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

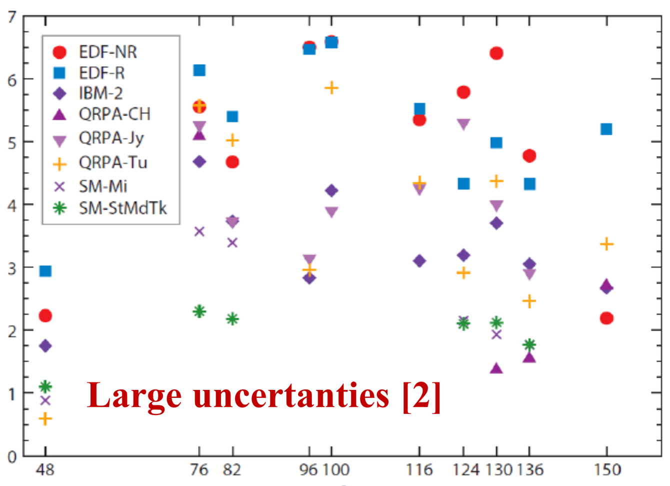
[1] Dipartimento di Fisica e Astronomia "E. Majorana", Università di Catania, Catania, Italy
[2] INFN- Laboratori Nazionali del Sud, Catania, Italy
[3] Institut fur Theoretische Physik, Justus–Liebig–Universitat Giessen, D-35392 Giessen, Germany

1. NUMEN PROJECT & DCE REACTION

decay time — phase space factor — neutrino effective mass

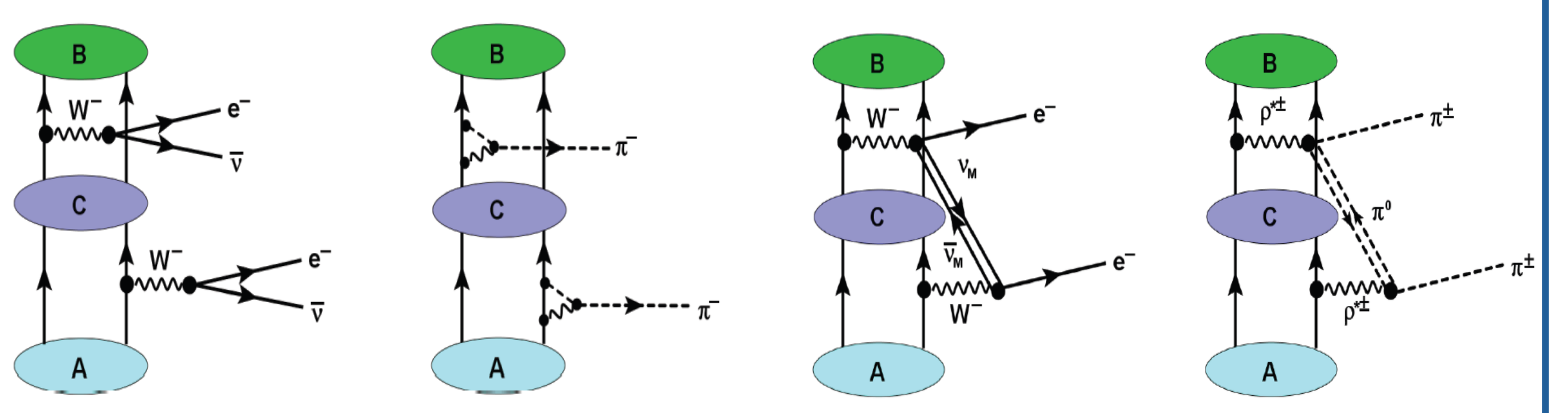
$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = G_{0\nu}\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2 \quad [1]$$

the $0\nu\beta\beta$ NME



NUclear Matrix Elements for Neutrinoless double beta decay [3]

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



Double Single Charge Exchange (DSCE) [4] — **Majorana Double Charge Exchange** (MDCE) [5]

⚠ There is also the **Multi-nucleon Transfer Double Charge Exchange** (TDCE) [6]

