Charge-exchange reactions and role of competing transfer channels

Recent advances and challenges
in the description of nuclear reactions
at the limit of stability

ECT*

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Authors:

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Introduction: 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**)

$$ {}^{a}_{z}a + {}^{A}_{Z}A \rightarrow {}^{a}_{z\pm1}b + {}^{A}_{Z\mp1}B $$

- **Isospin-flip** $\Rightarrow$ **Fermi** (F) and **Gamow-Teller** (GT) transitions (S_{12} rank-2 tensor)

$$ V_{NN} = \sum_{S,T} \left[V^{C}_{ST} (\sigma_1 \cdot \sigma_2)^S + V^{T}_{1T} S_{12} \right] (\tau_1 \cdot \tau_2)^T , \quad S_{12} = \frac{3\sigma_1 \cdot q \, \sigma_2 \cdot q - \sigma_1 \cdot \sigma_2 q^2}{q^2} $$

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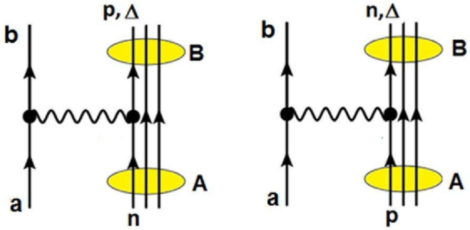

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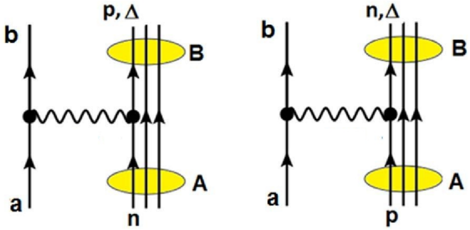

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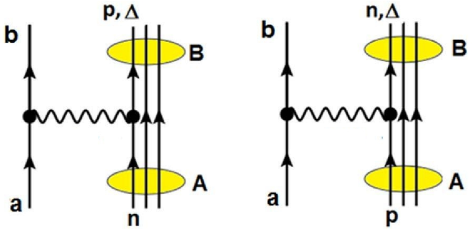

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Single CEX reactions: from light to heavy ions

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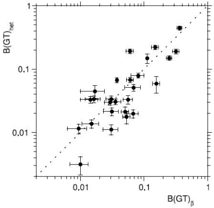

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- **Heavy ions** $\Rightarrow$ complex **many-body** nature
  - Description of projectile-target potential
  - Strong absorption $\Rightarrow$ peripheral collisions
- **Direct** reaction $\Rightarrow$ Distorted Wave (**DWBA**)
- Single CEX $A(a,b)B$ cross section (c.s.) ($\alpha \equiv$ initial, $\beta \equiv$ final, $\hat{J} \equiv \sqrt{2J+1}$)

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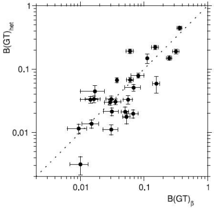

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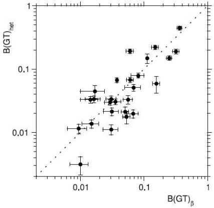

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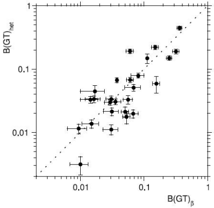

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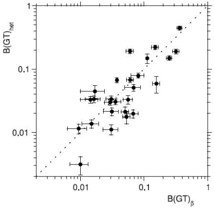

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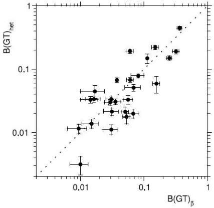

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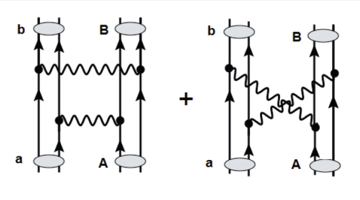

