Pair Correlations and Two-neutron transfer reactions

Kouichi Hagino
Kyoto University

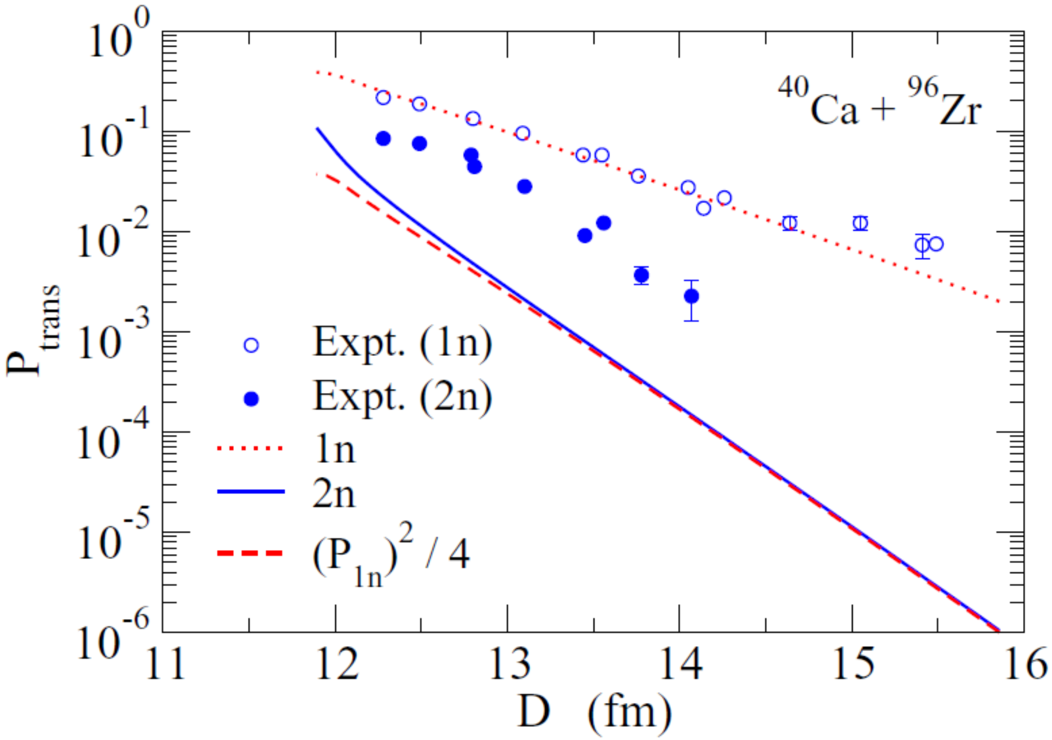
To what extent does a two-neutron transfer reaction provide a *direct* probe of pair correlations?

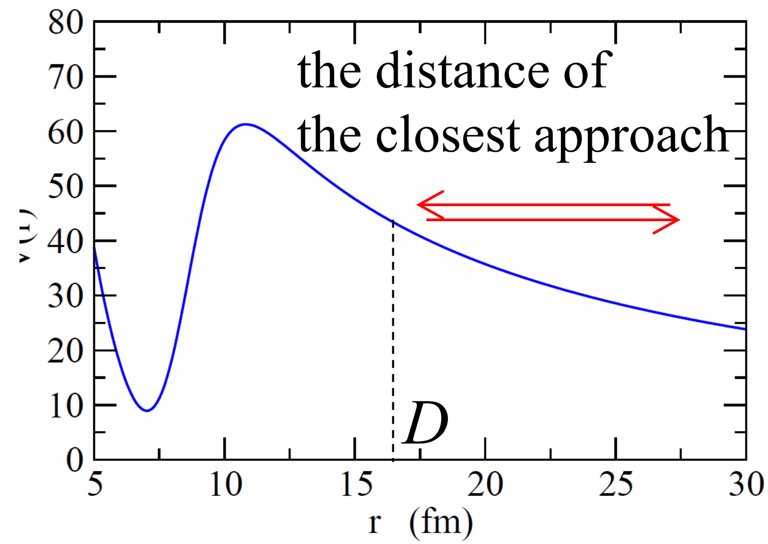
1. Overview of pair transfer reactions
2. How to extract information on pair correlations?
3. A simple one-dimensional 3-body model
4. T=1 np^{-1} correlation and deuteron tranfer
5. Summary

OMEG Workshop 2023.4.5

Pair transfer and pair correlations

Subbarrier two-neutron transfer reactions





$$D = \frac{Z_P Z_T e^2}{2E}\left[1 + \sqrt{1 + \cot^2\frac{\theta}{2}}\right]$$

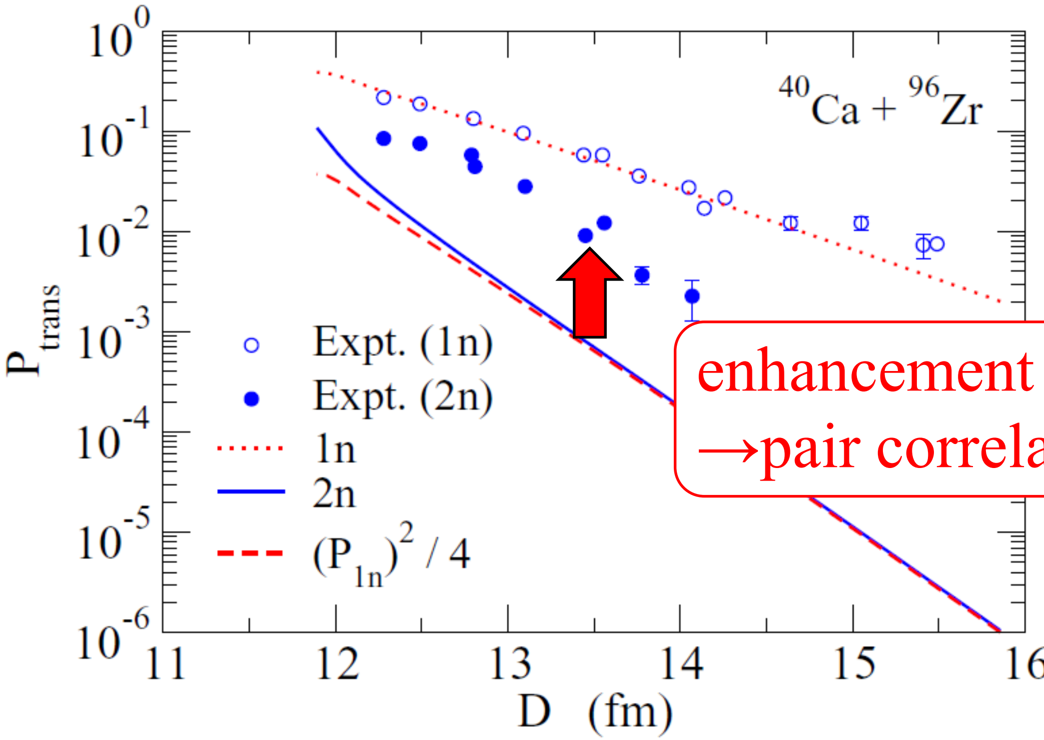
$$P_{\rm tr} \sim \frac{d\sigma_{\rm tr}}{d\sigma_R}$$

Calc. : K.H. and G. Scamps, PRC92 ('15) 064602

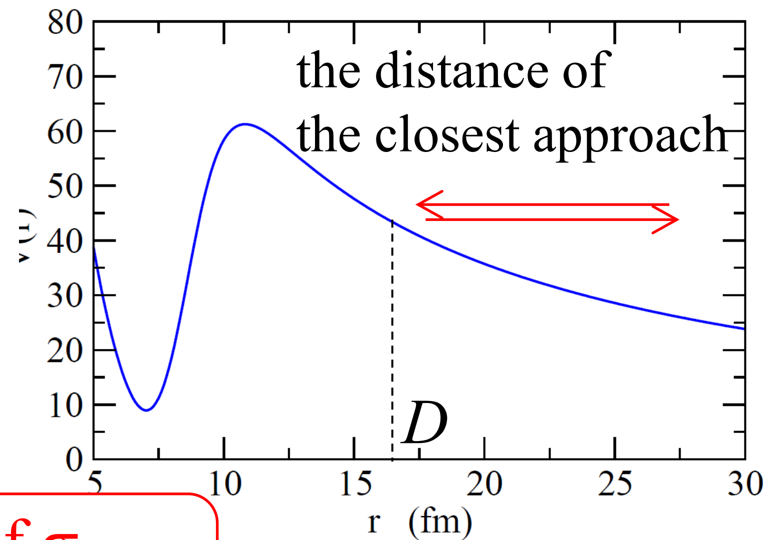
Exp. : L. Corradi et al., PRC84 ('11) 034603

Pair transfer and pair correlations

Subbarrier two-neutron transfer reactions



enhancement of σ_{2n}
→pair correlation



$$\frac{{}_P Z_T e^2}{2E}\left[1+\sqrt{1+\cot^2\frac{\theta}{2}}\right]$$

$$P_{\text{tr}} \sim \frac{d\sigma_{\text{tr}}}{d\sigma_R}$$

Calc.: K.H. and G. Scamps, PRC92 (‘15) 064602

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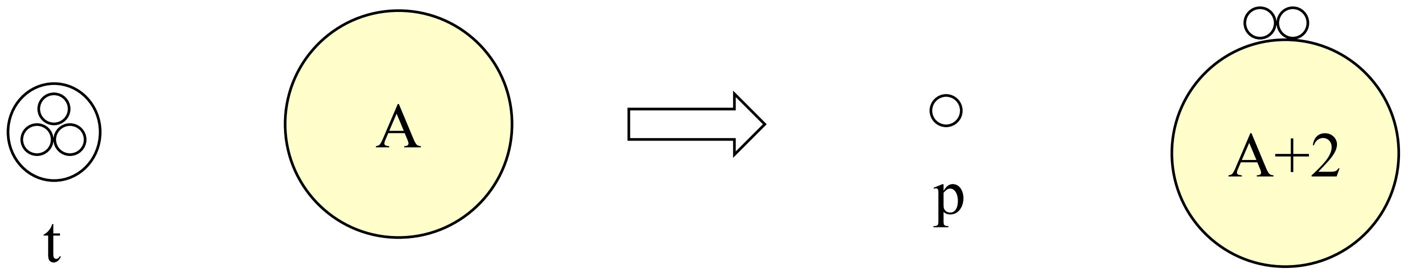
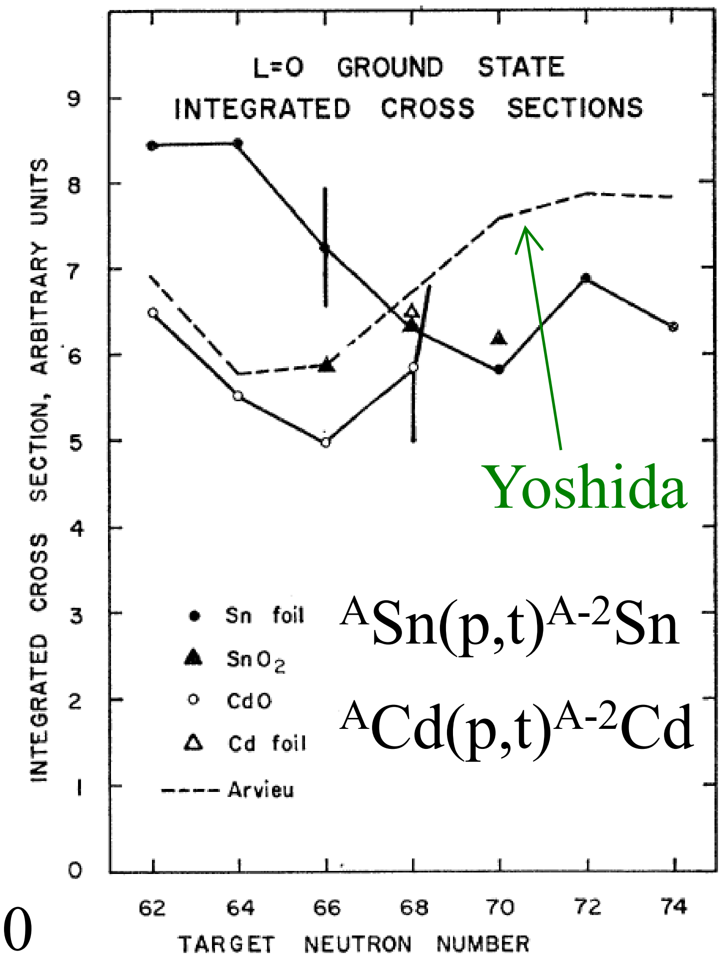
Estimate for (t,p) and (p,t) reactions based on a one-step DWBA



$$\frac{\sigma(\mathrm{BCS}\rightarrow\mathrm{BCS})}{\sigma_{\mathrm{sp}}}=\frac{1}{j+1/2}\left(\frac{\Delta}{G}\right)^2$$

