PROBING SHORT RANGE CORRELATIONS IN HEAVY-ION DOUBLE CHARGE EXCHANGE REACTIONS

C. Garofalo[1,2], F. Cappuzzello[1,2], M. Cavallaro[2], H. Lenske[3] for the NUMEN collaboration

[1] Dipartimento di Fisica e Astronomia "E. Majorana", Università di Catania, Catania, Italy
[2] INFN- Laboratori Nazionali del Sud, Catania, Italy
[3] Institut fur Theoretische Physik, Justus–Liebig–Universitat Giessen, D-35392 Giessen, Germany

caterina.garofalo@lns.infn.it

MAYORANA SCHOOL & WORKSHOP
MODICA, 16/06/2025 – 25/06/2025

DCE REACTION AND $0\nu\beta\beta$ DECAY

DCE reaction is a second-order nuclear process:

$$ {}^{a}_{z}a \;+\; {}^{A}_{Z}A \longrightarrow {}^{a}_{z\pm2}\, b \;+\; {}^{A}_{Z\mp2}B $$

$$\left[T^{0\nu\beta\beta}_{1/2}\right]^{-1} = G_{0\nu}\, |M_{0\nu}|^2\, \langle m_{\beta\beta}\rangle^2$$

Frank T Avignone et al., Rev. Mod. Phys. 80, 481, (2008)

- $\left[T^{0\nu\beta\beta}_{1/2}\right]^{-1}$ is the decay time
- $G_{0\nu}$ is the phase space factor
- $M_{0\nu}$ is the $0\nu\beta\beta$ NME
- $\langle m_{\beta\beta}\rangle$ is the neutrino effective mass

Large uncertainties

NUMEN

NUclear
Matrix
Elements for
Neutrinoless
double beta decay

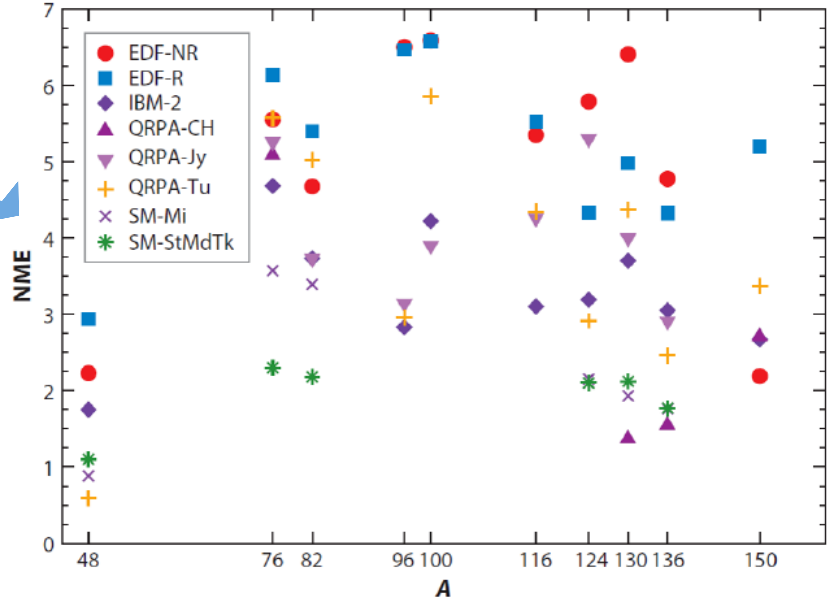
DCE REACTIONS

- **Nuclear physics**

Isospin dynamics
Effects of the rank-2 isotensor operators in bound nuclear systems

- **Neutrino physics**

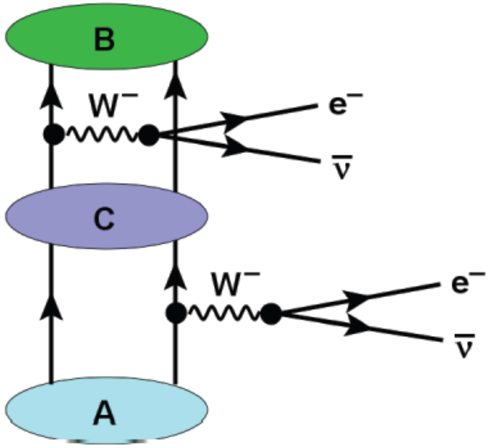
probing key quantities involved in $\beta\beta$ decay



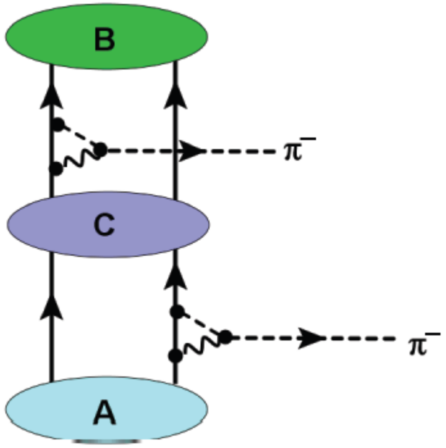
Michelle J Dolinski et al., Annu. Rev. Nucl. Part. Sci. 69, 219 (2019)