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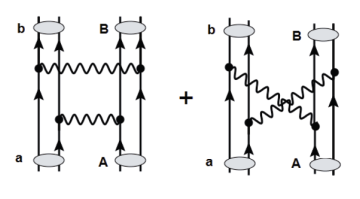

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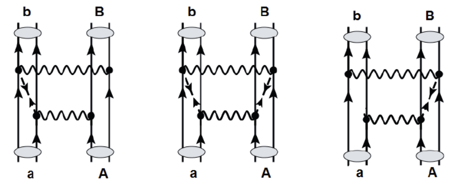

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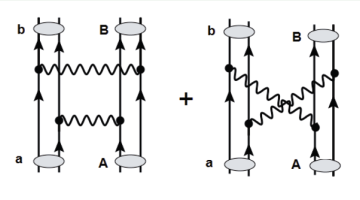

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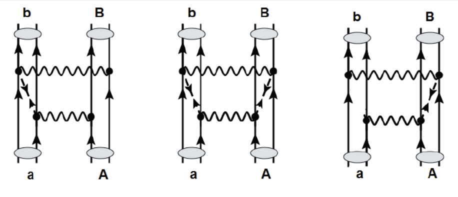

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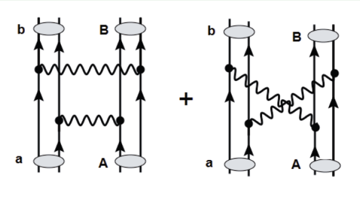

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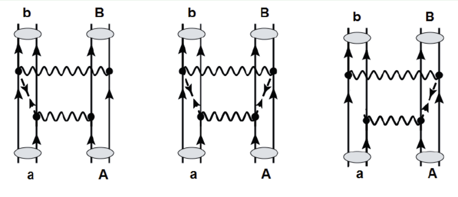

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- Contribution of **high multipolarity** to $0\nu2\beta$-decay $\Rightarrow$ **advantage** in DCEX case
- Need of **experimental** and **theoretical** techniques for description of data

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NUMEN @ LNS-INFN

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NUMEN @ LNS-INFN

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[see talk of M. Cavallaro]

- ^{40}Ca(^{18}O, ^{18}Ne)^{40}Ar @ 15 AMeV
- ^{116}Cd(^{20}Ne, ^{20}O)^{116}Sn @ 20 AMeV

Heavy ion DCEX and NUMEN project @LNS

- **Heavy ion** SCEX: **large momentum** transfer, even at forward angles
- Contribution of **high multipolarity** to $0\nu2\beta$-decay $\Rightarrow$ **advantage** in DCEX case
- Need of **experimental** and **theoretical** techniques for description of data

HIDCX @ RCNP / RIKEN

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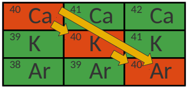
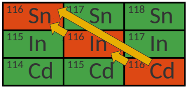
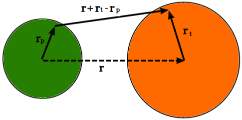




First exploratory steps: unit cross section

- **Optical potential** $\Rightarrow$ **double-folding** integrals
  - **Love & Franey** V_{NN} interaction
  - **Hartree-Fock-Bogoliubov** density profiles

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



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  - Single state dominance
    $\Rightarrow$
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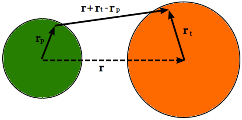

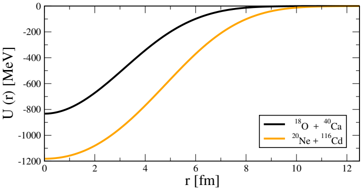

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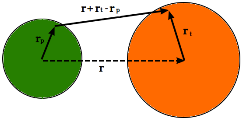

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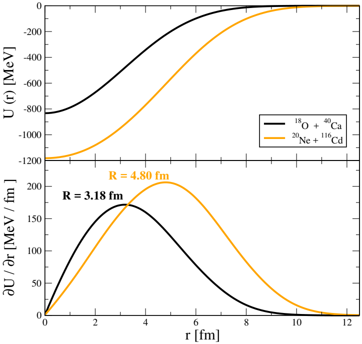

