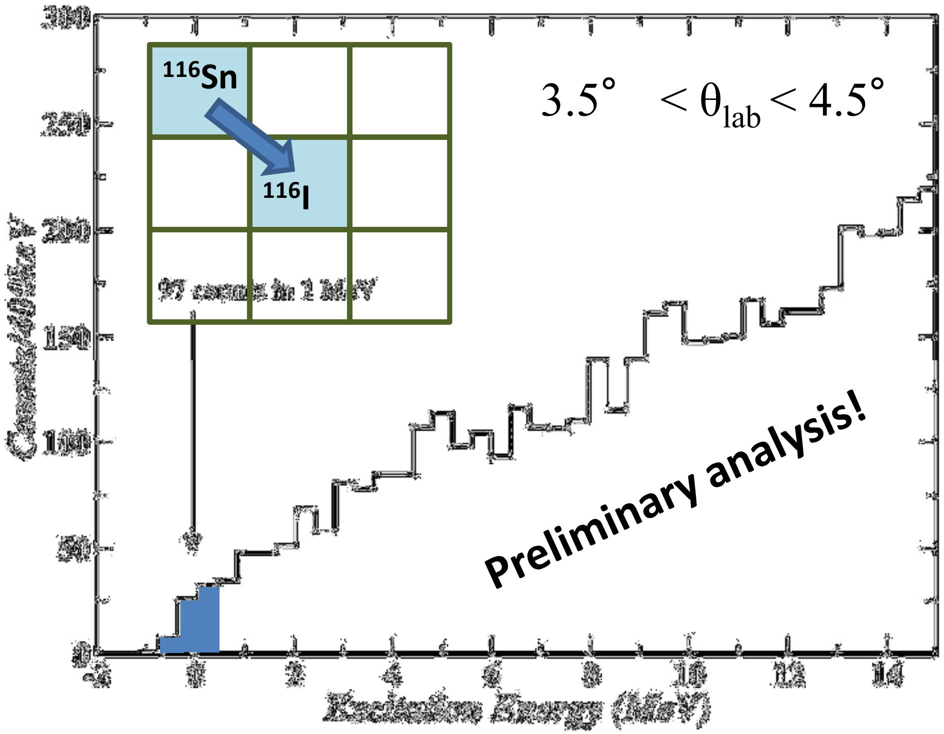
≈ 0.5 mb/sr

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)

