

# IUAC School on Nuclear Reactions: The CDCC and CRC methods

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Material available at: <https://github.com/ammoro/IUAC>



## Course outline I

### 1 The CDCC method

- Reminder of the coupled-channels method
- Single-particle and cluster excitations
- Partial wave analysis: radial equations
- Some examples of applications of the CDCC method
- Exploring the continuum with breakup reactions
- Radiative capture from Coulomb dissociation data

### 2 Advanced CDCC and extensions

- Extension to 3-body projectiles
- Core excitations

### 3 Application of CDCC to transfer reactions

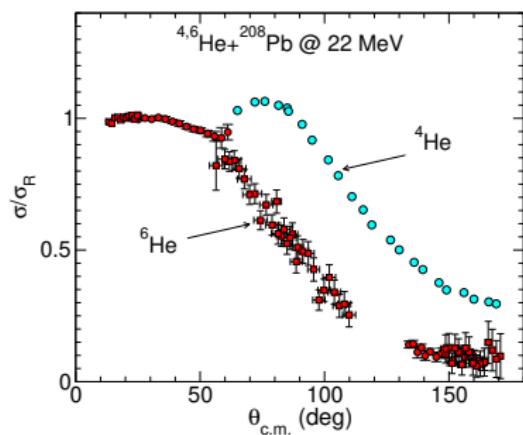
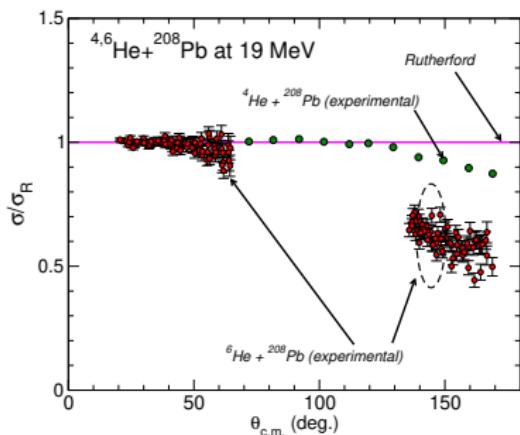
- Transfer reactions with weakly bound nuclei
- Transfer populating unbound states

### 4 The Coupled-Reaction Channels (CRC) formalism



## Motivation of the CDCC method

How does the halo structure affect the elastic scattering?

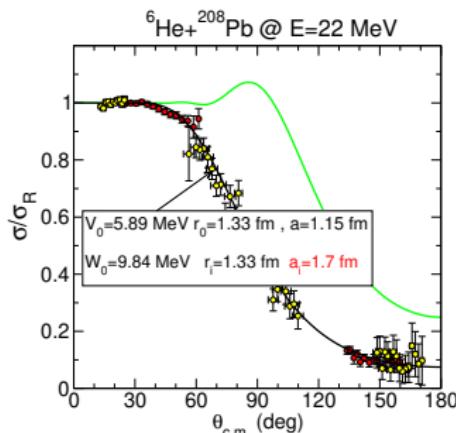
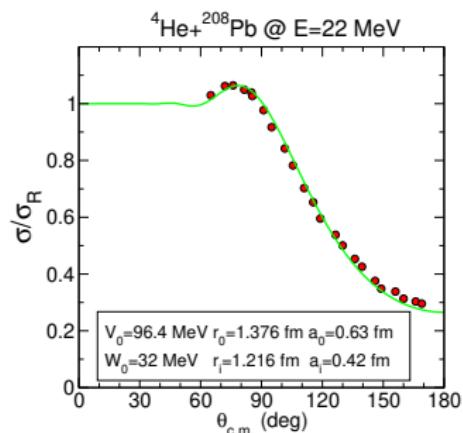


- For  $E = 19$  MeV (below the barrier,  $V_b \approx 21$  MeV)  $^4\text{He}$  follows Rutherford formula.
- $^6\text{He}$  drastically departs from Rutherford formula at both energies!



## Motivation of the CDCC method

How does the halo structure affect the elastic scattering?



