Understanding the isovector channel of nuclear interaction through heavy ion charge-exchange reactions

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Introduction: collective modes and interaction

- **Isovector** channel of interaction ⇒ **Symmetry energy** in **Equation of State** (EOS)

$$\frac{E}{A}(\rho,\beta) \approx \frac{E}{A}(\rho,\beta=0) + S(\rho)\beta^2 \qquad S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \dots \qquad \beta \equiv \frac{\rho_n-\rho_p}{\rho}$$

- **Collective phenomena** in **many-body** systems ⇒ properties of **interaction**
  - Probing collective **nuclear response** ⇒ Heavy-Ion (HI) collisions
- **Dipole excitations** in neutron-rich nuclei:
  - Giant Dipole Resonance (GDR)
  - Pygmy Dipole Resonance (PDR)

[S. Burrello et al., arXiV:1807.10118, (2018).]

- **Isospin-flip** transitions

⇒ **Charge-exchange** reactions

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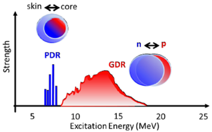

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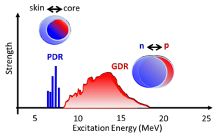

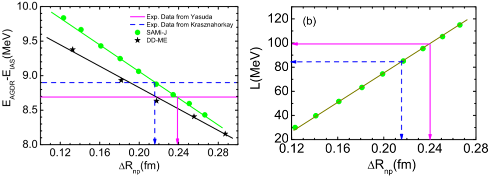

[X. Roca-Maza et al., Phys. Rev. C94, 044313 (2016).]

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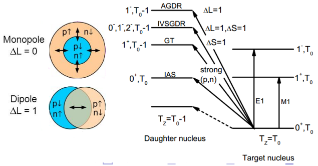

Spin-flip and isospin-flip transitions

- **Charge-exchange (CEX)** reactions: nuclei keep **mass constant** but **change charge**
- Contribution of **various mechanisms**:
  - multi-step transfers via intermediate states (**sequential** pick-up/stripping processes)
  - **direct conversion** of nucleon (N) (through meson exchange)

$$ {}^a_z a + {}^A_Z A \rightarrow {}^a_{z\pm 1} b + {}^A_{Z\mp 1} B $$

- Fermi (F) and Gamow-Teller (GT) transitions

$$ V_{NN} = \sum_{S,T} \left[V^C_{ST} (\sigma_1 \cdot \sigma_2)^S + V^T_{1T} S_{12} \right] (\tau_1 \cdot \tau_2)^T $$

- **Light ions** $\Rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{\theta=0} \propto B(GT)_\beta$

[Taddeucci T.N. et al., Nucl. Phys. A469, 125 (1987)]

- **Monopole** $\Rightarrow$ analogy to GT of β-decay
- **Heavy ions** $\Rightarrow$ complex **many-body** nature

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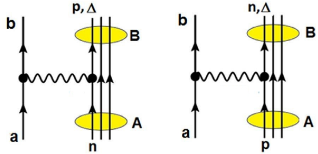

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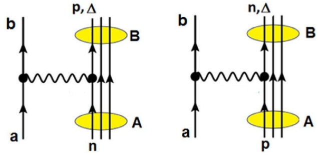

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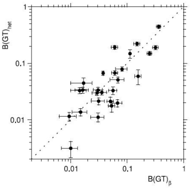

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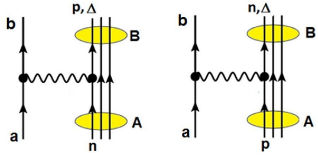

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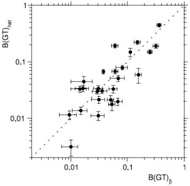

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Single CEX (SCEX) reactions with heavy ions

- **Direct** reaction $\Rightarrow$ Distorted Wave Born Approximation (**DWBA**)
- Single CEX $A(a,b)B$ cross section (c.s.) ($\alpha \equiv$ initial, $\beta \equiv$ final, $\hat{J} \equiv \sqrt{2J+1}$)

$$\frac{d\sigma}{d\Omega} = \frac{E_\alpha E_\beta}{(2\pi\hbar^2)^2}\frac{k_\beta}{k_\alpha}\frac{1}{\hat{J}_a^2 \hat{J}_A^2} \sum_{\substack{m_a, m_A \in \alpha \\ m_b, m_B \in \beta}} \left|M_{\alpha\beta}\right|^2, \quad M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_{S,T} \int d^3\mathbf{p}\, \mathcal{K}_{\alpha\beta}^{(ST)}(\mathbf{p})\, \mathcal{N}_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta, \mathbf{p})$$

$\mathcal{K}_{\alpha\beta}^{(ST)} \Rightarrow$ **Structure part** $\qquad \mathcal{N}_{\alpha\beta} \Rightarrow$ **Reaction part**

- Distortion factor $\mathcal{N}_{\alpha\beta} = \delta(\mathbf{p} - (\mathbf{k}_\alpha - \mathbf{k}_\beta)) = \delta(\mathbf{p} - \mathbf{q}_{\alpha\beta}) \Rightarrow$ Plane Wave (**PWBA**)
- **Factorization** at low $\mathbf{q}_{\alpha\beta} \Rightarrow \beta$-decay
  Nuclear Matrix Elements (**NME**)