S. Yoshida, Nucl. Phys. 33 (‘62) 685

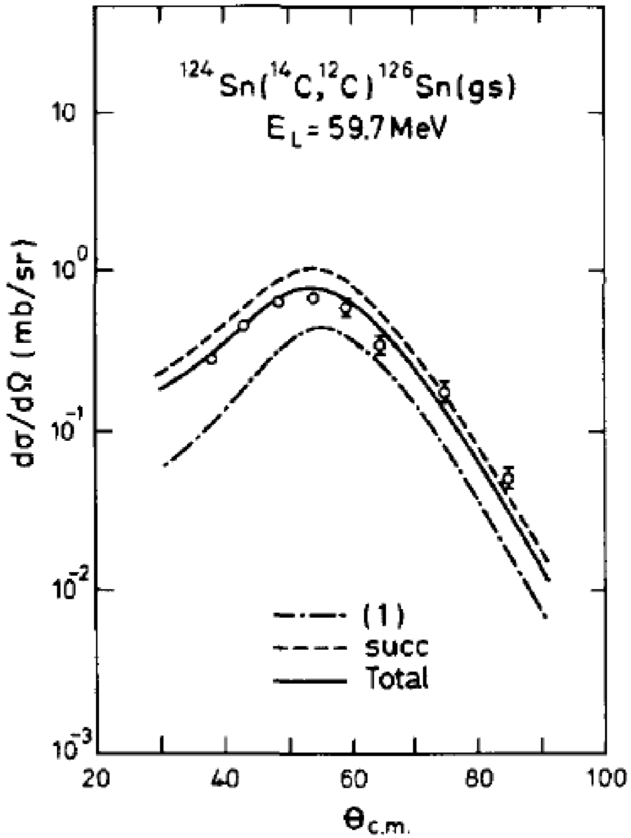
for Δ~1 MeV, G~0.15 MeV, j=5/2
→ enhancement: about 15 times



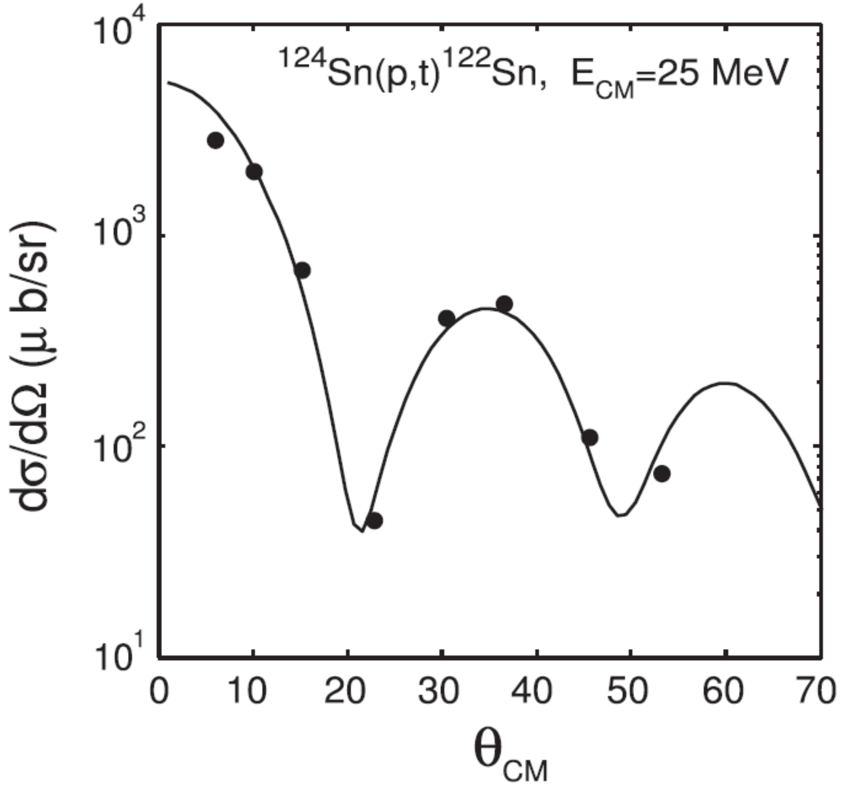
G. Bassani et al.,
Phys. Rev. 139 (‘65) B830

Pair transfer and pair correlations

Pair transfer reactions: complicated reaction dynamics
→ not straightforward to extract information on pairing from $\sigma_{transfer}$



2-step DWBA

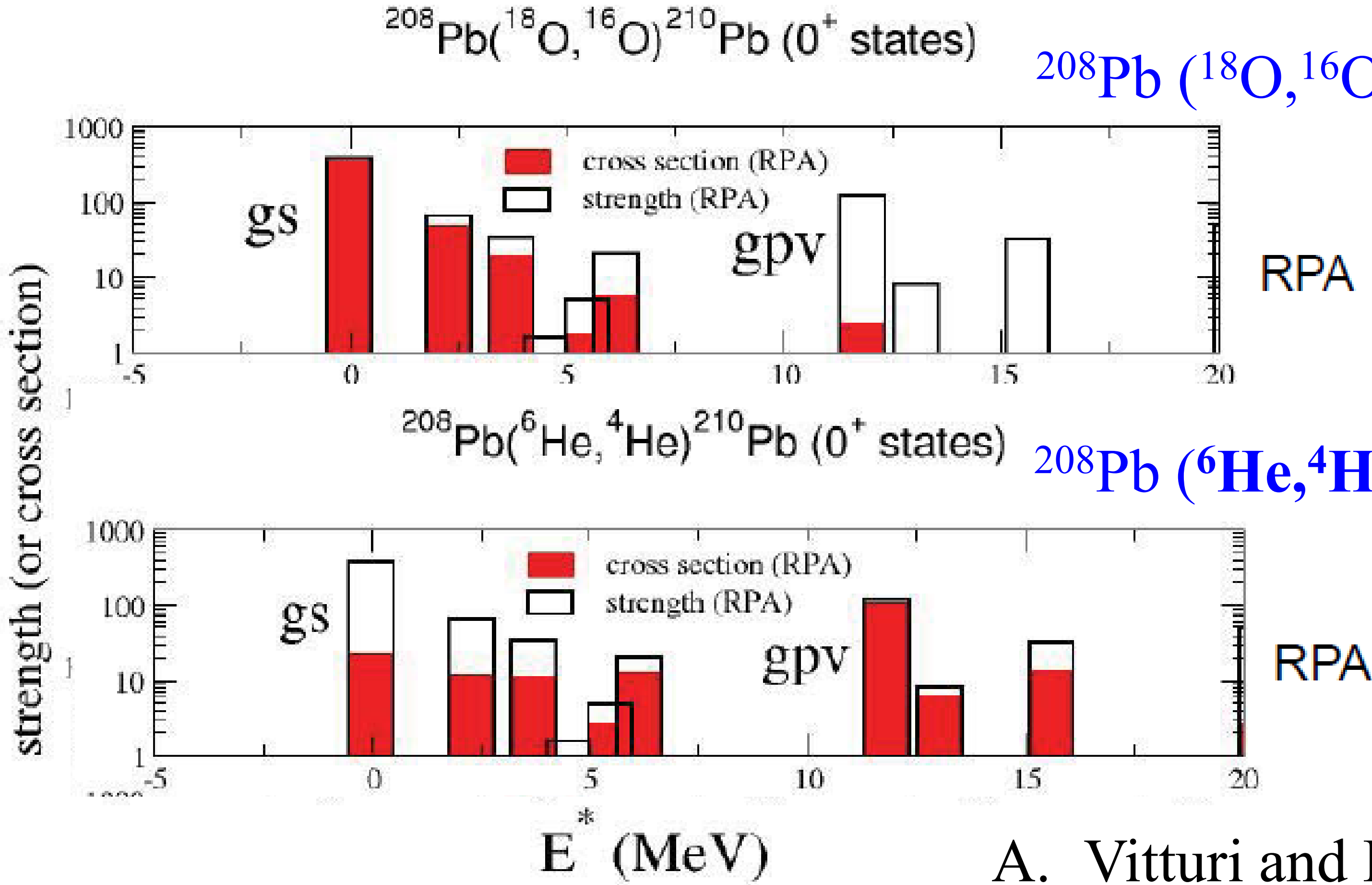


E. Maglione et al.,
Phys. Lett. 162B ('85) 59.

G. Potel et al.,
PRL 107 ('11) 092501

^{208}Pb (^{18}O,^{16}O)^{210}Pb (0$^+$)

^{208}Pb (^{6}**He**,^{4}**He**)^{210}Pb (0$^+$)



A. Vitturi and H.M. Sofia, PTP Suppl. 196 ('12) 72

White: strength for pair addition

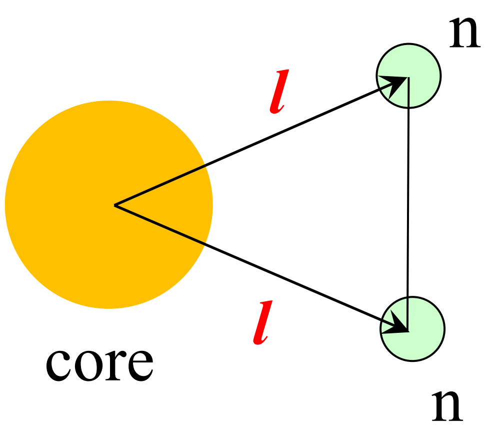
$$S = |\langle ^{210}\mathrm{Pb}|\psi^\dagger\psi^\dagger|^{208}\mathrm{Pb}\rangle|^2$$

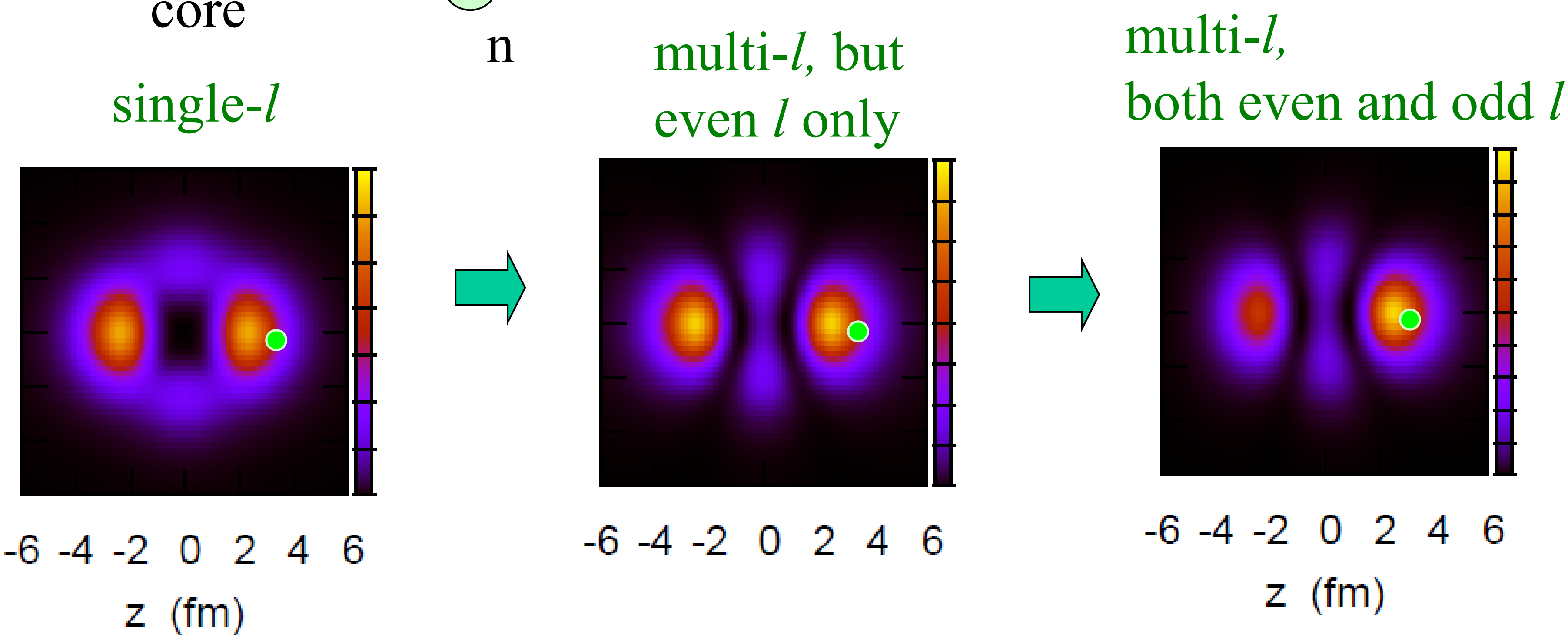
Red: Pair transfer cross sections

Cross sections may not be large even when the strength is large
→ due to reaction dynamics (e.g., Q-value matching)

