Nuclear Reactions to investigate Charge Exchange Transitions

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(STRENGTH + NUMEN collaboration)

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TNPI 2019 Cortona (Italy), 9-11 October 2019

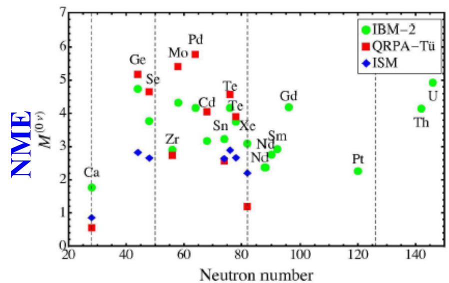
➢ Nuclear charge-exchange (CE) transitions:

- Collective nuclear excitations induced by strong interaction (Isobaric Analog Resonance, Gamow-Teller Resonance)

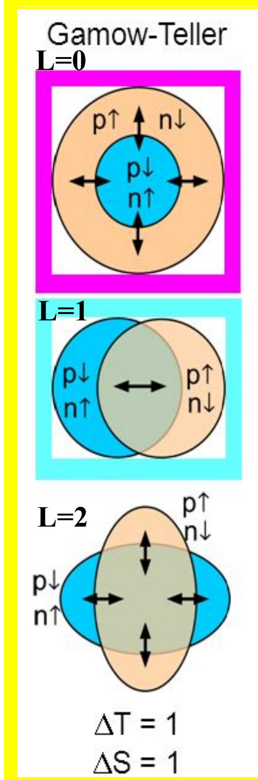
→ *Isospin and spin-isospin terms in the effective nucleon-nucleon interaction in the medium.*

- Spontaneous processes induced by weak interactions (β and double-β decays)

→ *Astrophysical processes*, Nuclear Matrix Elements (NME) *for neutrinoless double-β decays*

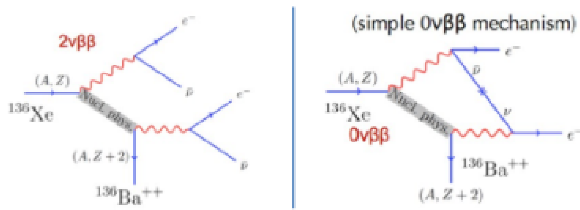


J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91 034304 (2015).



Double-β decay

Conventional
2nd order process
- wthin standard model



New process:
2nd order + correlations
- beyond standard model

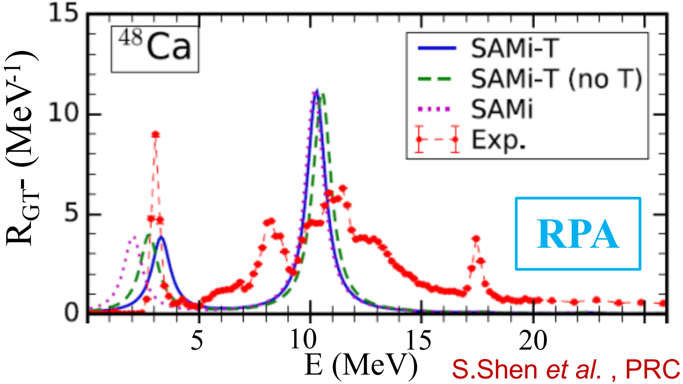
Nuclear interaction vs **Weak** interaction vertices: analogies

Strong Interaction | **Weak Interaction**

Strong Interaction		Weak Interaction	
$V_{NN} \sim V_{01}\left(q^2\right)\tau_\pm\tau_\mp$	$\leftrightarrow$	$g_F\left(q^2\right)\tau_\pm$	"Fermi"
$+V_{11}\left(q^2\right)\sigma_1\cdot\sigma_2\ \tau_\pm\tau_\mp$	$\leftrightarrow$	$g_A\left(q^2\right)\sigma\ \tau_\pm$	"Gamow-Teller"
$+V_{T1}\left(q^2\right)S_{12}\ \tau_\pm\tau_\mp$	$\leftrightarrow$	$g_M\left(q^2\right)\sigma\times\mathrm{q}\ \tau_\pm$	"weak magnetic"
$+\ldots$			

Rank-2 tensor operator: $S_{12} = \frac{1}{q^2}\left[3\sigma_1\cdot\vec{q}\,\sigma_2\cdot\vec{q} - \sigma_1\cdot\sigma_2 q^2\right]$

Structure model calculations for CE transitions



S.Shen *et al.* , PRC 99, 034322 (2019)

Gamow-Teller

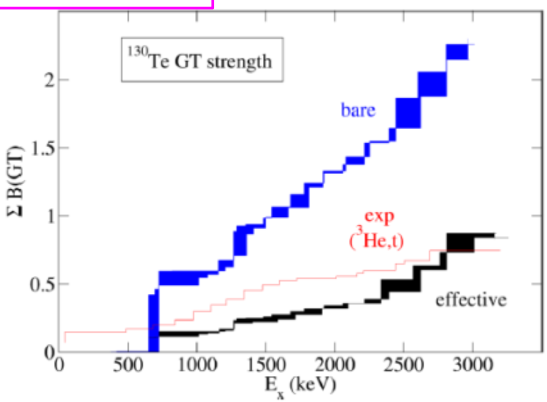
$$B(\mathrm{GT}^-) = \frac{\left|\langle \Phi_f \| \sum_j \vec{\sigma}_j \tau_j^- \| \Phi_i \rangle\right|^2}{2J_i + 1},$$

Double GT

$$B(\mathrm{DGT}^\pm; \lambda; i \to f) = \frac{1}{2J_i + 1} |\langle f \| \mathcal{O}_\pm^{(\lambda)} \| i \rangle|^2,$$

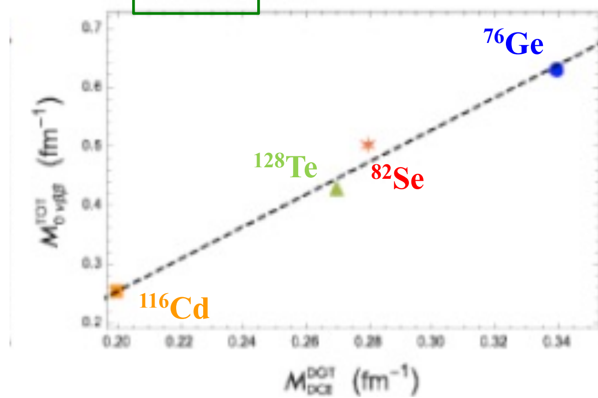
$$\mathcal{O}_\pm^{(\lambda)} = [\textstyle\sum_j \boldsymbol{\sigma}_j \tau_j^\pm \times \sum_j \boldsymbol{\sigma}_j \tau_j^\pm]^{(\lambda)}$$

Shell Model



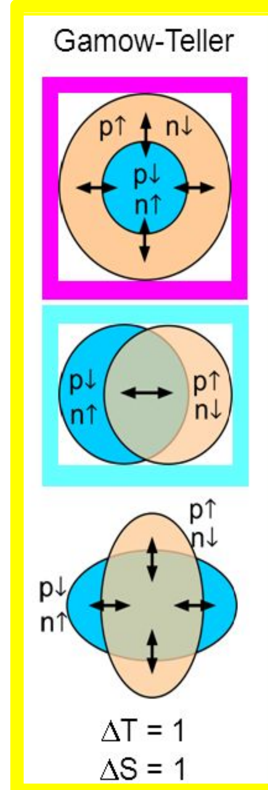
L.Coraggio *et al.* , PRC 95, 064324 (2017)

IBM $M_{0\nu\beta\beta}$ vs M_{DGT}



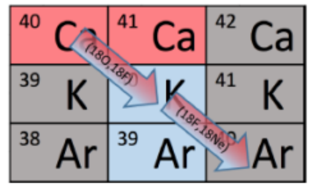
E.Santopinto *et al.* , PRC 98, 061601 (2018)

- **Charge exchange reactions** offer the possibility to explore nuclear transitions in the spin-isospin channel (ex: Fermi (S=0, T=1) and Gamow-Teller excitations (S=1, T=1))



- Double charge exchange reactions

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

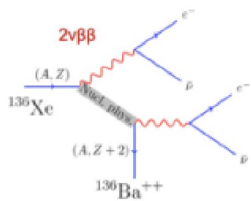


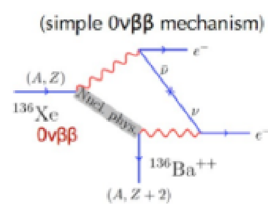
- RCNP / RIKEN ex: the search of the double GT resonance

- NUMEN@INFN-LNS: Input for Nuclear Matrix Elements of 0νββ decay

Double-β decay

Conventional
2nd order process
- wthin standard model





New process:
2nd order + correlations
- beyond standard model

Outline:

- Modeling **Heavy Ion** charge exchange reactions:
  is it possible to isolate the information on nuclear structure ?

