Heavy Ion Reactions as a Probe for Weak Interactions in Nuclei

H. Lenske
Institut für Theoretische Physik, JLU Giessen
and
GSI Darmstadt

…at the very beginning of microscopic physics: investigating $\gamma\gamma$ and γe^--emission:

Über Elementarakte mit zwei Quantensprüngen

Von Maria Göppert-Mayer

(Göttinger Dissertation)

(Ann. Phys. 401 (2931) 273)

…and a few years later considering $2\nu\beta\beta$ processes:

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*

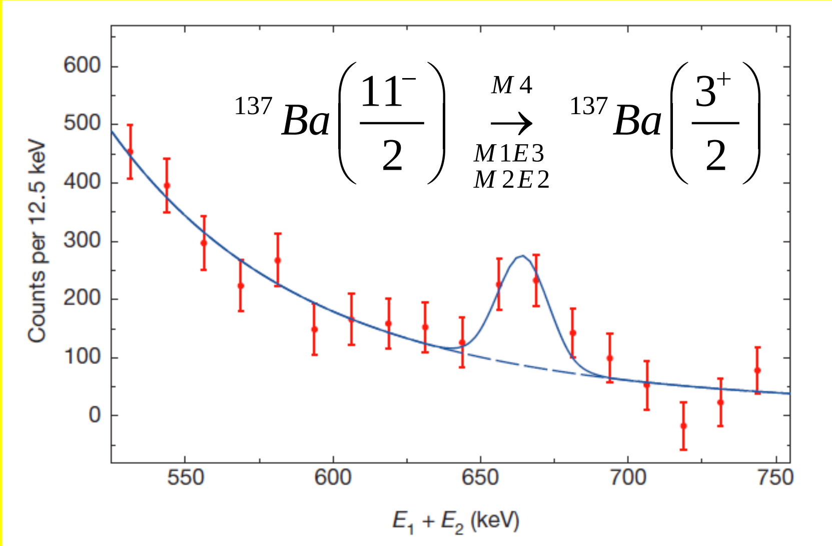
1st experimental proof: S. R. Elliott, A. A. Hahn, and M. K. Moe, "Direct evidence for two-neutrino double-beta decay in ^{82}Se," *PRL* 59,2020 (1987)

…and recently the first experimental proof of the coexistence of γ- and γγ-emission in nuclei

Observation of the competitive double-gamma nuclear decay

C. Walz[1], H. Scheit[1], N. Pietralla[1], T. Aumann[1], R. Lefol[1,2] & V. Yu. Ponomarev[1]

Nature 406, 526 (2015)



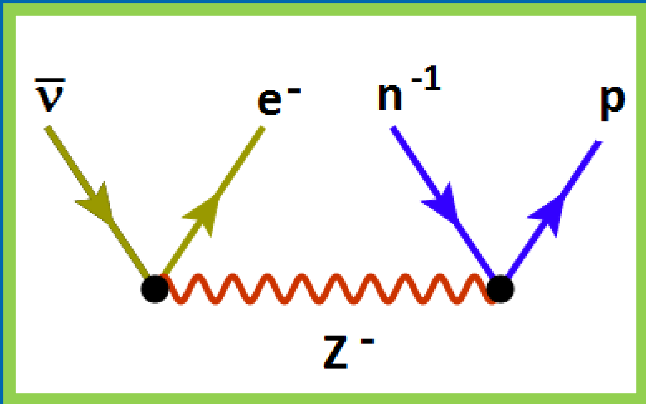
$$\alpha_{S'L'SL} = \sum_n \frac{\left\langle \frac{3}{2}^+ \| S'L' \| I_n \right\rangle \cdot \left\langle I_n \| SL \| \frac{11}{2}^- \right\rangle}{E_n - 0.5E_0}$$

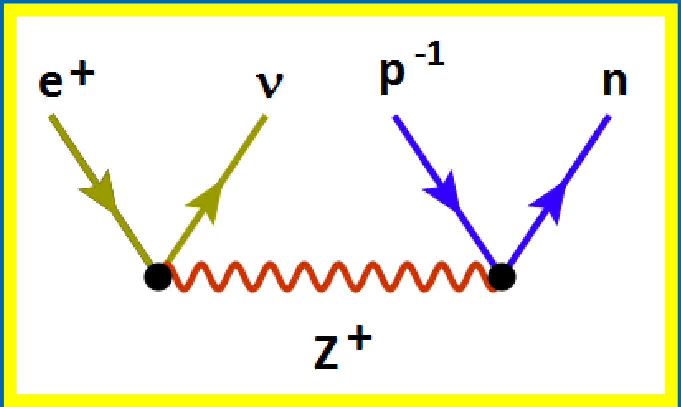
see also: H. Lenske, Phys.Jour. 14 (2015)

…our today's Agenda:

- Nuclear β– and ββ-decay
- Nucleon induced Single Charge Exchange (SCE) reactions and νβ-NME
- Heavy ion charge exchange reactions at low energy
- Double charge exchange (DCE) reactions and 0νββ NME
- Outlook to theory@NUMEN

Nuclear beta-decay: Weak Charged-Current Interactions and Gamov-Teller strength





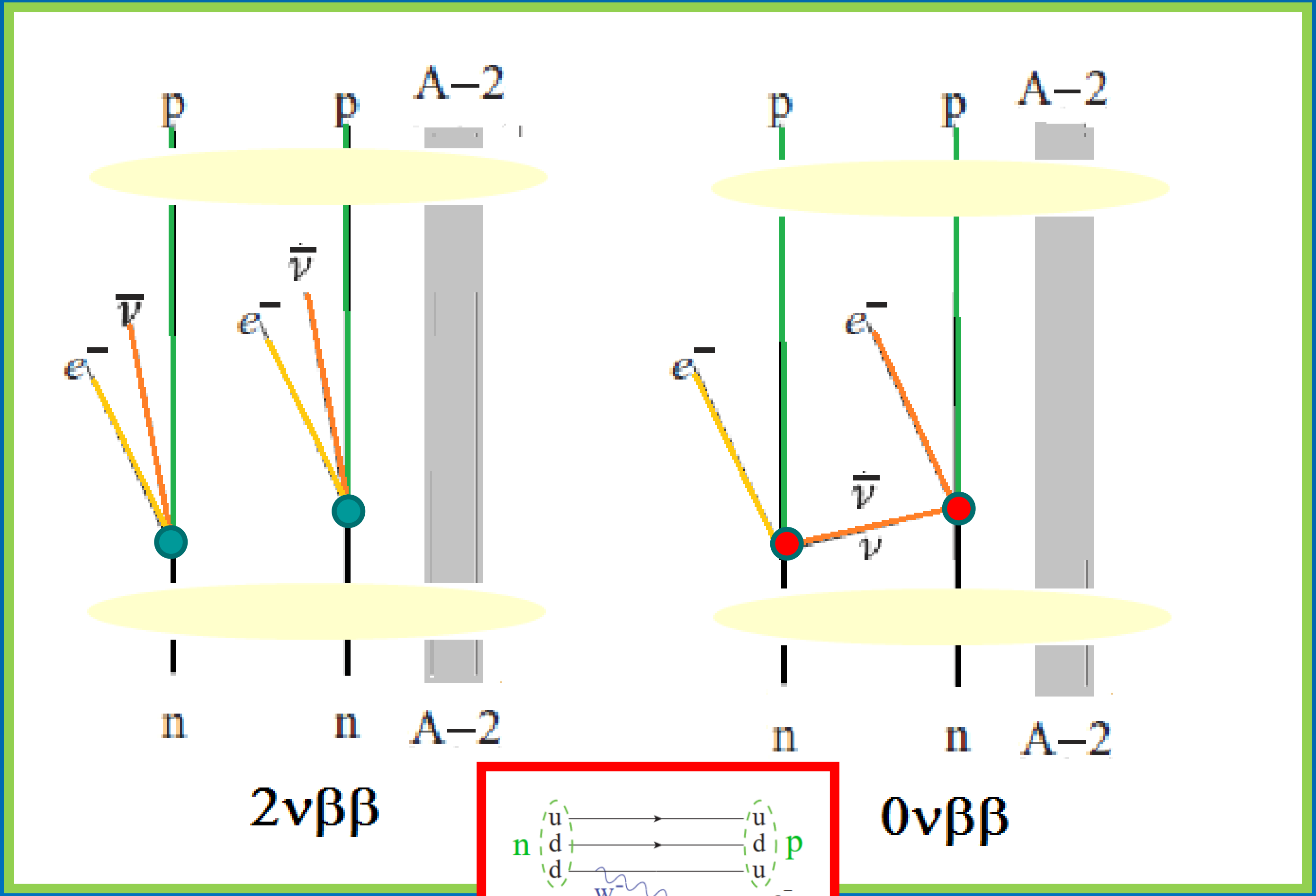
$$M(GT^{\pm}) \propto \left| \left\langle f \left\| \frac{\sigma}{2} \cdot \tau_{\pm} \right\| i \right\rangle \right|^2$$

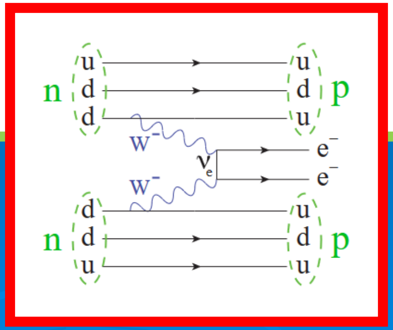
GT sum rule (model independent)

K. Ikeda PL 3, 271 (1963)

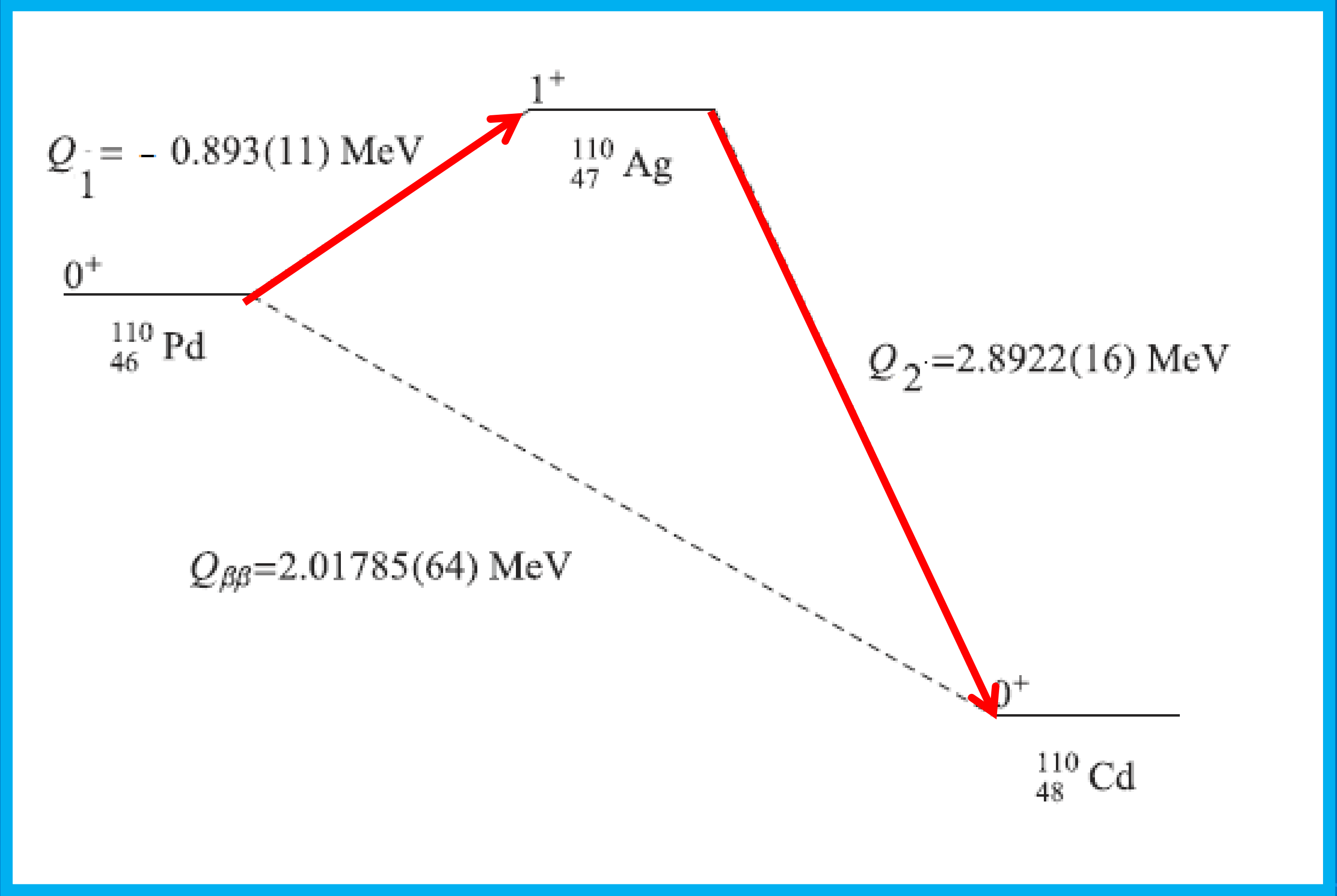
$$S_{\beta^-} - S_{\beta^+} = 3(N - Z)$$

