Theory of Heavy Ion Double Charge Exchange Reactions

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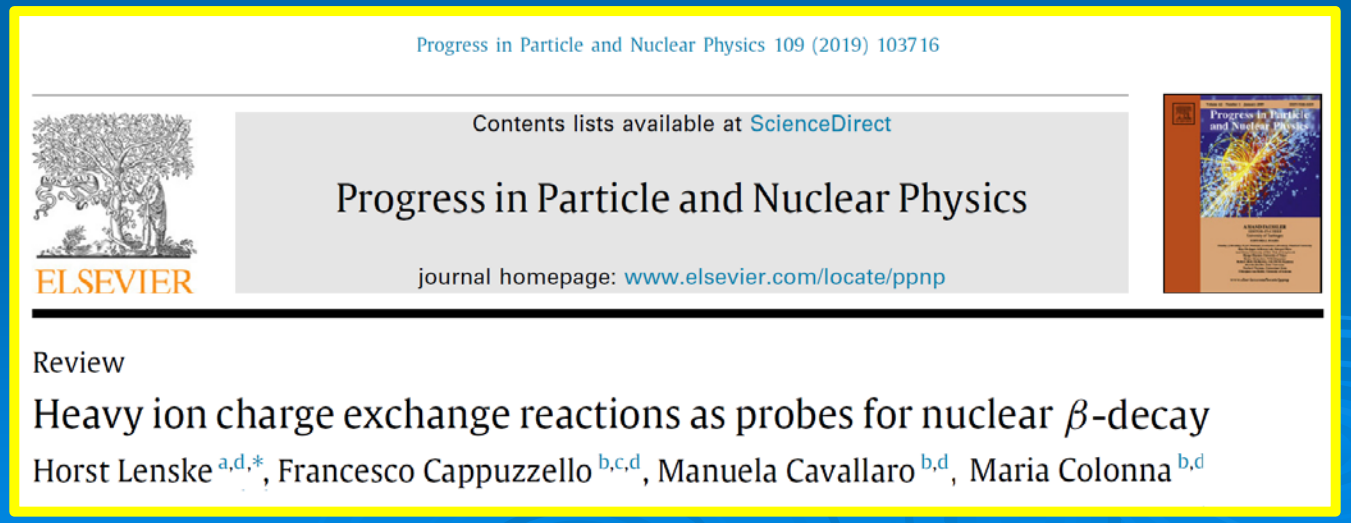
Agenda:

- Heavy ion Single Charge Exchange (SCE) reactions
- Nuclear SCE response functions
- 2-step Double Single Charge Exchange reactions (DSCE)
- 1-step DCE Mechanism: „Majorana“ DCE reactions (MDCE)
- Summary and Outlook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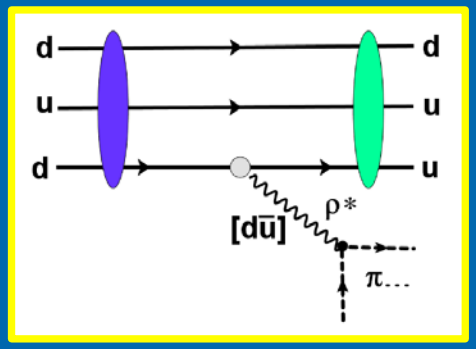
Review

Heavy ion charge exchange reactions as probes for nuclear β-decay

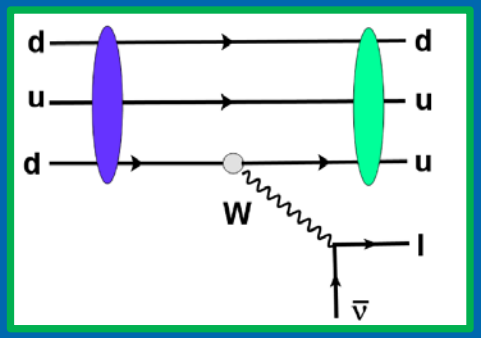
Horst Lenske [a,d,*], Francesco Cappuzzello [b,c,d], Manuela Cavallaro [b,d], Maria Colonna [b,d]

Single Charge Exchange Heavy Ion Reactions

Nuclear Interactions and beta-Decay



Strong Interaction



Weak Interaction

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

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

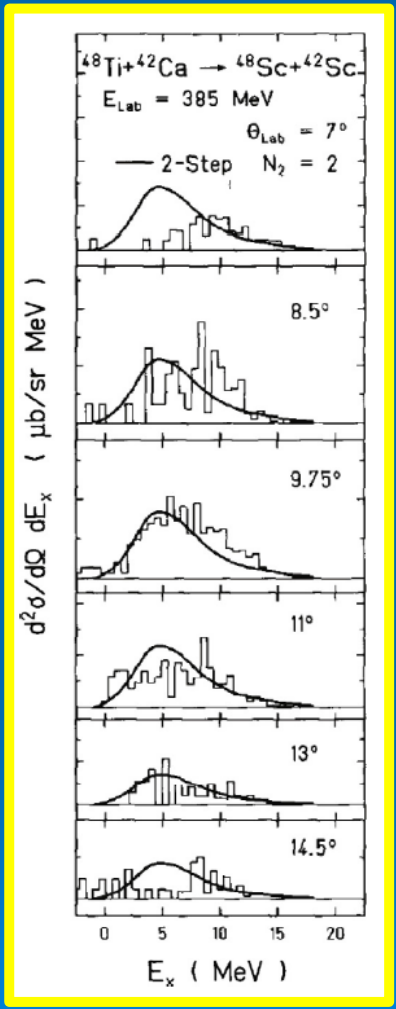
$$+V_{T1}\left(q^2\right)\begin{pmatrix} x_\pi\sigma_1\cdot q\tau_{\pm}\sigma_2\cdot q\tau_{\mp} \\ + \\ x_\rho\sigma_1\times q\tau_{\pm}\sigma_2\times q\tau_{\mp}\end{pmatrix} \quad \leftrightarrow \quad g_M\left(q^2\right)\sigma\times \mathrm{q}\ \tau_{\pm} \quad \text{"weak magnetic"}$$

$$+\ldots$$

Rank-2 tensor operator: $S_{12} = \frac{1}{q^2}\left[3\vec{\sigma}_1\cdot\vec{q}\sigma_2\cdot\vec{q} - \sigma_1\cdot\sigma_2 q^2\right]$

