JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Institut für Theoretische Physik

Heavy Ion Charge Exchange Reactions and the Relation to β-Decay

Horst Lenske

Institut für Theoretische Physik, JLU Giessen

NUMEN

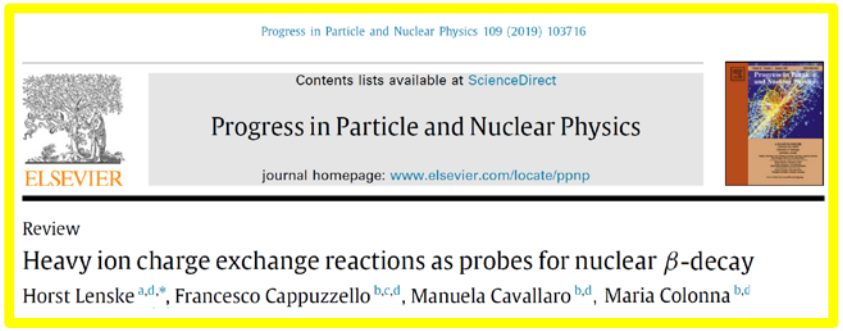
STRONG-2020

panda

NUSTAR

Agenda:

- **Charged current (cc) physics with heavy ion beams**
- **Single (SCE), Double Single (DSCE) and „Majorana“ (MDCE) reactions**
- **Relevance for and connections to single and double beta-decay**
- **Scrutinizing N* in-medium physics in peripheral HI cc-reactions at relativistic energies**
- **Summary and outlook**


Progress in Particle and Nuclear Physics 109 (2019) 103716

Contents lists available at ScienceDirect

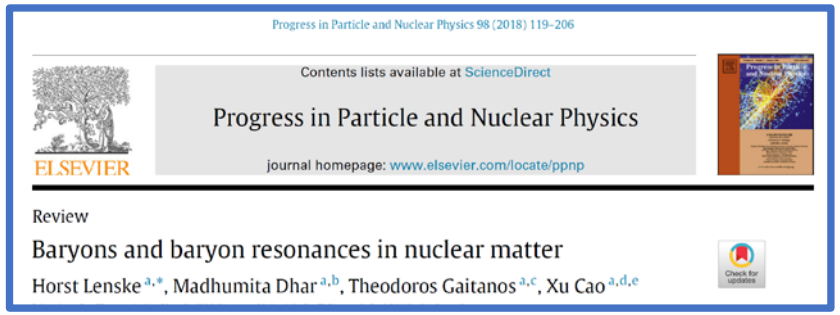
Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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]


Progress in Particle and Nuclear Physics 98 (2018) 119–206

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

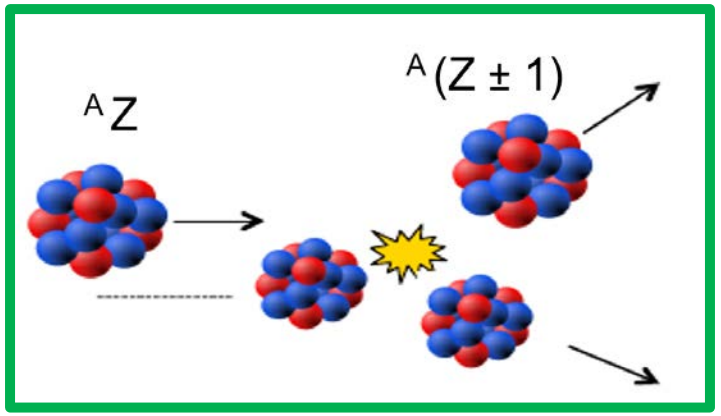
journal homepage: www.elsevier.com/locate/ppnp

Review

Baryons and baryon resonances in nuclear matter

Horst Lenske [a,*], Madhumita Dhar [a,b], Theodoros Gaitanos [a,c], Xu Cao [a,d,e]

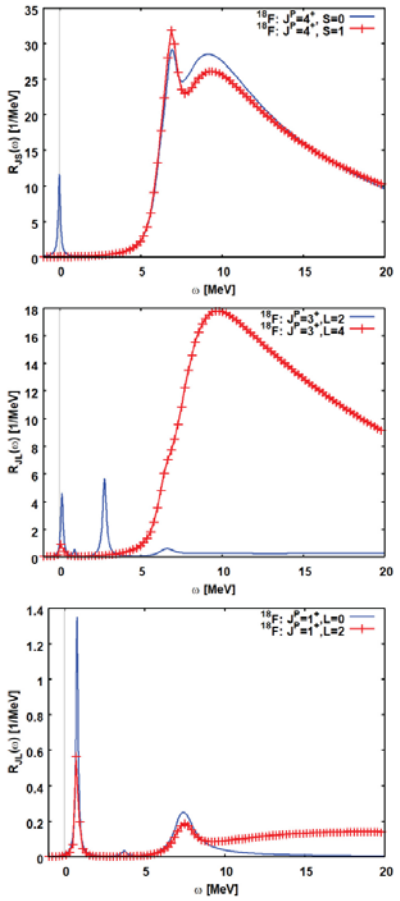
QuasiElastic Heavy Ion CC-Reactions@AMeV