- DCE cross section and comparison to data

- Analogies between (double) strong and weak charge exchange processes

Single Charge Exchange (SCE) Cross Section

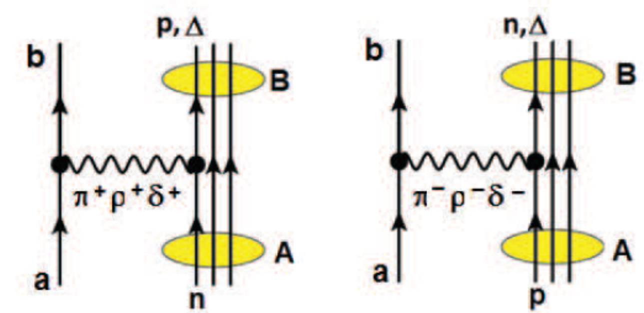
Theory: **DWBA**

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

$$M_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta) = \sum_{ST}\int d^3p K^{(ST)}_{\alpha\beta}(\mathbf{p})N_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta,\mathbf{p}),$$

$${}^a_z a + {}^A_Z A \rightarrow {}^a_{z\pm1} b + {}^A_{Z\mp1} B$$

α **β**



"Structure" term

nuclear interaction

➡ $$K^{(ST)}_{\alpha\beta}(\mathbf{p}) = (4\pi)^2 V^{(C)}_{ST}(p^2) F^{ab\dagger}_{ST}(\mathbf{p})\cdot F^{AB}_{ST}(\mathbf{p})$$

- $$\boxed{F^{(ab)}_{ST}(\mathbf{p}) = \frac{1}{4\pi}\langle J_b M_b | e^{+i\mathbf{p}\cdot\mathbf{r_a}} O_{ST} | J_a M_a\rangle}$$

transition density *with*

Ex: QRPA, …

$$O_{ST}(i) = (\boldsymbol{\sigma}_i)^S(\boldsymbol{\tau}_i)^T$$

"Reaction" term

➡ $$N_{\alpha\beta}(\mathbf{k}_\alpha,\mathbf{k}_\beta,\mathbf{p}) = \frac{1}{(2\pi)^3}\langle\chi^{(-)}_\beta | e^{-i\mathbf{p}\cdot\mathbf{r}} | \chi^{(+)}_\alpha\rangle.$$

Complex optical potentials

-- Momentum transfer $\mathbf{q}_{\alpha\beta} = \mathbf{k}_\alpha - \mathbf{k}_\beta$

if $N_{\alpha\beta} = \delta(p - q_{\alpha\beta})$ → plane waves: **PWBA**

SCE cross section factorization at small momentum transfer

➡ $M_{\alpha\beta}(\mathrm{k}_\alpha, \mathrm{k}_\beta) = \sum_{ST} \int d^3p K^{(ST)}_{\alpha\beta}(\mathrm{p}) N_{\alpha\beta}(\mathrm{k}_\alpha, \mathrm{k}_\beta, \mathrm{p}),$

Reaction amplitude

Structure kernel

Distortion coefficient

nuclear interaction

➡ $\sigma(q,\omega) = K(E_p,\omega)|J_{ST}|^2 \exp\left(-\tfrac{1}{3}q^2\langle r^2\rangle\right) \exp\left[-xA^{1/3}+p(\omega)\right] B(ST)$

→ *low momentum transfer* q (L = 0)

form factor (ang. distribution)

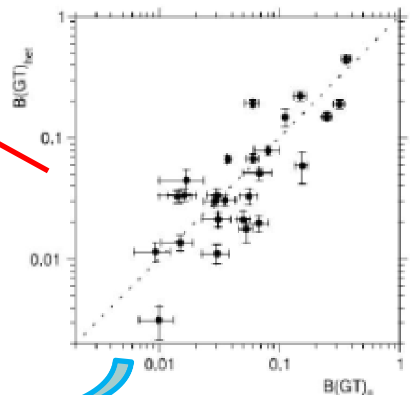
β-decay strength

- **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)]

Ex: (p,n), (t,3He) reactions

from CE reactions



$$(G_V)^2 B(F) + (G_A)^2 B(GT) = \frac{K}{ft},$$

$$\frac{K}{(G_V)^2} = 6166 \pm 2 \text{ sec},$$

$$\left(\frac{G_A}{G_V}\right)^2 = (1.260 \pm 0.008)^2.$$

from β-decay

[Fujita Y. et al., PPNP 66 (2011), 549]

Cross section factorization at small momentum transfer: heavy ions

Reaction amplitude

$$M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_{ST} \int d^3p K^{(ST)}_{\alpha\beta}(\mathbf{p}) N_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta, \mathbf{p}),$$

Low momentum transfer

β decay strengths

$$d\sigma_{\alpha\beta} = F(q_{\alpha\beta}, \omega)\sigma_U \left|b^{(ab)}_{0SS}\right|^2 \left|b^{(AB)}_{0SS}\right|^2$$

$$\sigma_U = K(E_{lab}, 0)|V^{(C)}_{ST}(0)|^2 f_{BD}$$

Unit cross section

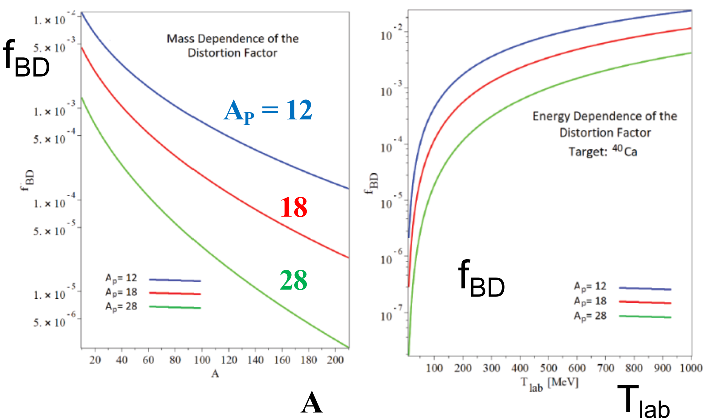
distortion factor

(for light projectiles) $f_{BD} \sim \exp(-A^{1/3})$

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

Trend of unit cross section for heavy ions (Black Disk Approximation)

T_{lab} = 270 MeV $\quad$ $A_T = 40$

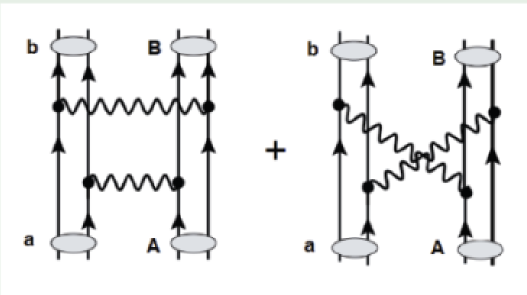


Lenske, Bellone,Colonna,Lay, PRC 98, 044620 (2018)

Bellone *et al.*, J.Phys. 1056, 012004(2018)

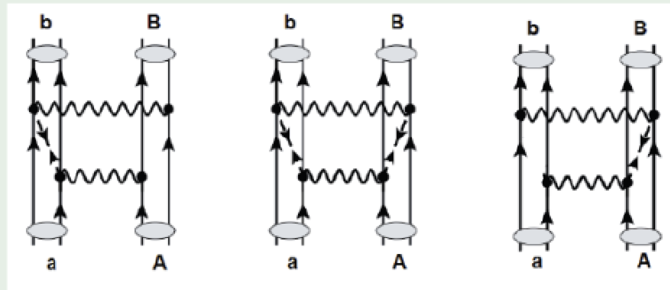
- **Second order** CEX reactions: **double charge-exchange (DCEX)** reactions

Double SCEX (dSCE)



$2\nu 2\beta$-“like”

Majorana DCEX (mDCE)

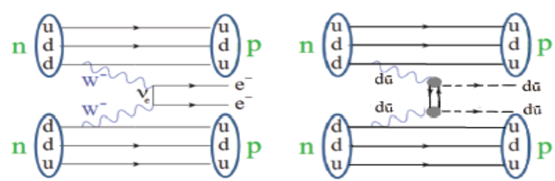


$0\nu 2\beta$-“like”

Conventional
2nd order process

2nd order + short range correlations

Theory was missing !



