Probing Beta-Decay by Heavy Ion Charge Exchange Reactions

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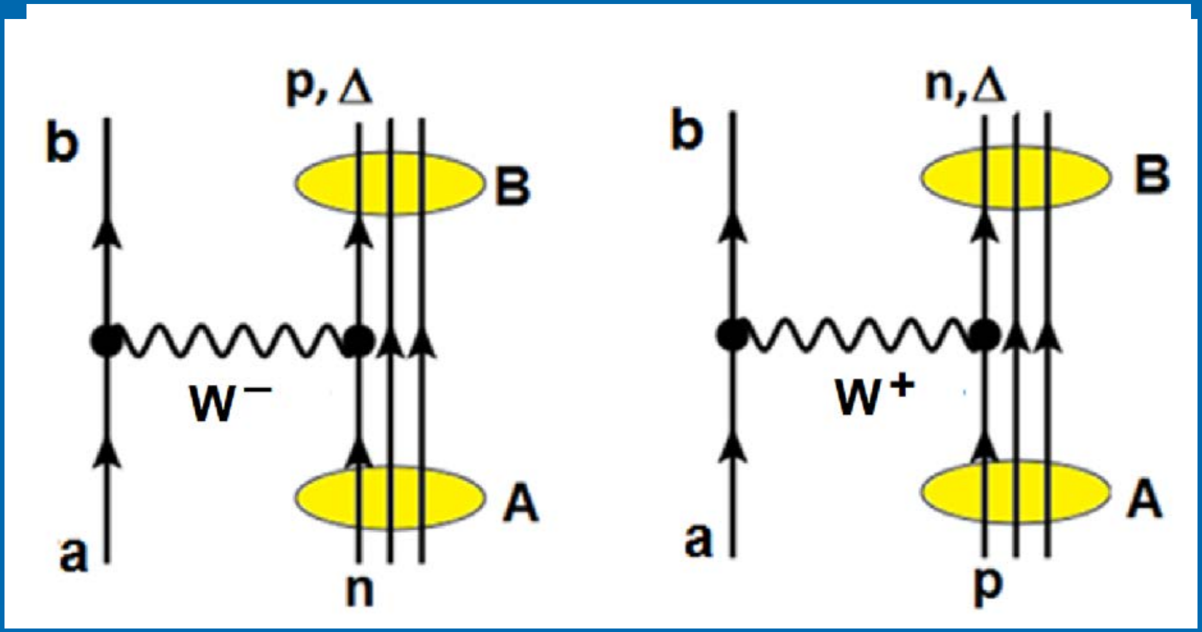
Agenda:

- Investigating nuclear charge changing excitations:
  - single charge exchange (SCE) reactions
  - double charge exchange (DCE) reactions
- „Majorana“ DCE reactions:
  - „$0\nu2\beta$“ operator structure in hadronic interactions
  - DCE reactions and nuclear matrix elements
- Outlook

Nuclear Reactions as Probes for Nuclear β-Matrix Elements

Charge Exchange Reactions ↔ Charged Currents:

$\Delta q=\pm 1$ excitation of Fermi- (J^{π}=0+,1-…) and GT- (J^{π}=0-,1+…) type states



Operators acting on projectile and target:

$$\left\{1_{\sigma}, \vec{\sigma}, \vec{\sigma}\times\vec{q}\right\}\otimes\tau_{\pm}$$

Nucleon-Nucleon Interaction and Weak Interaction Vertices

Strong Interaction **Weak Interaction**

$$V_{NN} \sim V_{01}\left(q^2\right)\tau_\pm\tau_\mp \quad \leftrightarrow \quad g_F\left(q^2\right)\tau_\pm \quad \text{"Fermi"}$$

$$+V_{11}\left(q^2\right)\sigma_1\cdot\sigma_2\ \tau_\pm\tau_\mp \quad \leftrightarrow \quad g_A\left(q^2\right)\sigma\ \tau_\pm \quad \text{"Gamow-Teller"}$$

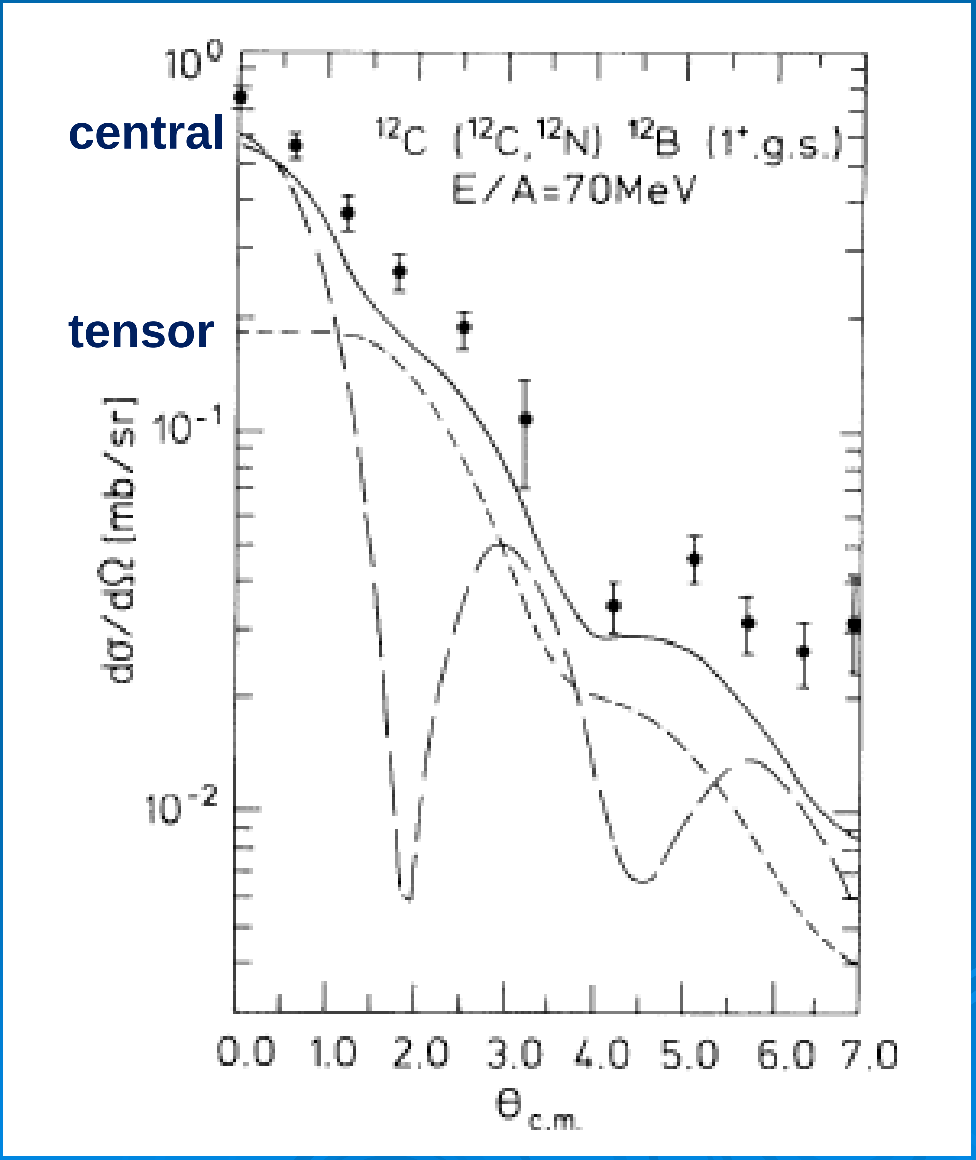
$$+V_{T1}\left(q^2\right)S_{12}\ \tau_\pm\tau_\mp \quad \leftrightarrow \quad g_M\left(q^2\right)\sigma\times q\ \tau_\pm \quad \text{"weak magnetic"}$$

