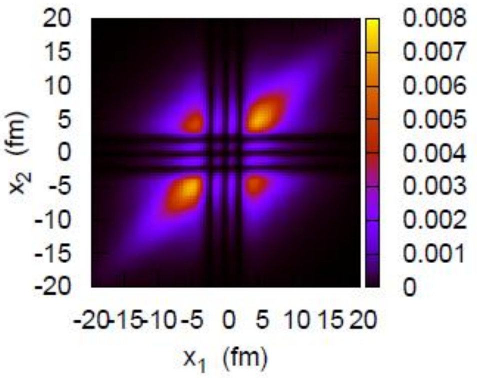
# Two-neutron halo nuclei in one dimension
# - dineutron correlation and breakup reaction -





**K. Hagino (Tohoku University)**
A. Vitturi (Padova)
F. Perez-Bernal (Huelva)
H. Sagawa (University of Aizu)


1. *Three-body model for $^{11}$Li and $^{6}$He:*
   *Borromean nuclei and Di-neutron correlation*
2. *One dimensional model*
   - *Ground state properties*
   - *Nuclear breakup process*
3. *Summary*

# Borromean nuclei and Di-neutron correlation

Borromean nuclei: unique three-body systems

Three-body model calculations:

strong di-neutron correlation
in $^{11}$Li and $^{6}$He

$x^2y^2\,\rho_2(x,y)$ for $^6$He

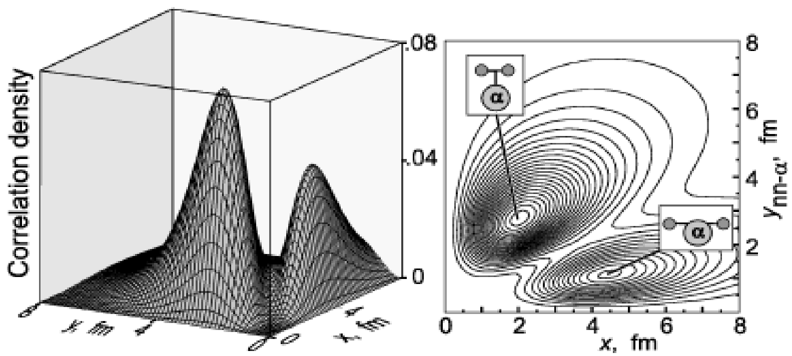
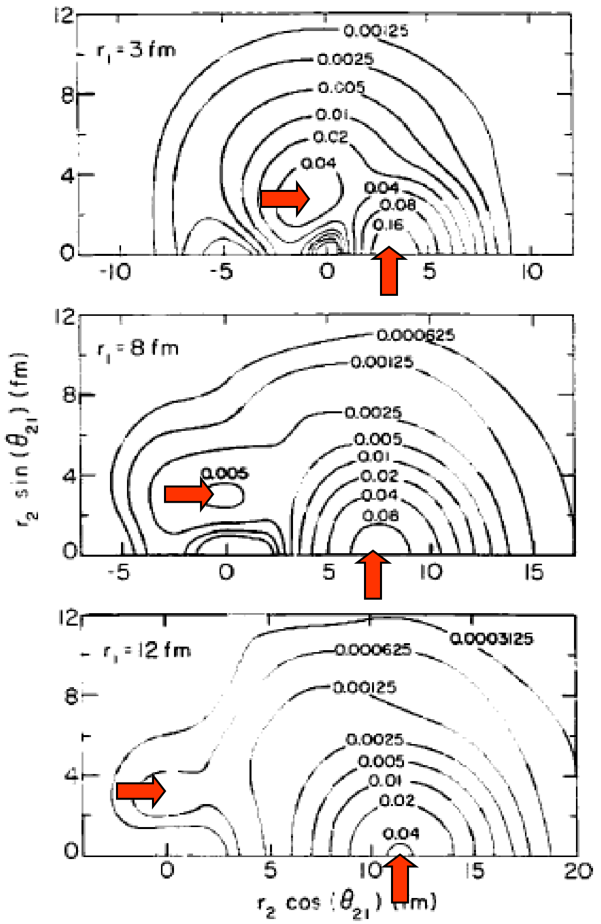


FIG. 1. Spatial correlation density plot for the $0^+$ ground state of $^6$He. Two components—di-neutron and cigarlike—are shown schematically.

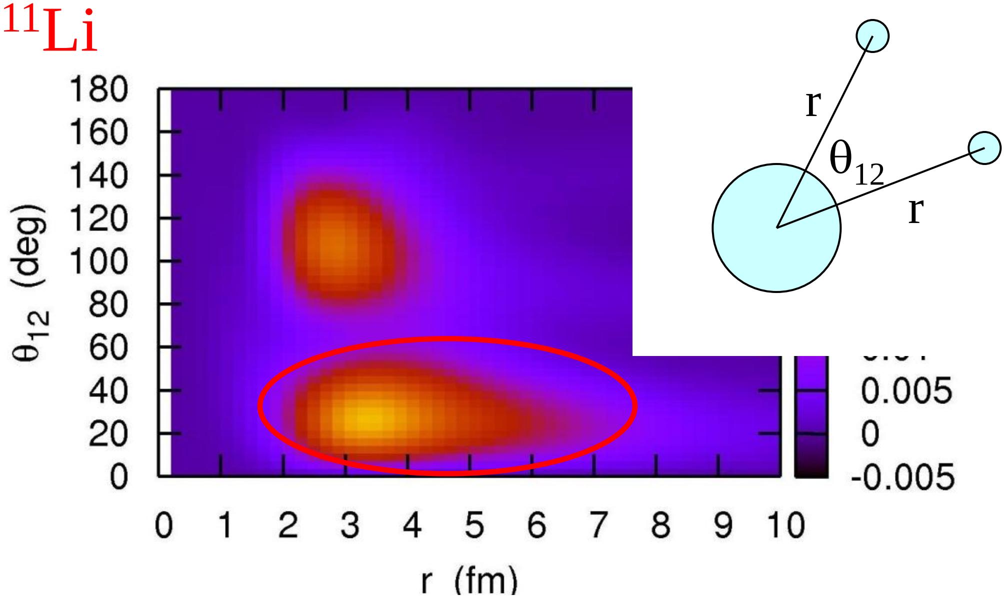
Yu.Ts. Oganessian, V.I. Zagrebaev,
and J.S. Vaagen, *PRL82('99)4996*
M.V. Zhukov et al., *Phys. Rep. 231('93)151*

$\rho_2(r_1, r_2, \theta_{12})$ for $^{11}$Li

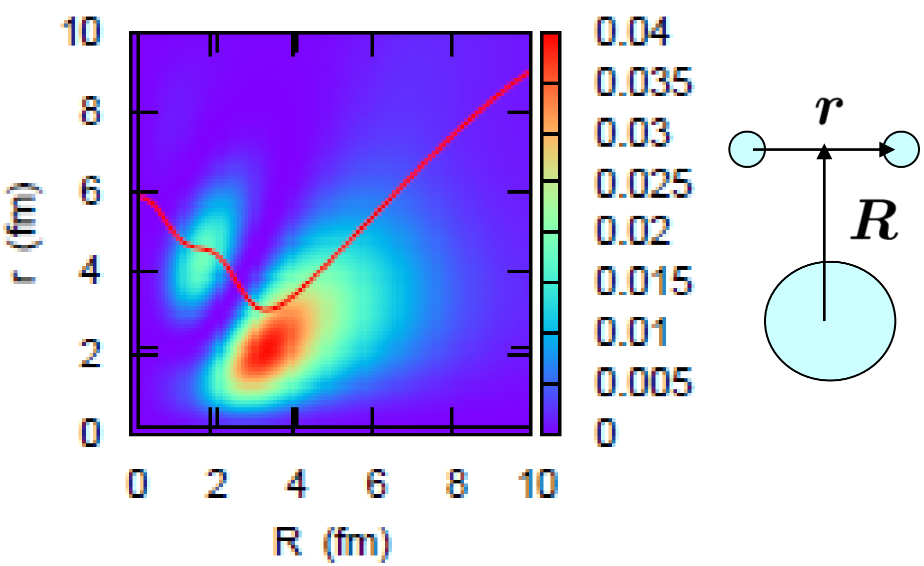



G.F. Bertsch, H. Esbensen,
*Ann. of Phys., 209('91)327*

$^{11}Li$

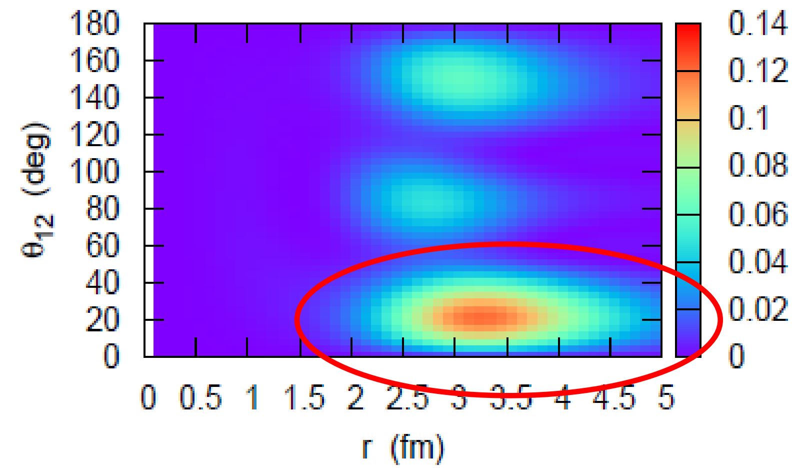



K.Hagino and H. Sagawa, PRC72('05)044321




K.Hagino, H. Sagawa, and P. Schuck,
J. of Phys. G37('10) 064040.