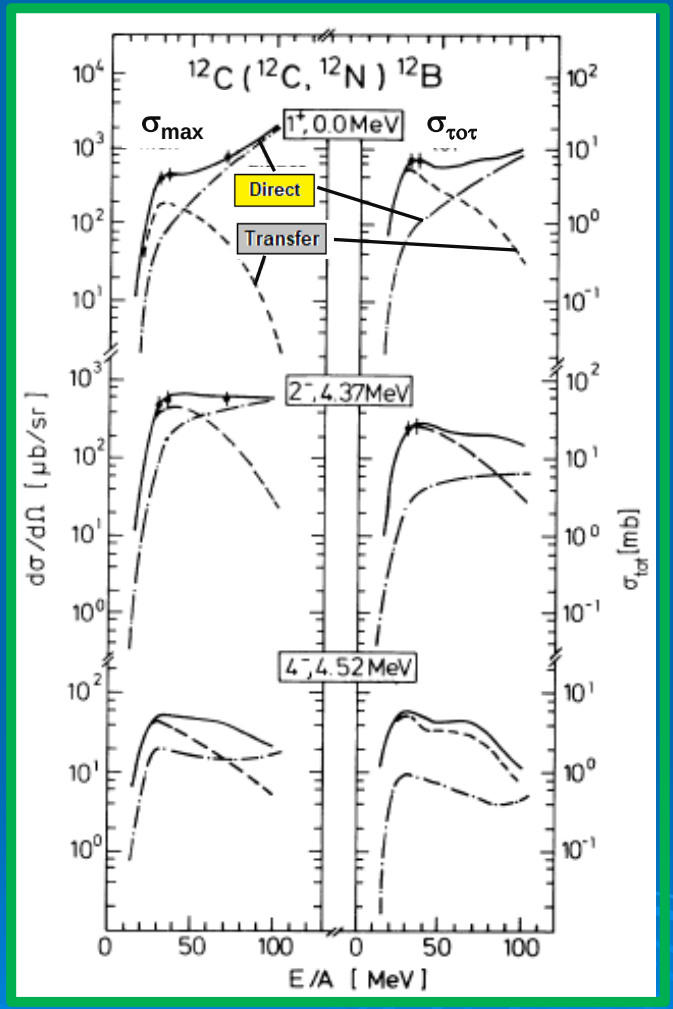
Direct Collisional 1-Step SCE and Transfer 2-Step SCE

SCE @ Coulomb-Barrier



C. Brendel, H.L. et al.
Nucl. Phys. A 477 (1988) 162

SCE @ „Fermi“ Energy Range



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

SCE Reaction Amplitude: Separation of Reaction and Nuclear Dynamics

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

Transition Potential

$$\mathcal{U}_{\alpha\beta}(\mathbf{r}_\alpha, \mathbf{r}_\beta) = \langle J_b M_b J_B M_B | T_{NN}^{(C)} + T_{NN}^{(Tn)} \ldots | J_a M_a J_A M_A \rangle$$

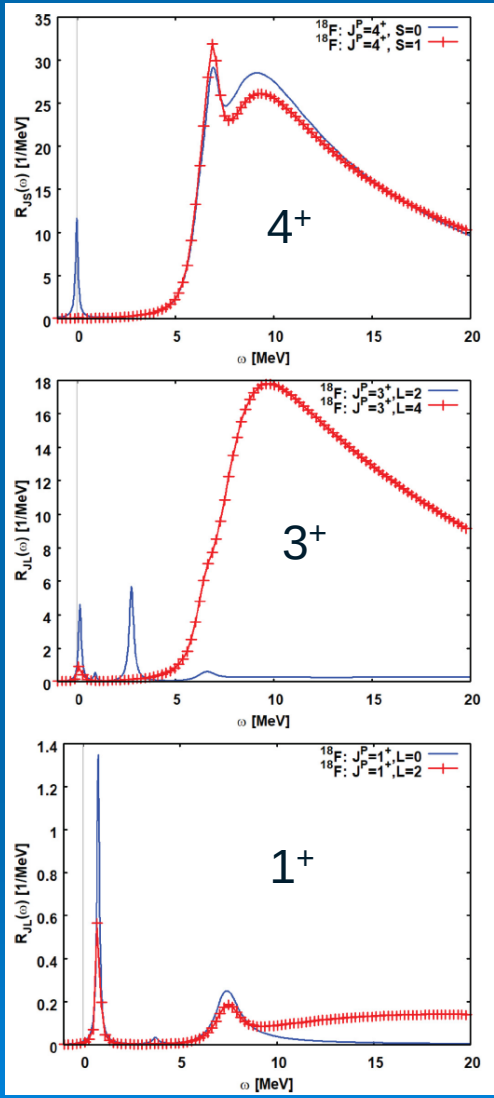
Distortion Coefficient

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

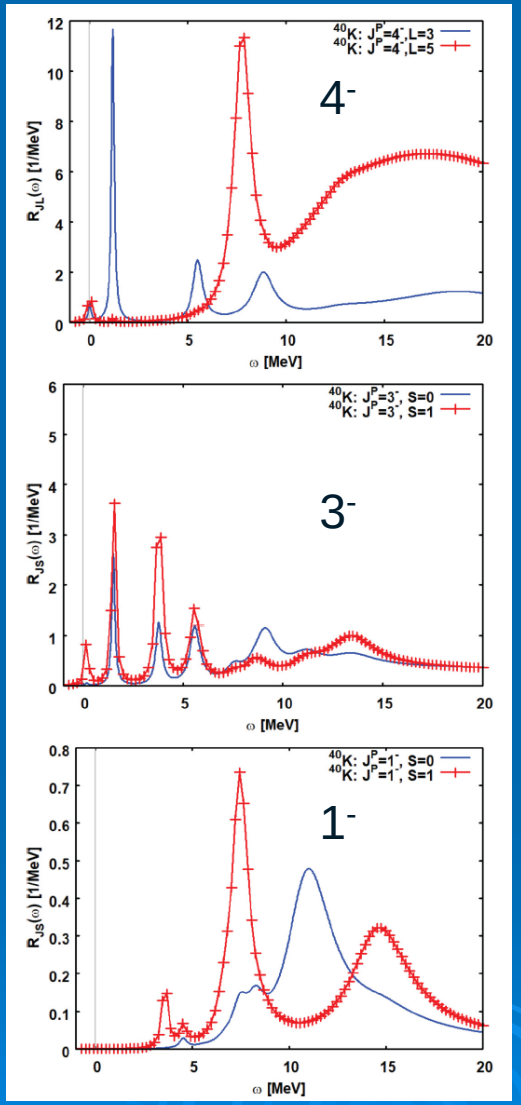
H. Lenske, J.I. Bellone, M. Colonna, J.-A. Lay, Phys. Rev. C 98 (2018) 044620

