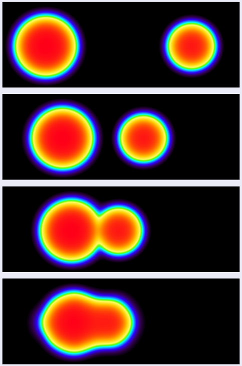


Description of multi-nucleon transfer and fusion reactions with the coupled channel method

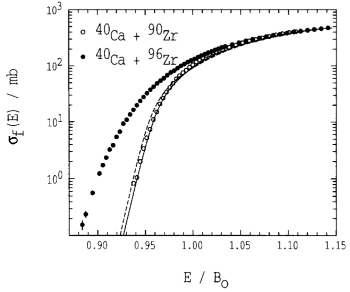
Guillaume SCAMPS

Tohoku University

Sept. 13th 2016

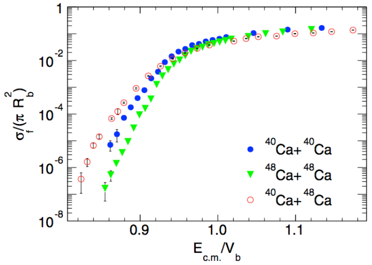
Collaboration : K. Hagino

Effect of transfer on fusion cross section



^{40}Ca + *x*n	^{40}Ca + ^{90}Zr	^{40}Ca + ^{96}Zr
1n	−3.611	+0.509
2n	−1.445	+5.525
3n	−5.861	+5.239
4n	−4.170	+9.637
5n	−9.658	+8.417
6n	−9.038	+11.617
7n	−14.928	+6.919
8n	−15.225	+7.549

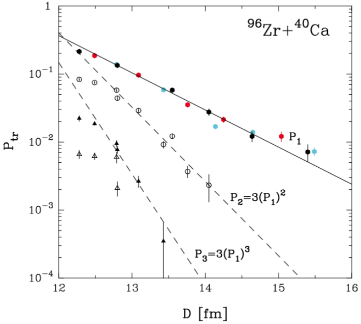
H. Timmers et al., Nucl. Phys. A 633 (1998) 421-445



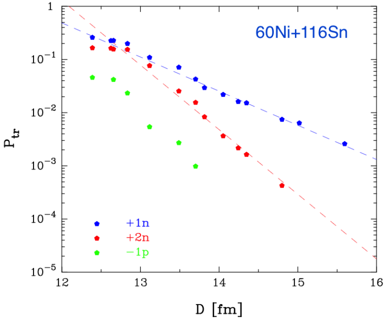
D. Bourgin, PRC 90, 044610 (2014)

Transfer enhances the fusion cross section at low energy.

Transfer reaction between heavy ions



L. Corradi, et al. PRC 84, 034603 (2011)



D. Montanari, et al., PRL 113, 052501 (2014)

Phenomenological approach

Goal of the study

- Sequential or direct 2-neutron transfer
- Understand the interplay between transfer and fusion
- Simultaneous phenomenological description of fusion cross section and transfer probabilities

Theory used

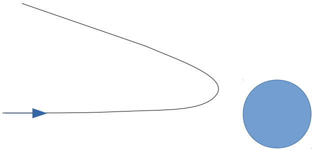
- Time-dependent coupled-channels (semi-classical trajectory)
- Coupled-channels theory

Strategy

Fit of the transfer coupling on the experimental data

Time-dependent coupled-channels with classical trajectory

Classical trajectory



distance between the nuclei as a function of time : r(t)

Coupling between the modes

$$F_{ij}(r) = S_{ij} e^{\frac{r-R_0}{a_{ij}}}$$

Transfer coupling

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \mathcal{H}[r(t)] |\Psi(t)\rangle$$

$$\mathcal{H}[r(t)] =$$

$$\begin{pmatrix} 0 & F_{01}(r) & F_{02}(r) \\ F_{01}(r) & -Q_1 & F_{12}(r) \\ F_{02}(r) & F_{12}(r) & -Q_2 \end{pmatrix}$$

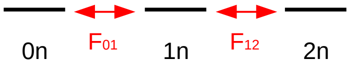
$$|\Psi(t)\rangle = \begin{pmatrix} a_o \\ a_1 \\ a_2 \end{pmatrix}$$