cf. di-*proton* correlation
in $^{17}Ne = {}^{15}O + p + p$

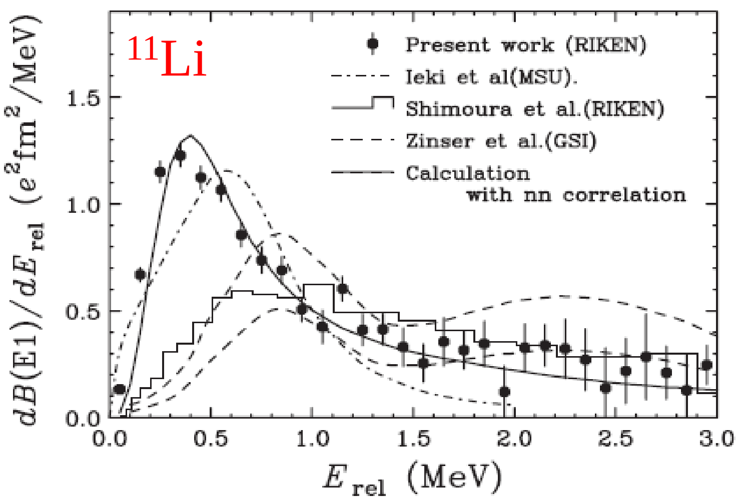



T. Oishi, K. Hagino, and
H. Sagawa, PRC82('10)024315.

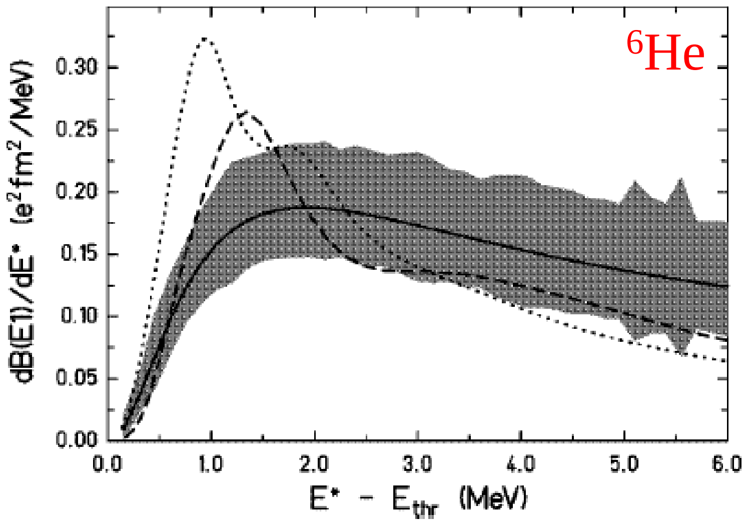
# Remaining problem:

## How to probe the strong dineutron correlation?

- Coulomb excitations?




T. Nakamura et al., PRL96('06)252502



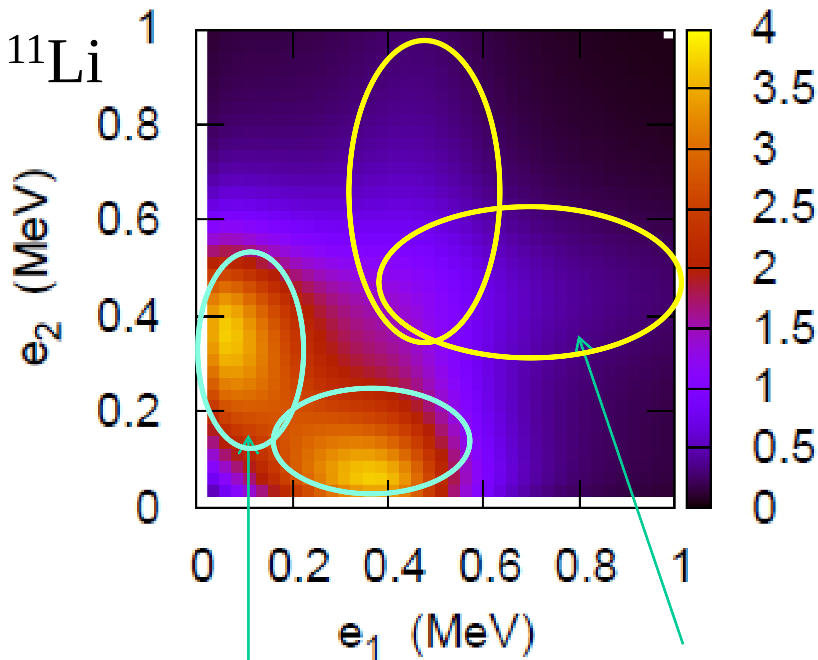

T. Aumann et al., PRC59('99)1252

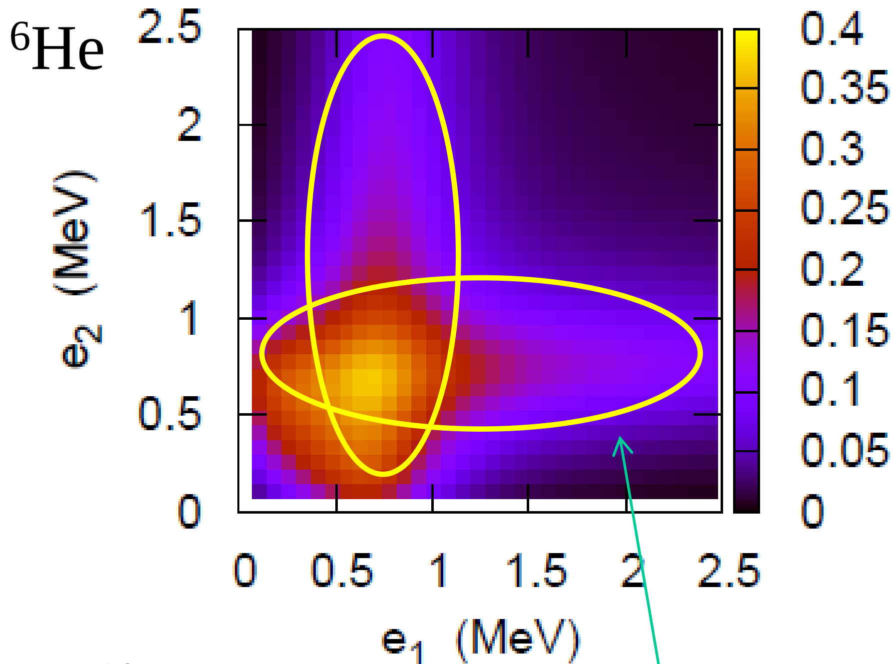
* (indirect) evidence for dineutron correlation

Remaining problem:

**How to probe the strong dineutron correlation?**

- Coulomb excitations? ⟶ A problem: an external field is too weak




s-wave virtual state in $^{10}$Li

$p_{1/2}$ resonance in $^{10}$Li at 0.54 MeV

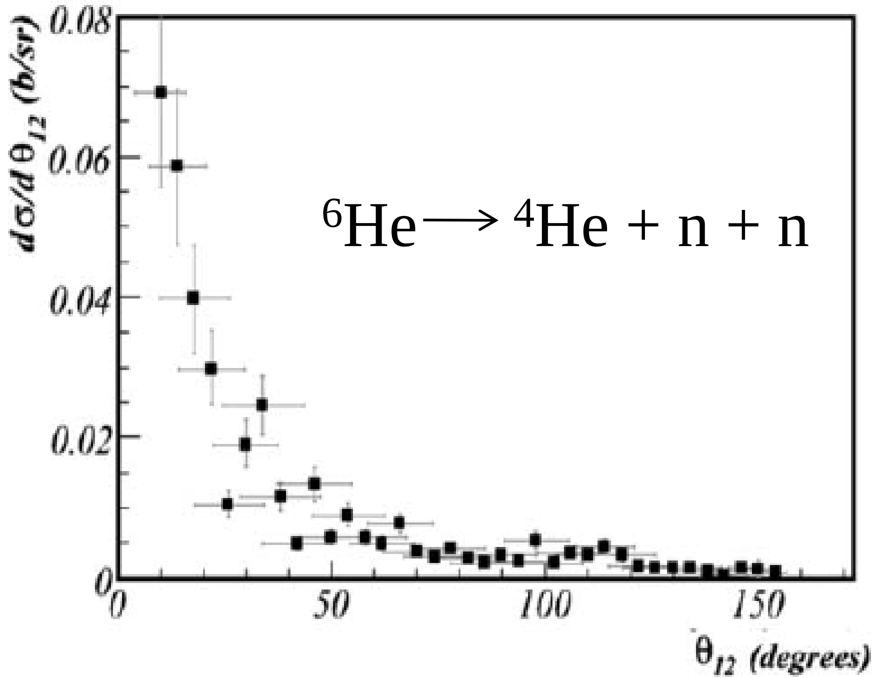
$p_{3/2}$ resonance for $^{5}$He at 0.91 MeV

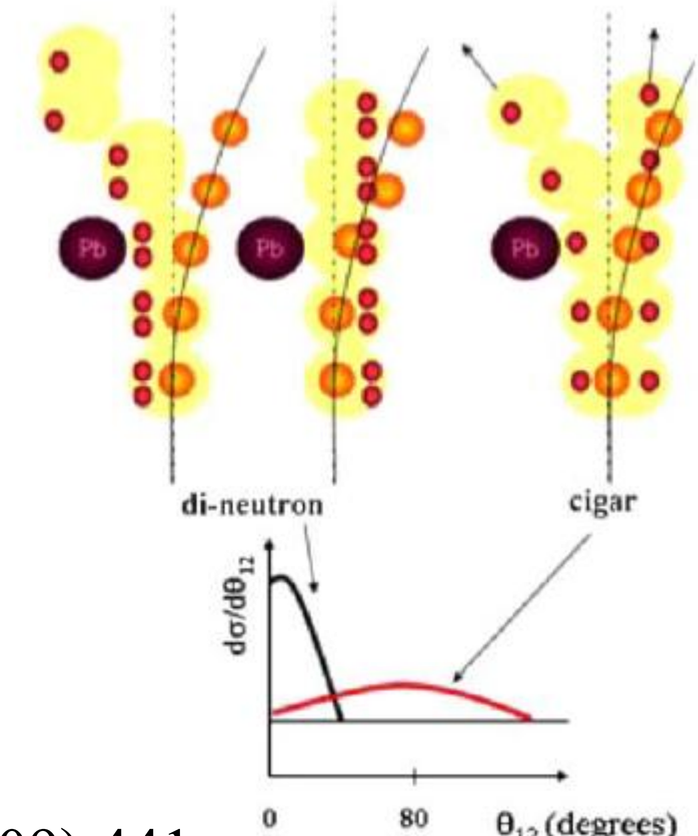
K.H., H. Sagawa, T. Nakamura, S. Shimoura, PRC80('09)031301(R)

Remaining problem:

**How to probe the strong dineutron correlation?**

- Coulomb excitations?
- Nuclear breakup?




M. Assie et al., Eur. Phys. J. A42 ('09) 441

cf. 4-body CDCC for exclusive cross sections?

