

# Direct reactions with weakly-bound systems: a one-dimensional model

**Laura Moschini**

Andrea Vitturi and Antonio Moro



# Outline

Introduction

The Model

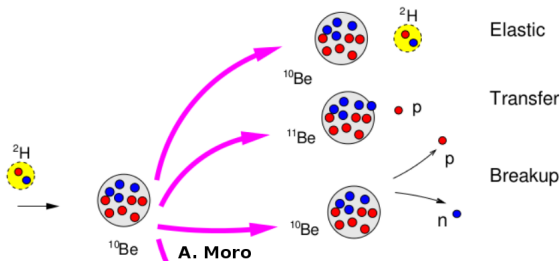
Results

Conclusions



# Introduction

**Direct reactions involve different channels simultaneously**



Study of **direct reactions** applied to **weakly-bound** halo systems on neutron drip-line: inert core + **one** or **two valence neutrons**

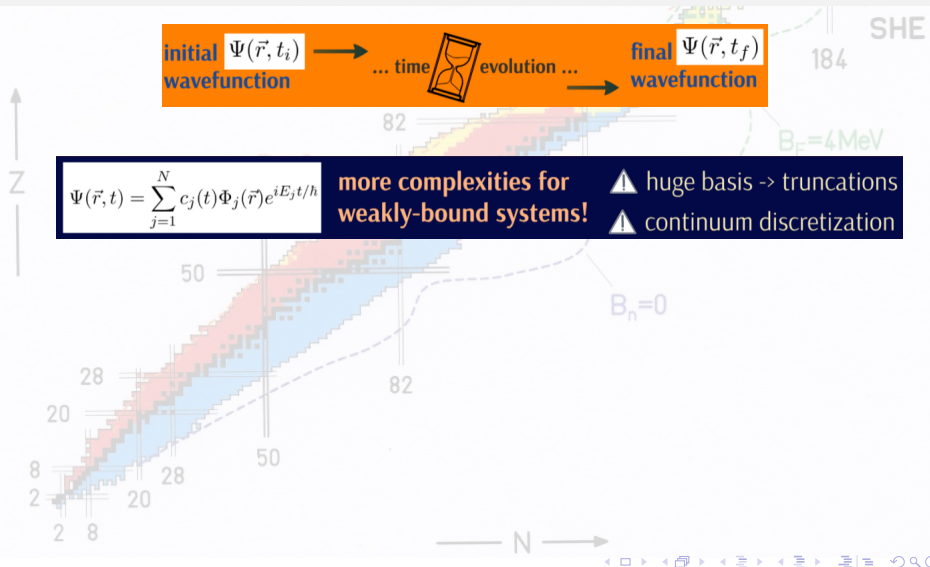
# Introduction



$$\Psi(\vec{r}, t) = \sum_{j=1}^N c_j(t) \Phi_j(\vec{r}) e^{iE_j t/\hbar}$$

**more complexities for weakly-bound systems!**

- ⚠ huge basis → truncations
- ⚠ continuum discretization



# Introduction



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**more complexities for weakly-bound systems!**

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**How to simplify the problem?**

Let's move to one dimension!

$$\Psi(x, t) = \sum_{j=1}^N c_j(t) \Phi_j(x) e^{iE_j t/\hbar}$$

we can follow both time evolutions using time dependent or coupled-channels methods, understand the limitations of approximations, and in particular study the **role of continuum**

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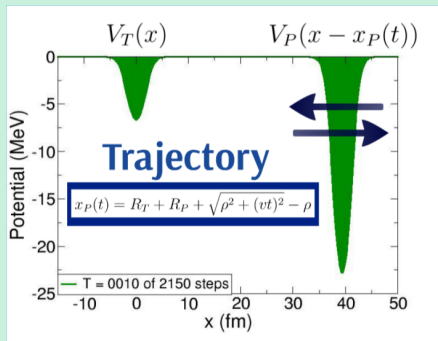
Conclusions



# Hamiltonian

## Potentials and trajectory

$$\mathcal{H}(x, t) = -\frac{\hbar^2}{2\mu} \frac{d^2}{dx^2} + V_T(x) + V_P(x - x_P(t))$$