At the end of the trajectory :
$P_1 = |a_1|^2$ and $P_2 = |a_2|^2$

Direct transfer or sequential transfer :

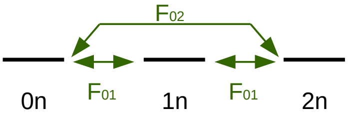
Sequential transfer

$$\mathcal{H}[r(t)] = \begin{pmatrix} 0 & F_{01}(r) & 0 \\ F_{01}(r) & -Q_1 & F_{12}(r) \\ 0 & F_{12}(r) & -Q_2 \end{pmatrix}$$



Sequential and direct transfer

$$\mathcal{H}[r(t)] = \begin{pmatrix} 0 & F_{01}(r) & F_{02}(r) \\ F_{01}(r) & -Q_1 & F_{01}(r) \\ F_{02}(r) & F_{01}(r) & -Q_2 \end{pmatrix}$$



Direct pair transfer or sequential transfer :

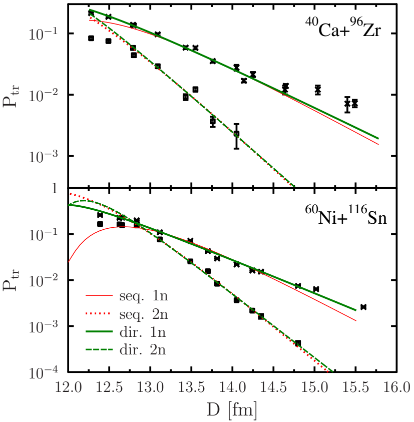
Sequential transfer

$$\mathcal{H}[r(t)] = \begin{pmatrix} 0 & F_{01}(r) & 0 \\ F_{01}(r) & -Q_1 & F_{12}(r) \\ 0 & F_{12}(r) & -Q_2 \end{pmatrix}$$

Sequential and direct transfer

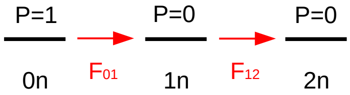
$$\mathcal{H}[r(t)] = \begin{pmatrix} 0 & F_{01}(r) & F_{02}(r) \\ F_{01}(r) & -Q_1 & F_{01}(r) \\ F_{02}(r) & F_{01}(r) & -Q_2 \end{pmatrix}$$

Results

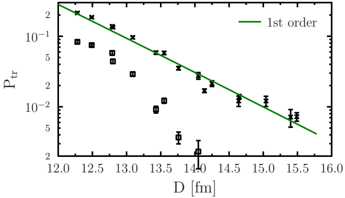


Time dependent perturbation theory

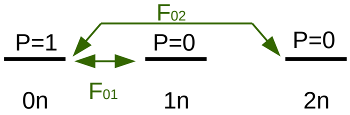
Sequential transfer



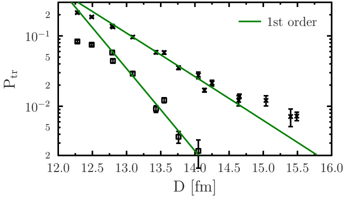
Results : ^{40}Ca+^{96}Zr seq. hyp.



Direct transfer

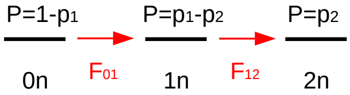


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

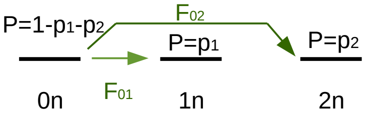
Sequential transfer



$P=1-p_1$ $\xrightarrow{F_{01}}$ $P=p_1-p_2$ $\xrightarrow{F_{12}}$ $P=p_2$

0n 1n 2n

Direct transfer

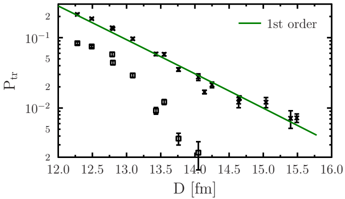


$P=1-p_1-p_2$ $\xrightarrow{F_{01}}$ $P=p_1$

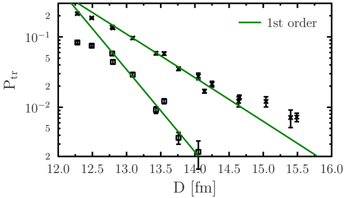
$P=1-p_1-p_2$ $\xrightarrow{F_{02}}$ $P=p_2$