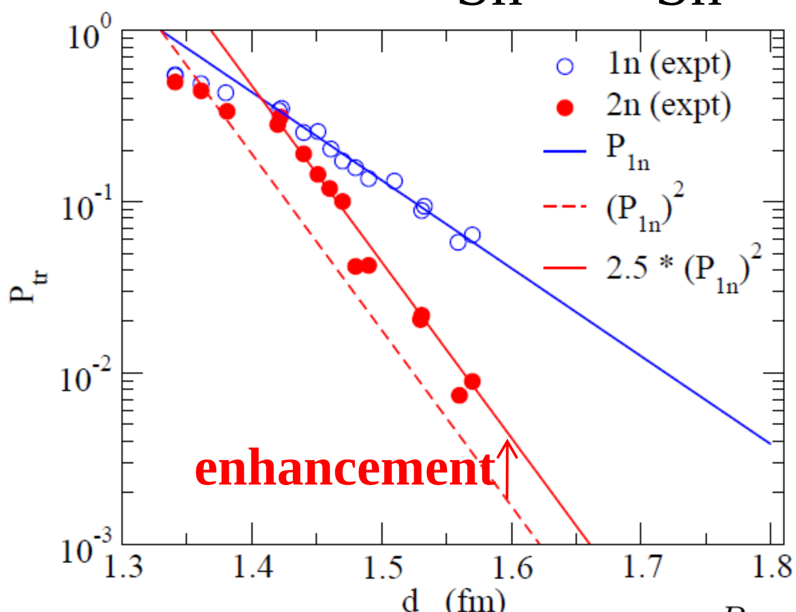
Remaining problem:

**How to probe the strong dineutron correlation?**

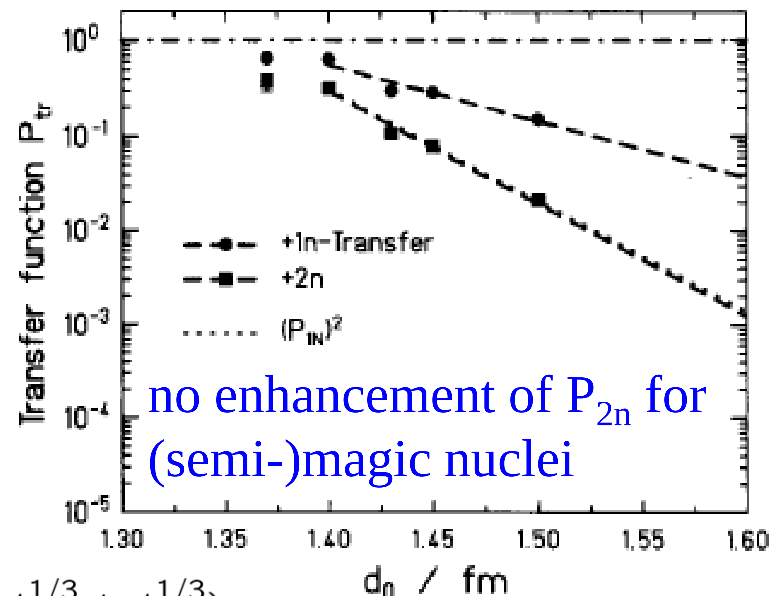
- Coulomb excitations?
- Nuclear breakup?

- Pair transfer?

$^{112}Sn + ^{120}Sn$




$^{144}Sm + ^{208}Pb$




$$R_{\rm min} = d\,(A_P^{1/3} + A_T^{1/3})$$

W. von Oertzen et al., Z. Phys. A326('87)463

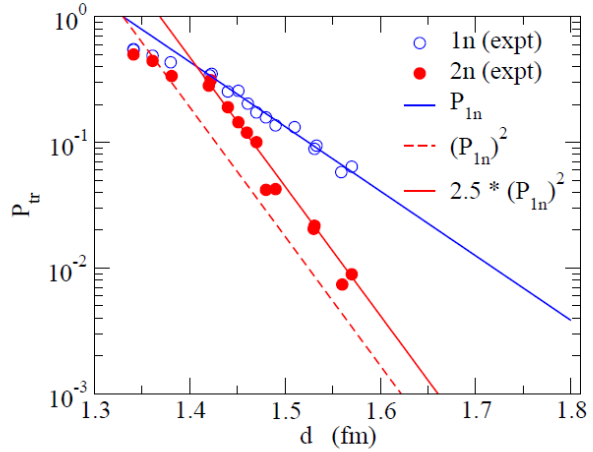
J. Speer et al., PLB259('91)422

Remaining problem:

## How to probe the strong dineutron correlation?

- Coulomb excitations?
- Nuclear breakup?

- Pair transfer?




✓**Reaction mechanism?**

- sequential vs simultaneous
- Q-value, angular momentum matchings

✓Role of dineutron correlation (on the surface)?

✓Influence to other reaction processes (e.g., subbarrier fusion)?

have not yet been fully clarified

# example of 2n transfer calculation

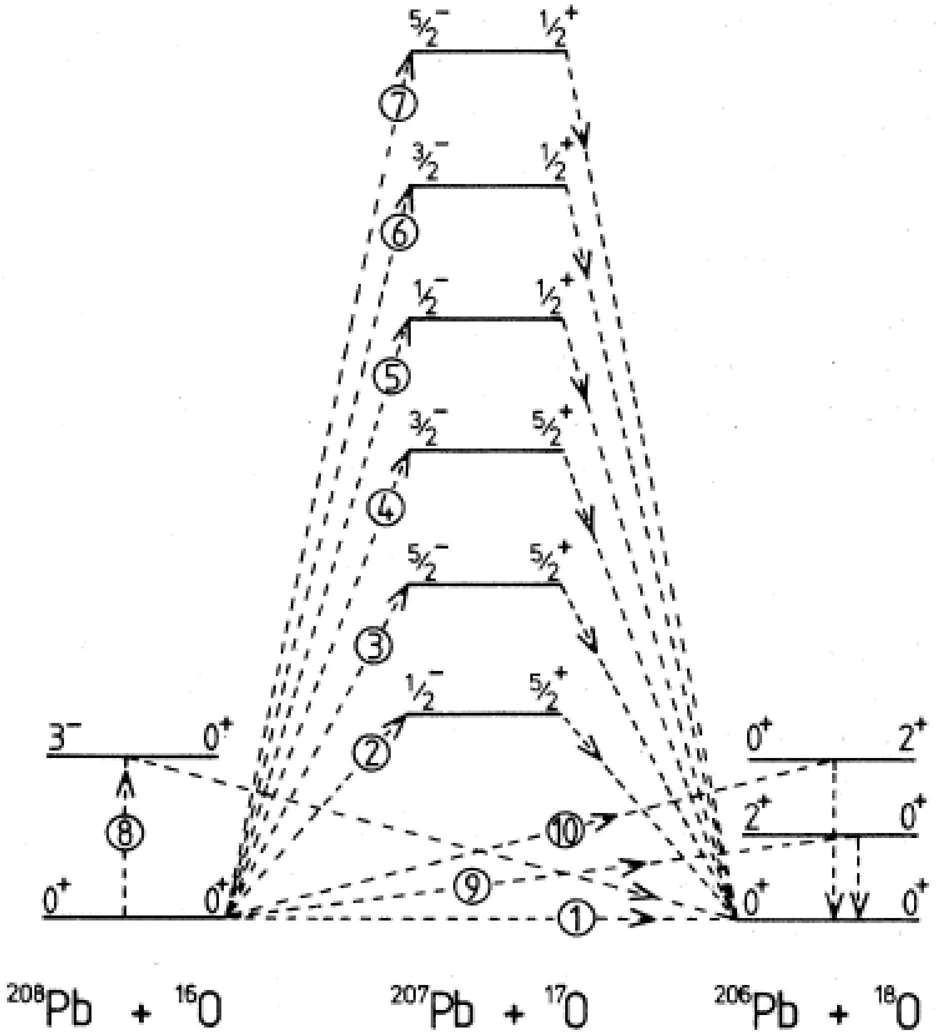
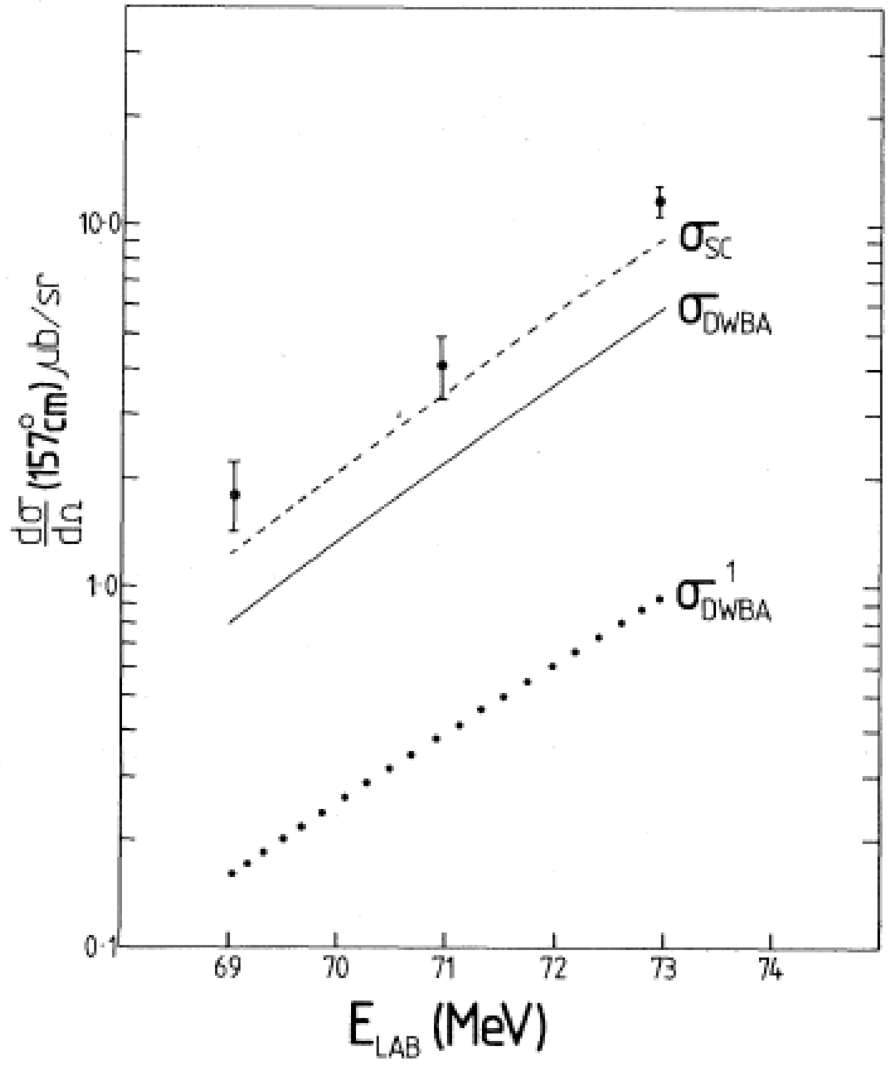



FIG. 2. The direct and two-step paths considered in the predictions of the cross section for the reaction $^{208}$Pb($^{16}$O, $^{18}$O)$^{206}$Pb. The levels in $^{207}$Pb and $^{17}$O concerned in the sequential transfer paths are the $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ single-hole states and the $d_{5/2}$ and $s_{1/2}$ single-particle states, respectively.