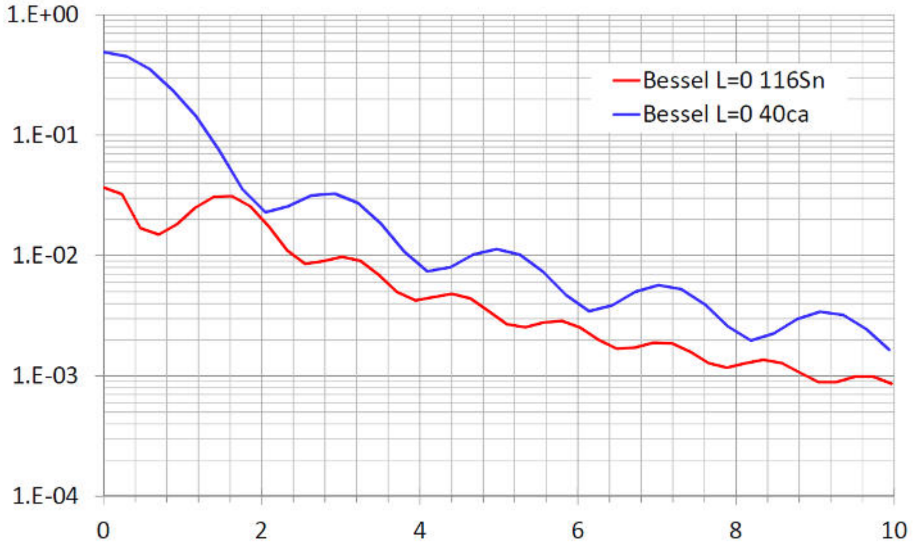
≈ 0.17 mb/sr

Extracted upper limit for B(GT) < 0.8

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

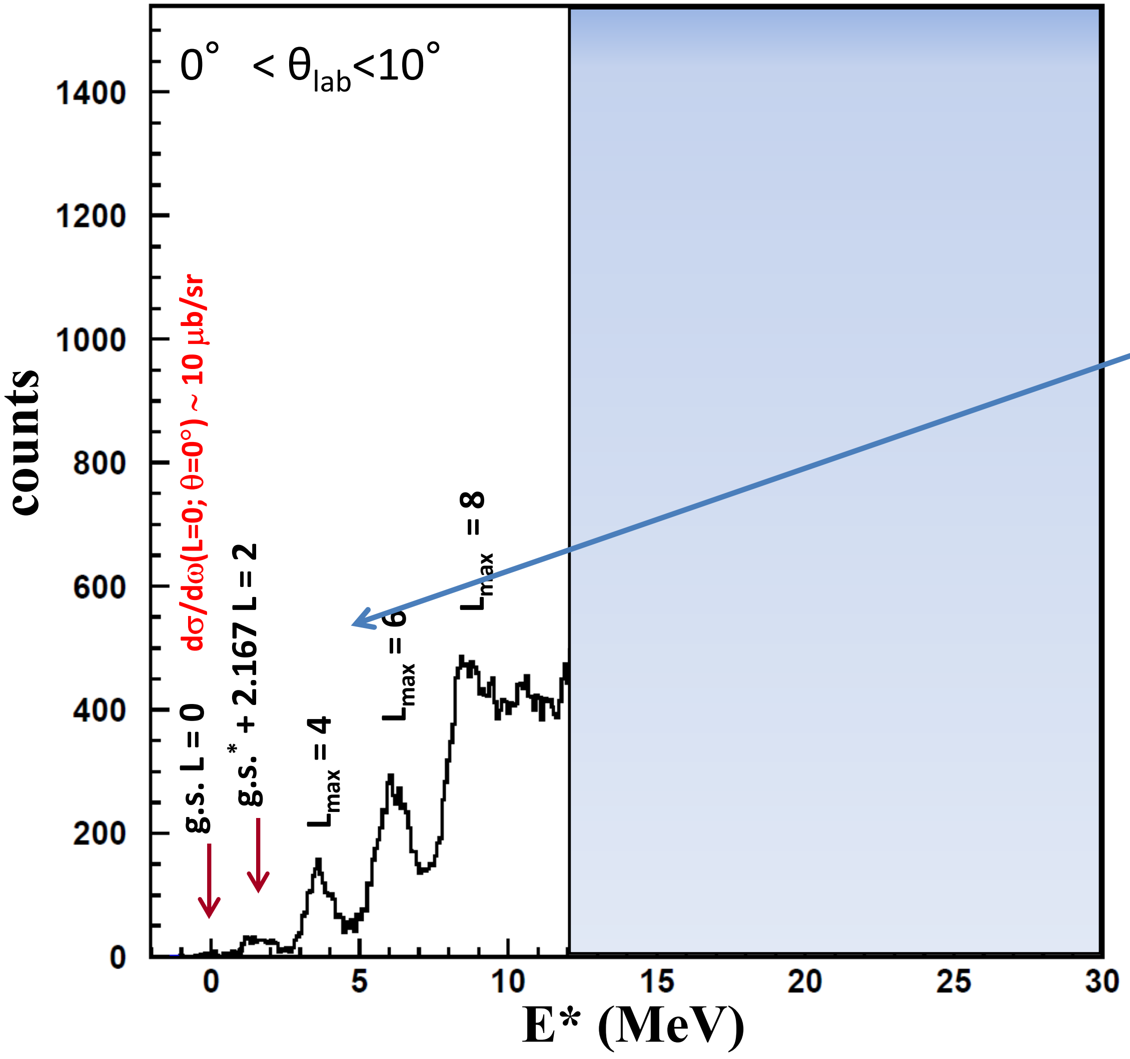
S.Rakers, et al., PRC 71 (2005) 054313

Bessel

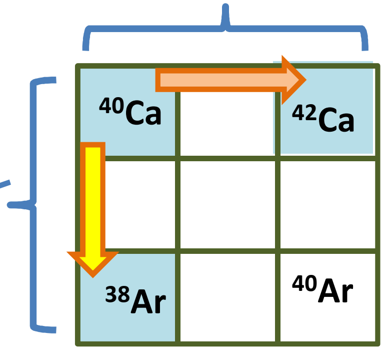

1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
0
2
4
6
8
10
Bessel L=0 116Sn
Bessel L=0 40ca