0n 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

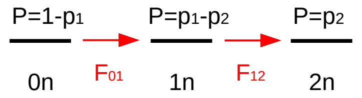


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

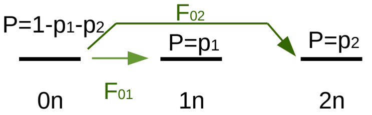
Sequential transfer



$P=1-p_1$ $P=p_1-p_2$ $P=p_2$

0n F_{01} 1n F_{12} 2n

Direct transfer

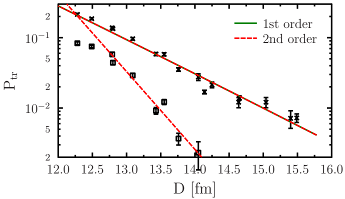


F_{02}

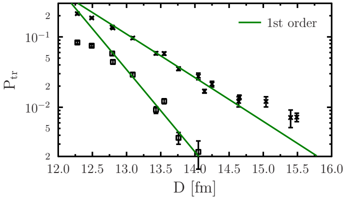
$P=1-p_1-p_2$ $P=p_1$ $P=p_2$

0n F_{01} 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

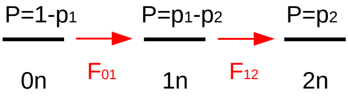


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

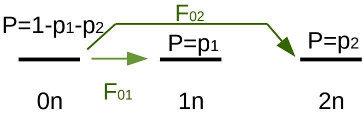
Sequential transfer



$P=1-p_1$ $\xrightarrow{F_{01}}$ $P=p_1-p_2$ $\xrightarrow{F_{12}}$ $P=p_2$

0n, 1n, 2n

Direct transfer

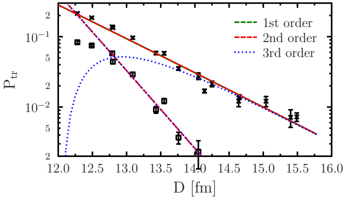


$P=1-p_1-p_2$ $\xrightarrow{F_{01}}$ $P=p_1$

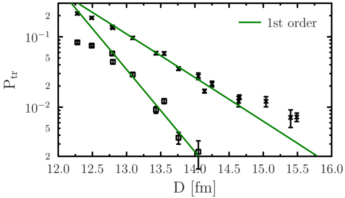
$P=1-p_1-p_2$ $\xrightarrow{F_{02}}$ $P=p_2$

0n, 1n, 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

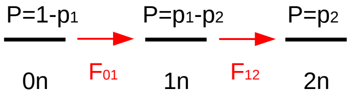


Results : ^{40}Ca+^{96}Zr dir. hyp.



