Heavy ion double charge exchange reactions and their role in probing double beta decay nuclear matrix elements

J. I. Bellone[1,2], D. Gambacurta[2], M. Colonna[2], H. Lenske[3]

[1]Università degli Studi di Catania, Catania, Italy

[2] Laboratori Nazionali del Sud, INFN, I-95123 Catania, Italy

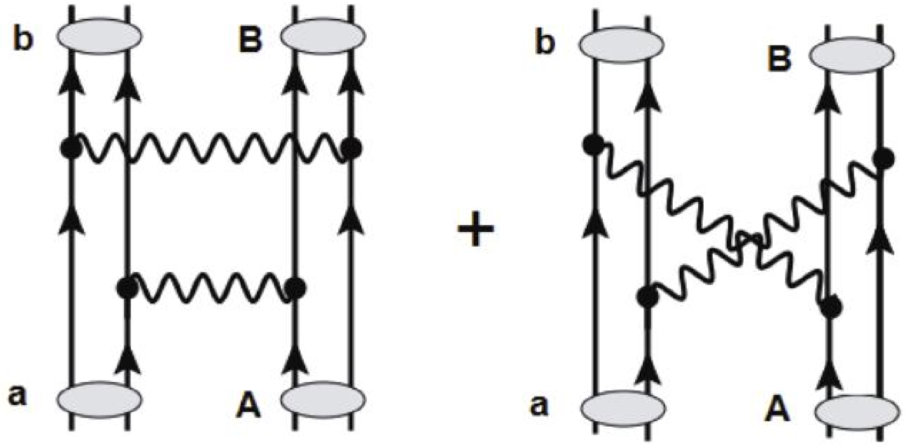
[3]Institut für Theoretische Physik, Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany

Reaction mechanisms for describing Heavy Ion Double Charge Exchange

$$A(Z_A, N_A) + a(Z_a, N_a) \rightarrow B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$$

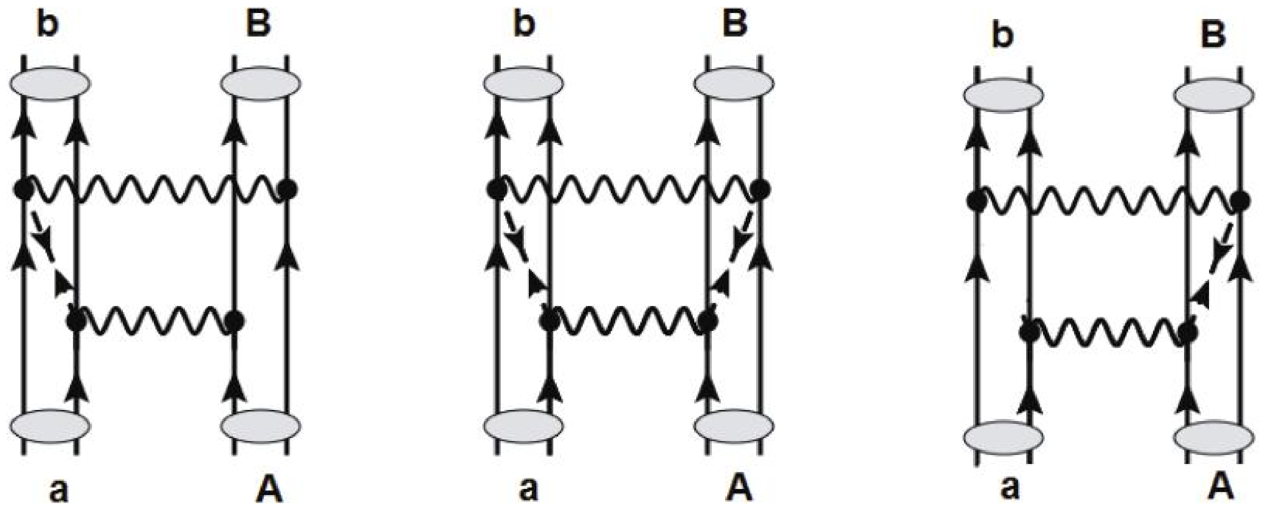
Sequential DCE (dSCE)

sequence of two ***Uncorrelated*** SCE reactions
(2νββ-like mechanism)



Majorana-like DCE (mDCE)

sequence of two ***Correlated*** SCE reactions
(0νββ-like mechanism)



J.I. B., S. Burrello, M. Colonna, J.A. Lay, H. Lenske, PLB 807 (2020) 135528
F. Cappuzzello et al., Progress in Particle and Nuclear Physics, submitted

H. Lenske, IOP Conf. Series: Journal of Physics: Conf. Series **1056 (2018) 012030**
E. Santopinto *et al.* , Phys. Rev. C 98 061601 (R) (2018)
H. Lenske et al., Progress in Particle and Nuclear Physics 109 (2019) 103716
F. Cappuzzello et al., Progress in Particle and Nuclear Physics, submitted

...focusing on sequential Double Charge exchange process...

$$A(Z_A, N_A) + a(Z_a, N_a) \rightarrow B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$$

(β) $B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$

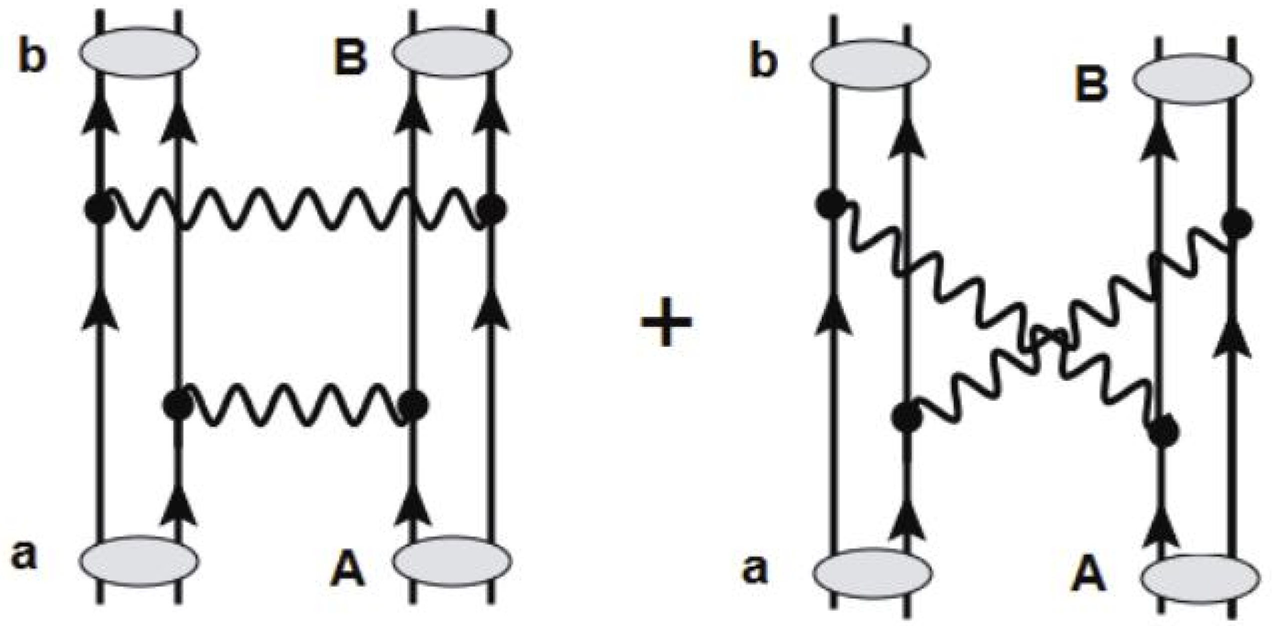
$\uparrow$

(γ) $C(Z_A \pm 1, N_A \mp 1) + c(Z_a \mp 1, N_a \pm 1)$

$\uparrow$

(α) $A(Z_A, N_A) + a(Z_a, N_a)$

sequence of two ***uncorrelated*** SCE reactions
(2νββ-like mechanism)