$$+\ldots$$

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

Heavy Ion Single Charge Exchange Reaction (SCE)

Heavy Ion SCE Reactions: Rank-1 Central and Rank-2 Tensor Interaction



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

CNNP 2017:
H. Ejiri,
J. Bellone,
J.A. Lay,
G. Potel…

Initial and Final State Interactions

a+A Initial (ISI) and b+B Final State Interactions (FSI): The reaction coefficient

(→ J. Bellone, poster on Thursday)

$$M_{\beta\alpha}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \langle \chi_\beta^{(-)} | \mathcal{U}_{\beta\alpha} | \chi_\alpha^{(+)} \rangle$$

$$\mathcal{U}_{\alpha\beta}(\mathbf{r}) = \sum_{ST} \int \frac{d^3p}{(2\pi)^3} e^{-i\mathbf{p}\cdot\mathbf{r}} K_{\alpha\beta}^{(ST)}(\mathbf{p}).$$

$$N_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta, \mathbf{p}) = \frac{1}{(2\pi)^3} \langle \chi_\beta^{(-)} | e^{-i\mathbf{p}\cdot\mathbf{r}} | \chi_\alpha^{(+)} \rangle.$$

$$M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_{ST} \int d^3p K_{\alpha\beta}^{(ST)}(\mathbf{p}) N_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta, \mathbf{p}),$$

$$d\sigma_{\alpha\beta} = \frac{m_\alpha m_\beta}{(2\pi\hbar^2)^2} \frac{k_\beta}{k_\alpha} \frac{1}{(2J_a+1)(2J_A+1)} \sum_{M_a, M_A \in \alpha; M_b, M_B \in \beta} |M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta)|^2 d\Omega.$$

SCE cross section at small momentum transfer

NME: $b_{LSJ} \sim (B||T_{LSJ}||0)$

Fermi-type transition in both nuclei

$$\frac{d\sigma^{FF}}{d\Omega} \sim \frac{q^{2(J_a+J_A)}}{[(2J_a+1)!!(2J_A+1)!!]^2} \left| V_{01}^{(C)}(0) b^{AB}_{J_A 0 J_A} b^{ab}_{J_a 0 J_a} + e^{i\phi_{aA}} V_{11}^{(C)}(0) b^{(AB)}_{J_A 1 J_A} b^{(AB)}_{J_A 1 J_A} \right|^2 N_{\alpha\beta}$$

Gamov-Teller-type transition in both nuclei

$$\frac{d\sigma^{GG}}{d\Omega} \sim \frac{q^{2(J_a+J_A-2)}}{[(2J_a-1)!!(2J_A-1)!!]^2} |V_{11}^{(C)}(0)|^2$$