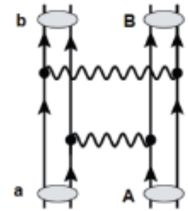
weak **strong**

E.Santopinto *et al.* , PRC 98, 061601 (2018)

Lenske, Cavallaro, Cappuzzello, Colonna,
PPNP 109, 103716 (2019)

Double Charge Exchange (DCE) as an (uncorrelated) 2-step process

$$_{z}a +_{Z} A \rightarrow_{z\pm 2} b +_{Z\mp 2} B$$

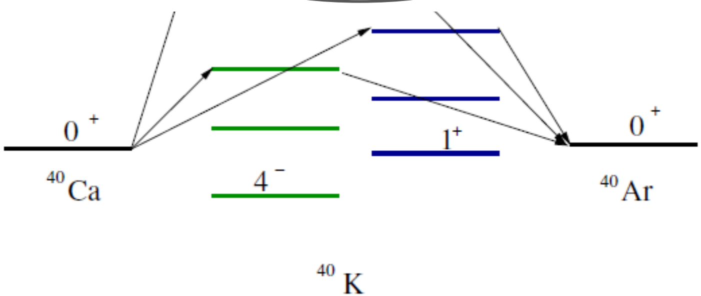


Transition matrix element

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

Single CEX *Single CEX*

intermediate states



propagator

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

energy

sum over multipoles

$$M^{DSCE}_{\alpha\beta} \approx \sum_{S_1\lambda_1\mu_1,S_2\lambda_2\mu_2} \rho^{S_1S_2}_{\lambda_1,\lambda_2}(\omega_\alpha,\bar{k}) \times\langle\chi^{(-)}_\beta|U_{S_2\lambda_2\mu_2}U_{S_1\lambda_1\mu_1}|\chi^{(+)}_\alpha\rangle.$$

form factors (first and second step)

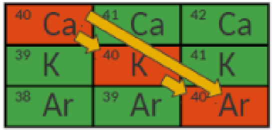
$$\rho^{S_1S_2}_{\lambda_1\lambda_2}(\omega_\alpha,k_\gamma) = \sum_{cC} \times \frac{\beta^{cb,CB}_{S_2\lambda_2}\beta^{ac,AC}_{S_1\lambda_1}}{\omega^{(+)}_\alpha - M_c - M_C - k^2_\gamma/2m_\gamma}$$

sum over energy

SCE transition strengths

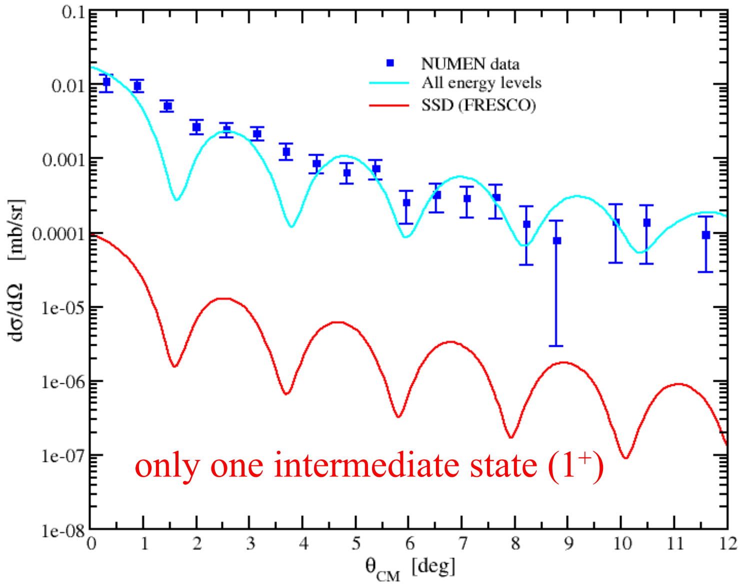
smaller f_{BD} than in SCE !

DCE as a two-step process:
comparison to exp data



$^{18}O + ^{40}Ca \rightarrow ^{18}F + ^{40}K \rightarrow ^{18}Ne + ^{40}Ar$
@ 15 MeV/A ($0^+ \rightarrow 0^+$)

data: F. Cappuzzello *et al.*,
EPJA51, 145 (2015), EPJA 54, 72 (2018)

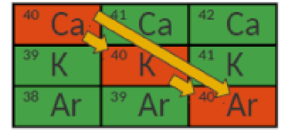


- SCE **transition strengths** evaluated with QRPA (M3Y effective nuclear interaction)

➡ **Full calculations**: intermediate states up to 15 MeV and J = 5
Might short range correlations («Majorana» mechanism) improve the agreement ?

Bellone *et al., in preparation*

DCE as a two-step process:
comparison to exp data



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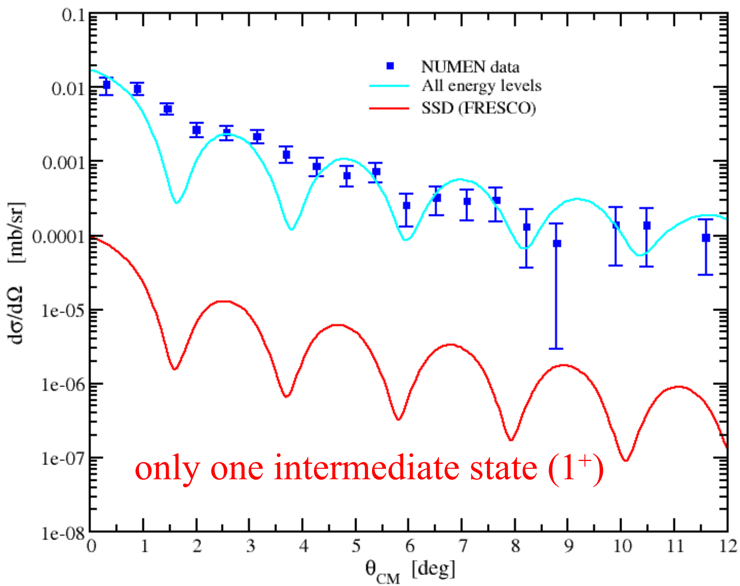

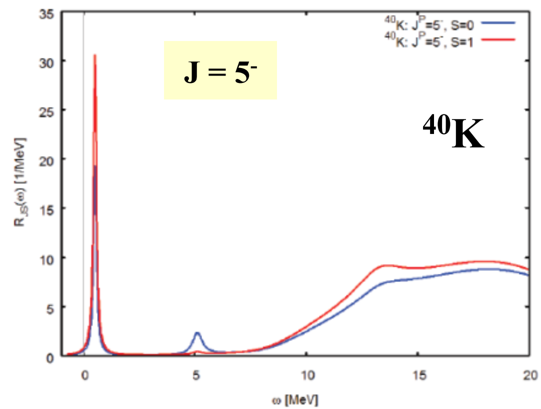

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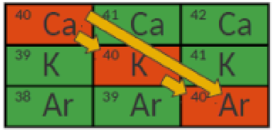