J.I. B., S. Burrello, M. Colonna, J.A. Lay, H. Lenske, PLB 807 (2020) 135528

Analogies between dSCE and 2νββ matrix elements

dSCE cross section

$$d\sigma_{\alpha\beta}^{(DSCE)} = \frac{m_\alpha m_\beta}{(2\pi\hbar^2)^2}\frac{k_\beta}{k_\alpha}\frac{1}{(2J_a+1)(2J_A+1)}\sum_{M_a,M_A\in\alpha;M_b,M_B\in\beta}\left|M_{\alpha\beta}^{(2)}(\mathbf{k}_\alpha,\mathbf{k}_\beta)\right|^2 d\Omega$$

dSCE transition matrix element

$$M_{\beta\alpha}^{(2)}(\mathbf{k}_\beta,\mathbf{k}_\alpha) = \int d^3p_1 d^3p_2 \oint_{C_+}\frac{d\nu}{2i\pi}\sum_{S_1,S_2}\Pi_{\alpha\beta}^{(S_2S_1)}(\mathbf{p}_2,\mathbf{p}_1;\nu)$$
$$\int \frac{d^3k_\gamma}{(2\pi)^3}N_{\beta\gamma}(\mathbf{p}_2)V_{S_2T}(p_2^2)\frac{\tilde{S}_\gamma^\dagger}{\omega_\alpha-\nu-T_\gamma+i\eta}N_{\gamma\alpha}(\mathbf{p}_1)V_{S_1T}(p_1^2).$$

$$\Pi_{\alpha\beta}^{(S_2S_1)}(\mathbf{p}_2,\mathbf{p}_1;\nu) = \sum_{cC}\frac{F_{S_2}^{(BC)}(\mathbf{p}_2)\cdot F_{S_2}^{(bc)}(\mathbf{p}_2)F_{S_1}^{(ca)}(\mathbf{p}_1)\cdot F_{S_1}^{(CA)}(\mathbf{p}_1)}{\nu-(E_A-E_C+E_a-E_c)}$$

H. Lenske, J.I. B., M. Colonna, D. Gambacurta, Universe 7 (2021) 4, 98

$$\Pi_{(S_1S_2)SM}^{(AB)}(\mathbf{p}_2,\mathbf{p}_1;\omega) = \sum_C \frac{\left[F_{S_2}^{(BC)}(\mathbf{p}_2)\otimes F_{S_1}^{(CA)}(\mathbf{p}_1)\right]_{SM}}{\omega-(E_A-E_C)}$$

dSCE NME

[J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91 034304 (2015)]

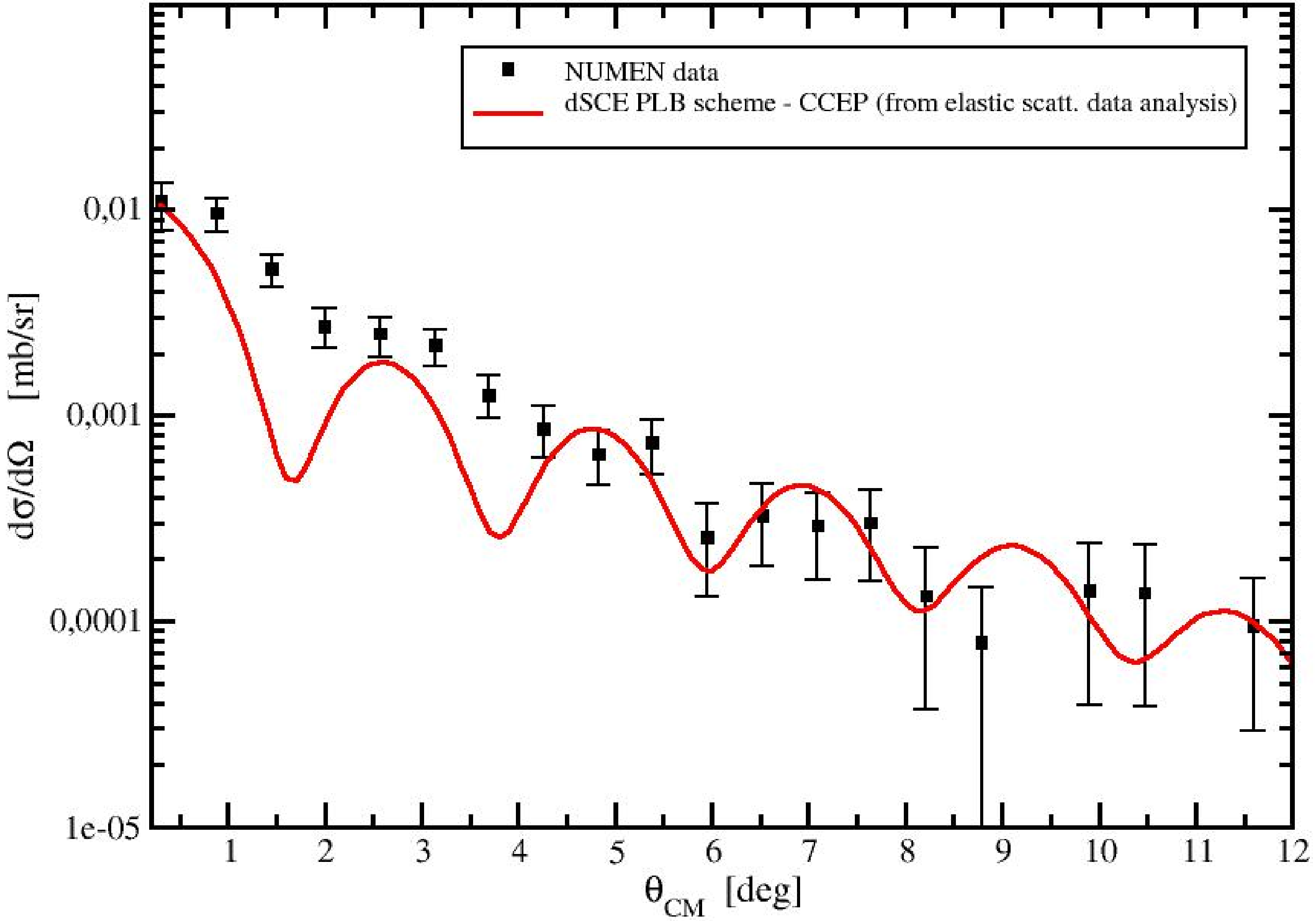
$$\mathcal{M}^{(2\nu)} = g_V^2\frac{\left\langle 0_F^+\right|\sum_{n,n'}\tau_n^\dagger\tau_{n'}^\dagger\left|0_I^+\right\rangle}{\frac{1}{2}(Q_{\beta\beta}+2m_ec^2)+\left\langle E_{0^+,N}\right\rangle-E_I} - g_A^2\frac{\left\langle 0_F^+\right|\sum_{n,n'}\tau_n^\dagger\tau_{n'}^\dagger\boldsymbol{\sigma}_n\cdot\boldsymbol{\sigma}_{n'}\left|0_I^+\right\rangle}{\frac{1}{2}(Q_{\beta\beta}+2m_ec^2)+\left\langle E_{1^+,N}\right\rangle-E_I}$$