QRPA Response Functions

$^{18}O \rightarrow {}^{18}F$



$^{40}Ca \rightarrow {}^{40}K$



Transition Operator:

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

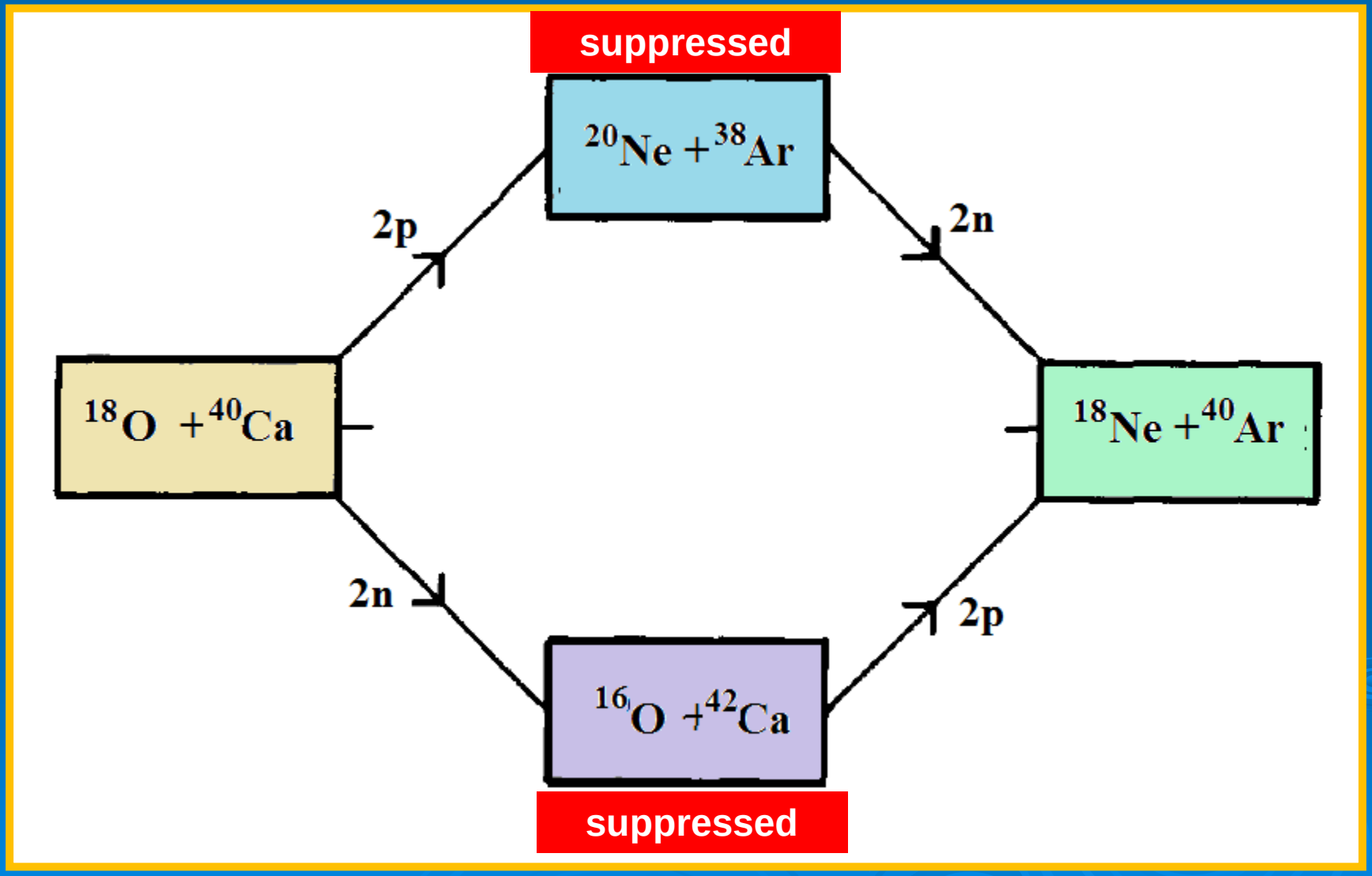
PHYSICAL REVIEW C **98**, 044620 (2018)

…including DCP self-energies and continuum effects

H. Lenske, CNNP 2020

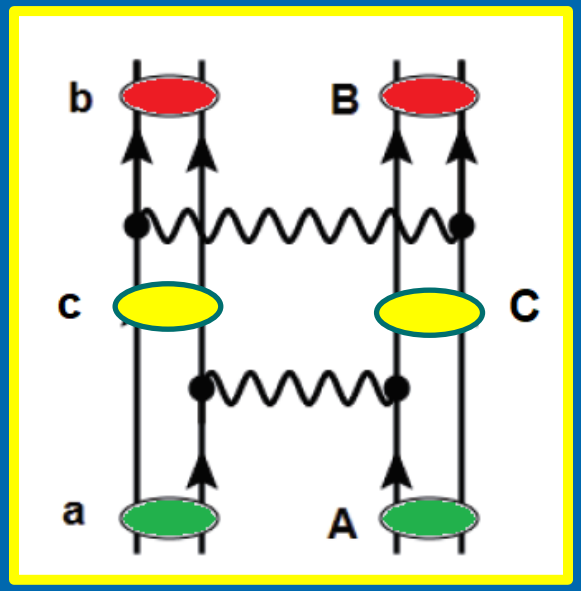
Nuclear Double Charge Exchange Reactions

Scheme of a Double Charge Exchange Reaction: Double-SCE (DSCE) plus Majorana-DCE (MDCE)