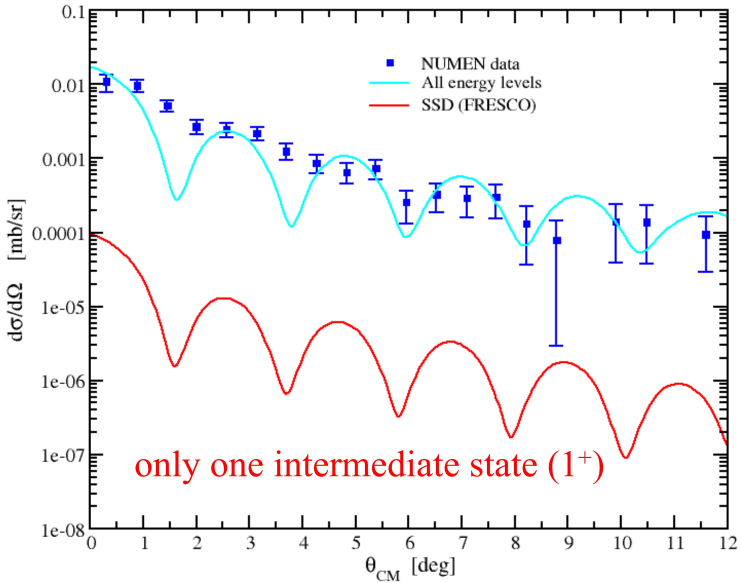

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- **Optical potential** (distortion effects):
double folding approach
NN interaction with HFB densities
(Franey & Love, PRC 31 (1985))

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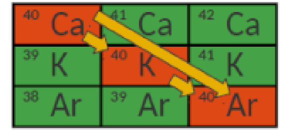

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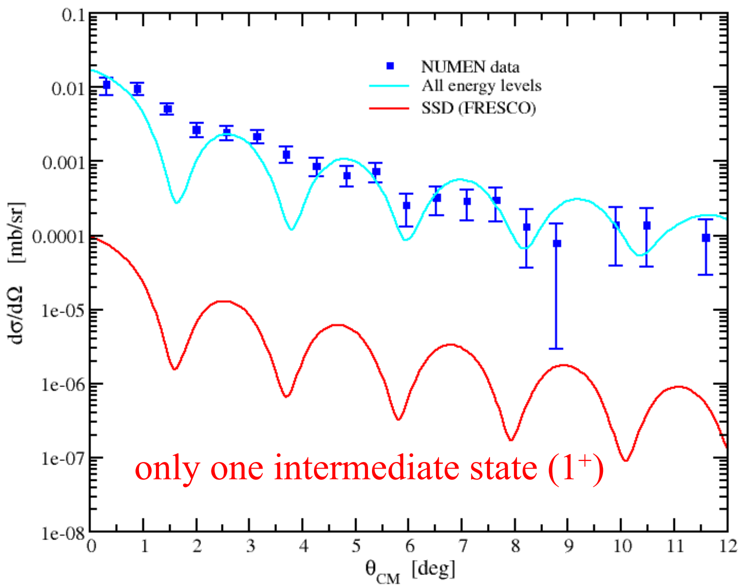

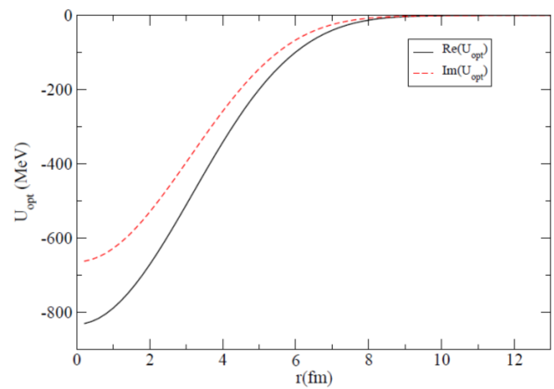

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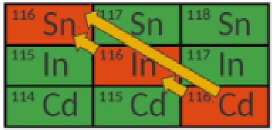
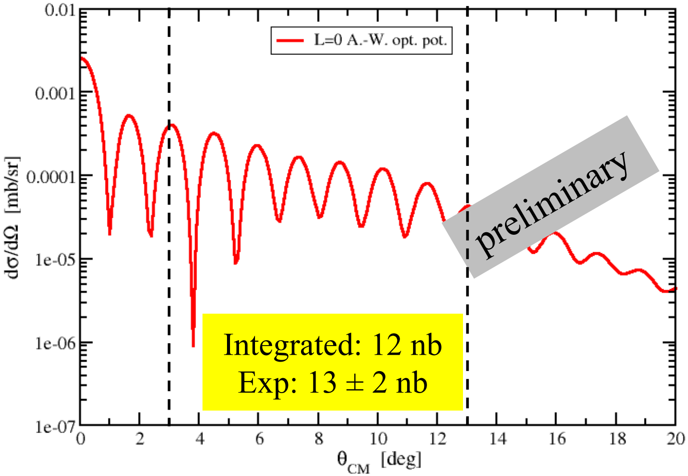


^{20}**Ne +** ^{116}**Cd → ^{20}F +** ^{116}**In →** ^{20}**O+** ^{116}**Sn @ 15 MeV/A ($0^+ \rightarrow 0^+$)**

data: F. Cappuzzello *et al.*, EPJA 54, 72 (2018)

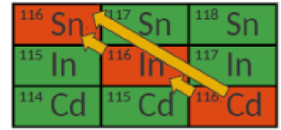


- SCE **transition strengths** evaluated with QRPA (M3Y effective nuclear interaction)
- **Optical potential** (distortion effects):
  - double folding approach NN interaction with HFB densities (Franey & Love, PRC 31 (1985))
  - Akyuz - Winther

➡ **Full calculations**: intermediate states up to 15 MeV and J = 9

Bellone *et al., in preparation*

DCE as a two-step process: comparison to exp data



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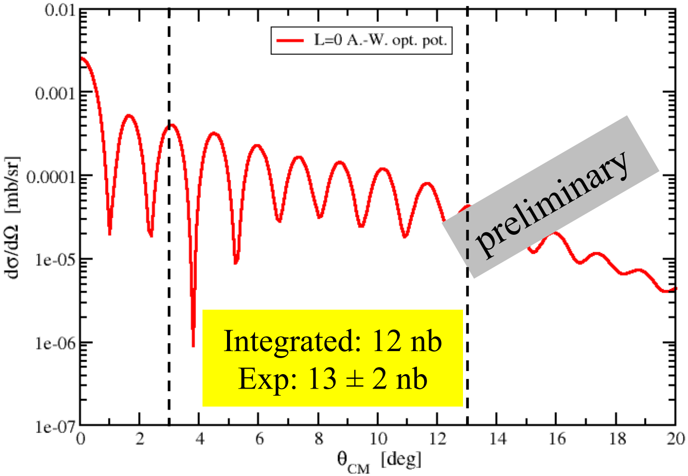
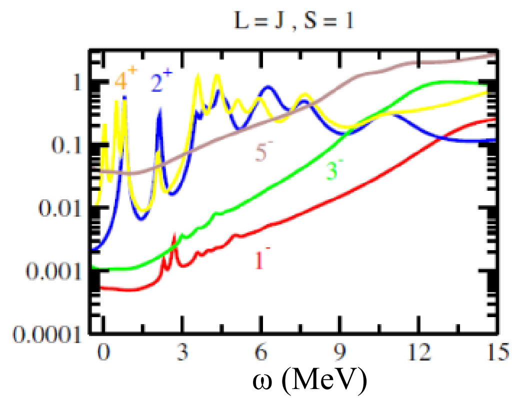