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



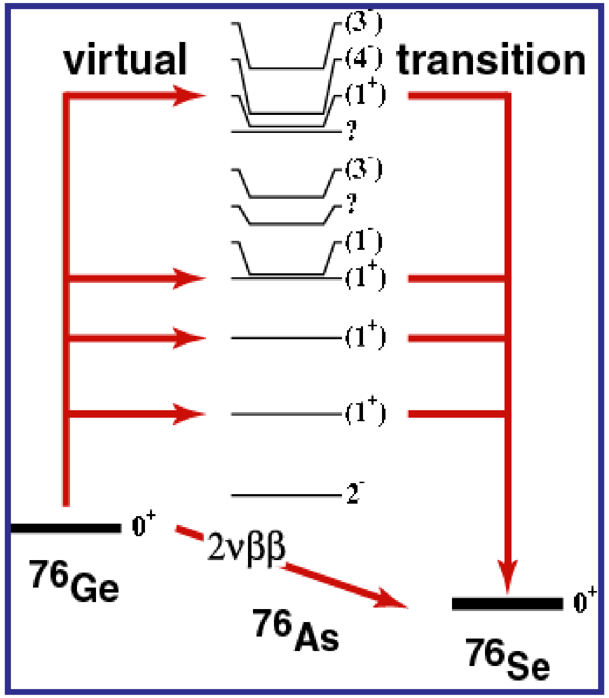
Suppression of L = 0 in the pair transfer

Suppression of L > 0 in the double pair transfer

Less than 1% effect in the DCE cross section

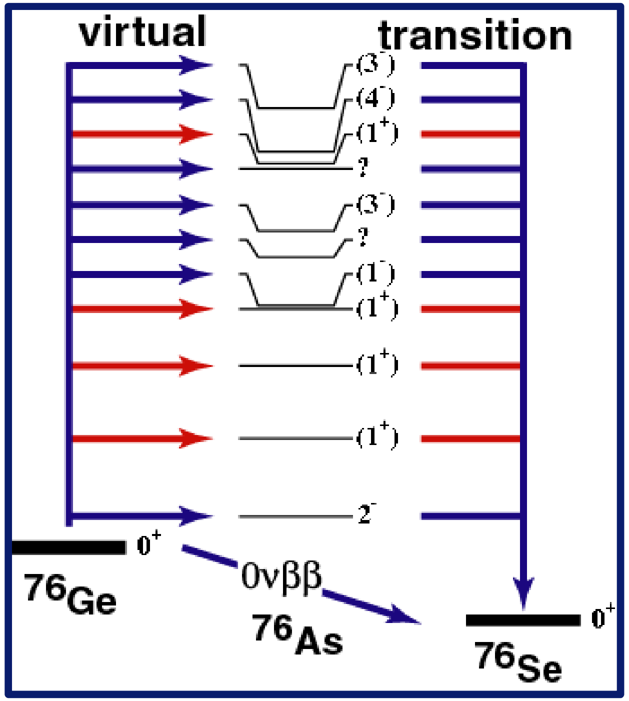
NME 2νββ - decay

q-transfer like ordinary β-decay
($q \sim 0.01\ \mathrm{fm}^{-1} \sim 2$ MeV/c)
only allowed decays possible
(L=0)



NME 0νββ - decay

neutrino enters as virtual particle,
$q \sim 0.5\mathrm{fm}^{-1}$ (~ 100 MeV/c)
degree of forbiddeness weakened
L=0,1,2……