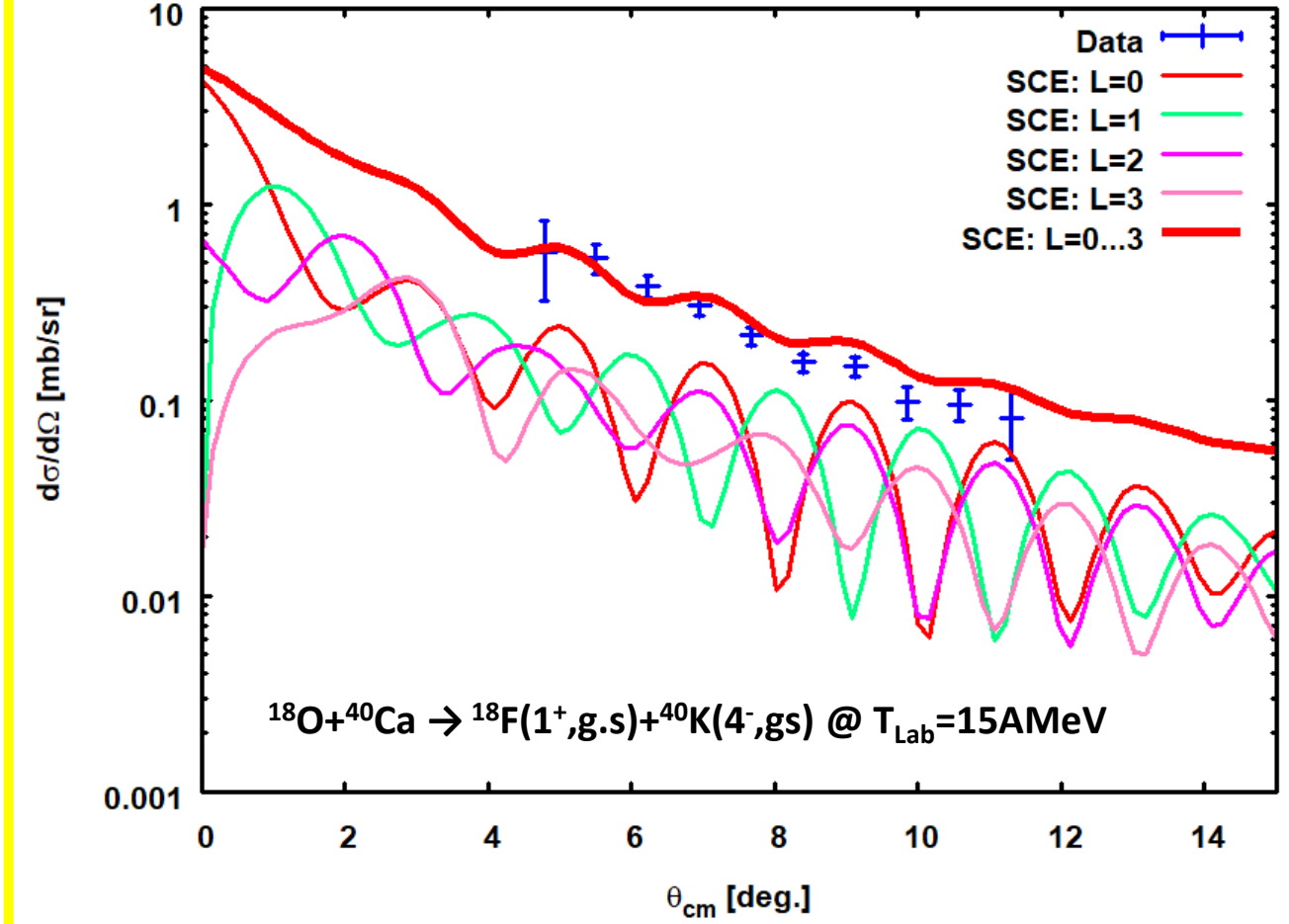


Single Charge Exchange (SCE) Reaction

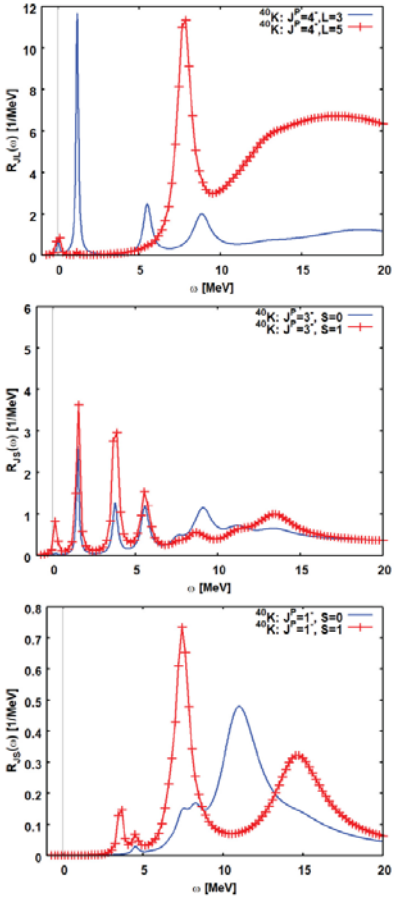
H. Lenske, J.I. Bellone, M. Colonna, J.-A. Lay, Phys. Rev. C 98 (2018) 044620,

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



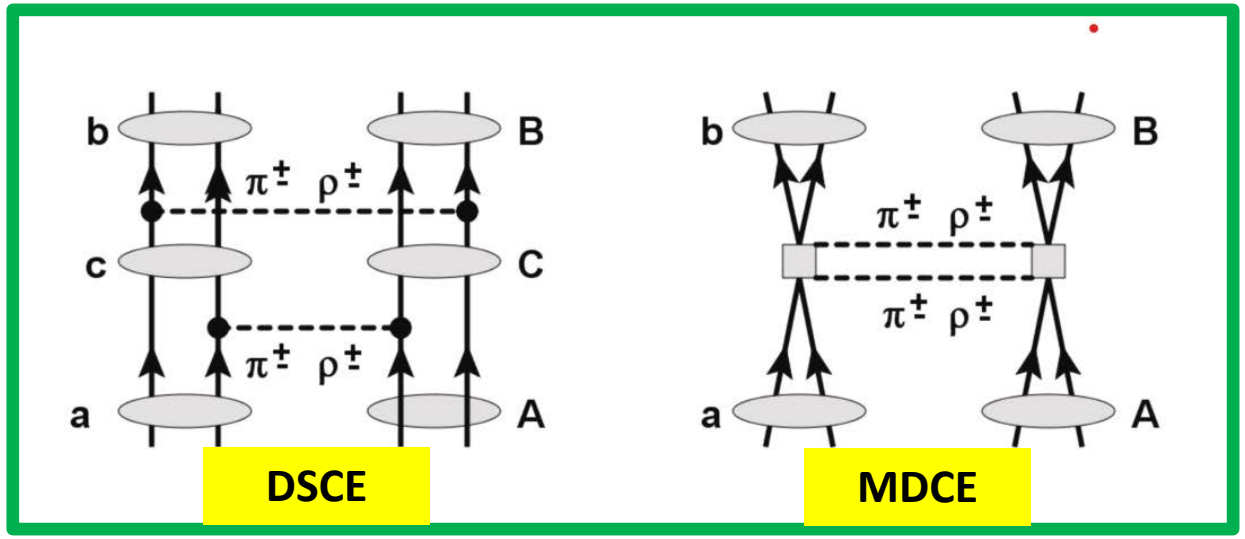


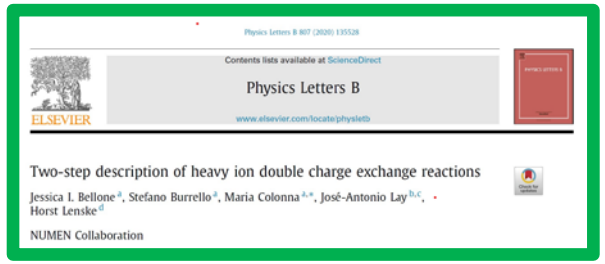
$^{40}Ca \rightarrow {}^{40}K$



Data: M. Cavallaro, et al., *Front.Astron.Space Sci.* 8 (2021) 659815

Double Charge Exchange Reactions




Physics Letters B 807 (2020) 135528

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Two-step description of heavy ion double charge exchange reactions

Jessica I. Bellone [a], Stefano Burrello [a], Maria Colonna [a,*], José-Antonio Lay [b,c], Horst Lenske [d]

NUMEN Collaboration


universe

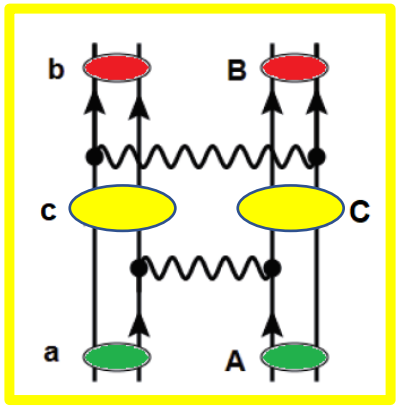
Universe 7 (2021) 4, 98

Article

Nuclear Matrix Elements for Heavy Ion Sequential Double Charge Exchange Reactions

Horst Lenske [1,*,†], Jessica Bellone [2,†], Maria Colonna [2,†] and Danilo Gambacurta [2,†]