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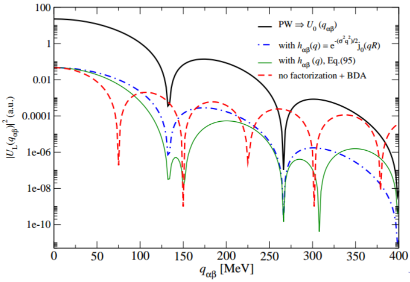
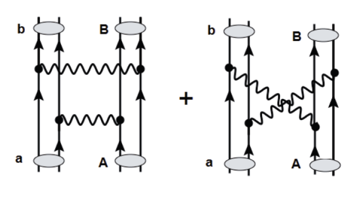


Double CEX and NUMEN project at LNS

- **Second order** CEX reactions: **double charge-exchange** (**DCEX**) reactions

Double SCEX (dSCE)



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Majorana DCEX (mDCE)

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- Missing **theory** for reaction mechanism $\Rightarrow$ renewed **experimental** interest
- double CEX $\Leftrightarrow$ **neutrino-less** 2β ($0\nu2\beta$) **decay** $\Rightarrow$ NUMEN project @LNS

[Cappuzzello, F. et al., EPJ A51 (2015)]

- ^{40}Ca(^{18}O, ^{18}Ne)^{40}Ar @ 15 AMeV
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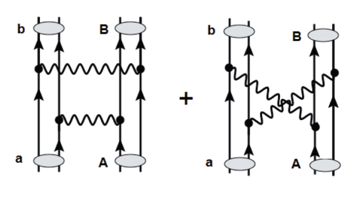

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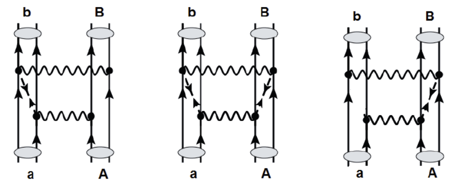

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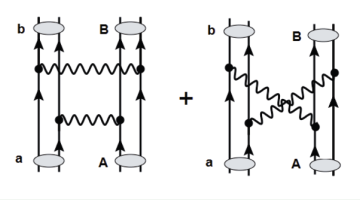

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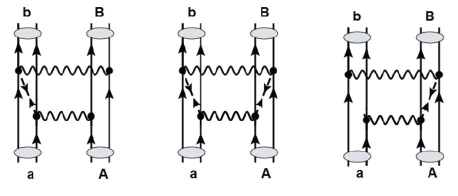

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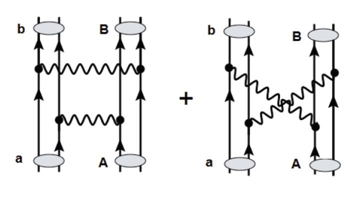

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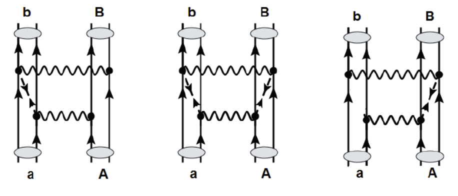

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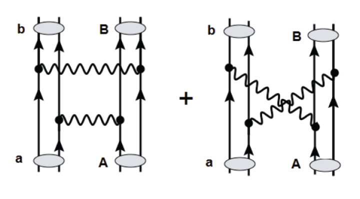

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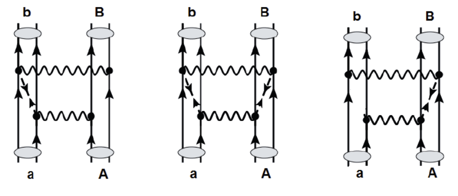

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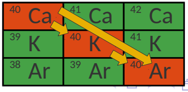
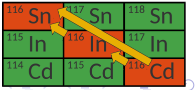
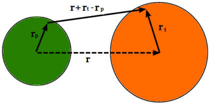




dSCE vs mDCE: diffraction pattern and distortion

- **Optical potential** ⇒ **double-folding** integrals

$$U_{pt}(\mathbf{r}) = \int d\mathbf{r}_t \int d\mathbf{r}_p \rho_t(\mathbf{r}_t)\rho_p(\mathbf{r}_p) V_{NN}(\mathbf{r} + \mathbf{r}_t - \mathbf{r}_p)$$



- Analytical **Form Factors (FF)**: $F_L(r) \propto \left(\frac{\partial U}{\partial r}\right)$
  - dSCE vs mDCE: - same θ **distribution**

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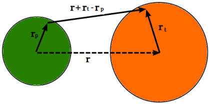

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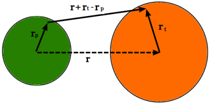

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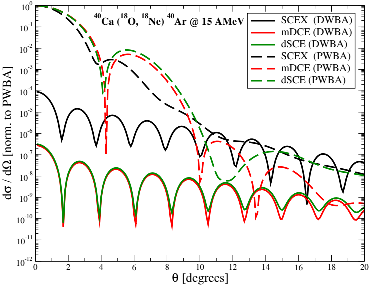