Double-Single Charge Exchange (DSCE) Reactions

DSCE:
Double Charge Exchange by Double Single Charge Exchange



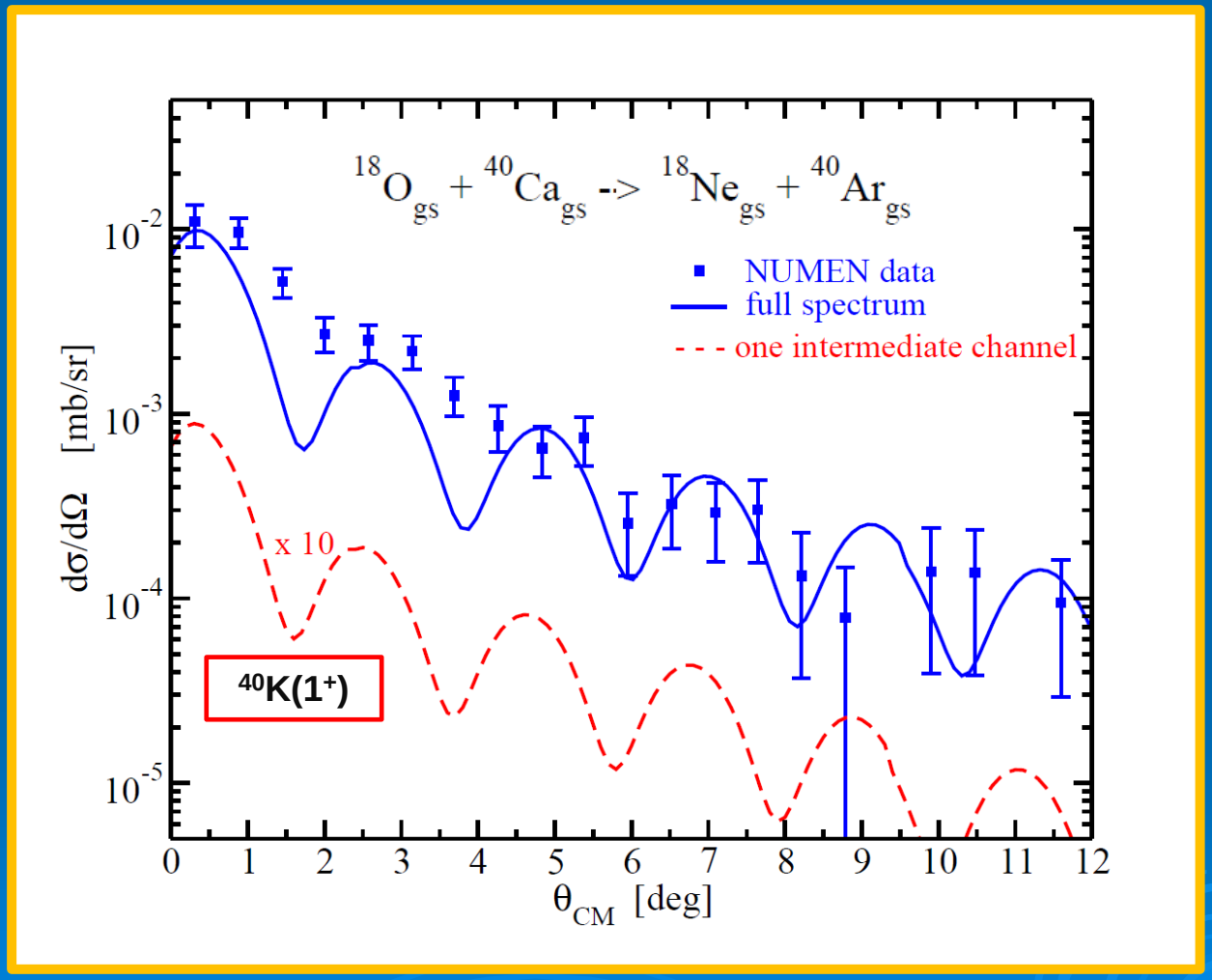
2nd Order DWA Reaction Amplitude

$$\mathcal{R}^{(DSCE)}_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta) \approx \tilde{N}_{\alpha\beta} \sum_{\gamma=cC} \int \frac{d^3k_\gamma}{(2\pi)^3} \frac{\mathcal{M}_{\beta\gamma}(\mathbf{k}_\beta-\mathbf{k}_\gamma)\mathcal{M}_{\gamma\alpha}(\mathbf{k}_\alpha-\mathbf{k}_\gamma)}{\tilde{\omega}^{(+)}_\alpha - \tilde{\omega}_\gamma - Q_{\alpha\gamma}}$$

J. Bellone, M. Colonna, J.-A. Lay, H.L., PLB (2020), e-Print: arXiv:1912.03043

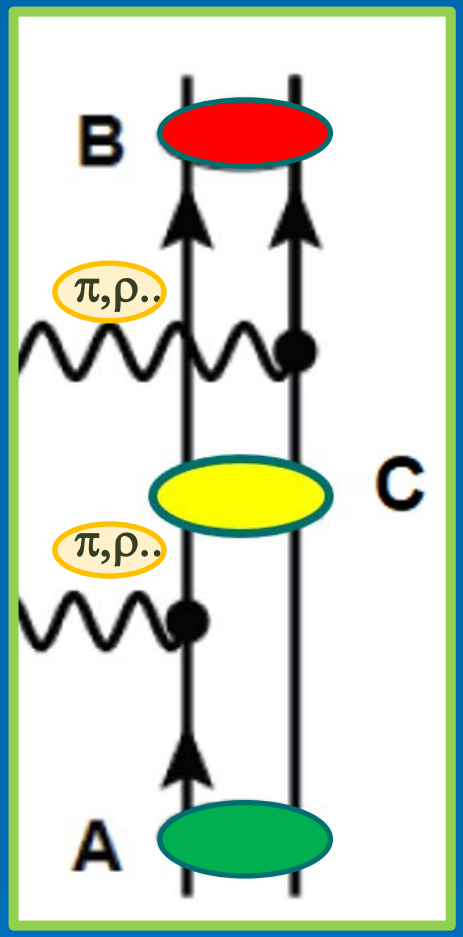
DSCE Results: 2nd Order DWA and QRPA ($J^{\pi} \leq 5^{\pm}$)

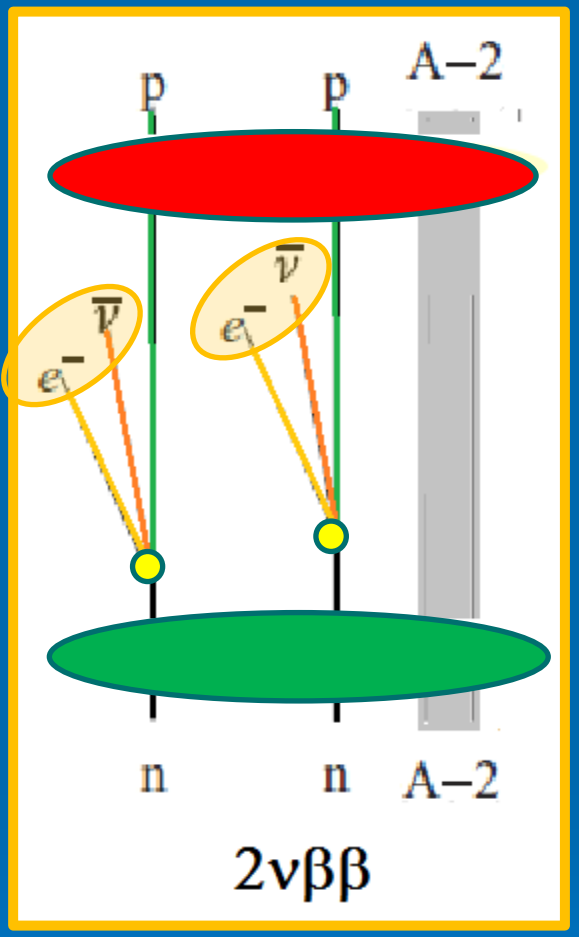
$^{18}O+^{40}Ca \rightarrow ^{18}Ne+^{40}Ar$ @ T_{lab}=15 MeV/A