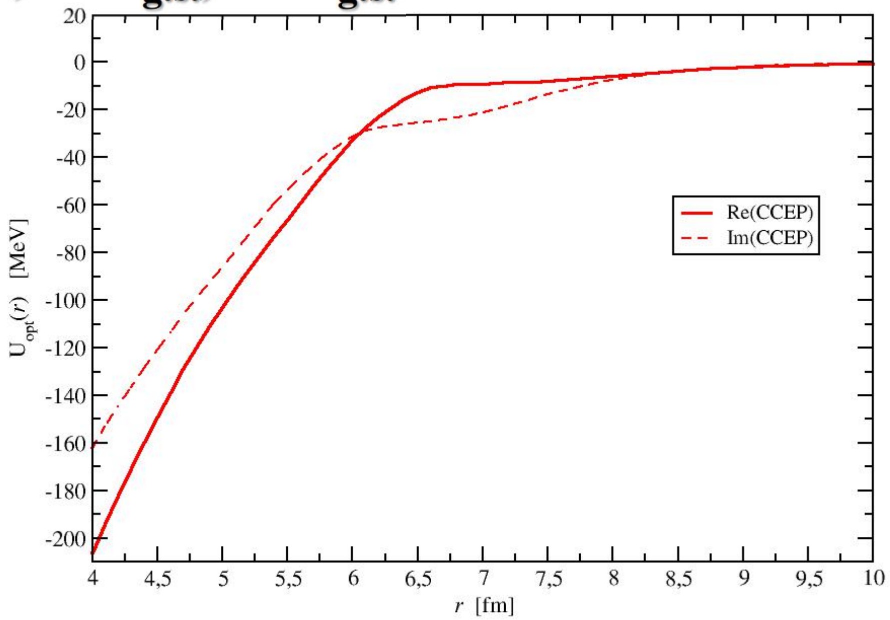
2νββ NME

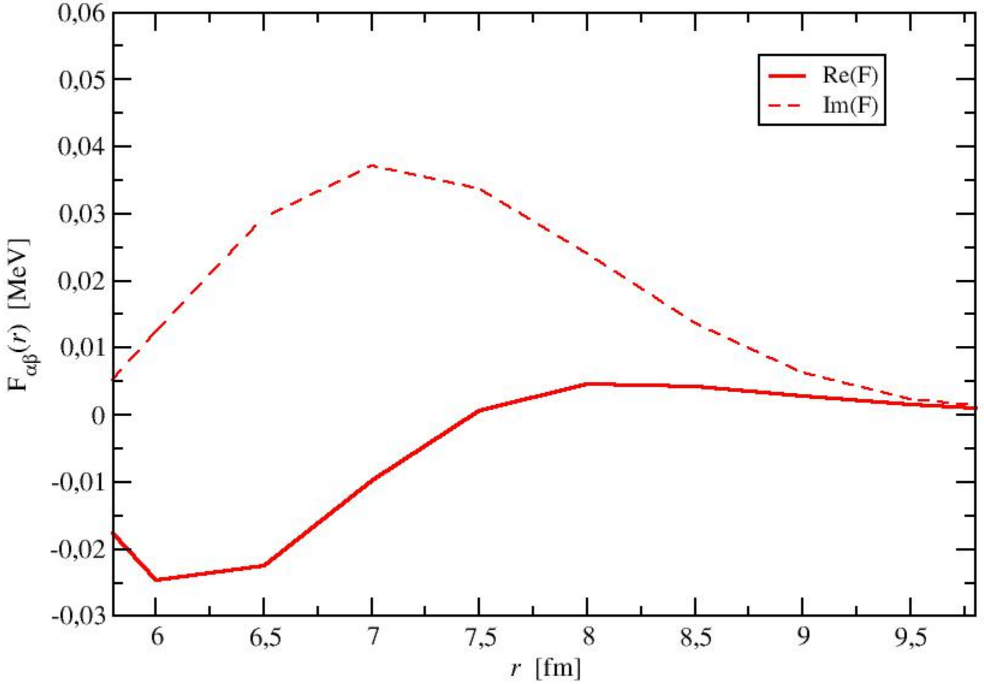
Sequential DCE Cross Section - $^{40}Ca(^{18}O,^{18}Ne_{g.s.})^{40}Ar_{g.s.}$

J.I. B., S. Burrello, M. Colonna, J.A. Lay, H. Lenske, PLB 807 (2020) 135528

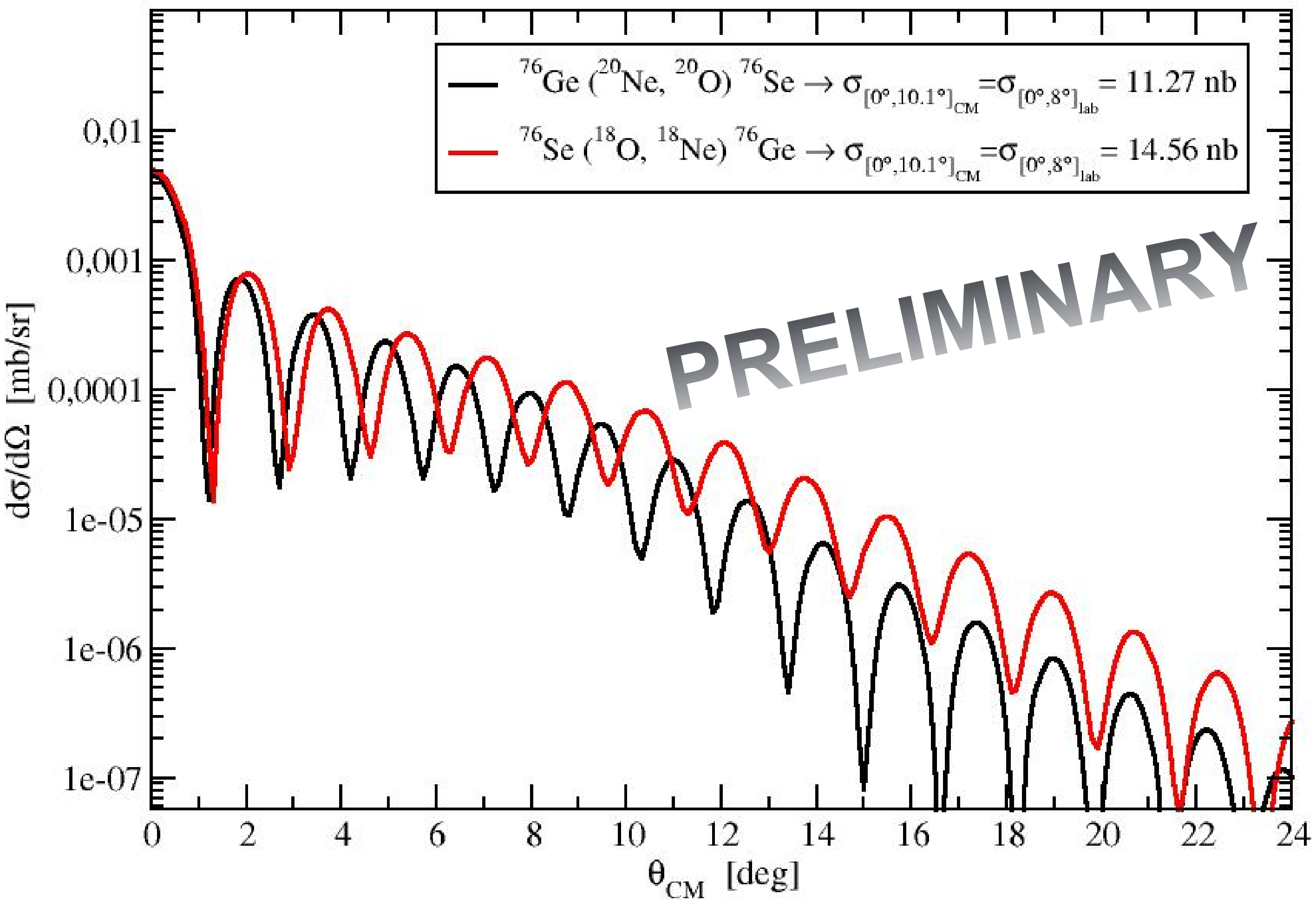
$^{40}Ca\,(^{18}O,\ ^{18}Ne)\ ^{40}Ar$ at E_{lab} = 275 MeV