DSCE Reactions:
Double Charge Exchange by Double Single Charge Exchange



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

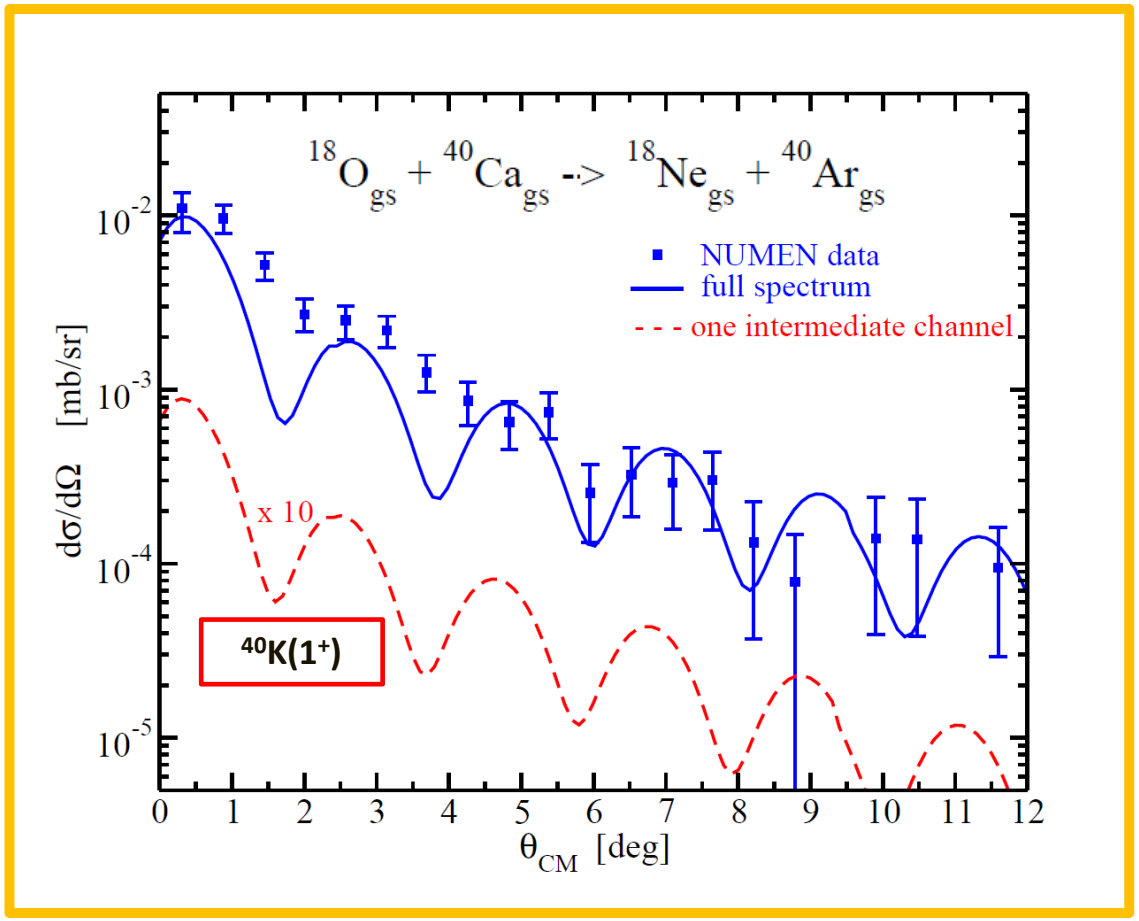
2nd Order DSCE by 1st Order (Half-Off shell) SCE Reaction Amplitudes

$$\mathcal{M}^{DSCE}_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_{\gamma=c,C} \int \frac{d^3k_\gamma}{(2\pi)^3} \mathcal{M}^{SCE}_{\gamma\beta}(\mathbf{k}_\gamma, \mathbf{k}_\beta) \frac{\tilde{S}^\dagger_\gamma(\mathbf{k}_\gamma)}{\omega^{(+)}_\alpha - \omega_\gamma} \mathcal{M}^{SCE}_{\alpha\gamma}(\mathbf{k}_\alpha, \mathbf{k}_\gamma)$$

J. Bellone, M. Colonna, J.-A. Lay, H.L., PLB 807 (2020); H.L. et al. *Universe* 7 (2021) 4, 98

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

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

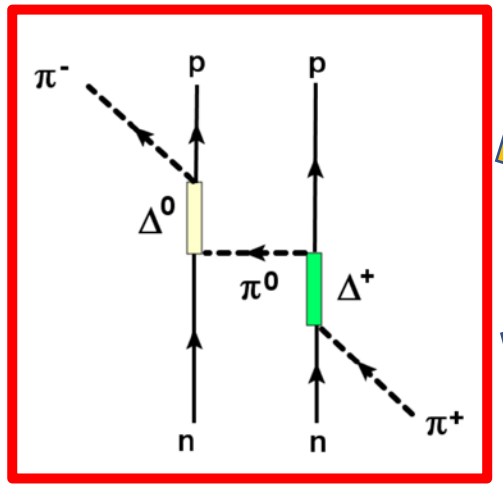


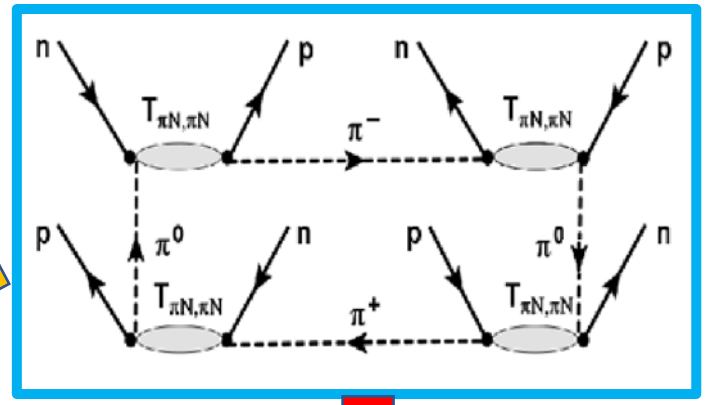
Theory: Jessica Bellone et al., PLB 807 (2020), e-Print: arXiv:1912.03043
Data: F. Cappuzzello et al., EPJ A51 (2015)

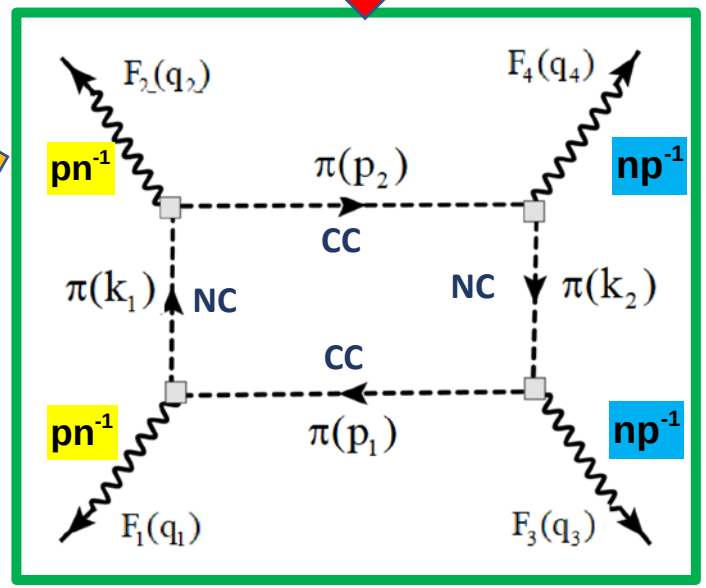
Could we change
two units of charge in a single interaction?

Mesonic Majorana DCE Reactions

Cooperation of Charged (CC) and Neutral (NC) Hadronic Currents
Virtual rank-2 Isotensor Interaction by Coherent Meson Exchange







