Core Excitations and Transfer Reactions in Exotic Nuclei

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TRIUMF, February 18th, 2014

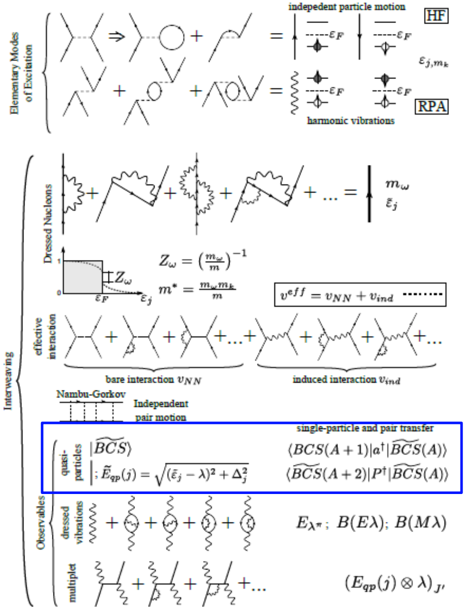
Introduction and Outline

Study of the interplay between nuclear elementary modes of excitation (single–particle motion, surface vibrations and pairing modes), probed with transfer reactions.

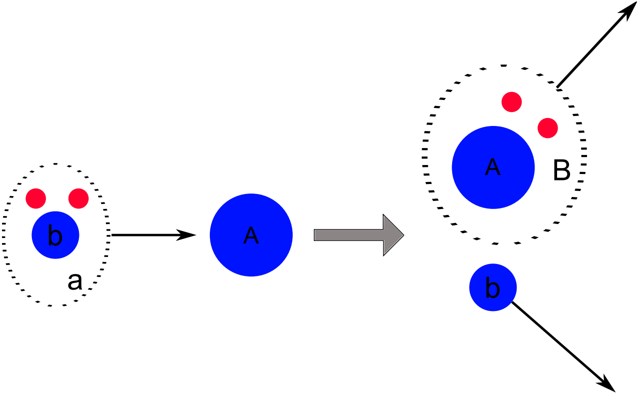
Outline:

- Structure: nuclear elementary modes of excitation.
- Reaction formalism: two–particle transfer in 2–step DWBA.
- Two–particle transfer in stable nuclei: a probe of pairing correlations.
- Coupling of pairing modes with surface modes in exotic nuclei: some results and perspectives.

interweaving of elementary modes of excitation: NFT

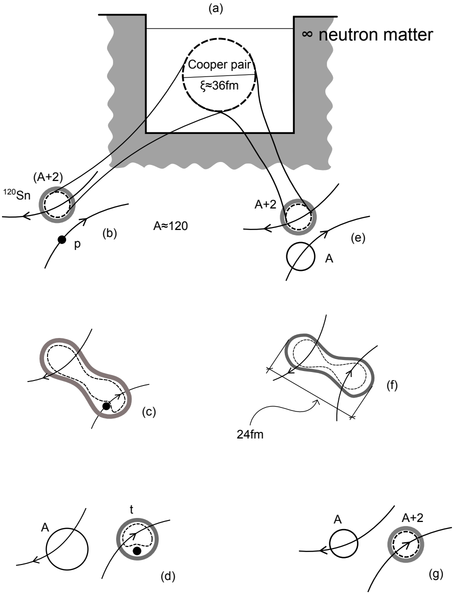


Two–Nucleon Transfer

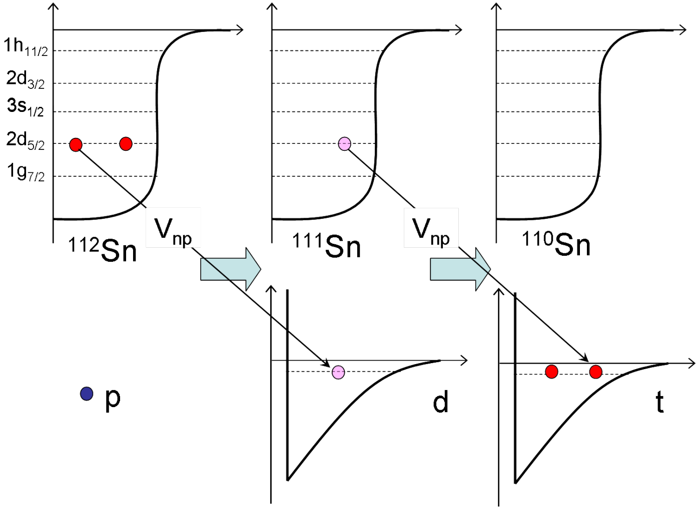


- Reaction $A + a(\equiv b + 2) \longrightarrow a + B(\equiv A + 2)$.
- Measure of the pairing correlations between the transferred nucleons.
- Need to correctly account for the correlated wavefunction.

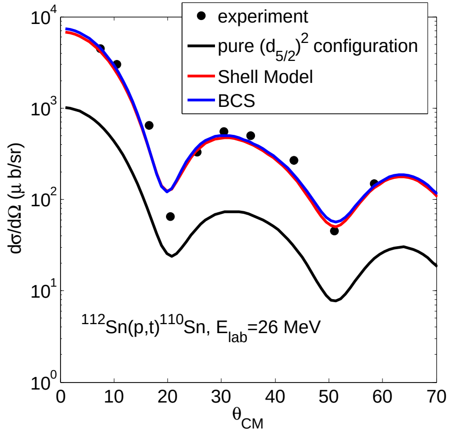
Pair transfer reaction mechanism: coherence length



Example: ^{112}Sn(p,t)^{110}Sn in 2–step DWBA



Probing pairing with 2–transfer: $^{112}Sn(p,t)^{110}Sn$

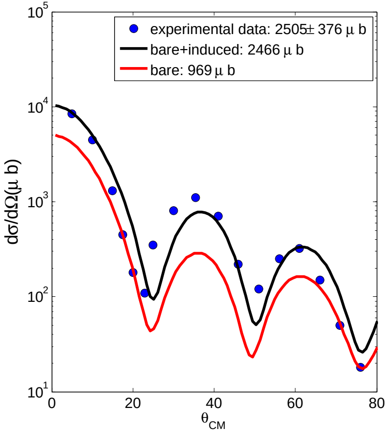


enhancement factor with respect to the transfer of uncorrelated neutrons: $\varepsilon = 20.6$

Experimental data and shell model wavefunction from Guazzoni *et al.* PRC **74** 054605 (2006)

experiment very well reproduced with mean field (BCS) wavefunctions

$^{122}Sn(p,t)^{120}Sn$ (gs): role of induced interaction



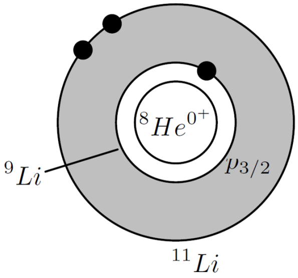
Differential cross section worked out making use of two different structure calculations:

- Skyrme in $p-h$ channel (mean field)+collective vibrations+bare v_{14} Argonne interaction and particle–vibration coupling (induced interaction) in $p-p$ channel (black line),
- Skyrme in $p-h$ channel (mean field)+bare v_{14} Argonne in $p-p$ channel (red line),

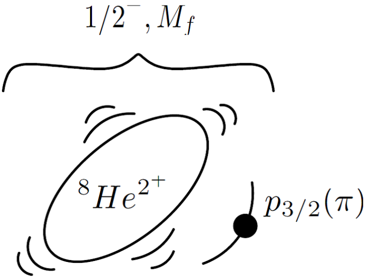
compared with experimental data.

$^{122}Sn(p,t)^{120}Sn$ at 26 MeV. Data from Guazzoni *et.al.* (1999).