DCE MECHANISMS

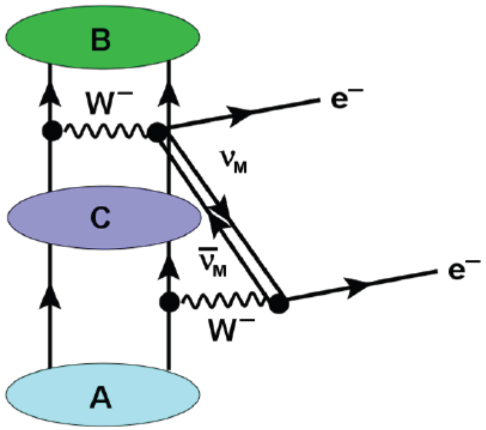
$$M_{0\nu} = \langle \phi_f | \hat{O}^{0\nu\beta\beta} | \phi_i \rangle \longleftrightarrow M_{DCE} = \langle \phi_f | \hat{O}^{DCE} | \phi_i \rangle$$



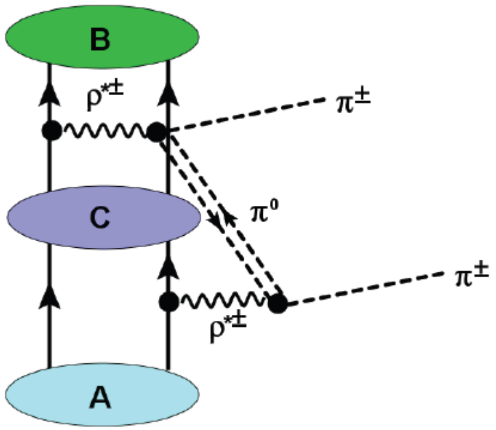
$2\nu\beta\beta$



DSCE



$0\nu\beta\beta$



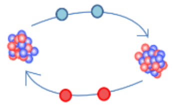
MDCE

Double Single Charge Exchange (DSCE)

J. I. Bellone et al., Phys. Lett. B **807**, 135528 (2020).

Majorana Double Charge Exchange (MDCE)

H. Lenske et al., Universe **10**, 202 (2024).



Warning: there is also the **Multi-nucleon Transfer Double Charge Exchange** (TDCE)

L. Ferreira et al., PRC **105**, 014630 (2022).

MDCE MECHANISMS

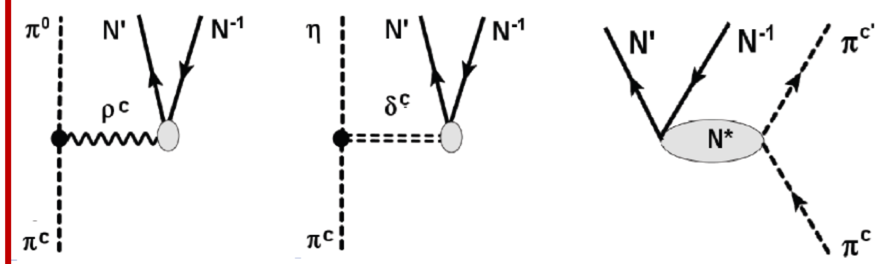
$$d\sigma_{\alpha\beta}^{(1)} \propto \sum_{,M_A\in\alpha,\, M_b,M_B\in\beta} \boxed{\left|\boldsymbol{M}_{\alpha\beta}^{(1)}\left(\vec{k}_\alpha\vec{k}_\beta\right)\right|^2} d\Omega_{\alpha\beta}\,, \quad M_{\alpha\beta}^{(1)}\left(\vec{k}_\alpha\vec{k}_\beta\right) = \langle\chi_\beta^{(-)}\,|\,\langle B|T_{\pi N}G_{\pi C}T_{\pi N}|A\rangle\, D_{\pi^q}\, D_{\pi^{q'}}\langle B'|T_{\pi N}G_{\pi' C'}T_{\pi N}|A'\rangle|\chi_\alpha^{(+)}\rangle$$

DISTORTED WAVE REACTION AMPLITUDE

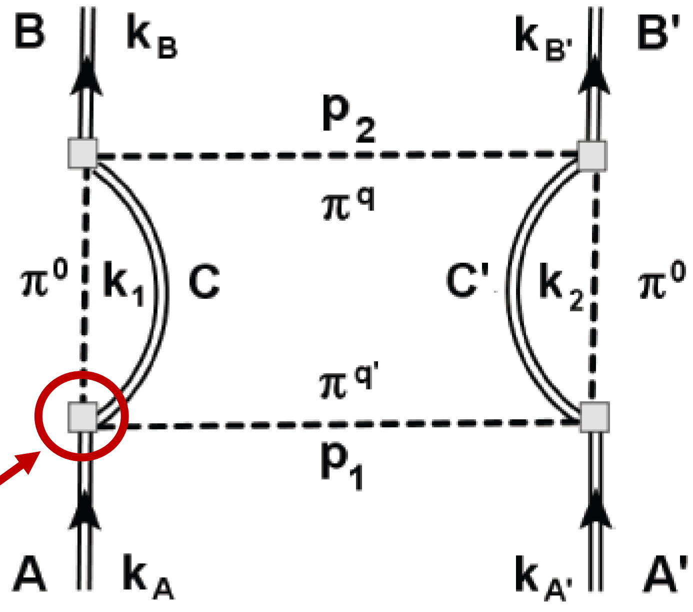
TRANSITION FORM FACTOR

Exit channel:
- Second SCE-type transition

Intermediate channel:
- π_0
- SCE-excited nucleus C
- Intermediate propagator $G_{\pi C}$



Pion-nucleon scattering leading to excitation of np⁻¹ or pn⁻¹ SCE particle–hole configurations



T channel exchange of the $\pi^{\pm}$:
- Product propagator $D_{\pi^q\pi^{q'}}$

- **Pion potentials**

Strong counterpart of the neutrino potential

$$U_\pi(\vec{x}) = \int \frac{d^3k}{(2\pi)^3}\, \boldsymbol{T}_{\pi N} e^{i\vec{k}\cdot\vec{x}}\, g_{\pi C}^{(+)}\, \boldsymbol{T}_{\pi N}$$

PION-NUCLEON ISOVECTOR T-MATRIX
- T_0 → S-WAVE
- T_1 → P-WAVE
- T_2 → P-WAVE

Partial waves!!