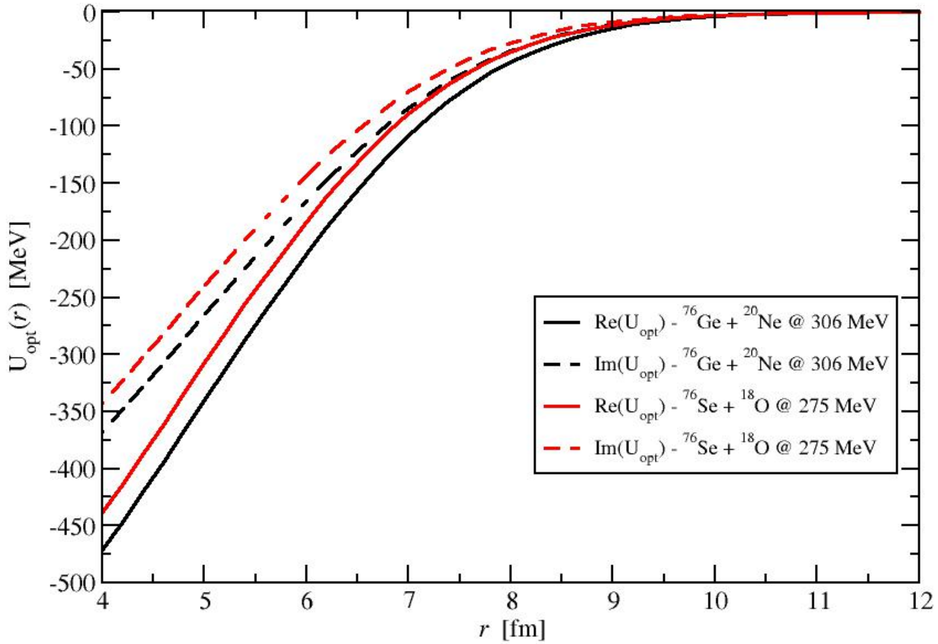


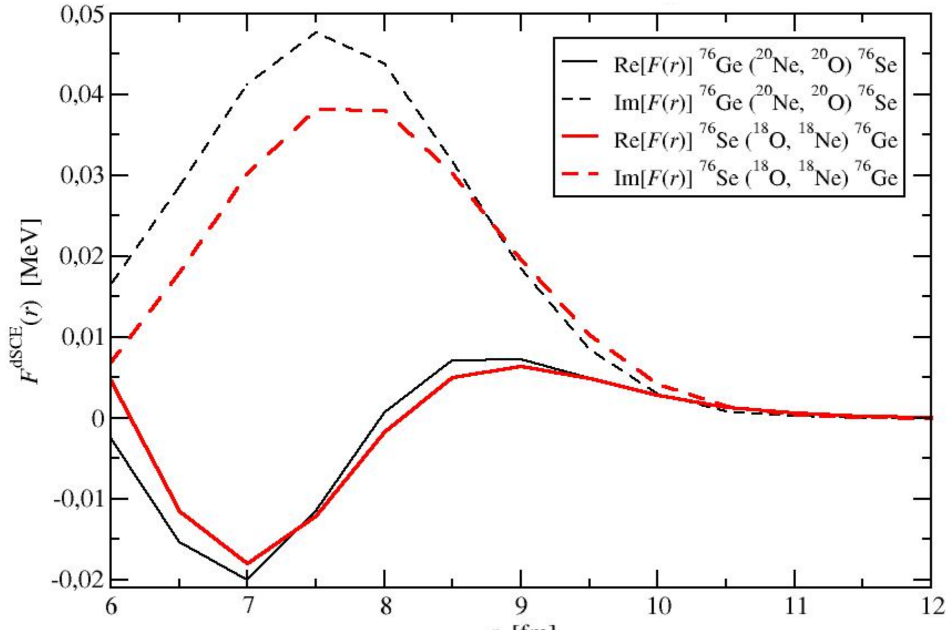




Sequential DCE Cross Section - $^{76}Se(^{18}O,^{18}Ne_{g.s.})^{76}Ge_{g.s.}$ vs $^{76}Ge(^{20}Ne,^{20}O_{g.s.})^{76}Se_{g.s.}$