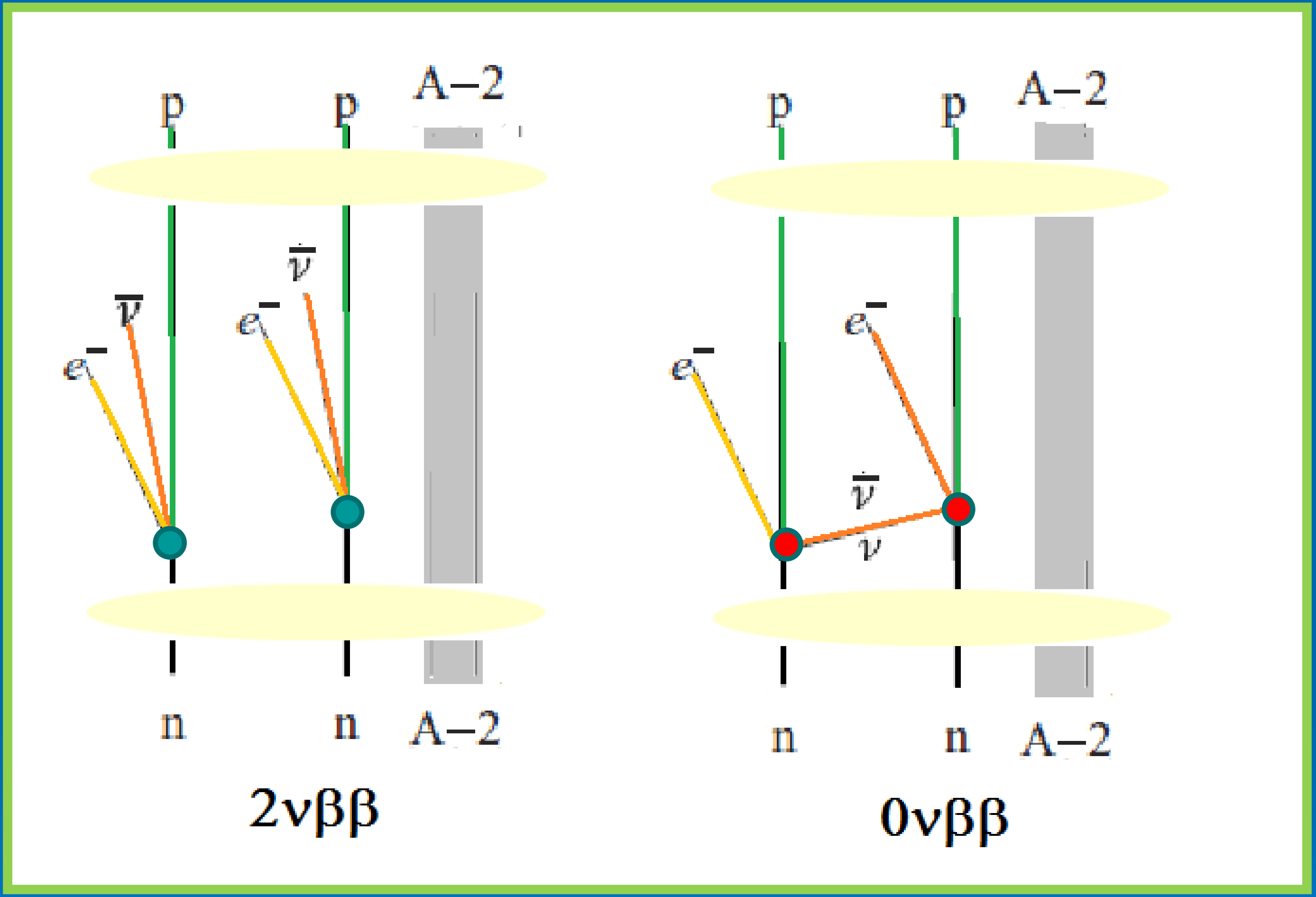
$$\left| b^{(AB)}_{J_A-1 1 J_A} + \frac{q^2}{(2J_A+1)(2J_A+3)} b^{(AB)}_{J_A+1 1 J_A} \right|^2 \left| b^{(ab)}_{J_a+1 1 J_a} + \frac{q^2}{(2J_a+1)(2J_a+3)} b^{(ab)}_{J_a+1 1 J_a} \right|^2 N_{\alpha\beta}$$

…and mixed σ^{FG} and σ^{GF} :

e.g. σ^{FG} spin-flip Fermi in a→b and GT in A → B

Double Charge Exchange Reactions and Double β-Decay

Nuclear *Double* Beta Decay



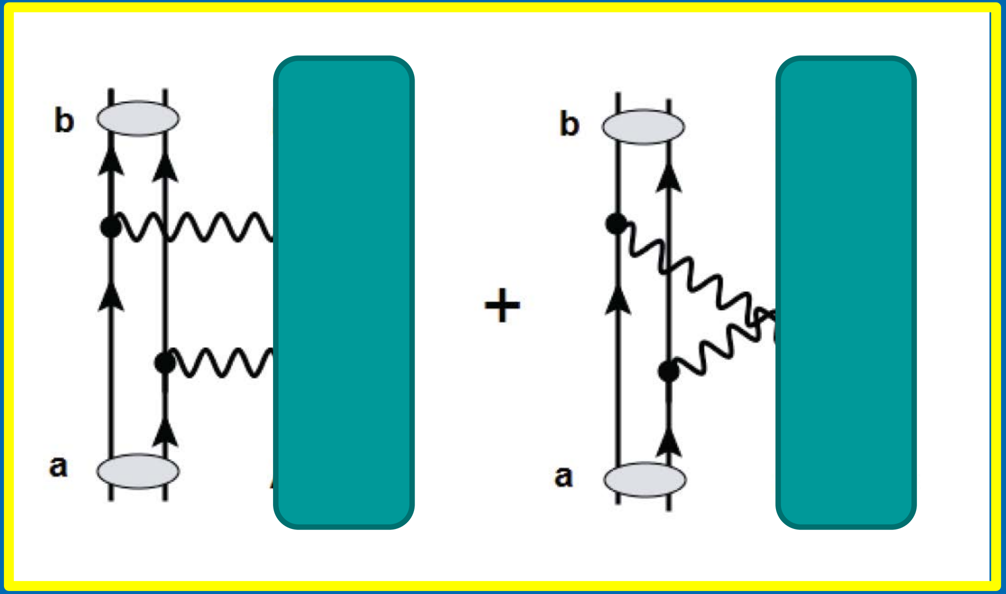
Conventional 2nd order QM process

Something new: 2nd order plus correlation

Double-SCE Reactions

dSCE:
Double Charge Exchange by sequential Single Charge Exchange

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



Reaction Amplitude

$$M^{(DCE)}_{\alpha\beta}(\mathbf{k}_{bB}, \mathbf{k}_{\alpha}) == \langle \chi^{(-)}_{\beta}, bB | T_{NN} \mathcal{G}^{(+)}(\omega) T_{NN} | aA, \chi^{(+)}_{aA} \rangle .$$

Evaluation of the dSCE Amplitude to a Tractable Form

Bi-Orthogonal set of channel states:

$$|\gamma\rangle = |cC, \chi_\gamma^{(+)}\rangle \quad , \quad |\tilde{\gamma}\rangle = |cC, \tilde{\chi}_\gamma^{(+)}\rangle$$

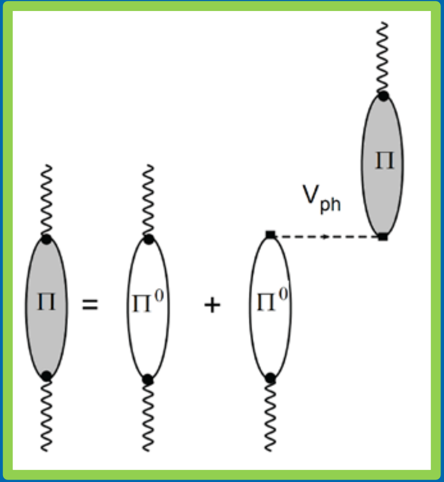
$$M_{\alpha\beta}^{(DCE)}(\mathbf{k}_\beta, \mathbf{k}_\alpha) = \sum_{c,C} \int \frac{d^3 k_\gamma}{(2\pi)^3} M_{bB,cC}^{(SCE)}(\mathbf{k}_\beta, \mathbf{k}_\gamma) G_{cC}(\omega_\gamma, \omega_\alpha) \tilde{M}_{cC,aA}^{(SCE)}(\mathbf{k}_\gamma, \mathbf{k}_\alpha)$$