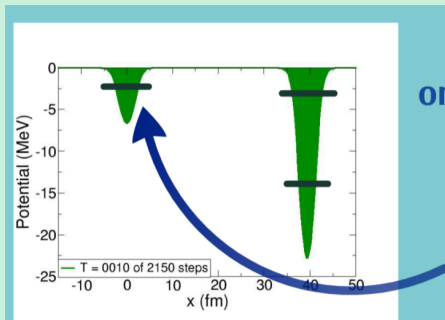
Esbensen H, Broglia RA and Winther A 1983 *Ann. Phys.* **146** 149–173

# Initial wavefunction

obtained by solving the time independent Schroedinger equation

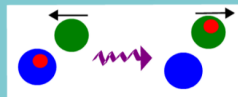
LM, Pérez-Bernal and Vitturi, *J. Phys. G: Nucl. Part. Phys.* **43** 045112 (2016)

$$\left[ -\frac{\hbar^2}{2\mu} \frac{d^2}{dx^2} + V_j(x) \right] \Phi_n^{(j)}(x) = E_n^{(j)} \Phi_n^{(j)}(x)$$



The choice depends  
on the kind of reaction!

Example:  
one-neutron pick-up





By definition we can expand the wavefunction  $\Psi(x, t)$  as a combination of target and projectile basis states depending on a set of coefficients  $c_j(t)$

$$\Psi(x, t) = \sum_{j=1}^{N_T} c_j^T(t) \Phi_j^T(x) e^{iE_j^T t/\hbar} + \sum_{j=1}^{N_P} c_j^P(t) \Phi_j^P(x) e^{iE_j^P t/\hbar}$$

We can follow the time evolution of:

$$\begin{aligned} \Psi(x, t) &\rightarrow \text{exact model} \\ c_j(t) &\rightarrow \text{coupled-channels formalism} \end{aligned}$$