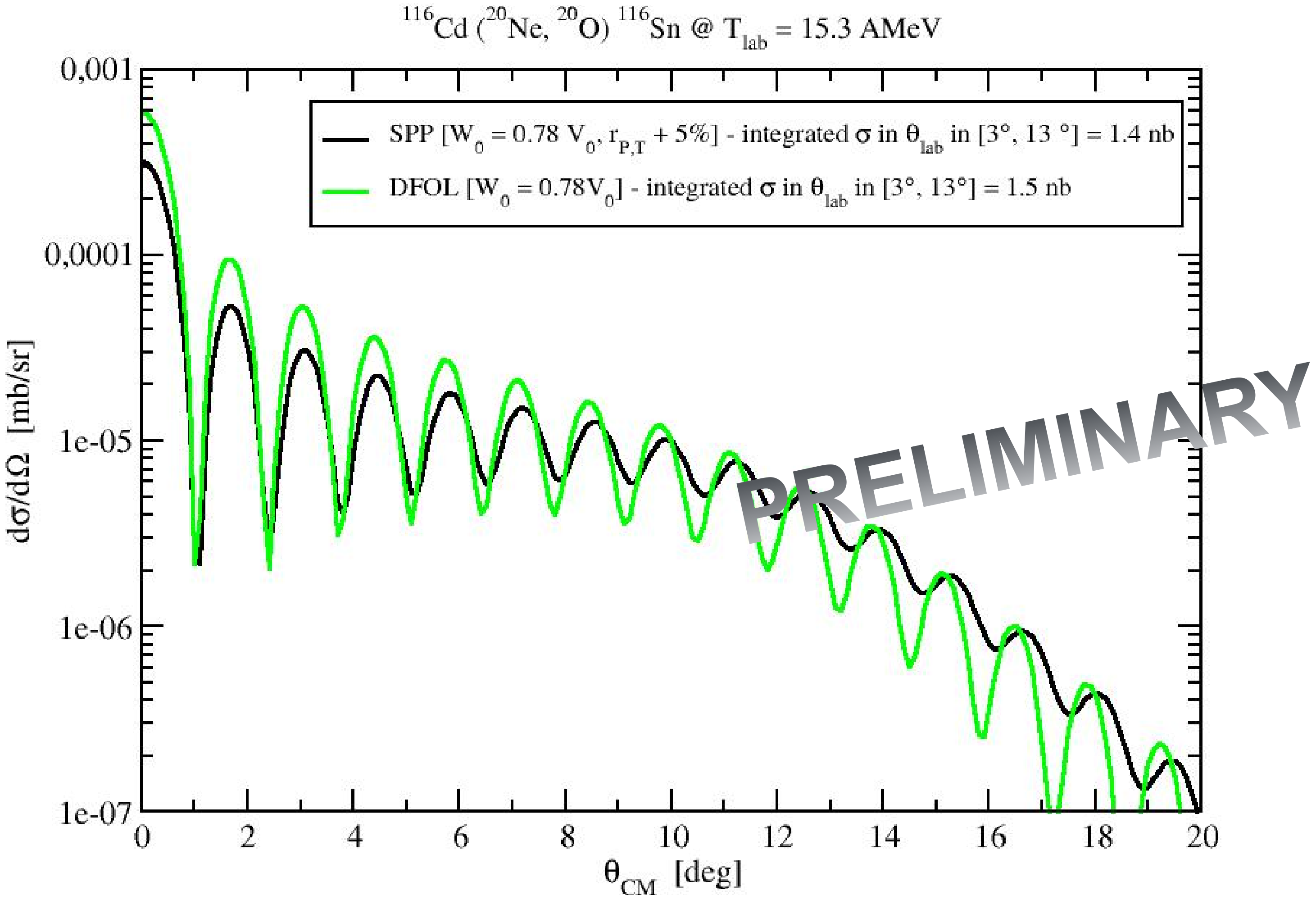


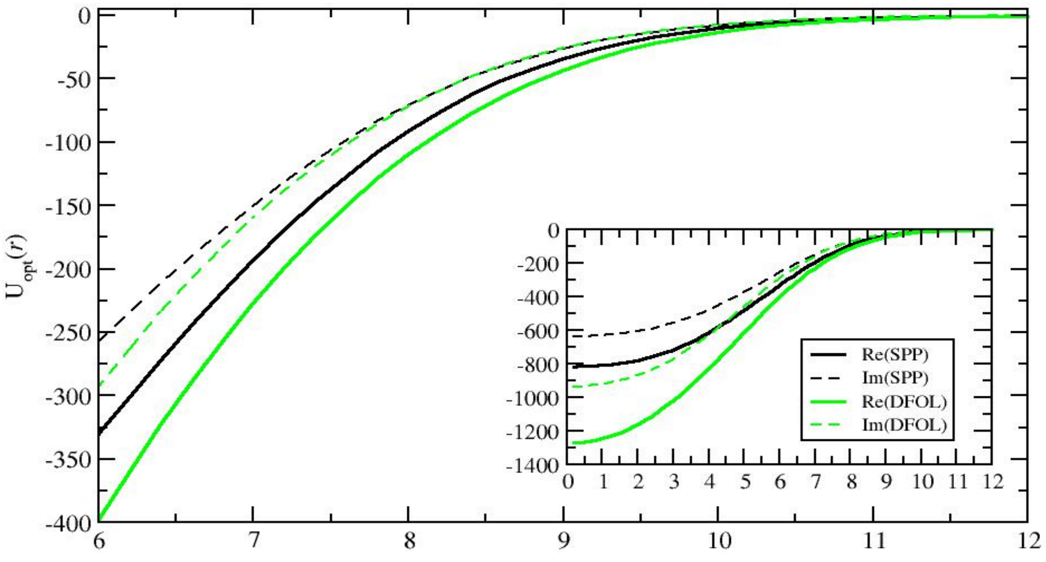


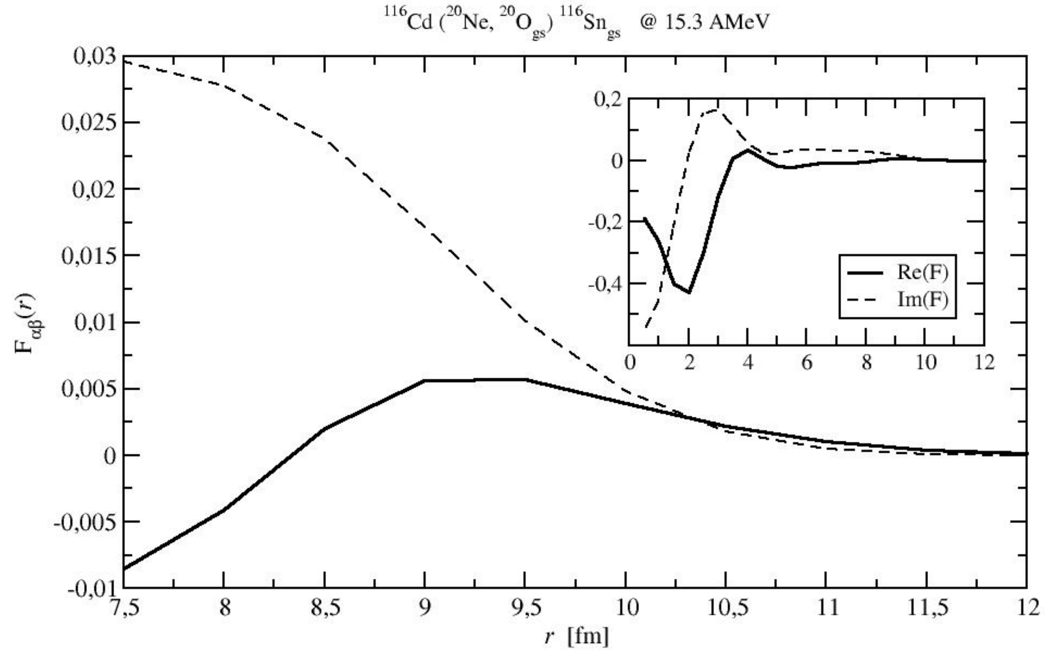


Integrated σ [nb] in 0°< θ_{lab} < 8°			
$^{76}Se(^{18}O,^{18}Ne)^{76}Ge$		$^{76}Ge(^{20}Ne,^{20}O)^{76}Se$	
exp.	theo.	exp.	theo.
29 ± 6	14.6	30 ± 6	11.3

Sequential DCE Cross Section - $^{116}Cd(^{20}Ne,^{20}O_{g.s.})^{116}Sn_{g.s.}$







Integral xsec (nb) in $3° < \theta_{lab} < 13°$	
$^{116}Cd(^{20}Ne,^{20}O)^{116}Sn$	
Exp.	Theo.
13 ± 2	1.4

...focusing on sequential Double Charge exchange process...

$$A(Z_A, N_A) + a(Z_a, N_a) \rightarrow B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$$