…and making use of the analytic properties of the Green's function

$$M_{\beta\alpha}^{(DCE)}(\mathbf{k}_\beta, \mathbf{k}_\alpha) = \sum_{S_1,S_2,T=1} \int \frac{d^3 k_\gamma}{(2\pi)^3} \int d^3 p_1 d^3 p_2 N_{\beta\gamma}(\mathbf{p}_2) \tilde{N}_{\gamma\alpha}(\mathbf{p}_1) t_{S_2 T}(p_2^2) t_{S_1 T}(p_1^2)$$
$$\times \oint \frac{d\zeta}{2i\pi} \Pi_{S_2 S_1}^{(ba)\dagger}\left(\frac{1}{2}\tilde{\kappa} - \zeta - i\eta, \mathbf{p}_2, \mathbf{p}_1\right) \cdot \Pi_{S_2 S_1}^{(BA)}\left(\frac{1}{2}\tilde{\kappa} + \zeta + i\eta', \mathbf{p}_2, \mathbf{p}_1\right)$$

Nuclear CC Polarization Propagator

$$\Pi_{ba}(\mathbf{q}', \mathbf{q}, \omega) = \langle 0|T_b^\dagger(\mathbf{q}')G(\omega)T_a(\mathbf{q})|0\rangle$$

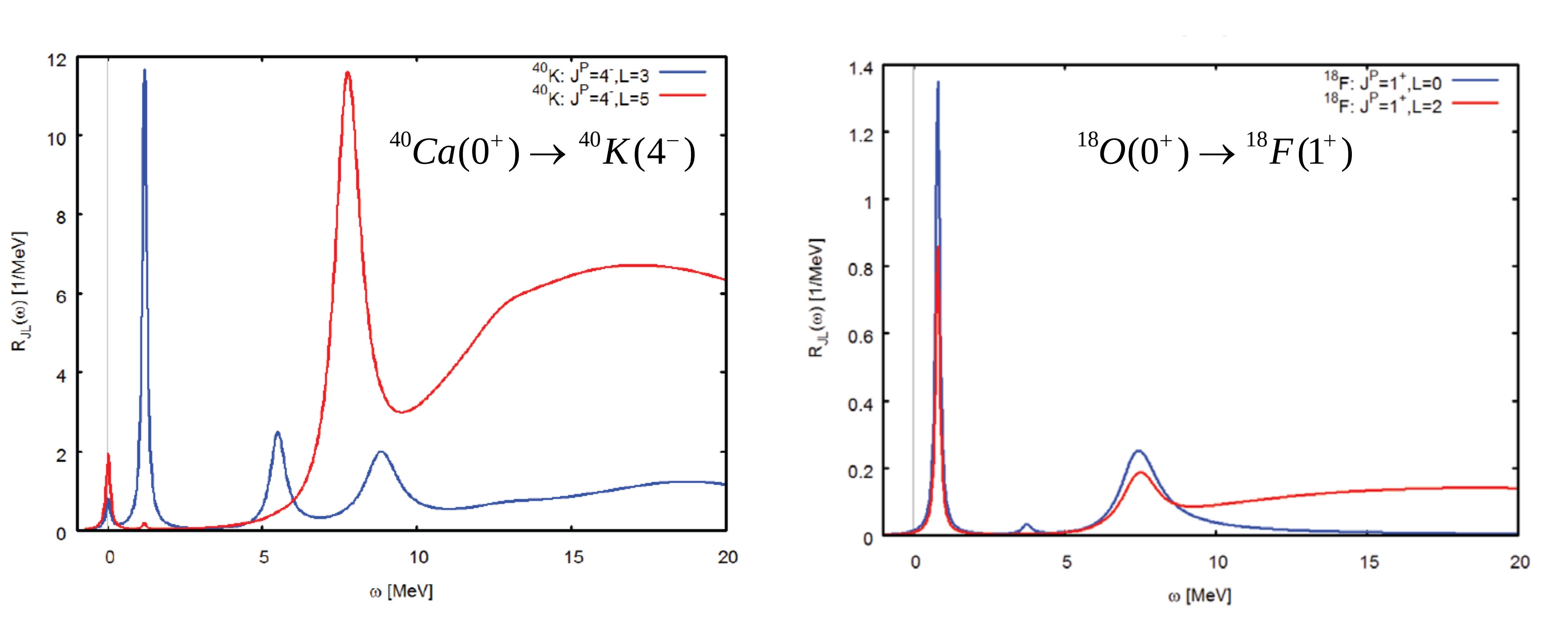


Nuclear CC Response Functions:

$$R_{ab}(\mathbf{q}, \omega) = -\frac{1}{\pi} Im\left[\Pi_{ab}(\mathbf{q}, \mathbf{q}, \omega)\right].$$

F.T. Baker, H.L. et al. Phys.Rept. 289 (1997) 235

CC Response Functions
$^{40}Ca \rightarrow {}^{40}K(4^-)$ and $^{18}O \rightarrow {}^{18}F(1^+)$



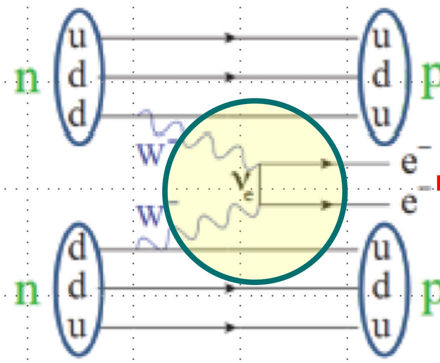
Operator:

$$T_{LSJM} = \left(\frac{r}{R_d}\right)^L \left[\boldsymbol{\sigma}^S \otimes Y_L\right]_{JM} \tau_\pm$$