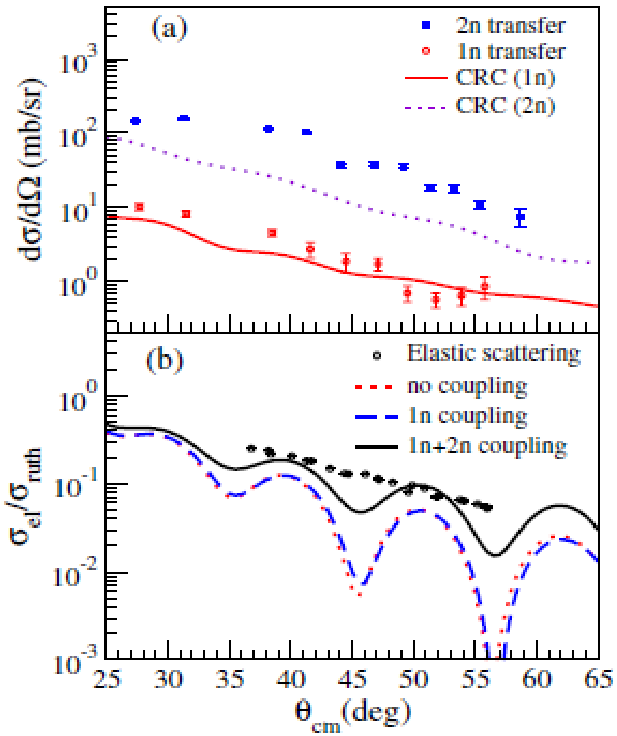



M.A. Franey et al., PRL41('78)837

**effects of unbound intermediate states?**

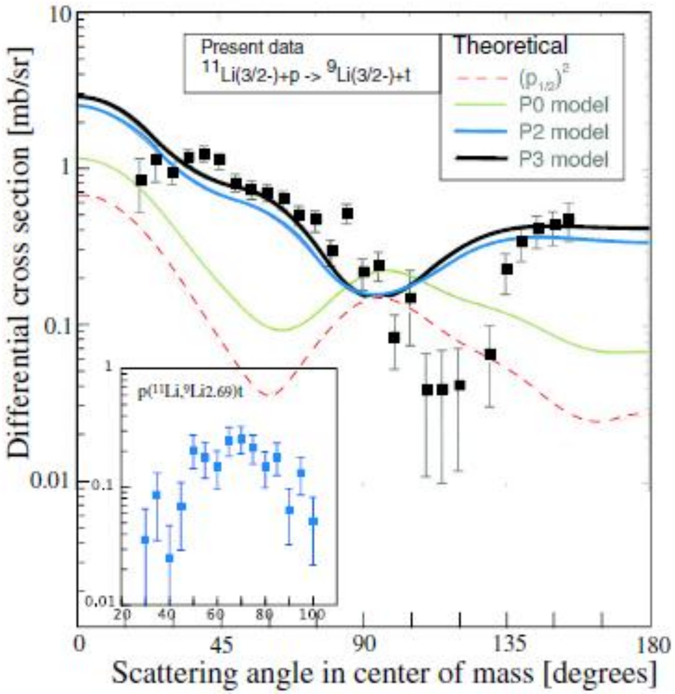
# Recent experiments for transfer reaction of neutron-rich nuclei

$^{6}$He + $^{65}$Cu




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

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




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

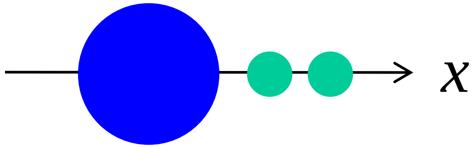
It is timely to construct:

a new theory of pair transfer with dineutron correlation.

⟶ need a deep understanding of reaction dynamics

➡ a simple and intuitive schematic model

# One-dimensional three-body model

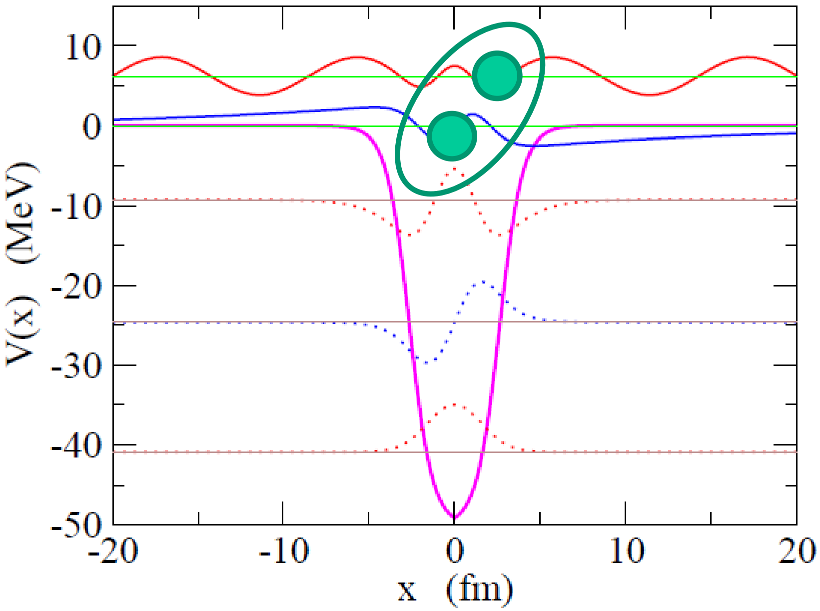



Two interacting neutrons in a one-dimensional potential well:

$$H = -\frac{\hbar^2}{2m}\frac{d^2}{dx_1^2} + V(x_1) - \frac{\hbar^2}{2m}\frac{d^2}{dx_2^2} + V(x_2) + v_{nn}(x_1, x_2)$$

density-dependent contact interaction:

$$v_{nn}(x, x') = -g\left(1 - \frac{1}{1 + e^{(|x|-R)/a}}\right)\delta(x - x')$$




$$\Psi_{gs}(x_1, x_2) = \sum_{n \leq n'} \alpha_{nn'}\Psi_{nn'}(x_1, x_2)$$

$$\Psi_{nn'}(x_1, x_2) \propto \mathcal{S}[\phi_n(x_1)\phi_{n'}(x_2)] \times |S = 0\rangle$$

•$S = 0$ state: symmetric for the spatial part of wf

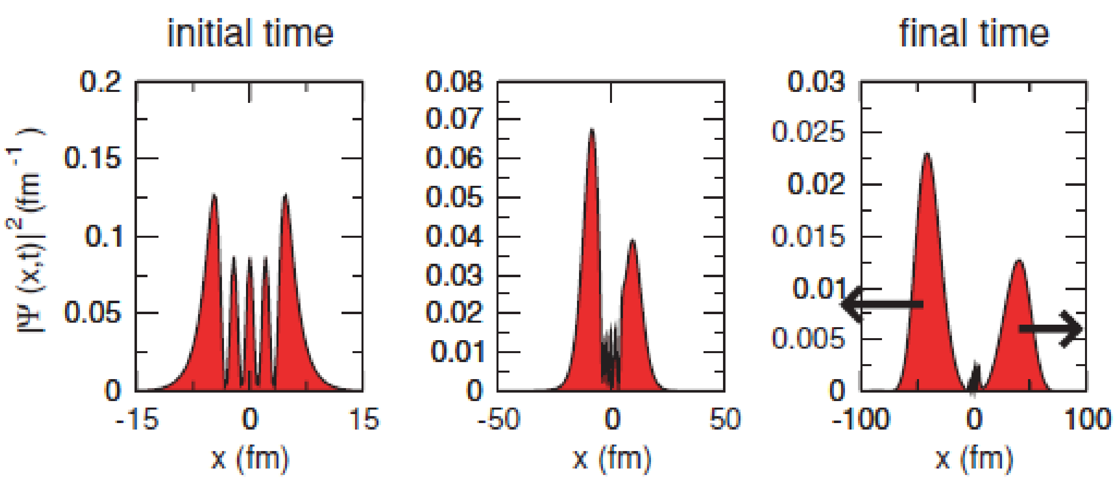
•$n$, $n'$: the same parity

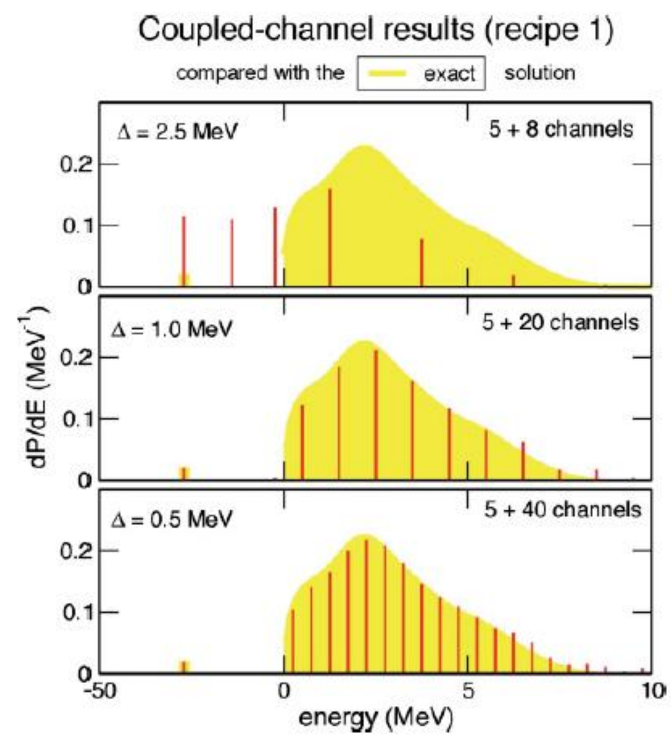
# One dimensional model for a one-neutron halo nucleus (Dasso & Vitturi)

PHYSICAL REVIEW C **79**, 064620 (2009)

**Role of the continuum in reactions with weakly bound systems: A comparative study between the time evolution of a break-up wave function and its coupled-channel approximation**

C. H. Dasso[1,2] and A. Vitturi[1,2]

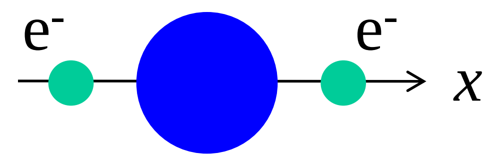



breakup of 1n halo nucleus (comparison with CDCC)