- **Transition Matrix Elements (TME)**

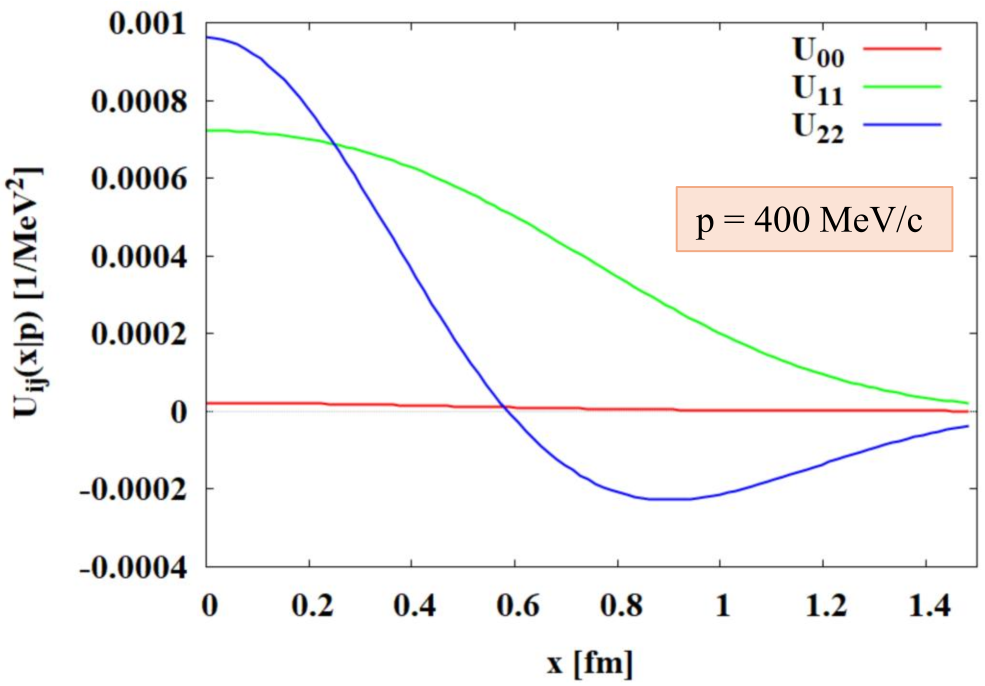
$$W_{AB} = \langle B|T_{\pi N}G_{\pi C}T_{\pi N}|A\rangle$$

NUMERICAL RESULTS

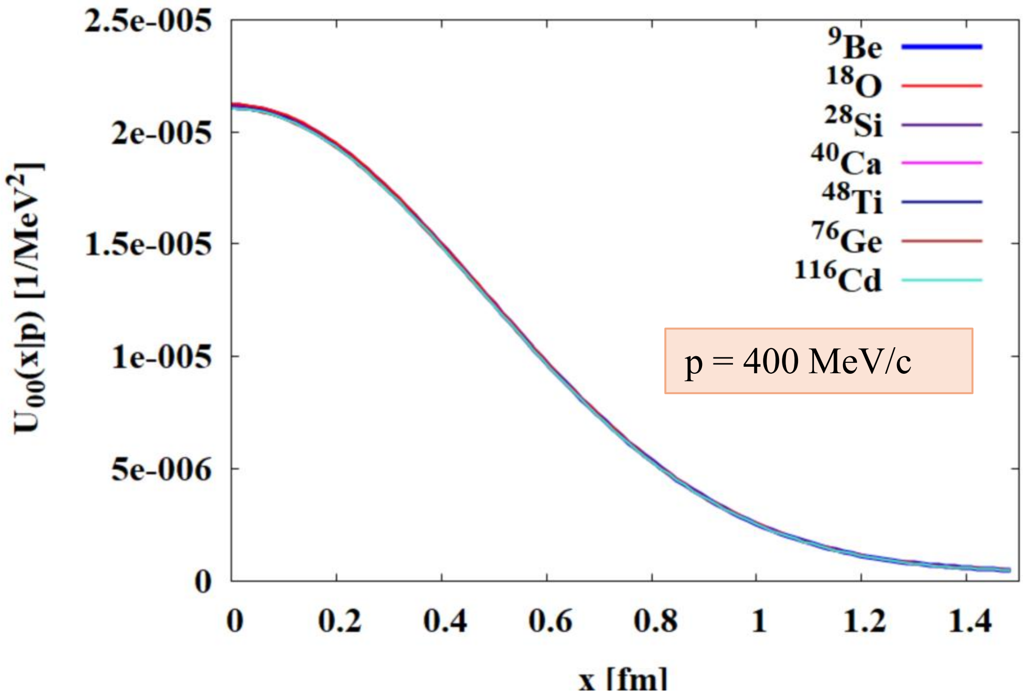
- Partial waves decomposition
- Closure form
- Collinear approximation

^{18}O as a projectile @ 275 MeV

➢ **P-wave potential** components dominate over the **S-wave** ones.