„Majorana“ DCE
and
$0\nu 2\beta$ Transitions

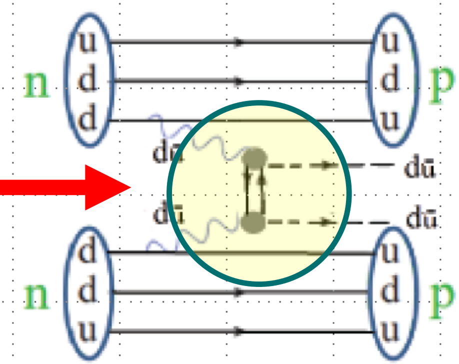
Weak Interaction 0ν2β decay and Strong Interaction Analogue

weak 0ν2β decay



- simultaneous d→u Δq=+1 transitions by emission of a virtual weak gauge boson W^-
- $W^- \to e^- + \bar{\nu}_e / \nu_e$: decay into electron and Majorana neutrino
- Correlation of the two events by exchange of the virtual $\nu_e \bar{\nu}_e$ pair
- Emission of two electrons ON their mass-shell: $p^2_e = m^2_e$
- Direct observation (GERDA@LNGS...)

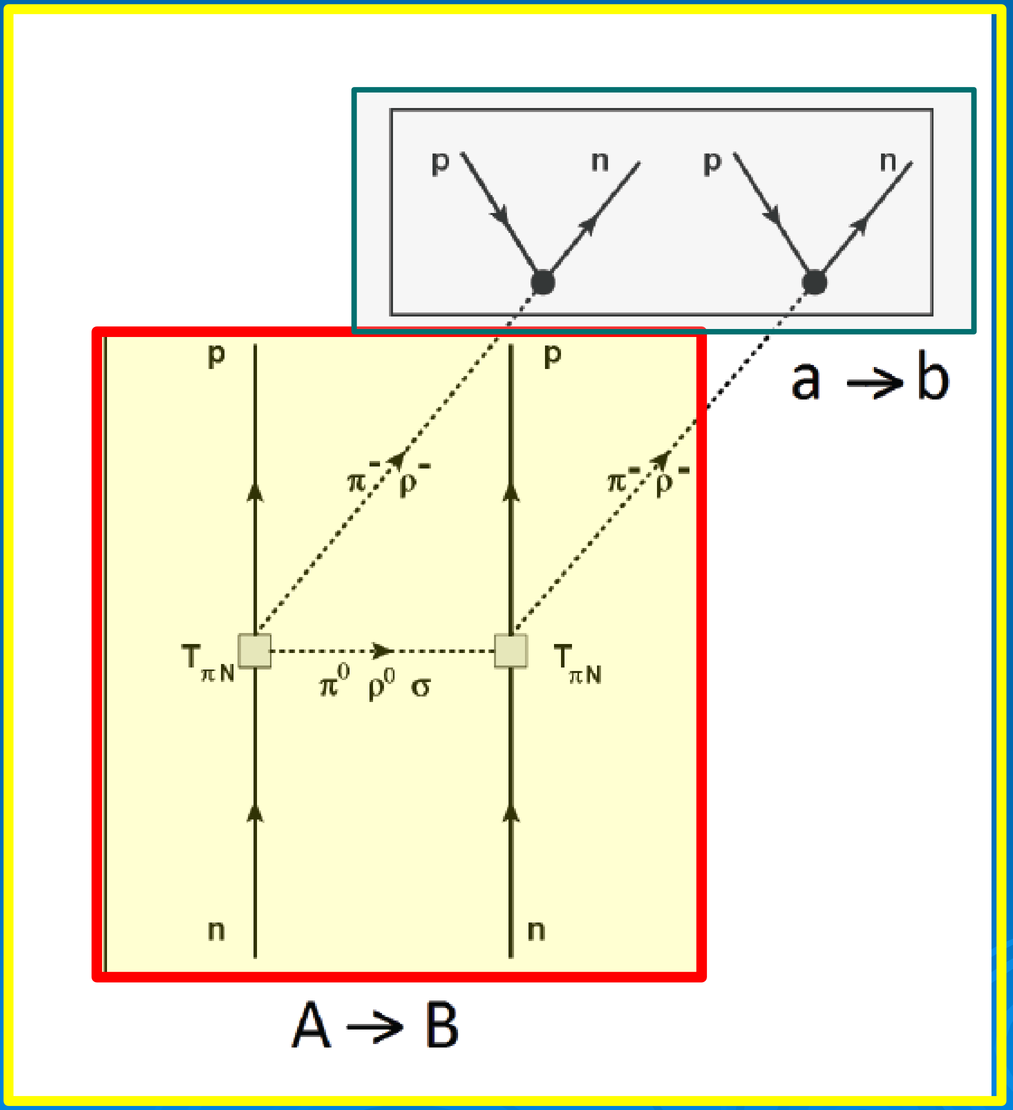
Hadronic analogue



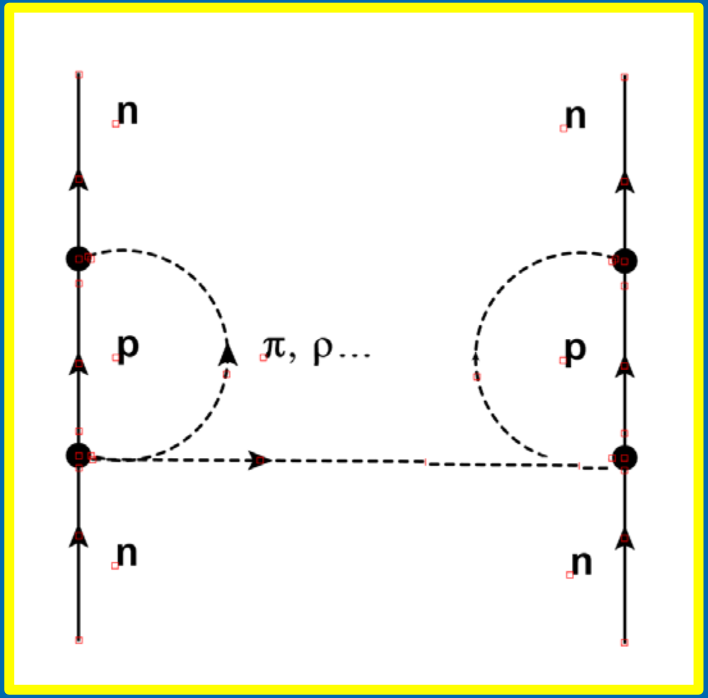
- simultaneous d→u Δq=+1 transitions by emission of a virtual $d\bar{u}$ vector pair ↔ ρ^- meson
- $\rho^- \to \pi^- + \pi^0$: decay into a pair of pions
- Heavy vector mesons ρ^{-*}
- Correlation of the two events by exchange of the virtual $q\bar{q}$ pair as contained in $\pi^0 \cong (d\bar{d}+u\bar{u})/\sqrt{2}$
- Emission of two π^- OFF their mass-shell: $p^2_\pi \neq m^2_\pi$
- No direct observation