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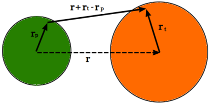

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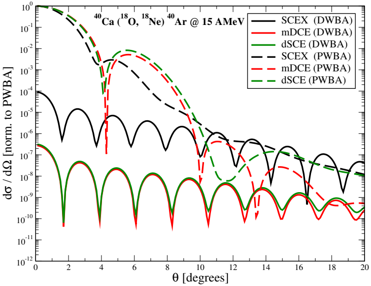

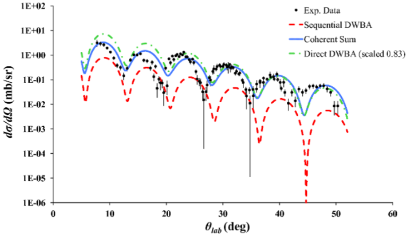

[M. Cavallaro et al., EPJ WC 66, (2014)]

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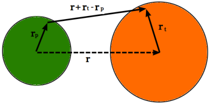

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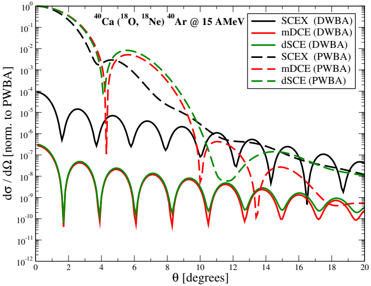

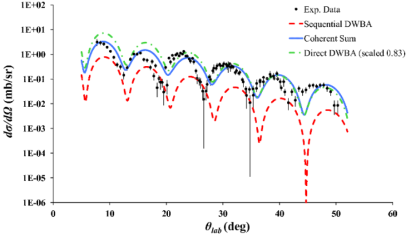

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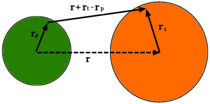

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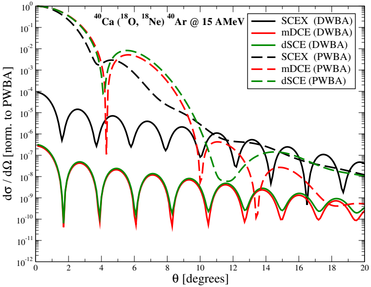

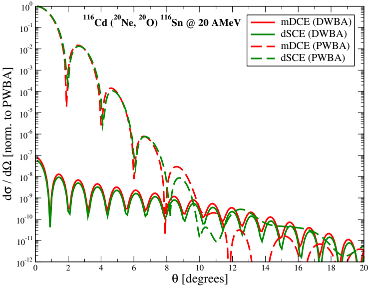

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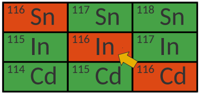
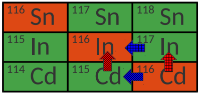
WARNING

Distortion effects act **only once** also in two-step process!

Preliminary results: single CEX vs transfer

- Isolate CEX from exp. **cross section**
  $\Rightarrow$ description of **competing** processes





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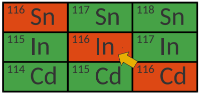

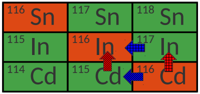

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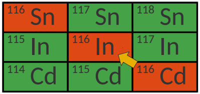

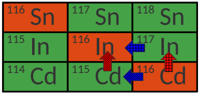

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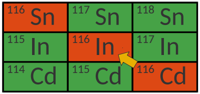

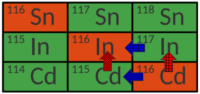

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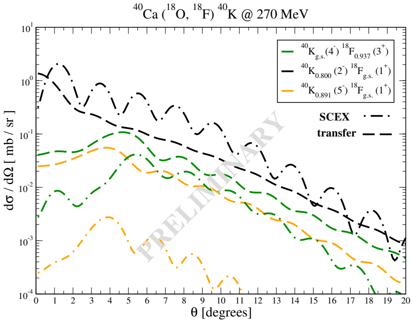

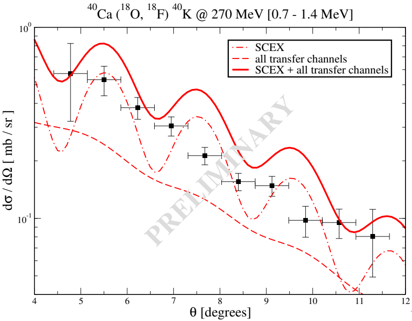

Final remarks and conclusions

Summary

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- **Charge-exchange** reactions with **heavy ions** in view of **experimental** interest
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- Role of **distortion effects** in **direct** and **two-step** double charge exchange
- Importance of **coherent interference** between **transfer** and **charge-exchange**

Further developments and outlooks

- **Complete** theory of **double charge exchange**, of interest in 2β-**decay** studies
- Full determination of **higher order** combination of **multi-transfer**
- Behavior of **nuclear interaction** in **isospin** channels: support to **RIB**

Acknowledgements

THANK YOU FOR YOUR KIND ATTENTION!