- ⇒  ${}^4\text{He} + {}^{208}\text{Pb}$  shows typical Fresnel pattern and “standard” optical model parameters
- ⇒  ${}^6\text{He} + {}^{208}\text{Pb}$  shows a prominent reduction in the elastic cross section, suggesting that part of the incident flux goes to nonelastic channels (e.g. breakup, transfer...)
- ☞ Understanding and disentangling these nonelastic channels requires going beyond the optical model (eg. [coupled-channels method](#))

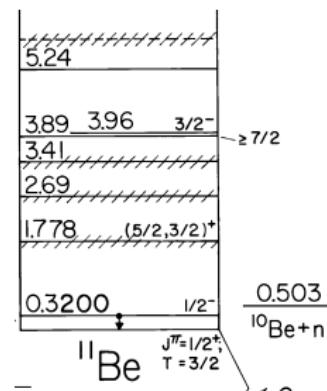
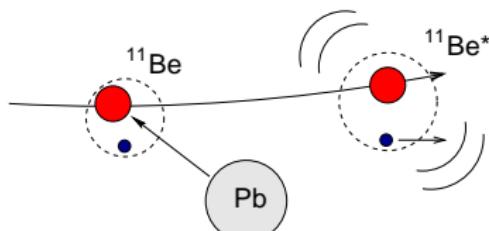


## Reminder of the coupled-channels method



## Inelastic scattering

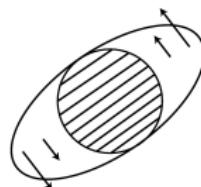
- ⇒ Nuclei are not inert or *frozen* objects; they do have an internal structure of protons and neutrons that can be modified (excited) during the collision.
- ⇒ Quantum systems exhibit, in general, an energy spectrum with bound and unbound levels.



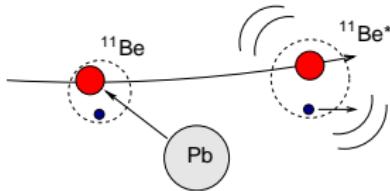


## Models for inelastic excitations

- ① **COLLECTIVE:** Involve a collective motion of several nucleons which can be interpreted macroscopically as **rotations** or **surface vibrations** of the nucleus.



- ② **FEW-BODY/SINGLE-PARTICLE:** Involve the excitation of a nucleon or cluster.





## The coupled-channels method for inelastic scattering

We need to incorporate explicitly in the Hamiltonian the internal structure of the nucleus being excited (e.g. projectile).

$$H = T_R + h(\xi) + V(\mathbf{R}, \xi)$$

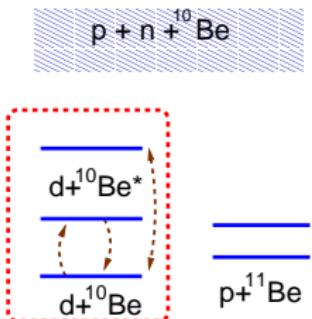
- ⇒  $T_R$ : Kinetic energy for projectile-target relative motion.
- ⇒  $\{\xi\}$ : Internal degrees of freedom of the projectile (depend on the model).
- ⇒  $V(\mathbf{R}, \xi)$ : Projectile-target interaction.
- ⇒  $h(\xi)$ : Internal Hamiltonian of the projectile.

$$h(\xi)\phi_n(\xi) = \varepsilon_n\phi_n(\xi)$$

- ⇒  $\phi_n(\xi)$ : internal states of the projectile.