Nuclear Currents and Matrix Elements

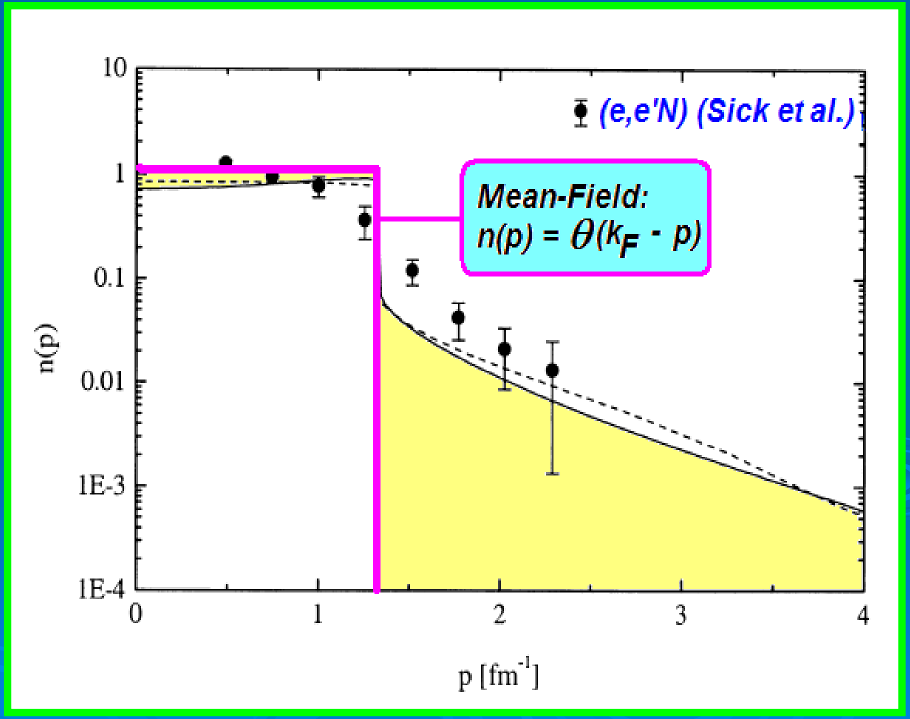
The Target A→B coherent DCE Transitions



…plus „crossed“ diagrams!



…a class of diagrams known from nuclear ground state correlations!



…~ 10…20% contribution to nuclear ground states

(P. Konrad, H.L. NPA 756 2005).

The $0\nu 2\beta$ $0^+ \rightarrow 0^+$ Nuclear Matrix Element

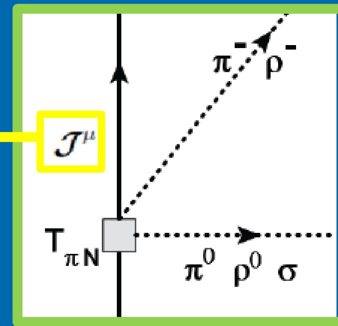
$$M^{0\nu} = \frac{4\pi R}{g_A^2(0)} \sum_L \int d^3x_1 \int d^3x_2 \int \frac{d^3q}{(2\pi)^3} \frac{e^{i\mathbf{q}\cdot(\mathbf{x}_1-\mathbf{x}_2)}}{q(q+E_d)} \langle 0_F^+ | \mathcal{J}_{L,\mu}^\dagger(\mathbf{x}_1) \mathcal{J}_L^{\mu\dagger}(\mathbf{x}_2) | 0_I^+ \rangle$$

Nuclear charge-changing Currents $\mathcal{J}_L$:

- **Vector**
- **Pseudo-vector**
- **Axial-vector**
- **Magnetic**

Nuclear CC Currents and CC Transition Amplitude

$$\mathcal{J}_V^\mu = \bar{\Psi}_N \gamma^\mu \boldsymbol{\tau} \Psi_N$$
$$\mathcal{J}_A^\mu = \bar{\Psi}_N \gamma^\mu \gamma_5 \boldsymbol{\tau} \Psi_N$$
$$\mathcal{J}_S = \bar{\Psi}_N \gamma_5 \boldsymbol{\tau} \Psi_N .$$



$$\begin{aligned} m_\pi \mathcal{T}_{\pi N}^{(CC)} &= T_V(s,t)\, \mathcal{J}_V^\mu \cdot \partial_\mu \left(\phi_\pi \times \phi_\pi\right) \\ &+ T_A(s,t)\, \mathcal{J}_A^\mu \cdot \left(\phi_{\mu,\rho} \times \phi_\pi\right) \\ &+ T_P(s,t)\, \mathcal{J}_A^\mu \cdot \partial_\mu \left(\phi_\sigma \phi_\pi\right) \\ &+ T_S(s,t)\, \mathcal{J}_S \cdot \left(\phi_\sigma \phi_\pi\right) . \end{aligned}$$

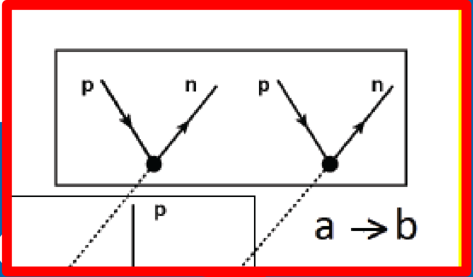
Nucleon Iso-spinor Fields: $\Psi_N \equiv (\psi_p, \psi_n)^T$