An additional issue : pair transfer reactions and dineutron correlations

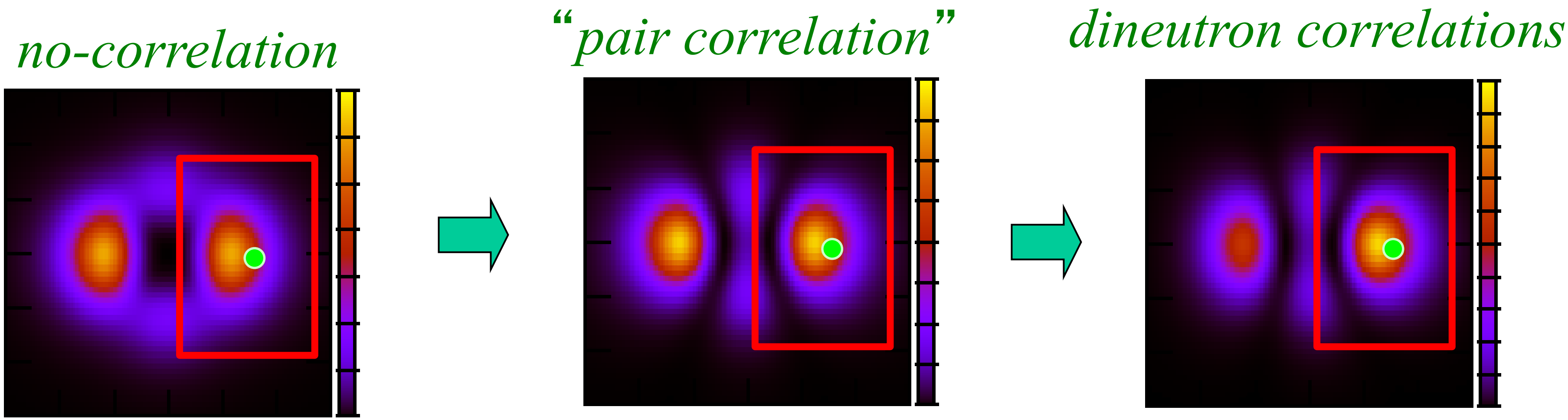
$^{18}\mathrm{O} = {}^{16}\mathrm{O} + \mathrm{n} + \mathrm{n} \rightarrow \quad \rho_2(\boldsymbol{r}) = |\Psi_{\mathrm{g.s.}}(\boldsymbol{r},\boldsymbol{r}')|^2_{\boldsymbol{r}'=z_0}$





K. Hagino, H. Sagawa, P. Schuck, J. of Phys. G 37, 064040 (2010)

An additional issue : pair transfer reactions and dineutron correlations



If a pair transfer reaction probes the region of the red square

→pair transfer: distinguish between uncorrelated and correlated,
but not between the "pair correlation" and dineutron correlation ?

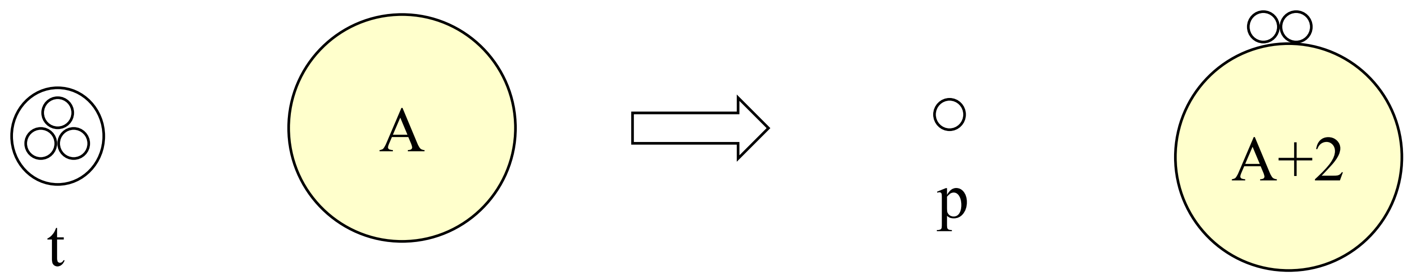
cf. A. Insolia, R.J. Liotta, and E. Maglione,
J. of Phhys. G15 ('89) 1249

→an open problem: need a new perspective

cf. (^{4}He,^{6}He) reaction@OEDO

A further additional issue

After all, a one-step pair transfer process is not dominant



Remarks

* 1-step and 2-step are terminologies based on perturbation theory
* a relative importance of each process depends also on the post form or the prior form formulations (a choice of H_0)

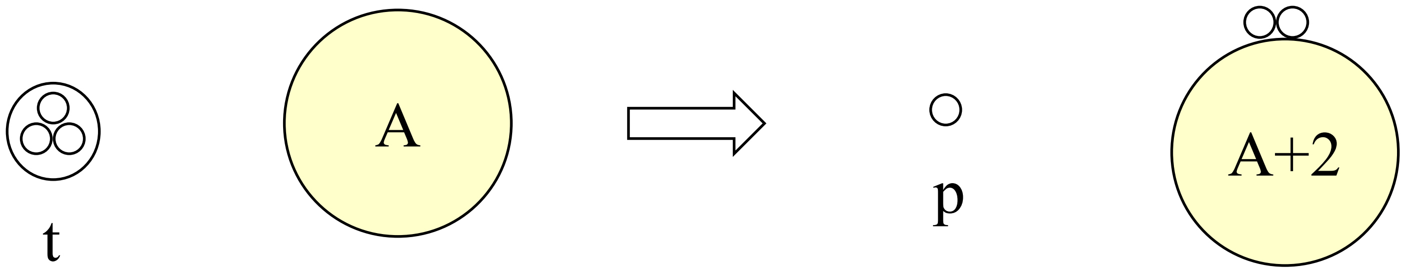
$$h = t + V_T(r) + V_P(r)$$

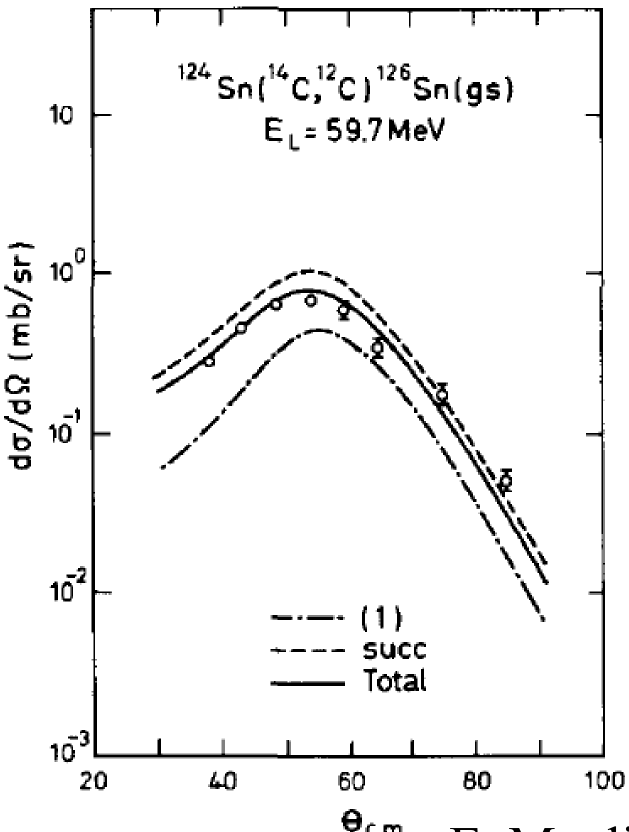
Broglia et al.,

$$a_{\rm tr} = a_{\rm sim} + a_{\rm succ} + a_{\rm non-orthog} \sim a_{\rm succ}$$
$$= \tilde{a}_{\rm sim} + \tilde{a}_{\rm succ} + \tilde{a}_{\rm non-orthog}$$