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- ▶ distance of closest approach
- ▶ incident energy
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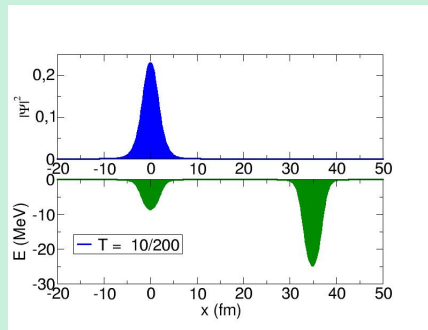
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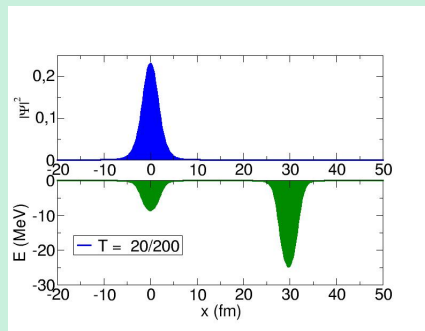
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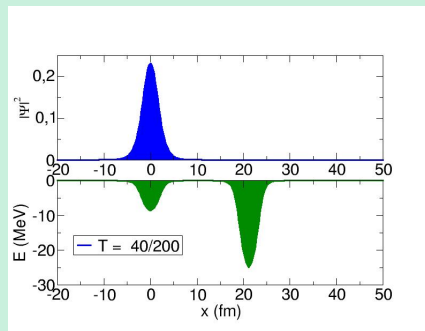
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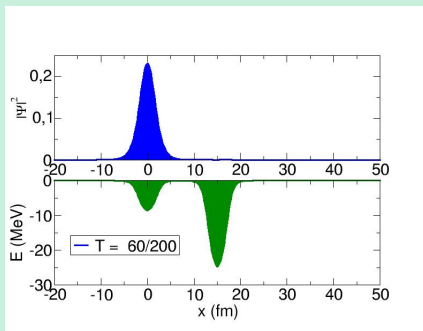
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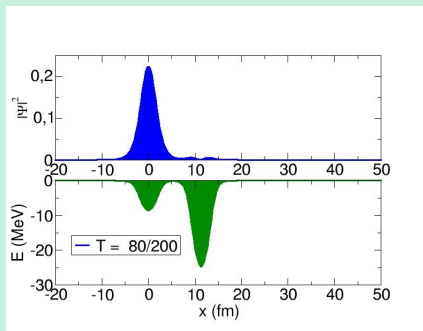
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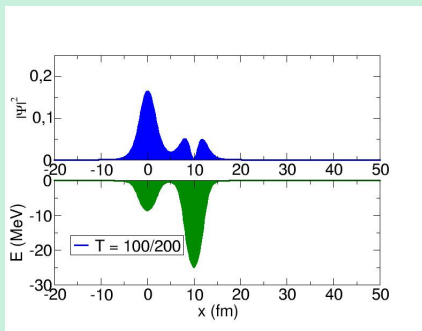
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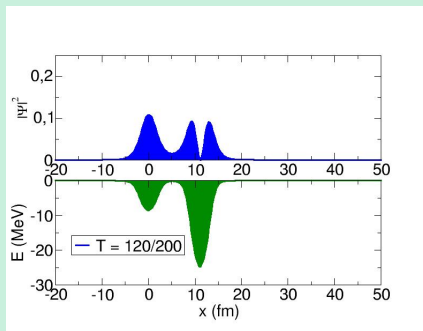
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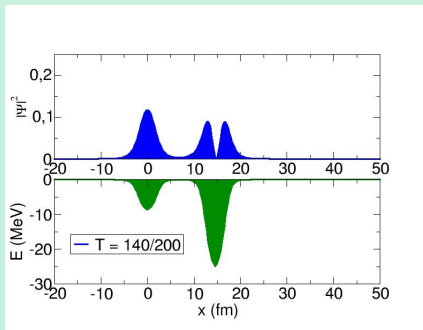
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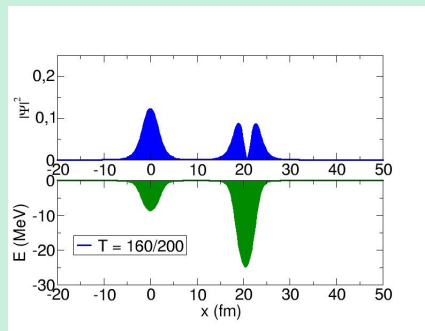
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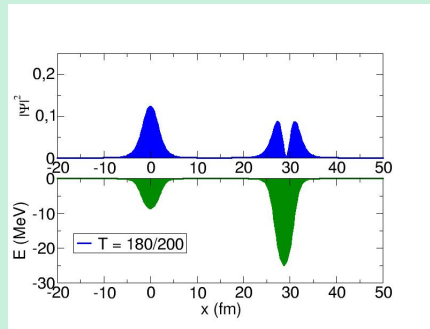
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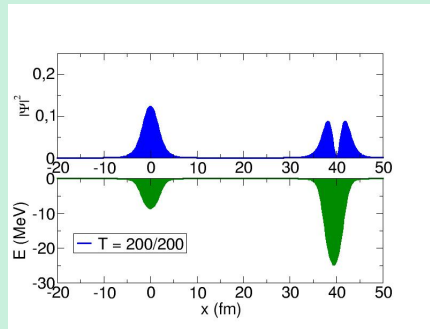
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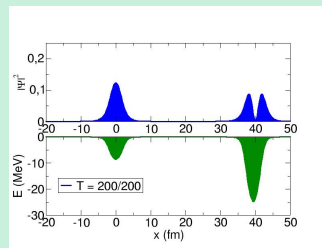
## Final probabilities

$$P_{inelastic} = |\langle \Psi(x, t_{fin}) | \Phi(x)_{target} \rangle|^2$$

$$P_{transfer} = |\langle \Psi(x, t_{fin}) | \Phi(x)_{proj} \rangle|^2$$

$$P_{break-up} = 1 - P_{inelastic} - P_{transfer} = \left| \int \langle \Psi(x, t_{fin}) | \Phi(k) \rangle dk \right|^2$$

overlap with continuum  
 (pseudostates, exact continuum ...)