Nuclear Double-Beta Decay





…a concrete case under investigation:



Beyond-the-Standard Model Physics of Double-beta Decay

Nuclear Matrix Element

Phase Space

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} g_A^4(0) \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 |M^{0\nu}(0_I^+ \rightarrow 0_F^+)|^2$$

effective Majorana
Neutrino Mass

$$\langle m_\nu \rangle = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 m_k e^{i\alpha_k} \right| .$$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) Matrix

Double-beta Decay and Nuclear Physics

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} g_A^4(0) \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 |M^{0\nu}(0_I^+ \rightarrow 0_F^+)|^2$$

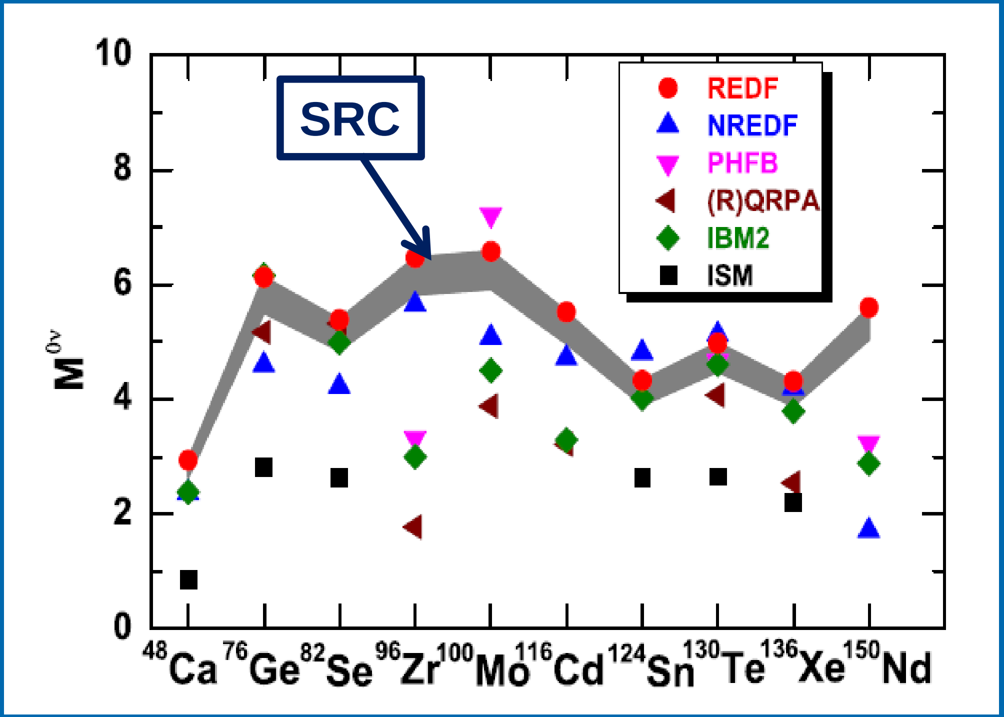
Nuclear Matrix Element…

…a quantum-mechanical 2nd-order nuclear process:

$$M_{\beta\beta}^{\mathrm{GT}} = \sum_N G_{\beta\beta,N}^{(i)} \frac{\langle 0_F^+ || \tau^+ \vec{\sigma} || 1_N^+ \rangle \langle 1_N^+ || \tau^+ \vec{\sigma} || 0_I^+ \rangle}{\frac{1}{2}(Q_{\beta\beta} + 2m_e c^2) + E_N - E_I}$$

Double beta-Decay Nuclei and Matrix Elements

^{48}Ca	CANDLES
^{64}Zn	COBRA
^{76}Ge	GERDA
^{82}Se	NEMO
^{96}Zr	NEMO
^{100}Mo	MOON/NEMO
^{116}Cd	COBRA
$^{128/130}Te$	CUORE
^{136}Xe	KAMLAND-ZEN
^{150}Nd	SNO+

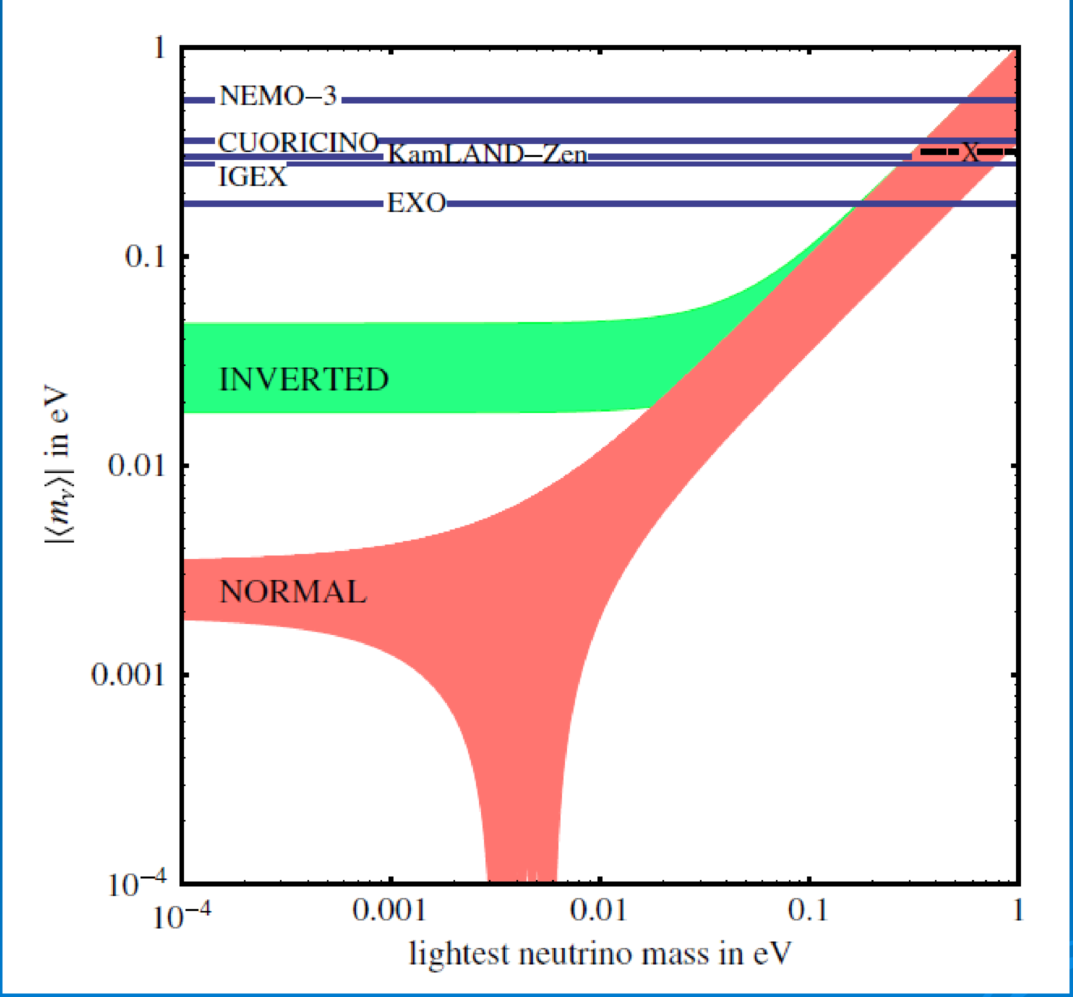


Presently active Experiments: Surveying 0νββ Candidates

Recent RMF calculations
Yao et al., PRC91, 024316 (2015)

$$T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+) \sim 10^{18}\text{–}10^{22}\ \mathrm{y}$$

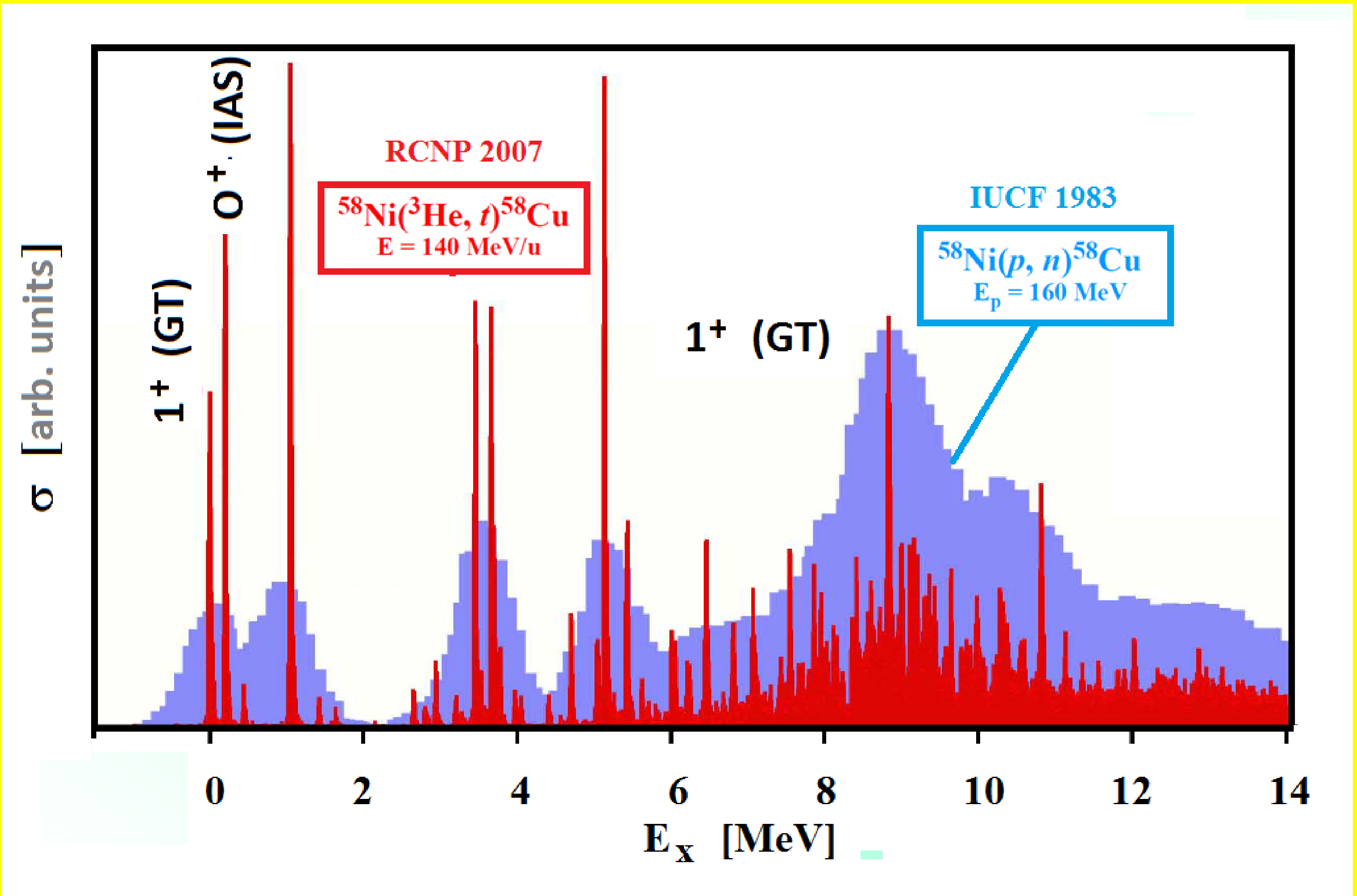
Experimental Constraints on the Majorana ν Mass



L. Barea et al., PRL 109, 042501 (2012)

Light Ions as Probes for Nuclear β-Matrix Elements

Progress in 35 Years of Nuclear Single Charge Exchange (SCE) Physics with Light Ions



Nuclear SCE Reactions and Spectroscopy
(Taddeucci, Rapaport et al. NPA469 (1987) 125)

$$\sigma = \frac{E_i E_f}{(2\pi\hbar^2 c^2)^2} \frac{k_f}{k_i} \frac{1}{2} \hat{J}_i^{-2} \sum |T(M_F M_I m_p m_n)|^2$$

$$T^{DW} = \langle \chi_f^{(-)} | (\boldsymbol{r}, \boldsymbol{k}_f) \langle n, \Phi_F | \sum t_{ip} | \Phi_I, p \rangle | \chi_i^{(+)} (\boldsymbol{r}, \boldsymbol{k}_i) \rangle$$
$$= \int d^3 q\, t(q) \rho_{ST}(q) d(q, k_i, k_f)$$

Nuclear and Reaction Transition Densities

$$\rho_{ST}(q) = \langle \Phi_F | \sum O_i(ST)\, e^{iq \cdot r_i} | \Phi_I \rangle \cdot \langle n | O_p(ST) | p \rangle$$
$$d(q, k_i, k_f) = \frac{1}{(2\pi)^3} \int d^3 r\, \chi_f^{(-)*}(\boldsymbol{r}, \boldsymbol{k}_f) \chi_i^{(+)}(\boldsymbol{r}, \boldsymbol{k}_i)\, e^{-iq \cdot r}$$

$$O(ST) = \begin{cases} \boldsymbol{\sigma\tau} & S=1, \quad T=1 \quad (\mathrm{GT}) \\ \boldsymbol{\tau} & S=0, \quad T=1 \quad (\mathrm{F}), \end{cases}$$