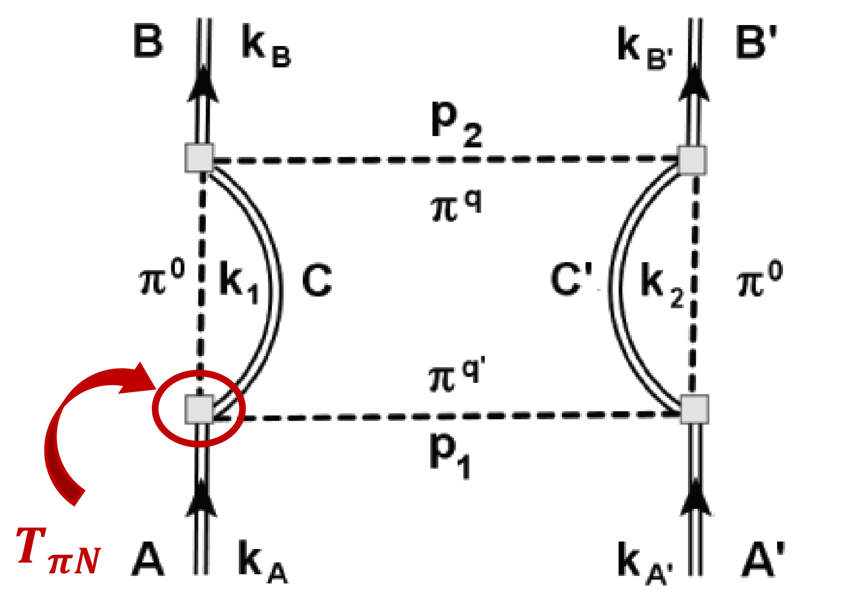
2. MDCE MECHANISM

DISTORTED WAVE REACTION AMPLITUDE

$$d\sigma_{\alpha\beta}^{(1)} \propto \sum_{M_A\in\alpha,\,M_b,M_B\in\beta} \left|M_{\alpha\beta}^{(1)}\left(\vec{k}_\alpha \vec{k}_\beta\right)\right|^2 d\Omega_{\alpha\beta}\,,$$

TRANSITION FORM FACTOR

$$M_{\alpha\beta}^{(1)}\left(\vec{k}_\alpha \vec{k}_\beta\right) = \langle\chi_\beta^{(-)}|\,\langle B|T_{\pi N}G_{\pi C}T_{\pi N}|A\rangle\, D_{\pi^q}\, D_{\pi^{q'}} \langle B'|T_{\pi N}G_{\pi C'}T_{\pi N}|A'\rangle|\chi_\alpha^{(+)}\rangle$$



Exit channel β:
- Second SCE-type transition

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

Incident channel α:
- **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:

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

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

$$T_{\pi N}(\boldsymbol{p},\boldsymbol{p}') = \left[T_0(s_{\pi N}) + \frac{1}{m_\pi^2}\left(T_1(s_{\pi N})\, p\cdot p' + i\,T_2(s_{\pi N})\, \boldsymbol{\sigma}\cdot(\boldsymbol{p}\times\boldsymbol{p}')\right)\right] \boldsymbol{T}_\pi\cdot\boldsymbol{\tau}_N$$

➢ Transition Matrix Elements (TMEs)