➢ **Short range – conjecture**

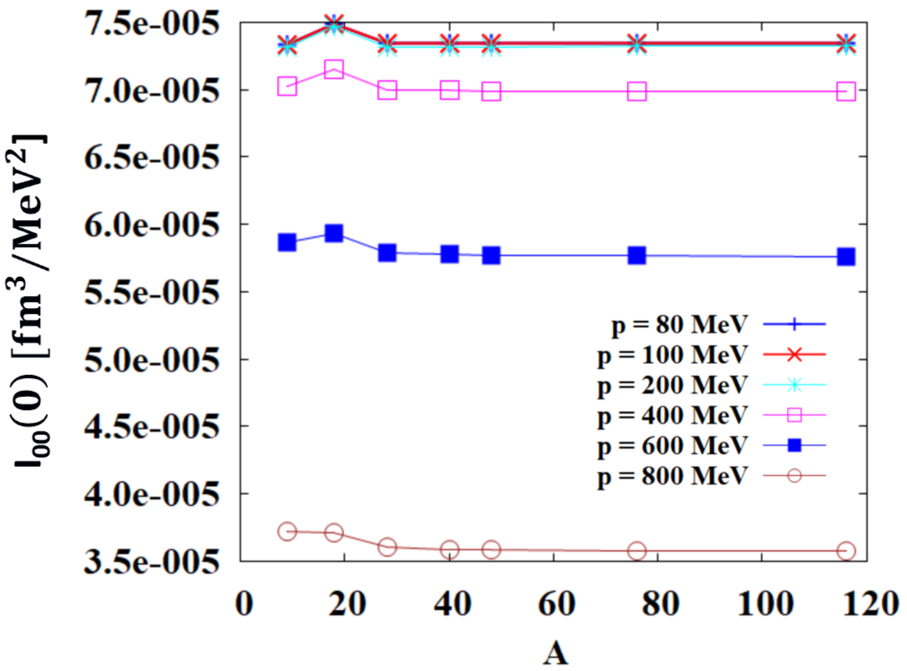


NUMERICAL RESULTS

Moments of pion potentials:

$$I_{ij}(n) = \int d^3r\, r^n\, U_{ij}(r)$$

$\langle r \rangle_{ij}$	**Normalized linear radial monopole moments**	potential radius
$\langle r^2 \rangle_{ij}$	**Quadratic radial monopole moments**	mean square radius
$\nu_{ij} = \langle r^2 \rangle_{ij} - \langle r \rangle_{ij}^2$	**Potential distribution variance**	potential spatial extension



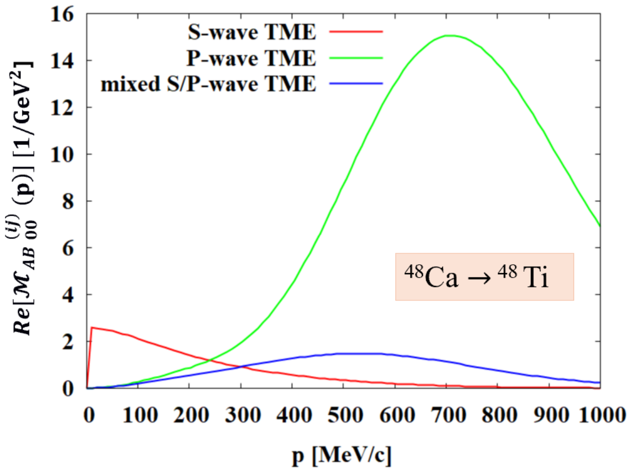
Components	$\langle \bar{r} \rangle_{ij}$ (fm)	ν_{ij} (fm^2)
00	1.89	0.10
11	1.04	0.03
22	1.49	0.06
01	1.41	0.05
02	1.20	0.04
12	1.06	0.03

- **Moments of pion potentials are near-independent with respect to the nuclear system**
- **The MDCE pion potential covers a radius of about 1 fm & only a small dispersion around the mean value is present.**

