JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Institut für Theoretische Physik

Exploring Isotensor Modes in Double Charge Exchange Reactions

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and

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…the Topic to be addressed:

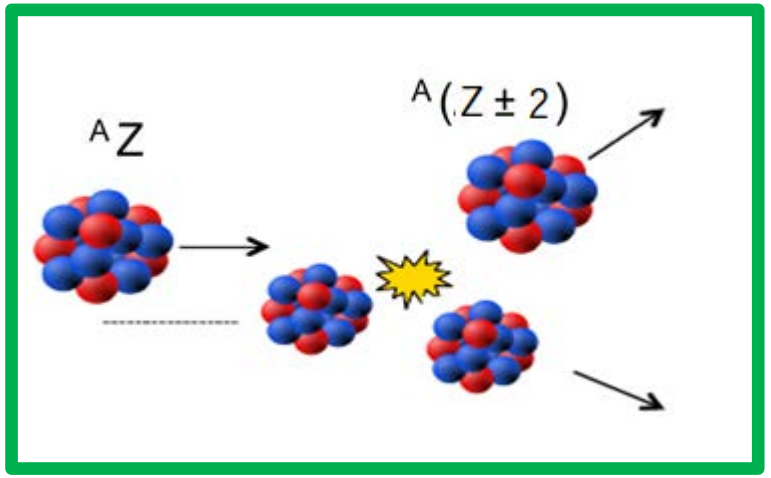
$$A(Z,N) \rightarrow B(Z \pm 2, N \mp 2)$$

- **Single Nuclei: Double-γ and Double-β Decay**

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

- **Dynamical: Double Charge Exchange (DCE) Reactions with Pions and Heavy Ions**
- **Nuclear Structure: np^{-2} and pn^{-2} "Two-Phonon" Modes**
- **How to Excite: $[\tau \times \tau]_{2\pm2}$ rank-2 isotensor operators**
- **Heavy Ion DCE: Explore Isotensor Spectroscopy**
- **Theory: $\left[A^\dagger_{pn} \otimes A^\dagger_{p'n'}\right]_{J_B M_B}$ Configurations, Isotensor Operators, and DCE Reaction Mechanism**

In the Following:
Heavy Ion Double Charge Exchange Reactions

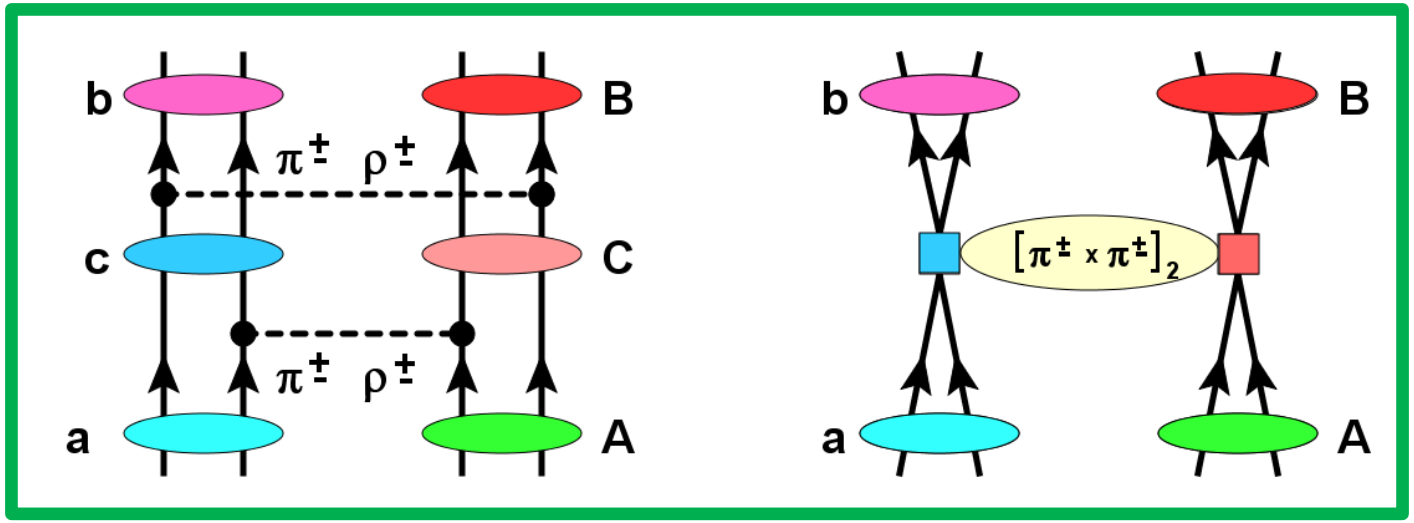


- **Peripheral Direct Reactions of Heavy Ions**
- **DCE Dynamics by Collisional NN Interactions**
- **DCE Reactions as Probes for Nuclear Isotensor Spectroscopy**