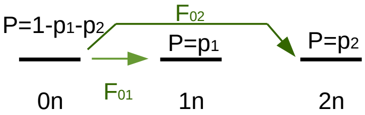
Time dependent perturbation theory

Sequential transfer


P=1-p_1 P=p_1-p_2 P=p_2

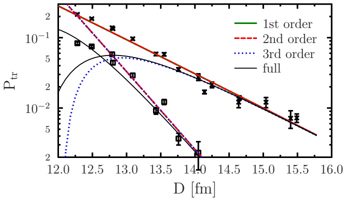
0n F_{01} 1n F_{12} 2n

Direct transfer

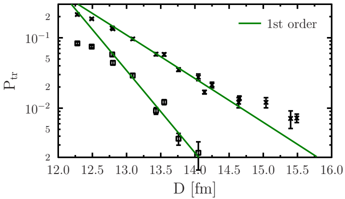

P=1-p_1-p_2 F_{02} P=p_1 P=p_2

0n F_{01} 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

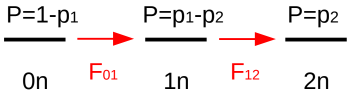


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

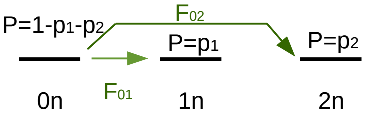
Sequential transfer



$P=1-p_1$ $P=p_1-p_2$ $P=p_2$

0n F_{01} 1n F_{12} 2n

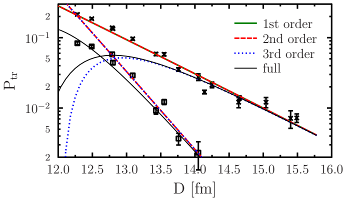
Direct transfer



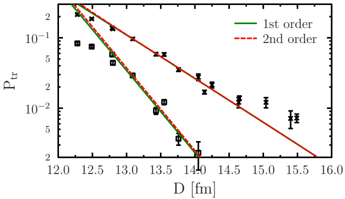
$P=1-p_1-p_2$ F_{02} $P=p_1$ $P=p_2$

0n F_{01} 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

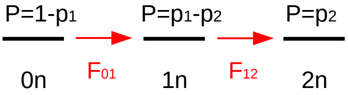


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

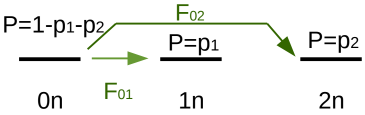
Sequential transfer



$P=1-p_1$ $P=p_1-p_2$ $P=p_2$

0n F_{01} 1n F_{12} 2n

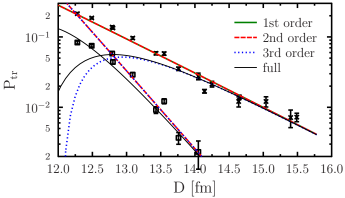
Direct transfer



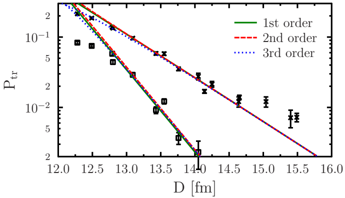
$P=1-p_1-p_2$ F_{02} $P=p_1$ $P=p_2$

0n F_{01} 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.

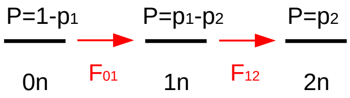


Results : ^{40}Ca+^{96}Zr dir. hyp.



Time dependent perturbation theory

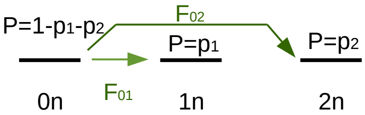
Sequential transfer



$P=1-p_1$ $\xrightarrow{F_{01}}$ $P=p_1-p_2$ $\xrightarrow{F_{12}}$ $P=p_2$

0n 1n 2n

Direct transfer

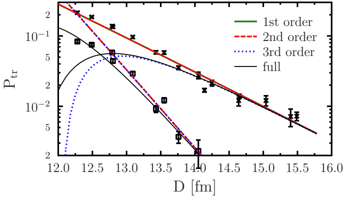


$P=1-p_1-p_2$ $\xrightarrow{F_{01}}$ $P=p_1$

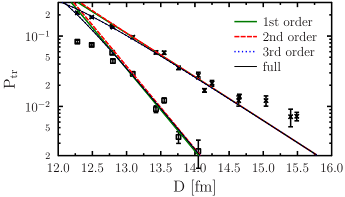
$P=1-p_1-p_2$ $\xrightarrow{F_{02}}$ $P=p_2$

0n 1n 2n

Results : ^{40}Ca+^{96}Zr seq. hyp.



Results : ^{40}Ca+^{96}Zr dir. hyp.



Two messages from this simple model

Warning

Third order evolution can play an important role for transfer reactions.

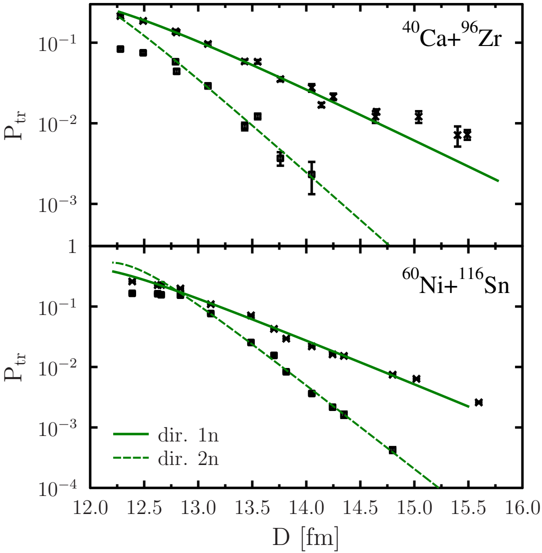
Sequential or direct pair transfer

Important difference for the probability to transfer one neutron.