# Coupled-Channels

**Initial condition:**  $c_j^P(t = -\infty) = 0$  and  $c_j^T(t = -\infty) = \delta_{i,j}$

$$i\hbar \frac{\partial c_j^T}{\partial t} = \sum c_k^T \langle \omega_j^T | V^P | \Psi_k^T \rangle + \sum c_k^P \langle \omega_j^T | V^T | \Psi_k^P \rangle$$

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- ▶ inclusion of target  $\Psi^T$  AND projectile  $\Psi^P$  bases
- ▶ dual bases: time-dependent functions associated with the two wells ( $\omega^T$  and  $\omega^P$ ) based on overlaps between target and projectile states to solve non-orthogonal problem
 
$$\langle \Psi_m^I | \omega_n^J \rangle = \delta_{I,J} \delta_{n,m}$$



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**New feature: continuum included!!!**

pseudostates obtained by diagonalizing the potential in different bases  
(infinite square well, harmonic oscillator, transformed HO)

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## Final probabilities

$$P_j^{(T,P)}(t_f) = |c_j^{(T,P)}(t_f)|^2$$

non-orthogonal basis states  
 $\Rightarrow$  tot probability is not  
 conserved during collision

**To be calculated  
 after the collision  
 when overlaps are zero**

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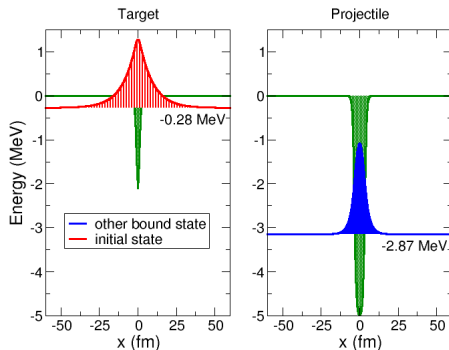
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# Results