SCE Cross Sections and Nuclear Transition Probability

$$\rho_{ST}^{(\ell)}(q) \underset{q\to 0}{\rightarrow} \frac{q^{\ell} Y_{\ell m}^{\dagger}(\hat{q})}{(2\ell+1)!!} \langle \Phi_F | O_{ST}^{\dagger} r^{\ell} i^{\ell} Y_{\ell m}(\hat{r}) | \Phi_I \rangle \langle n | O_{ST} | p \rangle + O(q^{\ell+2})$$

$$B_{ST}^{(\ell)}(i \rightarrow f) \sim \left| \langle \Phi_F \| O_{ST}^{\dagger} r^{\ell} i^{\ell} Y_{\ell}(\hat{r}) \| \Phi_I \rangle \right|^2$$

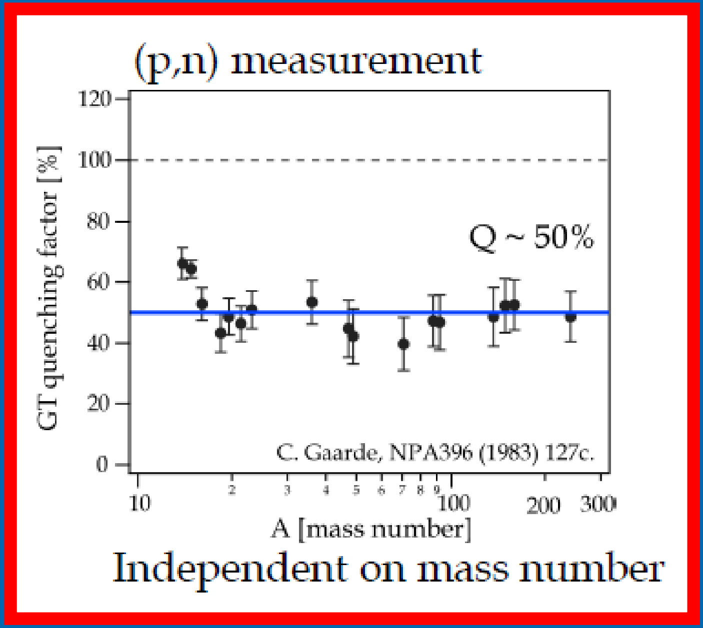
$$d(q, k_i, k_f) = \delta^3 \left(k_i - k_f - q \right) N_A(k_i, k_f)$$

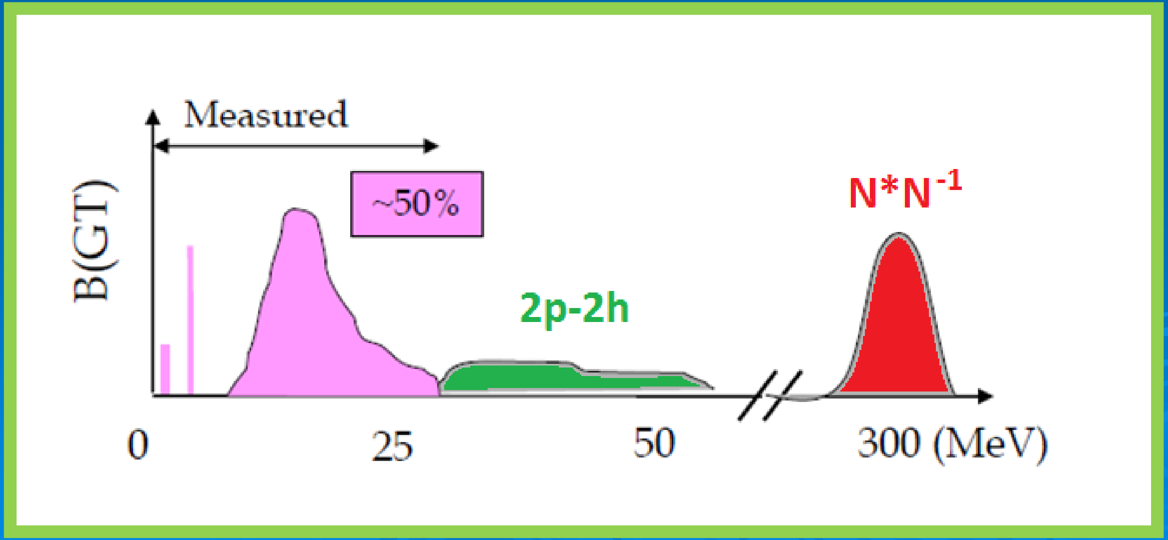
$$T^{\mathrm{DW}} = \int \mathrm{d}^3 q \, t(q) \rho_{ST}(q) d(q, k_i, k_f)$$

$$\left[\frac{(2\ell+1)!!}{p^{\ell}} \right]^2 \sigma_{\ell ST}^{DW}\left(k_i, k_f \right) \sim B_{ST}^{(\ell)}(i \rightarrow f) \left| t_{ST}(p) N_A \right|^2 \left| F_{ST}^{(A,\ell)}(p) \right|^2_{|p=k_i-k_f} + O(p^2)$$

$$\underset{p\to 0}{\rightarrow} B_{ST}^{(\ell)}(i \rightarrow f) \left| t_{ST}(0) N_A \right|^2$$

The GT-Quenching Problem:
50% of the *Ikeda Sum Rule* is missing

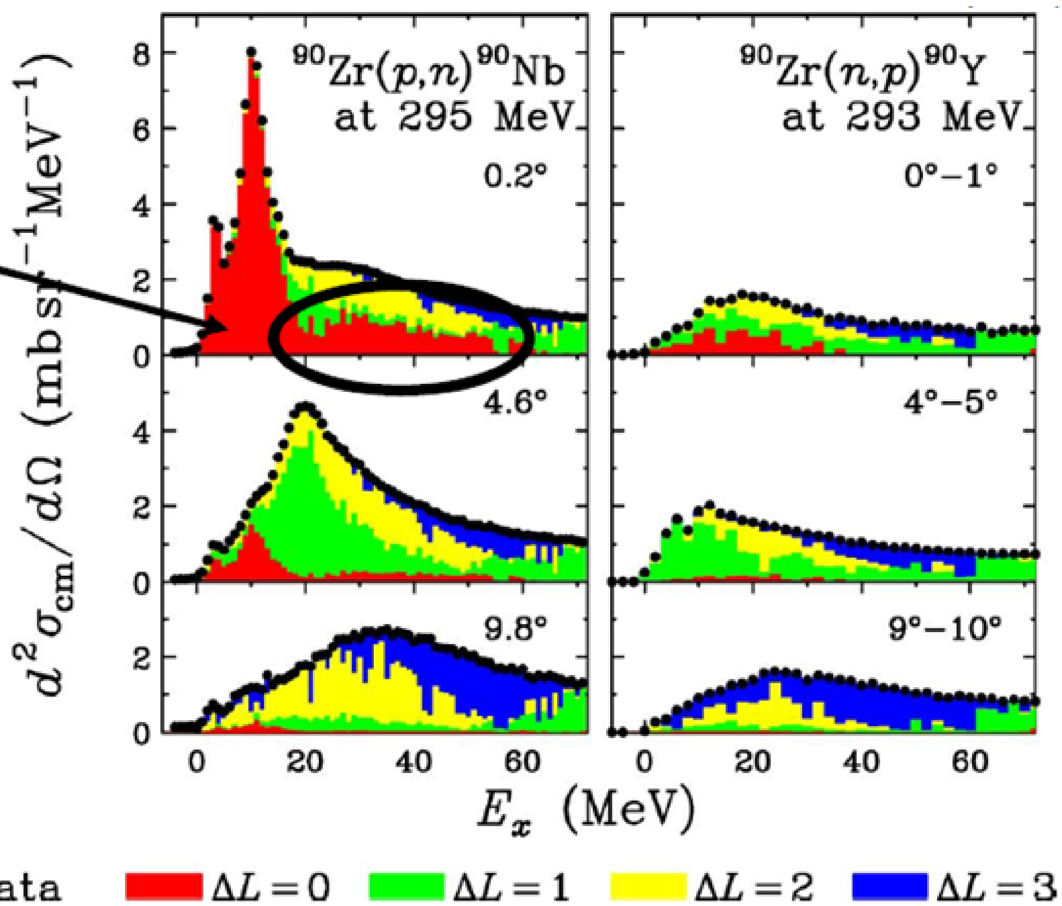




Investigating the GT-Quenching Problem at RCNP@Osaka

GT strength in continuum region

2p2h excitation



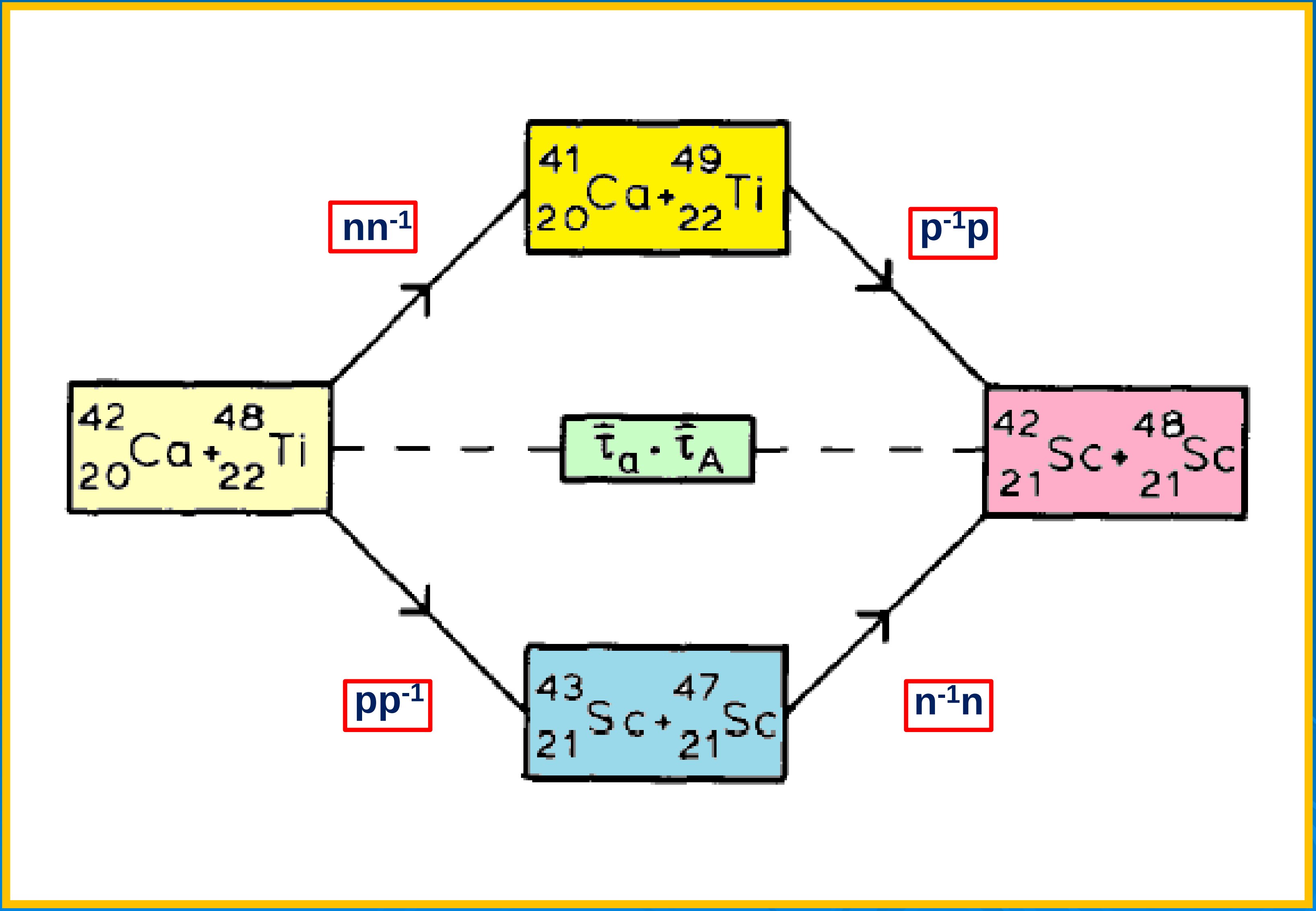
Main part of missing GT strength has been observed up to 50 MeV.

→ 2p2h excitation was found to be a main source of GT quenching.