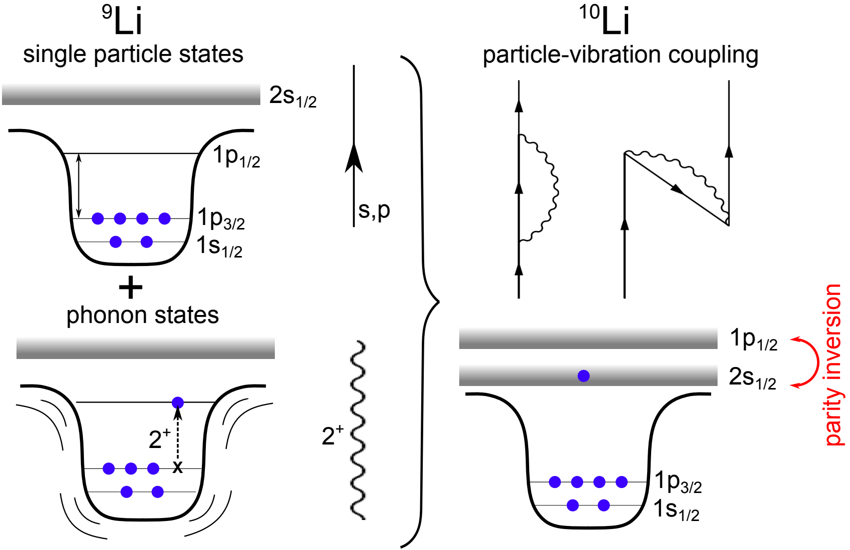
We will try to draw information about the halo structure of ^{11}Li from the reactions ^{1}H(^{11}Li,^{9}Li)^{3}H and ^{1}H(^{11}Li,^{9}Li*(2.69 MeV))^{3}H (I. Tanihata *et al.*, Phys. Rev. Lett. **100**, 192502 (2008))



Schematic depiction of ^{11}Li



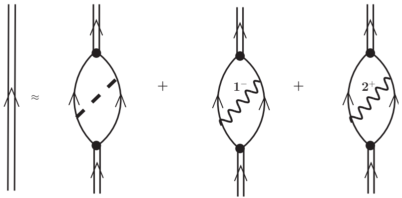
First excited state of ^{9}Li



^{9}Li
single particle states
$2s_{1/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
+
phonon states
2^+
x
s,p
2^+
^{10}Li
particle-vibration coupling
$1p_{1/2}$
$2s_{1/2}$
parity inversion
$1p_{3/2}$
$1s_{1/2}$

Structure of the ^{11}Li $(3/2^-)$ ground state

^{11}Li$=^{9}$Li core+2–neutron halo (single Cooper pair). According to Barranco *et al.* (2001), the two neutrons correlate by means of the bare interaction (accounting for $\approx 20\%$ of the ^{11}Li binding energy) and by exchanging 1^- and 2^+ phonons ($\approx 80\%$ of the binding energy)

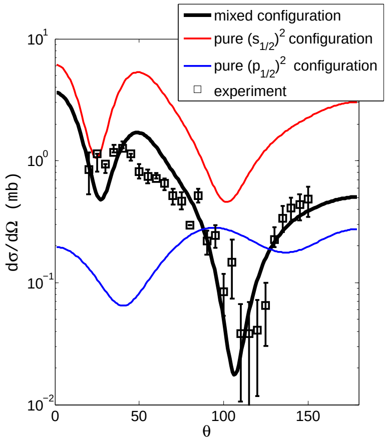


Within this model, the ^{11}Li wavefunction can be written as

$$|\tilde{0}\rangle = 0.45|s^2_{1/2}(0)\rangle + 0.55|p^2_{1/2}(0)\rangle + 0.04|d^2_{5/2}(0)\rangle$$
$$+ 0.70|(ps)_{1^-} \otimes 1^-;0\rangle + 0.10|(sd)_{2^+} \otimes 2^+;0\rangle.$$

highly renormalized single particle states coupled to excited states of the core

Transition to the ground state of ^{9}Li



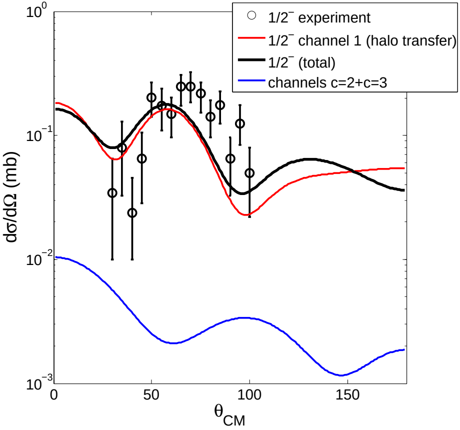
differential cross section calculated with three ^{11}Li ground state model wavefunctions:

- pure $(s_{1/2})^2$ configuration
- pure $(p_{1/2})^2$ configuration
- $20\%(s_{1/2})^2+30\%(p_{1/2})^2$ configuration (Barranco *et al.* (2001)).

compared with experimental data.

^{1}H(^{11}Li,^{9}Li)^{3}H at 33 MeV. Data from Tanihata *et.al.* (2008).

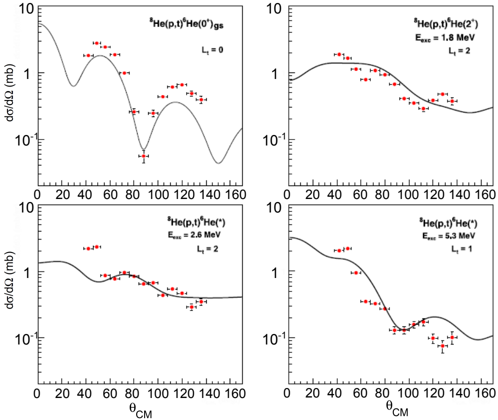
Transition to the first $1/2^-$(2.69 MeV) excited state of ^{9}Li



differential cross section calculated with the Barranco *et. al.* (2001) ^{11}Li ground state wavefunction, compared with experimental data. According to this model, the ^{9}Li excited state is found after the transfer reaction because it is already present in the ^{11}Li ground state.

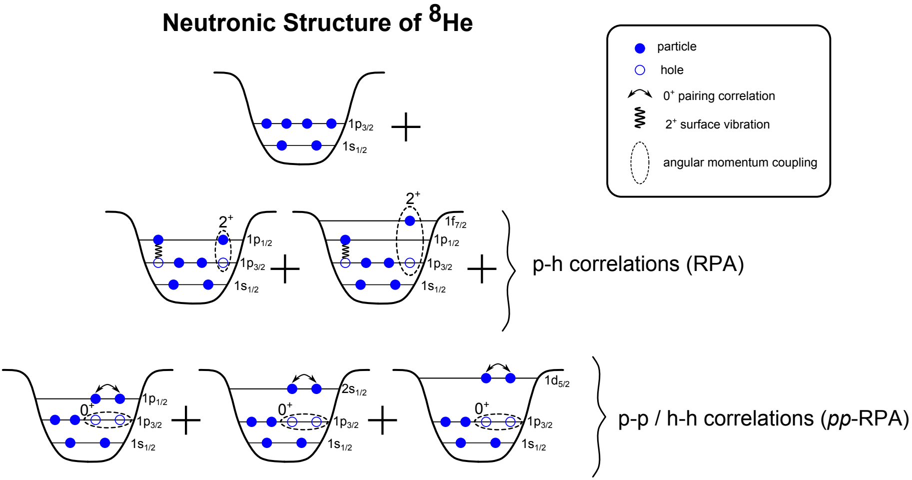
^{1}H(^{11}Li,^{9}Li*(2.69 MeV))^{3}H at 33 MeV. Data from Tanihata *et.al.* (2008).

Two–neutron transfer with ^{8}He

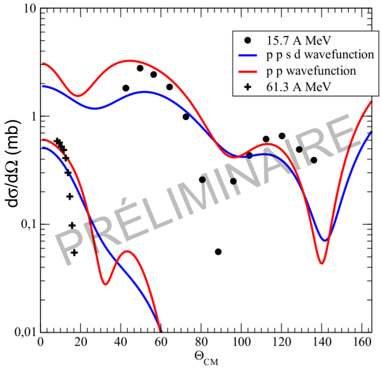


- X. Mougeot *et al.* PLB **718**, 441 (2012) ^{8}He(p,t)^{6}He(gs),^{8}He(2^{+}) with SPIRAL and MUST2;
- Coupled Reaction Channels (CRC) analysis by N .Keeley.