Collisional Nuclear Double Charge Exchange (DCE) Reactions by Isovector Mesons

Sequential Double Single CE

Isotensor „Majorana“ DCE



DSCE ~ $O(g^4_{\pi NN})$

$\sigma^{DSCE}(E) \sim 1/E^2$

NME → $2\nu2\beta$

***H.L. et al., Universe* 10:93 (2024)**

MDCE ~ $O(T^4_{\pi N})$

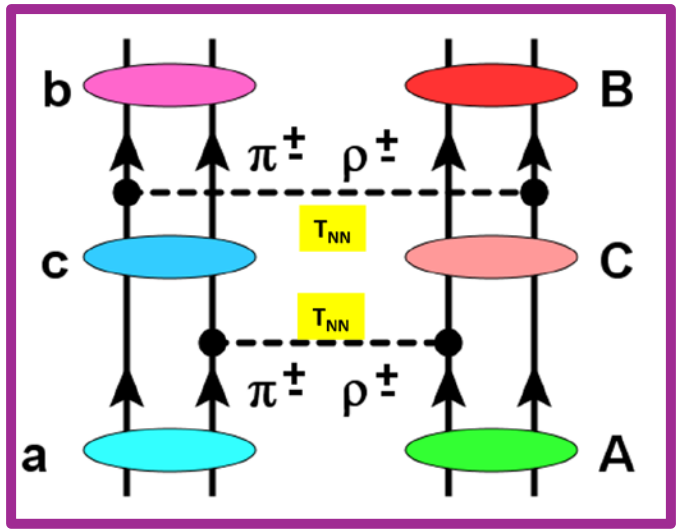
$\sigma^{MDCE}(E) \sim 1$

NME → $0\nu2\beta$

H.L. et al,. Universe 10:202 (2024)

Double Single Charge Exchange Reactions

DCE by 2nd Order NN Isovector Interactions ~T^2_{NN}

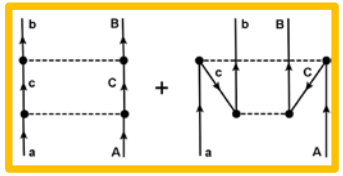


$$\mathcal{M}^{(2)}_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \langle \chi^{(-)}_\beta, bB | \mathcal{T}_{NN} \mathcal{G}^{(+)}_{aA}(\omega_\alpha) \mathcal{T}_{NN} | aA, \chi^{(+)}_\alpha \rangle .$$

FSI **Rank-2 Isotensor Op.** **ISI**

H.L. et al., Universe **10:93 (2024)**

DSCE Reaction Amplitude in Momentum Representation



$$\mathcal{M}^{(2)}_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta) = \int d^3p_1 \int d^3p_2 \int \frac{d^3k_\gamma}{(2\pi)^3} \widehat{K}_{\alpha\beta}(\mathbf{p}_1,\mathbf{p}_2) \mathcal{N}_{\alpha\beta}(\mathbf{p}_1,\mathbf{p}_2|\mathbf{k}_\gamma)$$

ISI/FSI Spectroscopy

DSCE Nuclear Transition Matrix Element (TME)

$$\mathcal{N}_{\alpha\beta}(\mathbf{p}_1,\mathbf{p}_2) = \sum_{cC} \langle bB|\mathcal{S}_{NN}(\mathbf{p}_2|(34))|cC\rangle g^{(+)}_{\alpha\gamma}(k_\gamma) \langle cC|\mathcal{S}_{NN}(\mathbf{p}_1|(12))|aA\rangle$$

$$\mathcal{S}_{NN}(\mathbf{p}|ik) = e^{i\mathbf{p}(\mathbf{r}_i-\mathbf{r}_k)} T_{NN}(\mathbf{p}|ik)\tau_\pm(i)\tau_\mp(j).$$