(β) $B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$

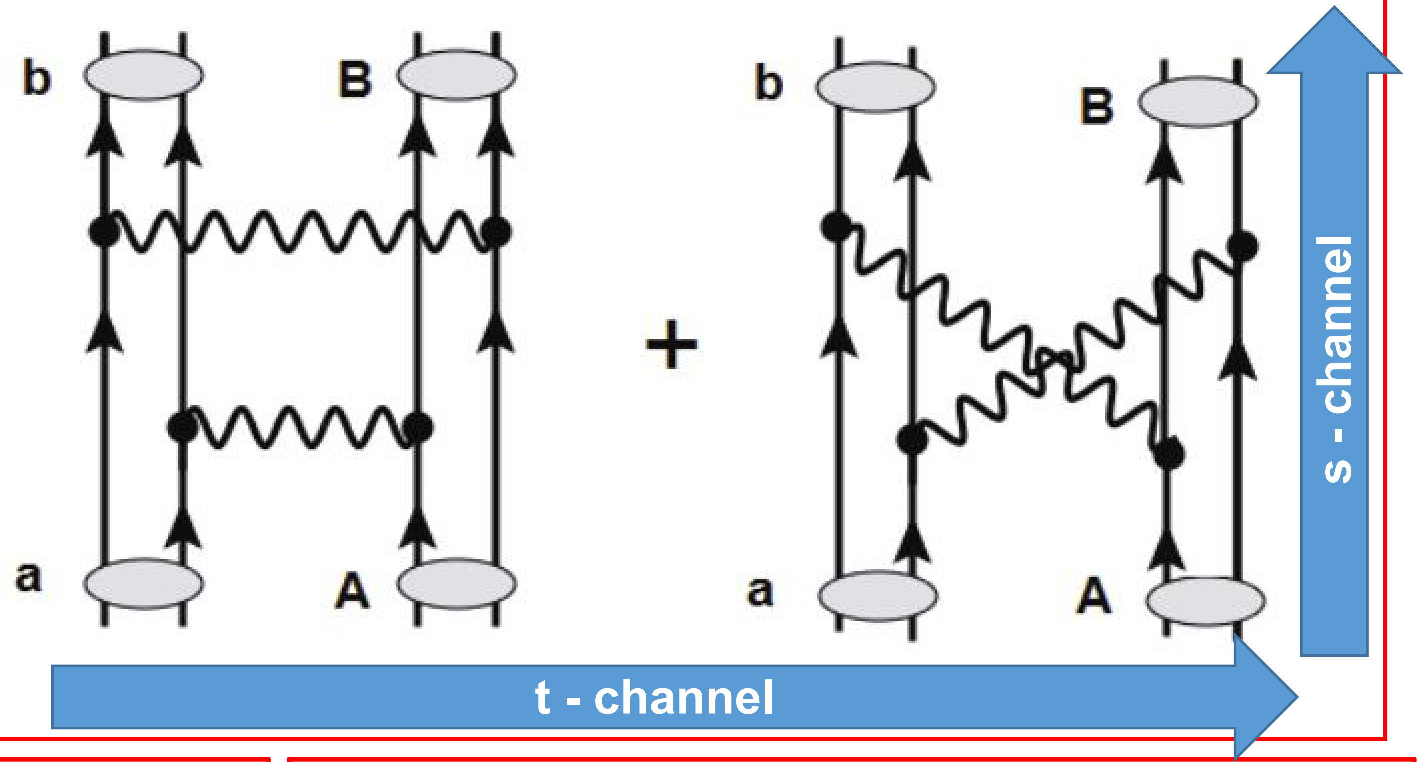
$\uparrow$

(γ) $C(Z_A \pm 1, N_A \mp 1) + c(Z_a \mp 1, N_a \pm 1)$

$\uparrow$

(α) $A(Z_A, N_A) + a(Z_a, N_a)$

sequence of two ***uncorrelated*** SCE reactions
(2νββ-like mechanism)



J.I. B., S. Burrello, M. Colonna, J.A. Lay, H. Lenske, PLB 807 (2020) 135528

H. Lenske, J.I. B., M. Colonna, D. Gambacurta, Universe 7 (2021) 4, 98

Sequential DCE Cross Section - s-channel formalism

- dSCE transition matrix element in momentum space

H. Lenske, J.I.B., M. Colonna, D. Gambacurta, Universe 7(4):98 (2021)

$$\mathcal{T}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \int d^3q_1 \int d^3q_2\, \tilde{\rho}_{1P}(\mathbf{q}_1)\tilde{\rho}_{1T}(\mathbf{q}_1)\tilde{V}_{PT}(\mathbf{q}_1)\tilde{\rho}^*_{2P}(\mathbf{q}_2)\tilde{\rho}^*_{2T}(\mathbf{q}_2)\tilde{V}^*_{PT}(\mathbf{q}_2)N_{\alpha\beta}(\mathbf{q}_1 - \mathbf{q}_2)$$

- changing variables $\begin{cases} \mathbf{q}_1 + \mathbf{q}_2 = \xi \\ \mathbf{q}_1 - \mathbf{q}_2 = \eta \end{cases}$

$$\rightarrow \frac{1}{4}\int d^3\xi d^3\eta\, \tilde{\rho}_{1P}(\frac{\xi+\eta}{2})\tilde{\rho}_{1T}(\frac{\xi+\eta}{2})\tilde{V}_{PT}(\frac{\xi+\eta}{2})\tilde{\rho}^*_{2P}(\frac{\xi-\eta}{2})\tilde{\rho}^*_{2T}(\frac{\xi-\eta}{2})\tilde{V}^*_{PT}(\frac{\xi-\eta}{2})N_{\alpha\beta}(\eta)$$

- $\tilde{\rho}_{1P}(\frac{\xi+\eta}{2})\tilde{\rho}^*_{2P}(\frac{\xi-\eta}{2}) \rightarrow \frac{1}{\bar{\xi}^3}\int d^3\xi\, \tilde{\rho}_{1P}(\frac{\xi+\eta}{2})\tilde{\rho}^*_{2P}(\frac{\xi-\eta}{2}) = \frac{1}{\bar{\xi}^3}\int d^3r\, e^{i\boldsymbol{\eta}\cdot\mathbf{r}}\rho_{1P}(\mathbf{r})\rho^*_{2P}(\mathbf{r}) \equiv \tilde{\rho}^{2BTD}_P(\boldsymbol{\eta})$

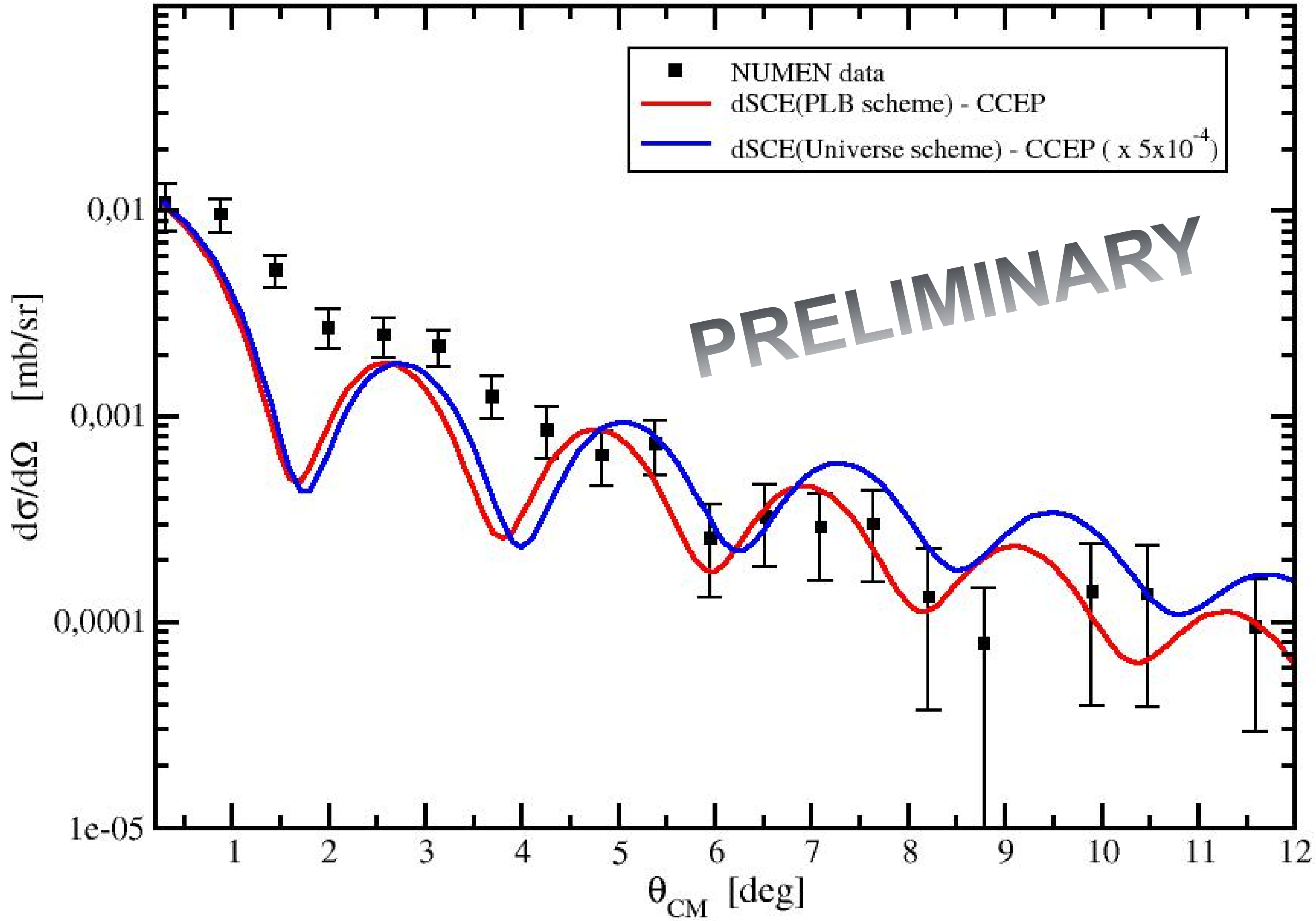
- Thus, the only quantity depending on ξ is $\int d^3\xi\, \tilde{V}_{PT}(\frac{\xi+\eta}{2})\tilde{V}^*_{PT}(\frac{\xi-\eta}{2}) = \int d^3r\, e^{i\boldsymbol{\eta}\cdot\mathbf{r}}|V(\mathbf{r})|^2 \equiv \tilde{V}^{dSCE}_{NN}(\boldsymbol{\eta})$