- SCE **transition strengths**



^{116}In

➡ **Full calculations**: intermediate states up to 15 MeV and J = 9

Bellone *et al., in preparation*

Analogies with double-β decay

Reaction amplitude

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

low momentum transfer

$$\mathcal{M}_{\alpha\beta}^{DSCE}\approx N_{\alpha\beta}\sum_{SS'}V_{\alpha\beta}^{S'S}$$

nuclear interaction

$$\times\langle b|\mathcal{R}_{S'T}(\mathbf{q}_{\gamma_r R\beta},1'_a)|r\rangle\langle r|\mathcal{R}_{ST}(\mathbf{q}_{\alpha\gamma_r R},1_A)|a\rangle$$

$$\otimes\langle B|\mathcal{R}_{S'T}(\mathbf{q}_{\gamma_r R\beta},2'_A)|R\rangle\langle R|\mathcal{R}_{ST}(\mathbf{q}_{\alpha\gamma_r R},2_A)|A\rangle$$

All multipolarities could contribute for intermediate states

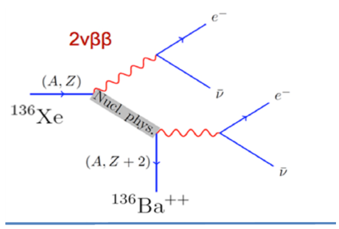
$$R=\mathrm{e}^{\mathrm{i}\mathbf{qr}}\quad O_{ST}(i)=(\boldsymbol{\sigma}_i)^S\,(\boldsymbol{\tau}_i)^T\,\mathrm{e}^{\mathrm{i}\mathbf{qr}}$$

2ν double beta decay

Transition matrix element

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

Within standard model



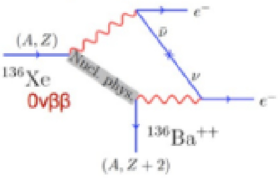
Analogies with double-β decay

..but intermediate transitions with several multipolarities play a role in DCE…

0ν double beta decay

Transition matrix element

(simple 0νββ mechanism)



$$M^{0\nu}_{\alpha} = \sum_{\kappa}\sum_{1234}\langle 13|\mathcal{O}_{\alpha}|24\rangle\langle f|\hat{c}^{\dagger}_{3}\hat{c}_{4}|\kappa\rangle\langle\kappa|\hat{c}^{\dagger}_{1}\hat{c}_{2}|i\rangle,$$

Ex: Gamow-Teller $\longrightarrow$ $\mathcal{O}_{GT} = \tau_{1-}\tau_{2-}\,(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\,H_{GT}(r,E_{\kappa}),$

Bessel function form factor

$$H_{\alpha}(r,E_{\kappa}) = \frac{2R}{\pi}\int_0^{\infty}\frac{f_{\alpha}(qr)h_{\alpha}(q^2)qdq}{q+E_{\kappa}-(E_i+E_f)/2},$$

Two-nucleon correlation

All multipolarities become involved ! → Similar virtual states as in DCE

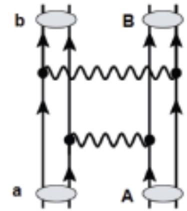
$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{F} + M^{0\nu}_{T},$$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}|M^{0\nu}|^2\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

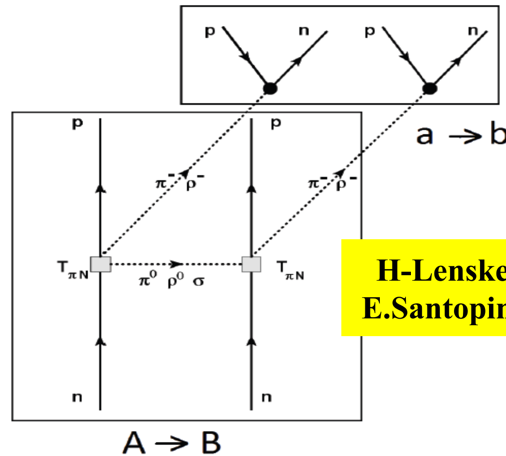
$$\langle m_{\beta\beta}\rangle = \left|\sum_k m_k U^2_{ek}\right|.$$

Summary and Perspectives :

- New development for: → SCE modeling
  - Cross section factorisation for heavy ion reactions
  - Evaluation of distortion factor



- DCE reactions as a two-step process



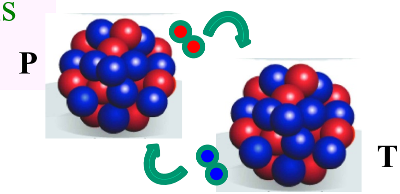
H-Lenske, E.Santopinto

- «Majorana» DCE mechanism :

The two charge changing nucleons in the target (or in the projectile) are correlated through the exchange of a neutral meson (the process can be off shell)

⟶ **Short range correlations**

- Interplay between CE processes and competing channels **(multi-nucleon transfer)**



also in collaboration with
J.Ferreira, J.Lubian, E.Santopinto

NUMEN Theory Group (main collaborations)

- *H.Lenske* **Giessen Univ. – Germany**
- *E. Santopinto and coll.* **Genoa Univ. and INFN – Italy**
- *M.Colonna and coll.* **LNS - Italy**
- *N.Auerbach* **Tel Aviv Univ. – Israel**
- *J.Ferreira, J.Lubian* **Niteroi – Rio de Janeiro – Brazil**
- *J.A. Lay Valera* **University of Sevilla – Spain**

Theory WP coordinators

Back-up

Analogies with double-β decay

Reaction amplitude

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

Single CEX *Single CEX*

low momentum transfer

$$V^{S'S}_{\alpha\beta}\simeq\int\frac{d^3k_\gamma}{(2\pi)^3}\frac{V^{(C)}_{S'T}(\mathbf{q}_{\gamma\beta})V^{(C)}_{ST}(\mathbf{q}_{\alpha\gamma})}{\omega^{(+)}_\alpha - M_r - M_R - k^2_\gamma/2m_\gamma}$$

$$\mathcal{M}^{DSCE}_{\alpha\beta}\approx N_{\alpha\beta}\sum_{SS'}V^{S'S}_{\alpha\beta}$$

$$\times\langle b|\mathcal{R}_{S'T}(\mathbf{q}_{\gamma_rR\beta},1'_a)|r\rangle\langle r|\mathcal{R}_{ST}(\mathbf{q}_{\alpha\gamma_rR},1_A)|a\rangle$$

$$\otimes\langle B|\mathcal{R}_{S'T}(\mathbf{q}_{\gamma_rR\beta},2'_A)|R\rangle\langle R|\mathcal{R}_{ST}(\mathbf{q}_{\alpha\gamma_rR},2_A)|A\rangle$$

If only one intermediate state is considered (ex. 1^+)

$$R=e^{i\mathbf{qr}}\quad O_{ST}(i)=(\boldsymbol{\sigma}_i)^S(\boldsymbol{\tau}_i)^Te^{i\mathbf{qr}}$$

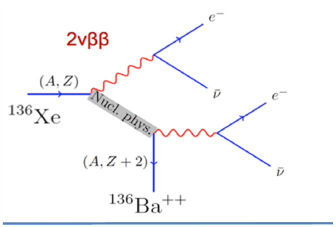
2ν double beta decay

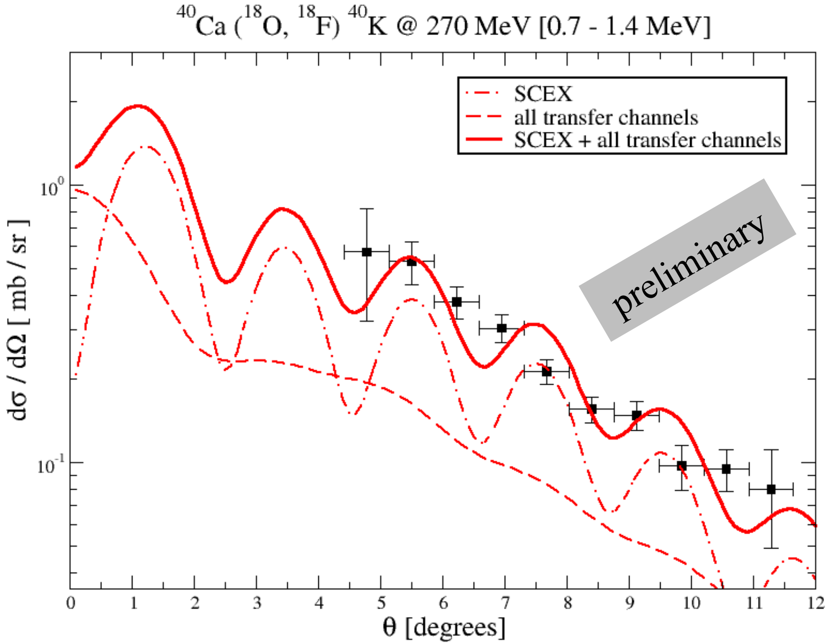
Transition matrix element

$$M^{(2\nu)}(\mathrm{DGT})$$

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

Within standard model





^{18}O + ^{40}Ca → ^{18}F + ^{40}K @ 15 MeV/A (0^+ → 0^+)

data: F. Cappuzzello *et al.*, EPJA51, 145 (2015)