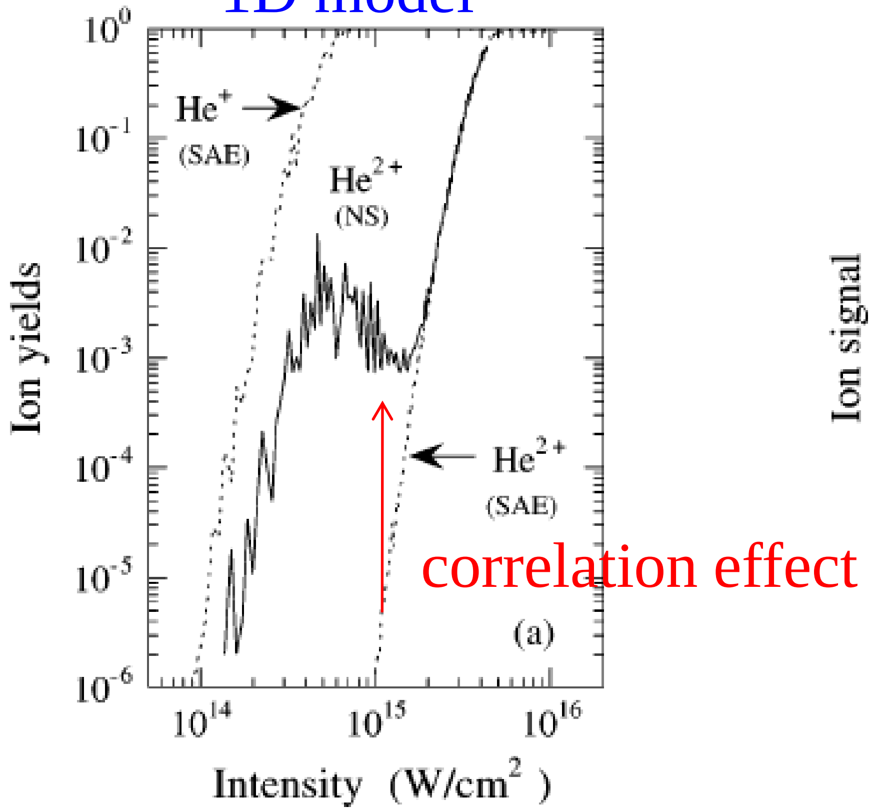
# Similar one-dimensional model for two-electron systems

He atom ($^4He + e^- + e^-$)
$H^-$ atom ($p + e^- + e^-$)

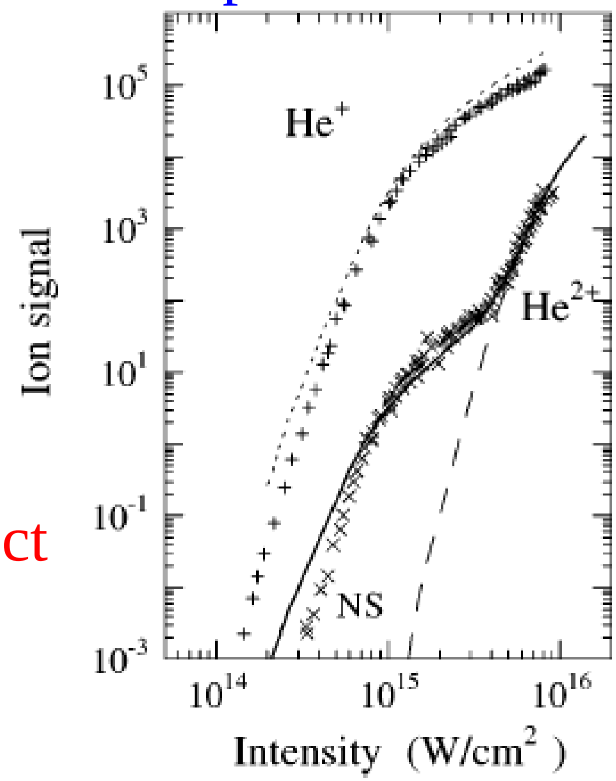



double ionization by intense laser fields

1D model




Experimental Data




J.B. Watson et al., PRL78('97)1884

# cf. TDH(F) for a one-dimensional system

B. Yoon and J.W. Negele, PRA16('77) 1451

PHYSICAL REVIEW A VOLUME 16, NUMBER 4 OCTOBER 1977

**Time-dependent Hartree approximation for a one-dimensional system of bosons with attractive δ-function interactions***

B. Yoon and J. W. Negele[†]

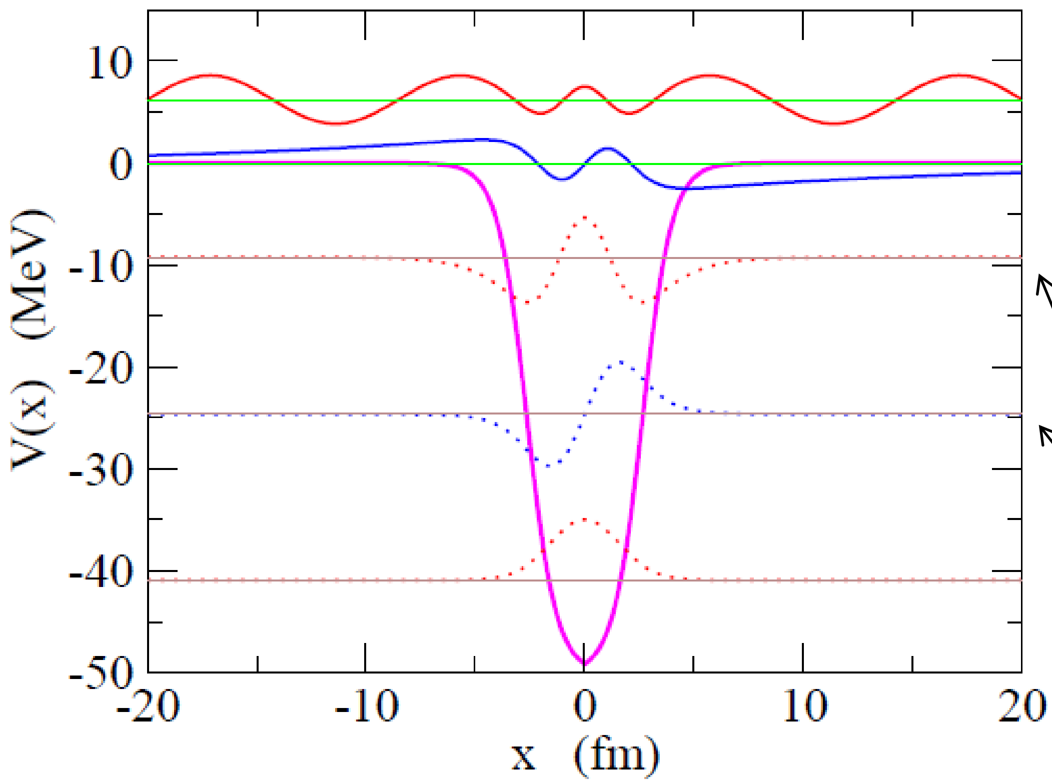
*Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(Received 29 November 1976)

The time-dependent Hartree approximation is compared with an exact solution for the scattering between two $N$-particle bound states in the case of a 1-dimensional system of bosons with attractive δ-function interactions. It is shown that to leading order in $N$, the approximation is exact, and arguments are presented relating this asymptotic agreement to the nonsaturation of the bound states.

$$H = -\frac{1}{2}\sum_{i=1}^{N}\frac{\partial^2}{\partial x_i^2} - g\sum_{i<j=1}^{N}\delta(x_i - x_j)$$