Theory: Jessica Bellone et al., PLB (2020), e-Print: arXiv:1912.03043
Data: F. Cappuzzello et al., EPJ A51 (2015)

DSCE and 2ν2β Beta Decay





2nd order
Strong Interaction

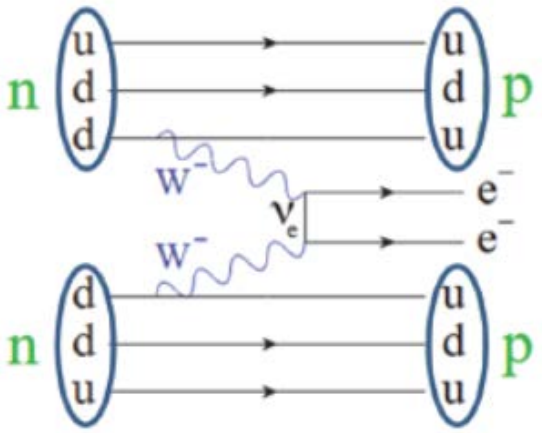
2nd order
Weak Interaction

„Direct“ Double Charge Exchange

„Majorana“ DCE

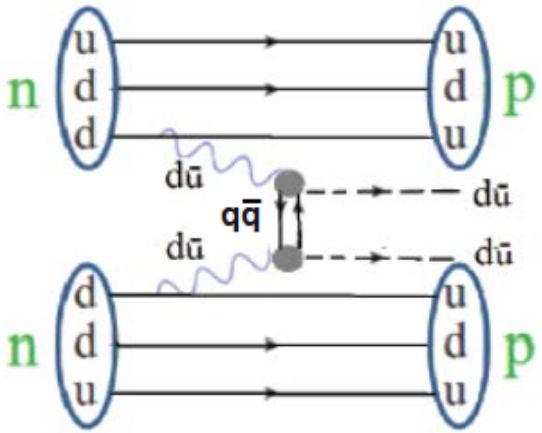
Weak 0ν2β Decay and Strong Interaction Analogue

0ν2β Decay



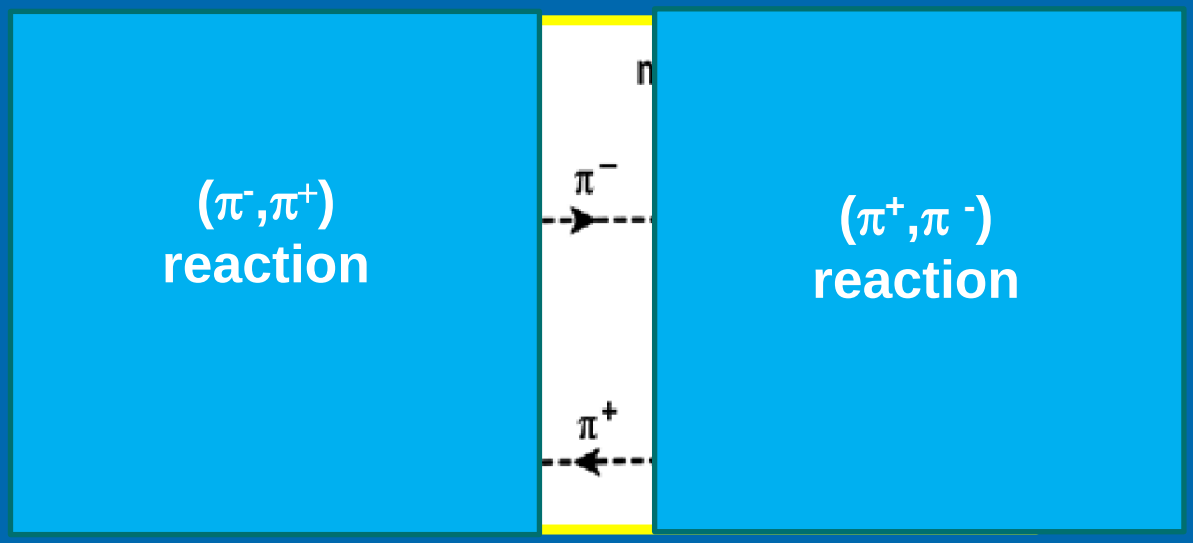
- simultaneous d→u Δq=+1 transitions by emission of a virtual weak gauge boson W⁻
- $W^- \rightarrow e^- + \bar{\nu}_e / \nu_e$: decay into electron and Majorana neutrino
- Correlation of the two events by exchange of the virtual $\nu_e \bar{\nu}_e$ pair
- Emission of two electrons ON their mass-shell: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

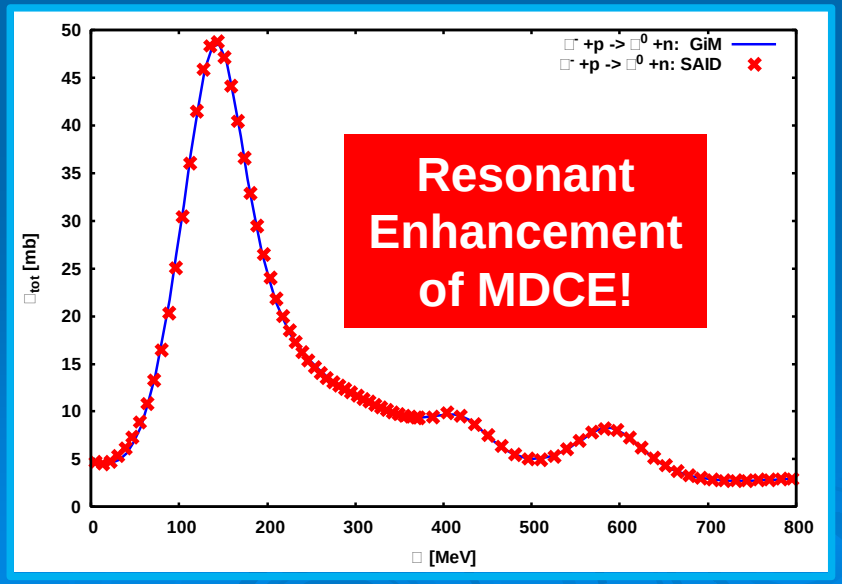
Hadronic Analogue



- simultaneous d→u Δq=+1 transitions by emission of a virtual $d\bar{u}$ vector pair ↔ ρ⁻ meson
- $\rho^- \rightarrow \pi^- + \pi^0$: 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