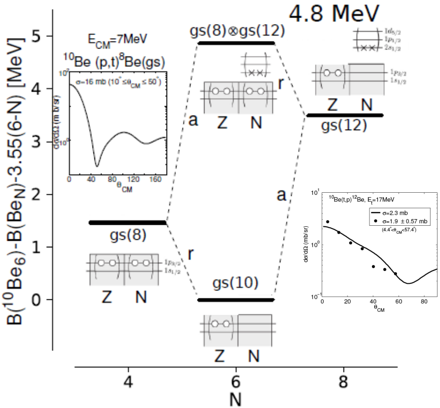
schematic structure of ^{8}He in NFT



^{8}He(p, t) reaction in 2–step DWBA

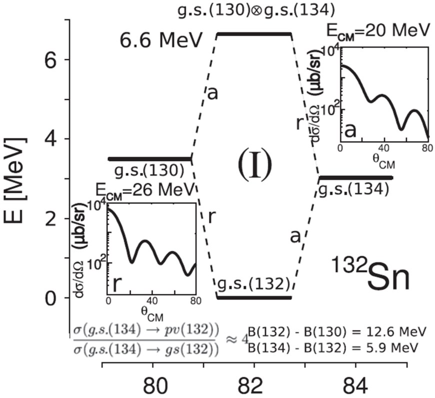


- Sensitive to ^{8}He structure.
- Nuclear Fied Theory calculations for ^{8}He(g.s.),^{6}He(g.s,2^{+}) (^{6}He as a pair removal mode of ^{8}He?).
- Consistent description of elastic and one–neutron transfer channels and the overlap ^{8}He(g.s.)/^{6}He(2^{+}) is essential.



^{8}Be(p,t)^{10}Be and ^{10}Be(t,p)^{12}Be reactions can probe the pairing vibrations around ^{10}Be ($N = 6$ shell closure).

^{10}Be(t,p)^{12}Be data by Fortune *et al*, PRC **50** (1994) 1355.

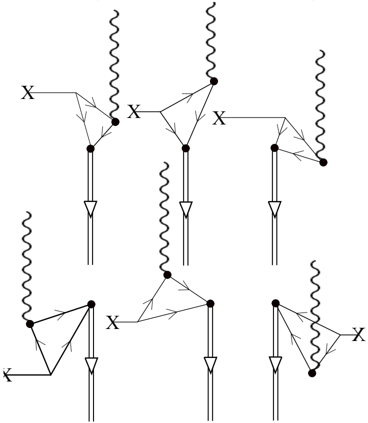


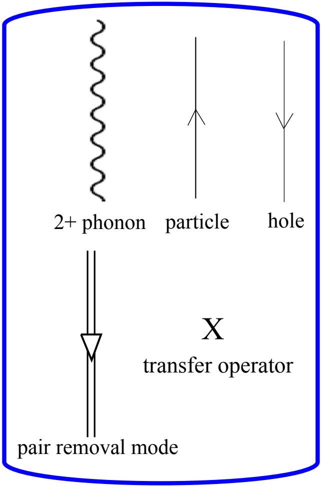
^{132}Sn(p,t)^{130}Sn and ^{134}Sn(p,t)^{132}Sn reactions can probe the predicted pairing vibrations of the exotic double magic nucleus ^{132}Sn.
Foreseen experiments at GANIL with SPIRAL2

Coupling of pairing vibrations with phonons

Population of excited 2^+ state with (t,p) reaction

Diagrams contributing





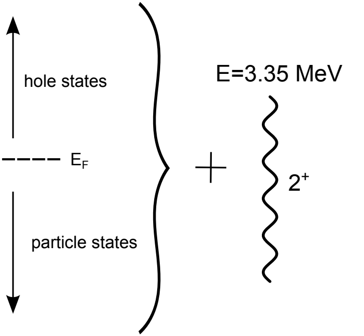
^{130}Sn(t,p)^{132}Sn(2^+)

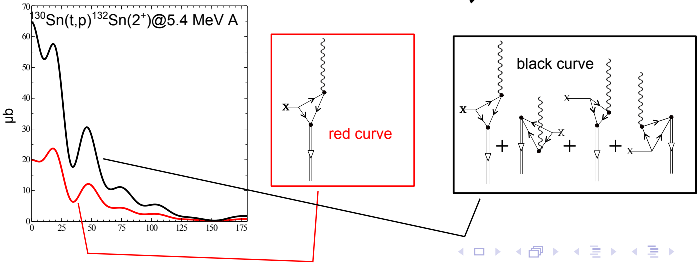
^{132}Sn

	Ω_j	ε_j	X_{rem}	Y_{add}	$X_{rem}Y_{add}$	$\sqrt{\Omega_j}\Lambda_{rem}$	$\sqrt{\Omega_j}\Lambda_{add}$
$g_{7/2}$	4	−9.78	0.229	0.080	0.018	3.20	2.16
$d_{5/2}$	3	−9.01	0.255	0.078	0.020	2.78	1.88
$s_{1/2}$	1	−7.68	0.286	0.058	0.017	1.60	1.08
$h_{11/2}$	6	−7.52	0.791	0.147	0.116	3.92	2.64
$d_{3/2}$	2	−7.35	0.529	0.088	0.047	2.26	1.52

E_F

	Ω_j	ε_j	Y_{rem}	X_{add}	$X_{add}Y_{rem}$	$\sqrt{\Omega_j}\Lambda_{add}$	$\sqrt{\Omega_j}\Lambda_{rem}$
$f_{7/2}$	4	−2.44	0.209	0.922	0.192	3.20	2.16
$p_{3/2}$	2	−1.59	0.121	0.265	0.032	2.26	1.52
$h_{9/2}$	5	−0.88	0.166	0.281	0.046	3.58	2.42
$p_{1/2}$	1	−0.78	0.073	0.120	0.009	1.60	1.08
$f_{5/2}$	3	−0.44	0.119	0.180	0.021	2.78	1.88



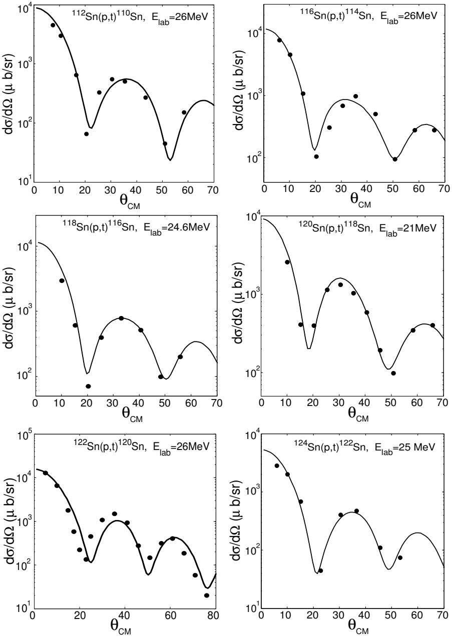


Conclusions

- Atomic nuclei can be consistently described as interacting elementary modes of excitation (NFT).
- The interweaving of these modes can be studied at profit with transfer reactions.
- We have presented examples of the study of coupling between pairing and collective modes with the help of two–nucleon transfer reaction within a 2–step DWBA formalism.
- Good agreement with experiment is obtained essentially without adjustable parameters.

Thank You!