Meson Iso-vector Fields: $\phi_\pi = (\phi_{\pi^-}, \phi_{\pi^0}, \phi_{\pi^+})^T, \; \phi_\rho^\mu = \left(\phi_{\rho^-}^\mu, \phi_{\rho^0}^\mu, \phi_{\rho^+}^\mu\right)^T$

Meson Iso-scalar Field: ϕ_σ

The Target DCE$^{(M)}$ Transition Amplitude

$$
\begin{aligned}
M^{(\pi\pi)}_{AB}(k_1,k_2) &= T^{(\pi\pi)}_V(s_1)G^{(\pi\pi,\pi\pi)}_{VV}(k_1,k_2)T^{(\pi\pi)}_V(s_2)\\
&+ T^{(\rho\pi)}_A(s_1)H^{(\rho\pi,\rho\pi)}_{VV}(k_1,k_2)T^{(\rho\pi)}_A(s_2)\\
&- T^{(\rho\pi)}_A(s_1)G^{(\rho\pi,\rho\pi)}_{AA}(k_1,k_2)T^{(\rho\pi)}_A(s_2)\\
&+ T^{(\sigma\pi)}_A(s_1)G^{(\sigma\pi,\sigma\pi)}_{AA}(k_1,k_2)T^{(\rho\pi)}_A(s_2)\\
&+ T^{(\sigma\pi)}_S(s_1)G^{(\sigma\pi,\sigma\pi)}_{SS}(k_1,k_2)T^{(\rho\pi)}_S(s_2),
\end{aligned}
$$



The full DCE$^{(M)}$ Transition Amplitude

$$
\begin{aligned}
\mathcal{M}_{aA,bB}(k_1,k_2) &= M^{(\pi\pi)}_{AB}(k_1,k_2)\langle b|\phi_{\pi^-}(k_1)\phi_{\pi^-}(k_2)|a\rangle\\
&+ M^{(\rho\rho)\kappa\lambda}_{AB}(k_1,k_2)\langle b|\phi_{\kappa,\rho^-}(k_1)\phi_{\lambda,\rho^-}(k_2)|a\rangle\\
&+ M^{(\pi\rho)\lambda}_{AB}(k_1,k_2)\langle b|\phi_{\pi^-}(k_1)\phi_{\lambda,\rho^-}(k_2)|a\rangle\\
&+ M^{(\rho\pi)\kappa}_{AB}(k_1,k_2)\langle b|\phi_{\kappa,\rho^-}(k_1)\phi_{\pi^-}(k_2)|a\rangle.
\end{aligned}
$$

The Reaction Kernel

$$\mathcal{K}^{(CC)}_{\alpha\beta}(\mathbf{r}) = \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} e^{-i(\mathbf{k}_1+\mathbf{k}_2)\cdot\mathbf{r}} \mathcal{M}_{aA,bB}(\mathbf{k}_1, \mathbf{k}_2),$$

The Reaction Amplitude

$$\mathcal{R}^{(CC)}_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \langle \chi^{(-)}_\beta | \mathcal{K}^{(CC)}_{aA,bB} | \chi^{(+)}_\alpha \rangle.$$

Plane Wave Limit

$$\mathcal{R}^{(PW)}_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} (2\pi)^3 \delta(\mathbf{q} - \mathbf{k}_1 - \mathbf{k}_2) \mathcal{M}_{aA,bB}(\mathbf{k}_1, \mathbf{k}_2)$$

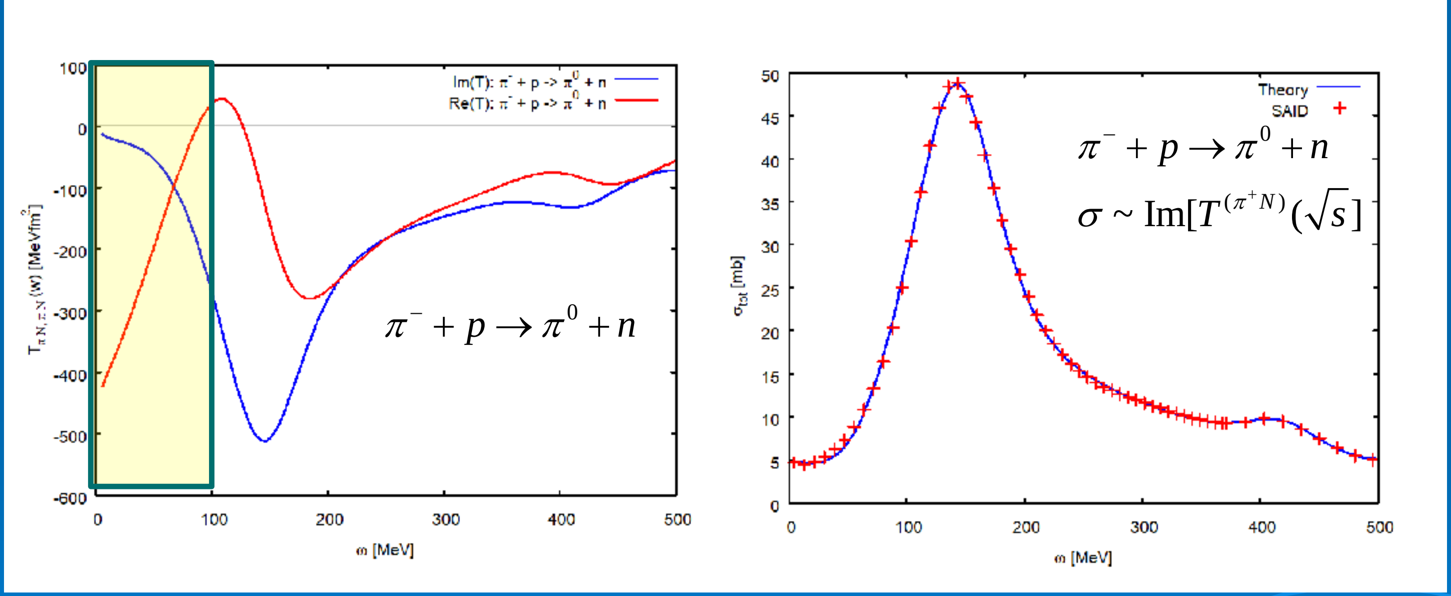
Application:
$^{18}O + ^{40}Ca \rightarrow ^{18}Ne + ^{40}Ar$