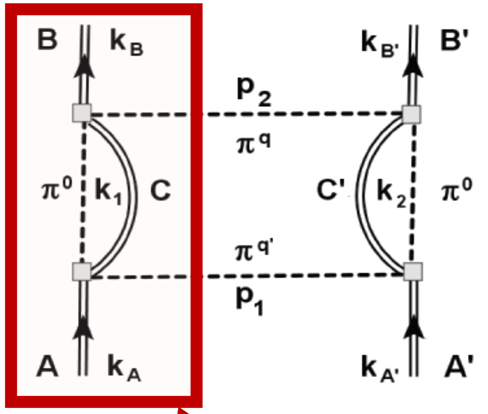
NUMERICAL RESULTS

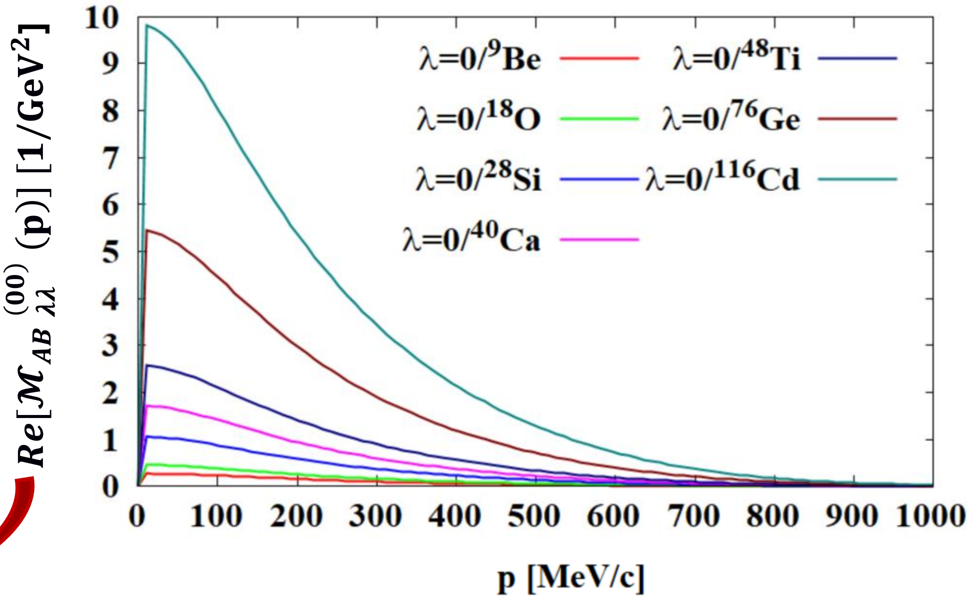
$$W_{AB} = \langle B|T_{\pi N} G_{\pi C} T_{\pi N}|A\rangle \;\rightarrow W_{AB} \sim \sum_{ij} \boxed{\mathcal{M}_{AB}{}^{(ij)}}$$

nine partial TMEs



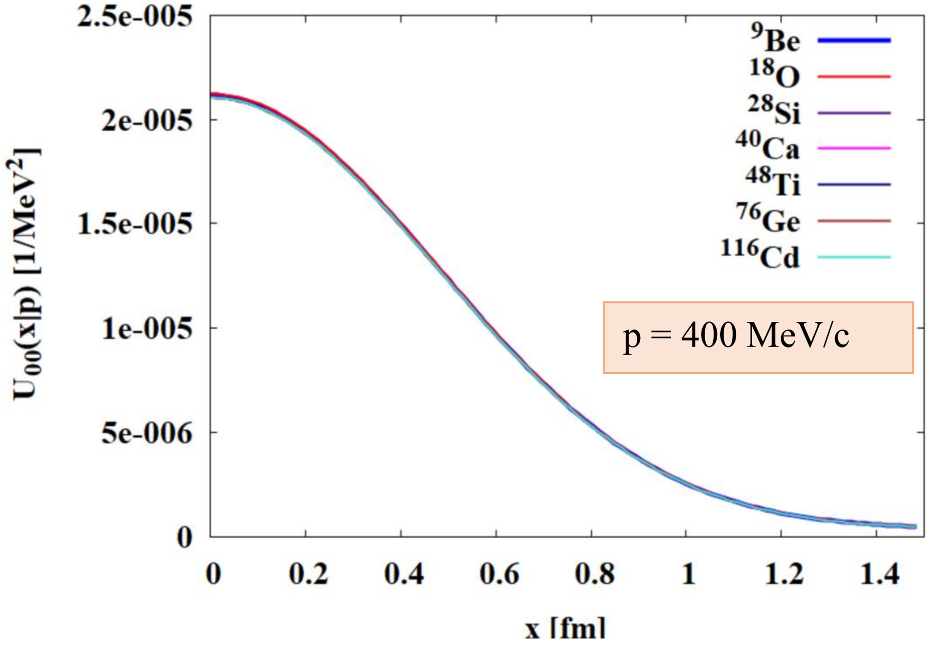
- **The double P-wave TME increase strongly with momentum, exceeding the strength of the S-wave TME by large factors.**
- **The imaginary part of TMEs is of moderate strenghts**
- **TMEs grow with the mass involved in the DCE transition**
  - $^{9}Be \rightarrow {}^{9}He$
  - $^{18}O \rightarrow {}^{18}Ne$
  - $^{28}Si \rightarrow {}^{28}Mg$
  - $^{40}Ca \rightarrow {}^{40}Ar$
  - $^{48}Ca \rightarrow {}^{48}Ti$
  - $^{76}Ge \rightarrow {}^{76}Zn$
  - $^{116}Cd \rightarrow {}^{116}Pd$





CONCLUSIONS & FUTURE PERSPECTIVES

- The pion potential presents a radius of $\sim$ **1 *fm*** pronounced **short-range character** of the MDCE mechanism;
- The MDCE mechanism is a near - independent from the nuclear system, especially for medium and heavy nuclei, at the level of a few per cent.