F. Cappuzzello, C. Agodi, M. Cavallaro, D. Carbone, S. Tudisco, D. Lo Presti, J. R. B. Oliveira, P. Finocchiaro, M. Colonna, D. Rifuggiato, L. Calabretta, D. Calvo, L. Pandola, L. Acosta, N. Auerbach, J. Bellone, R. Bijker, D. Bonanno, D. Bongiovanni, T. Borello-Lewin, I. Boztosun, O. Brunasso, S. Burrello, S. Calabrese, A. Calanna, E.R. Chávez Lomelí, G. D'Agostino, P.N. De Faria, G. De Geronimo, F. Delaunay, N. Deshmukh, J.L. Ferreira, M. Fisichella, A. Foti, G. Gallo, H. Garcia, V. Greco, M.A. Guazzelli, A. Hacisalihoglu, F. Iazzi, R. Introzzi, G. Lanzalone, J.A. Lay, F. La Via, H. Lenske, R. Linares, G. Litrico, F. Longhitano, J. Lubian, N. Medina, D.R. Mendes, M. Moralles, A. Muoio, A. Pakou, H. Petrascu, F. Pinna, S. Reito, A. D. Russo, G. Russo, G. Santagati, E. Santopinto, R.B.B. Santos, O. Sgouros, S.O. Solakci, G. Souliotis, V. Soukeras, A. Spatafora, D. Torresi, R.I.M. Vsevolodovna, V.A.B. Zagatto, A. Yildirin

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ENSAR2

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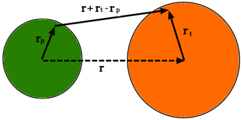
Backup slides

BACKUP SLIDES

First exploratory steps: unit cross section



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  - **Love & Franey** V_{NN} interaction
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  - **Single state dominance**
  - **Closure approximation**

    ⇒ **mDCE** $\sim \langle K' | F^2 | K \rangle$

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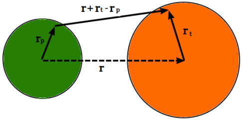

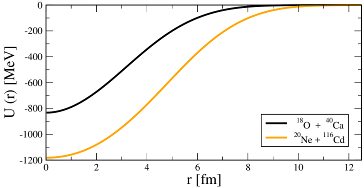

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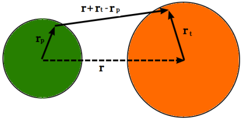

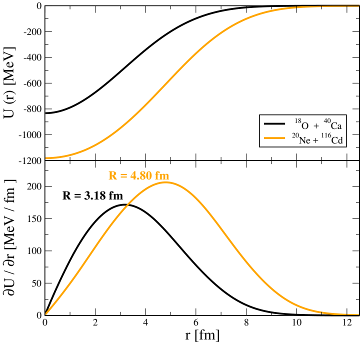

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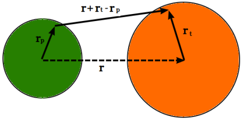
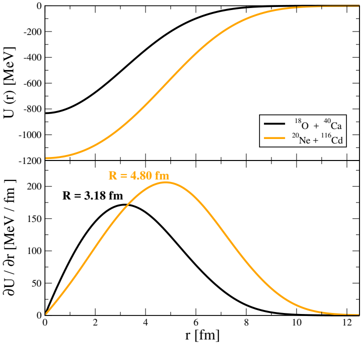
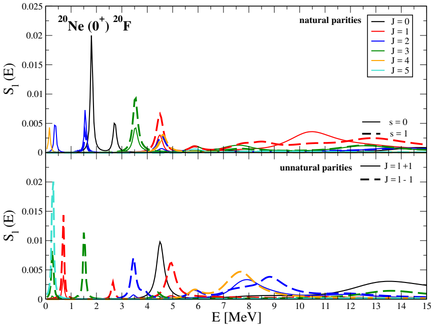




Microscopic form factors: QRPA calculations

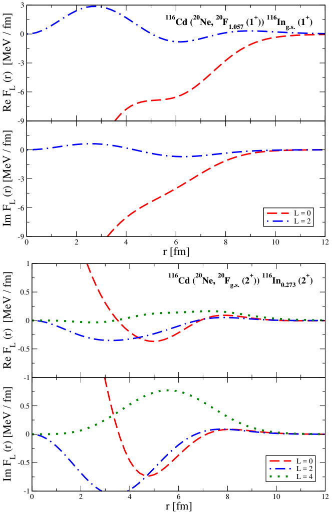
- **Realistic** calculations: microscopic FF from **QRPA** (with **HIDEX** code)
  - Difficult to isolate **contributions** for each state
  - Excitation energies do not match experimental ones
  - Main contributions at **larger** values of E

$$S_l(E) = \int drr^2 \, (\delta\rho_l(r,E))^2 \qquad \delta\rho_l(r,E) \equiv \text{QRPA transition densities}$$



SCEX reaction ^{116}Cd (^{20}Ne,^{20}F)^{116}In: results

$L = 0$ generally **dominates** at very **forward** angles, but other contributions become **important** at larger θs!