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

nine partial TMEs

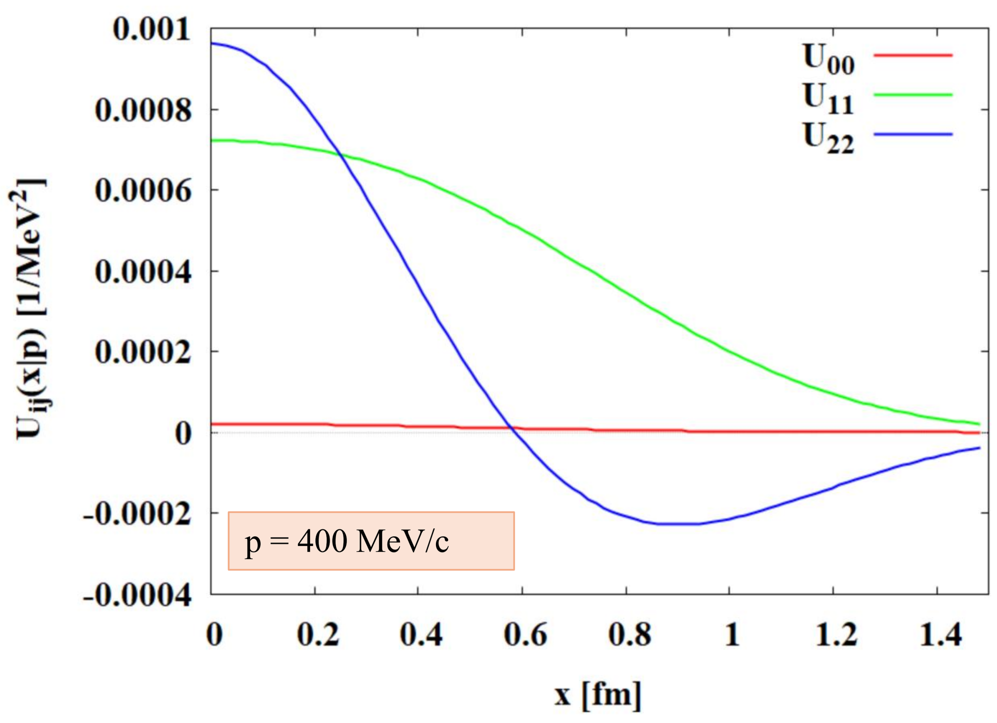
REFERENCES

[1] F. Cappuzzello et al., Prog. Part. Nucl. Phys. **128**, 103999 (2023).
[2] M. Agostini et al., Rev. Mod. Phys **95**, 025002 (2023).
[3] F. Cappuzzello et al., EPJ A **54**, 72 (2018).
[4] J. I. Bellone et al., Phys. Lett. B **807**, 135528 (2020).
[5] H. Lenske et al., Universe **10**, 202 (2024).
[6] L. Ferreira et al., PRC **105**, 014630 (2022).

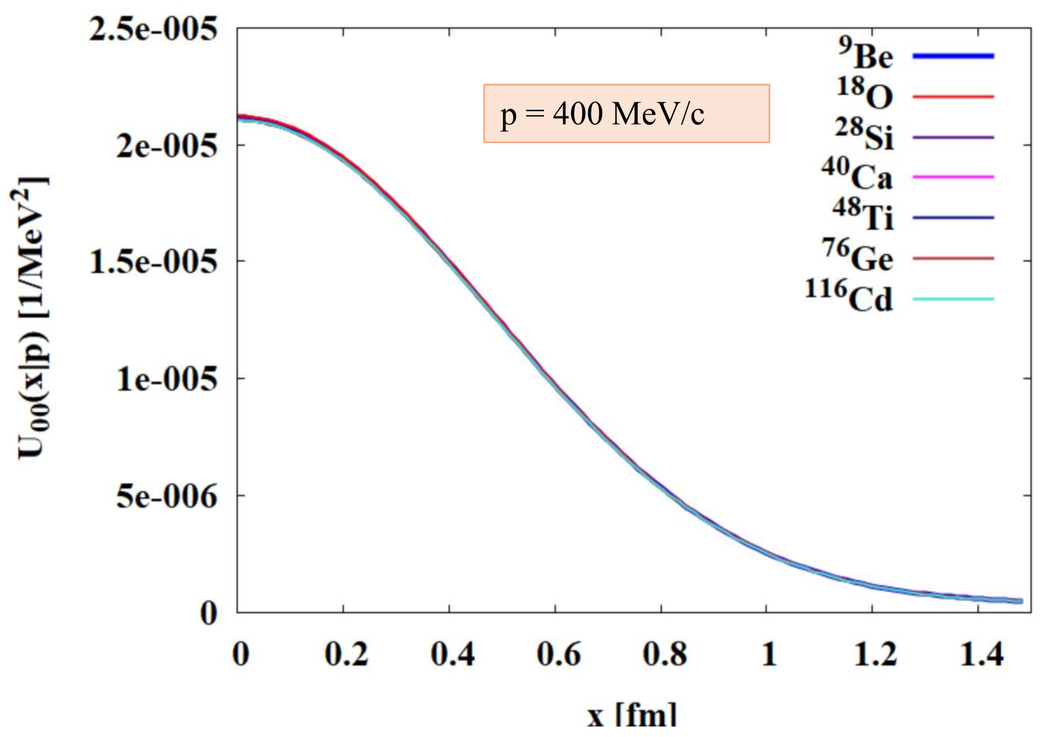
3. NUMERICAL RESULTS

Note: U_π & TMEs were derived in **closure approximation** and using the **collinear approximation.**

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



➢ **Short range – conjecture**



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

n = 0	→ strength of the potential
n = 1, 2	→ potential spatial distribution

$$\langle r\rangle_{ij} = \frac{\int d^3r\, r\, U_{ij}(r)}{\int d^3r\, U_{ij}(r)}$$

$$\langle r^2\rangle_{ij} = \frac{\int d^3r\, r^2\, U_{ij}(r)}{\int d^3r\, U_{ij}(r)}$$