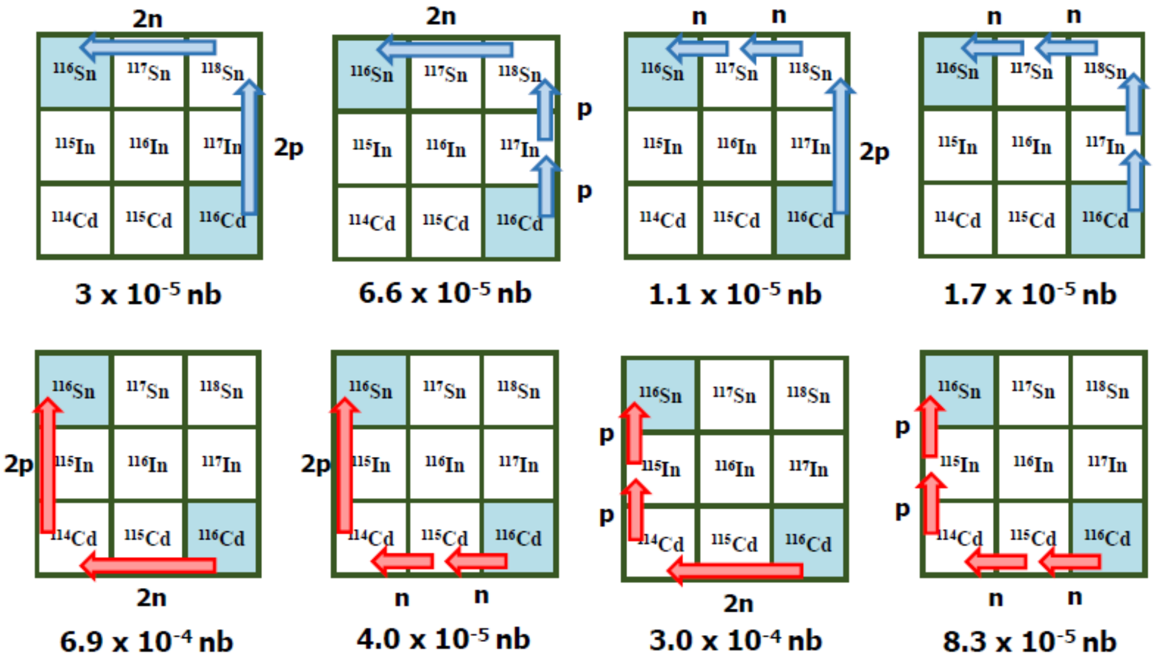
SCE vs. two-nucleon transfer

Competing channels: DCE vs Transfer

$^{20}Ne + {}^{116}Cd$ at 20 MeV/A

Ferreira - Lubian

The role of multi-nucleon transfer routes
vs
The diagonal process (experimental cross section 12 ± 2 nb)



D.Carbone talk
at CNNP2017)

Ferreira - Lubian

The role of multi-nucleon transfer routes
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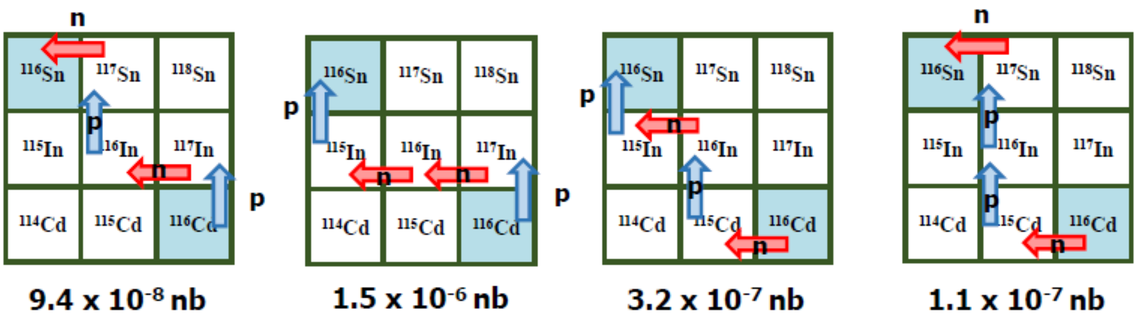


Quite small transfer contribution
with respect to measured cross section !

D.Carbone talk at CNNP2017

Cross section factorization at small momentum transfer: heavy ions ?

Reaction amplitude

$$M_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_{ST} \int d^3p K^{(ST)}_{\alpha\beta}(\mathbf{p}) N_{\alpha\beta}(\mathbf{k}_\alpha, \mathbf{k}_\beta, \mathbf{p}),$$

low momentum transfer

β decay strengths

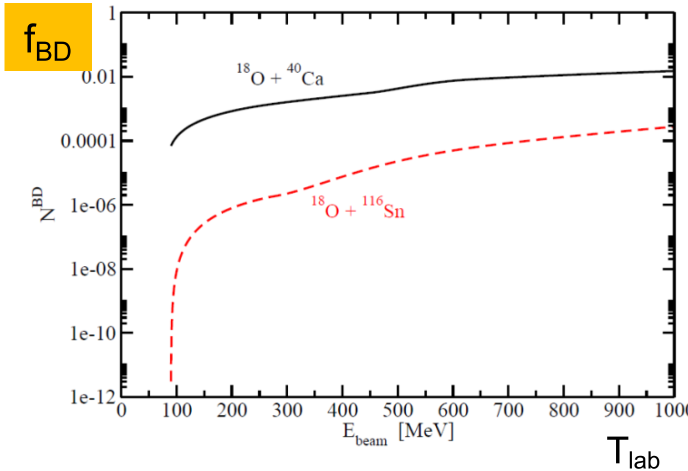
$$d\sigma_{\alpha\beta} = F(q_{\alpha\beta}, \omega)\sigma_U \left|b^{(ab)}_{0SS}\right|^2 \left|b^{(AB)}_{0SS}\right|^2$$

$$\sigma_U = K(E_{lab}, 0)|V^{(C)}_{ST}(0)|^2 f_{BD}(R_{abs}, R, \sigma)$$

Unit cross section

distortion factor

Trend of unit cross section for heavy ions (numerical)



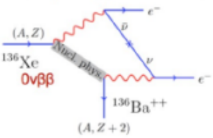
Lenske, Bellone,Colonna,Lay,
PRC 98, 044620 (2018)

0ν double beta decay:

$$M_\alpha^{0\nu} = \sum_{1234} \langle 13 | \mathcal{O}_\alpha | 24 \rangle \langle f | \hat{c}_3^\dagger \hat{c}_4 \hat{c}_1^\dagger \hat{c}_2 | i \rangle .$$

$$\mathcal{O}_{GT} = \tau_{1-} \tau_{2-} \, (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \, H_{GT}(r, E_\kappa),$$

(simple 0νββ mechanism)