# Model Setup for core+2n




discretized continuum states

Weakly bound s.p. level at -0.15 MeV

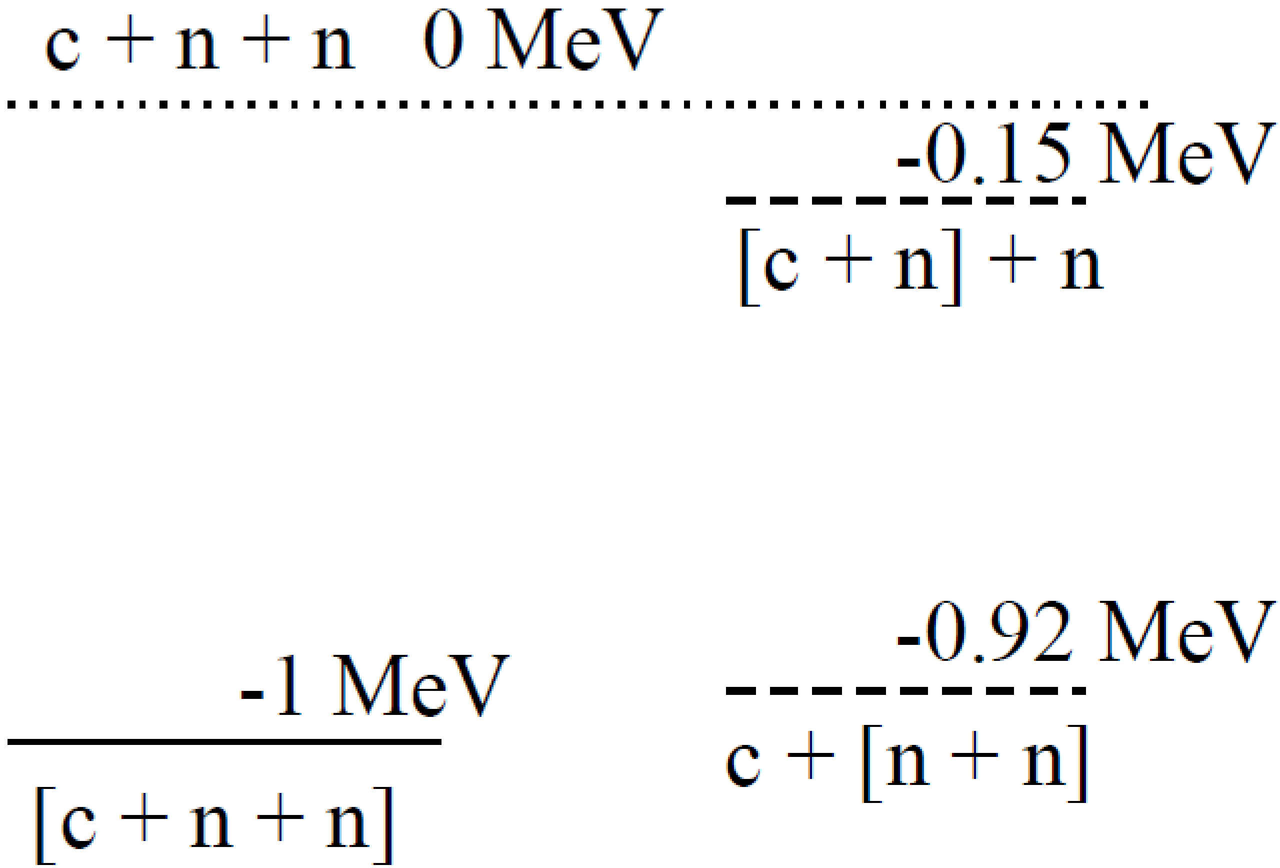
occupied by the core nucleus

the strength of the pairing interaction $g$: adjusted so that $E_{gs}$ = -1 MeV

$E_{cut}$ = 30 MeV, $R_{box}$ = 90 fm

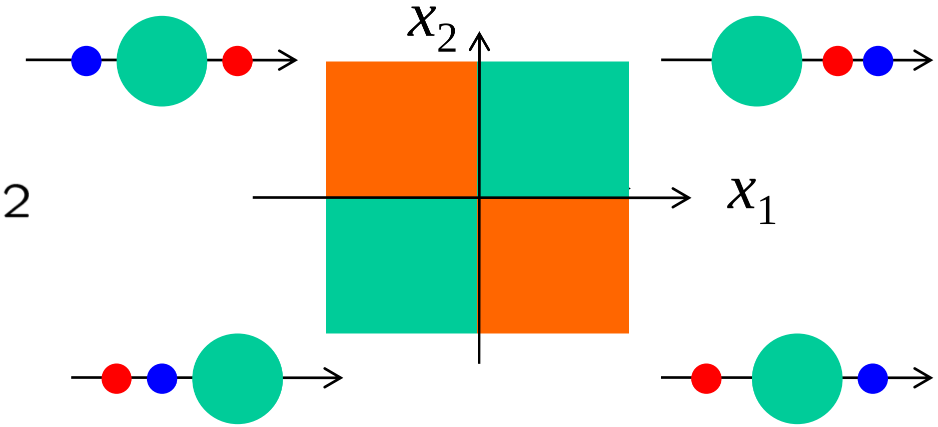
$$P_{\rm bb}^{(gs)} = 81.2\%$$

# spectrum



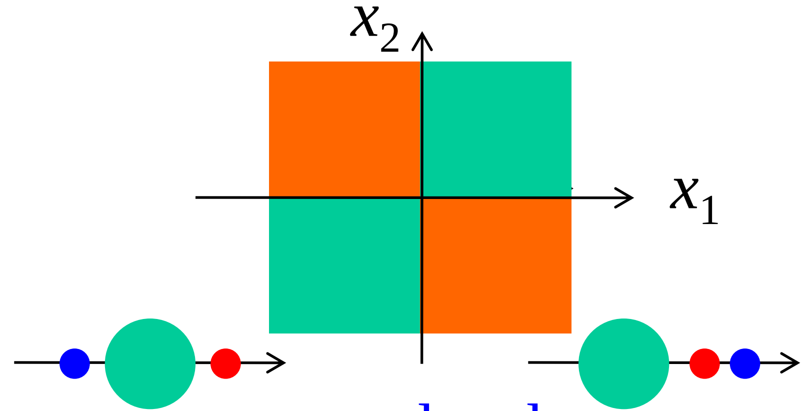
# Ground state properties

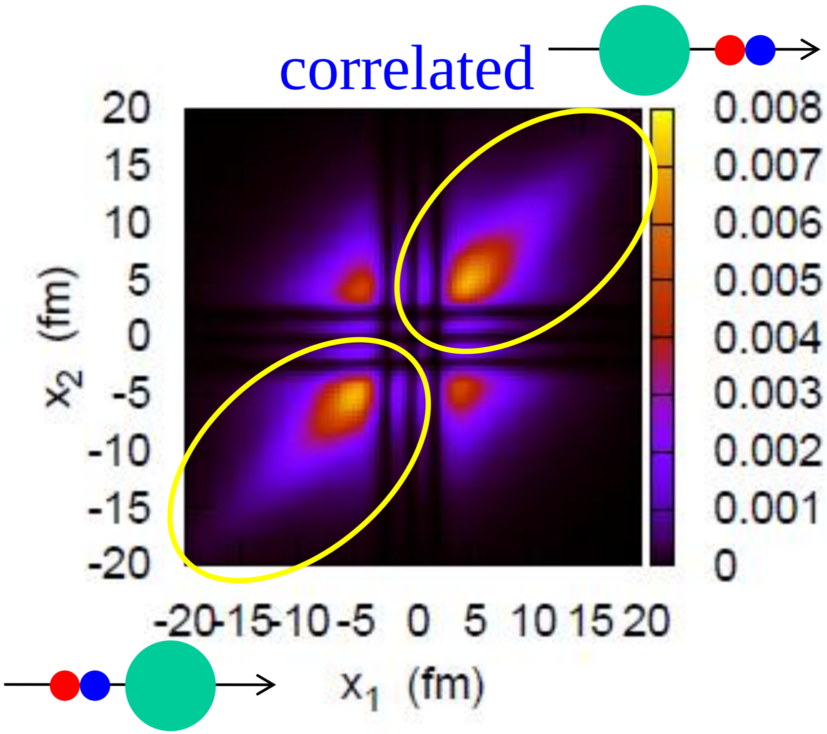
two-particle density: $|\Psi_{\mathrm{gs}}(x_1, x_2)|^2$



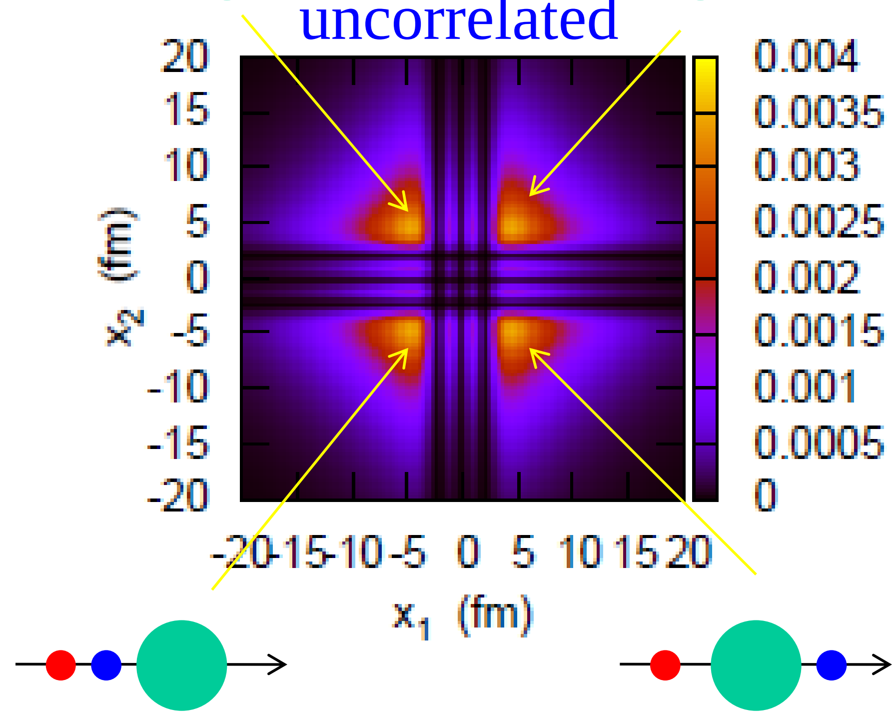
# Ground state properties

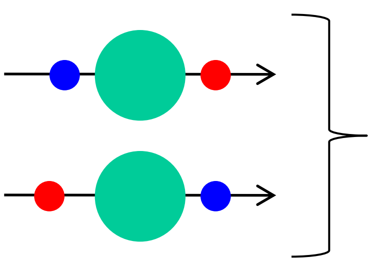
two-particle density: $|\Psi_{\text{gs}}(x_1, x_2)|^2$




dineutron correlation



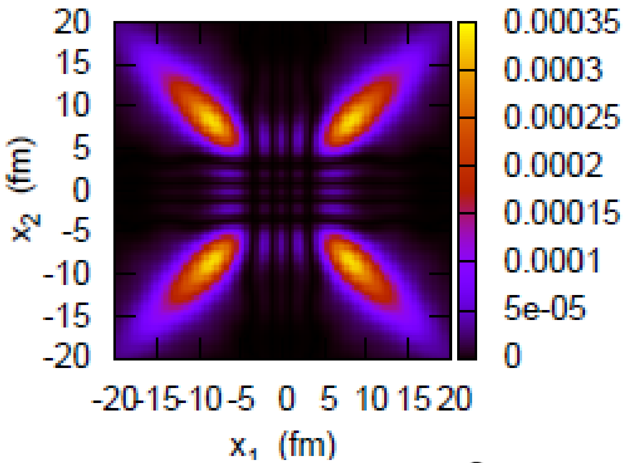
largely suppressed

four symmetric peaks

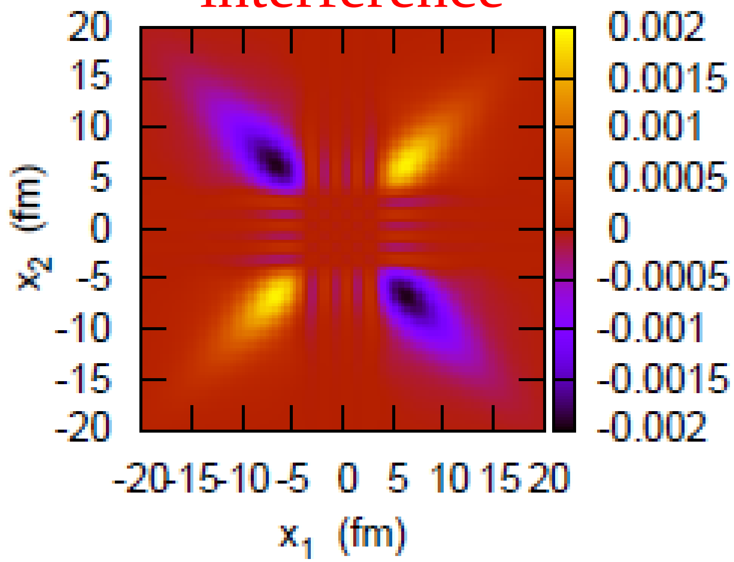
$$\Psi_{\rm gs}(x_1,x_2) = \Psi_{\rm ee}(x_1,x_2) + \Psi_{\rm oo}(x_1,x_2)$$

$$\longrightarrow \rho_2(x_1,x_2) = |\Psi_{\rm ee}(x_1,x_2)|^2 + |\Psi_{\rm oo}(x_1,x_2)|^2 + 2\Psi_{\rm ee}(x_1,x_2)\Psi_{\rm oo}(x_1,x_2)$$