Single state dominance

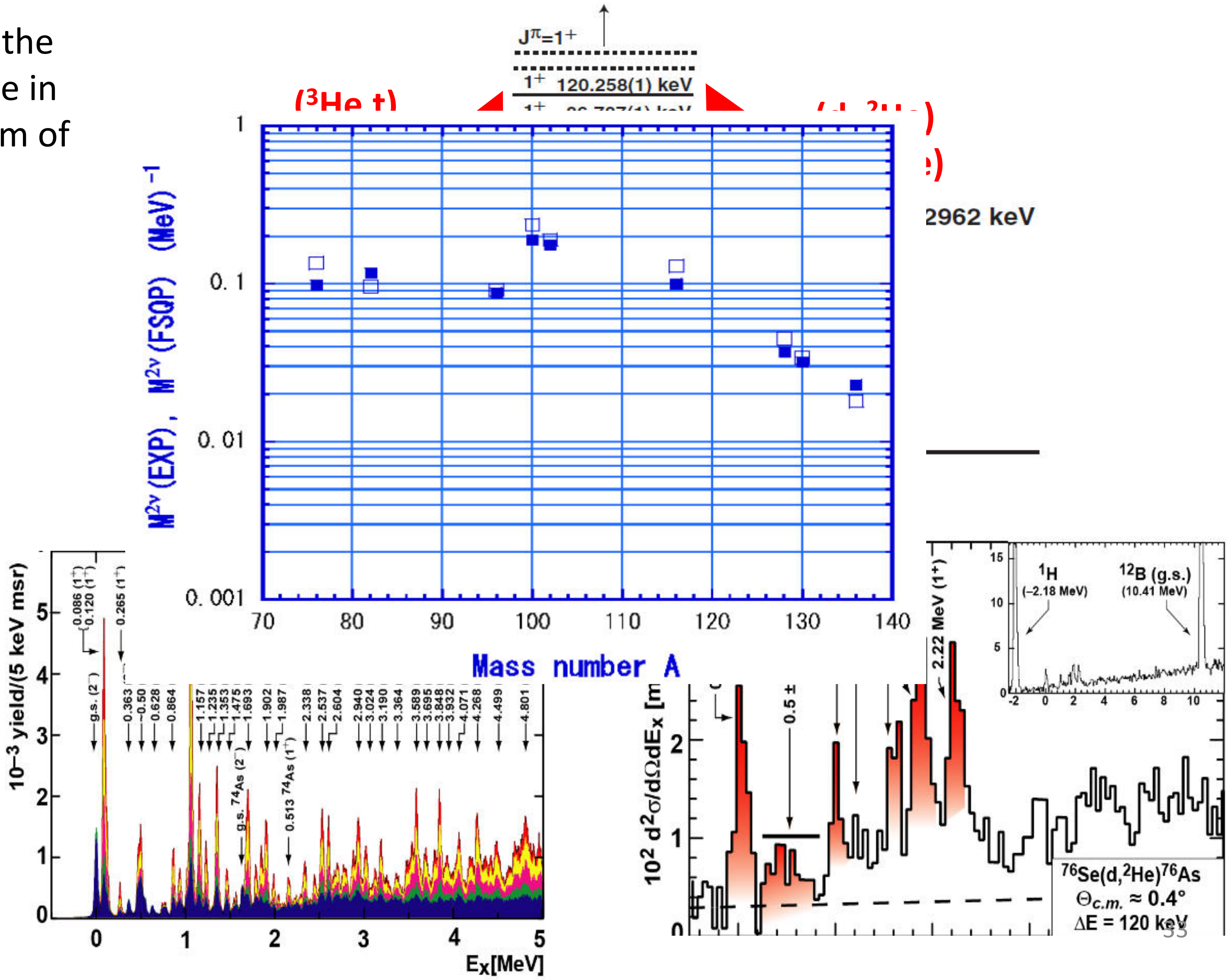
$$G = \sum_n \frac{|n\rangle\langle n|}{E_n - (E_i + E_f)/2}$$