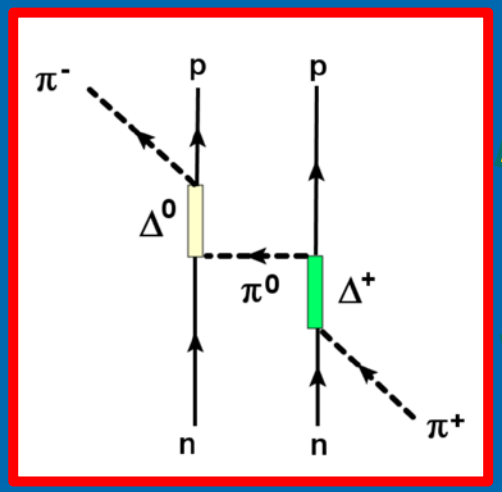
Pion Exchange and the MDCE Box-Diagrams



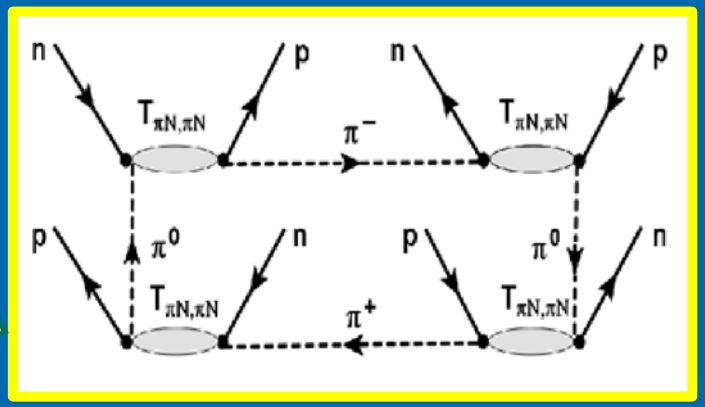


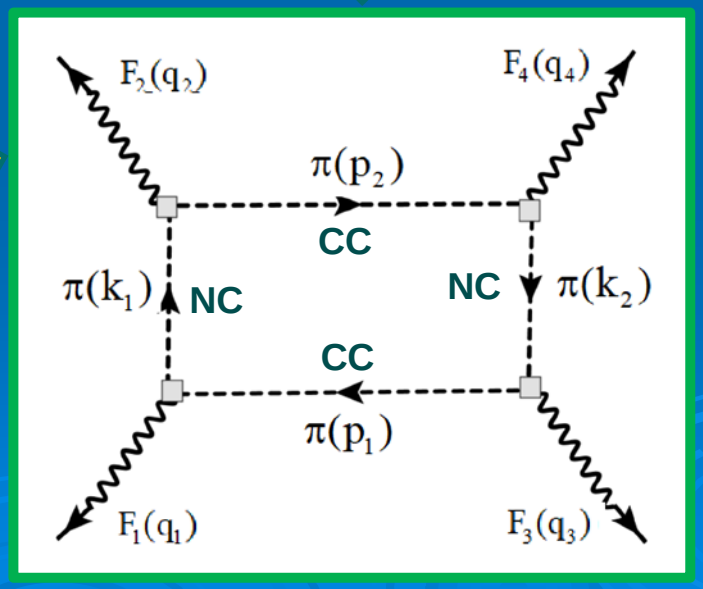
H. Lenske, CNNP 2020

Transition Form Factors, Charged (CC) and Neutral (NC) Currents



Elementary (π^+,π^-) reaction





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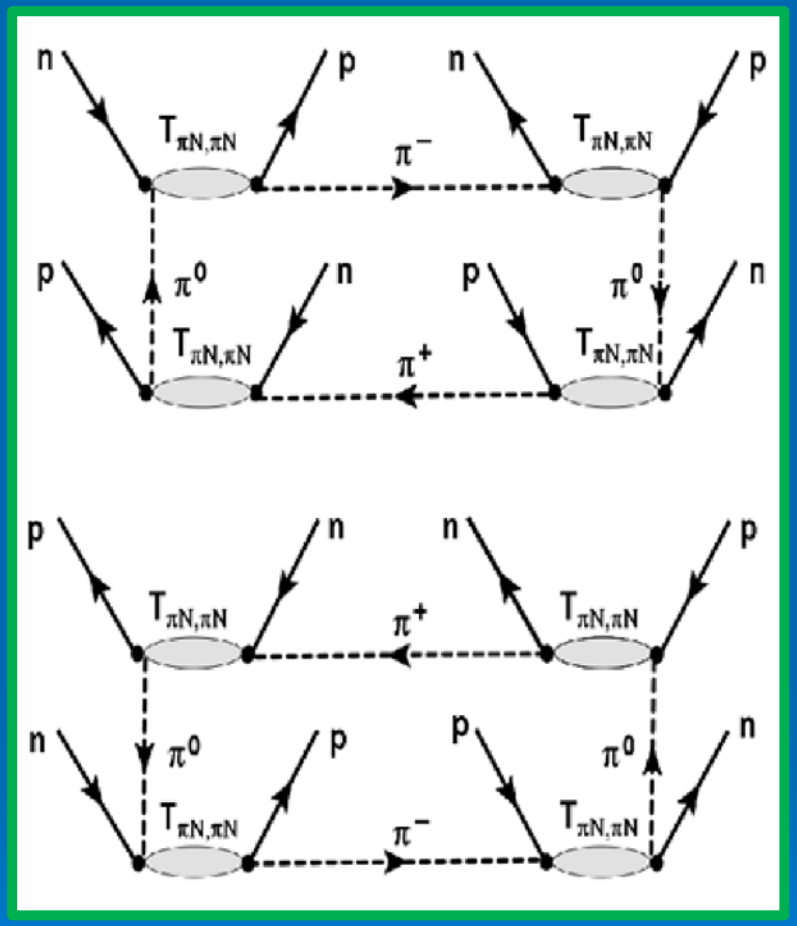
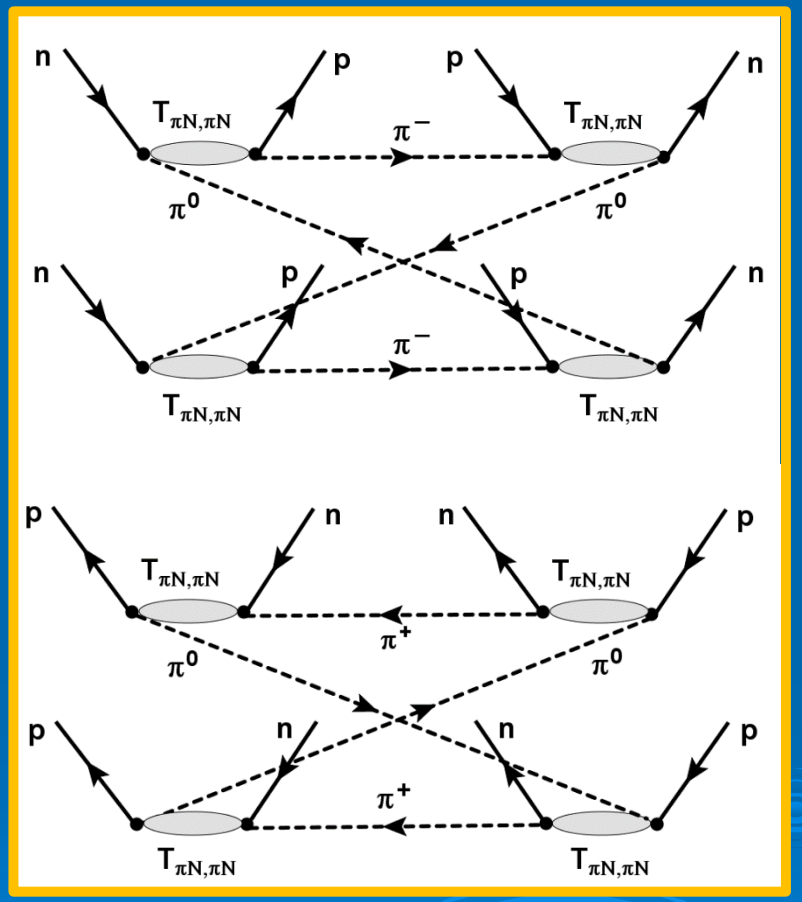
The Complete Set of Pionic MDCE Box Diagrams



$$\left(\pi^+,\pi^-\right) \;\&\; \left(\pi^-,\pi^+\right)$$



$$\left(\pi^-,\pi^-\right) \;\&\; \left(\pi^+,\pi^+\right)$$

The MDCE Reaction Amplitude