## Modelscape and scattering wavefunction: d+<sup>10</sup>Be → d+<sup>10</sup>Be\* example



The modelspace is composed by ground states (elastic channel) and some excited states (inelastic scattering)

Boundary conditions for scattering wavefunction:

$$\Psi_{\mathbf{K}_0}^{(+)}(\mathbf{R}, \xi) \xrightarrow{R \gg} e^{i\mathbf{K}_0 \cdot \mathbf{R}} \phi_0(\xi) + f_{0,0}(\theta) \frac{e^{iK_0 R}}{R} \phi_0(\xi) + \underbrace{\sum_{n>0} f_{n,0}(\theta) \frac{e^{iK_n R}}{R} \phi_n(\xi)}_{\text{inelastic}}$$

incident                    elastic                    inelastic

Cross sections:

$$\left( \frac{d\sigma(\theta)}{d\Omega} \right)_{0 \rightarrow n} = \frac{K_n}{K_0} |f_{n,0}(\theta)|^2 \quad f_{n,0}(\theta) = \text{scattering amplitude}$$



## CC model wavefunction (target excitation)

We expand the total wave function in a subset of internal states representing the adopted modelspace:

$$\Psi_{\text{model}}(\mathbf{R}, \xi) = \phi_0(\xi)\chi_0(\mathbf{K}_0, \mathbf{R}) + \sum_{n>0} \phi_n(\xi)\chi_n(\mathbf{K}_n, \mathbf{R})$$

and impose the boundary conditions for the (unknown)  $\chi_n(\mathbf{R})$ :

$$\begin{aligned} \chi_0^{(+)}(\mathbf{K}_0, \mathbf{R}) &\rightarrow e^{i\mathbf{K}_0 \cdot \mathbf{R}} + f_{0,0}(\theta) \frac{e^{iK_0 R}}{R} && \text{for } n=0 \text{ (elastic)} \\ \chi_n^{(+)}(\mathbf{K}_n, \mathbf{R}) &\rightarrow f_{n,0}(\theta) \frac{e^{iK_n R}}{R} && \text{for } n>0 \text{ (non-elastic)} \end{aligned}$$



## Calculation of $\chi_n^{(+)}(\mathbf{R})$ : the coupled equations

- ⇒ The model wavefunction must satisfy the Schrödinger equation:

$$[H - E]\Psi_{\text{model}}^{(+)}(\mathbf{R}, \xi) = 0$$

- ⇒ Multiply on the left by each  $\phi_n^*(\xi)$ , and integrate over  $\xi \Rightarrow$  coupled channels equations for  $\{\chi_n(\mathbf{R})\}$ :

$$[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})$$

- ⇒ The structure information is embedded in the coupling potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\xi \phi_{n'}^*(\xi) V(\mathbf{R}, \xi) \phi_n(\xi)$$

☞  $\phi_n(\xi)$  will depend on the assumed structure model (collective, few-body, etc).

# Optical Model vs. Coupled-Channels method

## Optical Model

⇒ The Hamiltonian:

$$H = T_R + V(\mathbf{R})$$

⇒ Internal states: Just  $\phi_0(\xi)$

⇒ Model wavefunction:

$$\Psi_{\text{mod}}(\mathbf{R}, \xi) \equiv \chi_0(\mathbf{K}, \mathbf{R})\phi_0(\xi)$$

⇒ Schrödinger equation:

$$[H - E]\chi_0(\mathbf{K}, \mathbf{R}) = 0$$



## Optical Model vs. Coupled-Channels method

### Optical Model

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- ⇒ Internal states: Just  $\phi_0(\xi)$
- ⇒ Model wavefunction:  

$$\Psi_{\text{mod}}(\mathbf{R}, \xi) \equiv \chi_0(\mathbf{K}, \mathbf{R})\phi_0(\xi)$$
- ⇒ Schrödinger equation:  

$$[H - E]\chi_0(\mathbf{K}, \mathbf{R}) = 0$$

### Coupled-channels method

- ⇒ The Hamiltonian:  

$$H = T_R + h(\xi) + V(\mathbf{R}, \xi)$$
- ⇒ Internal states:  

$$h(\xi)\phi_n(\xi) = \varepsilon_n\phi_n(\xi)$$
- ⇒ Model wavefunction:  

$$\Psi_{\text{model}}(\mathbf{R}, \xi) = \phi_0(\xi)\chi_0(\mathbf{K}, \mathbf{R}) + \sum_{n>0} \phi_n(\xi)\chi_n(\mathbf{K}, \mathbf{R})$$
- ⇒ Schrödinger equation:  

$$[H - E]\Psi_{\text{model}}(\mathbf{R}, \xi) = 0$$

↓

$$[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{K}, \mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{K}, \mathbf{R})$$