Closure approximation

Methodology for NME
2νββ - decay

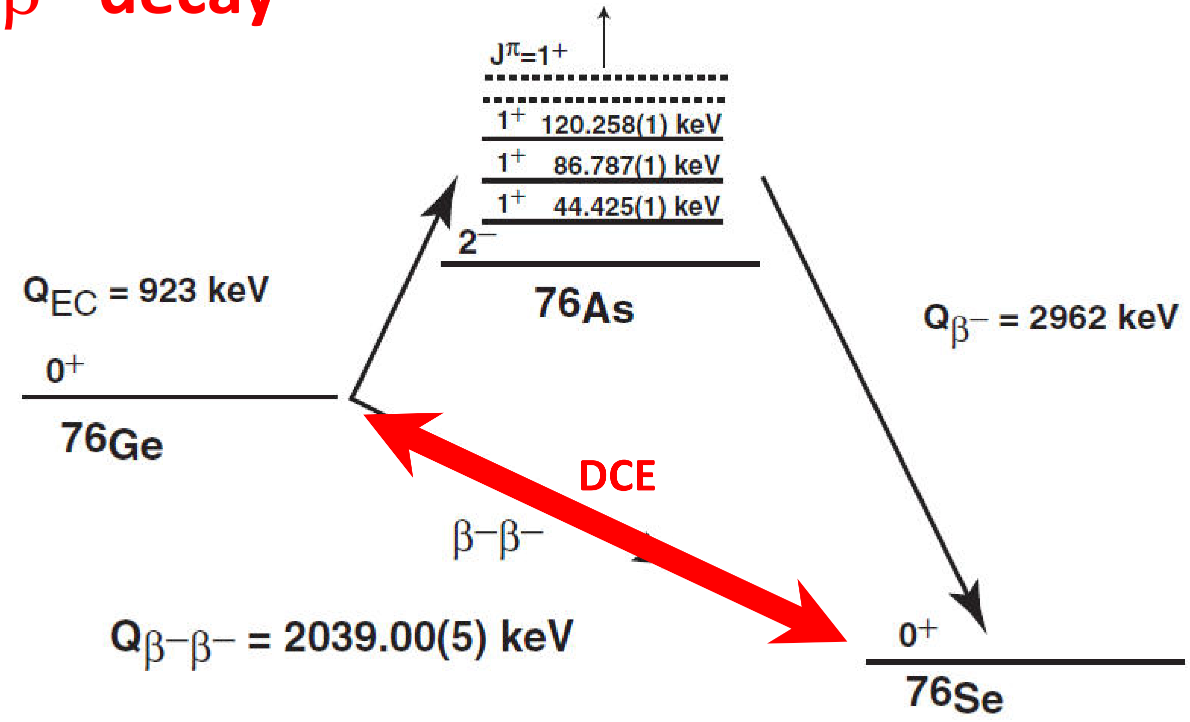
$$1/T^{2\nu}_{1/2}(0^+ \to 0^+) = G_{2\nu}\left|M^{\beta\beta 2\nu}\right|^2$$

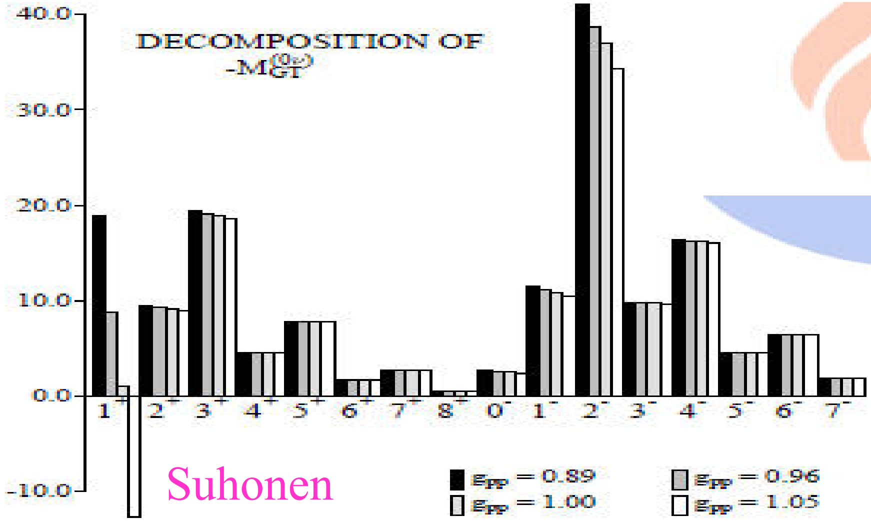
Assumption: all the signs are positive in the coherent sum of the amplitudes!