2–transfer in well bound nuclei $^{A}Sn(p,t)^{A-2}Sn$



Comparison with the experimental data available so far for superfluid tin isotopes

Potel *et al.*, PRL **107**, 092501 (2011)

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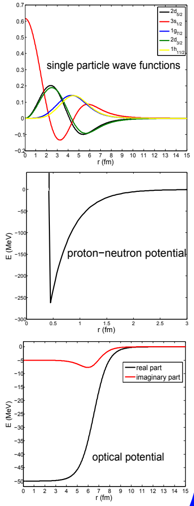
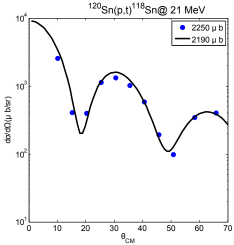
Reaction formalism, between structure and experiment

structure

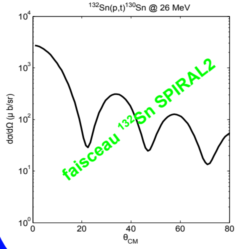


formalisme de réaction

calcul réaction + expérience



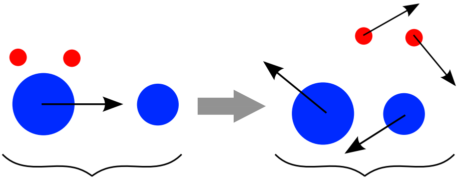
Potel *et al.*, PRL **107** 092501 (2011)



Reaction mechanism:

2–step DWBA

DWBA revisited



- lowest order in the interaction potential,
- explicitly incorporates microscopic structure inputs,
- adapted to a variety of reaction channels

Transition amplitude

Matrix element of interaction potential between initial (i) and final (f) states

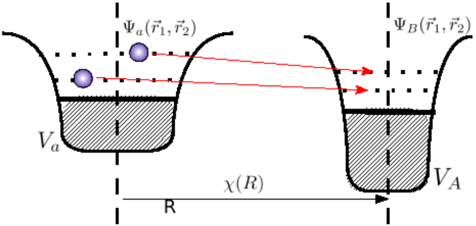
$$\langle \chi_f(R)\phi_f(\xi)|V(\xi)|\chi_i(R)\phi_i(\xi)\rangle$$

can be applied to **1– and 2–nucleon transfer** and **knock–out**

Elements of the calculation

$\Psi_a(\vec{r}_1, \vec{r}_2)$, $\Psi_B(\vec{r}_1, \vec{r}_2)$: internal wave functions of the transferred nucleons in each nucleus

$\chi(R)$: distorted wave describing the relative motion in the optical potential $U(R) = V(R) + iW(R)$ $\left(\frac{P_R^2}{2\mu} + U(R)\right)\chi(R) = E_{CM}\chi(R)$



V_A, V_a: mean field potentials of the two nuclei

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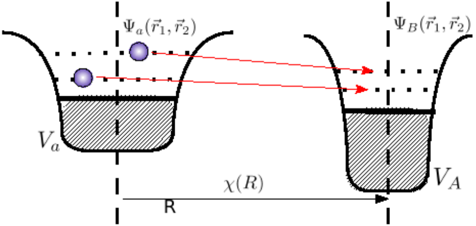

V_A, V_a: mean field potentials of the two nuclei

V_A (V_a) is the interaction potential that transfers the nucleons from one nucleus to the other in the *prior* (*post*) representation

Elements of the calculation

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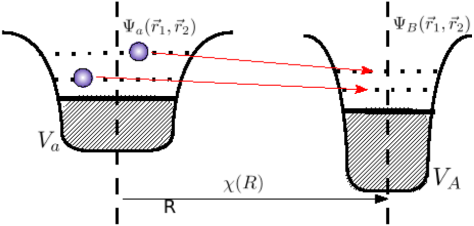
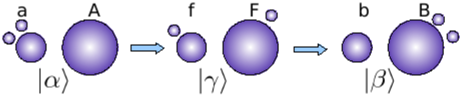
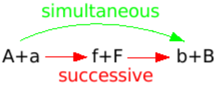


V_A, V_a: mean field potentials of the two nuclei

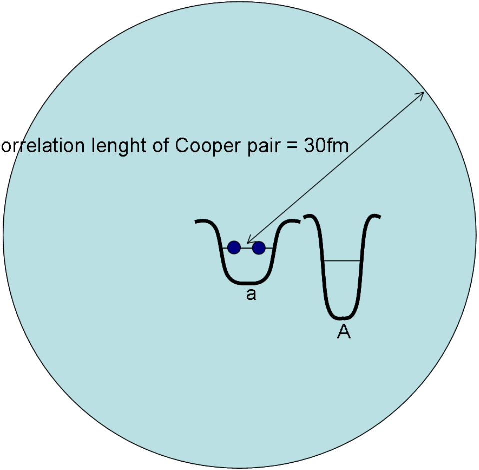
V_A (V_a) is the interaction potential that transfers the nucleons from one nucleus to the other in the *prior* (*post*) representation

it is a single particle potential!!

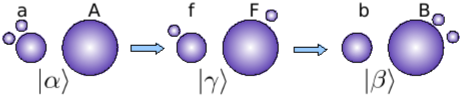


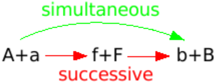


$$|\alpha\rangle = \phi_a(\xi_b, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\phi_A(\xi_A)\chi_{aA}(\mathbf{r}_{aA})$$
$$|\beta\rangle = \phi_b(\xi_b)\phi_B(\xi_A, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\chi_{bB}(\mathbf{r}_{bB})$$



simultaneous and successive contributions





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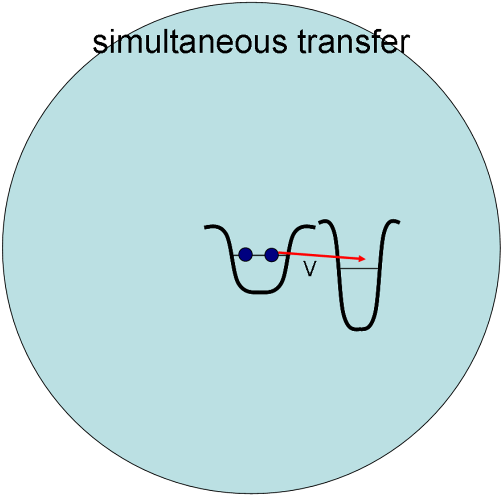

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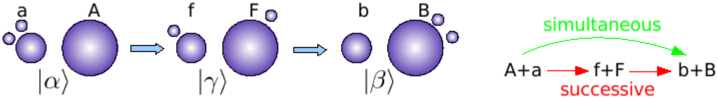

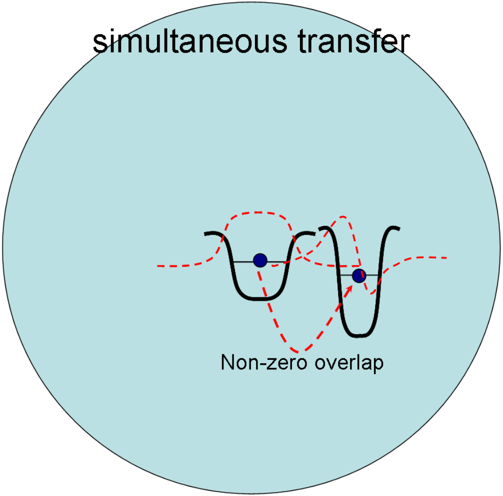

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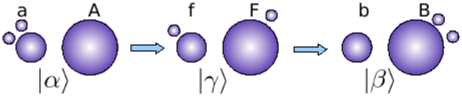
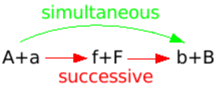
simultaneous and successive contributions





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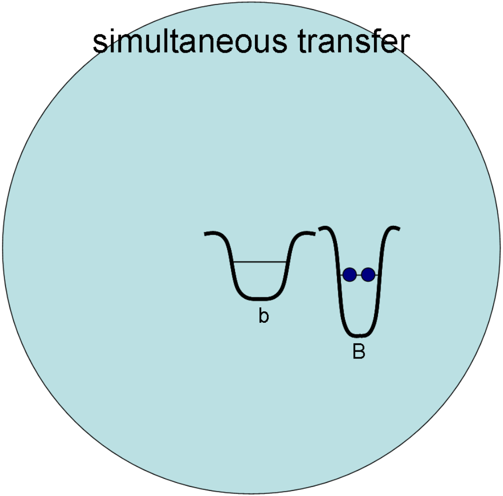