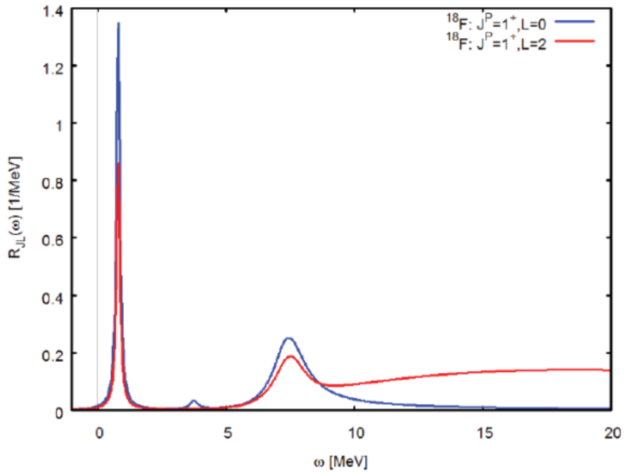
$$H_\alpha(r, E_\kappa) = \frac{2R}{\pi} \int_0^\infty \frac{f_\alpha(qr) h_\alpha(q^2) q dq}{q + E_\kappa - (E_i + E_f)/2},$$

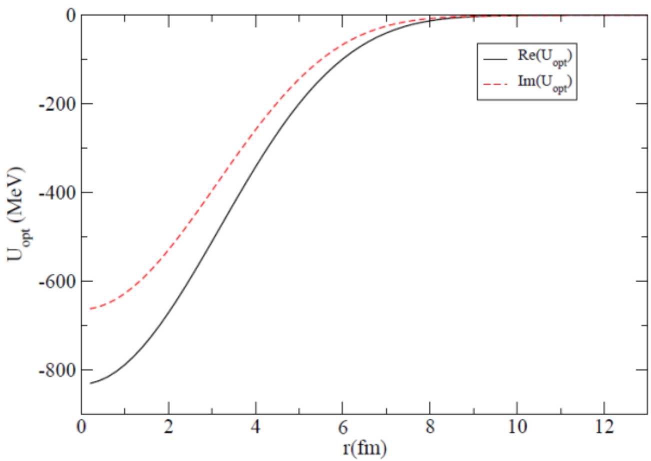
$$\mathcal{M}_{aA,bB}(k_1, k_2) \;=\; M_{AB}^{(\pi\pi)}(k_1, k_2) \langle b | \phi_{\pi^-}(k_1) \phi_{\pi^-}(k_2) | a \rangle$$

$$M_{AB}^{(\pi\pi)}(k_1, k_2) = \int \frac{d^3 k}{(2\pi)^3}$$

$$\Big(T^{(\pi\pi)}(s_1, t_1) D_\rho(k) T^{(\pi\pi)}(s_2, t_2) \langle B | \tilde{\mathcal{J}}(q_1) \tilde{\mathcal{J}}(q_2) | A \rangle$$

SCE: $^{18}O + {}^{40}Ca \rightarrow {}^{18}F + {}^{40}K$, 15 MeV/A --- « Crucial » ingredients





HIDEX code: *Lenske,* PRL62 (1989)

"Structure" term

- Transition density:

QRPA, with EDF

F. Hofmann and H. Lenske, Phys. Rev. C **57**, 2281 (1998)

for $^{18}O \rightarrow {}^{18}F$ g.s. (1^+)

Integral * (2J+1) * $(g_A/g_V)^2 \sim 2.5$ →
$B_{GT} \sim 3$ [Mercer, PRC 49 (1994)]

"Reaction" term

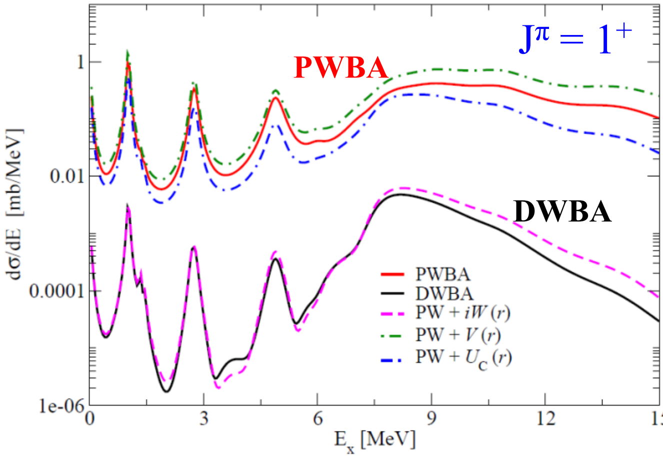
- Optical potential:

double folding approach
NN interaction with HFB densities
(Franey & Love, PRC 31 (1985))

- real and imaginary part

$^{18}O + {}^{40}Ca$ at 15 MeV/A: cross sections for Gamow Teller-like transitions (S=1, T=1)

HIDEX code

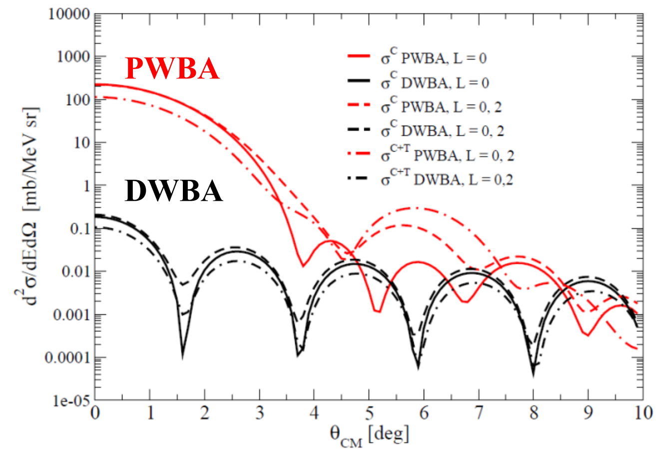


target excitation energy

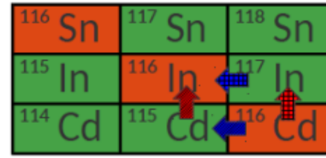
DWBA vs PWBA:
strong absorption effects in HIC !
- large absorption cross section

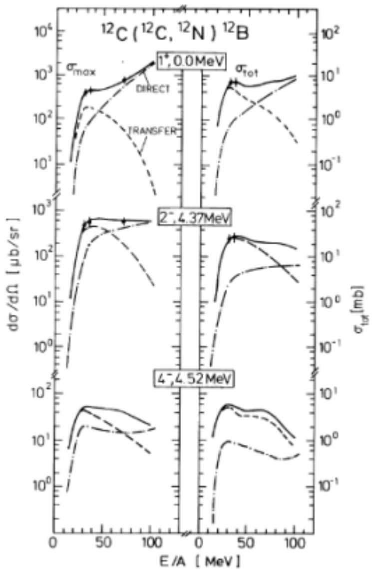
→ Black Disk Approximation (**BDA**)