## DWBA approximation as 1st order CC

⇒ Two-states model  $n = 0, 1$ :

$$\Psi(\mathbf{R}, \xi) = \underbrace{\phi_0(\xi)\chi_0(\mathbf{R})}_{\text{elastic}} + \underbrace{\phi_1(\xi)\chi_1(\mathbf{R})}_{\text{inelastic}}$$

⇒ Coupled-channels equations:

$$[E - \varepsilon_0 - T_0 - V_{00}(\mathbf{R})]\chi_0(\mathbf{R}) = V_{01}(\mathbf{R})\chi_1(\mathbf{R})$$

$$[E - \varepsilon_1 - T_1 - V_{11}(\mathbf{R})]\chi_1(\mathbf{R}) = V_{10}(\mathbf{R})\chi_0(\mathbf{R})$$

⇒ Iterative solution of the CC equations (DWBA):

$$[E - \varepsilon_0 - T_0 - V_{00}(\mathbf{R})]\chi_0(\mathbf{R}) \approx 0$$

$$[E - \varepsilon_1 - T_1 - V_{11}(\mathbf{R})]\chi_1(\mathbf{R}) \approx V_{10}(\mathbf{R})\chi_0(\mathbf{R})$$

## DWBA approximation as 1st order CC

⇒ Asymptotically:

$$\chi_1^{(+)}(\mathbf{R}) \rightarrow f_{10}(\theta) \frac{e^{iK_1 R}}{R}$$

with (not proven here!)

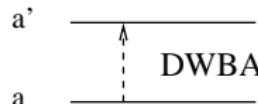
$$f_{10}(\theta) = -\frac{2\mu}{4\pi\hbar^2} \int d\mathbf{R} \tilde{\chi}_1^{(-)*}(\mathbf{K}_1, \mathbf{R}) V_{10}(\mathbf{R}) \tilde{\chi}_0^{(+)}(\mathbf{K}_0, \mathbf{R})$$

where  $\tilde{\chi}_0(\mathbf{K}_0, \mathbf{R}), \tilde{\chi}_1(\mathbf{K}_1, \mathbf{R})$  are solutions of:

$$[E - \varepsilon_0 - T_0 - V_{00}(\mathbf{R})] \tilde{\chi}_0(\mathbf{K}_0, \mathbf{R}) = 0$$

$$[E - \varepsilon_1 - T_1 - V_{11}(\mathbf{R})] \tilde{\chi}_1(\mathbf{K}_1, \mathbf{R}) = 0$$

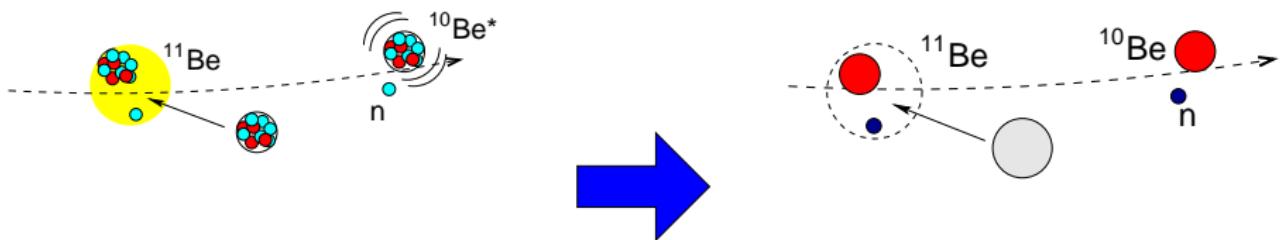
☞ The DWBA approximation amounts at solving the CC equations to 1st order (Born approximation)