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- Differential cross section to compare with the experimental data: **in progress!**

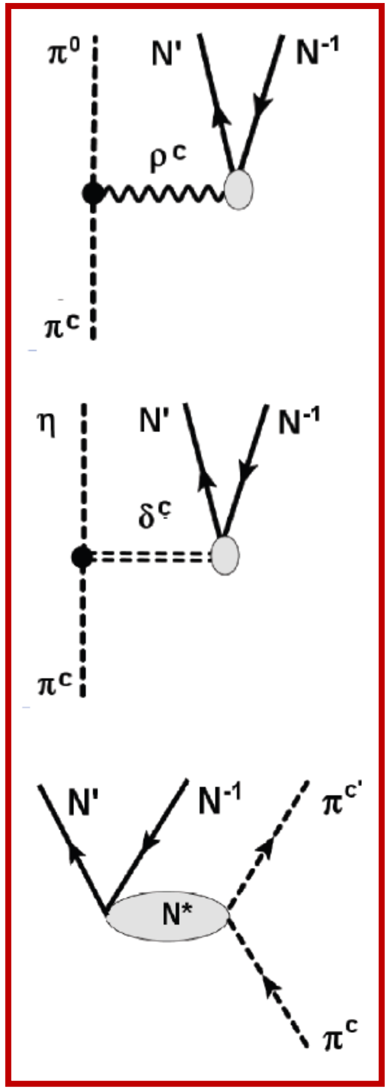
THANK YOU FOR YOUR ATTENTION

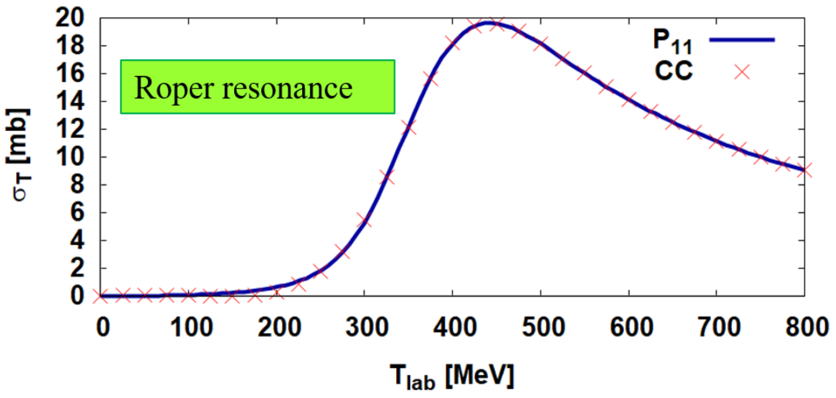
MODICA, 23/06/2025

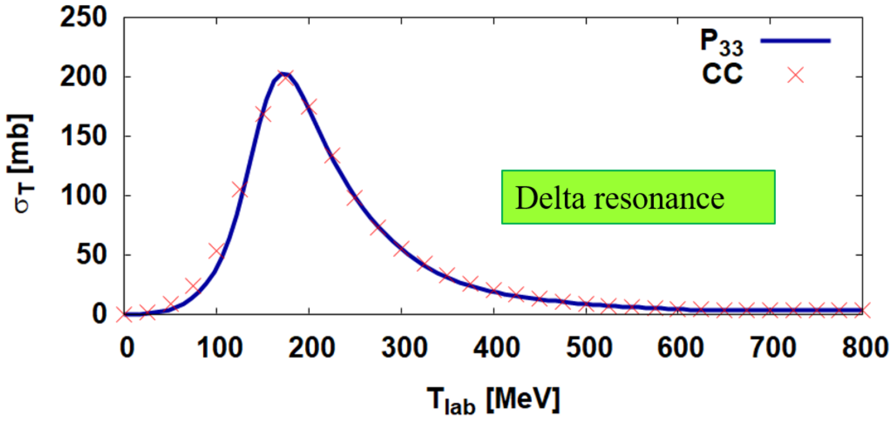
caterina.garofalo@lns.infn.it

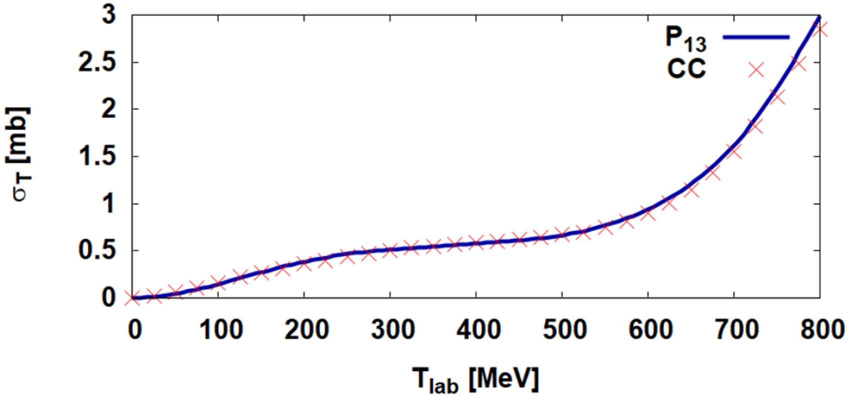
Backup slides

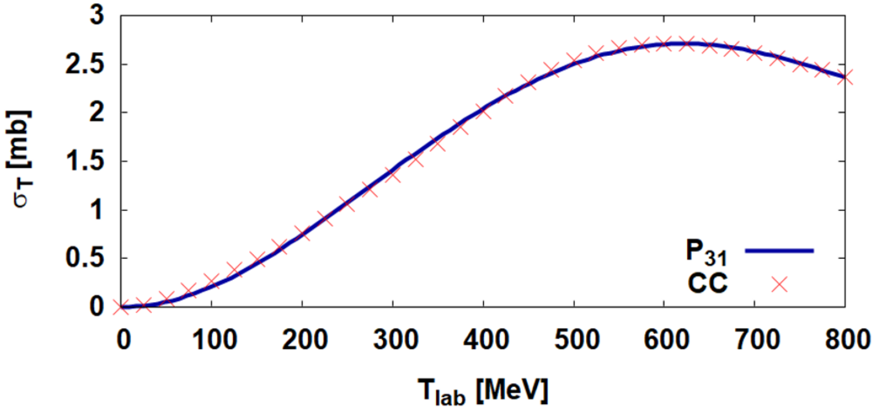
BACKUP SLIDES