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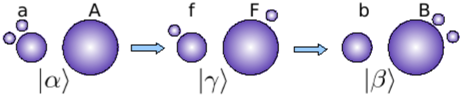

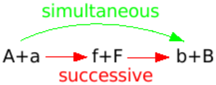

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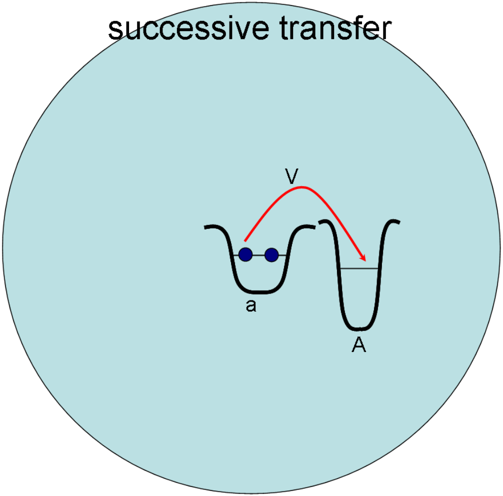
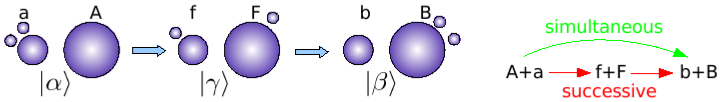
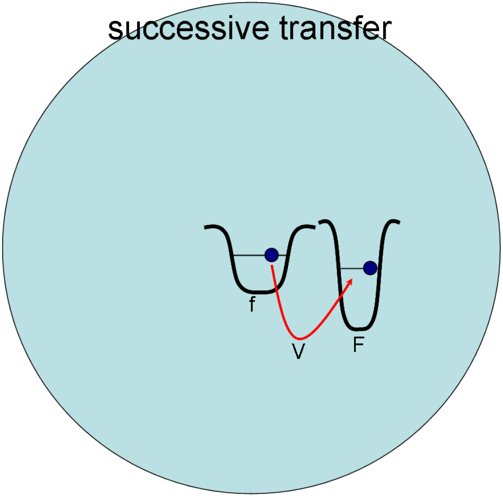
$$\chi_{bB}(\mathbf{r}_{bB})$$



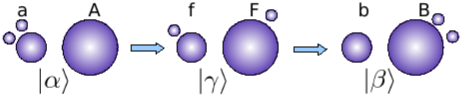
simultaneous and successive contributions

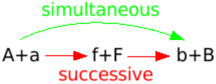


$$|\alpha\rangle = \phi_a(\xi_b, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\phi_A(\xi_A)\chi_{aA}(\mathbf{r}_{aA})$$
$$|\beta\rangle = \phi_b(\xi_b)\phi_B(\xi_A, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\chi_{bB}(\mathbf{r}_{bB})$$



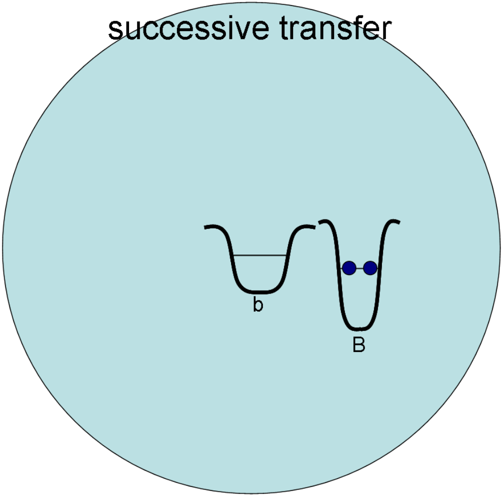
simultaneous and successive contributions



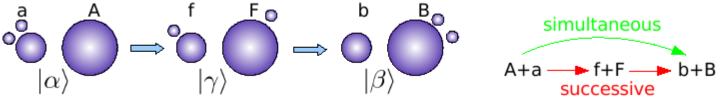


$$|\alpha\rangle = \phi_a(\xi_b, \mathbf{r}_1, \mathbf{r}_2) \times \phi_A(\xi_A)\chi_{aA}(\mathbf{r}_{aA})$$

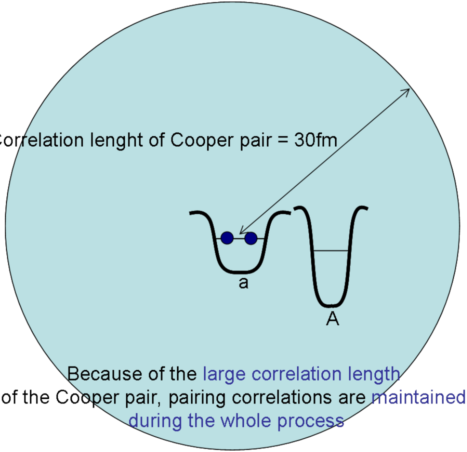
$$|\beta\rangle = \phi_b(\xi_b)\phi_B(\xi_A, \mathbf{r}_1, \mathbf{r}_2) \times \chi_{bB}(\mathbf{r}_{bB})$$



simultaneous and successive contributions

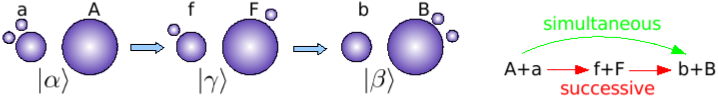


$$|\alpha\rangle = \phi_a(\xi_b, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\phi_A(\xi_A)\chi_{aA}(\mathbf{r}_{aA})$$
$$|\beta\rangle = \phi_b(\xi_b)\phi_B(\xi_A, \mathbf{r}_1, \mathbf{r}_2)\times$$
$$\chi_{bB}(\mathbf{r}_{bB})$$



Two particle transfer in second order DWBA

Some details of the calculation of the differential cross section for two–nucleon transfer reactions



$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(4\pi\hbar^2)^2} \frac{k_f}{k_i} |T_{2NT}|^2$$

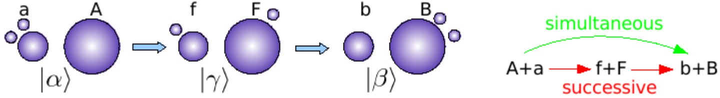
Simultaneous transfer

$$T^{(1)}(j_i, j_f) = 2 \sum_{\sigma_1 \sigma_2} \int d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1) \Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_0 \chi^{(-)*}_{bB}(\mathbf{r}_{bB})$$

$$\times\, v(\mathbf{r}_{b1}) [\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1) \Psi^{j_i}(\mathbf{r}_{b2}, \sigma_2)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}_{aA})$$

Two particle transfer in second order DWBA

Some details of the calculation of the differential cross section for two–nucleon transfer reactions



$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

Successive transfer

$$T^{(2)}_{succ}(j_i, j_f) = 2 \sum_{K,M} \sum_{\substack{\sigma_1 \sigma_2 \\ \sigma'_1 \sigma'_2}} \int d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1)\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_0$$

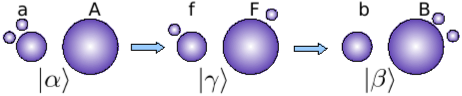
$$\times \chi^{(-)*}_{bB}(\mathbf{r}_{bB}) v(\mathbf{r}_{b1}) [\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1)]^K_M$$

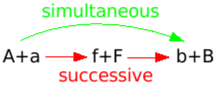
$$\times \int d\mathbf{r}'_{fF} d\mathbf{r}'_{b1} d\mathbf{r}'_{A2} G(\mathbf{r}_{fF}, \mathbf{r}'_{fF}) [\Psi^{j_f}(\mathbf{r}'_{A2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^K_M$$

$$\times \frac{2\mu_{fF}}{\hbar^2} v(\mathbf{r}'_{f2}) [\Psi^{j_i}(\mathbf{r}'_{b2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}'_{aA})$$