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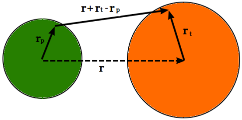
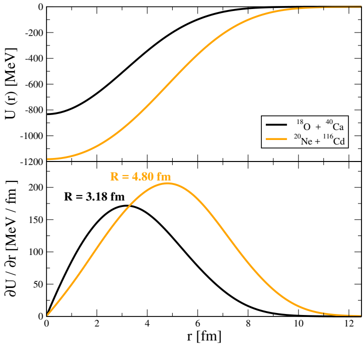
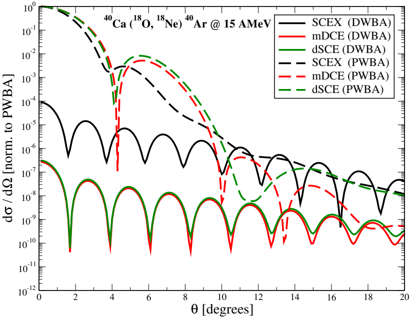




Diffraction pattern and distortion effects



- Same θ **distribution** $\Rightarrow$ analogy with **simultaneous** vs **sequential transfer**
- **PWBA** vs **DWBA**: similar **distortion factor** $N_D = \left(\frac{d\sigma/d\Omega(DWBA)}{d\sigma/d\Omega(PWBA)}\right)_{\theta=0}$

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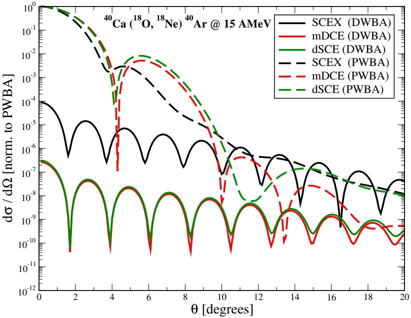

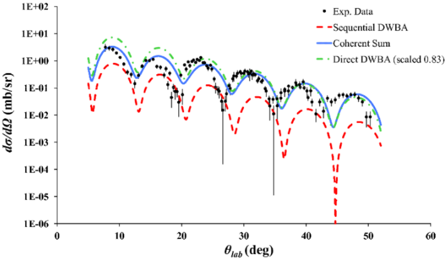

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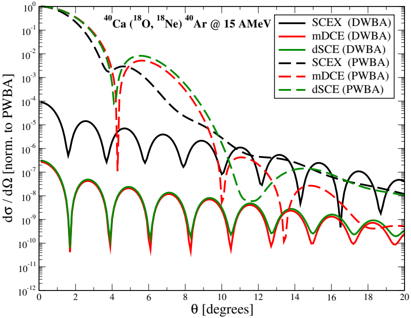

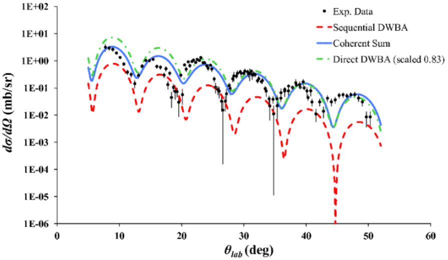

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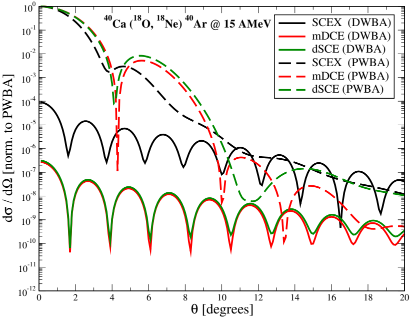