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

$$\mathcal{U}_{aA,bB}(\mathbf{r}_\beta, \mathbf{r}_\alpha) = \int \frac{d^3p_1}{(2\pi)^3} \int \frac{d^3p_2}{(2\pi)^3} e^{i(\mathbf{p}_1\cdot\mathbf{r}_\alpha + \mathbf{p}_2\cdot\mathbf{r}_\beta)} \mathcal{M}_{\alpha\beta}(\mathbf{p}_1, \mathbf{p}_2)$$

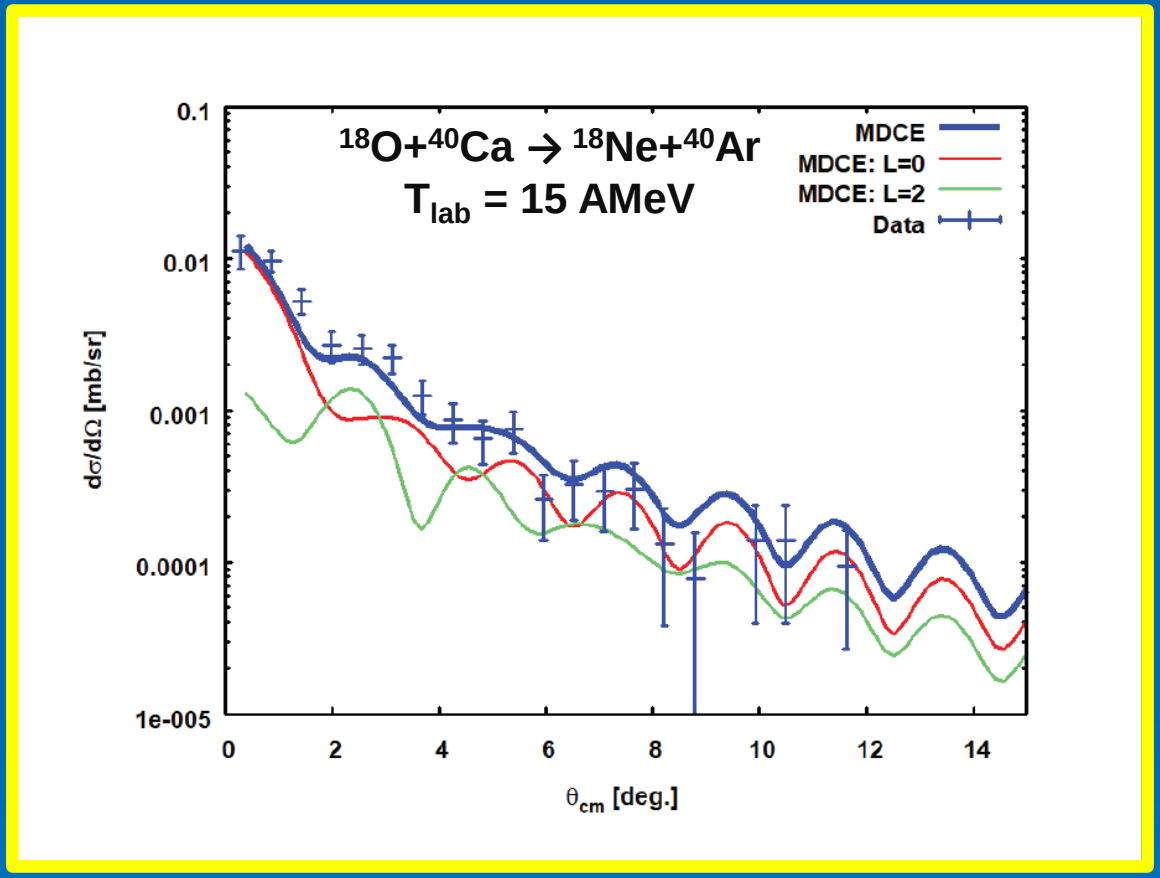
$$\mathcal{M}^{(MDCE)}_{\alpha\beta}(\mathbf{p}_1, \mathbf{p}_2) = D_{\pi^\pm}(\mathbf{p}_2) \langle B | \mathcal{V}^{(2)}(\mathbf{1}, \mathbf{2}) | A \rangle \langle b | \mathcal{V}^{(2)}(\mathbf{3}, \mathbf{4}) | a \rangle D_{\pi^\mp}(\mathbf{p}_1)$$