BACKUP SLIDES

$$k^2 = \frac{1}{4s_{\pi N}}(s_{\pi N} - (m_N + m_\pi)^2)(s_{\pi N} - (m_N - m_\pi)^2)$$

$$T_{lab} = \frac{1}{2m_N}\left(s_{\pi N} - (m_N + m_\pi)^2\right)$$

$\downarrow$

1. $s_{\pi N} > (m_N + m_\pi)^2 \rightarrow$ physically accessible region

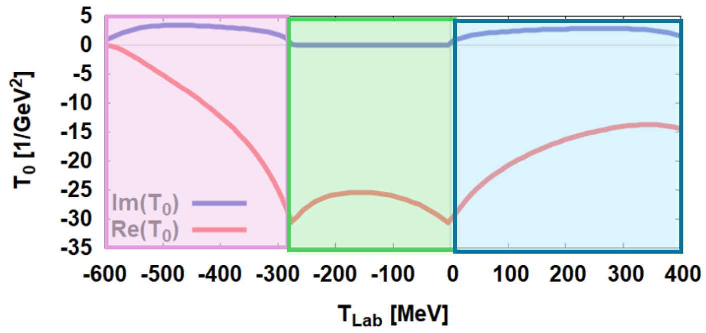
$k^2 > 0, \quad T_{lab} > 0$

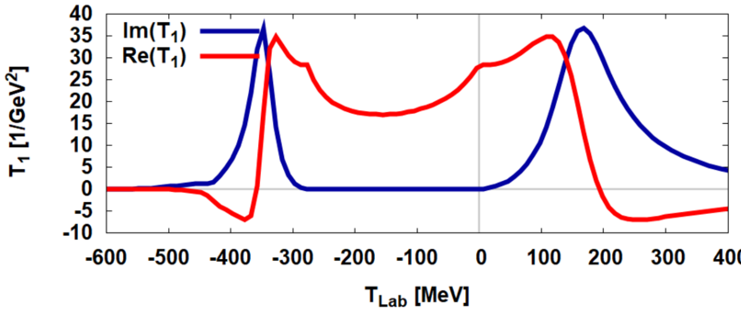
2. $(m_N - m_\pi)^2 < s_{\pi N} < (m_N + m_\pi)^2 \rightarrow$ first sub-threshold region