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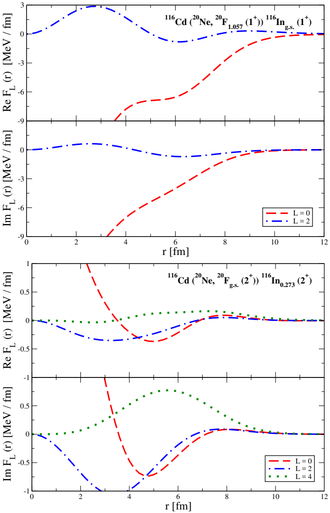

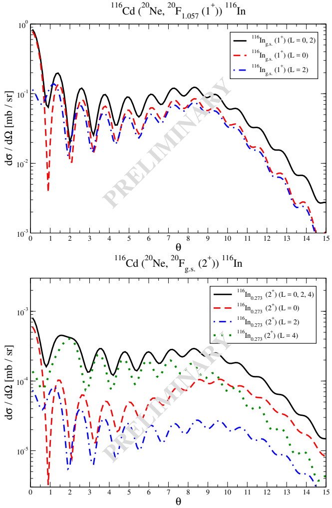

Competing channels: two-nucleon (2N) transfers

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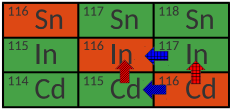

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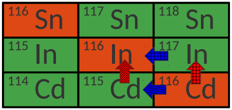

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  - Direct process **dominant** at energy E∼100 AMeV
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QUESTION

What is the role of **transfer** processes at **intermediate** E for **heavier** colliding systems?

[Lenske H., Wolter H.H., Bohlen H.G., PRL62 (1989).]

Competing channels: two-nucleon (2N) transfers

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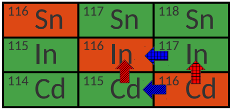

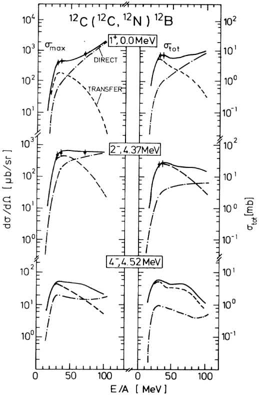

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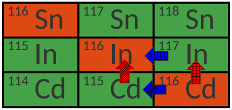

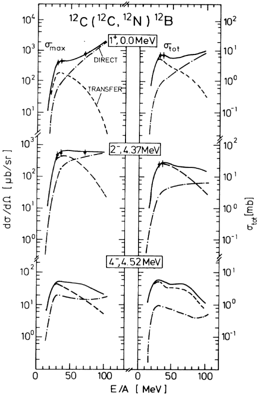

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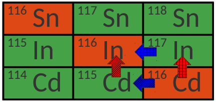
Post/prior representation and non-orthogonality



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- **Structure** ingredients: overlap functions
  $\langle ^{116}Cd | ^{115}Cd \rangle$, $\langle ^{116}Cd | ^{117}In \rangle$, $\langle ^{20}Ne | ^{21}Ne \rangle$, ...
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  - (SM) with zbm and glekpn interactions (NuShellX code)
    [in coll. with Ferreira J., Lubian J.]

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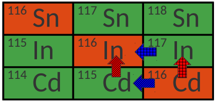

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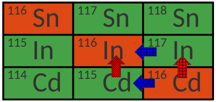

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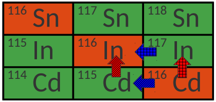

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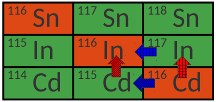

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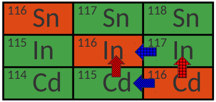

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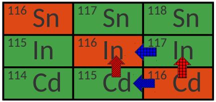

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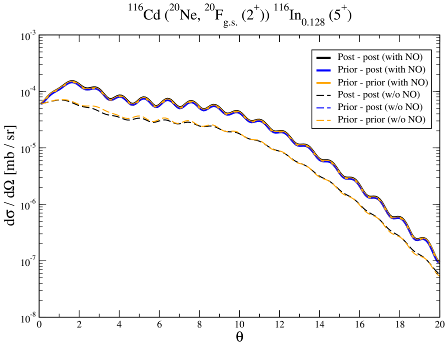

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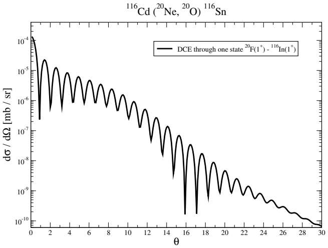
Perspectives and outlooks: towards DCEX



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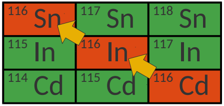

- 3^{rd} order processes:
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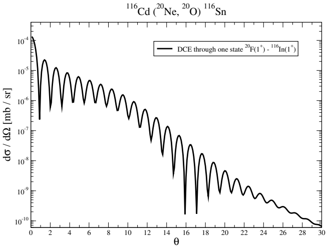

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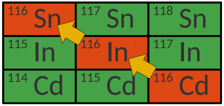

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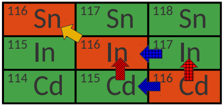