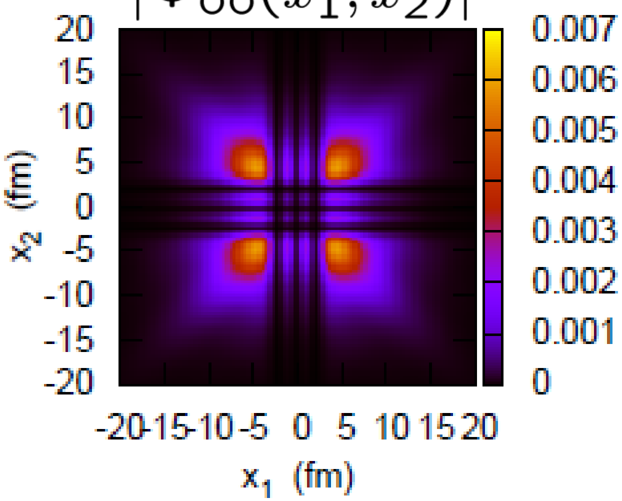
$|\Psi_{\rm ee}(x_1,x_2)|^2$




interference



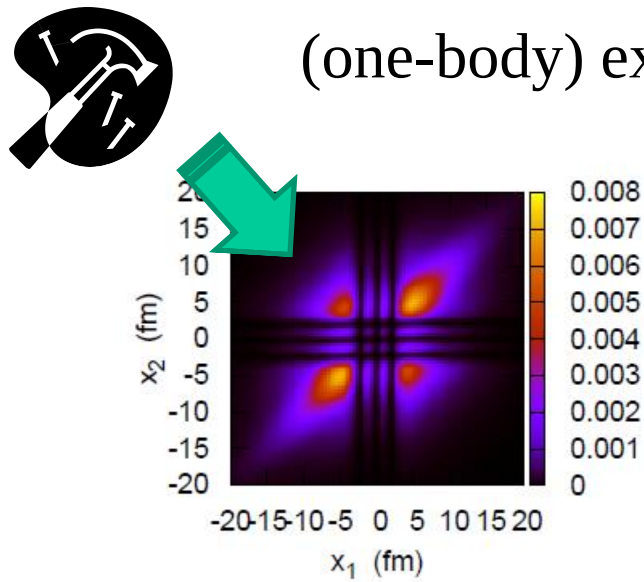

$|\Psi_{\rm oo}(x_1,x_2)|^2$




$$\Psi_{\rm ee}(x_1,x_2)\Psi_{\rm oo}(x_1,x_2) = -\Psi_{\rm ee}(x_1,-x_2)\Psi_{\rm oo}(x_1,-x_2)$$

# Nuclear Breakup Process

(one-body) external field




$$\Psi_{\rm gs}(x_1, x_2)$$

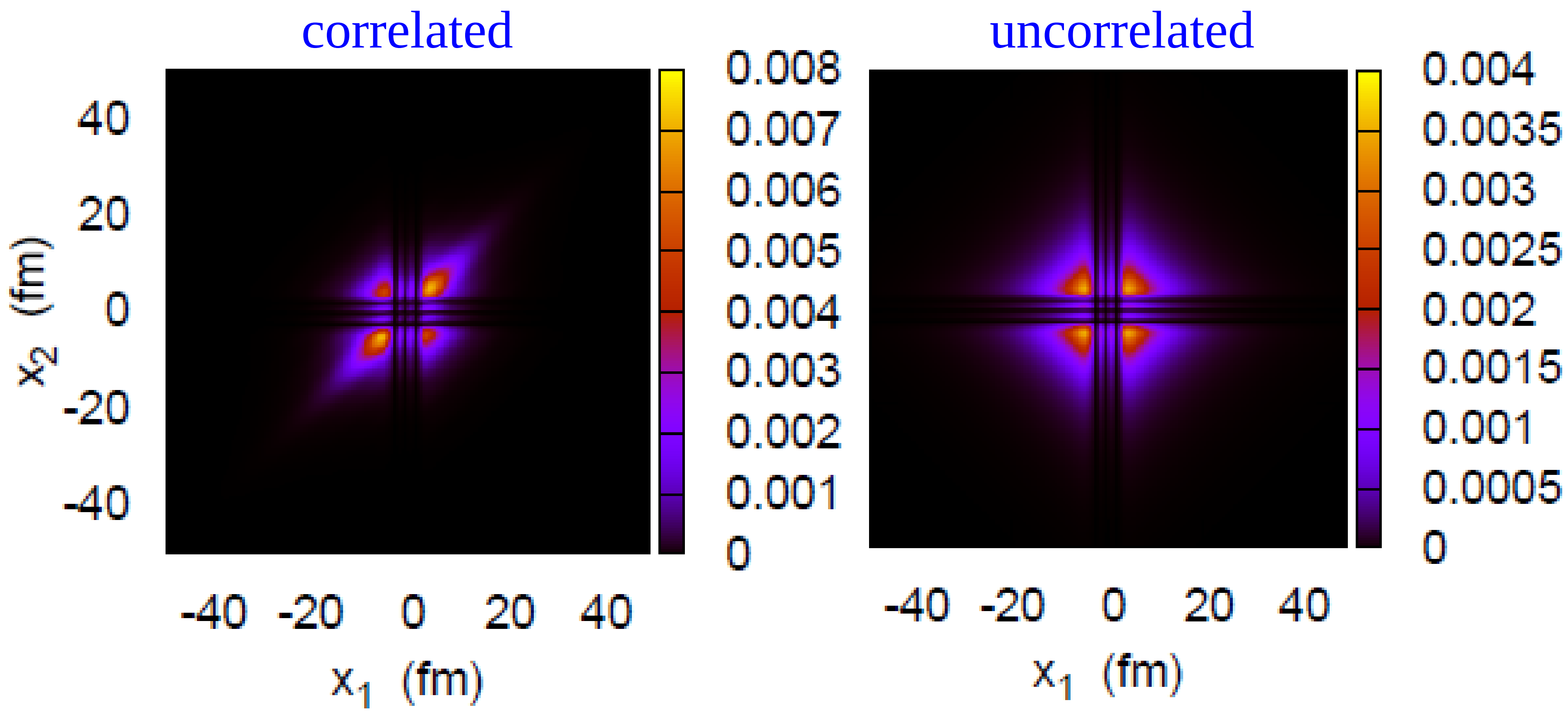
Time-dependent two-particle Schroedinger equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(x_1, x_2, t) = [H + V_{\rm ext}(x_1, x_2, t)]\Psi(x_1, x_2, t)$$

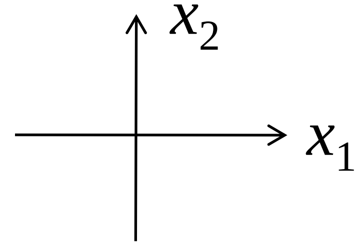
$$V_{\rm ext}(x_1, x_2, t) = \sum_{i=1,2} V_c\, e^{-t^2/2\sigma_t^2} e^{-(x_i - x_0)^2/2\sigma_x^2}$$