2-Body Isovector Transition Operators

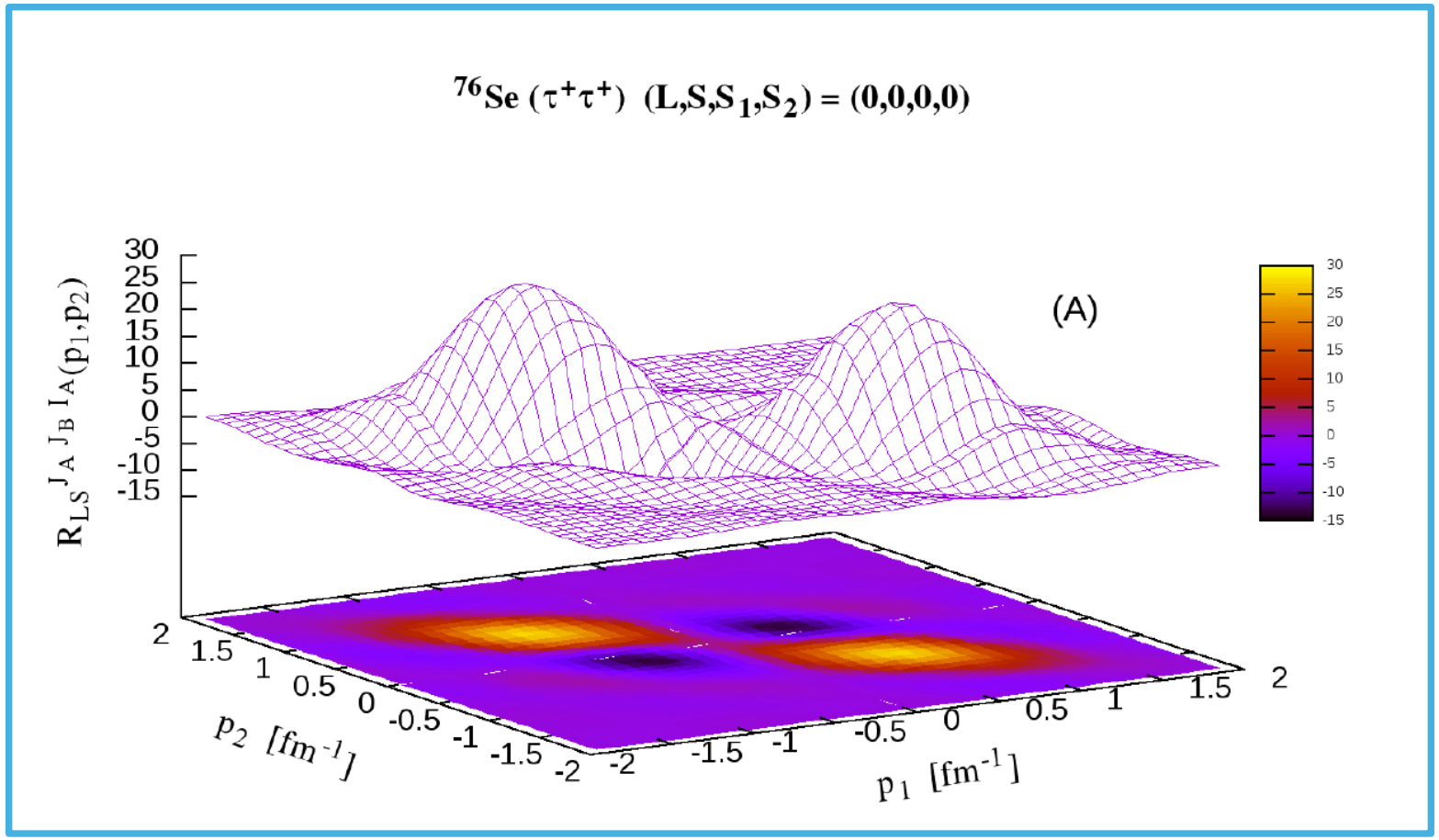
H.L. et al., Universe 10:93 (2024)

J. Bellone et al., PLB 807:135528 (2020)

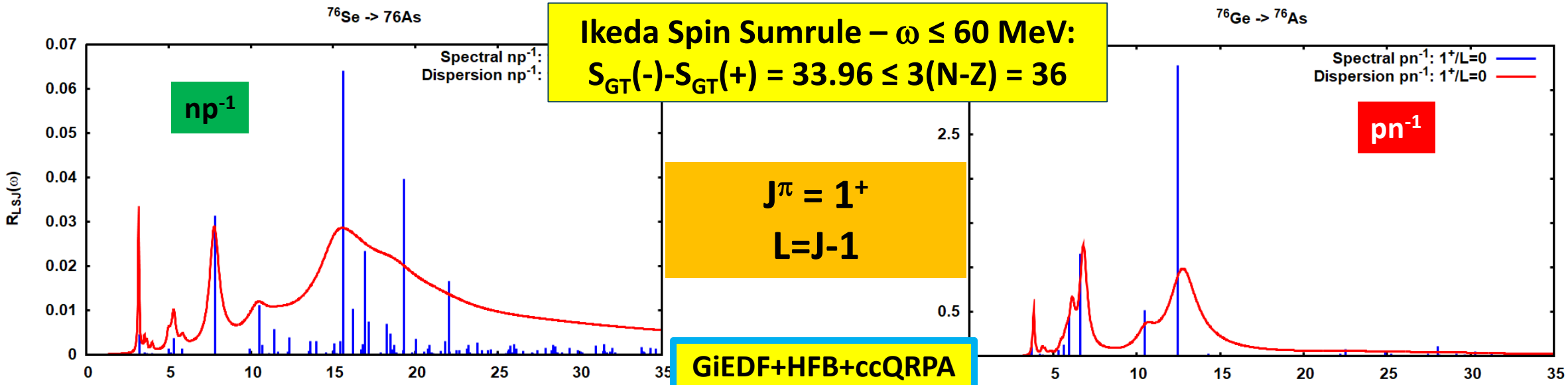
H.L. et al., Universe 7:98 (2021)