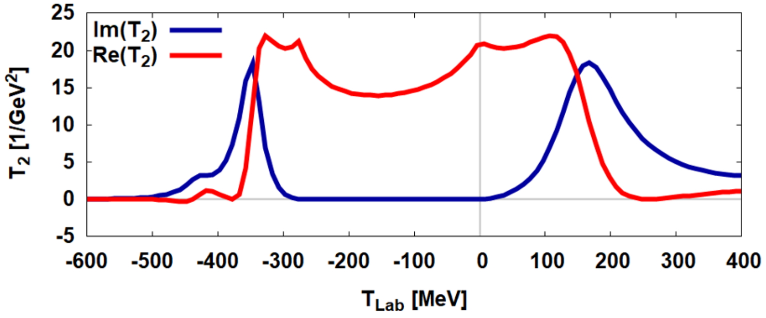
$k^2 < 0, \quad T_{lab} < 0$

3. $s_{\pi N} < (m_N - m_\pi)^2 \rightarrow$ second sub-threshold region

$k^2 > 0, \quad T_{lab} < 0$





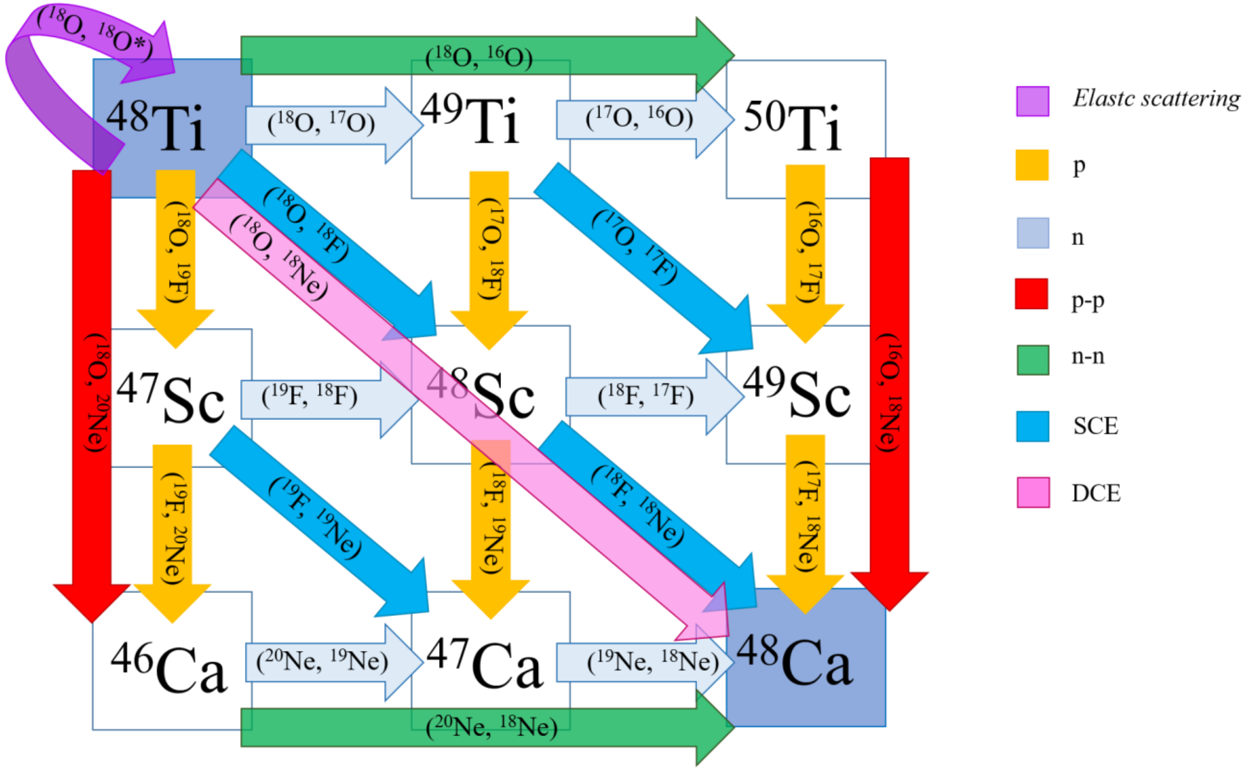


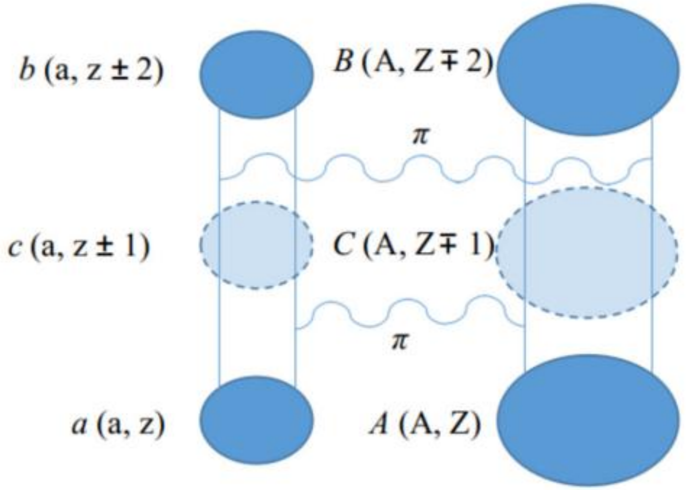
$$\mathcal{U}_\pi(\mathbf{x}|\mathbf{p}_{1,2}\sigma_{1,3}) = -m_\pi \int \frac{d^3k}{(2\pi)^3} \mathcal{T}_{\pi N}(\mathbf{p}_2, \mathbf{k}|\sigma_3) \boxed{\frac{e^{i\mathbf{k}\cdot\mathbf{x}}}{m_\pi^2 + k^2}} \mathcal{T}_{\pi N}(\mathbf{p}_1, \mathbf{k}|\sigma_1).$$

$$k^2 = \frac{1}{4s_{\pi N}}(s_{\pi N} - (m_N + m_\pi)^2)(s_{\pi N} - (m_N - m_\pi)^2)$$

$$s_{\pi N} = \frac{s_{\pi C}}{A^2}$$

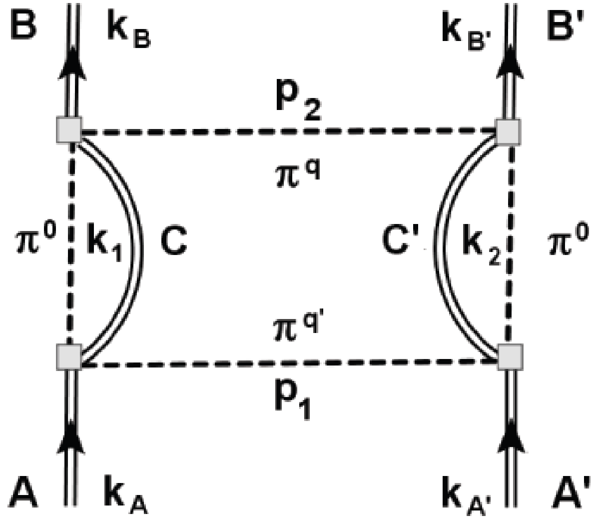
$$\mathcal{W}_{AB}(\mathbf{p}_1, \mathbf{p}_2) = \langle \mathcal{I}^{(\pi)}_{2,\mp 2} \rangle \langle B | e^{-i\mathbf{p}_2\cdot\mathbf{r}_2} \mathcal{U}_\pi(\mathbf{x}|\mathbf{p}_{1,2}\sigma_{1,3}) e^{i\mathbf{p}_1\cdot\mathbf{r}_1} \mathcal{I}^{(N)}_{2\pm 2} | A \rangle,$$





DSCE

T_{nn}



MDCE

$T_{\pi n}$