## Initial conditions and time evolution



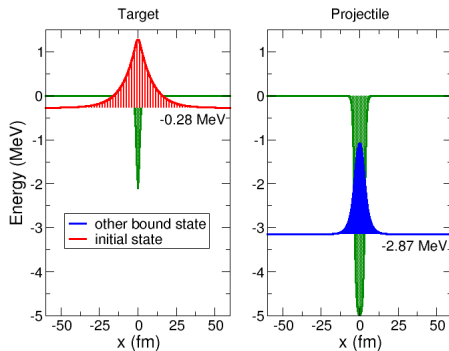
Evolution of exact wavefunction

Target and projectile potentials  
and corresponding eigenstates

Incident energy: 5MeV

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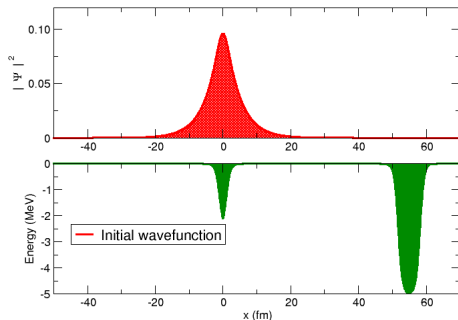
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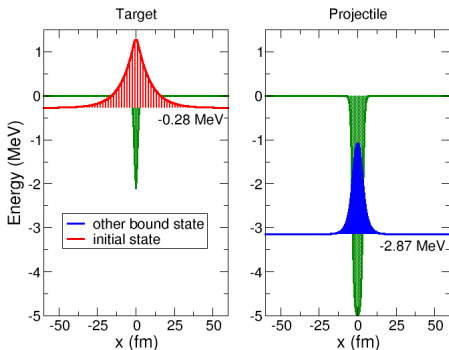
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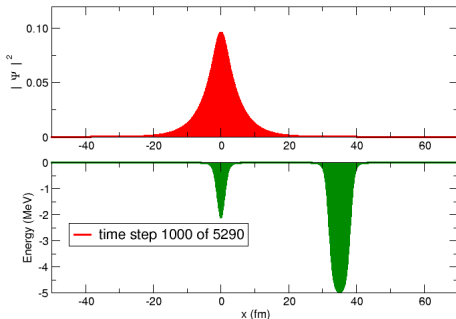
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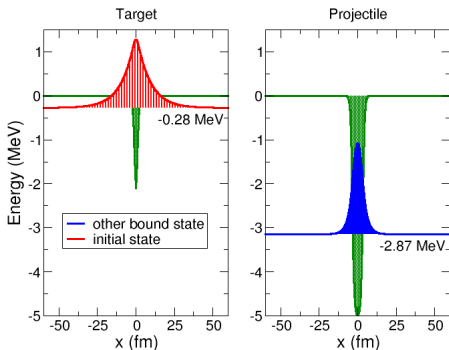
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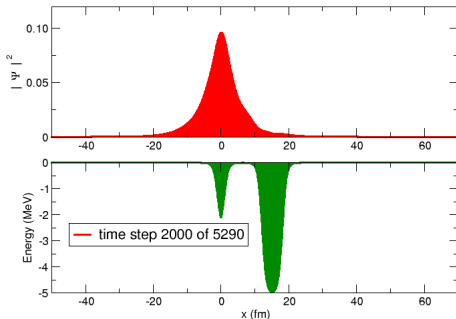
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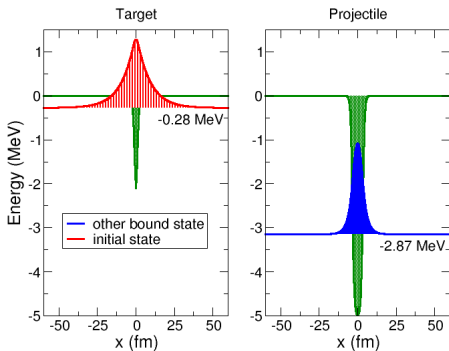
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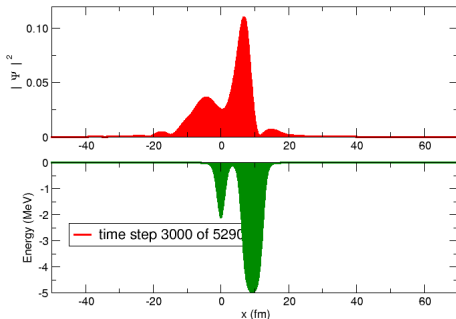
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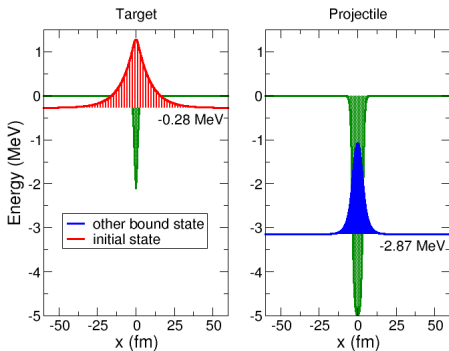
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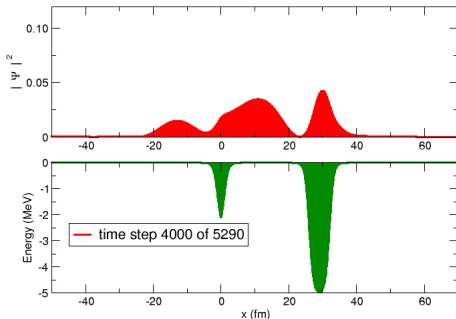
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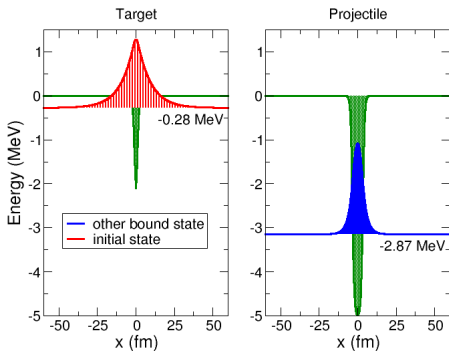
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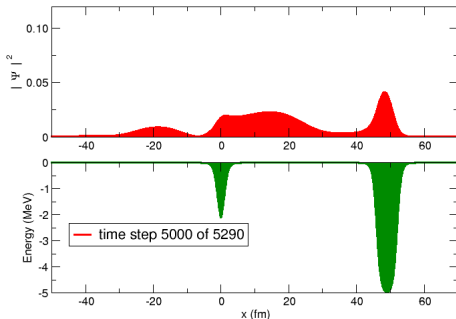
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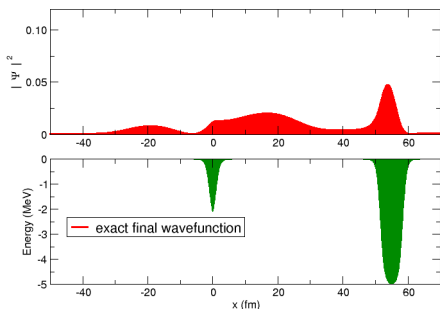
## Evolution of exact wavefunction