$$\rightarrow \mathcal{T}(\mathbf{k}_\alpha, \mathbf{k}_\beta) \simeq \int d^3\eta\, \tilde{\rho}^{2BTD}_P(\boldsymbol{\eta})\tilde{\rho}^{2BTD}_T(\boldsymbol{\eta})\tilde{V}^{dSCE}_{NN}(\boldsymbol{\eta})N_{\alpha\beta}(\boldsymbol{\eta})$$

like SCE !

Sequential DCE Cross Section - s-channel formalism

$^{40}Ca\,(^{18}O,\ ^{18}Ne)\ ^{40}Ar$ at $E_{lab} = 275$ MeV



SUMMARY and CONCLUSIONS

- Sequential DCE (dSCE) cross section calculations for the pilot system allow to recover the order of magnitude of the data, but for heavier nuclear systems dSCE the data are progressively underestimated:

  → possible effect of nuclear deformation not properly treated (already affecting SCE)
  - - -> further improvement of nuclear structure inputs → check the effect of nuclear deformations
  → try to establish a protocol allowing to better reproduce experimental energy spectra

  → contribution of Majorana-like DCE reaction mechanism, which should be coherently added to the sequential one

- to refine dSCE - s-channel fomalism in order to be able to extract separately projectile and target nuclear matrix elements from DCE cross section measurements

SUMMARY and CONCLUSIONS

- Sequential DCE (dSCE) cross section calculations for the pilot system allow to recover the order of magnitude of the data, but for heavier nuclear systems dSCE the data are progressively underestimated:

  → possible effect of nuclear deformation not properly treated (already affecting SCE)
  further improvement of nuclear structure inputs → check the effect of nuclear deformations
  → try to establish a protocol allowing to better reproduce experimental energy spectra

  → contribution of Majorana-like DCE reaction mechanism, which should be coherently added to the sequential one

- to refine dSCE - s-channel fomalism in order to be able to extract separately projectile and target nuclear matrix elements from DCE cross section measurements

THANK YOU FOR YOUR ATTENTION !

BACKUPS

Why Heavy Ion Double Charge Exchange (DCE) nuclear reactions?

Heavy Ion Double Charge Exchange (DCE) direct reactions:

$$A(Z_A, N_A) + a(Z_a, N_a) \rightarrow B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$$

- powerful and alternative tool to gain information on 0νββ decay Nuclear Matrix Element (NME)

F. Cappuzzello *et al.,* Eur. Phys. J. A (2018) **54** : 72

- 0νββ NME information are embedded in HI DCE transition matrix element:

$$\frac{d^2\sigma}{dE_x d\Omega} = \frac{E_\alpha E_\beta}{(2\pi\hbar^2 c^2)^2}\frac{k_\beta}{k_\alpha}\frac{1}{(2J_A+1)(2J_a+1)}\sum_{\substack{m_A,m_a\\ m_B,m_b}} |\mathcal{M}^{(DCE)}_{\alpha\beta}(\mathbf{k}_{\alpha\beta})|^2$$

- in momentum space

$$\mathcal{M}_{\alpha\beta}(\mathbf{k}_{\alpha\beta}) = \sum_{S,T}\int d^3p\, K(\mathbf{k}_{\alpha\beta},\mathbf{p})\, N^D(\mathbf{k}_{\alpha\beta},\mathbf{p})$$

distortion factor

reaction kernel

- at low momentum transfer, the nuclear structure term containing information on 0νββ NME can be factorized from all the other ingredients entering the HI one-step Charge Exchange cross section

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

E. Santopinto *et al.* , Phys. Rev. C 98 061601 (R) (2018)

...before analyzing sequential Double Charge Exchange process, let's check Single Charge Exchange reactions ...

(β) $B(Z_A \pm 2, N_A \mp 2) + b(Z_a \mp 2, N_a \pm 2)$

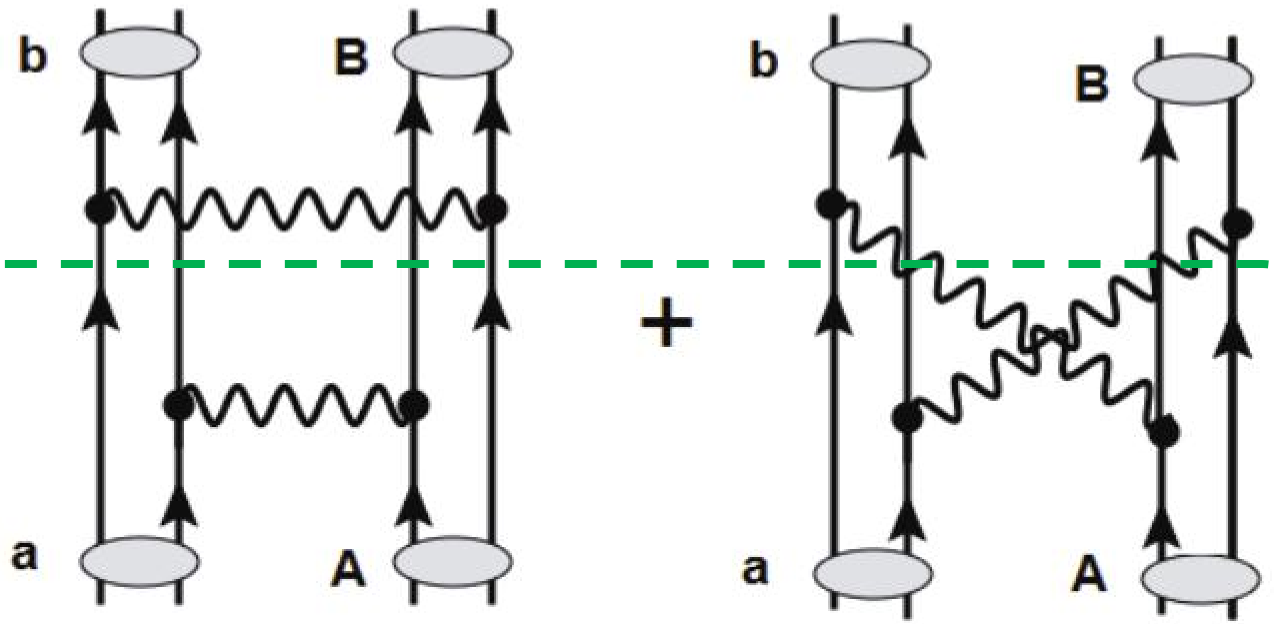
$\uparrow$

(γ) $C(Z_A \pm 1, N_A \mp 1) + c(Z_a \mp 1, N_a \pm 1)$

$\uparrow$

(α) $A(Z_A, N_A) + a(Z_a, N_a)$

sequence of two ***uncorrelated*** SCE reactions
(2νββ-like mechanism)