G. Scamps and K. Hagino, PRC 92, 054614 (2015)

→ We will assume the direct hypothesis in the following

Effect of fusion on the transfer reaction



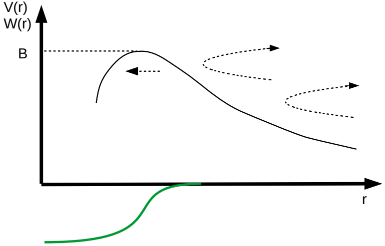
TDCC with absorbing potential

Absorbing potential

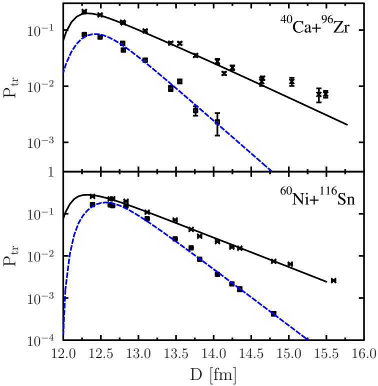
$$\mathcal{H}[r(t)] =$$

$$\begin{pmatrix} 0 + iW_1(r) & F_{01}(r) & F_{02}(r) \\ F_{01}(r) & -Q_1 + iW_1(r) & F_{01}(r) \\ F_{02}(r) & F_{01}(r) & -Q_2 + iW_2(r) \end{pmatrix}$$

$$iW(r) = \frac{-iW_0}{1 + \exp[(r - R_W)/a_W]},$$



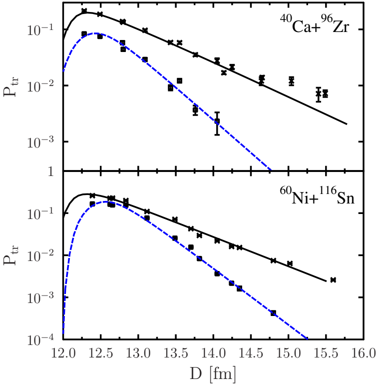
Result



TDCC with absorbing potential

System	Trsf.	B (MeV)	σ (MeV)
^{40}Ca+^{96}Zr	0n	95	1.3
	1n	95	1.3
	2n	92	1.8
^{60}Ni+^{116}Sn	0n	166	1.3
	1n	166	1.5
	2n	160	2.8

Result



Full quantal Coupled-channels calculation (CCFULL)

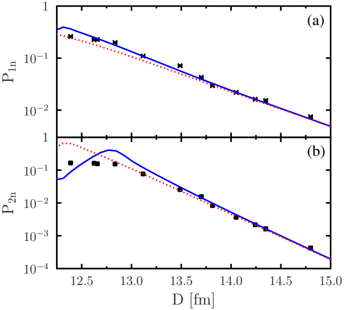
$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{J(J+1)\hbar^2}{2\mu r^2}+V_N^{(0)}(r)+\frac{Z_PZ_Te^2}{r}+\epsilon_n-E\right]\psi_n(r)+\sum_m V_{nm}(r)\psi_m(r)=0,$$

CC calculation

Full quantal approach → same formalism for fusion and transfer

Result, ^{60}Ni+^{116}Sn

Comparison with and without fusion



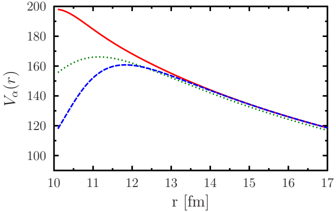
Full quantal Coupled-channels calculation (CCFULL)

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{J(J+1)\hbar^2}{2\mu r^2} + V_N^{(0)}(r) + \frac{Z_P Z_T e^2}{r} + \epsilon_n - E \right]\psi_n(r) + \sum_m V_{nm}(r)\psi_m(r) = 0,$$