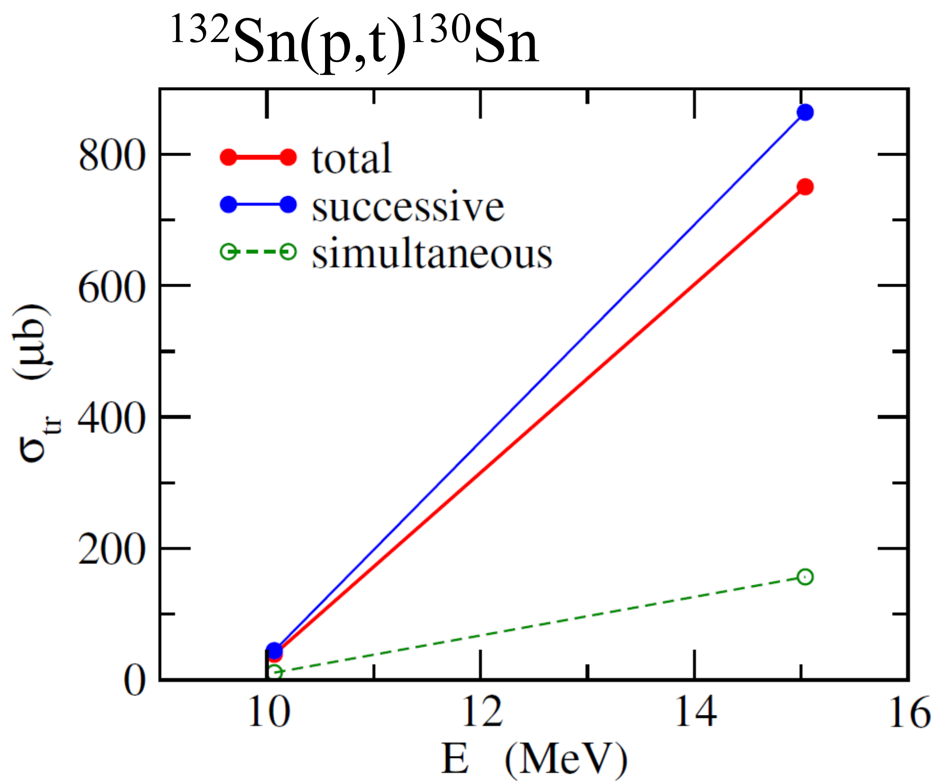
A further additional issue

After all, a one-step pair transfer process is not dominant





E. Maglione et al. PLB ('85)

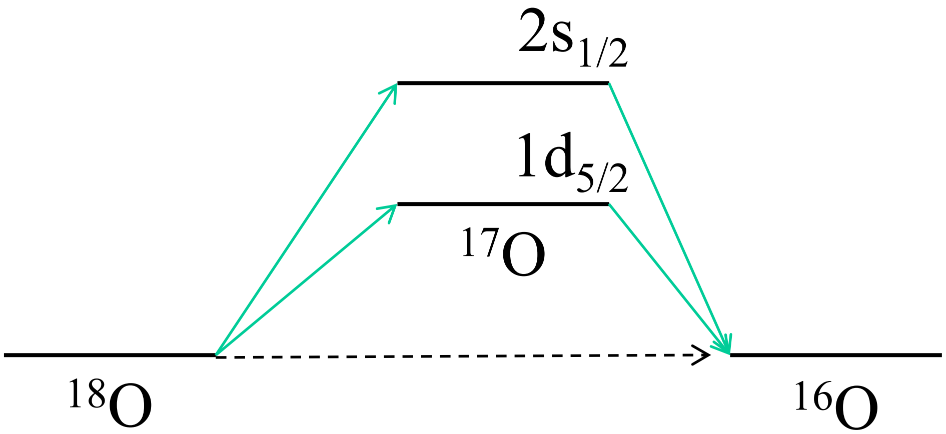


G. Potel et al., PRL ('11)

A further additional issue

After all, a one-step pair transfer process is not dominant

→the main process is a sequential 1n transfer



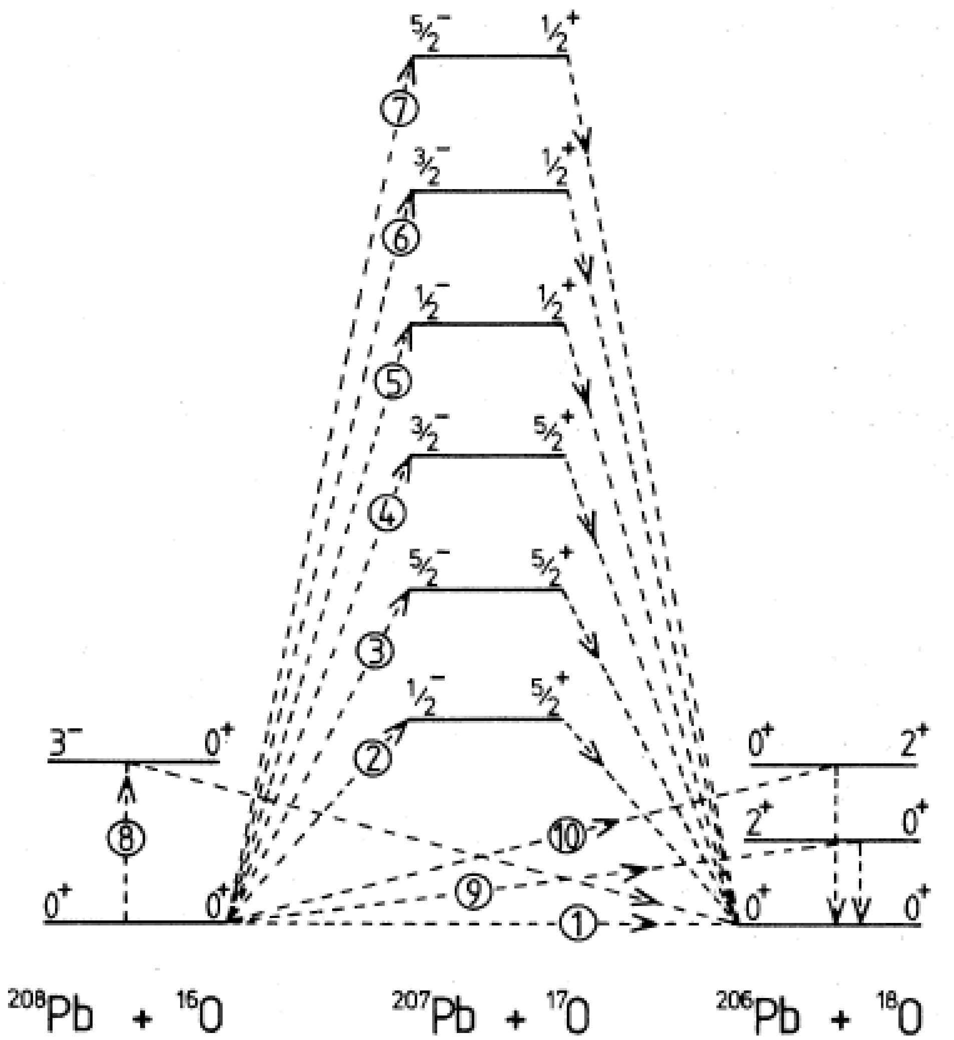
$0.8\ (1d_{5/2})^2$
$+0.6\ (2s_{1/2})^2$

pair correlation→a coherent superposition of many 1n transfer processes

* In reality, superfuidity in a target nucleus has also to be taken into account

dependence of incident energy? → still an open problem

A related problem: Pair transfer reactions of neutron-rich nuclei



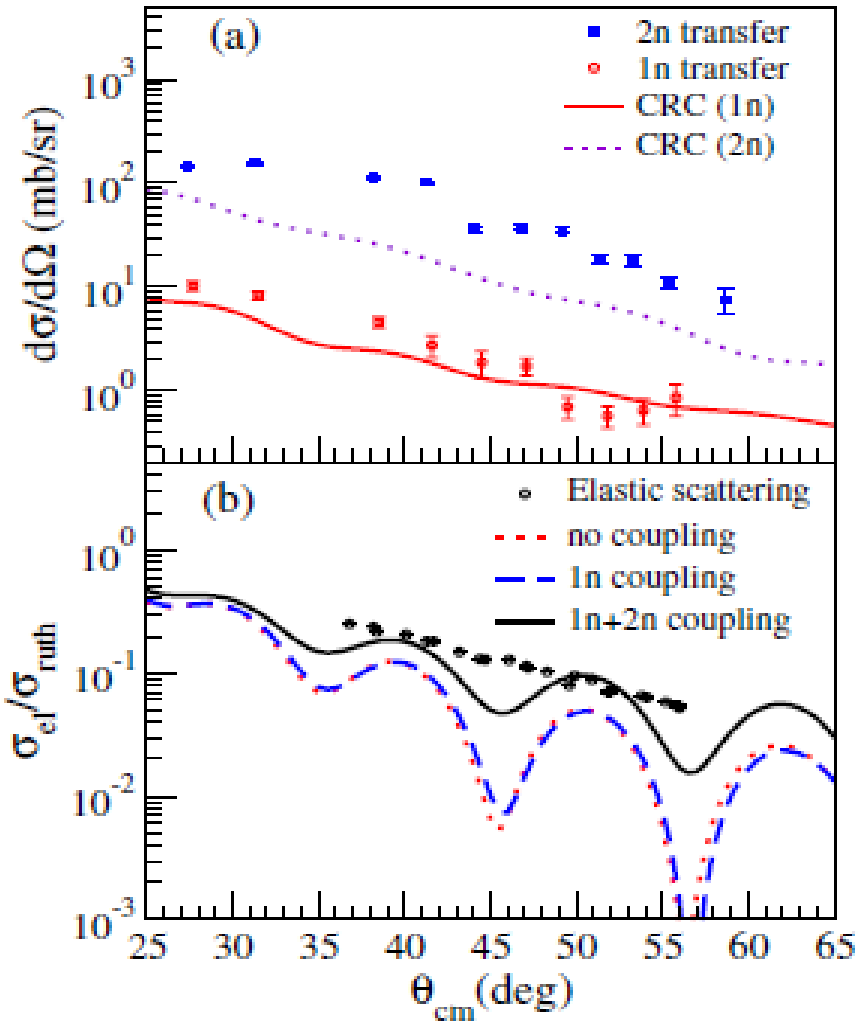
For neutron-rich nuclei, many intermediate states will be unbound

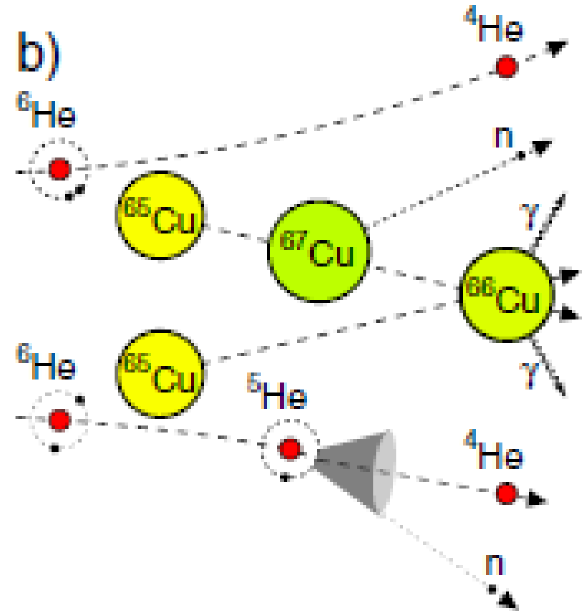
How much will the reaction dynamics be altered?

Another open problem

Pair transfer of Borromean nuclei (Expt.)

$^6He + ^{65}Cu$ (GANIL)





E_{lab} = 22.6 MeV

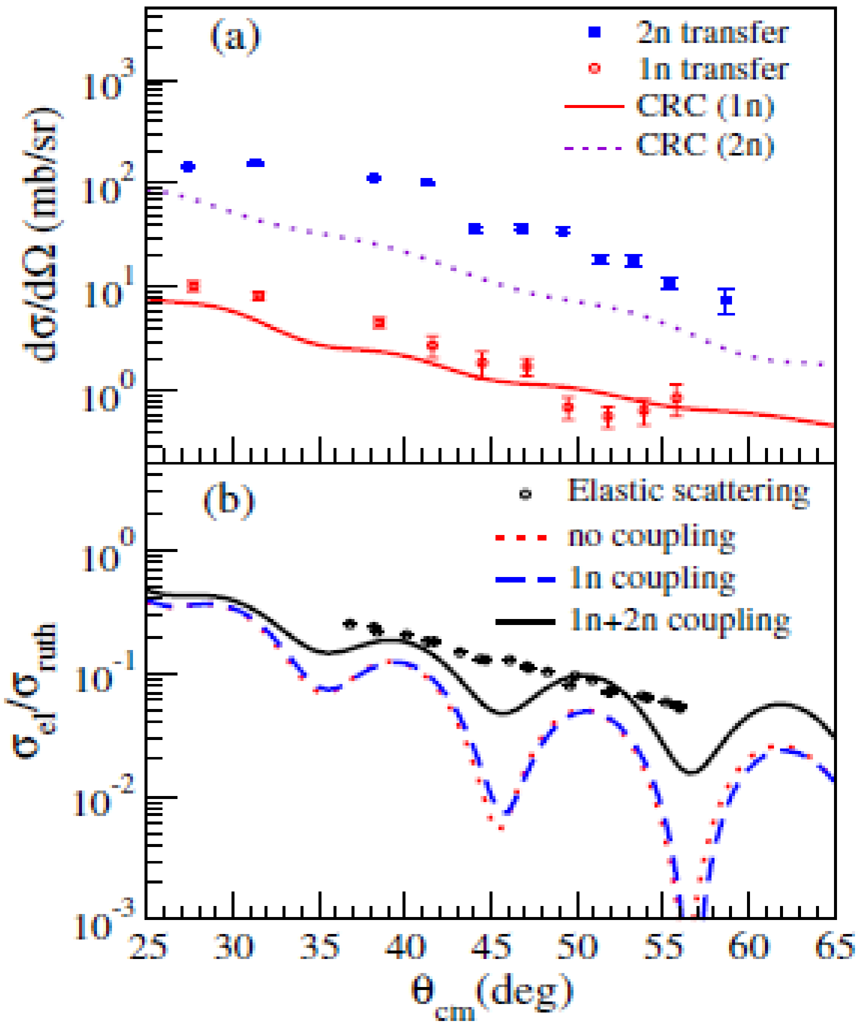
separation of *1n* and *2n* transfer from angular corr. between *n* and α (1*n* transfer: a strong correlation between *n* and α due to b.u. of ^{5}He)

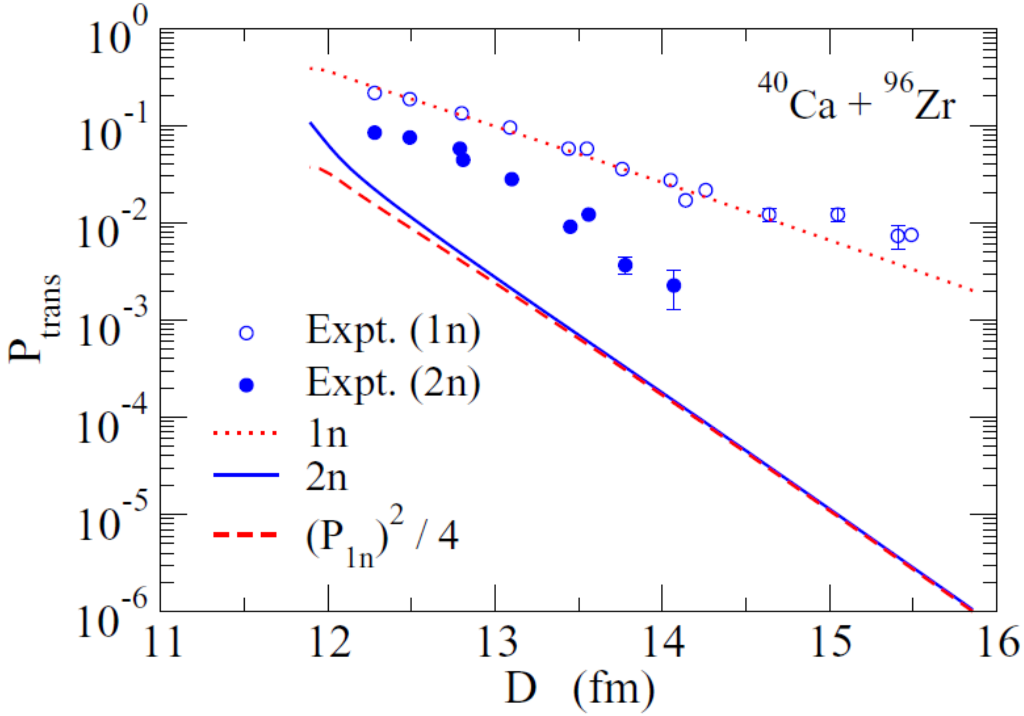
- larger 2*n* than 1*n*
- opposite to stable nuclei

A. Chatterjee et al., PRL101('08)032701

Pair transfer of Borromean nuclei (Expt.)