Heavy Ion Double Charge Exchange Reactions as Probes for Two-Body Transition Densities

Jessica I.Bellone[1,2], Maria Colonna[1], Danilo Gambacurta[1], and Horst Lenske[3]



Ikeda Spin Sumrule – ω ≤ 60 MeV:
$S_{GT}(-)-S_{GT}(+) = 33.96 \leq 3(N-Z) = 36$

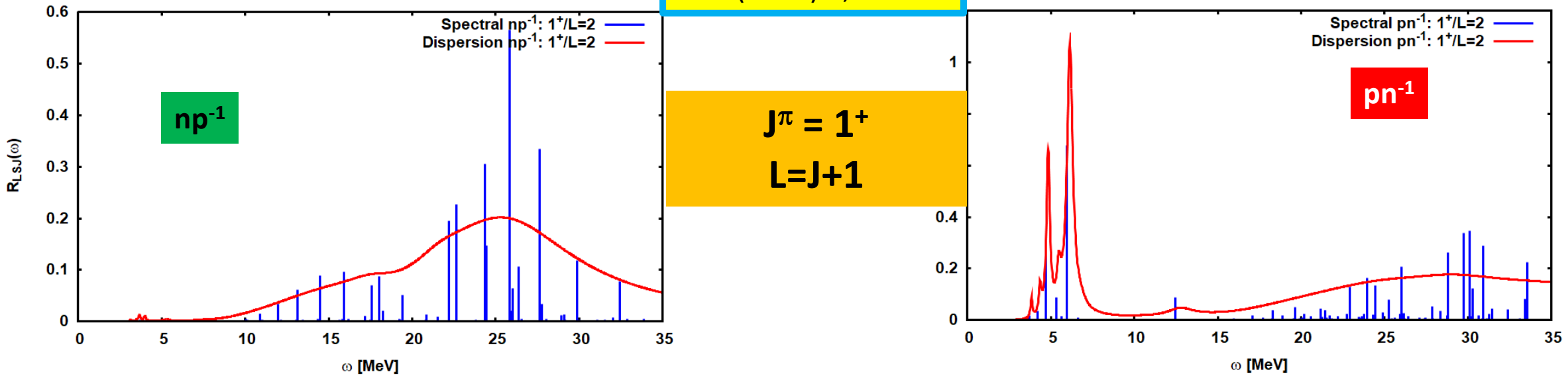


$J^\pi = 1^+$
L=J-1

GiEDF+HFB+ccQRPA
e.g. *Eur.Phys.J.A* 57 (2021) 3, 89

^{76}Se → ^{76}As

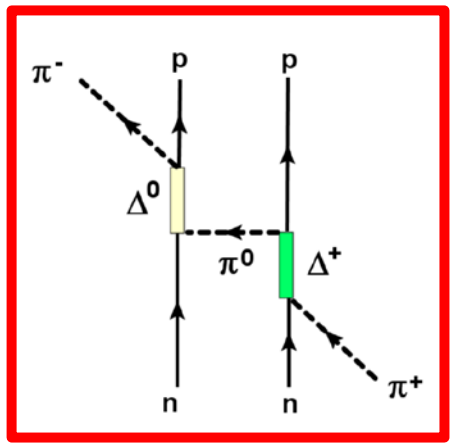
^{76}Ge → ^{76}As



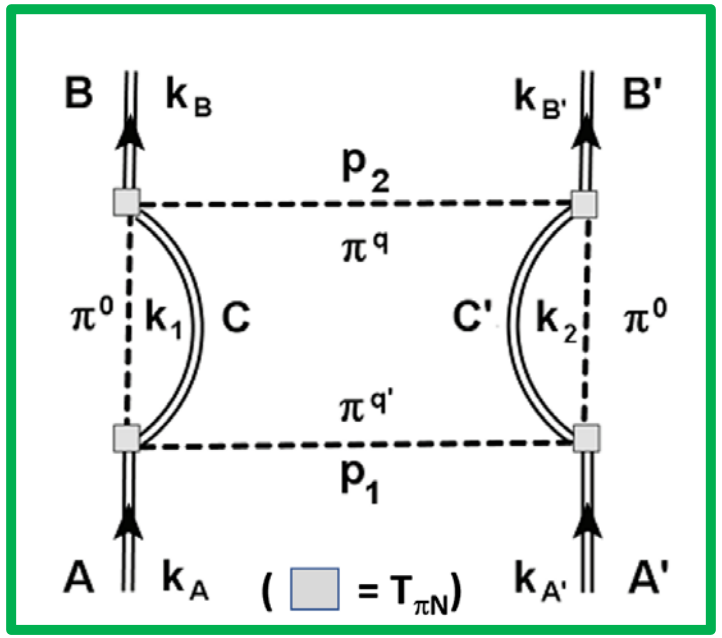
$J^\pi = 1^+$
L=J+1

Majorana DCE (MDCE) Scenario

DCE via 2nd Order (off-shell) πN Isovector Interactions



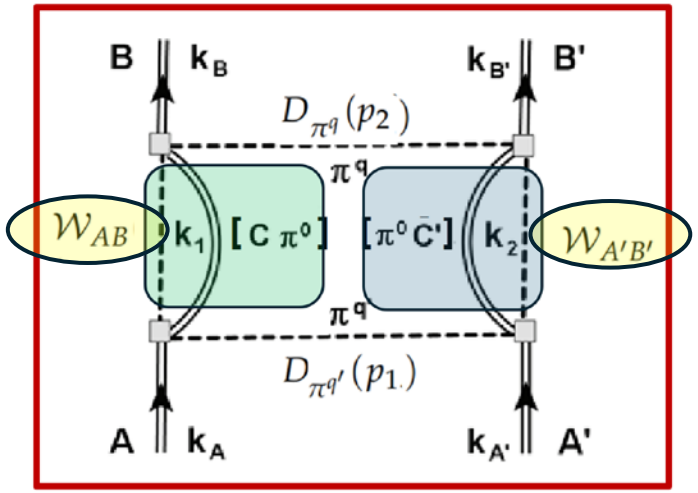