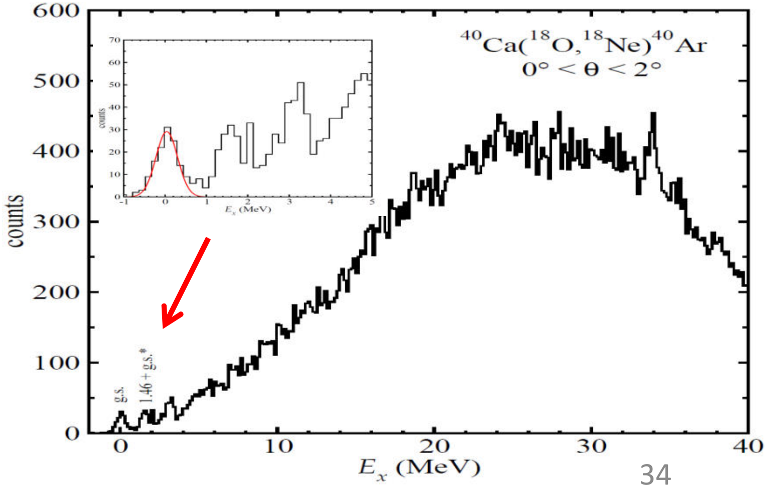
Methodology for NME
0νββ - decay

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





Suhonen



A fundamental property

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

$$V_\alpha (r_\alpha ,\chi_\alpha) = \underset{\substack{\downarrow \\ \text{Optical potential}}}{U_\alpha} (r_\alpha) + \underset{\substack{\searrow \\ \text{Residual interaction}}}{W_\alpha(r_\alpha ,\chi_\alpha)}$$

For charge exchange reactions the $W_\alpha(r_\alpha ,\chi_\alpha)$ is ‘small’ and can be treated perturbatively

In addition the reactions are strongly localized at the surface of the colliding systems and consequently large overlap of nuclear densities are avoided

Accurate description in fully quantum approach, eg. Distorted Wave techniques

Microscopic derived double folding potentials are good choices for $U_\alpha (r_\alpha)$

Microscopic form factors work for charge exchange reactions

$0\nu\beta\beta$ 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;

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

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

3. **Large momentum available:** A linear momentum as high as 100 MeV/c or so is characteristic of both processes;

0νββ vs HI-DCE

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;

0νββ vs HI-DCE

5. **In-medium** processes: both processes happen in the same nuclear medium, thus **quenching** phenomena are expected to be similar;

0νββ vs HI-DCE

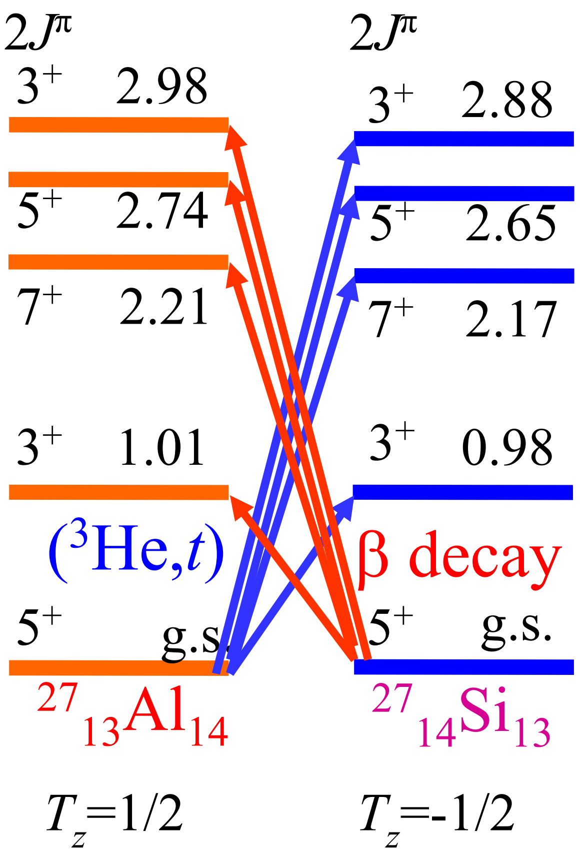
6. Relevant **off-shell propagation** in the intermediate channel: both processes proceed via the same intermediate nuclei off-energy-shell even up to 100 MeV.