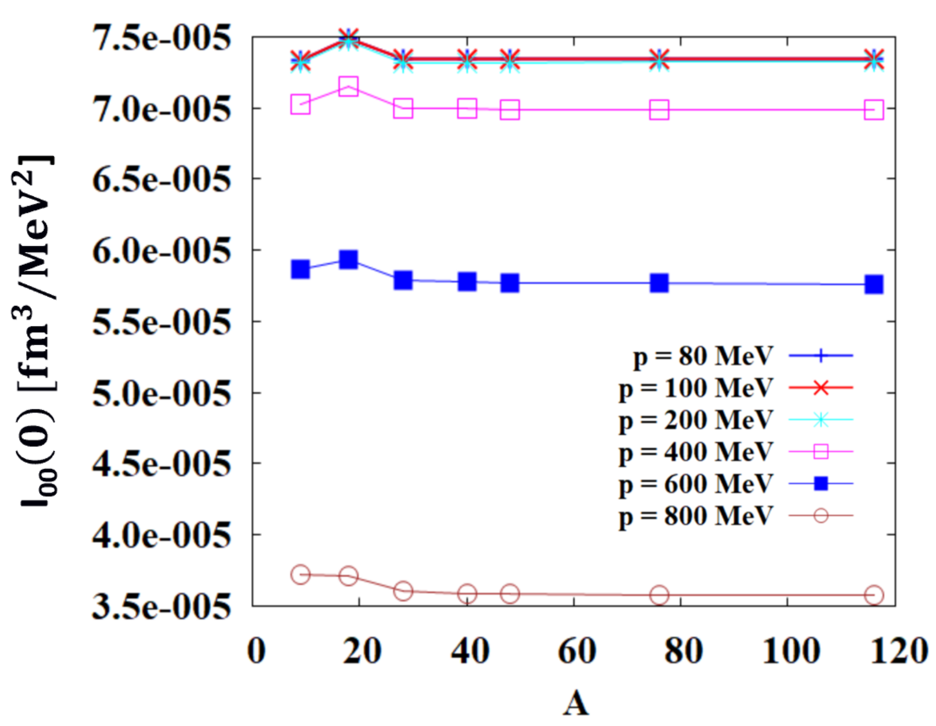
$$\nu_{ij} = \langle r^2\rangle_{ij} - \langle r\rangle_{ij}^2$$

Normalized linear radial monopole moments → potential radius;

Quadratic radial monopole moments → extension of the potential with respect to the origin

Potential distribution variance → potential spatial extension

➢ **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.**

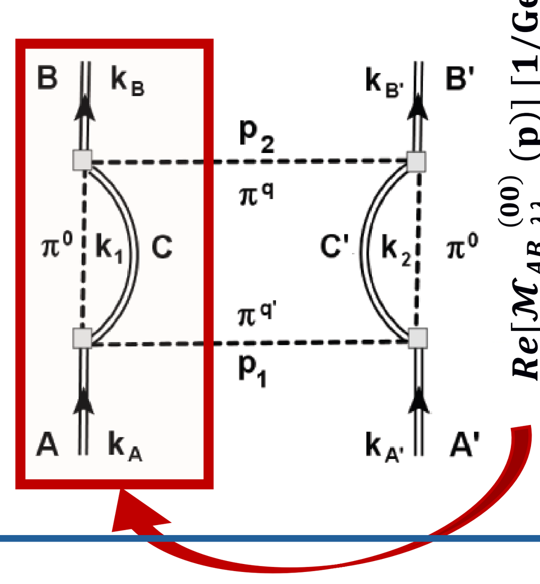
Components	$\langle\bar{r}\rangle_{ij}$ (fm)	ν_{ij} (fm^2)
00	1.89	0.10
11	1.04	0.03
22	1.49	0.06
01	1.41	0.05
02	1.20	0.04
12	1.06	0.03

$\langle\bar{r}\rangle_{ij}$ is the mean value of the normalized moments with respect to A for each component, having averaged with respect to the momentum p.