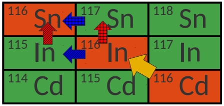

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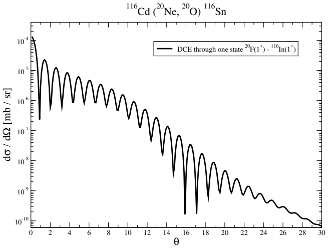

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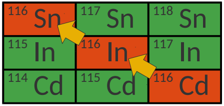

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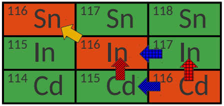

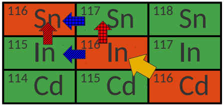

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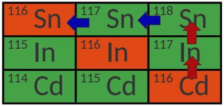

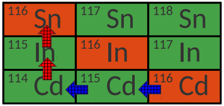

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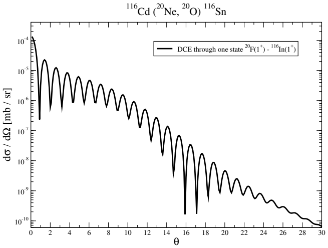

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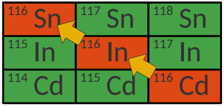

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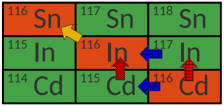

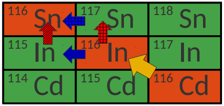

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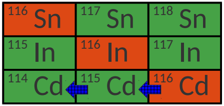
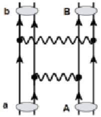


Back-up

Double Charge Exchange (DCE) as a 2-step process: analogies with 2ν double beta decay

$$_z a +_Z A \rightarrow_{z\pm2} b +_{Z\mp2} B$$



Transition matrix element

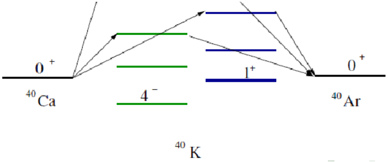
$$M^{(DCE)}_{\alpha\beta}(\mathbf{k}_{bB},\mathbf{k}_\alpha) = \langle \chi^{(-)}_\beta, bB|T_{NN}\mathcal{G}^{(+)}(\omega)T_{NN}|aA,\chi^{(+)}_{aA}\rangle.$$

nuclear interaction

$$\mathcal{G}(\omega) = \sum_{\gamma=c.C} |\gamma\rangle G_\gamma(\omega_\alpha)\langle\gamma|, \longrightarrow$$ *intermediate states*

➡ $$M^{(DCE)}_{\alpha\beta}(\mathbf{k}_\beta,\mathbf{k}_\alpha) = \sum_{c,C}\int \frac{d^3k_\gamma}{(2\pi)^3} M^{(SCE)}_{bB,cC}(\mathbf{k}_\beta,\mathbf{k}_\gamma) G_{cC}(\omega_\gamma,\omega_\alpha) \tilde{M}^{(SCE)}_{cC,aA}(\mathbf{k}_\gamma,\mathbf{k}_\alpha),$$

Single CEX *Single CEX*



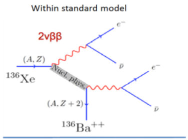
propagator

$$G_\gamma(\omega_\gamma,\omega_\alpha) = \frac{1}{\omega_\alpha - \omega_\gamma + i\eta}$$

energy

2ν double beta decay

➡ $$M^{(2\nu)}(\mathrm{DGT}) = \sum_m \frac{\langle 0^{(f)}_{\mathrm{g.s.}} \| \sum_k \sigma_k\tau_k^- \| 1^+_m\rangle\langle 1^+_m \| \sum_k \sigma_k\tau_k^- \| 0^{(i)}_{\mathrm{g.s.}}\rangle}{{}^1\!/_2\, Q_{\beta\beta}(0^{(f)}_{g.s.}) + E_x(1^+_m) - E_0}$$



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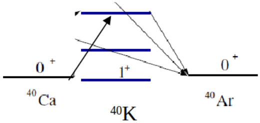
- Single state dominance (ex: 0^+ ✉ 1^+ ✉ 0^+)



small momentum transfer ~F(q)

$$\frac{d^2\sigma}{dE\,d\Omega} = \frac{E_\alpha E_\beta}{(2\pi\hbar c)^4} \frac{k_\beta}{k_\alpha} k^2_\omega \mu^2_\omega |K^{(SCE)}(\mathbf{q}_{\alpha\omega})|^2 |K^{(SCE)}(\mathbf{q}_{\omega\beta})|^2 \; f_{BD}$$

Product of beta decay strengths associated with the two steps

- Closure approximation (one-step process)

$$\bar{M}^{(DCE)}_{\beta\alpha}(\mathbf{k}_\beta, \mathbf{k}_\alpha) \simeq \sum_{SM, S_1 S_2} (-)^{S_1+S_2-S+M} M^{(ba)\dagger}_{(S_1 S_2)S-M}(\mathbf{q}_{\alpha\beta}) M^{(BA)}_{(S_1 S_2)S-M}(\mathbf{q}_{\alpha\beta}) V_{S_2 S_1}(\mathbf{k}_\beta, \mathbf{k}_\alpha).$$