## Single-particle and cluster excitations

Many-body to few-body reduction



$$\mathcal{V}_{pt} = \sum_{ij} V_{ij}(\mathbf{r}_{ij})$$

$$\mathcal{V}_{pt} = U_{ct}(\mathbf{r}_{ct}) + U_{nt}(\mathbf{r}_{nt})$$

⇒ Effective **three-body** Hamiltonian:

$$H = T_{\mathbf{R}} + h_r(\mathbf{r}) + U_{ct}(\mathbf{r}_{ct}) + U_{nt}(\mathbf{r}_{nt})$$

⇒  $U_{ct}(\mathbf{r}_{ct})$ ,  $U_{nt}(\mathbf{r}_{nt})$  are optical potentials describing fragment-target elastic scattering (eg. target excitation is treated effectively, through absorption)



## Inelastic scattering in a few-body model

- ⇒ Some nuclei allow a description in terms of two or more clusters:  
 $d=p+n$ ,  ${}^6\text{Li}=\alpha+d$ ,  ${}^7\text{Li}=\alpha+{}^3\text{H}$ .
- ⇒ Projectile-target interaction:

$$V(\mathbf{R}, \xi) \equiv V(\mathbf{R}, \mathbf{r}) = U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)$$

- ⇒ Transition potentials:

$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n^*(\mathbf{r}) [U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)] \phi_{n'}(\mathbf{r})$$



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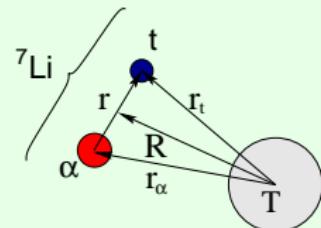
$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n^*(\mathbf{r}) [U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)] \phi_{n'}(\mathbf{r})$$

**Example:**  ${}^7\text{Li}=\alpha+t$

$$\mathbf{r}_\alpha = \mathbf{R} - \frac{m_t}{m_\alpha + m_t} \mathbf{r}; \quad \mathbf{r}_t = \mathbf{R} + \frac{m_\alpha}{m_\alpha + m_t} \mathbf{r}$$

**Internal states:** (two-body cluster model)

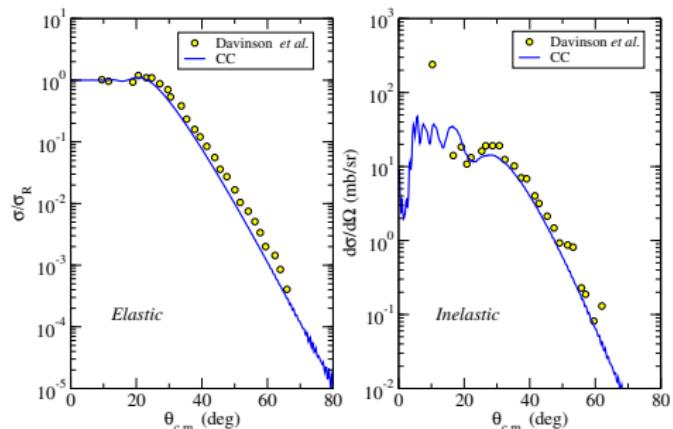
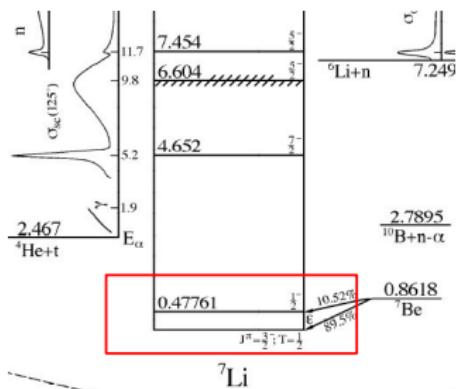
$$[T_{\mathbf{r}} + V_{\alpha-t}(\mathbf{r}) - \varepsilon_n] \phi_n(\mathbf{r}) = 0$$





## Example: ${}^7\text{Li}(\alpha+t) + {}^{208}\text{Pb}$ at 68 MeV

⇒ CC calculation with 2 channels ( $3/2^-$ ,  $1/2^-$ ):



Data from [Davinson et al, Phys. Lett. 139B \(1984\) 150](#)