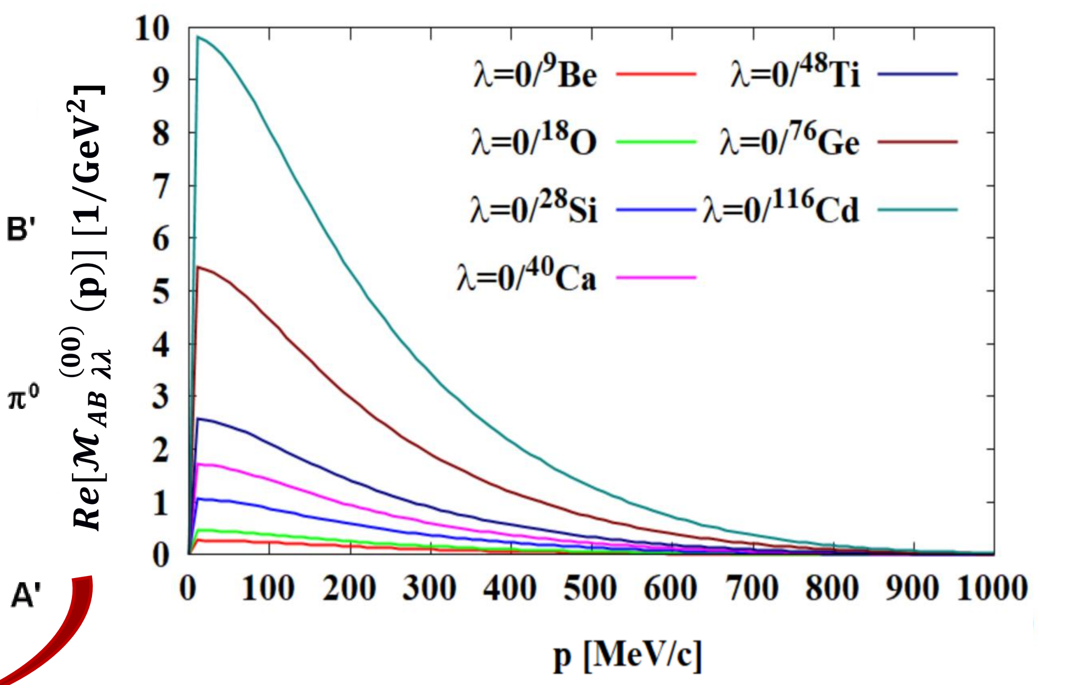
➢ **The P-wave TME increase strongly with momentum, exceeding the strength of the S-wave TME by large factors.**

➢ **TMEs grow with the mass involved in the DCE transition**

- ^{9}Be → ^{9}He
- ^{18}O → ^{18}Ne
- ^{28}Si → ^{28}Mg
- ^{40}Ca → ^{40}Ar
- ^{48}Ca → ^{48}Ti
- ^{76}Ge → ^{76}Zn
- ^{116}Cd → ^{116}Pd

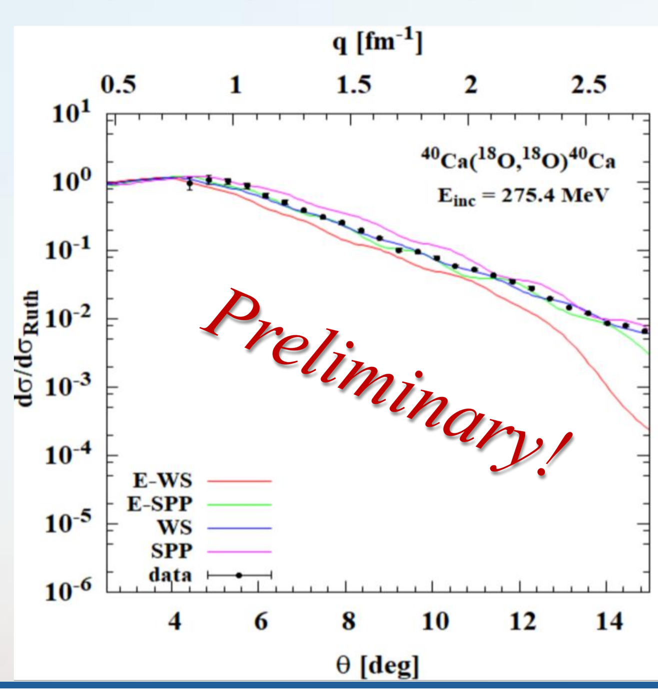


➢ **The imaginary part of TMEs is of moderate strenght**



4. CONCLUSIONS & FUTURE PERSPECTIVES

- The pion potentials are of pronounced **short-range character** with radii of ~ **1 fm**;
- MDCE transitions proceed on **short-range NN correlations** as expected for $0\nu\beta\beta$ *decay*;
- MDCE is a universal mechanism becoming **independent of the nuclear system** for medium and heavy nuclei, at the level of a few per cent;
- Differential cross section to compare with the experimental data: **in progress!**



caterina.garofalo@lns.infn.it

EUROPEAN NUCLEAR PHYSICS CONFERENCE 2025
CAEN, 21/09/2025 – 26/09/2025