$V_c$ = 3 MeV, $\sigma_t$ = 2.1 hbar/MeV, $x_0 = 0$

two-particle density at $t = t_{ini}$

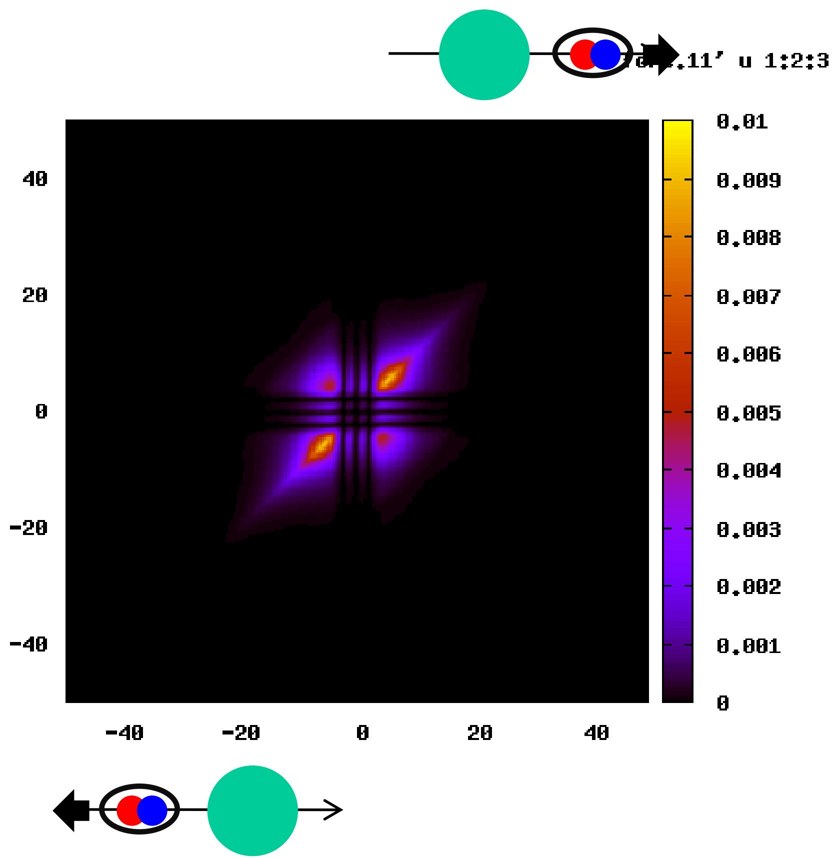


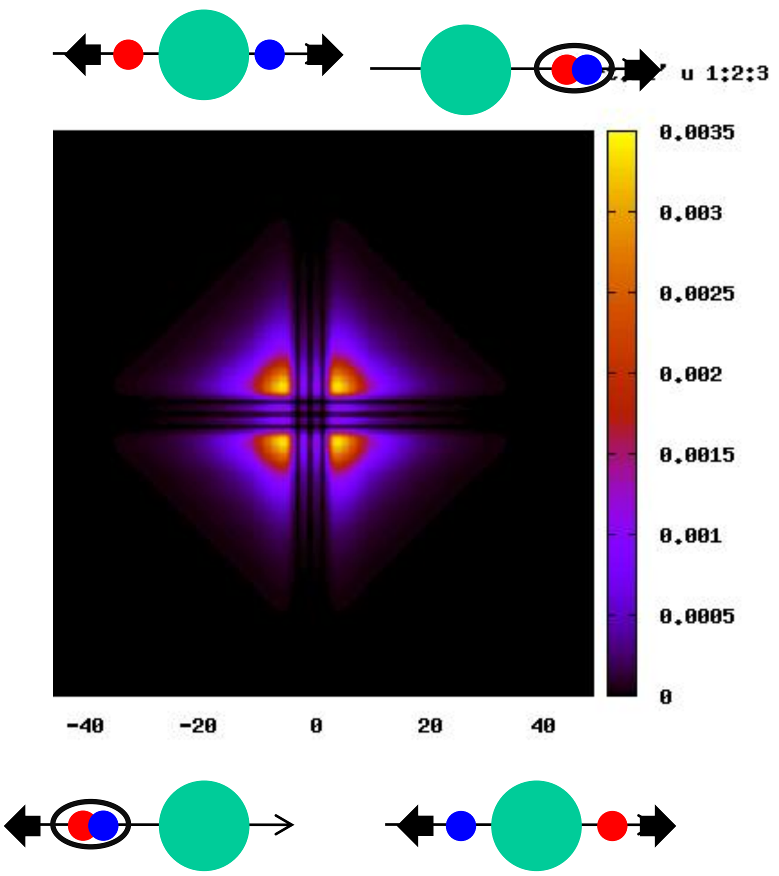
time evolution




**correlated**

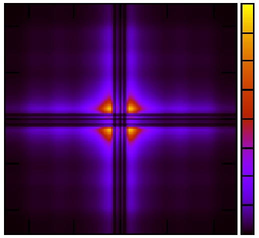
**uncorrelated**

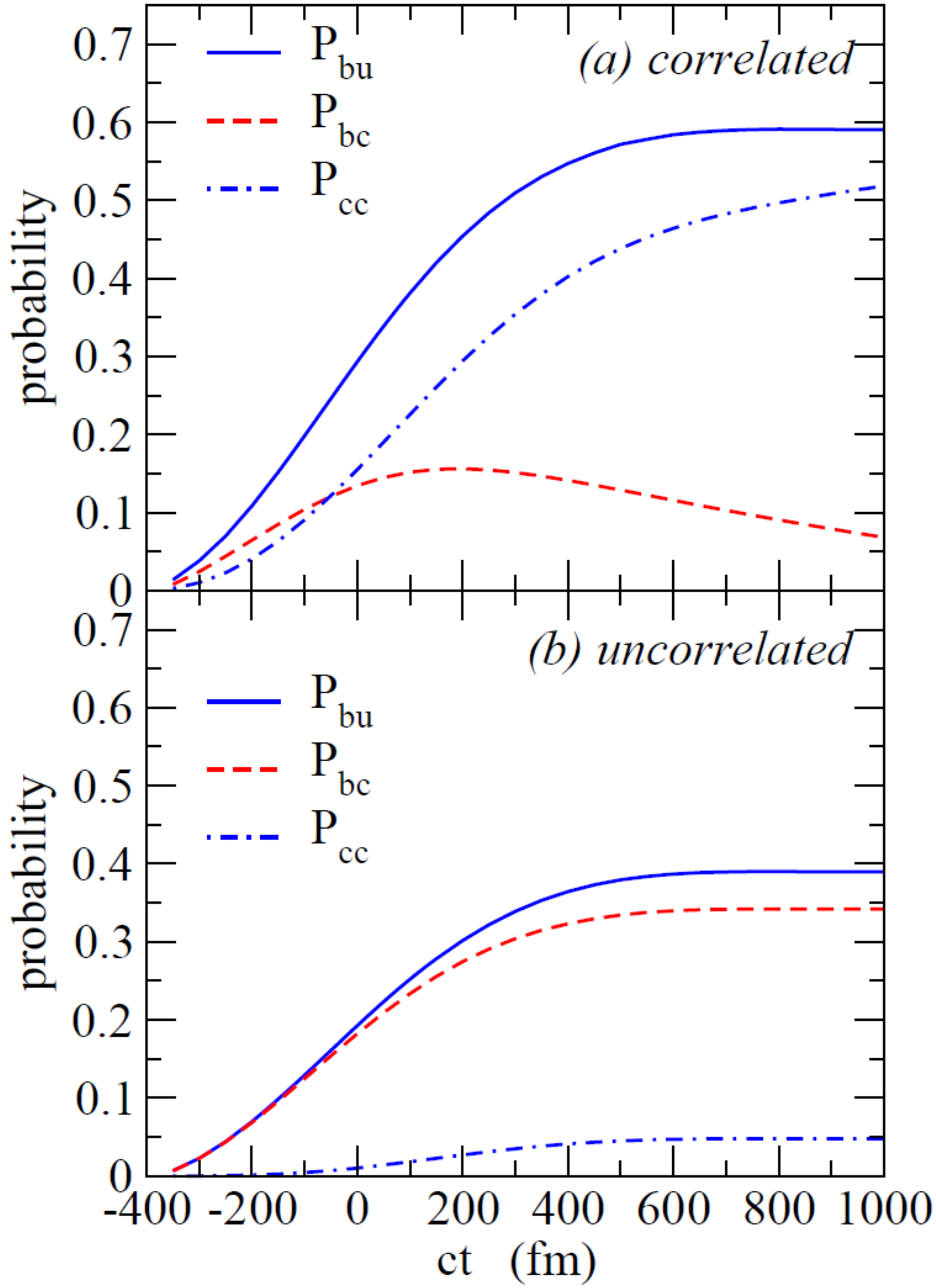



“dineutron emission”

large (bc) component





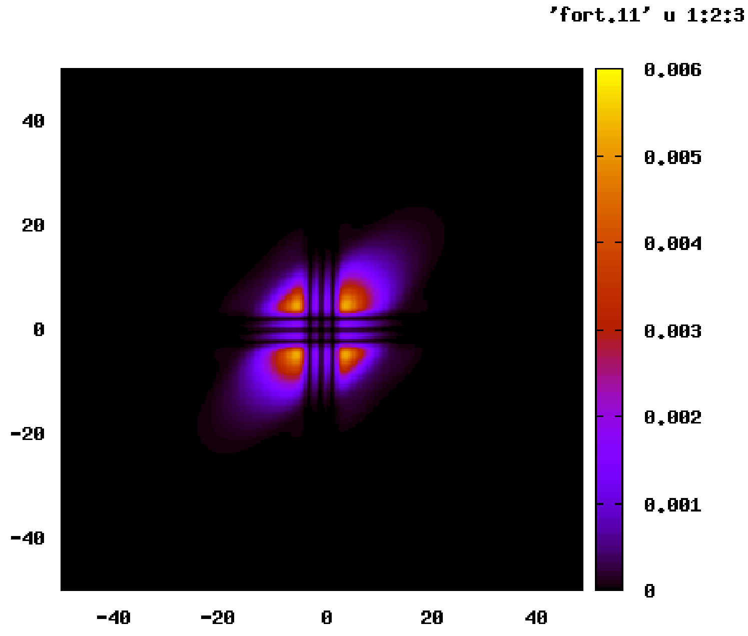

- ➢Pairing: enhances the breakup
- ➢Correlated: (cc) process
- ➢Uncorrelated: (bc) process

$P_{cc}$: 2 neutron breakup
$P_{bc}$: 1 neutron breakup

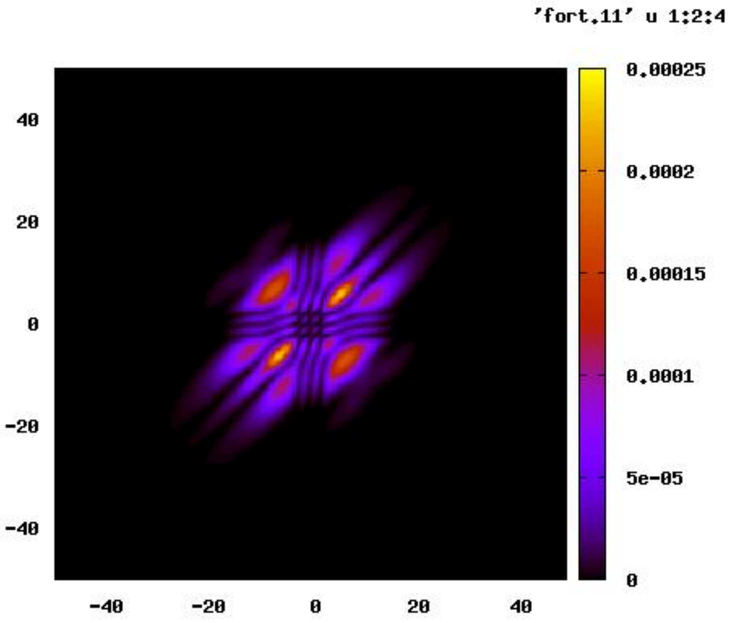
time evolution: start with the correlated g.s. state

but neglect $v_{nn}$ during the time evolution

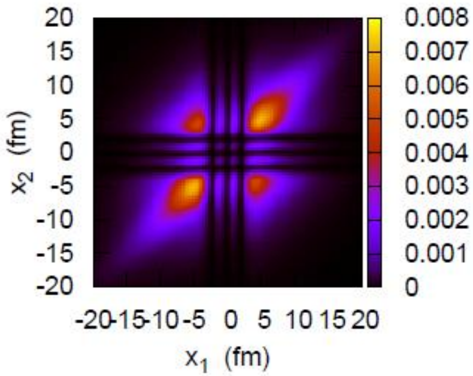
total

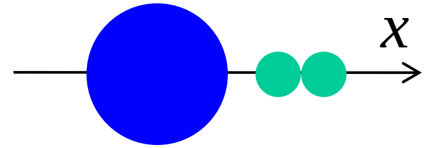


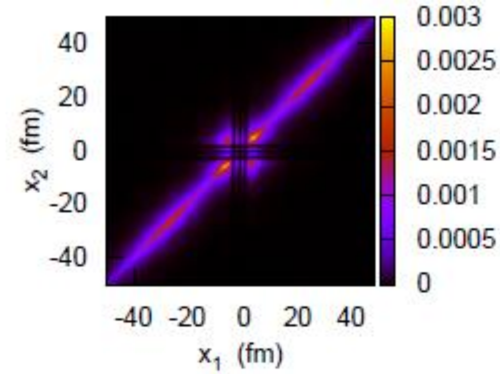

breakup component



# Summary




## One-dimensional three-body model for 2n halo nuclei

- simple schematic model
- allows detailed studies on the dynamics of 2n halo nuclei
- intuitive pictures
- dineutron correlation in the ground state
- nuclear breakup: enhanced 2n breakup due to pairing
  emission in the same direction: ‘*dineutron emission*’

## Other applications on the agenda:

- two-proton radioactivity
- **pair transfer**
- subbarrier fusion of 2n halo nuclei

cf. Yabana-Suzuki, NPA (‘95)