CC calculation

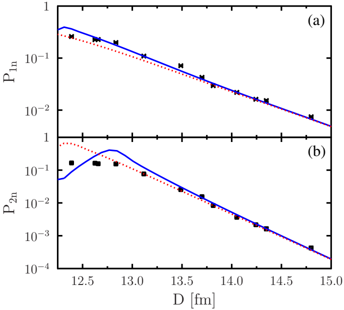
Full quantal approach → same formalism for fusion and transfer

Eigen-states



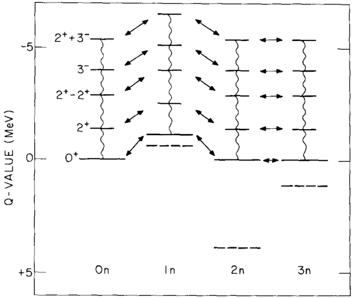
Result, ^{60}Ni+^{116}Sn

Comparison with and without fusion

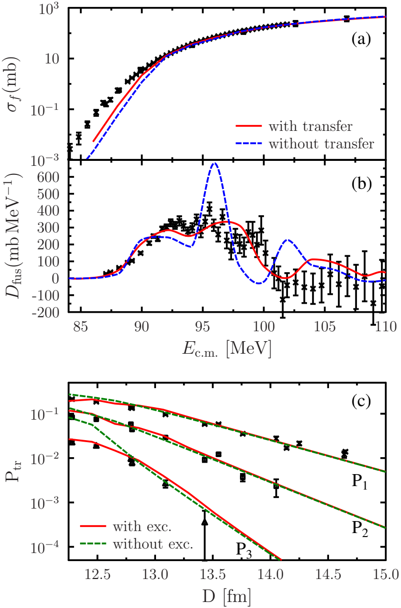


Full quantal Coupled-channels calculation : ^{40}Ca+^{96}Zr

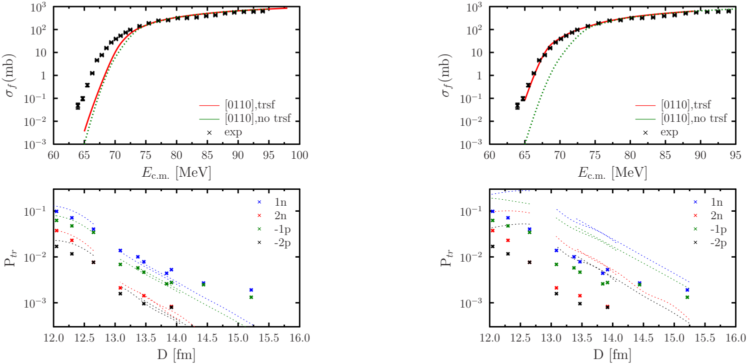
	λ^{π}	β_C	β_N	E (MeV)
^{40}Ca	3^-	0.43	0.43	3.737
^{96}Zr	3^-	0.27	0.305	1.89



H. Esbensen, Nucl. Phys. A492 (1989)



Preliminary results ^{40}Ca+^{64}Ni



Preliminary PRISMA experimental data from D. Bourgin and S. Courtin.

Preliminary conclusion

It is not possible to reproduce simultaneously the fusion cross section and transfer probabilities.

Conclusion

Summary

- Description of experimental data with only the two first orders may be incomplete
- Better reproduction of the experimental data with sequential plus direct transfer
- Sequential or direct pair transfer change the one neutron transfer probability
- The capture absorbs the 2-neutron transfer amplitude more than the 1-neutron
- Simultaneous description of fusion and transfer reaction

G. Scamps and K. Hagino, PRC 92, 054614 (2015)

Future work

- Understand theoretically the connection between transfer and the enhancement of the fusion cross section

Thank you

Full quantal Coupled-channels calculation (CCFULL)

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{J(J+1)\hbar^2}{2\mu r^2}+V_N^{(0)}(r)+\frac{Z_P Z_T e^2}{r}+\epsilon_n-E\right]\psi_n(r)+\sum_m V_{nm}(r)\psi_m(r)=0,$$

Comparison full-CC vs Semi-classical coupled channel