$^6He + ^{65}Cu$ (GANIL)





E_{lab} = 22.6 MeV

- larger 2*n* than 1*n*
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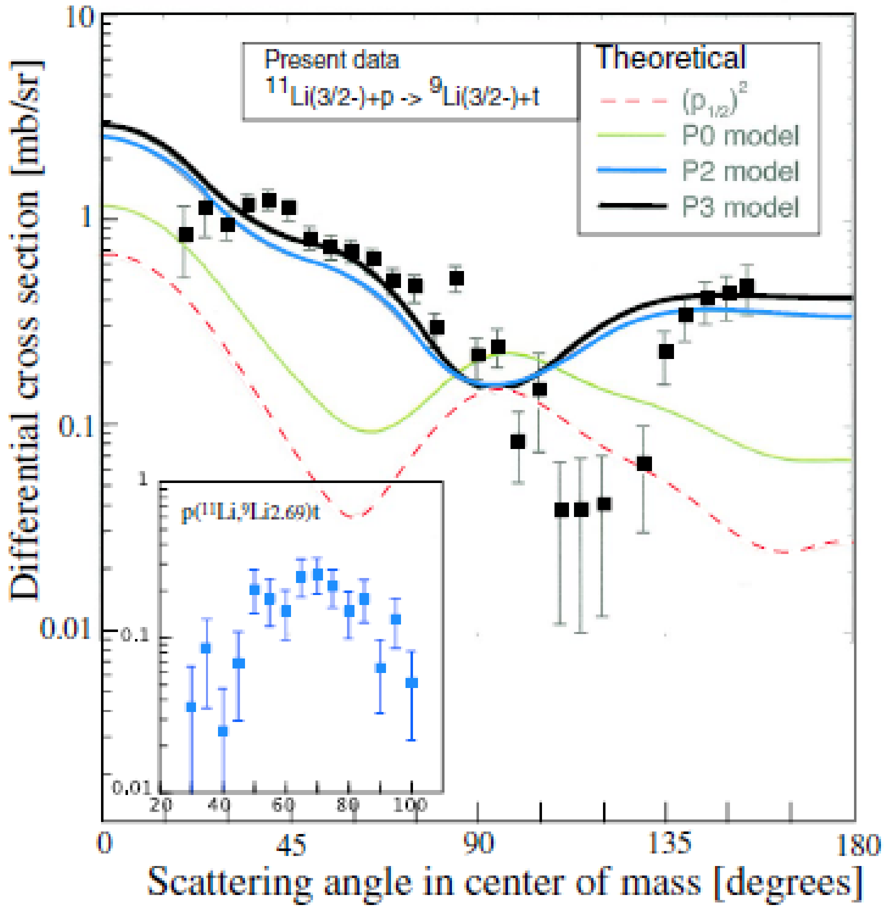
A. Chatterjee et al., PRL101('08)032701

Pair transfer of Borromean nuclei (Expt.)

$^1H(^{11}Li,^9Li)^3H$ (TRIUMF)



- Uncorrelated: not reproduce the data
- P2 (31% $(s_{1/2})^2$) and P3 (45%) reproduce the data at forward angles
- But not for backward angles (Opt. pot.? intermediate states?)

↑

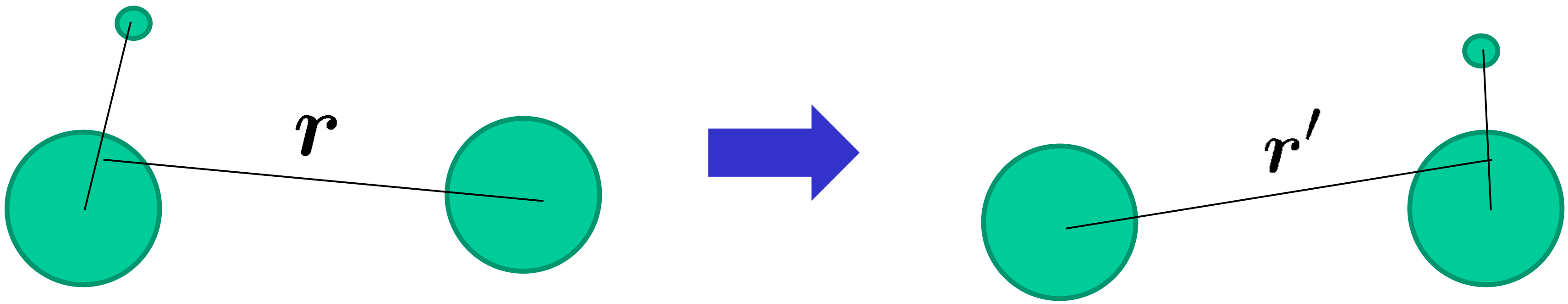
a treatment of ^{10}Li as intermediate states

E_{lab} = 3 MeV/A

I. Tanihata et al., PRL100('08)192502

Pair transfer reactions: a complicated reaction dynamics

1. Recoil effects



Dirrerent coordinate systems before and after transfer → non-local pot.

$$\left[-\frac{\hbar^2}{2\mu_1}\nabla^2 + V_1(r) - E\right]\psi_1(\boldsymbol{r}) + \int d\boldsymbol{r}' V_{\rm tr}(\boldsymbol{r},\boldsymbol{r}')\psi_2(\boldsymbol{r}') = 0$$

* For heavy-ion transfer reactions, no-recoil approximation works OK

2. Large number of channels

For each channel, a spectroscopic factor has to be considered

A large number of channels → Q-value distribution

An example of Q-value distribution

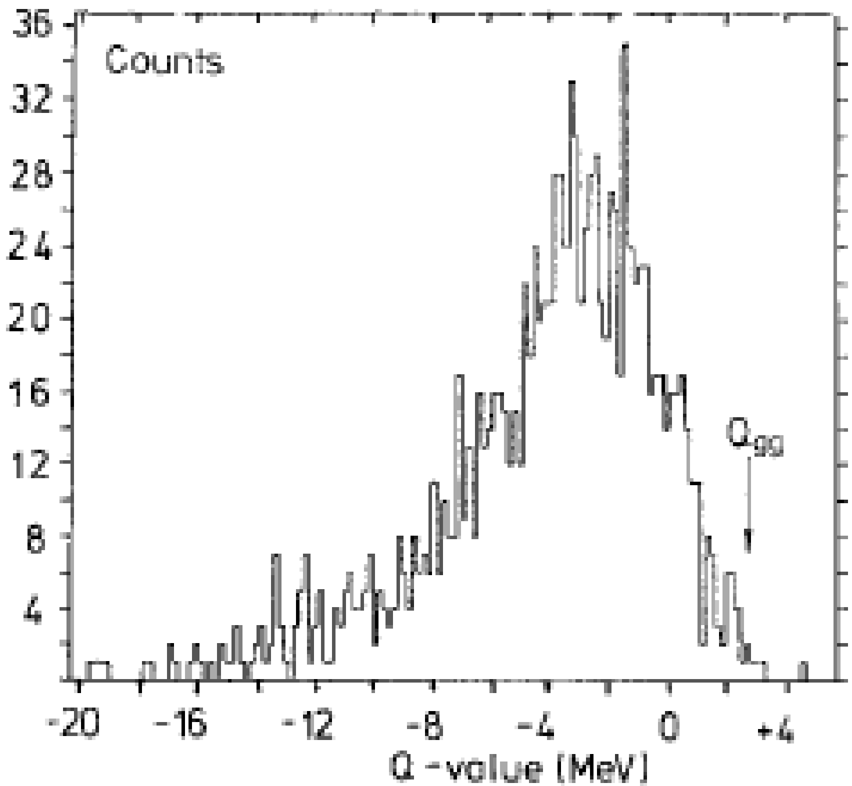
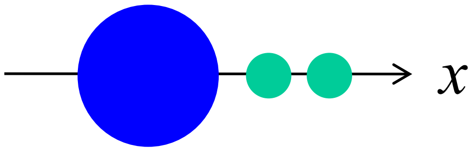


Fig. 6. *Q*-distribution for one angle of detection (85°) measured at 110.8 MeV for the one-neutron pickup reaction on ^{92}Zr. The *Q*-distributions for different angles agree within the limits of statistics

^{92}Zr(^{33}S, ^{34}S)^{91}Zr reaction

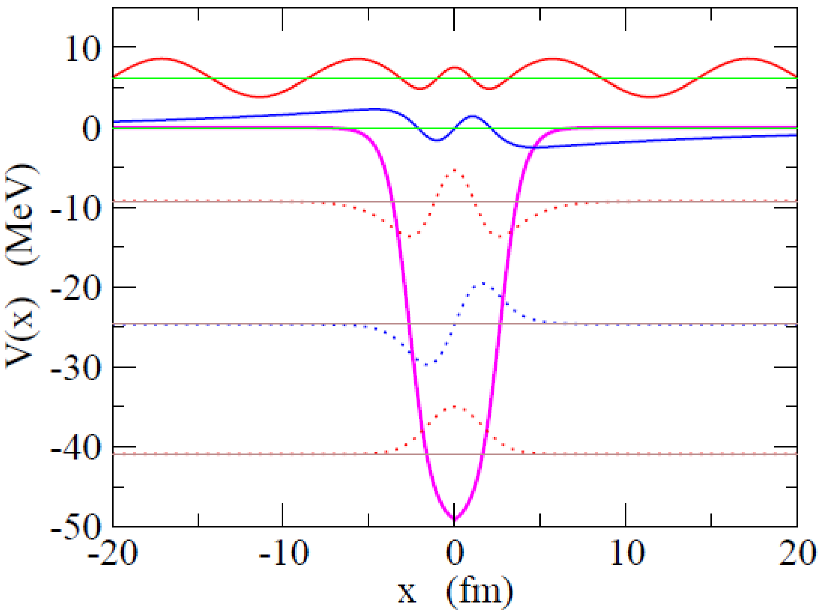
L. Corradi et al.,
Z. Phys. A334('90)55

Pair transfer reaction with a one-dimensional 3-body model



based on
K.H., A. Vitturi, F. Perez-Bernal,
and H. Sagawa, J. of Phys. G38 (‘11) 015105