DWBA *calculations:*
1^+ transitions (L = 0) dominate at very forward angles



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



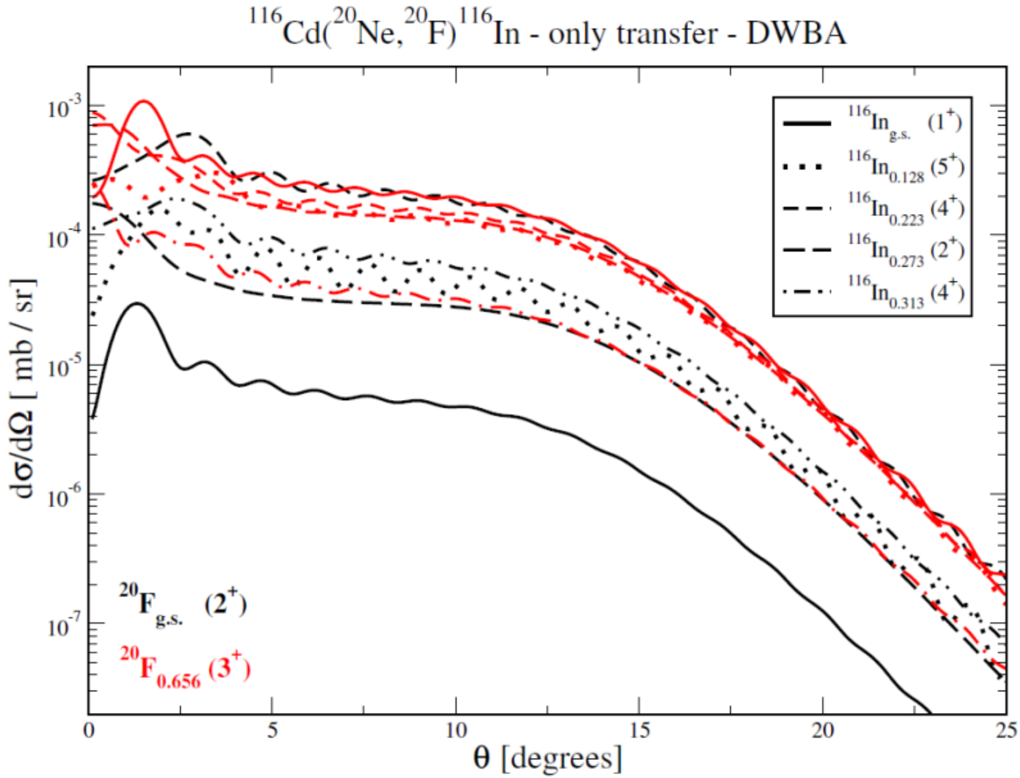


[Lenske H., Wolter H.H., Bohlen H.G., PRL62 (1989).]

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

QUESTION

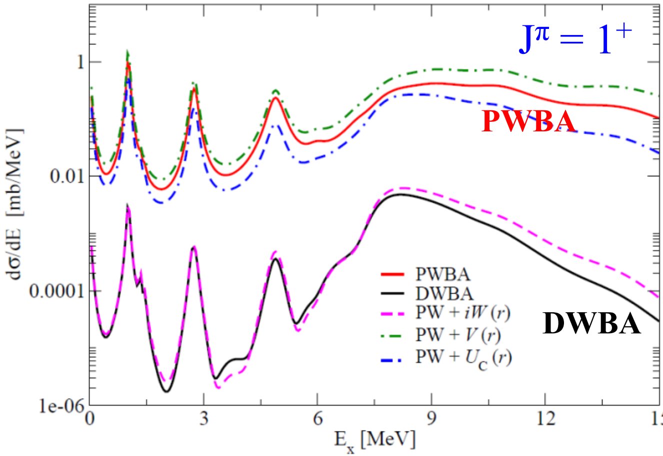
What is the role of **transfer** processes at **intermediate** E for **heavier** colliding systems?



^{116}Cd(^{20}Ne,^{20}F)^{116}In - only transfer - DWBA
dσ/dΩ [mb / sr]
θ [degrees]
^{116}In$_{g.s.}$ (1$^+$)
^{116}In$_{0.128}$ (5$^+$)
^{116}In$_{0.223}$ (4$^+$)
^{116}In$_{0.273}$ (2$^+$)
^{116}In$_{0.313}$ (4$^+$)
^{20}F$_{g.s.}$ (2$^+$)
^{20}F$_{0.656}$ (3$^+$)

$^{18}O + {}^{40}Ca$ at 15 MeV/A: cross sections for Gamow Teller-like transitions (S=1, T=1)

HIDEX code



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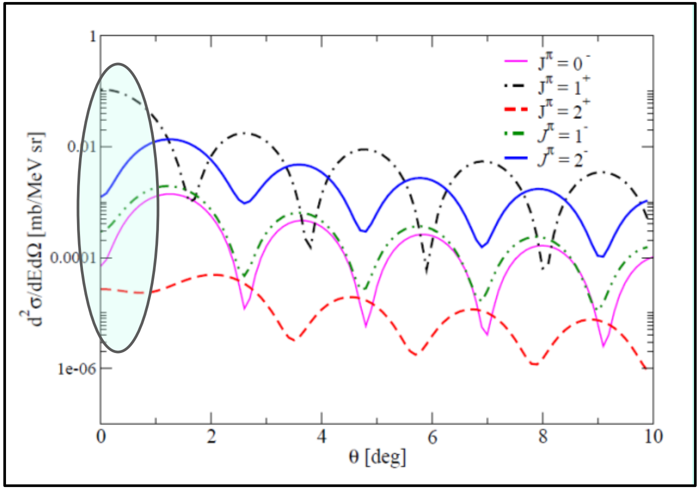


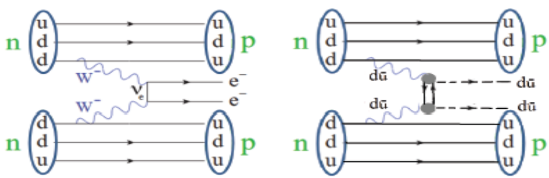
DWBA vs PWBA:
strong absorption effects in HIC !
- large absorption cross section

→ Black Disk Approximation (**BDA**)

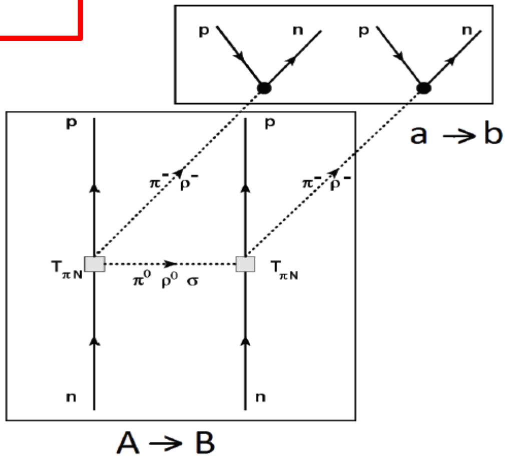
H-Lenske

Double Charge Exchange (DCE) as a 1-step process: analogies with 0ν double beta decay

weak interaction *strong interaction*



$nn \rightarrow pp\pi^-\pi^-$ reaction. *Ex: in the target*

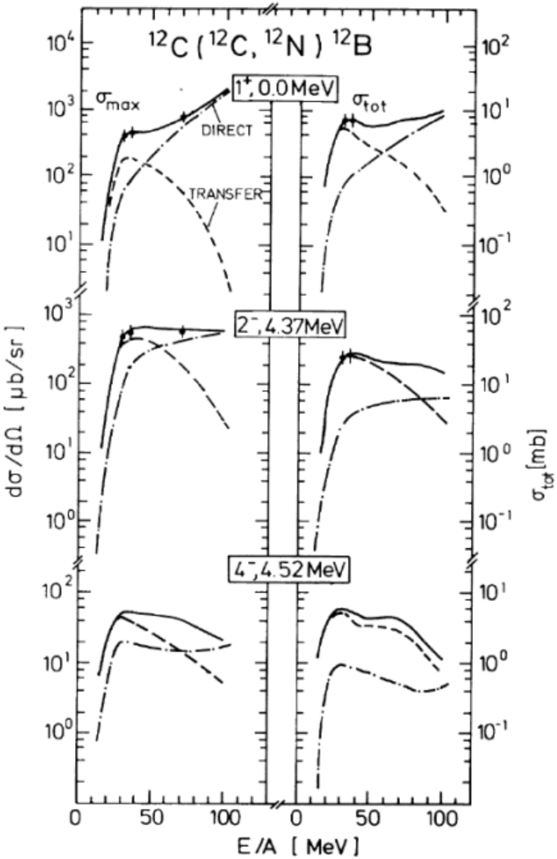


The two charge changing nucleons in the target (or in the projectile) are correlated through the exchange of a neutral meson (the process can be off shell)

→ **Short range correlations**

conjugated reaction $pp \rightarrow nn\pi^+\pi^+$ reaction and other double-pion production channels were in fact already investigated experimentally

COSY, HADES, …



Single Charge Exchange vs. Transfer

⇒ H. Lenske et al., PRL62 (1989) 1457

- E/A → 100 MeV/A

× States at Q_{opt}

Double CE vs. Transfer

× Not much known

✓ An opportunity to exctract further information on the Wavefunction