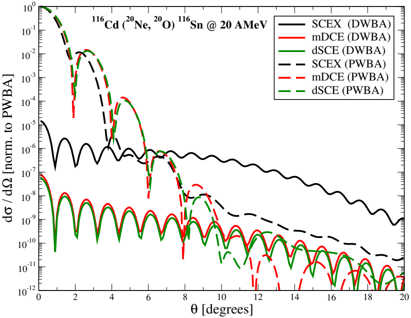

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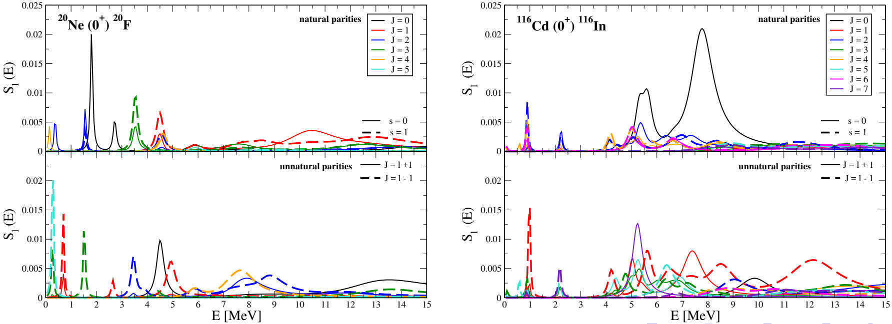
Microscopic form factors: QRPA calculations

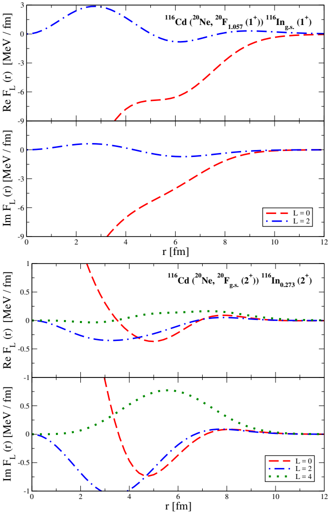
- **Realistic** calculations: microscopic FF from **QRPA** (with **HIDEX** code)
  - Difficult to isolate **contributions** for each state
  - Excitation energies do not match experimental ones
  - Main contributions at **larger** values of E

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



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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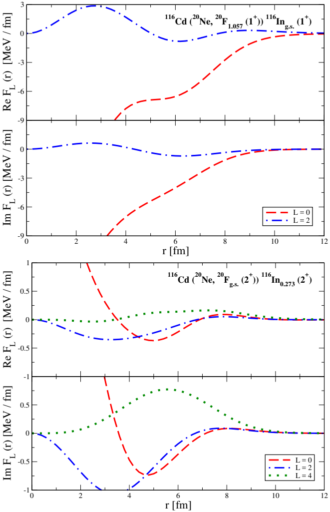

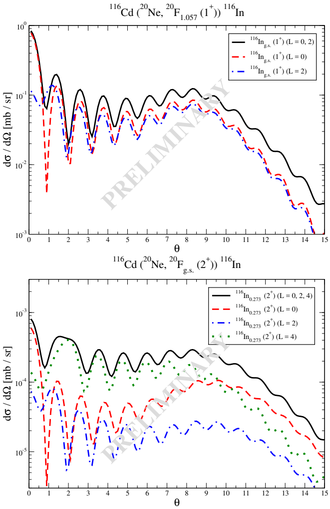

Competing channels: two-nucleon (2N) transfers

- Isolate CEX contribution from **cross section**
  ⇒ description of **competing** processes (**2N-transfer**)
- **Transfer** sensitive to N-nucleus **mean-field** potential
  ⇒ no probe of V_{NN} responsible for **F** and **GT** response

- **SCEX** vs **transfer** for **intermediate mass** nuclei:
  - Direct process **dominant** at energy $E>100$ AMeV
  - Important contribution of **both** at **intermediate** E

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

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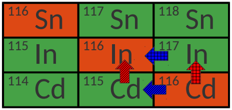

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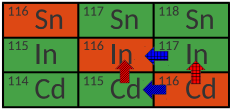