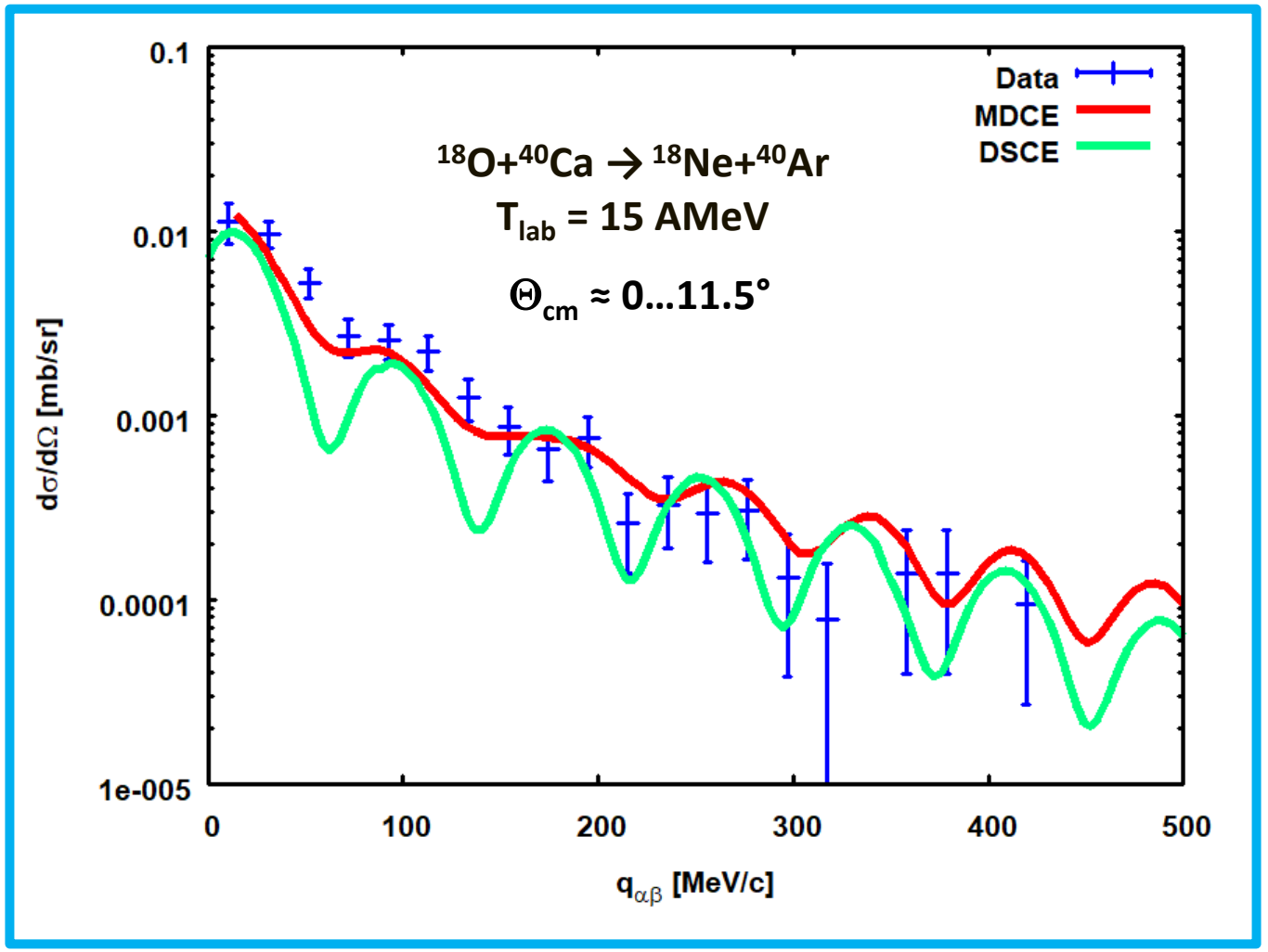
MDCE
Box Diagrams

On-shell counterpart:
(π^+,π^-) reaction

Particle and Nuclear Physics 109 (2019) 103716

…similarity to electro-weak interactions:
light-by-light scattering,
lepton-lepton scattering

MDCE: Probing Nuclear Physics @ High Momentum Transfer



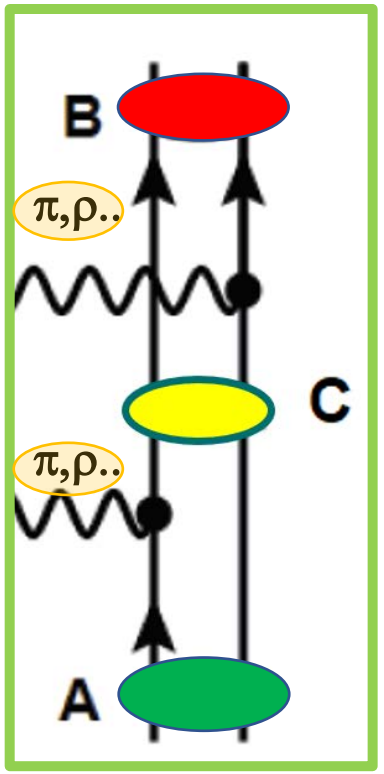
2-step DSCE: intermediate states with $J^{\pi} \leq 5^{\pm}$

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

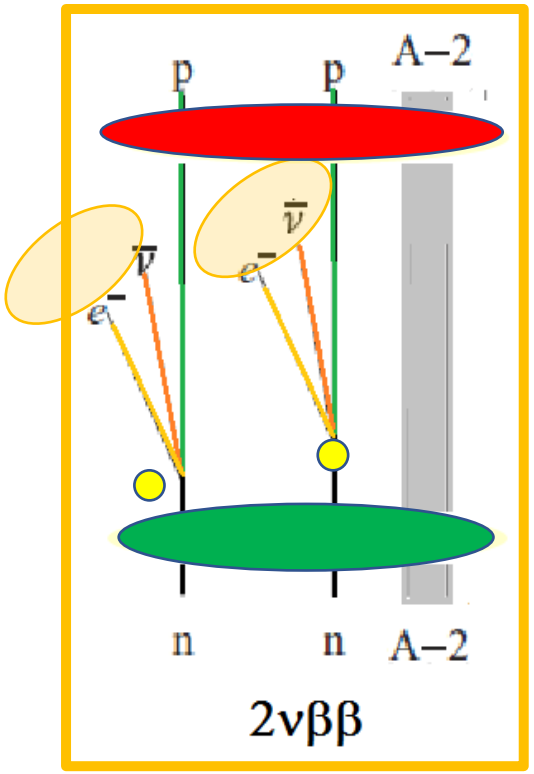
Data: F. Cappuzzello et al., EPJ A51 (2015)

Nuclear Matrix Elements

DSCE and 2ν2β Beta Decay



2nd order
Strong Interaction

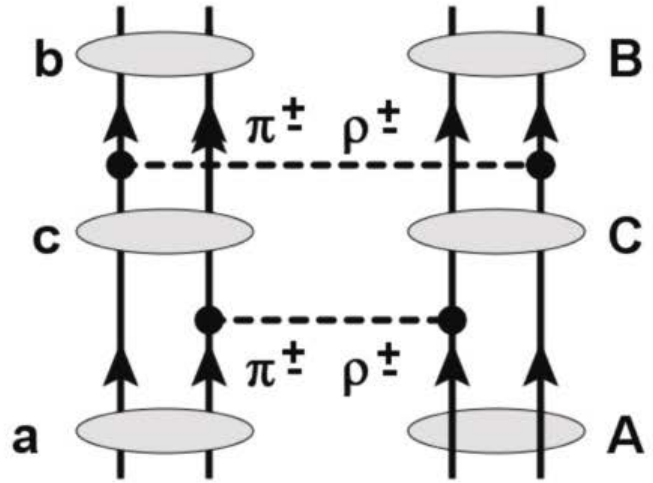


2nd order
Weak Interaction

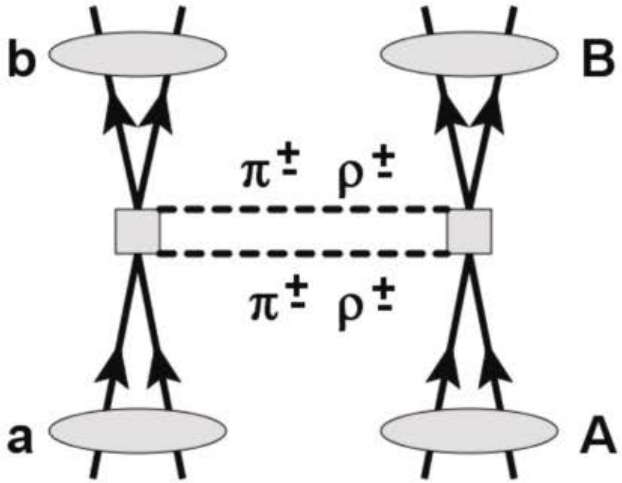
DCE and NME:
H.L. et al., *Universe* 7 (2021) 4, 98