Two particle transfer in second order DWBA

Some details of the calculation of the differential cross section for two–nucleon transfer reactions





$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

Non–orthogonality term

$$T^{(2)}_{NO}(j_i, j_f) = 2 \sum_{K,M} \sum_{\substack{\sigma_1\sigma_2 \\ \sigma_1'\sigma_2'}} \int d\mathbf{r}_{fF}\, d\mathbf{r}_{b1}\, d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1)\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_0$$

$$\times\, \chi^{(-)*}_{bB}(\mathbf{r}_{bB}) v(\mathbf{r}_{b1}) [\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1)]^K_M$$

$$\times \int d\mathbf{r}'_{b1}\, d\mathbf{r}'_{A2} [\Psi^{j_f}(\mathbf{r}'_{A2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^K_M$$

$$\times\, [\Psi^{j_i}(\mathbf{r}'_{b2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}'_{aA})$$

Cancellation of simultaneous and non-orthogonal contributions

very schematically, the first order (*simultaneous*) contribution is

$$T^{(1)} = \langle \beta | V | \alpha \rangle,$$

while the second order contribution can be separated in a *successive* and a *non-orthogonality* term

$$\begin{aligned} T^{(2)} &= T^{(2)}_{succ} + T^{(2)}_{NO} \\ &= \sum_{\gamma} \langle \beta | V | \gamma \rangle G \langle \gamma | V | \alpha \rangle - \sum_{\gamma} \langle \beta | \gamma \rangle \langle \gamma | V | \alpha \rangle. \end{aligned}$$

If we sum over a complete basis of intermediate states γ, we can apply the closure condition and $T^{(2)}_{NO}$ exactly cancels $T^{(1)}$

the transition potential being single particle, two-nucleon transfer is a second order process.

Reaction and structure models

Structure:

$$\Phi_i(\mathbf{r}_1,\sigma_1,\mathbf{r}_2,\sigma_2) = \sum_{j_i} B_{j_i} \left[\psi^{j_i}(\mathbf{r}_1,\sigma_1)\psi^{j_i}(\mathbf{r}_2,\sigma_2)\right]^{\Lambda}_{\mu}$$

$$\Phi_f(\mathbf{r}_1,\sigma_1,\mathbf{r}_2,\sigma_2) = \sum_{j_f} B_{j_f} \left[\psi^{j_f}(\mathbf{r}_1,\sigma_1)\psi^{j_f}(\mathbf{r}_2,\sigma_2)\right]^{0}_{0}$$

Reaction:

$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i,j_f) + T^{(2)}_{succ}(j_i,j_f) - T^{(2)}_{NO}(j_i,j_f) \right)$$

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(4\pi\hbar^2)^2}\frac{k_f}{k_i}|T_{2NT}|^2$$

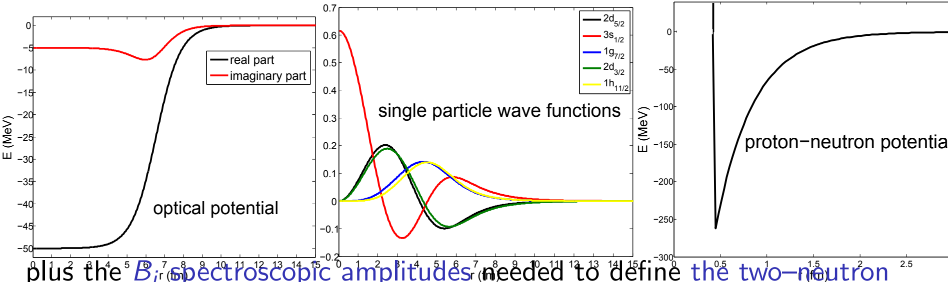
with:

$$T^{(1)}(j_i,j_f) = 2\sum_{\sigma_1\sigma_2}\int d\mathbf{r}_{fF}\, d\mathbf{r}_{b1}\, d\mathbf{r}_{A2}[\psi^{j_f}(\mathbf{r}_{A1},\sigma_1)\psi^{j_f}(\mathbf{r}_{A2},\sigma_2)]^{0*}_{0}\chi^{(-)*}_{bB}(\mathbf{r}_{bB})$$

$$\times\, v(\mathbf{r}_{b1})[\psi^{j_i}(\mathbf{r}_{b1},\sigma_1)\psi^{j_i}(\mathbf{r}_{b2},\sigma_2)]^{\Lambda}_{\mu}\chi^{(+)}_{aA}(\mathbf{r}_{aA})$$

etc...

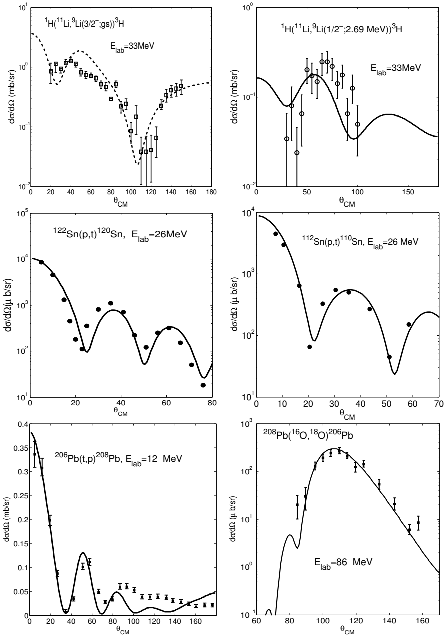
Structure input for, e.g., the ^{112}Sn(p,t)^{110}Sn reaction:

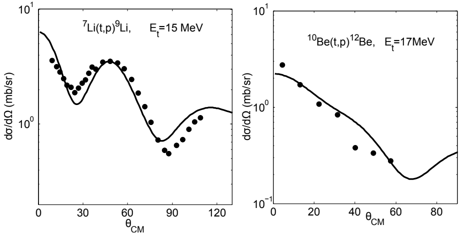


plus the B_j spectroscopic amplitudes needed to define the two−neutron wavefunction:

$$\Phi(\mathbf{r}_1, \sigma_1, \mathbf{r}_2, \sigma_2) = \sum_j B_j \left[\psi^j(\mathbf{r}_1, \sigma_1)\psi^j(\mathbf{r}_2, \sigma_2)\right]^0_0$$

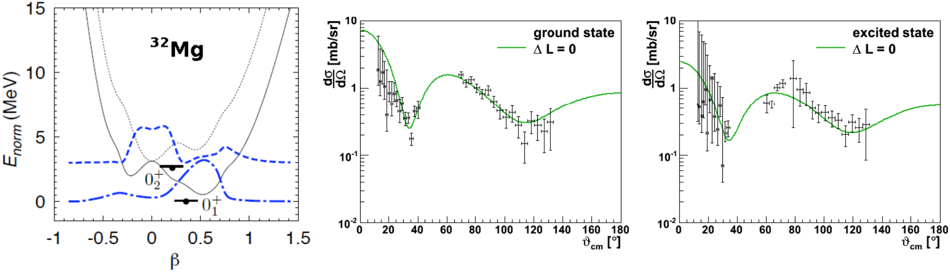
Examples of calculations





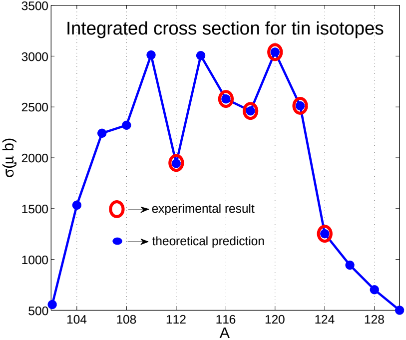
good results obtained for halo nuclei,
population of excited states,
superfluid nuclei,
normal nuclei (pairing vibrations),
heavy ion reactions...
Potel *et al.*, arXiv:0906.4298.