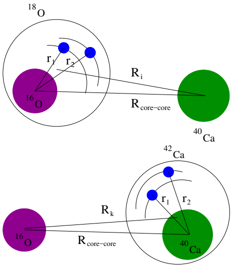
~ $F^2(r)$

➡ $M^{(fi)}_{(S_1,S_2)SM}(\mathbf{q}_{\alpha\beta}) = \langle \mathbf{k}_\beta, f | e^{i\mathbf{q}_{\beta\alpha}\cdot\mathbf{r}} S_{(S_2 S_1)SM}(1,2) \tau_\pm(2) \tau_\pm(1) | \mathbf{k}_\alpha i \rangle.$

$$V_{S_2 S_1}(\mathbf{k}_\beta, \mathbf{k}_\alpha) = \int \frac{d^3 k_\gamma}{(2\pi)^3} \frac{t_{S_2 T}(q^2_{\beta\gamma}) t_{S_1 T}(q^2_{\gamma\alpha})}{\omega(k_\alpha) - \bar{\omega}(k_\gamma) + i\eta},$$

Two-body transition operator, similar to DGT

The Schrödinger Equation



$$A + b \rightarrow a + B$$

Set of Coupled Equations:

$$\langle \phi_j | \mathcal{H} - E | \phi_j \rangle \psi_j(R_j) + \sum_{i \neq j} \langle \phi_j | \mathcal{H} - E | \phi_i \rangle \psi_i(R_i) = 0$$

Distorted Wave:

$$\langle \phi_j | \mathcal{H} - E | \phi_j \rangle \chi_j(R_j) = 0$$

Plane Wave:

$$\langle \phi_j | \mathcal{K} - E | \phi_j \rangle e^{-i\vec{k}\cdot\vec{R}_j}(R_j) = 0$$

Distorted Wave Born Approximation

1. i→j→k:

$$\langle\phi_i|\mathcal{H}-E|\phi_i\rangle\chi_i(R_i)\approx 0$$
$$\langle\phi_j|\mathcal{H}-E|\phi_j\rangle\psi_j(R_j)\approx -\langle\phi_j|\mathcal{H}-E|\phi_i\rangle\chi_i(R_i)$$
$$\langle\phi_k|\mathcal{H}-E|\phi_k\rangle\psi_k(R_k)\approx$$
$$-\langle\phi_k|\mathcal{H}-E|\phi_i\rangle\chi_i(R_i)-\langle\phi_k|\mathcal{H}-E|\phi_j\rangle\psi_j(R_j)$$

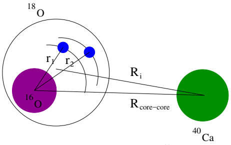
2. T_{ki} amplitudes:

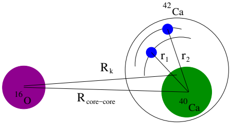
$$T_{ki}^{(1)}=\langle\chi_k^{(-)}\phi_k|\mathcal{H}-E|\phi_i\chi_i^{(+)}\rangle$$

$$T_{ki}^{(2)}=\langle\chi_k^{(-)}\phi_k|\mathcal{H}-E|\phi_j\psi_j^{(+)}\rangle$$

$$T_{ki}^{(2)}=\langle\chi_k^{(-)}|\langle\phi_k|\mathcal{H}-E|\phi_j\rangle G_j^{(+)}\langle\phi_j|\mathcal{H}-E|\phi_i\rangle|\chi_i^{(+)}\rangle$$

The Hamiltonian





$$A + b \rightarrow a + B$$

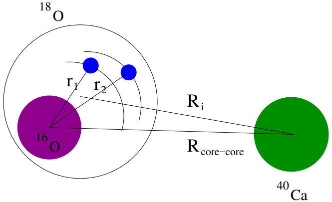
Prior

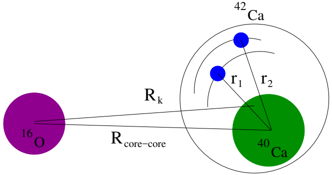
$$\mathcal{H} = \mathcal{K} + V_{core-core} + V_1(r_1) + V_2(r_2)$$
$$= \mathcal{K} + U_{Ab}(R_i) +$$
$$+ V_{core-core}(R_{cc}) - U_{Ab}(R_i) + V_{1B}(r_{1B}) + V_{2B}(r_{2B})$$
$$= H(R_i) + V$$

Post

$$\mathcal{H} = \mathcal{K} + V_{core-core} + V_1(r_1) + V_2(r_2)$$
$$= \mathcal{K} + U_{aB}(R_k) +$$
$$+ V_{core-core}(R_{cc}) - U_{aB}(R_k) + V_{1A}(r_{1A}) + V_{2A}(r_{2A})$$
$$= H(R_k) + V$$

Prior vs. Post





Evaluating the previous brakets:

$\langle \phi_j | \mathcal{H} - E | \phi_j \rangle = H_j - E_j$;