M. Ichimura, H. Sakai and T. Wakasa, PPNP. 56, 446 (2006).

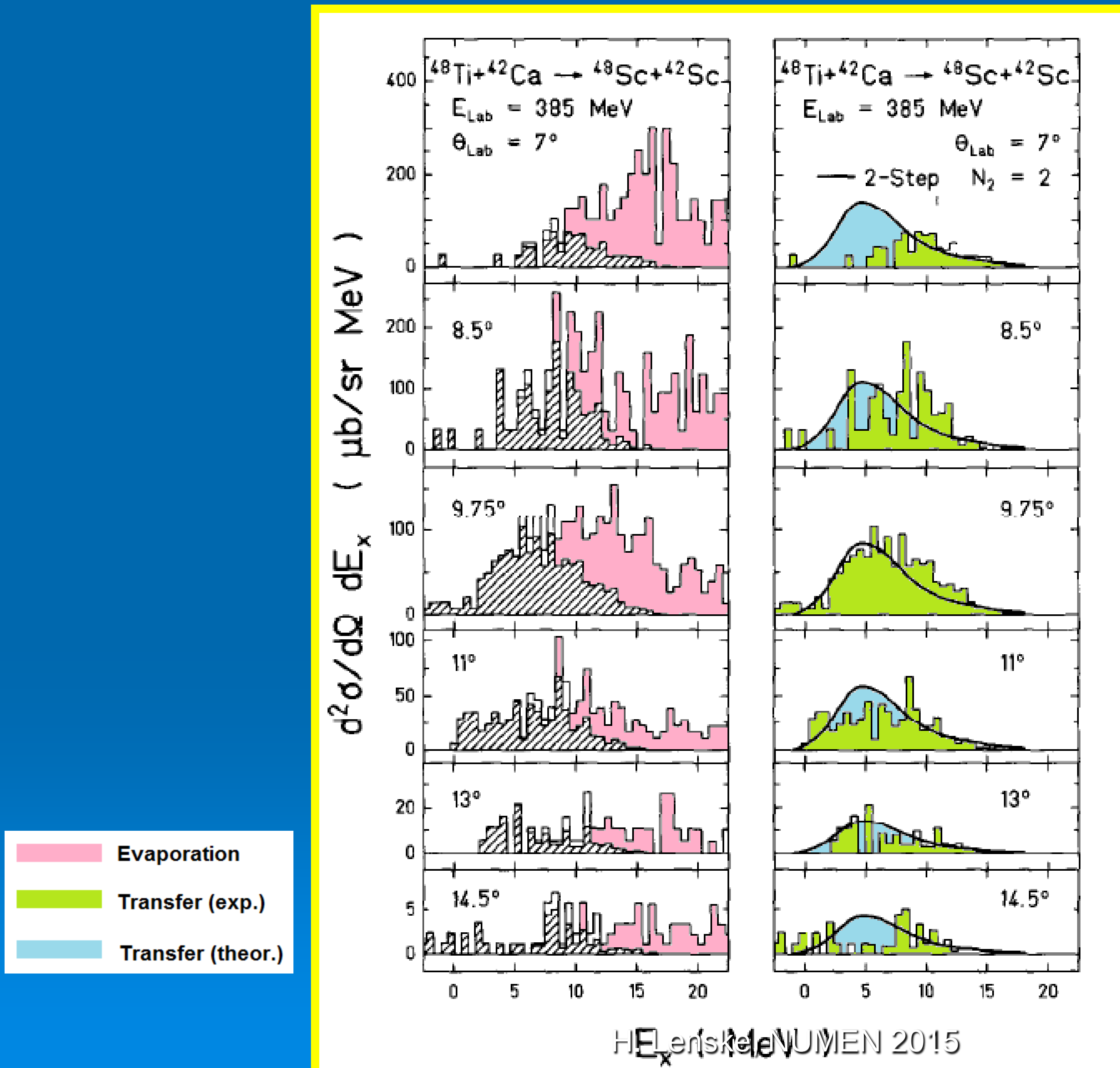
Heavy Ion Single Charge Exchange at the Coulomb-Barrier

Heavy Ion Single Charge Exchange Dynamics:
1-Step Direct and 2-Step Transfer Sequential Charge Exchange



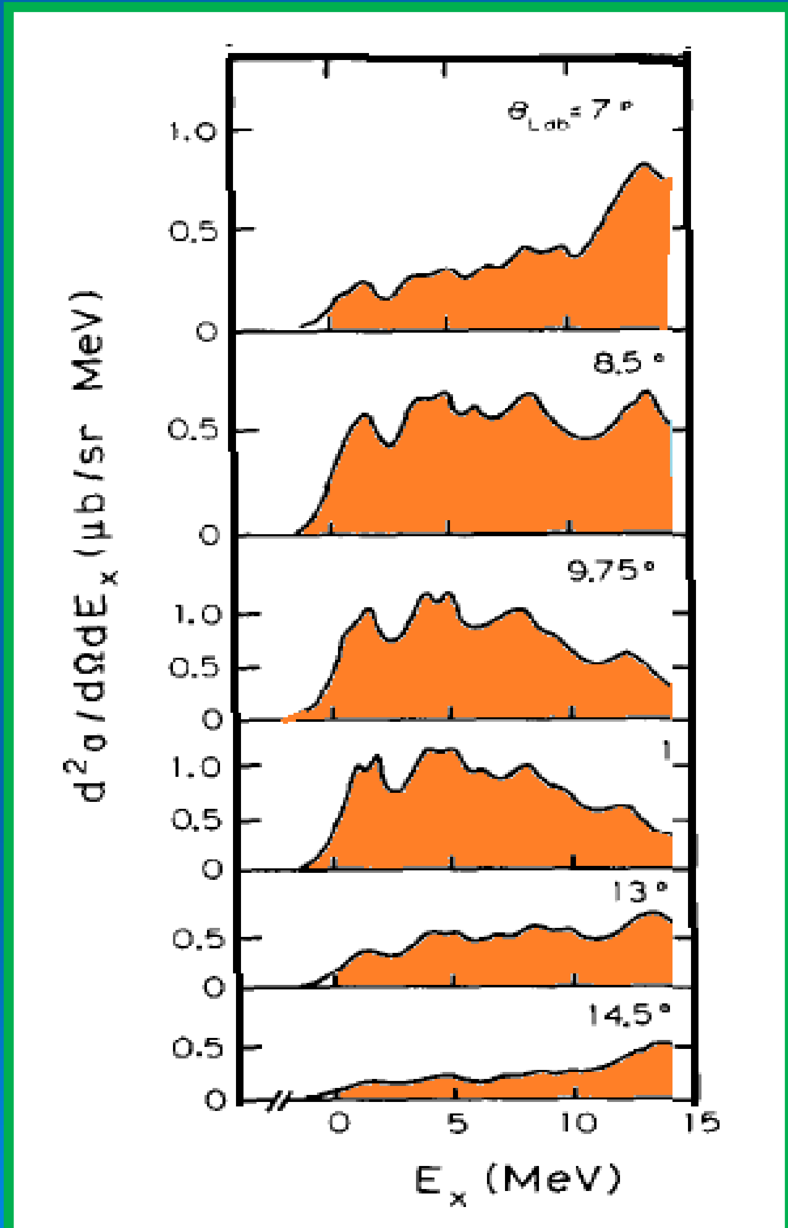
C. Brendel, H.L. *et al.*, Nuclear Physics A477 (1988) 162

Sequential Transfer Charge Exchange Contributions



- **HFB energies, wave functions, spectroscopic amplitudes**
- **2-Step (non-local) EFR-DWA**
- **Statistical model for neutron evaporation from inermediate nuclei**

1-Step Direct Charge Exchange Contribution



$^{42}Ca(^{48}Ti,^{48}Sc)^{42}Sc$

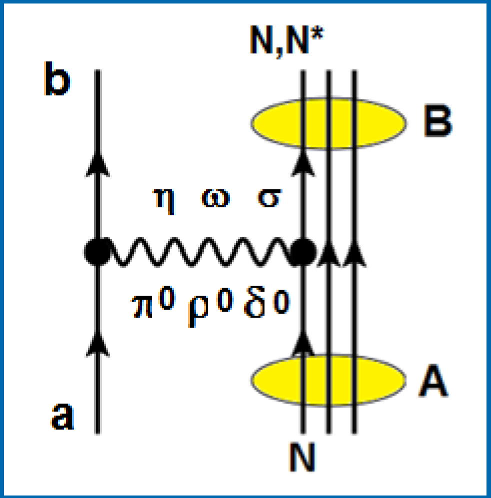
E_{Lab}=385MeV

1% contribution!
→ Transfer kinematically favored

- **HFB+QRPA**
- **Fermi and Gamow-Teller-type Response Functions for $J^{\pi}=0^{\pm}\ldots6^{\pm}$**
- **DWBA calculations**
- **Empirical Optical Potentials**
- **Microscopic Form Factors**

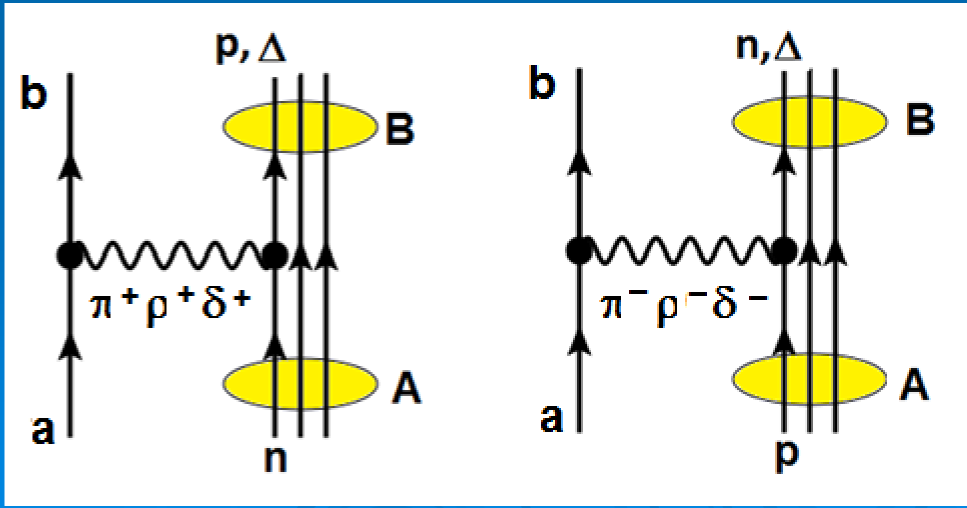
Interactions in Heavy Ion SCE Reactions

Inelastic Reactions:
Quasi-elastic Excitation of Nuclear States



$$\left\{1_\sigma, \vec{\sigma}\right\} \otimes \left\{1_\tau, \tau^0\right\}$$

Charge Exchange Reactions:
Δq=±1 Excitation of Fermi- (Jπ=0+,1-…) and GT- (Jπ=0-,1+…) type States



$$\left\{1, \vec{\sigma}\right\} \otimes \tau^{\pm}$$

Probing Charged-Current (CC) Response by Nuclear Reactions

$$V_{NN} \sim V_{01}\left(q^2\right)\tau_1\cdot\tau_2 + V_{11}\left(q^2\right)\sigma_1\cdot\sigma_2\;\;\tau_1\cdot\tau_2 + V_{T1}\left(q^2\right)S_{12}\;\;\tau_1\cdot\tau_2$$

$$S_{12} = \frac{1}{q^2}\left[3\sigma_1\cdot\vec{q}\,\sigma_2\cdot\vec{q} - \sigma_1\cdot\sigma_2 q^2\right]$$

SCE-Reaction Amplitude a(z,n)+A(Z,N) → b(z',n')+B(Z',N')

$$M_{\alpha\beta}(\mathrm{aA}\rightarrow\mathrm{bB}) \sim$$

$$\int\frac{d^3q}{(2\pi)^3}V_{11}(q^2)\left\langle\chi_\beta^{(-)}\middle|\mathrm{e}^{i\vec{q}\cdot\vec{x}_{aA}}\middle|\chi_\alpha^{(+)}\right\rangle\left\{\left\langle b\,|\,\mathrm{e}^{i\vec{q}\cdot\vec{x}_a}\;\sigma\tau_\pm\,|\,a\right\rangle\left\langle \mathrm{B}\,|\,\mathrm{e}^{-i\vec{q}\cdot\vec{x}_A}\;\sigma\tau_\mp\,|\,A\right\rangle + V_{T1}\ldots\right\}$$

(p,n) or (n,p) $\rightarrow$ GT

$$M(GT^\pm) \propto \left|\left\langle f\left\|\frac{\sigma}{2}\cdot\tau_\pm\right\|i\right\rangle\right|^2$$

Hadronic Tensor in CC Reactions:

$$d\sigma \sim \sum_{bB} \left| M_{aA\to bB}(\omega,\vec{q}) \right|^2 = \sum_{\mu\nu} W_{a,\mu\nu}(\omega,\vec{q}) W_A^{\mu\nu}(\omega,\vec{q})$$

Hadronic Tensor:

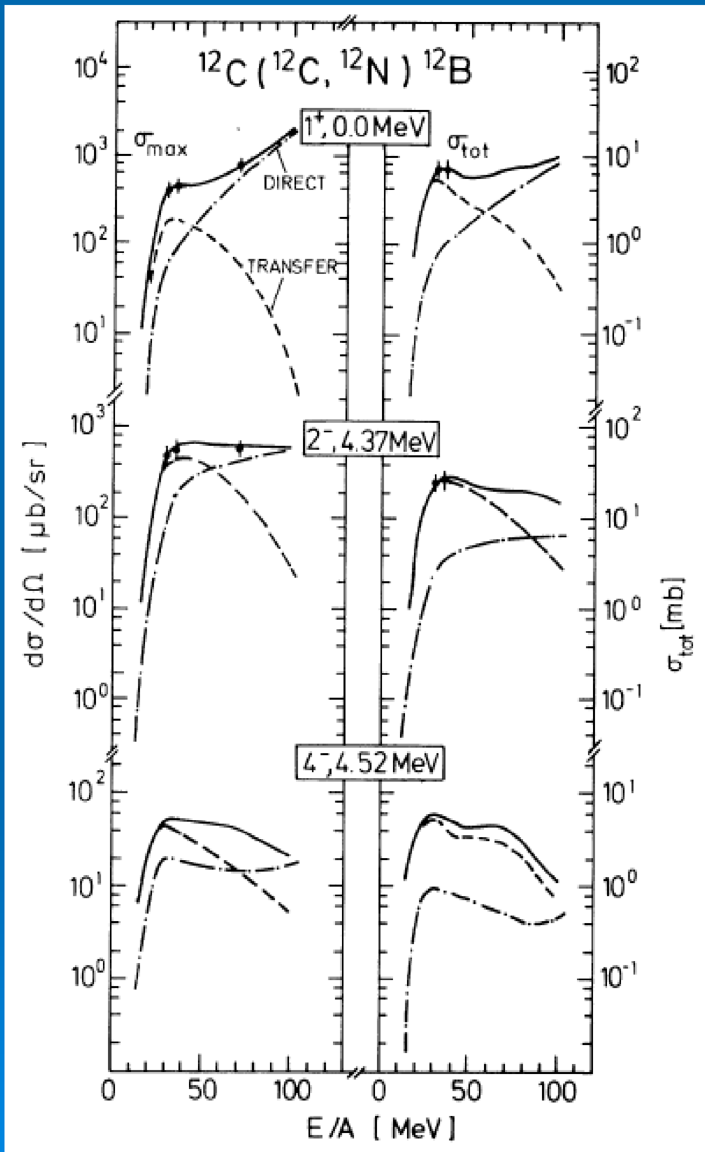
$$W_X^{\mu\nu}(\omega,\vec{q}) = \sum_Y T_{XY}^{\mu}(\omega,\vec{q}) T_{XY}^{\nu}(\omega,\vec{q}) = -\frac{1}{\pi} \mathrm{Im}\left(\left\langle X \left| T^{\dagger\mu} G_X(\omega,\vec{q}) T^{\nu} \right| X \right\rangle \right)$$

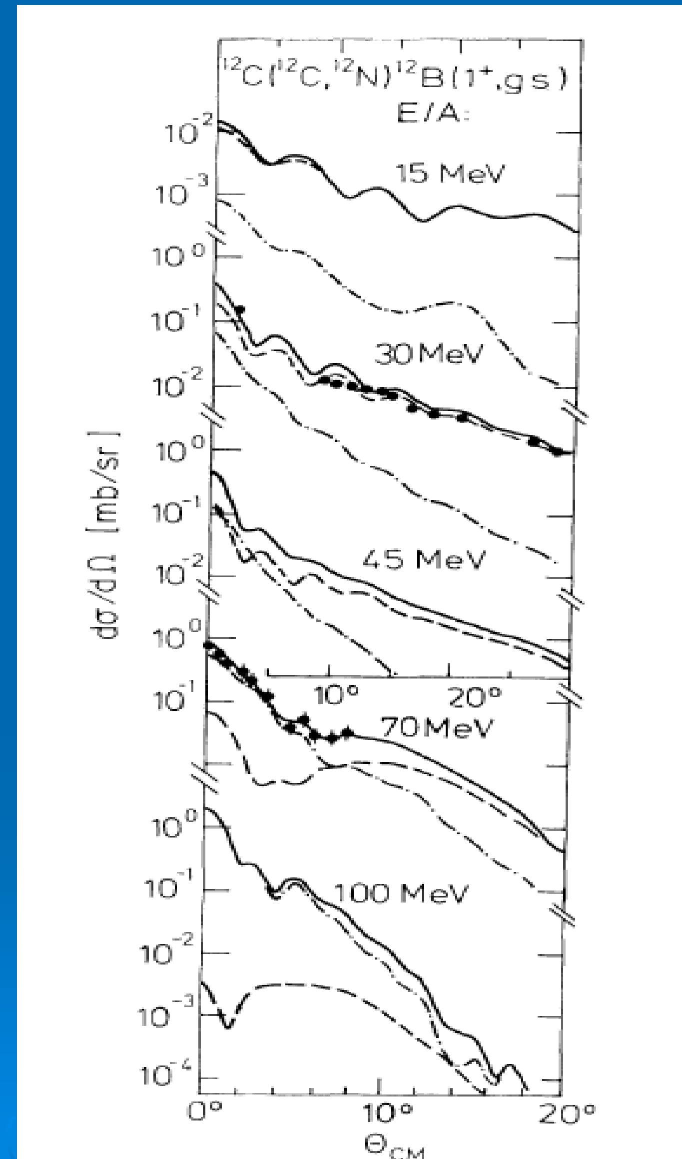
Factorization into Transition Form Factors and Response Functions (Polarization Tensor):

$$W_X^{\mu\nu}(\omega,\vec{q}) \sim \left| F_X(\vec{q}) \right|^2 R^{\mu\nu}(\omega,\vec{q})$$

SCE Reaction Mechanism

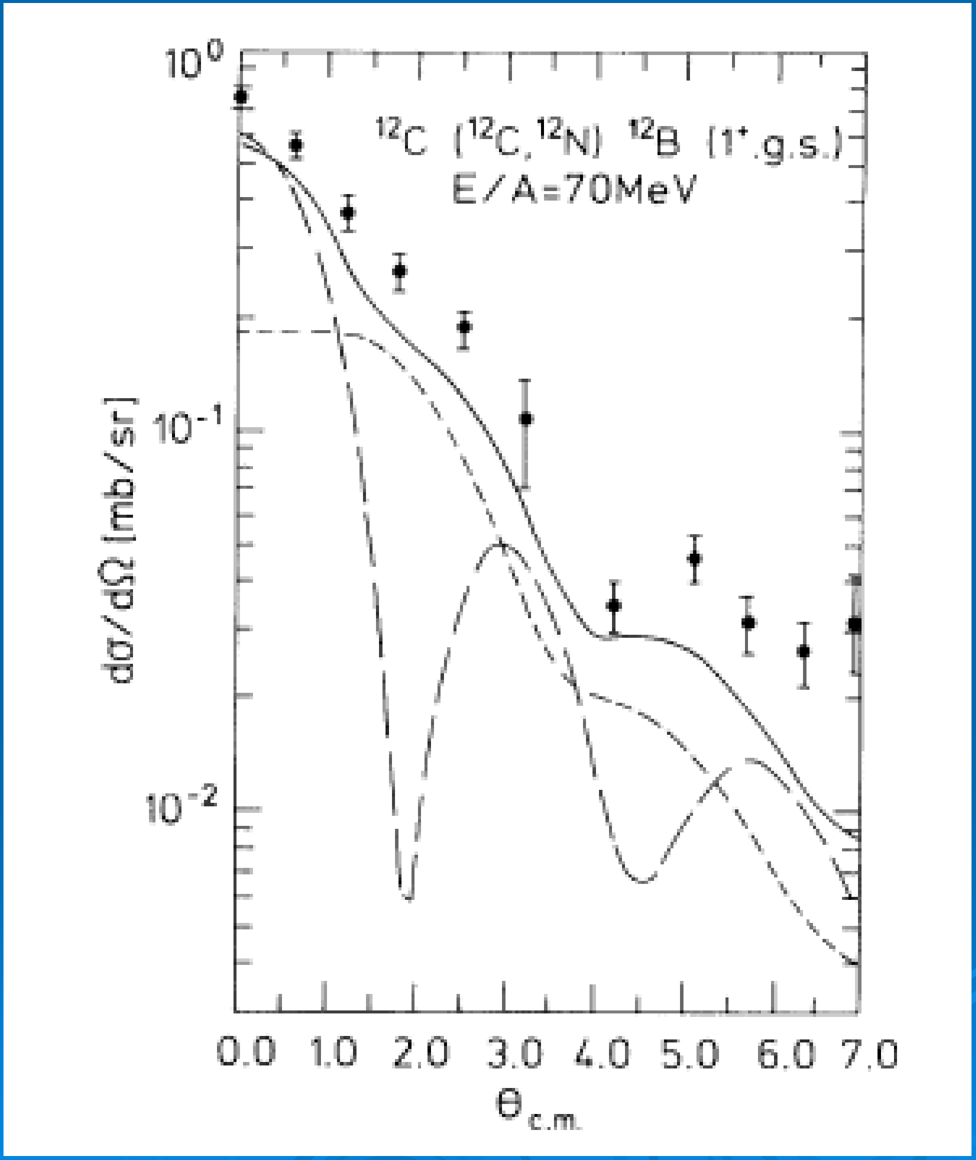
1-step Direct and 2-step Transfer Dynamics





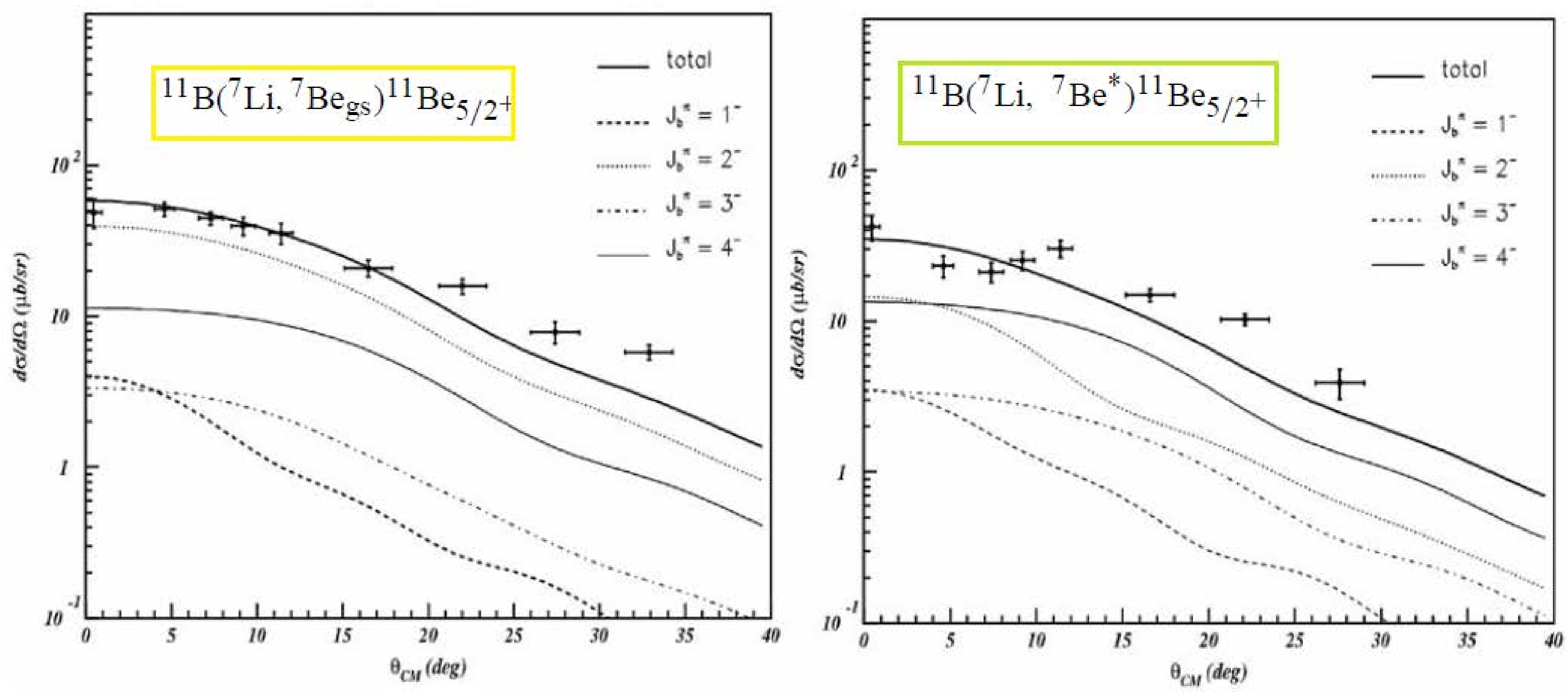
H. Lenske at al., Phys. Rev. Lett. 62, 1457 (1989

SCE Reaction Mechanism:
Rank-1 Central and Rank-2 Tensor Interaction



H. Lenske at al., Phys. Rev. Lett. 62, 1457 (1989

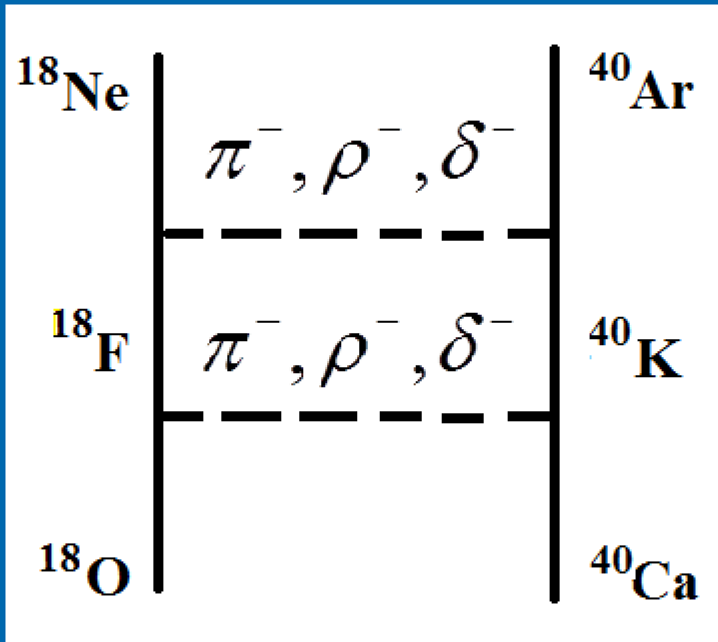
(^{7}Li, ^{7}Be) SCE Reaction@E_{lab}=8AMeV:
Dominance of direct *collisional* SCE
HFB-QRPA and DWBA