# Results

## Final probability

### Final exact wavefunction



	Exact	First approx	CC (a)	CC (b)	CC (c)
elastic	21%	-	21.4%	95%	21%
transfer	5%	100%	-	5%	0.04%
breakup	74%	150%	78.6%	-	79%

**Exact:** exact time evolution results

**First approx:** probability to excite directly the system from initial to final state

**CC (a):** only target basis, including continuum pseudostates

**CC (b):** target AND projectile bases, no continuum

**CC (c):** target AND projectile bases, including target's continuum pseudostates

# Results

## Breakup probability

$$|\langle \Psi(x, t_f) | \Phi_{T,P}(x, E) \rangle|^2$$

final wavefunction

Projectile  
or target eigenfunction  
for positive energy E

# Results

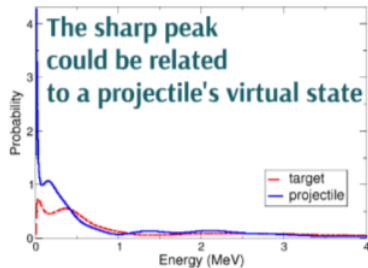
## Breakup probability

$$|\langle \Psi(x, t_f) | \Phi_{T,P}(x, E) \rangle|^2$$

final wavefunction

Projectile  
or target eigenfunction  
for positive energy E

## Breakup probability



# Results

## Breakup probability

$$|\langle \Psi(x, t_f) | \Phi_{T,P}(x, E) \rangle|^2$$

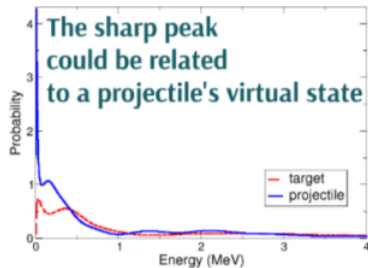
final wavefunction

Projectile  
or target eigenfunction  
for positive energy E

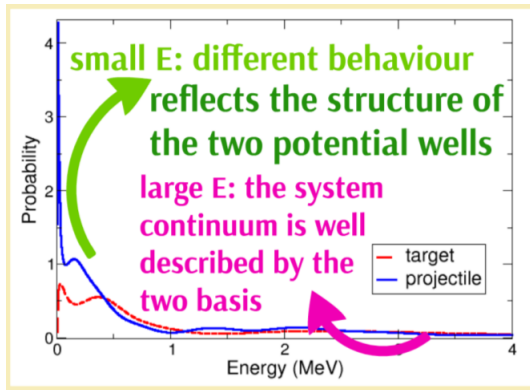
→ large E: same behaviour  
independent to  
the basis

→ small E: different behaviour

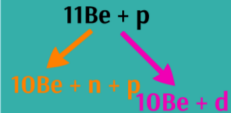
## Breakup probability



# Conclusions



Example: a 3D system



It is important  
to consider the  
continuum of each  
system because at  
small energy the  
different bases are  
not equivalent

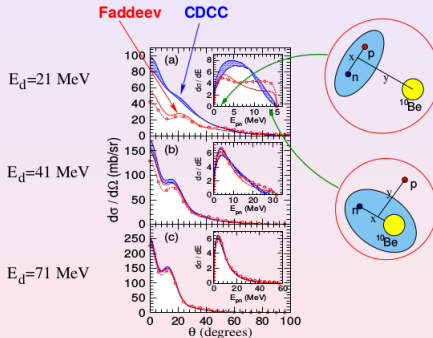
**DREB2016**  
Direct Reactions with Exotic Beams  
July 11-15, 2016  
Halifax, Canada