On-shell counterpart:
(π^+,π^-) and (π^-,π^+)
Isotensor DCE reactions



$$\mathcal{F}_{\alpha\beta}(\mathbf{p}_1,\mathbf{p}_2) = \mathcal{W}_{AB}(\mathbf{p}_1,\mathbf{p}_2)D_{\pi^q\pi^{q'}}(p_1,p_2)\mathcal{W}_{A'B'}(\mathbf{p}_1,\mathbf{p}_2),$$

H.L. et al,. Universe 10:202 (2024)

Key Elements:
Spectroscopic Form Factor and n^2p^{-2}/p^2n^{-2} Transition Matrix Elements



Nuclear Transition Matrix Elements (TME)

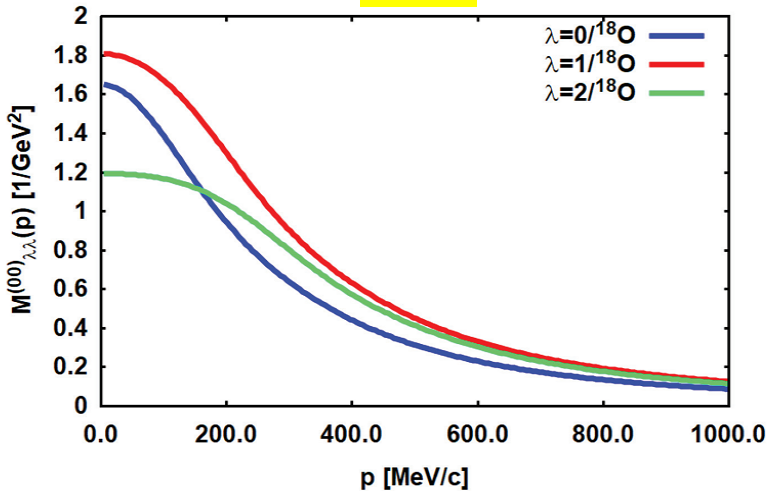
$$\mathcal{W}_{AB}(\mathbf{p}_1,\mathbf{p}_2) = \langle B|\mathcal{T}_{\pi N}(\mathbf{p}_2,\mathbf{k}|\sigma_3)\mathcal{G}_{\pi C}(k_1)\mathcal{T}_{\pi N}(\mathbf{p}_1,\mathbf{k}|\sigma_1)|A\rangle,$$