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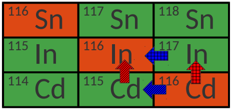

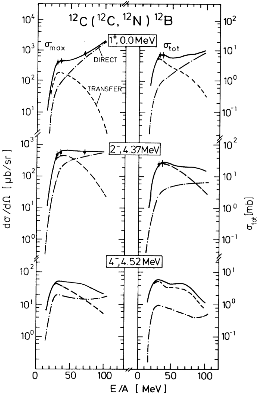

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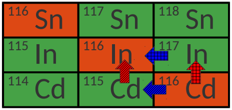

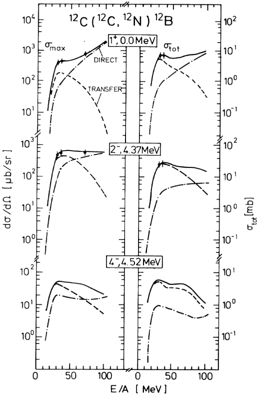

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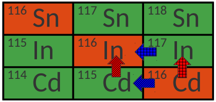
Post/prior representation and non-orthogonality



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- **Structure** ingredients: **overlap** functions
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- Overlaps ≈ product of single particle **wave functions** and **spectroscopic amplitudes**
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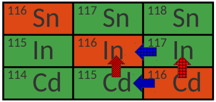

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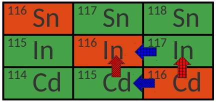

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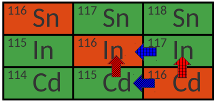

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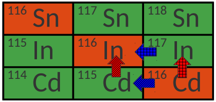

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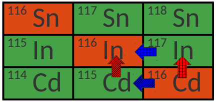

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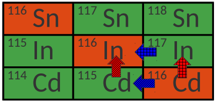
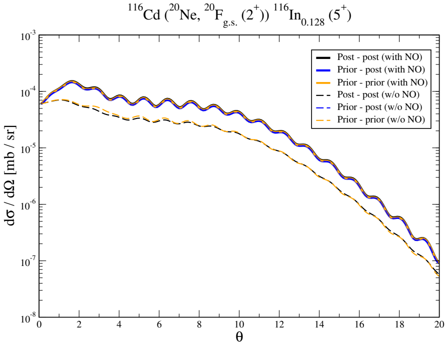


- Overlaps ≈ product of single particle **wave functions** and **spectroscopic amplitudes**
  - **Shell Model** (SM) with **zbm** and **glekpn** interactions (**NuShellX** code)

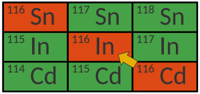
[in coll. with Ferreira J., Lubian J.]

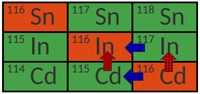


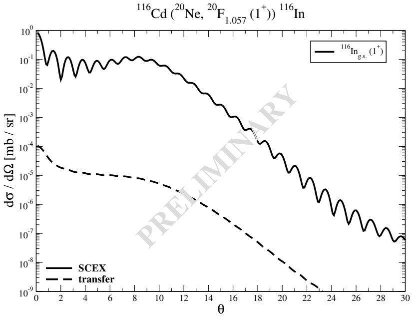
- Lack of **consistency** ⇒ overlap within the **same structure** calculations of CEX (in future!)
- Check dependence on SM **model space** of **valence orbits**
- **Post-post**, **prior-post**, **prior-prior** equivalence only when including **non-orthogonality** (NO) terms

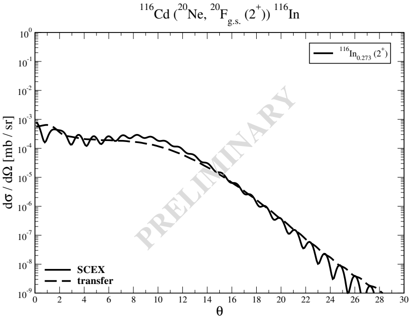
Preliminary results: SCEX vs transfer

- **SCEX** vs **transfer** for heavy ions:
  - Coherent **interference** of paths
  - **Dominance** of **direct** process (SCEX)
  - Comparison with **experiments** (asap)