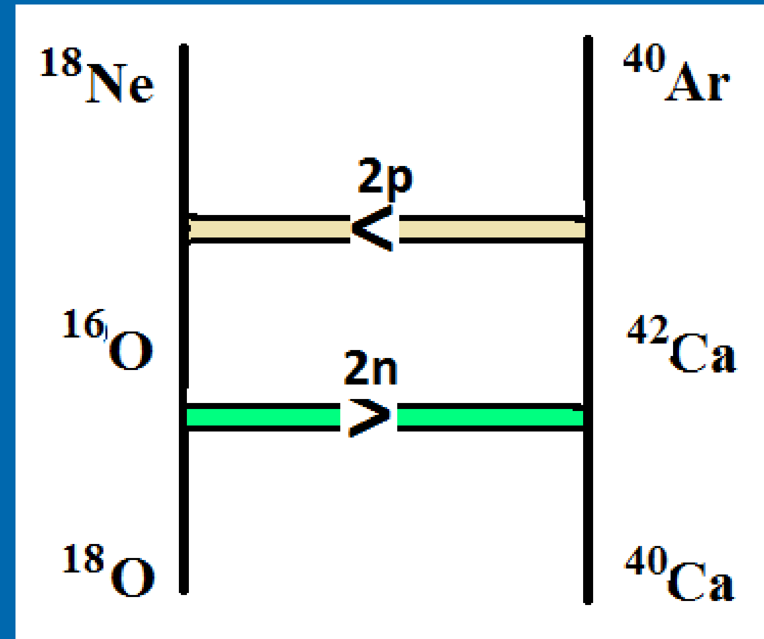
F. Cappuzzello, H.L. et al., NPA 739 (2004) 30

Heavy Ion Double Charge Exchange Reactions

Dynamics of Heavy Ion DCE Reactions



Collisional „hard“ process via NN-interaction



Mean-field „soft“ process via NA-potential

Operator Structure:

$$\left[a_p^+ a_n\right]_a \left[c_n^+ c_p\right]_A + \left[a_p^+ a_n\right]_a \left[c_n^+ c_p\right]_A$$

Operator Structure:

$$\left[a_n a_n\right]_a \left[c_n^+ c_n^+\right]_A + \left[a_p^+ a_p^+\right]_a \left[c_p c_p\right]_A$$

→ solvable as a 2-step scattering problem

Reduction of the *collisional* DCE T-Matrix

$$T^{DCE}_{aA,bB} = \sum_{\gamma=cC} \int \frac{d^3k_\gamma}{(2\pi)^3} T^{SCE}_{bB,cC}(k_\beta, k_\gamma) G_{\gamma,cC}(k_\gamma) \tilde{T}^{SCE}_{cC,aA}(k_\gamma, k_\alpha)$$

$$M^{\mathrm{GT}}_{\beta\beta} = \sum_N \langle 0^+_F || \tau^+ \vec{\sigma} || 1^+_N \rangle G_N \langle 1^+_N || \tau^+ \vec{\sigma} || 0^+_I \rangle$$

Fourier-Transformation Techniques:

$$T^{SCE}_{bB,cC}(k_\beta, k_\gamma) = \left\langle bB, k^{(-)}_\beta \right| t_{ST} O^{(1)}_{ST} O^{\dagger(2)}_{ST} \left| cC, k^{(+)}_\gamma \right\rangle = M^{(bc)}_{ST} M^{(BC)}_{ST} \overline{T}^{SCE}_{bB,cC}(k_\beta, k_\gamma)$$

Nuclear Matrix Element:

$$M^{(BC)}_{ST} = \left\langle B \right| O_{ST} r^\ell Y_{\ell m} \left| C \right\rangle$$

Reduced "*Unit Strength*" Multipole T-matrix:

$$\overline{T}^{SCE}_{bB,cC}(k_\beta, k_\gamma) \cong N_{\beta\gamma}(k_\beta, k_\gamma) t_{ST}(p) F^{(bc)}_{ST}(p) F^{(BC)}_{ST}(p)_{|p=k_\gamma - k_\beta}$$

The Nuclear Matrix Element

- **Green's Function:**

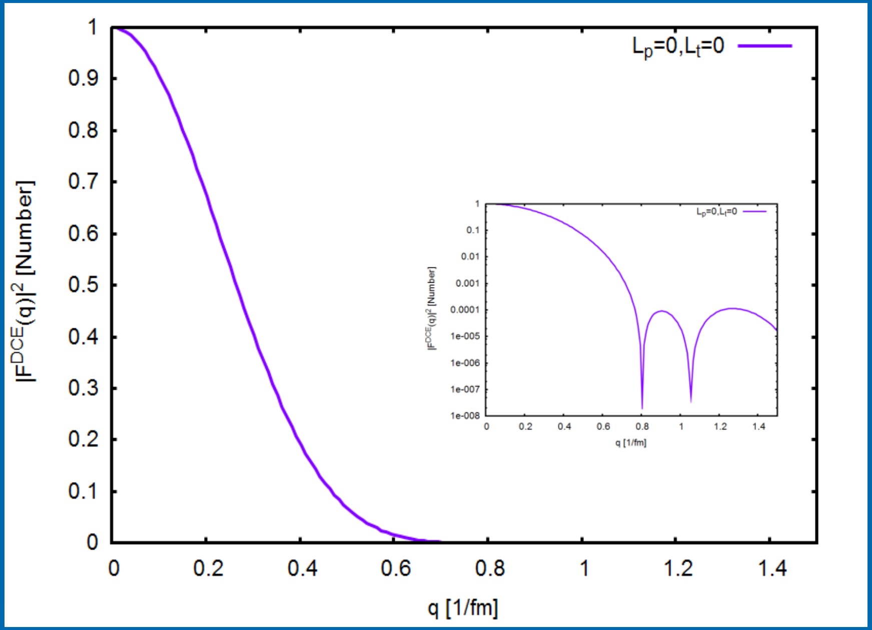
$$G_{\gamma,cC}\left(k_\gamma\right)=\frac{1}{(M_a+M_A)-(M_c+M_C)+T_{aA}-T_{cC}+i\eta}\sim G_{cC}\left(M_a+M_A\right)/\left(1+\frac{\partial T_{cm}}{\partial M}_{|a+A}\right)$$

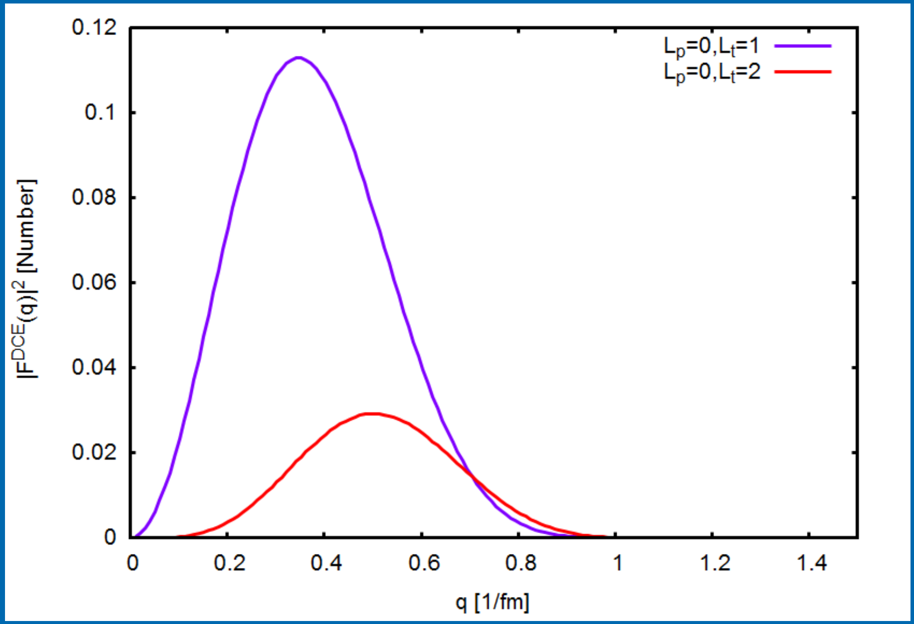
$$G_{cC}\left(\omega\right)=\frac{1}{\omega-M_c+M_C+i\eta}$$

- **Double-Charge Exchange NME (α,β~ST):**

$$M^{DCE}_{ba,BA}=\sum_{cC}M^{bc}_{\beta}M^{BC}_{\beta}G_{cC}\left(\omega\right)M^{ca}_{\alpha}M^{CA}_{\alpha}{}_{|\omega=M_a+M_A}$$

The reduced *unit* SCE T-matrix/Cross Section $^{18}O+^{40}Ca$



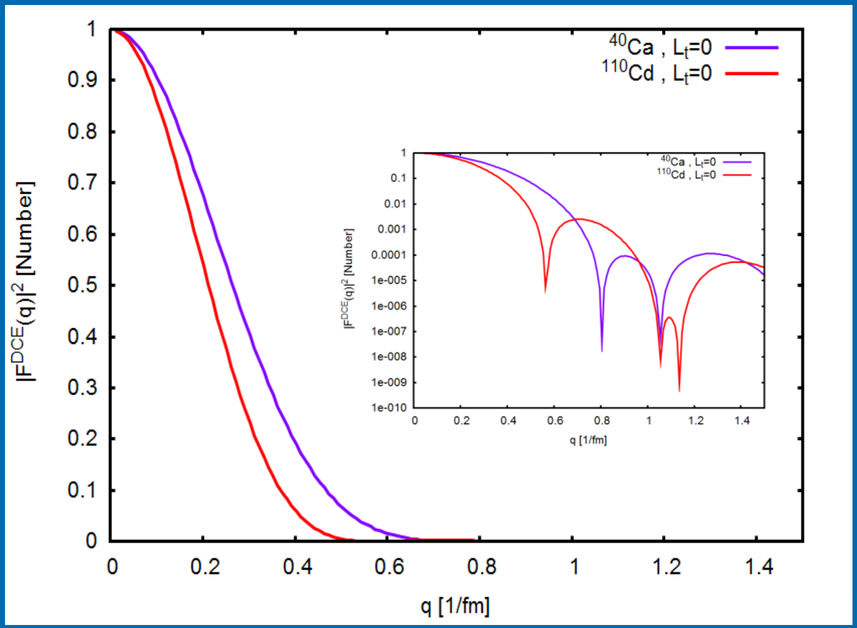


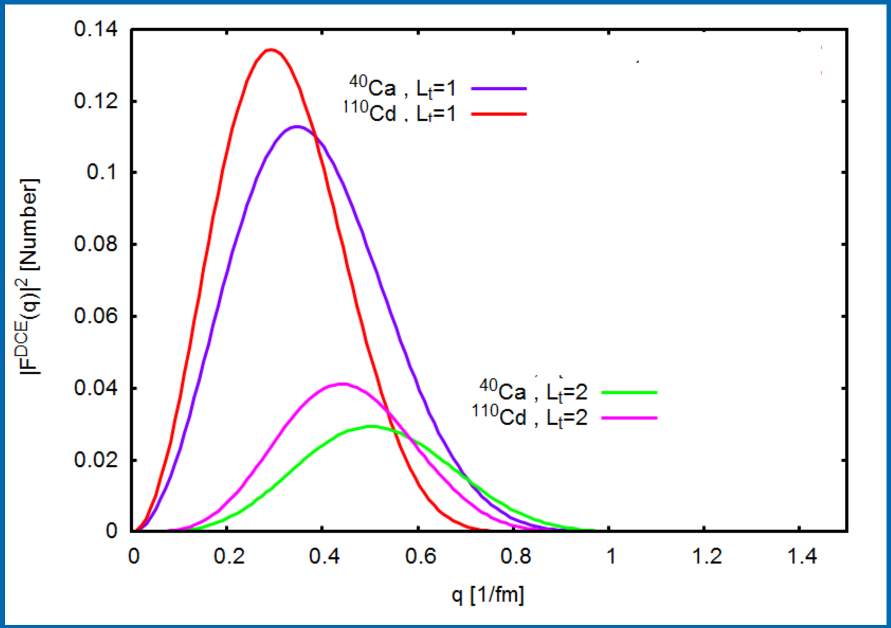
Angular Momentum Transfer
$\ell_p=0$, $\ell_t=0$

Angular Momentum Transfer
$\ell_p=0$, $\ell_t=1,2$

- **Dominance of low angular momentum transfer at q~0**
- **Angular Focussing: narrow range of momentum transfers**

The reduced *unit* SCE Cross Section
$^{18}O + ^{110}Cd \rightarrow ^{18}Ne + ^{110}Pd$ vs. $^{18}O + ^{40}Ca \rightarrow ^{18}Ne + ^{40}Ar$