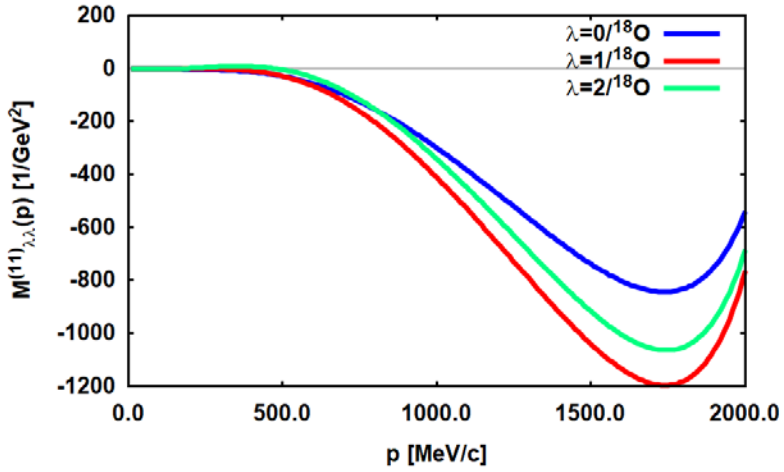
Rank-2 Isotensor Interaction 2nd Order $T_{\pi N}$ → Pion Potentials

$$T_{\pi N}(p_j,k) = T_0(w) + \frac{1}{m_\pi^2}\left(T_1(w)p_j\bullet k + iT_2(w)\sigma_j\bullet(p_j\times k)\right)$$