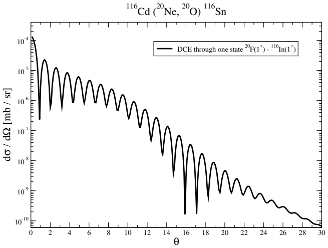




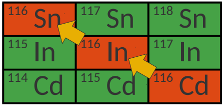




Perspectives and outlooks: towards DCEX

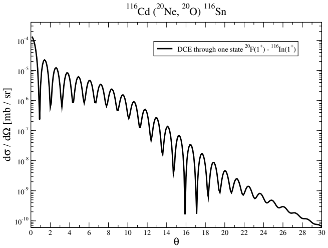


- **Two-step process**:
  - One state only ($^{116}\text{In}_{g.s.}$)
    $\Rightarrow$ 0.3 nb (exp. 50 nb)
  - Several intermediate states
  - Contribution of continuum



- **3^{rd} order processes**:
  - Accurate evaluation of NO
    $\Rightarrow$ work in progress
- **4^{th} order processes**:
  - No implementation yet of NO
  - Exp. c.s. reproduced for 2n/2p transfer (sim + seq)
    $\Rightarrow$ Good performances of FRESCO

Perspectives and outlooks: towards DCEX



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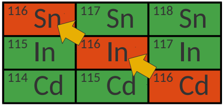

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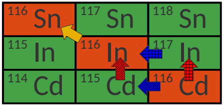

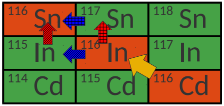

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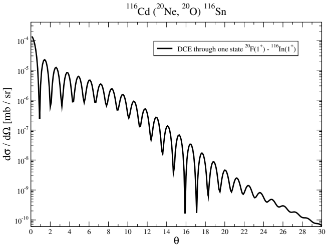

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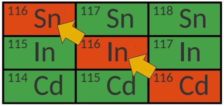

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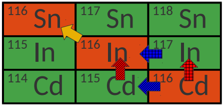

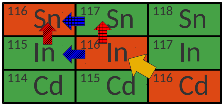

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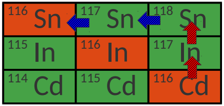

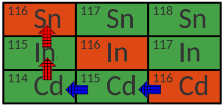

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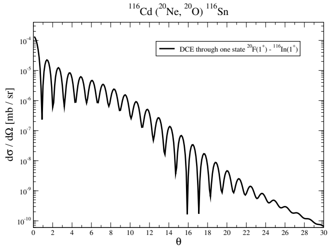

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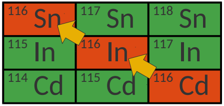

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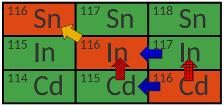

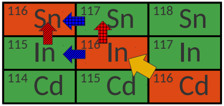

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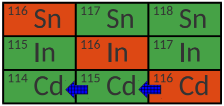

Final remarks and conclusions

Summary

- **Charge-exchange** reactions with **heavy ions** in view of **experimental** interest
- **DWBA** calculations with **analytical** and **microscopic form factors**
- **Interplay** with **multi-nucleon transfers** feeding same outgoing channels

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- Role of **distortion effects** in **direct** and **two-step** double charge exchange
- Importance of **structure** inputs for evaluation of **cross section**
- **Dominance** of **single charge exchange** to competing two-nucleon transfer

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Further developments and outlooks

- **Consistency** of structure inputs between **transfer** and **charge exchange**
- Full and **coherent** determination of **higher order** combination
- **Complete** theory of **double charge exchange**, of interest in 2β-**decay** studies

Acknowledgements

THANK YOU FOR YOUR KIND ATTENTION!

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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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