DSCE and MDCE Reaction Amplitudes

$O([V_{\pi NN}]^4)$
~[120 MeVfm^3]^4



Two 1st-order NN-Interactions



One 2nd-order Interaction

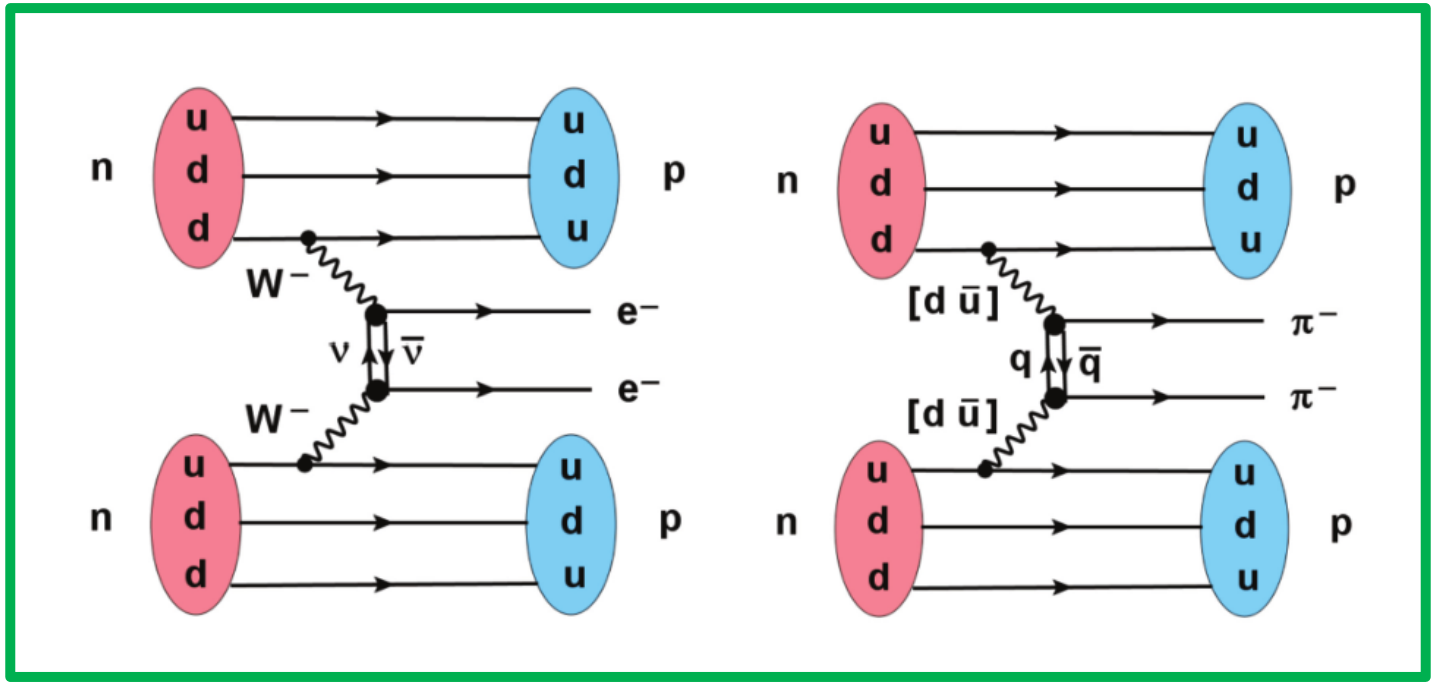
$O([T_{\pi N}]^4)$
~[300 MeVfm^3]^4

DSCE:
Sequential
Single-meson
Isovector Exchange

MDCE:
Coherent
Double-meson
Isotensor Exchange

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 Surrogate Reaction for 0ν2β-NME**
- **DSCE as a Surrogate Reaction for 2ν2β-NME**

„BSM “-Physics and Neutrino-less Double-beta Decay: Dirac or Majorana Neutrinos?

GERDA, 2021: $T^{0\nu}_{1/2} > 10^{+26}$yr

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

Ejiri et al., Phys.Rept. 797 (2019) 1

$$\langle m_\nu \rangle = \left|\sum_k U_{ek}^2 m_k\right| = \left|\sum_k |U_{ek}|^2 m_k e^{i\alpha_k}\right|.$$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) Matrix

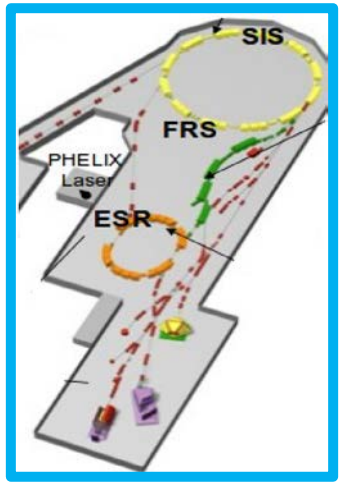
effective Majorana ν-Mass

$$M^{GT}_{\beta\beta} = \sum_N G^{(i)}_{\beta\beta,N} \frac{\langle 0^+_F || \tau^+ \vec{\sigma} || 1^+_N \rangle \langle 1^+_N || \tau^+ \vec{\sigma} || 0^+_I \rangle}{\frac{1}{2}(Q_{\beta\beta} + 2m_e c^2) + E_N - E_I}$$

Nuclear Matrix Element
→ DCE Reactions as probes for nuclear models

H.L. et al., *Universe* 7 (2021) 4, 98

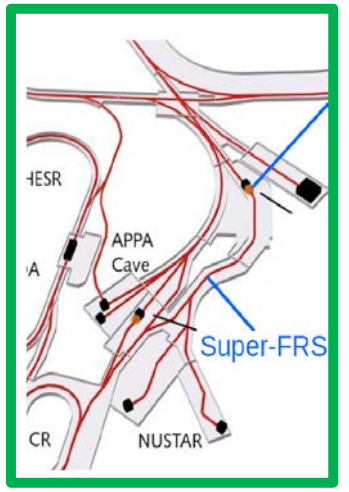
Studying Nucleon Resonances in CC-Reactions@AGeV Energies



←

NUSTAR@GSI/FAIR

→



Physics Letters B 807 (2020) 135565

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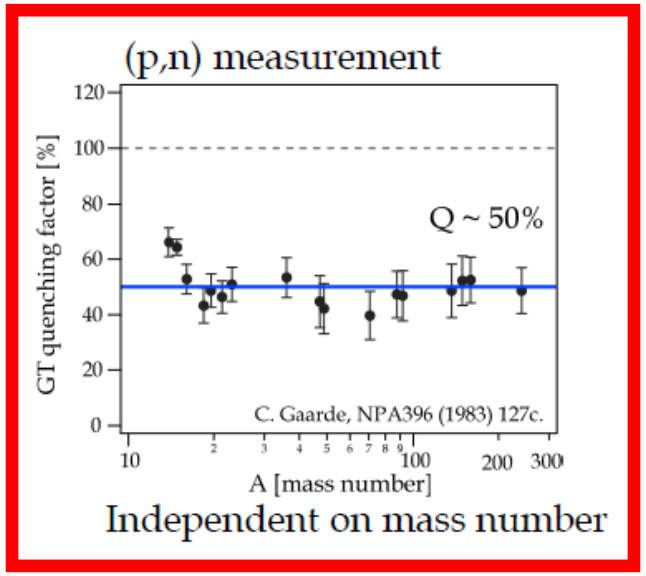
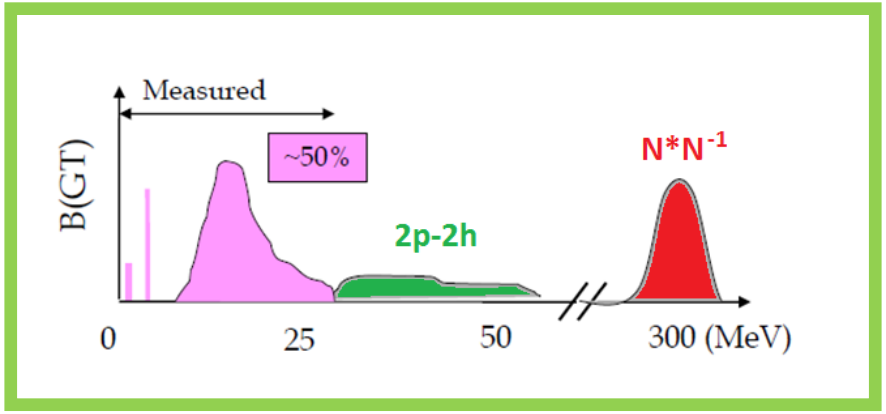
Study of Δ excitations in medium-mass nuclei with peripheral heavy ion charge-exchange reactions