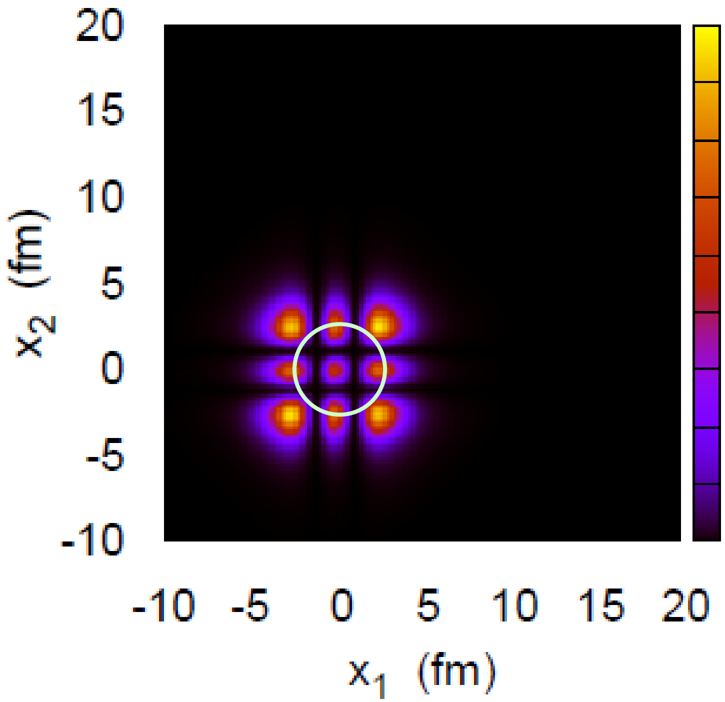
$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_1^2} + V(x_1) - \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_2^2} + V(x_2) + v_{nn}(x_1, x_2)$$

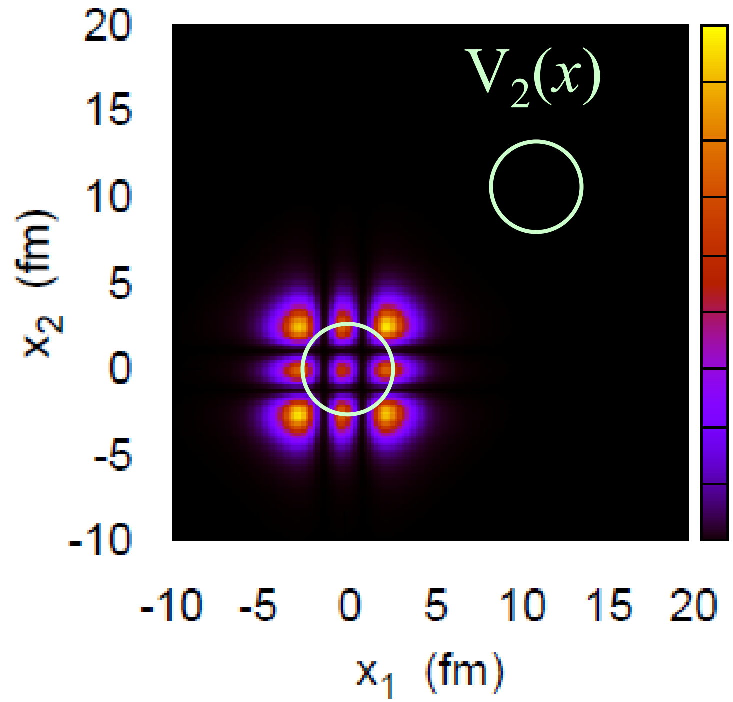


$$v_{nn}(x_1, x_2) = -g\left(\frac{V(\bar{x})}{V_0}\right)\delta(x_1 - x_2)$$

pairing correlation only
inside a nucleus

$$\rho(x_1, x_2) = |\Psi_{\mathrm{gs}}(x_1, x_2)|^2$$



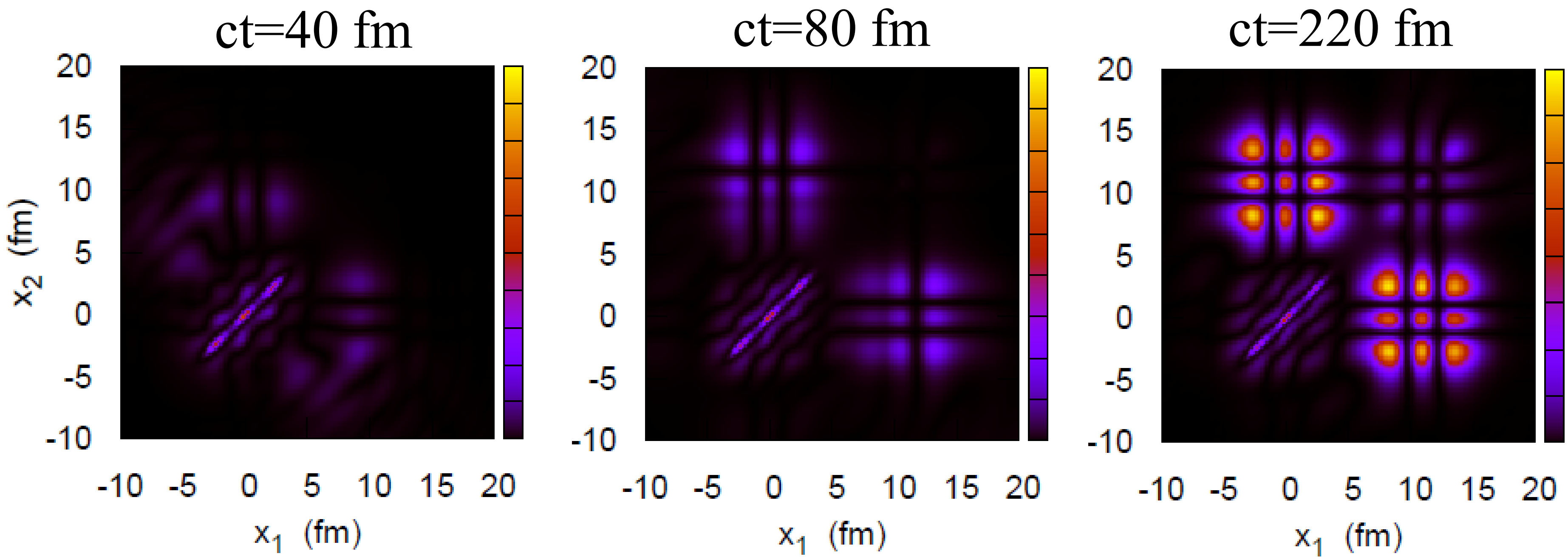


time-evolution

$$i\hbar \frac{\partial}{\partial t} \Psi(x_1, x_2, t) = H \Psi(x_1, x_2, t)$$

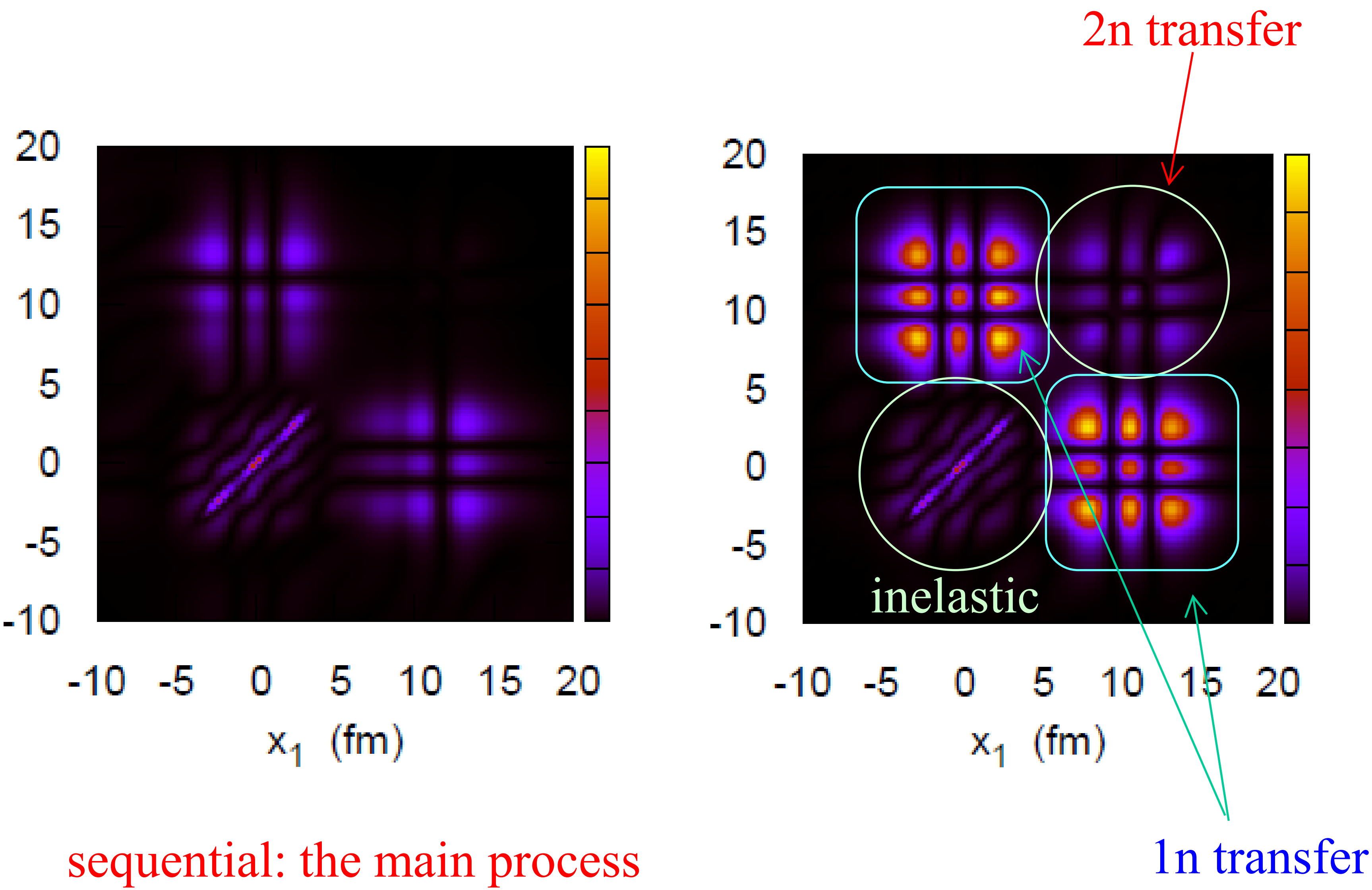
$$\Psi(x_1, x_2, t) = \alpha \Psi_{\rm gs}(x_1, x_2) + \tilde{\Psi}(x_1, x_2, t)$$