[laura.moschini@pd.infn.it](mailto:laura.moschini@pd.infn.it)

# Breakdown of the CDCC ansatz: $d + {}^{10}\text{Be} \rightarrow p + n + {}^{10}\text{Be}$

☞ But...differences have been evidenced for breakup at small incident energies (N.J. Upadhyay, A. Deluva, F.M. Nunes, PRC85, 054621 (2012))

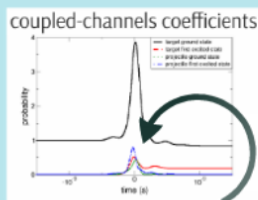
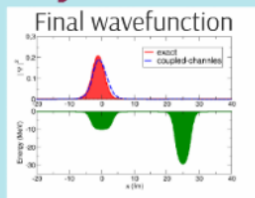
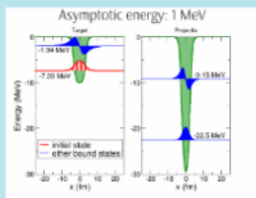


☞ CDCC can be (and must be!) improved



# Well-bound system

## Well bound system



	Exact	CC
elastic	83%	84%
inelastic	14%	16%
transfer (g.s.)	0.6%	0.002%
transfer (1st excited)	0.03%	0.2%
breakup	2.4%	-

non-orthogonality  $\Rightarrow$  tot probability is not conserved during collision

# Two-neutron system

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

**Hamiltonian:**

$$\mathcal{H}(x_1, x_2, t) = KIN + V_T(x_1, x_2) + V_P(x_1, x_2, t) + V_{int}(x_1, x_2)$$

**Two-body wavefunction**  
obtained by diagonalizing the residual pairing interaction in a two-particle basis, including continuum states by a discretization procedure  
Phys. Rev. Lett. 101, 042501 (2008)  
Phys. Rev. Lett. 101, 042501 (2008)  
LMU Muenchen, arXiv:1001.2814

**Density dependent residual interaction**

$$V_{int}(x_1, x_2) = -V \left[ \frac{\rho[(x_1 + x_2)/2]}{\rho_0} \right] \delta(x_1 - x_2)$$

(acting only when the two particles are both inside the same well)

**What happens turning on or off the pairing?**

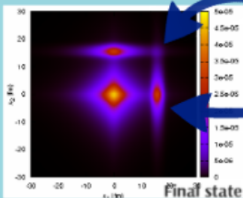
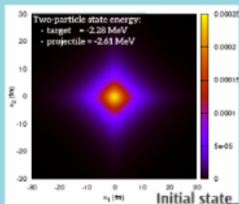
# Two-neutron system

## Uncorrelated neutrons

i.e. zero residual interaction

Initially:

- two neutrons are bound in the target
- equal probability to find them
  - close together
  - or on opposite sides



two-neutron  
transfer:  
 $P2 = 0.04$

one-neutron  
transfer:  
 $P1 = 0.20$

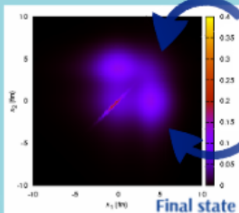
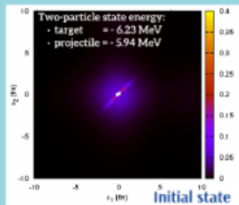
Perturbative estimate  
successive transfer of single particles  
induced by the mean-field of the moving well  
 $P2 \sim (P1)^2 = 0.2 \times 0.2 = 0.04$

# Two-neutron system

## Correlated neutrons

i.e. non zero residual interaction

The two neutrons stay as close as possible!



two-neutron transfer:  
 $P2 = 0.13$

one-neutron transfer:  
 $P1 = 0.26$

From a perturbative estimate:  
 $P2$  (uncorr) =  $0.26 \times 0.26 = 0.07$   
What is really measured:  
 $P2$  (corr) =  $0.13 = 2 \times P2$  (uncorr)  
Enhancement factor: 2

The perturbing interaction is a one-body field  
 $\Rightarrow$  at least a second-order process  
to produce the pair transfer  
So the enhanced two-particle transfer originates from the pairing correlation and not from the reaction mechanism

# Virtual state