Connection between β-decay and Single Charge Exchange

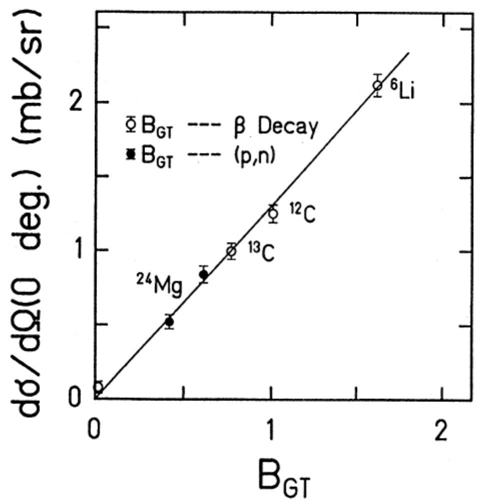
Y. Fujita Prog. Part. Nuc. Phys. 66 (2011) 549 **F. Osterfeld** Rev. Mod. Phys. 64 (1992) 491
H. Ejiri Phys. Rep. 338 (2000) 256 **T.N. Taddeucci** Nucl. Phys. A 469 (1997) 125

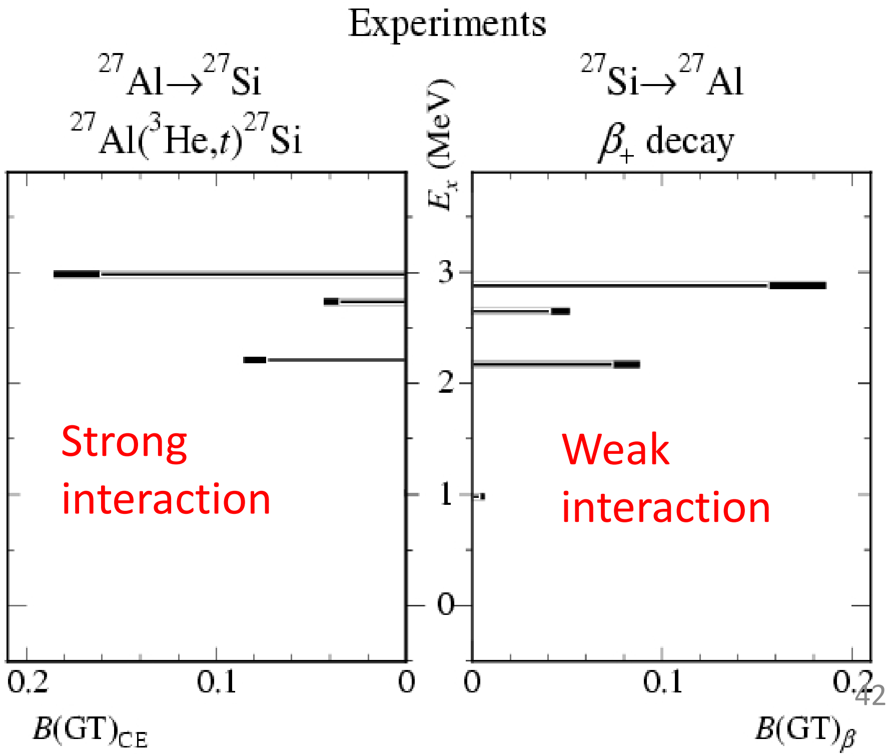
- (^{3}He,t) at low q: In general for B(GT)>0.05

$$\frac{B(GT)_{[(3\text{He},t);q=0]}}{B(GT)_{[\beta-\text{decay}]}} = 1 \pm 0.05$$