J.L. Rodríguez-Sánchez [a,b,c,*], J. Benlliure [a,b], I. Vidaña [d], H. Lenske [e], C. Scheidenberger [c],

N*-Coupling and the GT-Quenching Problem of (p,n)-Reactions

Up to 50% (!!) of the Expected Strength is "Missing"

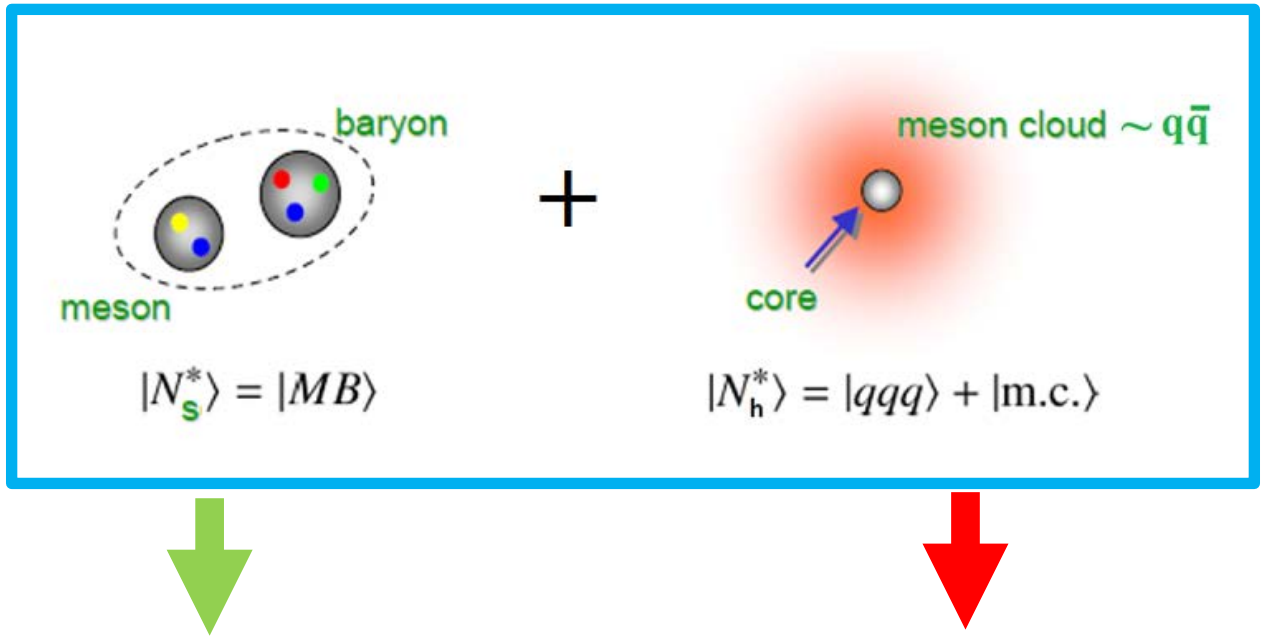




Wave Function of a Baryon Resonance

$$\left|N^*\right\rangle = \left|N_s^*\right\rangle + \left|N_h^*\right\rangle = x_1\left|MB\right\rangle + x_2\left|qqq\right\rangle + x_3\left|qqq\right\rangle \otimes \left|q\bar{q}\right\rangle + \ldots$$

- ***soft scale:*** **hadronic *molecular-type* components $|N_s\rangle$**
- ***hard scale:*** **QCD confined components $|N_h\rangle$**