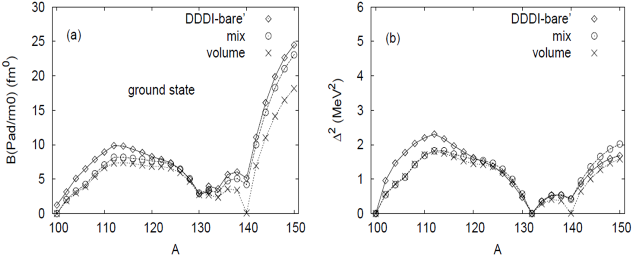
Shape coexistence and 2–neutron transfer



- Recent $t(^{32}\text{Mg},p)^{30}\text{Mg}$ @ 1.8 MeV.A at ISOLDE (Wimmer *et.al.*) reaction.
- Shape coexistence (low–lying 0^+ excited state).
- Ground state and first excited 0^+ populated with 2–neutron transfer

^{A}Sn(p,t)$^{A-2}$Sn, superfluid isotopic chain



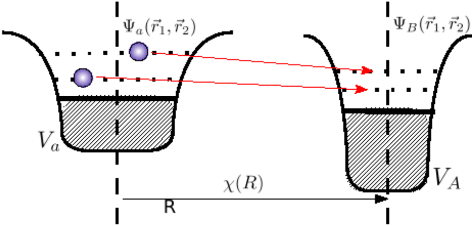


Shimoyama and Matsuo, nucl-th/1106.1715

Elements of the calculation

$\Psi_a(\vec{r}_1, \vec{r}_2)$, $\Psi_B(\vec{r}_1, \vec{r}_2)$: internal wave functions of the transferred nucleons in each nucleus

$\chi(R)$: distorted wave describing the relative motion in the optical potential $U(R) = V(R) + iW(R)$ $\left(\frac{P_R^2}{2\mu} + U(R)\right)\chi(R) = E_{CM}\chi(R)$



V_A, V_a: mean field potentials of the two nuclei

Elements of the calculation

$\Psi_a(\vec{r}_1, \vec{r}_2)$, $\Psi_B(\vec{r}_1, \vec{r}_2)$: internal wave functions of the transferred nucleons in each nucleus

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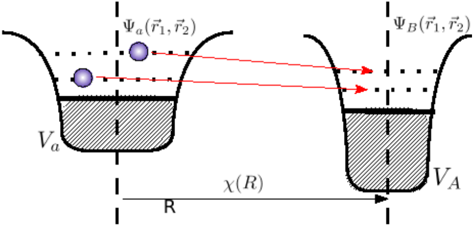

V_A, V_a: mean field potentials of the two nuclei

V_A (V_a) is the interaction potential that transfers the nucleons from one nucleus to the other in the *prior* (*post*) representation

Elements of the calculation

$\Psi_a(\vec{r}_1, \vec{r}_2)$, $\Psi_B(\vec{r}_1, \vec{r}_2)$: internal wave functions of the transferred nucleons in each nucleus

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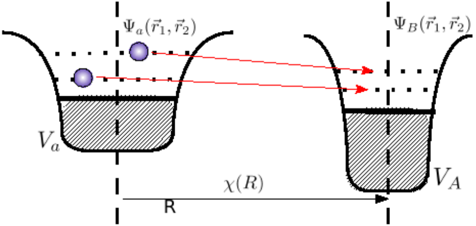
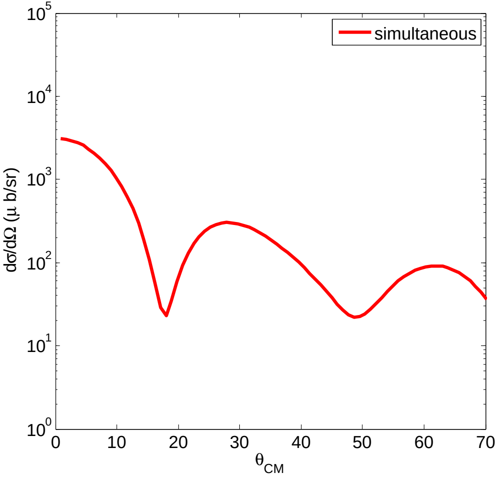


V_A, V_a: mean field potentials of the two nuclei

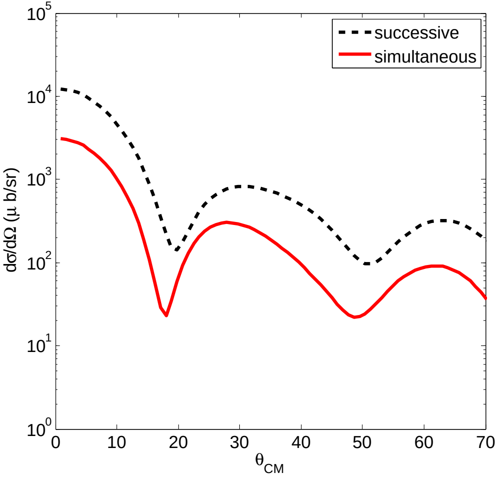
V_A (V_a) is the interaction potential that transfers the nucleons from one nucleus to the other in the *prior* (*post*) representation

it is a single particle potential!!

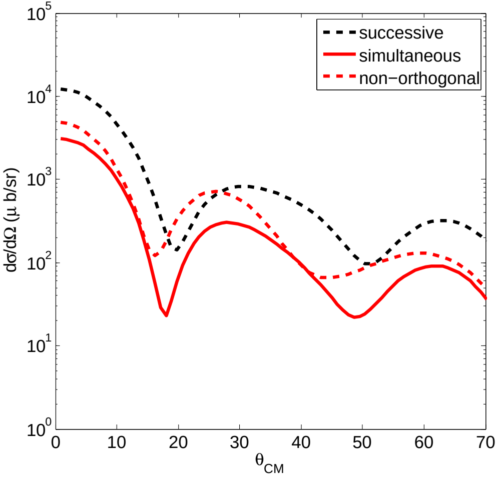
Contributions to the $^{112}Sn(p,t)^{110}$ total cross section



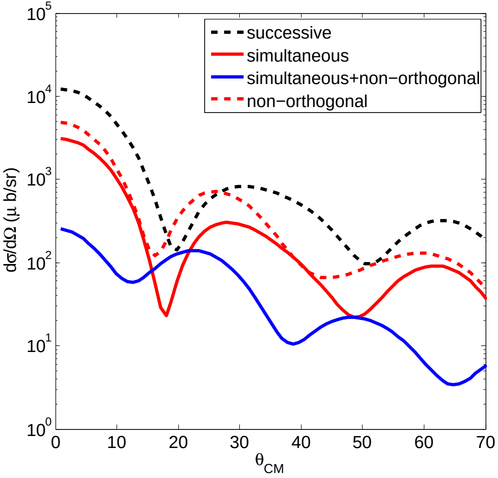
Contributions to the $^{112}Sn(p,t)^{110}$ total cross section



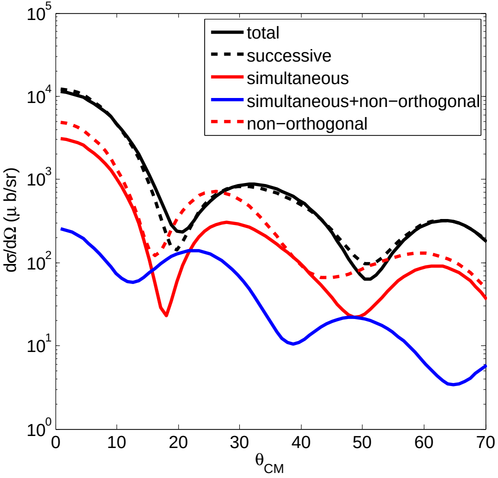
Contributions to the ^{112}Sn(p,t)^{110} total cross section



Contributions to the $^{112}Sn(p,t)^{110}$ total cross section



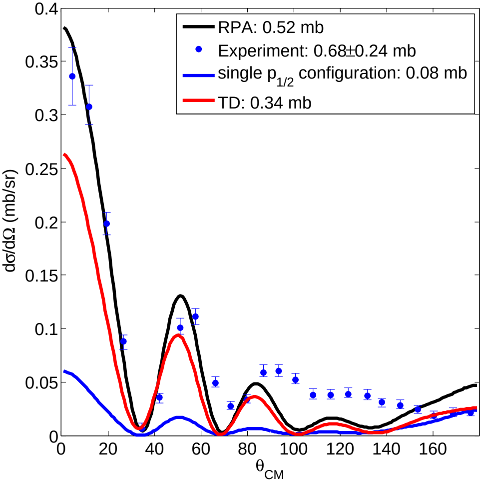
Contributions to the $^{112}Sn(p,t)^{110}$ total cross section



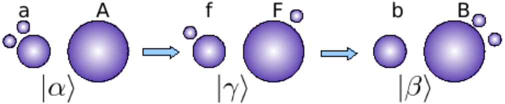
Essentially a successive process!