D. Carbone (Thursday, 2nd plenary): The NUMEN project
J.-A. Lay (Tuesday, parallel): DCE and Transfer
J. Bellone (Thursday, poster): Beta-decay and Heavy Ion SCE

Factorization of Energy and Momentum Dependence

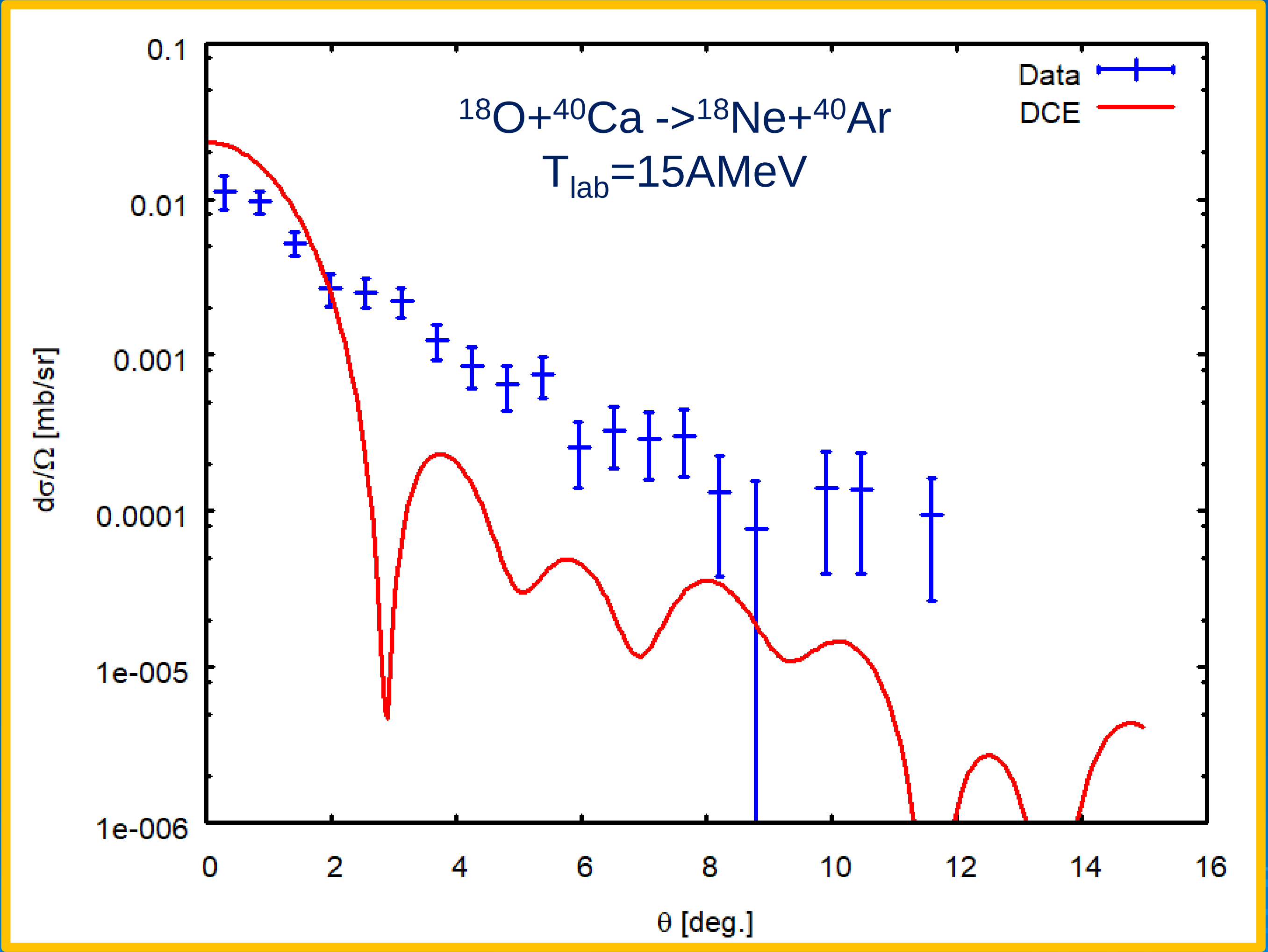
$$T_X^{(xy)}(s,t,u) \sim T_X^{(xy)}(s) F_X^{(xy)}(t,u)$$

(xy)=(π,π), (σπ), (ρπ), (ρρ)…, X = V,A,P,S…



- **T_X (s) ~ energy dependent „running scaling" ~ $\sigma_{\pi N}$**
- **Coupling/vertex form factor F_X (t,u) ~ F_X (q^2) ~ g^2_X (q^2)**

DCE Cross Section: dSCE and „$\pi^- \pi^0 \pi^-$“ Majorana-DCE



F. Cappuzzello et al., Eur.Phys.J. A51 (2015) no.11, 145

Predictions and Estimates

- **The most direct proof of a DCE$^{(M)}$ reaction:**

$$^{3}H + {}^{3}He \rightarrow 3p + 3n$$

- **Proof of a DCE$^{(M)}$ reaction on a heavy target:**

$$^{3}H + A(Z,N) \rightarrow 3p + A(Z-2,N+2)$$
$$^{3}He + A(Z,N) \rightarrow 3n + A(Z+2,N-2)$$

- **Rate of DCE$^{(M)}$?**
  - **GSC in nuclei ~ 10…20%**
  - **assume 1% of the special type of diagrams**
  - **→ DCE$^{(M)}$ ~ 0.1…1% of all DCE reactions**

Summary

- SCE, double-SCE, and Majorana-DCE heavy ion reactions
- Probing $0\nu2\beta$-type NME in a hadronic surrogate process:
  - NME of CC nuclear currents
  - Vertices by meson-nucleon T-matrix
- Interface to nuclear structure:
  - Nuclear CC response functions
  - Nuclear form factors
  - Heavy ion elastic interactions

…together with theory section of the NUMEN@LNS collaboration
M. Colonna (Catania), E. Santopinto (Genova), J.-A. Lay (Sevilla),
J. Lubian (Sao Paolo), N. Auerbach (Tel Aviv)