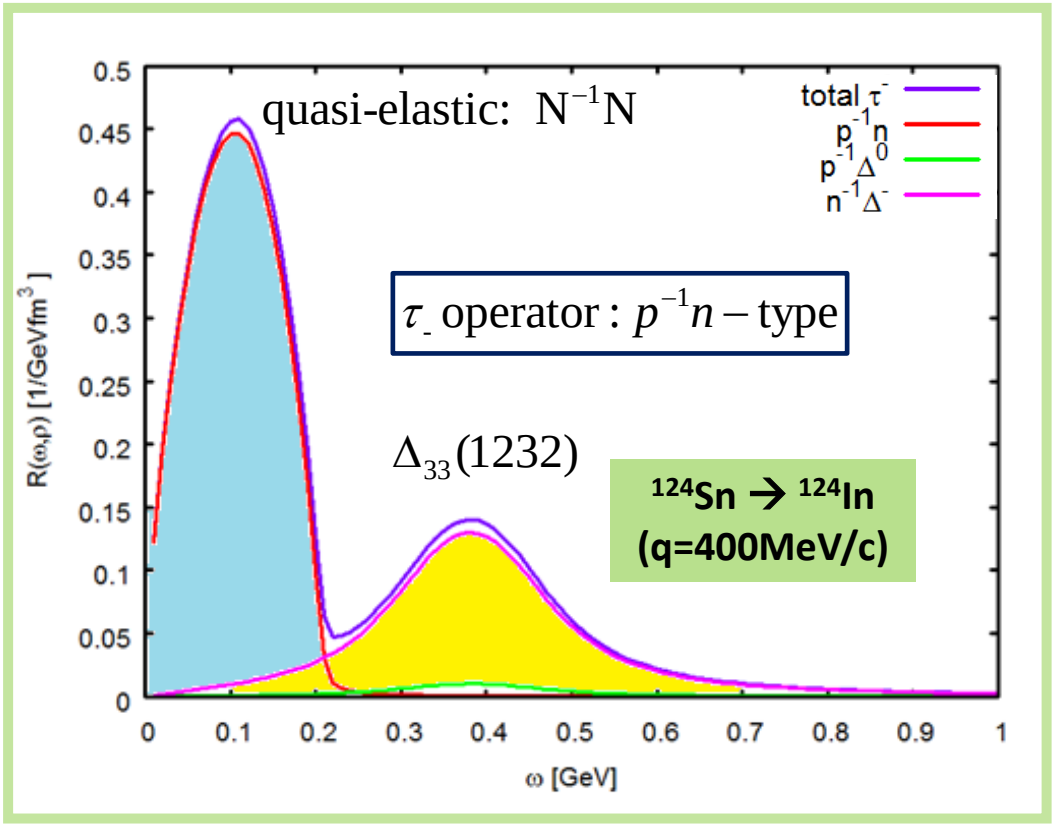
Some(?) Medium Dependence

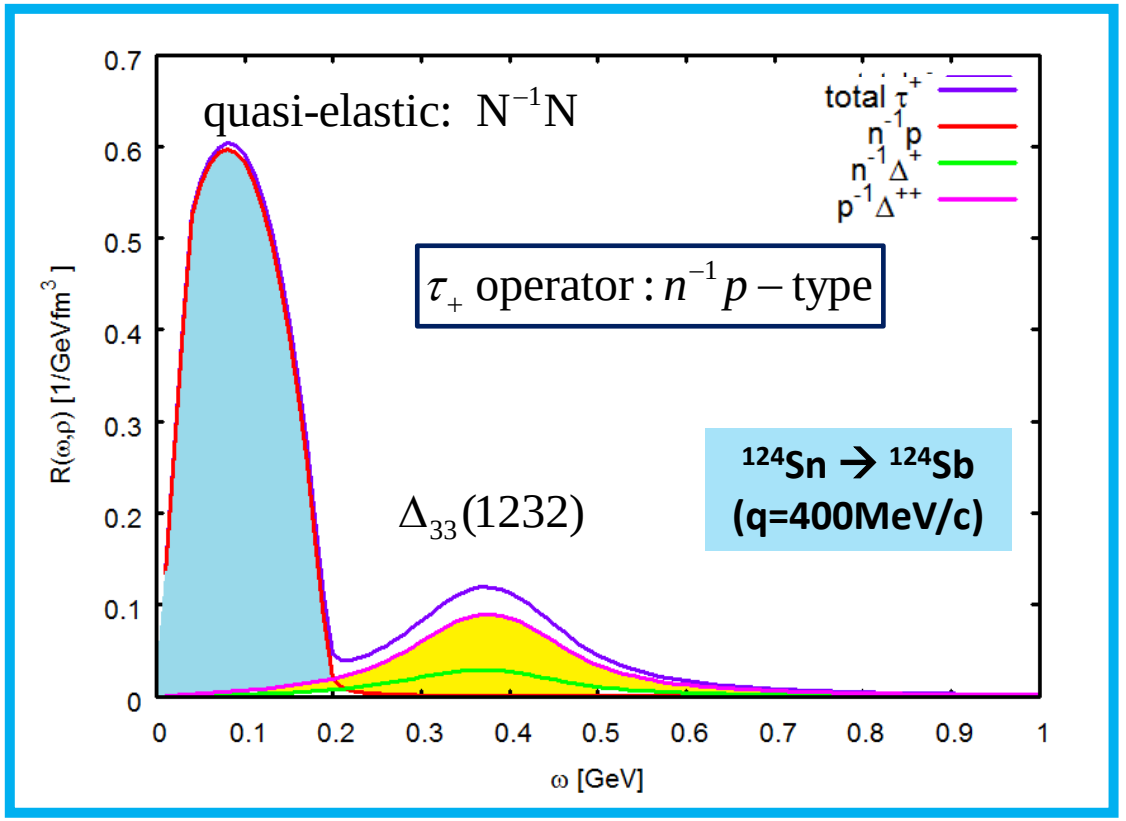
Weak Medium Dependence

Nuclear Spectroscopy by Dyson-Equation – N*RPA

$$\Pi = \Pi^0 + \Pi^0 \hat{V} \Pi$$

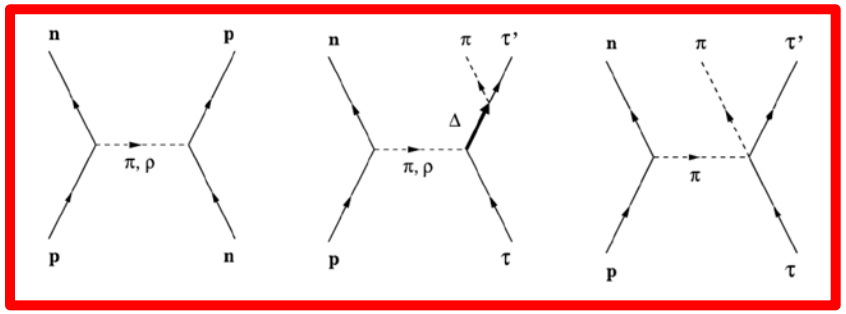
$$\begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix} = \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} + \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} V_{NN} & V_{N\Delta} \\ V_{\Delta N} & V_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix}$$



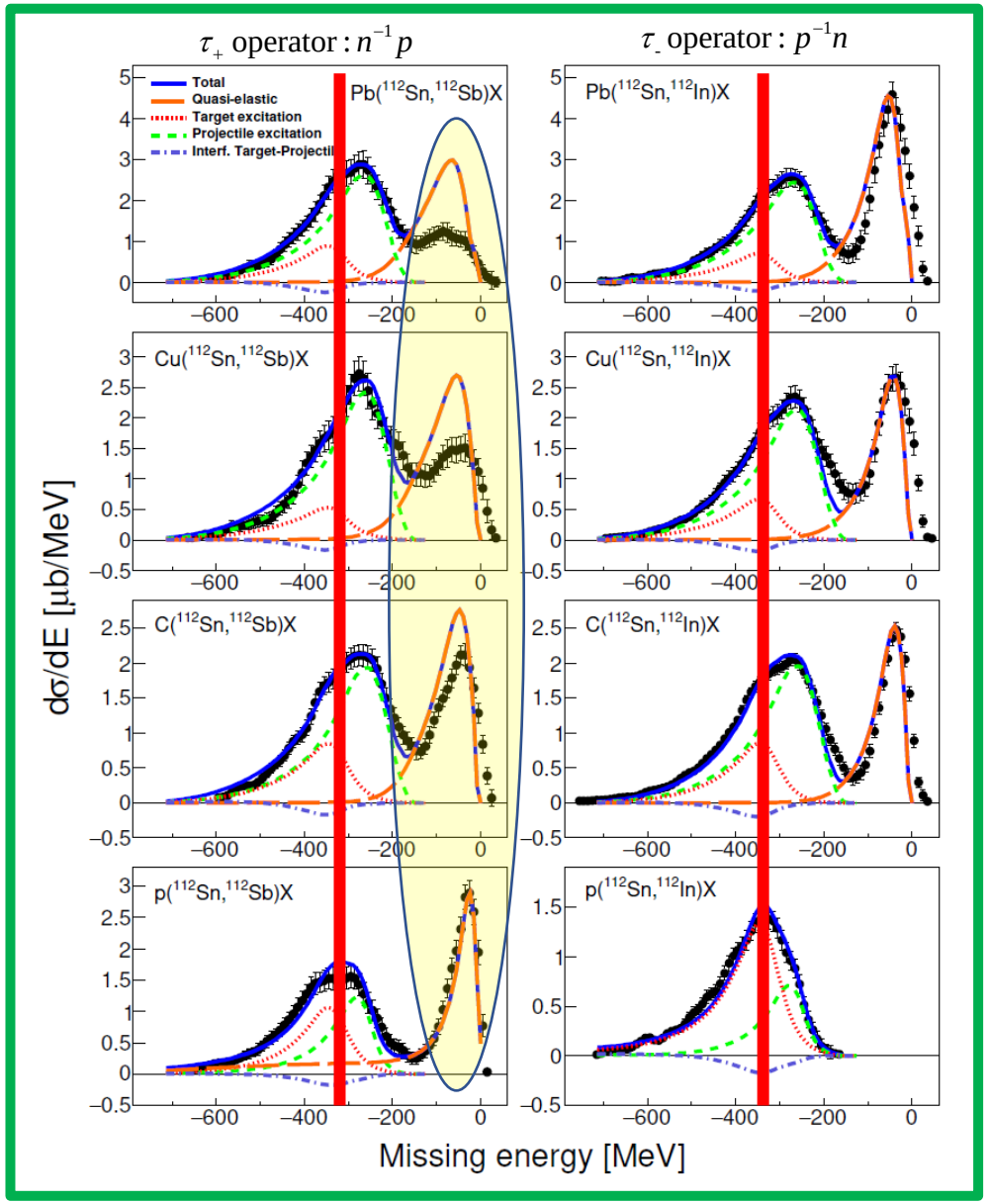


Glauber-Type Reaction Calculations
(by I.Vidana, Catania)

- **Nucleus-nucleon and nucleus-nucleus CC reactions**
- **In-medium effects: Pauli blocking, self-energies…**
- **Pion production in s-wave and p-wave channels**
- **Microscopic (N*RPA) response functions**
- **Δ-Mass Shift (~ - 63 MeV) due to reaction effects**
- **Upcoming: decay spectroscopy with WASA@FAIR**