Angular Momentum Transfer
ℓ_p=0 , ℓ_t=0

Angular Momentum Transfer
ℓ_p=0 , ℓ_t=1,2

- **Width ~ $1/R^2(A) \sim A^{-2/3}$**
- **Shift to small momentum transfer with increasing A**

Heavy-Ion DCE cross section

$$T^{DCE}_{aA,bB} = M^{DCE}_{\chi\alpha}(\omega)\int d^3k \bar{T}^{SCE}_{ST}(k,k_\beta,k_\alpha)\bar{\tilde{T}}^{SCE}_{ST}(k,k_\beta,k_\alpha)$$

$$\bar{T}^{SCE}_{ST}(k,k_\beta,k_\alpha) = N(k,k_\beta)t_{ST}(q_1)F^{SCE}_{ST}(q_1)z(k_\alpha)_{|q_1=k-(k_\beta-k_\alpha)/2}$$

$$\bar{\tilde{T}}^{SCE}_{ST}(k,k_\beta,k_\alpha) = \tilde{N}(k,k_\alpha)t_{ST}(q_2)F^{SCE}_{ST}(q_2)z(k_\alpha)_{|q_2=k+(k_\beta-k_\alpha)/2}$$

$$T^{DCE}_{aA,bB} \sim M^{DCE}_{\chi\alpha}(\omega)\bar{T}^{SCE}_{ST}(k_\beta,k_\alpha)\bar{\tilde{T}}^{SCE}_{ST}(k_\beta,k_\alpha) f(q,R_a,R_A)$$

$$T^{DCE}_{aA,bB}(k_\beta,k_\alpha) = M^{DCE}_{aA,bB}(\omega)\bar{T}^{DCE}_{\beta\alpha}(k_\beta,k_\alpha)$$

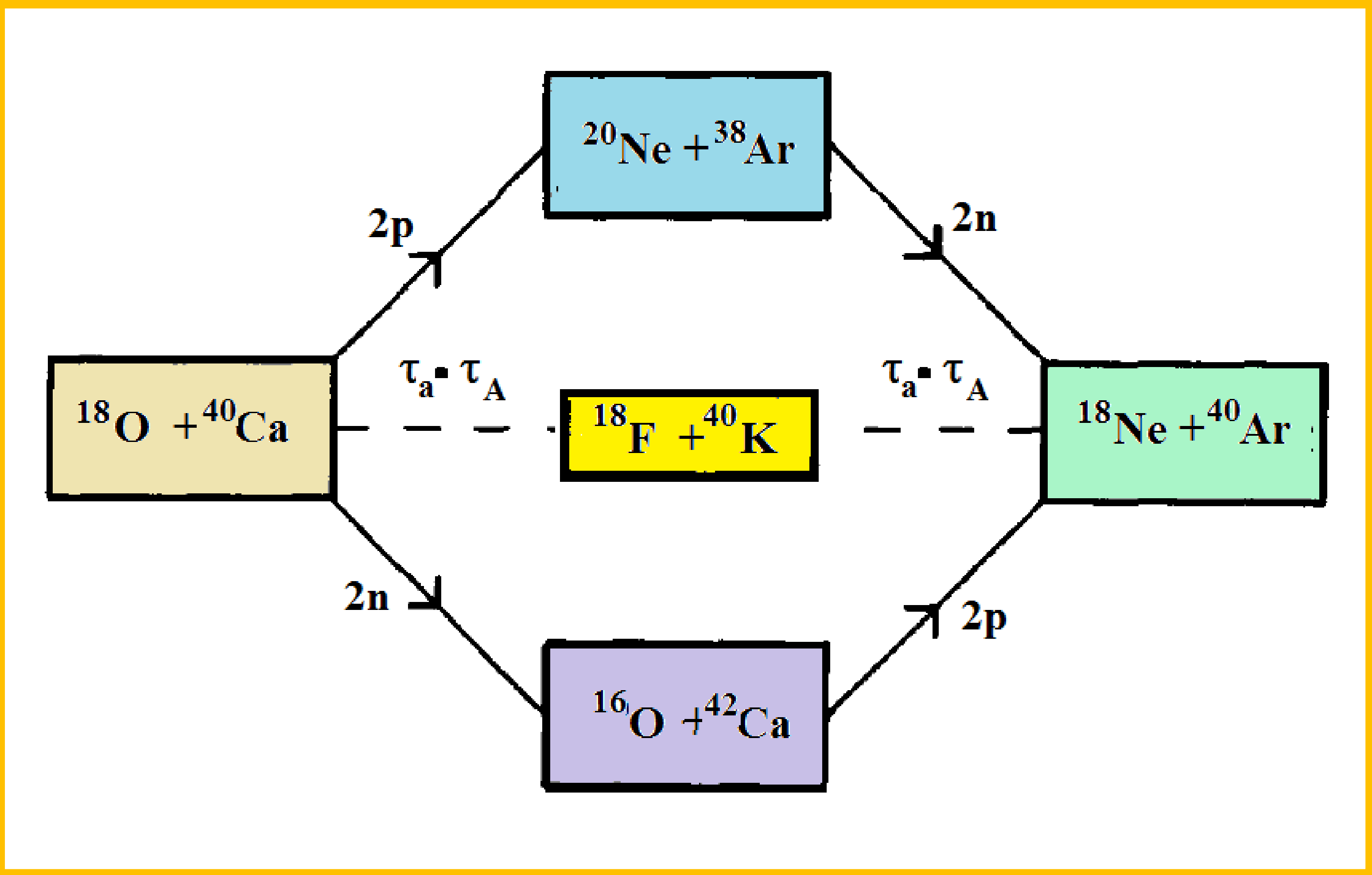
$$\sigma^{DCE}_{aA,bB} \sim \frac{k_\beta}{k_\alpha}\frac{1}{(2J_a+1)(2J_A+1)}\sum_{m_a m_b M_a M_b}\left|T^{DCE}_{aA,bB}(k_\beta,k_\alpha)\right|^2$$

$$\sigma^{DCE}_{aA,bB} = \sum_{S,S',T=1} M^{DCE}_{ST}(\omega)M^{*DCE}_{S'T'}(\omega)_{|\omega=M_a+M_A}\bar{\sigma}^{DCE}_{ST,S'T}$$