- Similar results for the (d,^{2}He)

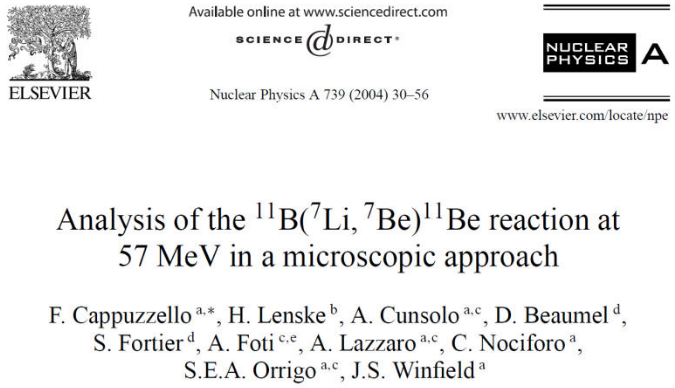




For heavier projectiles

(^{7}Li,^{7}Be)

$$\frac{B(GT)_{[(7Li,7Be);q=0]}}{B(GT)_{[\beta-decay]}} = 1 \pm 0.2$$



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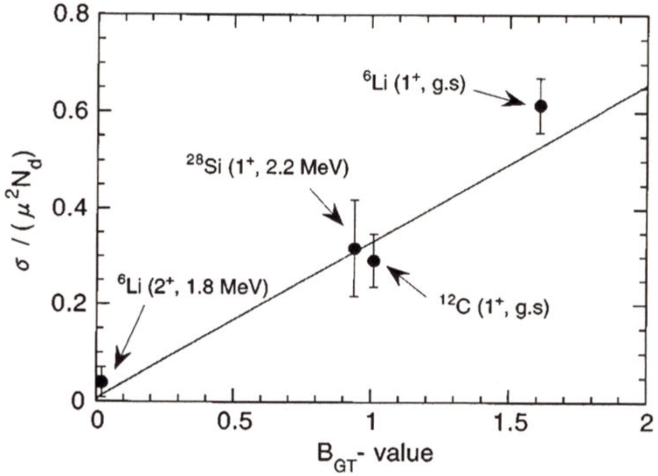
Analysis of the ^{11}B(^{7}Li, ^{7}Be)^{11}Be reaction at 57 MeV in a microscopic approach

F. Cappuzzello [a,*], H. Lenske [b], A. Cunsolo [a,c], D. Beaumel [d], S. Fortier [d], A. Foti [c,e], A. Lazzaro [a,c], C. Nociforo [a], S.E.A. Orrigo [a,c], J.S. Winfield [a]

See also
F.Cappuzzello et al. *Phys.Lett B* 516 (2001) 21-26
F.Cappuzzello et al. EuroPhys.Lett 65 (2004) 766-772
S.E.A.Orrigo, et al. *Phys.Lett. B* 633 (2006) 469-473
C.Nociforo et al. *Eur.Phys.J. A* 27 (2006) 283-288
M.Cavallaro Nuovo Cimento C 34 (2011) 1

S. Nakayama PRC 60 (1999) 047303



- ✓ Confirmed by us on different nuclei: ^{11}Be, ^{12}B, ^{15}C, ^{19}O
- ✓ Microscopic and unified theory of reaction and structure is mandatory for quantitative analyses
- ✓ Best results for transitions among isospin multiplets in the projectiles as (^{7}Li$_{gs(3/2-)}$,^{7}Be$_{gs(3/2-)}$)
- ✓ (^{18}O$_{gs(0+)}$,^{18}F$_{gs(1+)}$) should be better than (^{7}Li,^{7}Be) even if not really explored to now