$$\rightarrow \tilde{\rho}(x_1, x_2, t) = |\tilde{\Psi}(x_1, x_2, t)|^2$$

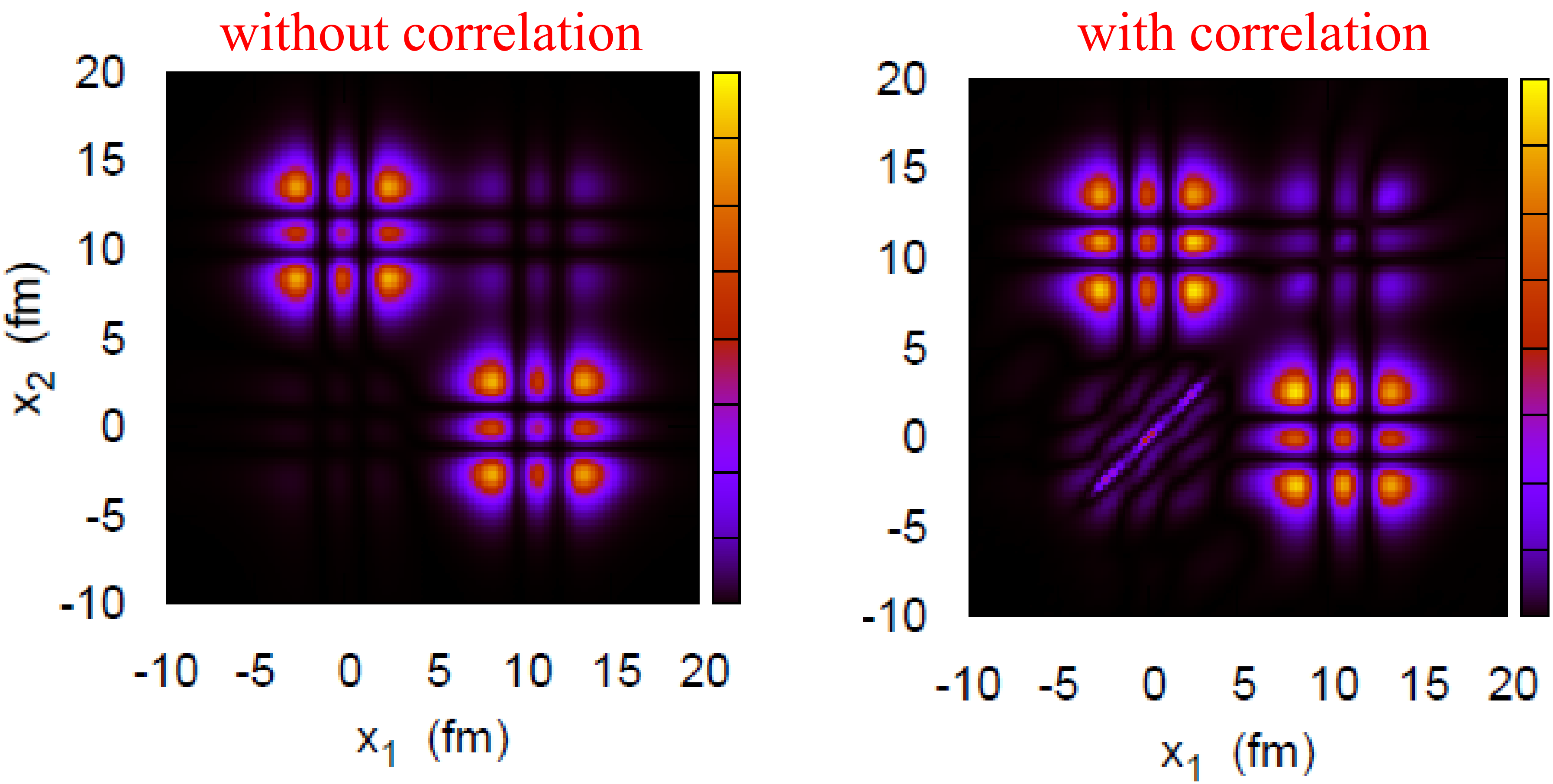


$$\Psi(x_1, x_2, t) = \alpha\Psi_{\rm gs}(x_1, x_2) + \tilde{\Psi}(x_1, x_2, t)$$

$$\rightarrow \tilde{\rho}(x_1, x_2, t) = |\tilde{\Psi}(x_1, x_2, t)|^2$$



ct=220 fm

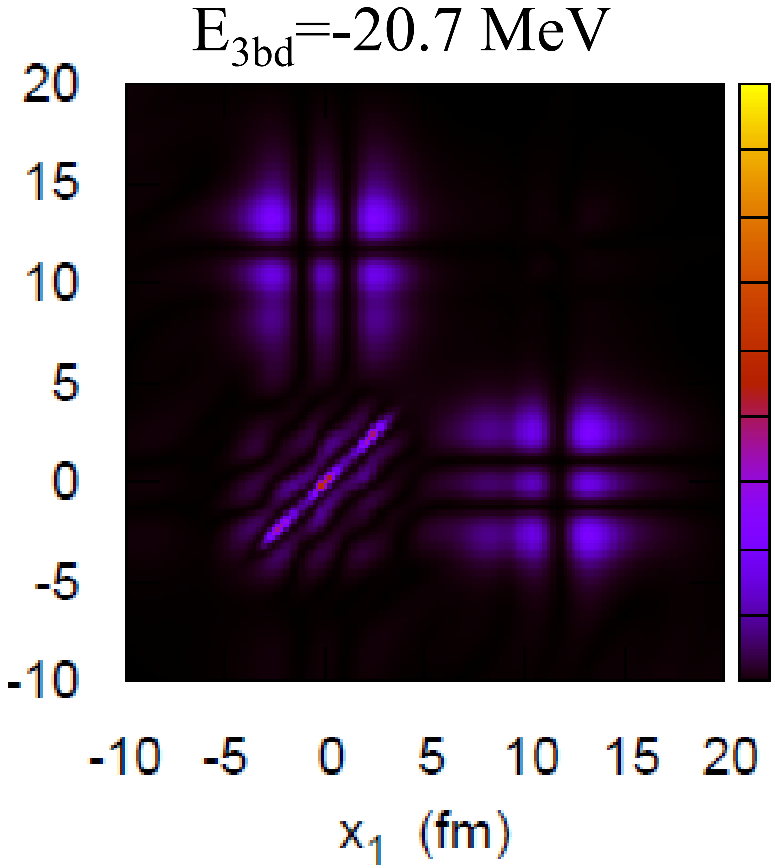


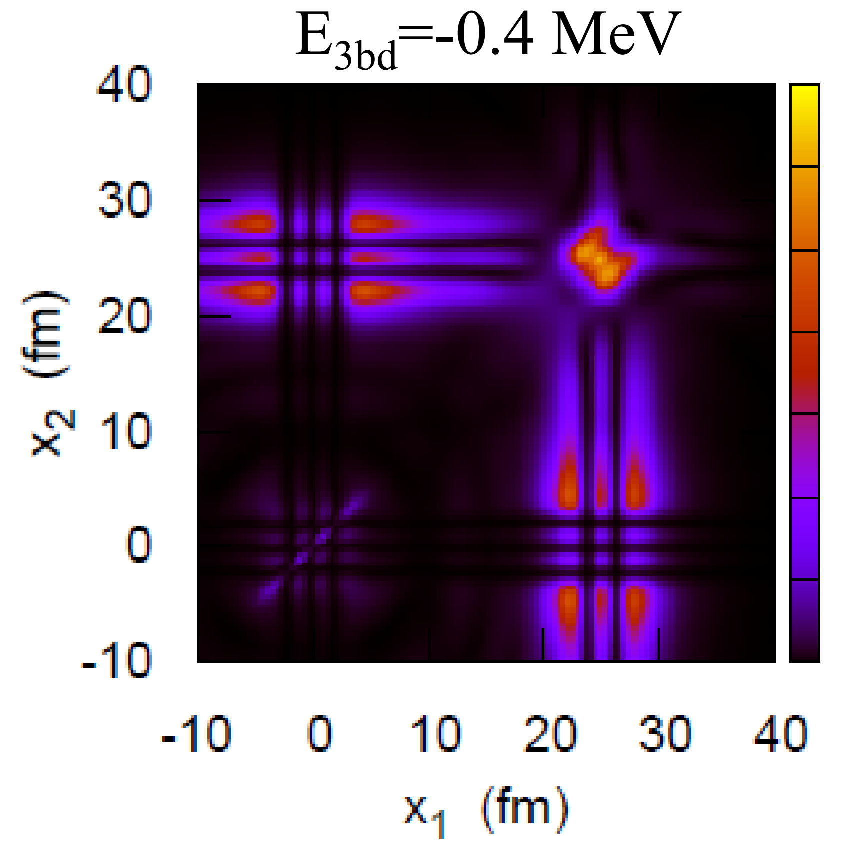
Due to correlations

- inelastic scattering
- 2n transfer reaction

are enhanced

ct=80 fm



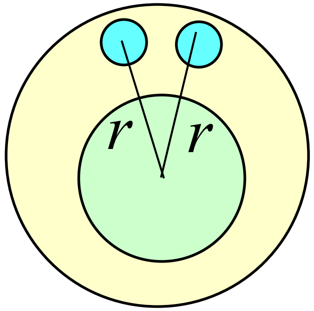


For weakly bound situation: $P_{2n} > P_{1n}$ (consistent with expt.)

Time-dep. approach: a good method to understand complicated pair transfer processes

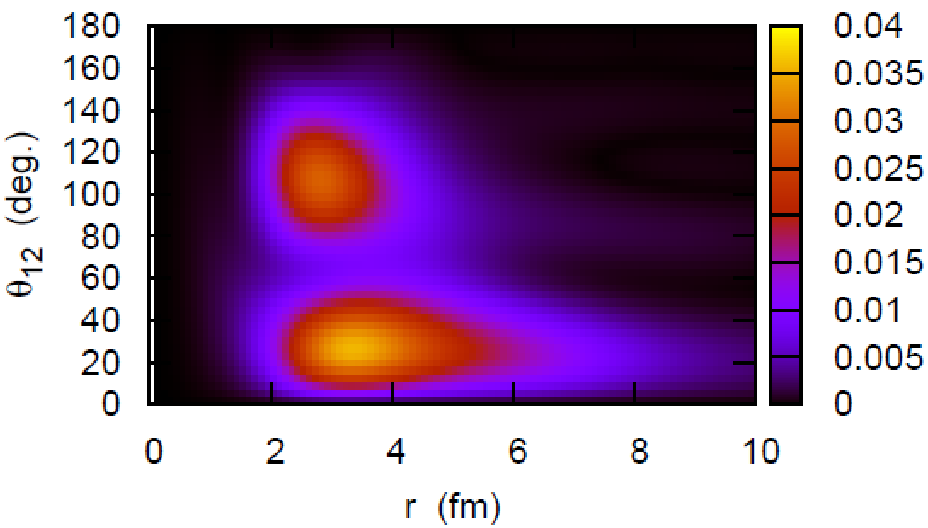
Future problesms: 3D calculations, dynamical calculations

T=1 np^{-1} correlation and a deuteron transfer

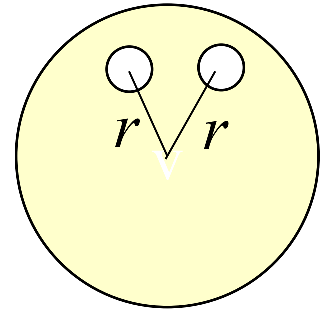


$^{11}Li = {}^{9}Li + n + n$

Di-neutron correlation

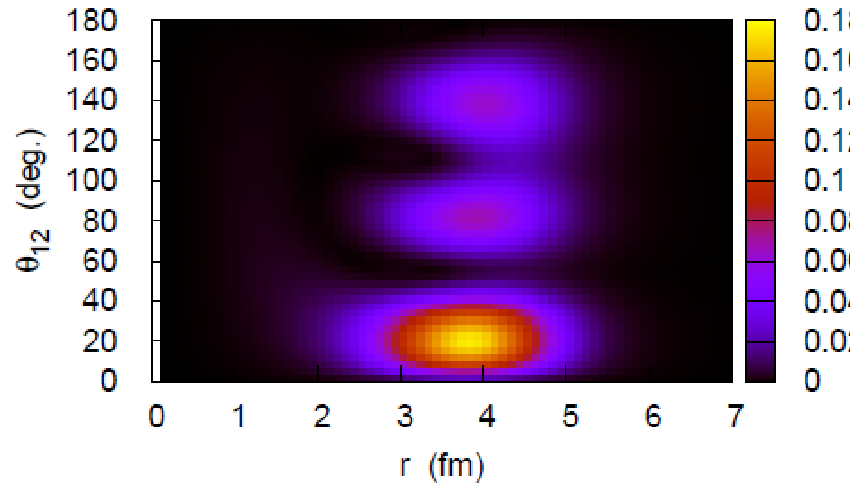


K.H. and H. Sagawa,
PRC72 (‘05) 044321



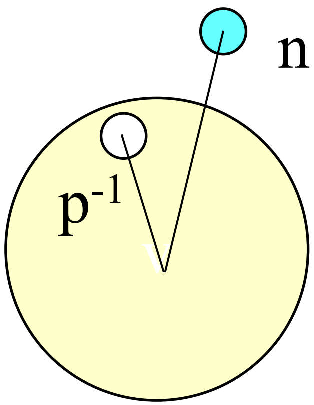
^{54}Fe (=^{56}Ni - 2p)