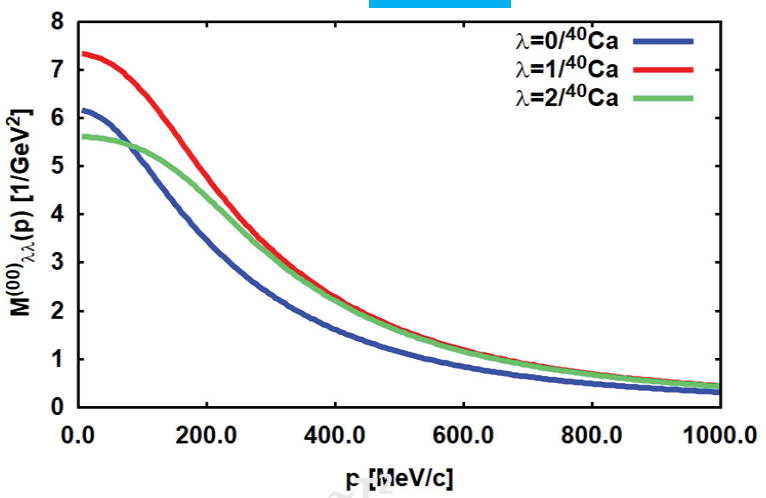
Spin-Scalar Fermi-Fermi Multipole TFF

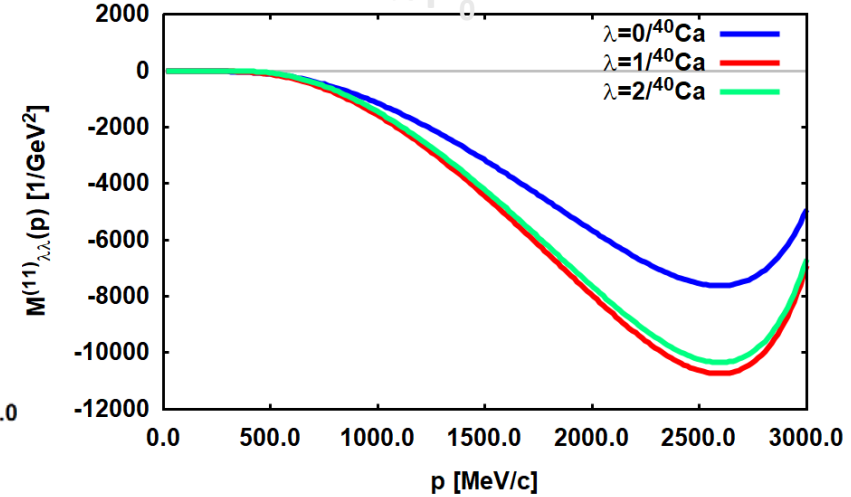
^{18}O





^{40}Ca



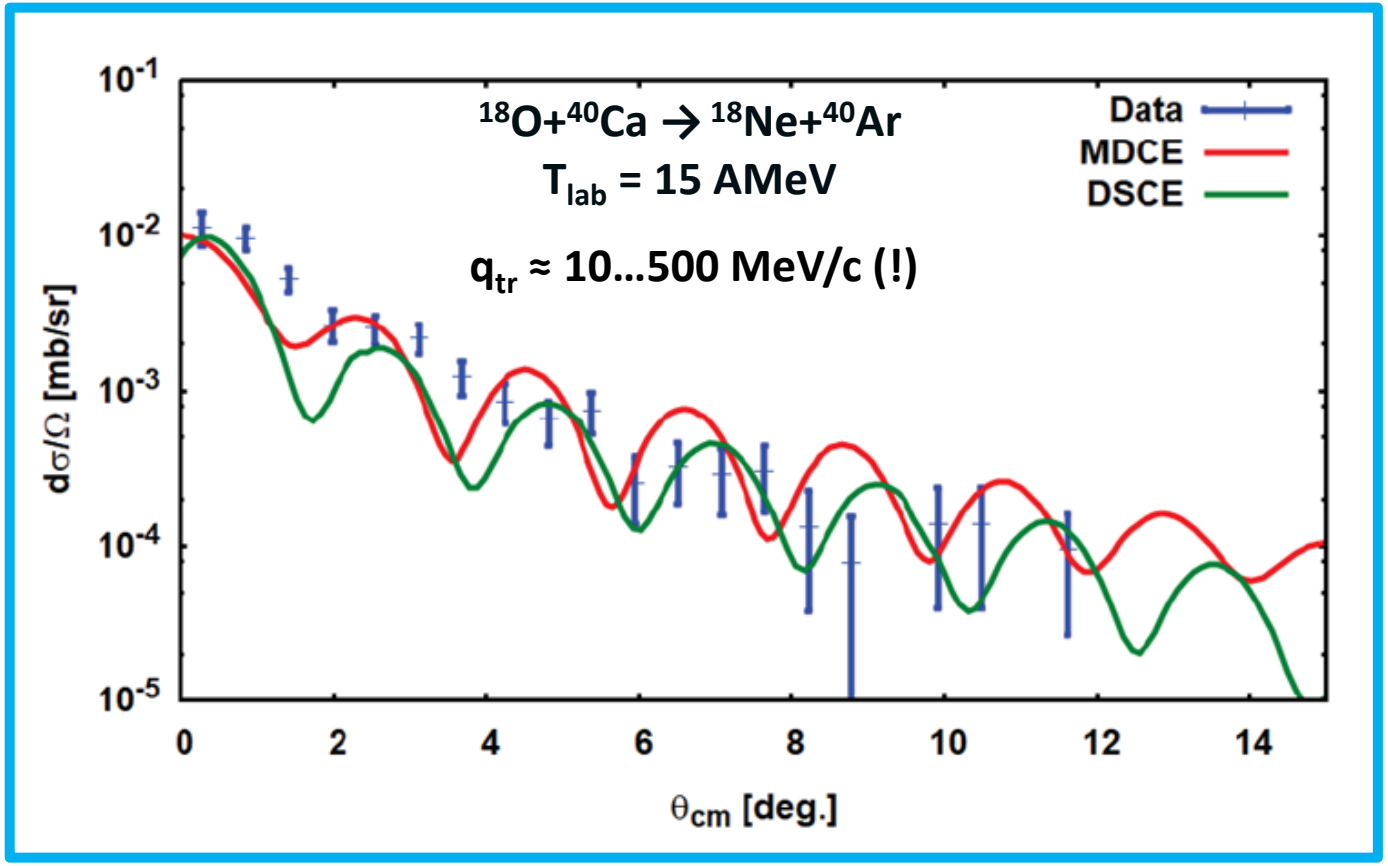


Double πN S-wave TFF
$\sim T^2_0$

Double πN P-wave TFF
$\sim T^2_1$

H.L. et al,. Universe 10:202 (2024)