^{206}Pb$(t,p)^{208}$Pb (gs): pairing in normal nuclei

^{206}Pb$(t,p)^{208}$Pb at 12 MeV. Data from Bjerregaard *et.al.* (1966)



	B_{nlj}	
state *nlj*	*pp*RPA	(TDA)
$1h_{9/2}$	0.15	(0.14)
$2f_{7/2}$	0.21	(0.26)
$1i_{13/2}$	0.29	(0.28)
$3p_{3/2}$	0.23	(0.22)
$2f_{5/2}$	0.32	(0.31)
$3p_{1/2}$	0.89	(0.85)
$2g_{9/2}$	0.18	
$1i_{11/2}$	0.15	
$1j_{15/2}$	0.13	
$3d_{5/2}$	0.06	(–)
$4s_{1/2}$	0.06	
$2g_{7/2}$	0.10	
$3d_{3/2}$	0.05	



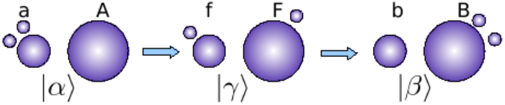
Potel *et al.*, PRL **107** 092501 (2011)
Potel *et al.*, PRL **105** 172502 (2010)

$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

Simultaneous transfer

$$T^{(1)}(j_i, j_f) = 2 \sum_{\sigma_1 \sigma_2} \int d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1) \Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_{0} \chi^{(-)*}_{bB}(\mathbf{r}_{bB})$$
$$\times\, v(\mathbf{r}_{b1}) [\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1) \Psi^{j_i}(\mathbf{r}_{b2}, \sigma_2)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}_{aA})$$

Two particle transfer in 2–step DWBA



Potel *et al.*, PRL **107** 092501 (2011)
Potel *et al.*, PRL **105** 172502 (2010)

$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

Successive transfer

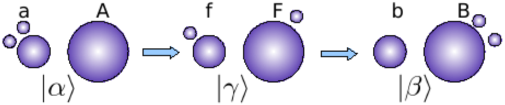
$$T^{(2)}_{succ}(j_i, j_f) = 2 \sum_{K,M} \sum_{\substack{\sigma_1 \sigma_2 \\ \sigma'_1 \sigma'_2}} \int d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1)\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_0$$

$$\times \chi^{(-)*}_{bB}(\mathbf{r}_{bB}) v(\mathbf{r}_{b1}) [\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1)]^K_M$$

$$\times \int d\mathbf{r}'_{fF} d\mathbf{r}'_{b1} d\mathbf{r}'_{A2} G(\mathbf{r}_{fF}, \mathbf{r}'_{fF}) [\Psi^{j_f}(\mathbf{r}'_{A2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^K_M$$

$$\times \frac{2\mu_{fF}}{\hbar^2} v(\mathbf{r}'_{f2}) [\Psi^{j_i}(\mathbf{r}'_{b2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}'_{aA})$$

Two particle transfer in 2–step DWBA



Potel *et al.*, PRL **107** 092501 (2011)
Potel *et al.*, PRL **105** 172502 (2010)

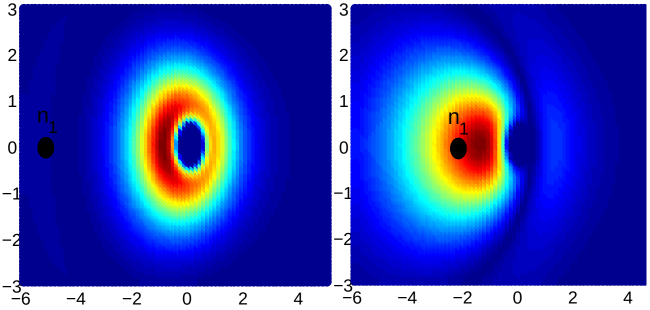
$$T_{2NT} = \sum_{j_f j_i} B_{j_f} B_{j_i} \left(T^{(1)}(j_i, j_f) + T^{(2)}_{succ}(j_i, j_f) - T^{(2)}_{NO}(j_i, j_f) \right)$$

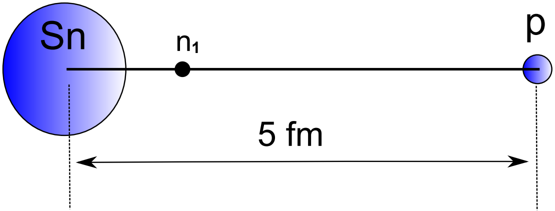
Non–orthogonality term

$$T^{(2)}_{NO}(j_i, j_f) = 2 \sum_{K,M} \sum_{\substack{\sigma_1\sigma_2 \\ \sigma'_1\sigma'_2}} \int d\mathbf{r}_{fF} d\mathbf{r}_{b1} d\mathbf{r}_{A2} [\Psi^{j_f}(\mathbf{r}_{A1}, \sigma_1)\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)]^{0*}_0$$
$$\times \chi^{(-)*}_{bB}(\mathbf{r}_{bB}) v(\mathbf{r}_{b1}) [\Psi^{j_f}(\mathbf{r}_{A2}, \sigma_2)\Psi^{j_i}(\mathbf{r}_{b1}, \sigma_1)]^K_M$$
$$\times \int d\mathbf{r}'_{b1} d\mathbf{r}'_{A2} [\Psi^{j_f}(\mathbf{r}'_{A2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^K_M$$
$$\times [\Psi^{j_i}(\mathbf{r}'_{b2}, \sigma'_2)\Psi^{j_i}(\mathbf{r}'_{b1}, \sigma'_1)]^{\Lambda}_{\mu} \chi^{(+)}_{aA}(\mathbf{r}'_{aA})$$

Non–local, correlated form factor

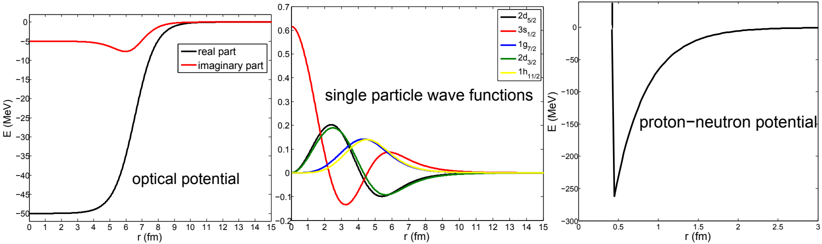
$$F(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_{Ap}) = \phi_f(\mathbf{r}_{p1}, \mathbf{r}_{p2}) V_{pn}(\mathbf{r}_{p1}) V_{pn}(\mathbf{r}_{p2}) \phi_i(\mathbf{r}_{A1}, \mathbf{r}_{A2})$$





Ingredients of the calculation

Structure input for, e.g., the ^{112}Sn(p,t)^{110}Sn reaction:



plus the B_j spectroscopic amplitudes needed to define the two–neutron wavefunction:

$$\Phi(\mathbf{r}_1, \sigma_1, \mathbf{r}_2, \sigma_2) = \sum_j B_j \left[\psi^j(\mathbf{r}_1, \sigma_1)\psi^j(\mathbf{r}_2, \sigma_2)\right]^0_0$$