Di-hole correlation



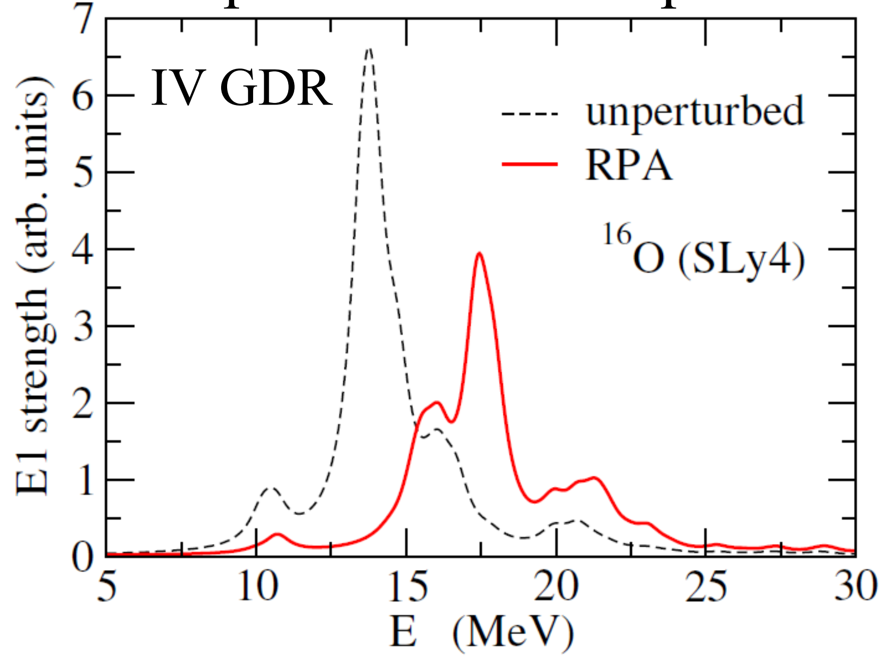
K.H. and H. Sagawa,
PRC106 (2022) 034313

T=1 np^{-1} correlation and a deuteron transfer

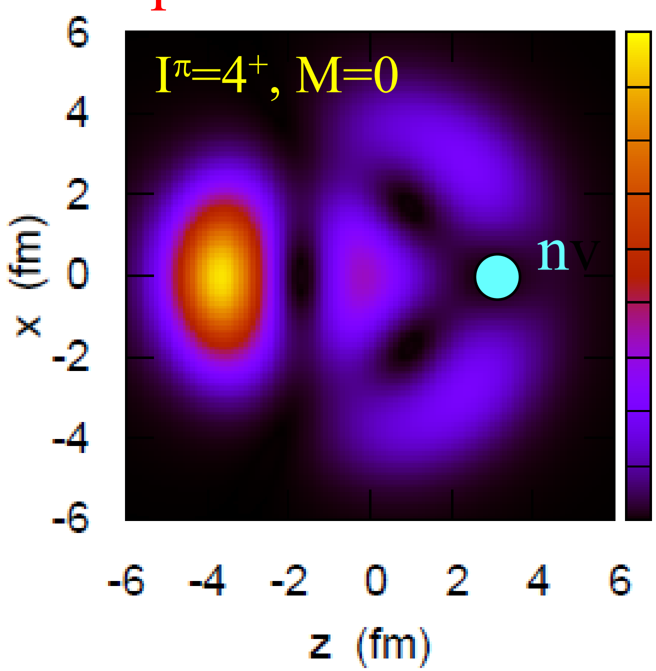


^{56}Co = ^{56}Ni + n - p

T=1 ph interaction: repulsive



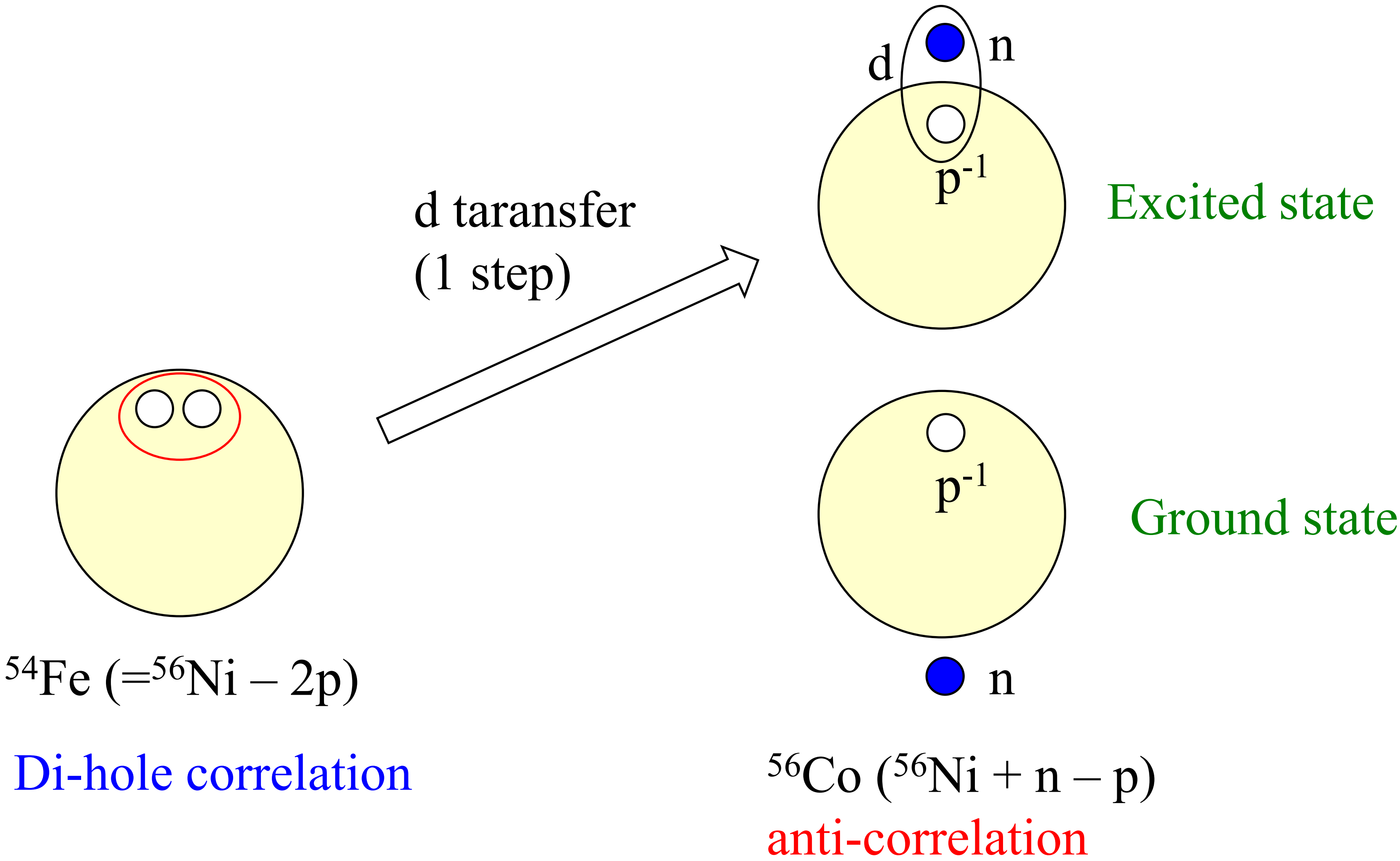
spatial distribution of
a proton hole



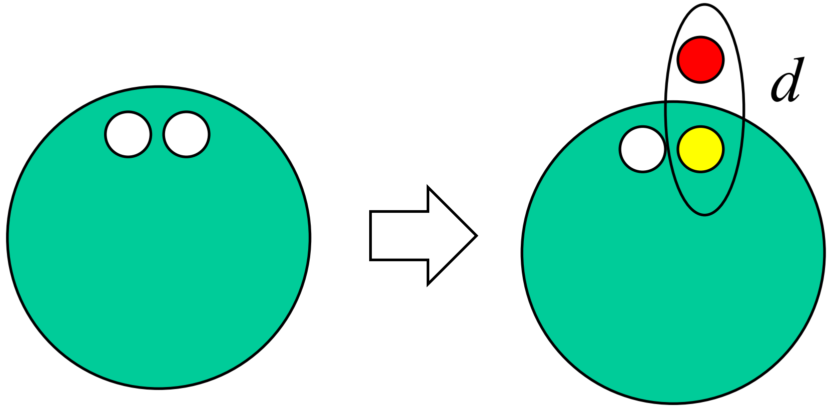
Skyrme TDA (SLy4)

$$|^{56}\mathrm{Co}\rangle = \sum_{p,h} C_{ph}\, a^\dagger_{\nu p} a_{\pi h}\, |^{56}\mathrm{Ni}\rangle$$

K.H. and H. Sagawa,
PRC106 (2022) 034313

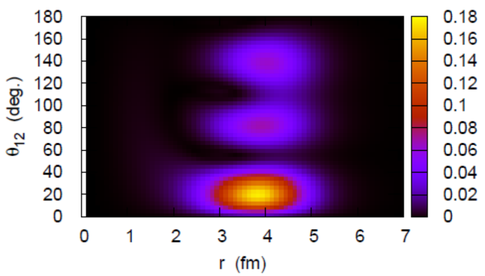


G.F. Bertsch,
Phys. Lett. 25B ('67) 62



^{54}Fe (=^{56}Ni – 2p)

^{56}Co



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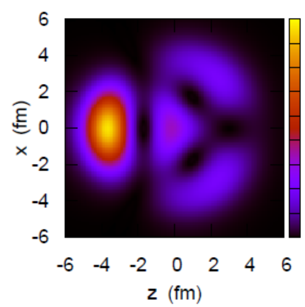
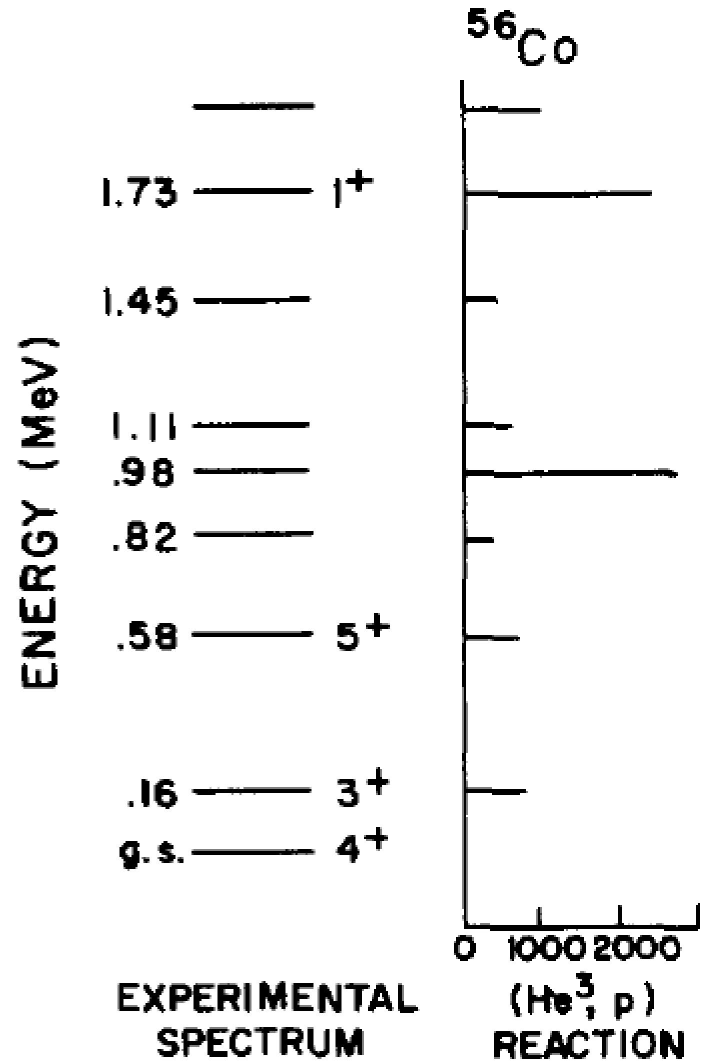
Excited state



suppression of g.s. transfer to ^{56}Co



Exp. data

- Data: appears consistent with this picture
- Contribution of 2-step process?

→ an open issue

G.F. Bertsch,
Phys. Lett. 25B ('67) 62

Summary

- Two-neutron transfer reactions: *sensitive* to the pair correlation
  - ✓ But, not straightforward to extract the pair correlation

➡ Open issue: how to sharply extract info. on pair correlation?

- Reaction mechanism→ 2-step DWBA
  - Treatments of intermediate states
  - Especially continuum states ← neutron-rich nuclei

Time-dependent approach: maybe a good alternative

necessary to extend from 1D to 3D

- T=1 np^{-1}correlation and a deuteron transfer

1 step process: a suppression of g.s. tranfer

→how will this picture be altered if 2-step is taken into account?

Complex reaction dynamics: a more systematic study will be needed in connection to neutron-rich nuclei