$\langle \phi_j | \mathcal{H} - E | \phi_i \rangle =$

prior

$$= \langle \phi_j | V_i | \phi_i \rangle + \langle \phi_j | \phi_i \rangle [H_i - E_i]$$

$$= V_{ji}^{prior} + K_{ji} [H_i - E_i]$$

post

$$= \langle \phi_j | V_j | \phi_i \rangle + [H_j - E_j] \langle \phi_j | \phi_i \rangle$$

$$= V_{ji}^{post} + [H_j - E_j] K_{ji}$$

$$[H_i - E_i] \chi(R_i) = 0$$

$$K_{ji} = \langle \phi_j | \phi_i \rangle$$

! Prior/Post and NO

$$T^{(1)}_{ki} = \langle \chi^{(-)}_k \phi_k | \mathcal{H} - E | \phi_i \chi^{(+)}_i \rangle$$

prior

$$T^{(1)}_{ki} = \langle \chi^{(-)}_k | V^{prior}_{ki} + K_{ki}[H_i - E_i] | \chi^{(+)}_i \rangle$$
$$T^{(1)}_{ki} = \langle \chi^{(-)}_k | V^{prior}_{ki} | \chi^{(+)}_i \rangle$$

post

$$T^{(1)}_{ki} = \langle \chi^{(-)}_k | V^{post}_{ki} + [H_k - E_k] K_{ki} | \chi^{(+)}_i \rangle$$
$$T^{(1)}_{ki} = \langle \chi^{(-)}_k | V^{post}_{ki} | \chi^{(+)}_i \rangle$$

!! Prior and post give the same in 1^{st} order if converged

! Prior/Post and NO

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | \langle \phi_k | \mathcal{H} - E | \phi_j \rangle G_j^{(+)} \langle \phi_j | \mathcal{H} - E | \phi_i \rangle | \chi_i^{(+)} \rangle$$

prior-prior

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | (V_{kj}^{prior} + K_{kj}[H_j - E_j]) G_j (V_{ji}^{prior} + K_{ji}[H_i - E_i]) | \chi_i^{(+)} \rangle =$$
$$= \langle \chi_k^{(-)} | V_{kj}^{prior} G_j V_{ji}^{prior} | \chi_i^{(+)} \rangle + \langle \chi_k^{(-)} | K_{kj}[H_j - E_j] G_j V_{ji}^{prior} | \chi_i^{(+)} \rangle$$

prior-post

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | (V_{kj}^{post} + [H_k - E_k] K_{kj}) G_j (V_{ji}^{prior} + K_{ji}[H_i - E_i]) | \chi_i^{(+)} \rangle =$$
$$= \langle \chi_k^{(-)} | V_{kj}^{post} G_j V_{ji}^{prior} | \chi_i^{(+)} (R_i) \rangle + 0$$

!! Prior-post has zero NO term

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | \langle \phi_k | \mathcal{H} - E | \phi_j \rangle G_j^{(+)} \langle \phi_j | \mathcal{H} - E | \phi_i \rangle | \chi_i^{(+)} \rangle$$

post-post

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | (V_{kj}^{post} + [H_k - E_k] K_{kj}) G_j (V_{ji}^{post} + [H_j - E_j] K_{ji}) | \chi_i^{(+)} \rangle =$$

$$= \langle \chi_k^{(-)} | V_{kj}^{post} G_j V_{ji}^{post} | \chi_i^{(+)}(R_i) \rangle + \langle \chi_k^{(-)} | V_{kj}^{post} G_j [H_j - E_j] K_{ji} | \chi_i^{(+)} \rangle$$

post-prior

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | (V_{kj}^{prior} + K_{kj} [H_j - E_j]) G_j (V_{ji}^{post} + [H_j - E_j] K_{ji}) | \chi_i^{(+)} \rangle =$$

$$= \langle \chi_k^{(-)} | V_{kj}^{prior} G_j V_{ji}^{post} | \chi_i^{(+)}(R_i) \rangle + \langle \chi_k^{(-)} | K_{kj} [H_j - E_j] G_j V_{ji}^{post} | \chi_i^{(+)} \rangle$$

$$+ \langle \chi_k^{(-)} | V_{kj}^{prior} G_j [H_j - E_j] K_{ji} | \chi_i^{(+)} \rangle +$$

$$+ \langle \chi_k^{(-)} | K_{kj} [H_j - E_j] G_j [H_j - E_j] K_{ji} | \chi_i^{(+)} \rangle$$

! Post-post and prior-prior in a full bases

$$T_{ki}^{(2)} = \langle \chi_k^{(-)} | \langle \phi_k | \mathcal{H} - E | \phi_j \rangle G_j^{(+)} \langle \phi_j | \mathcal{H} - E | \phi_i \rangle | \chi_i^{(+)} \rangle$$

In the limit $\epsilon \to 0$
$G_j^{(+)} \langle \phi_j | (\mathcal{H} - E) = G_j^{(+)} \langle \phi_j | V - \langle \phi_j |$

$$T_{ki}^{NO,post-post} = -\langle \chi_k^{(-)} \phi_k | V^{post} | \phi_j \rangle \langle \phi_j | \phi_i \chi_i^{(+)} \rangle$$

If $\sum |\phi_j\rangle\langle\phi_j| \approx \mathrm{I}$

$$T_{ki}^{NO,post-post} = -T_{ki}^{(1,post)}$$

And same for prior-prior