A Pilot Experiment

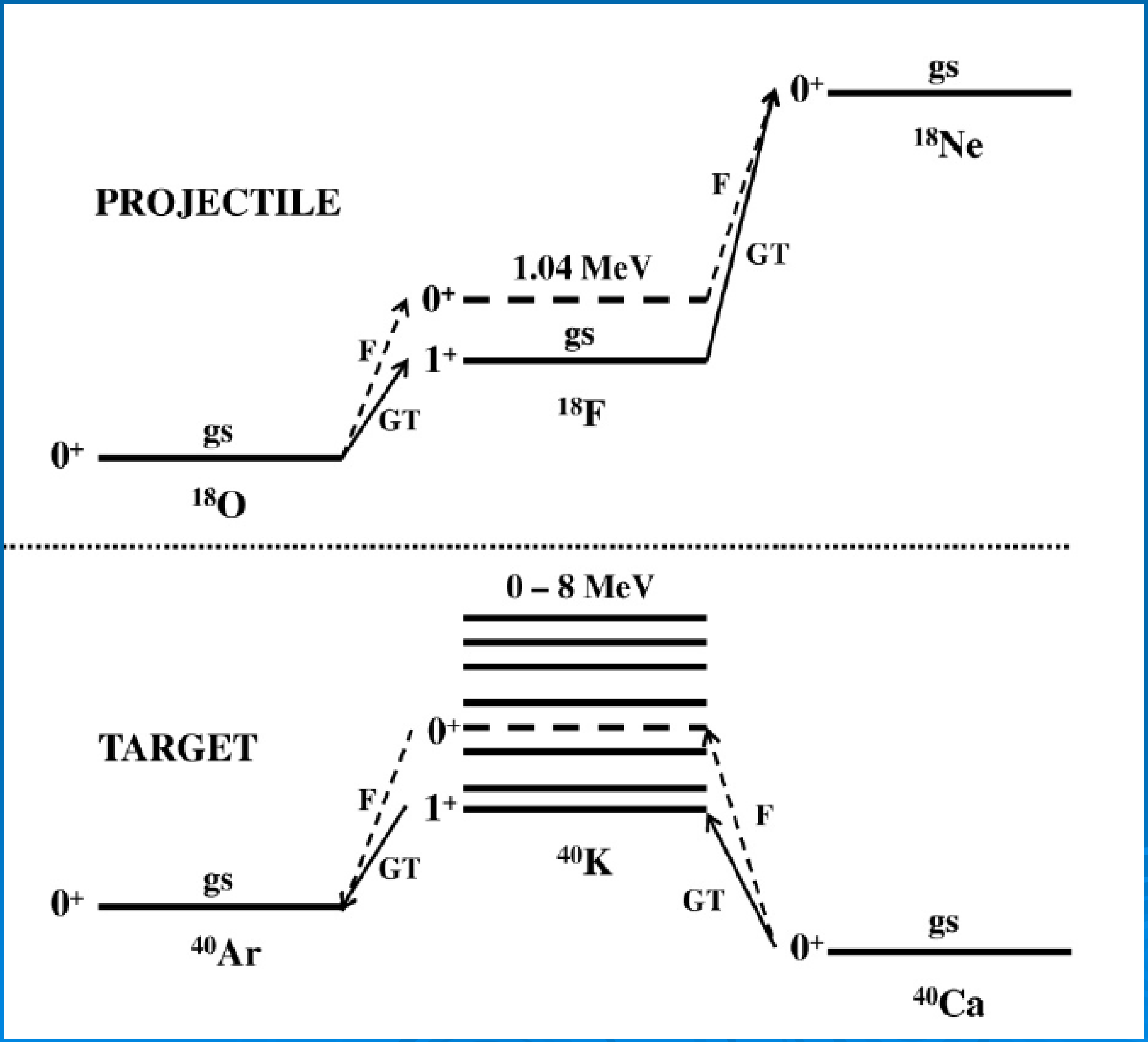
Heavy Ion Double Charge Exchange

$^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$

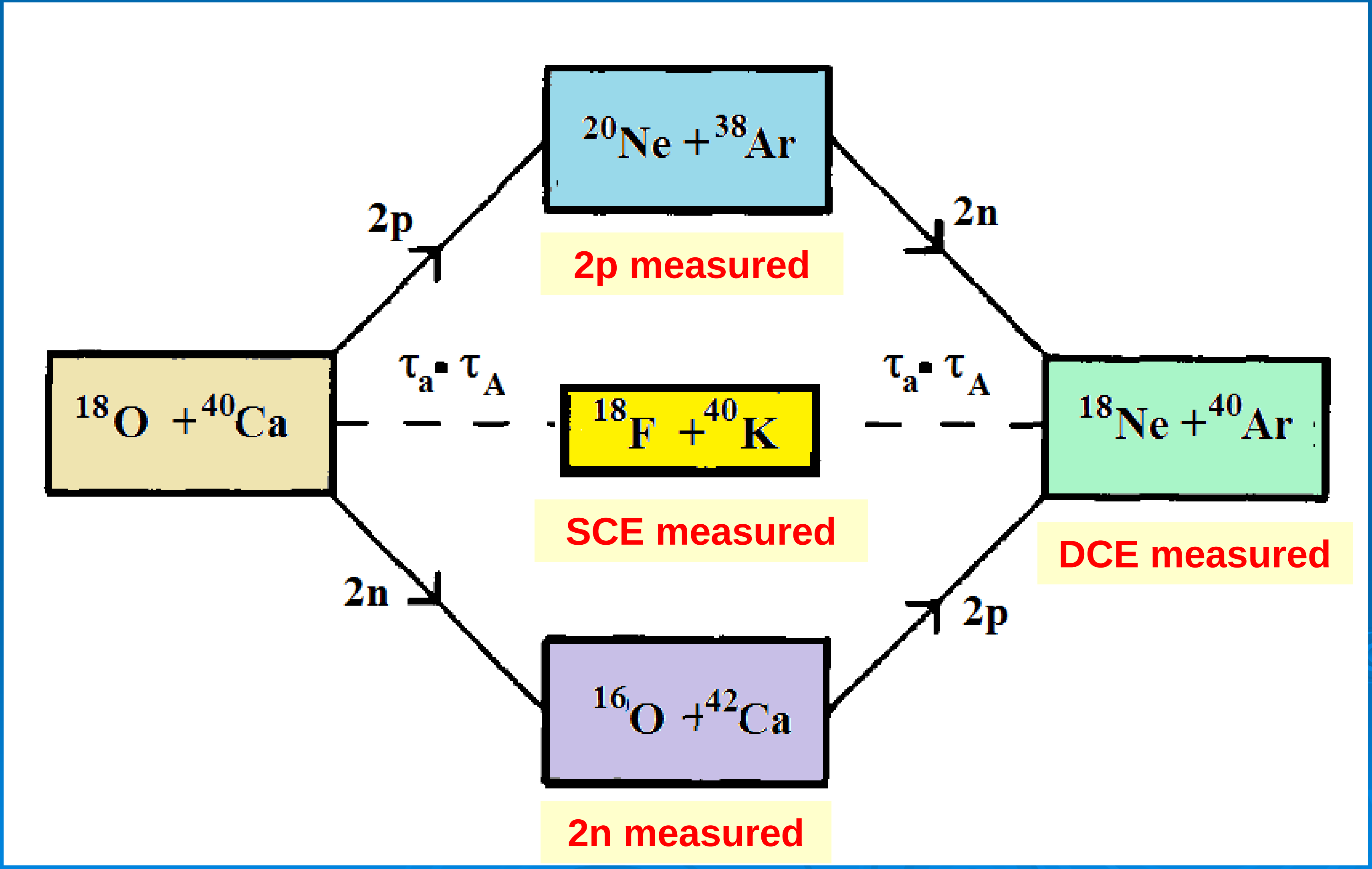


…transfer DCE suppressed by large Q_{opt}~50MeV

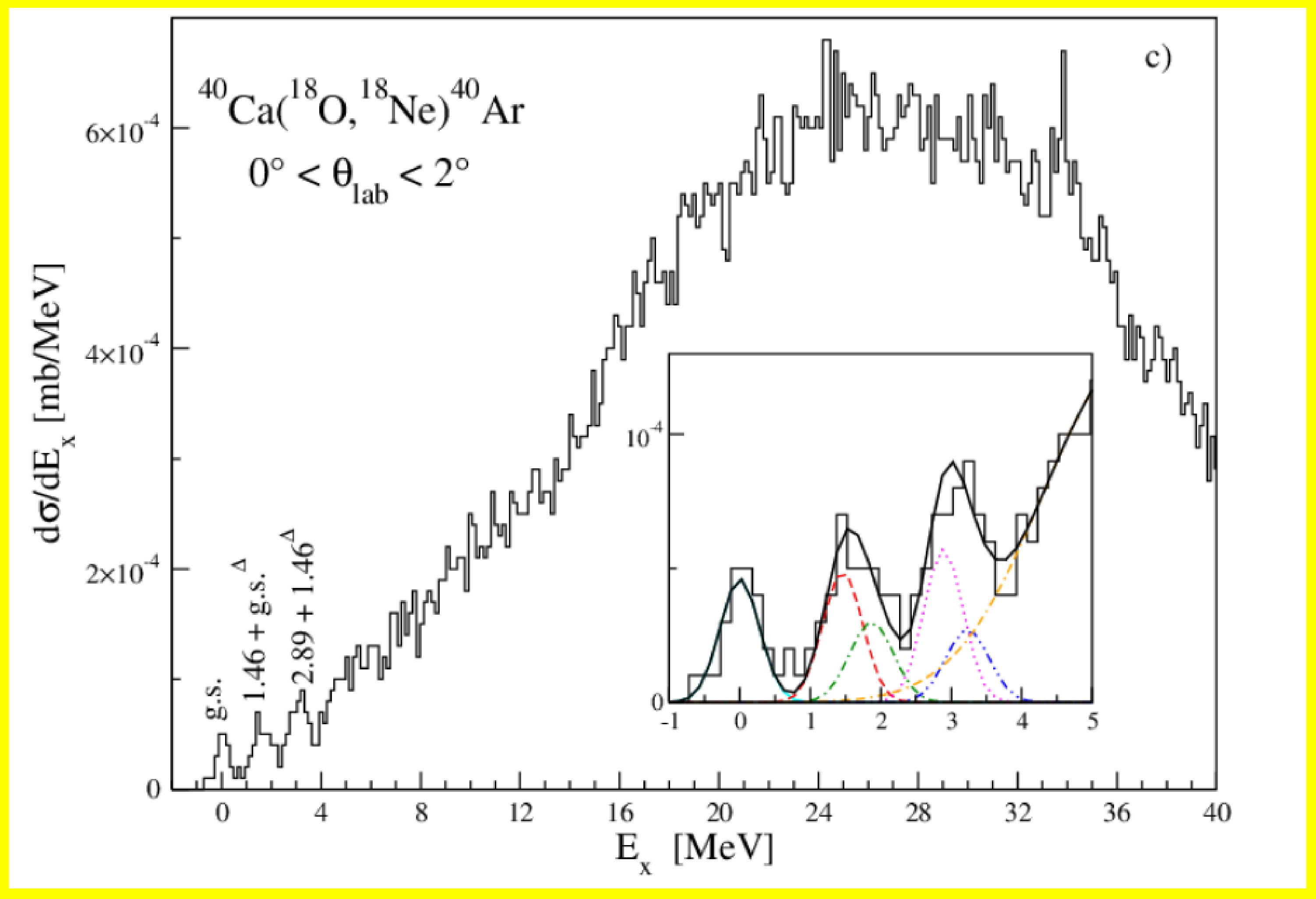
$^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$
DCE Level Scheme



Pilot DCE Experiment@LNS
$^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$ at 15AMeV

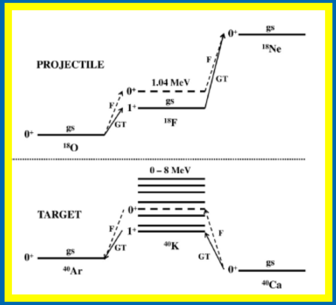


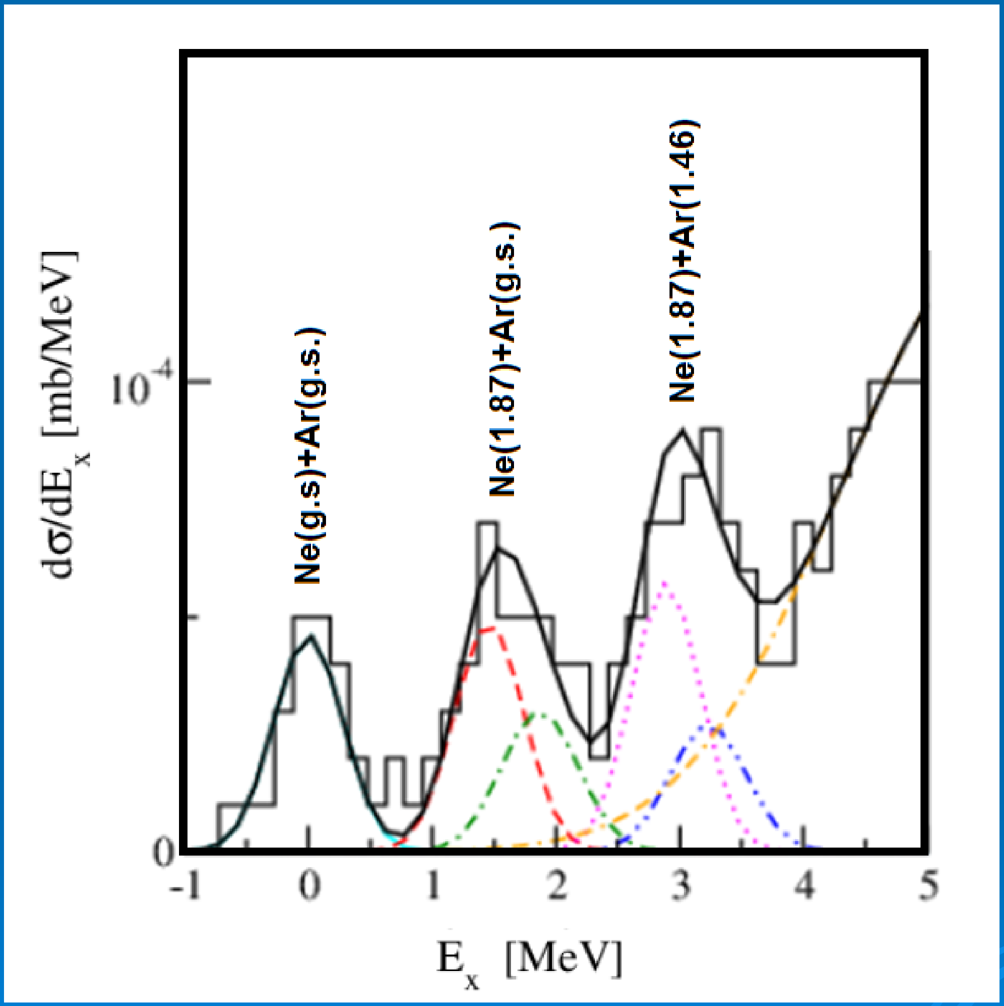
Demonstrator/Pilot-Experiment at LNS
$^{18}O + ^{40}Ca \rightarrow {}^{18}Ne + ^{40}Ar$ @ 15AMeV



$^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$ @ 15AMeV

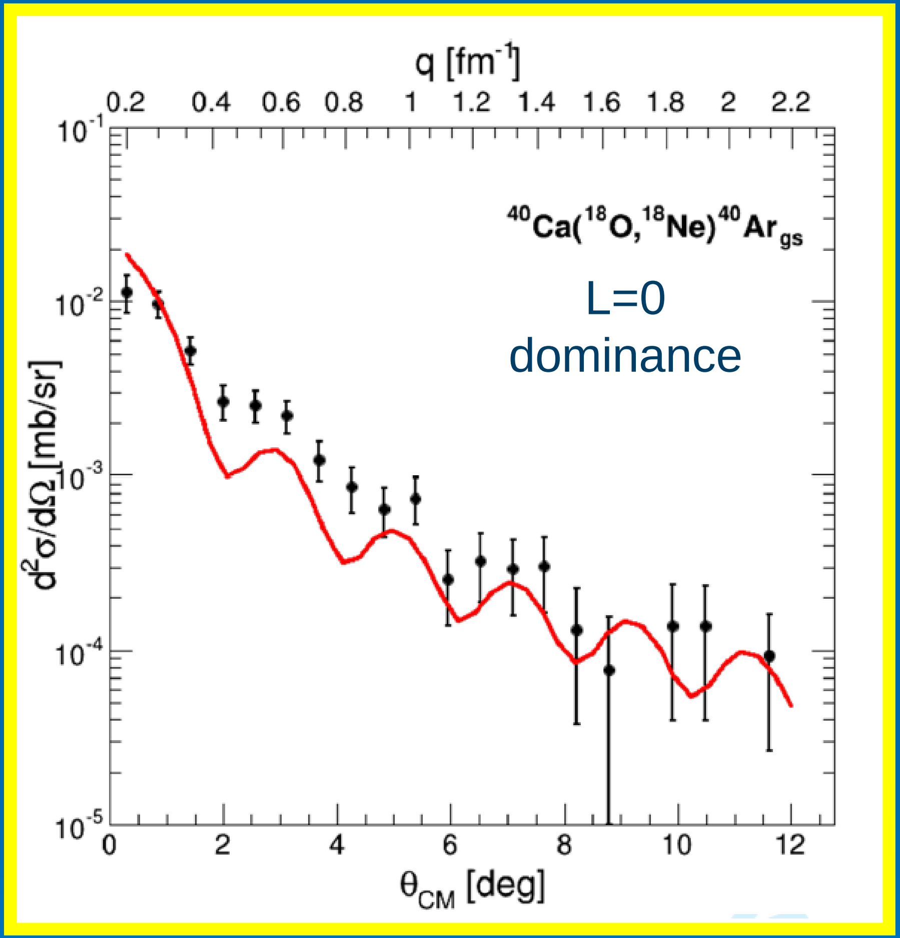
Spectral Analysis: resolving 6 components (!)





…plus (three) additional contributions through $^{18}F(1.04)$

Angular Distribution and Momentum Structure



- convincing energy (~500keV) and angle (~0.6°) resolution
- large range of momentum transfers – test of SRC!
- Dominance of collisional DCE

Derivation of „^{40}Ca-M(0νββ)“
(F. Cappuzzello et al., EPJ A, 2015)

Forward direction x-section and transition probabilities:

$$\frac{d\sigma}{d\Omega}(\theta = 0°, E_x = 0) = \hat{\sigma}^{DCE}_{GT}\, F^{DCE}_{GT}\, B(2GT) + \hat{\sigma}^{DCE}_{F}\, F^{DCE}_{F}\, B(2F)$$

Matrix elements:

$$M(0\nu\beta\beta;\, {}^{40}\mathrm{Ca}) = [(g_v/g_a)^2 M^{DCE}(FF) + M^{DCE}(GG)] = 0.62 \cdot 0.24 + 0.22 = 0.37 \pm 0.18$$

Comparison to ^{48}Ca:

$$M(0\nu\beta\beta;\, {}^{40}\mathrm{Ca}) = 7\, M(0\nu\beta\beta;\, {}^{40}\mathrm{Ca}) = 2.6 \pm 1.3$$

Recent EDF result:

$$M(0\nu\beta\beta;\, {}^{48}\mathrm{Ca}) = 2.370^{1.914}_{0.456}$$

(Vaquero et al., PRL 111, 142501 (2013)):

Proposal: *to-do-list* for future theory work at NUMEN

- Theory of DCE reactions and double-beta decay
- Reaction mechanism and dynamics of heavy ion DCE
- Ion-Ion ISI and FSI
- Interface to nuclear structure input:
    - transition densities and response functions/matrix elements
    - In-medium T_{NN} and Form factors
- Short range correlations
- Large scale numerical simulations of HI SCE and DCE reactions
- Quenching problem in DCE!?

In historical roman religion:
„Numen“ (lat. *numen* Plural: *numina) means*
„behest, will, divine spirit“ of a figurative godhead