Exploratory DSCE and MDCE Study



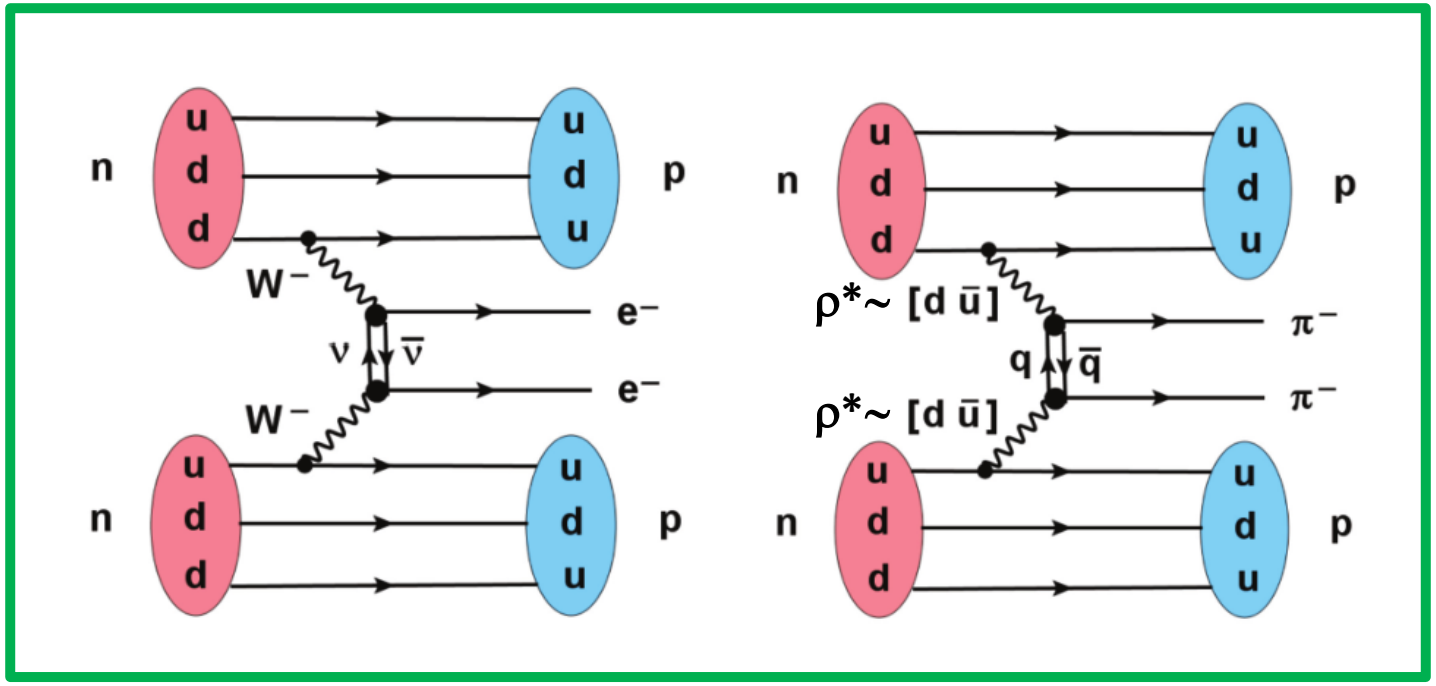
2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$

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

NUMEN & Data: *F. Cappuzzello et al. Prog.Part.Nucl.Phys.* 128 (2023) 103999

MDCE and 0ν2β Double Beta-Decay

The Majorana Aspect



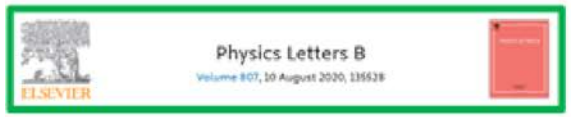
Ettore Majoran
*Aug., 5, 1906, at Catania
disappeared, Mar, 1938
+ 1959 in Venezuela?
+ in a Sicilian monastery?

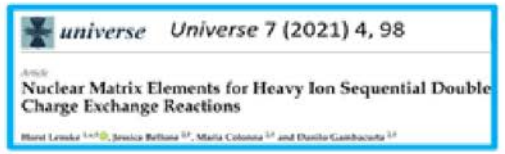
- **Topological Correspondence on the Diagrammatic Level**
- **MDCE as a Probe for 0ν2β-NME**
- **DSCE as a Probe for 2ν2β-NME**

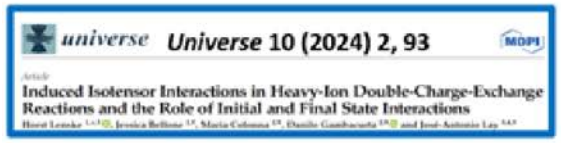
Summary

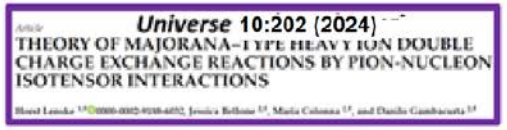
- **Double Single Charge Exchange (DSCE) and 2BTD**
- **„Majorana“ DCE (MDCE)**
- **DCE as a Tool for Nuclear Isotensor Spectroscopy**
- **Lepton DCE - a Probe for LNV and DBD?**

…with the NUMEN theory group:
J. Bellone, M. Colonna, D. Gambacurta (LNS Catania), and J.-A. Lay (U. Sevilla)









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