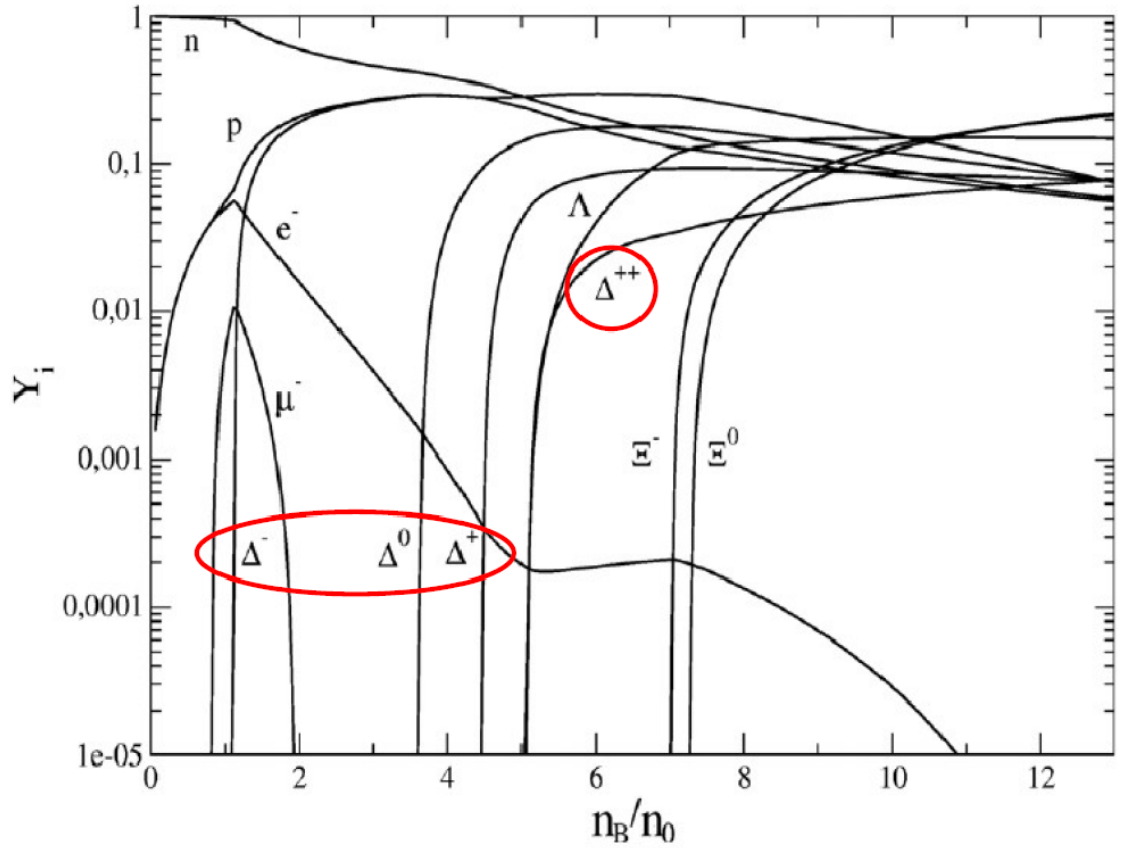
J-L. Rodriguez (Data), I. Vidana, H.L., et al., *Phys.Lett.B* 807 (2020) 135565
…and in preparation

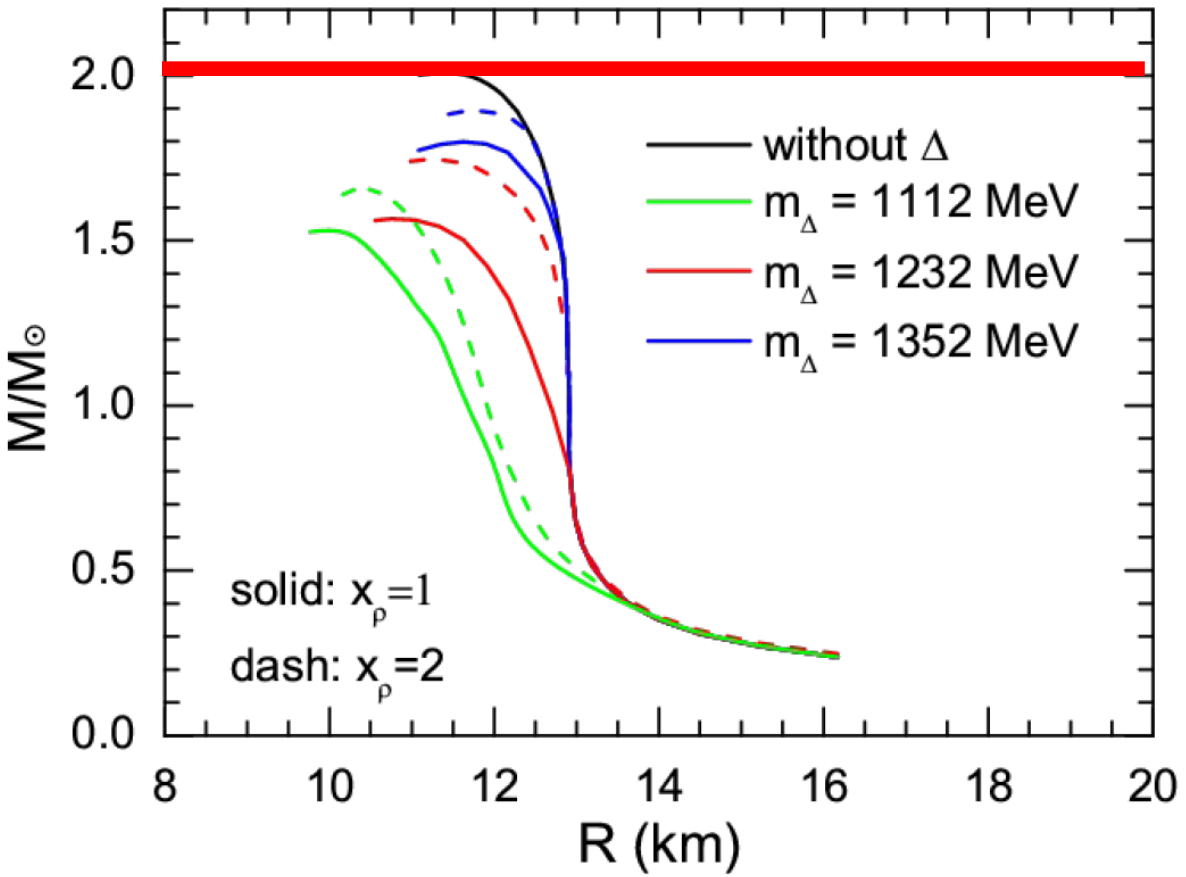


^{112}Sn @ T_{Lab}=1AGeV

Nucleon Resonances in Neutron Stars

N* Puzzle





T. Schürhoff *et al, Astrophys.J.Lett.* 724 (2010) L74
A. Drago et al., PRC 90, 065809 (2014)
J. Wilhelm, H. L. et al., *EPJ Web Conf.* 107 (2016) 10001

Summary and Outlook

- **Theory of DSCE reactions ↔ analogue /surrogate to $2\nu2\beta$ – decay**
- **Theory of MDCE reactions ↔ analogue /surrogate to $0\nu2\beta$ – decay**
- **Induced rank-2 IsoTensor interaction ↔ generic for heavy ion DCE reactions**
- **Study of N* in-medium dynamics in peripheral CC reactions at relativistic energies**

Spectroscopy Studies with heavy ion beams

…in collaboration with the NUMEN theory group:
J. Bellone, M. Colonna, D. Gambacurta, J.-A. Lay, and E. Santopinto
and the N*-Collaboration@GSI/FAIR
J.L. Rodriguez, J. Benliiure (U. Santiago de Compostela) et al., and I. Vidana (INFN Catania),

Suported by DFG, grant Le439/16, and AvH