J.I. B., S. Burrello, M. Colonna, J.A. Lay, H. Lenske, PLB 807 (2020) 135528

Checks on SCE reactions - ^{76}Se(^{18}O,^{18}F)^{76}As vs ^{76}Ge(^{20}Ne,^{20}F)^{76}As

Energy range (MeV)	Integrated σ [μb] ; $4° < \theta_{lab} < 11.5°$			
	^{76}Se(^{18}O,^{18}F)^{76}As		^{76}Ge(^{20}Ne,^{20}F)^{76}As	
	Exp.	Theo. Direct SCE	Exp.	Theo. Direct SCE
[0,3]	77 ± 2	20.1	37 ± 1	5.8
[0,5]	170 ± 3	36.5	93 ± 2	12.5
[0,10]	552 ± 6	163	347 ± 4	94.9

- multi-nucleon transfer mechanism contributions
- discrepancies could also be due to the deformed nature of interacting nuclei not properly accounted for in our nuclear structure inputs
  → part of the strength pushed out of the energy range of interest or at all underestimated?
  → NEWSRs for L = 0 modes are exhausted to a good extent, but how to check higher multipolarities (which dominate in these energy ranges)?

Checks on SCE reactions - $^{116}Cd(^{20}Ne,^{20}F)^{116}In$

SCE experimental cross section integrated in θ_{lab} in [4.5°,14.5°] and in [0,0.35] MeV excitation energy range

Energy range (MeV)	Integrated σ [μb] ; 4.5°< θ_{lab} < 14.5°		
	$^{116}Cd(^{20}Ne,^{20}F)^{116}In$		
	Exp.	Theo.	
		Transfer SCE	Direct SCE
[0,0.35]	0.7 ± 0.3	0.31	0.036* 0.042 *

* using **SPP** optical potential, evaluated from elastic and inelastic channels analysis

* using **DFOL** optical potential, evaluated from elastic and inelastic channels analysis

^{20}F excited states used	Direct SCE σ [μb]
2^+ g.s.	$3.69\cdot10^{-3}$ $4.15\cdot10^{-3}$
3^+ (0.4 MeV- theo.)	$1.62\cdot10^{-2}$ $1.86\cdot10^{-2}$
4^+ (0.15 MeV-theo)	$5.76\cdot10^{-7}$ $6\cdot10^{-7}$
5^+ (0.3 MeV-theo.)	$1.64\cdot10^{-2}$ $1.93\cdot10^{-2}$

- discrepancies mainly due to the deformed nature of interacting nuclei not properly accounted for in our nuclear structure inputs
  → part of the strength pushed out of the energy range of interest or simply underestimated?
  → too much small excitation energy range vs too high nuclear (fragment) level density to asses the quality of nuclear structure inputs used

DCE state – of – art

- **π – N reactions** ⟶ spin – isospin transition operator different from beta decay ones

$$t_{\pi N} = t_{00} + t_{10}\sigma \cdot (\mathbf{k} \times \mathbf{k}') + (t_{01}^{(1)} + t_{01}^{(2)}(\tau_\pi \cdot \tau_N) + t_{11}\sigma \cdot (\mathbf{k} \times \mathbf{k}'))(\tau_\pi \cdot \tau_N)$$ ***(acting twice)***

J. Alster and J. Warszawski, Phys. Rep.52, 2 (1979) 87-132

D. S. Koltun and M. K. Singham, Phys. Rev. C 39, (1989) 704

⟶ no information on ββ decay NMEs !

- Light Ion DCE reactions

⟶ more than 2 fragments in the final channel ! ⟶ difficulties in measurement and reconstruction of trajectories

- Heavy Ion DCE reactions ⟶ Past attempts ⟶ low statistics
  ⟶ high background

J. Cerny, 3rd International Conference on Nuclei Far from Stability, Cargese, France, 19 - 26 May 1976, pp.225-34 (CERN-1976-013).

⟶ **Brink's kinematical conditions** matched

⟹ multi-nucleon transfer dominates

D.M. Drake et al., Phys. Rev. Lett. 45, 1765 (1980)

⟶ no information on ββ decay NMEs !

⟶ **Recent attempts** ⟶high resolution experiments allow to reach:

- significant statistics
- low background

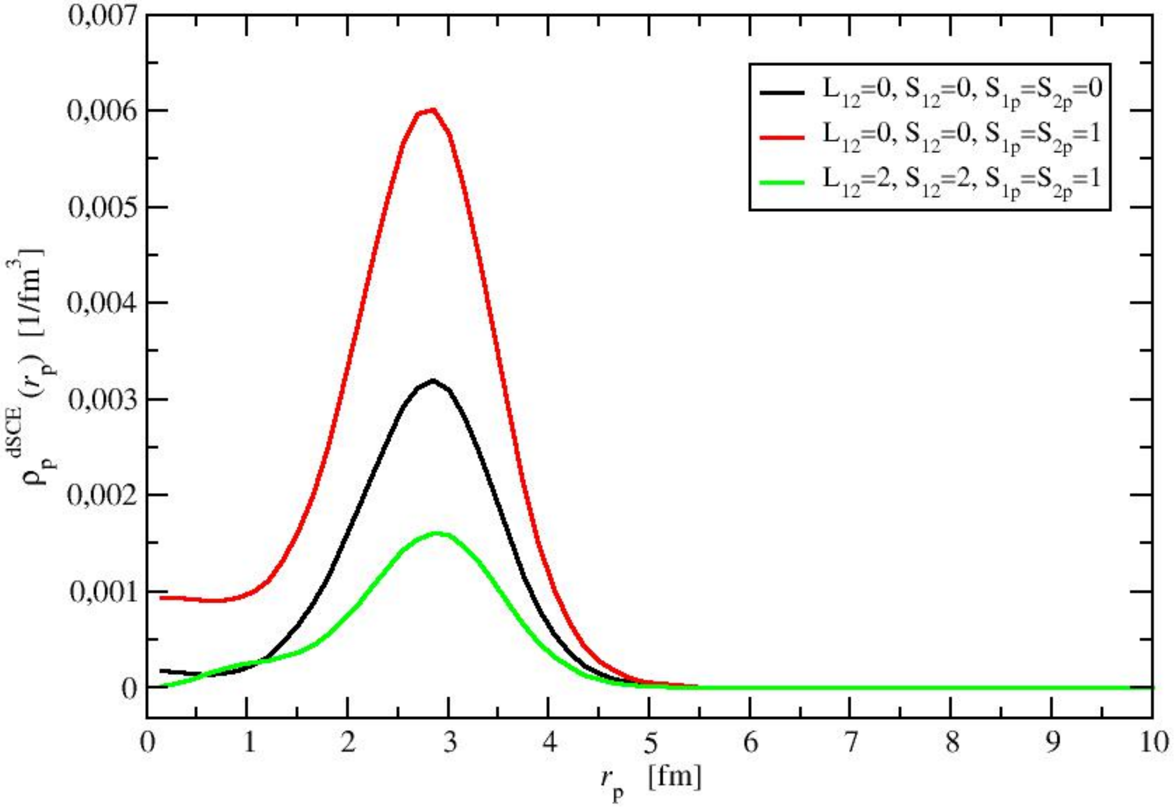
H. Matsubara *et al*., Few-Body System 54, 1433 (2013)

M. Takaki *et al*., CNS Ann. Rep. 94, 9 (2014)

F. Cappuzzello *et al*., Eur. Phys. J. A (2015), 51

Two-body Transition Densities - s-channel formalism

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



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