$$\mathcal{V}^{(2)}(\mathbf{i}, \mathbf{j}) = \mathcal{T}_{\pi^b N_2, \pi^0 N_2'}(\mathbf{i}) \mathcal{G}_{\pi^0}(\mathbf{i} - \mathbf{j}) \mathcal{T}_{\pi^0 N_1', \pi^a N_1}(\mathbf{j})$$

First MDCE Results

MDCE Cross Section

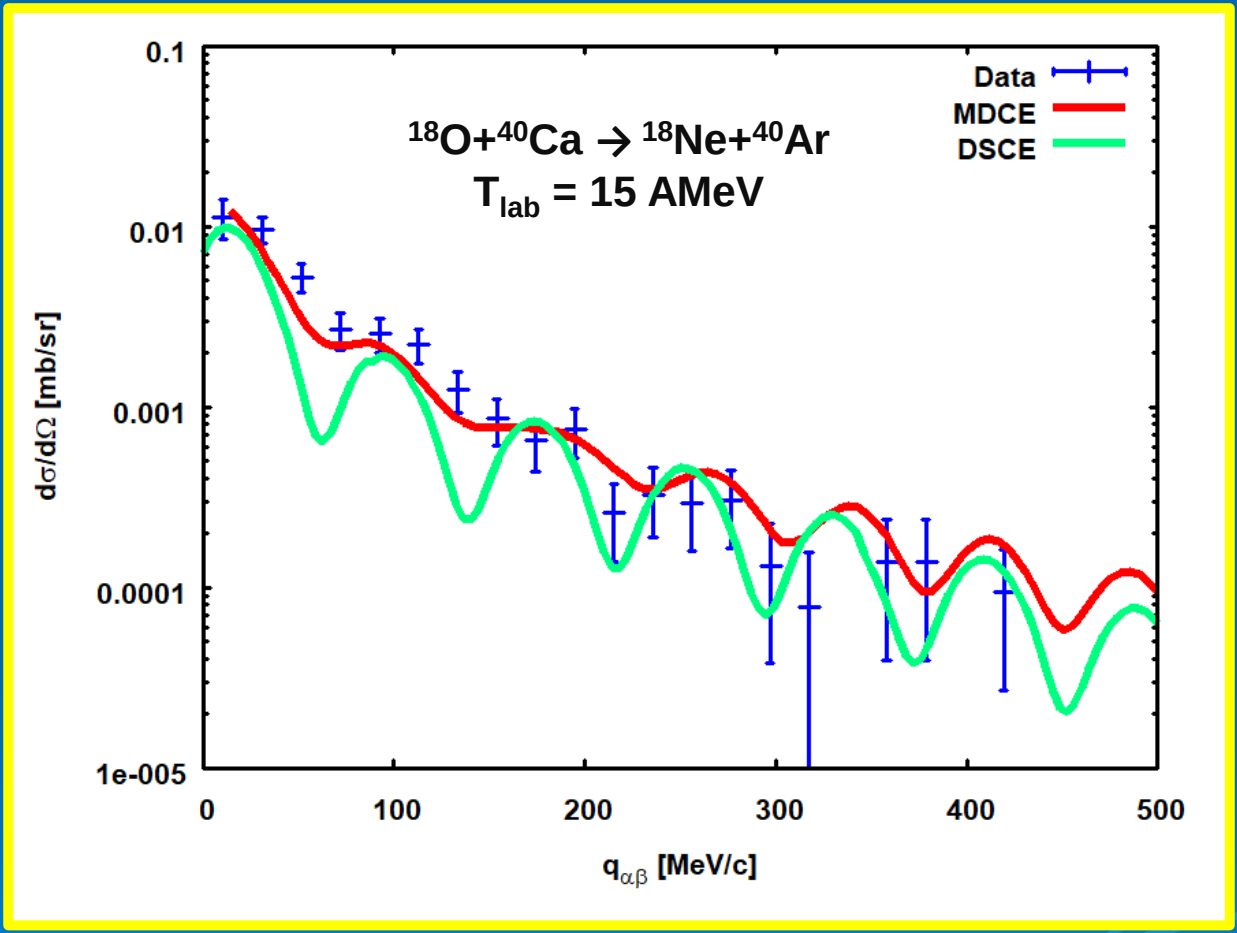
- pions only -



$^{40}Ca(0^+) \rightarrow ^{40}Ar([n^{-2}p^2]0^+)$: $J=0^+$ with $L=S=0$ & $[L=2 \times S=2]_{0+}$

Data: F. Cappuzzello et al., EPJ A51 (2015)

MDCE Reactions:
Probing Nuclear Physics @ High Momentum Transfer



2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$

1-step MDCE: $^{40}Ca(0^+) \rightarrow {}^{40}Ar([n^{-2}p^2]0^+)$: J=0+ with L=S=0 & $[L=2 \times S=2]_{0+}$

Data: F. Cappuzzello et al., EPJ A51 (2015)

Summary and Outlook

- **Theory of heavy ion SCE reactions: direct 1-step, transfer 2-step**
- **2-step DSCE reaction mechanism ↔ $2\nu2\beta$ – decay analogue**
- **1-step MDCE ↔ $0\nu2\beta$ – decay analogue**
- **Effective rank-2 IsoTensor interaction**
- **Investigations of rare processes :**
  - **Probing nuclear 2-body CC currents and short range correlations**
  - **Probing $2\nu2\beta$ & $0\nu2\beta$-type NME in a hadronic analogue process**

Precision physics with heavy ions

…together with the NUMEN theory group J. Bellone, S. Burello, M. Colonna (Catania), D. Gambacurta, J.-A. Lay (Sevilla), E. Santopinto (Genova) and the NUMEN@LNS collaboration