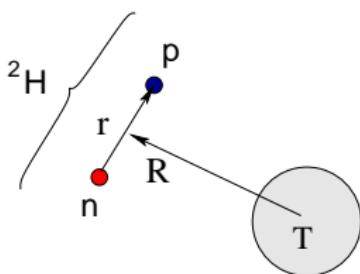
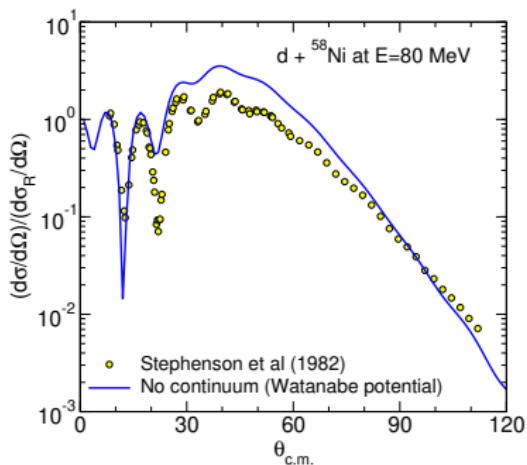
Fresco input available at <https://github.com/ammoro/IUAC>



## Application of the CC method to weakly-bound systems

**Example:** Three-body calculation ( $p+n+^{58}\text{Ni}$ ) with Watanabe potential:

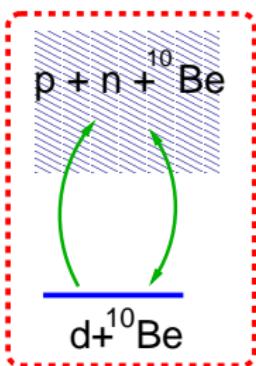
$$V_{dt}(\mathbf{R}) = \int d\mathbf{r} \phi_{gs}^*(\mathbf{r}) \left\{ V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt}) \right\} \phi_{gs}(\mathbf{r})$$



☞ Three-body calculations omitting breakup channels fail to describe the experimental data.

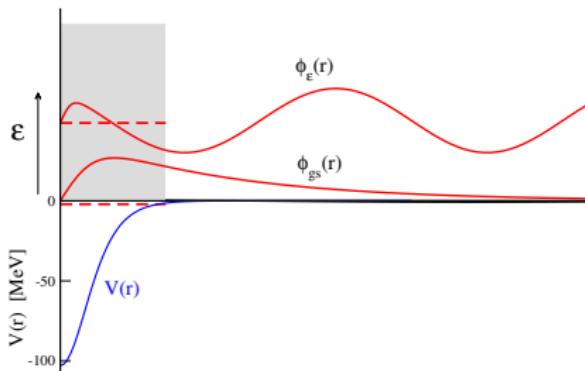


## Extension of the CC to unbound states



We want to include explicitly in the modelspace the breakup channels of the projectile or target.

## Bound versus scattering states

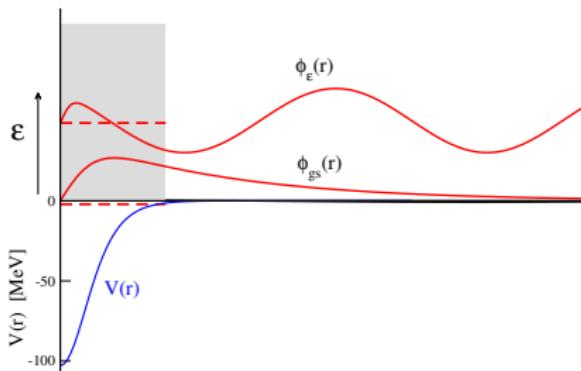


Continuum wavefunctions:

$$\varphi_{k,\ell jm}(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r} [Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

$$\epsilon = \frac{\hbar^2 k^2}{2\mu}$$

## Bound versus scattering states



Continuum wavefunctions:

$$\varphi_{k,\ell jm}(\mathbf{r}) = \frac{u_{k,\ell j}(r)}{r} [Y_\ell(\hat{r}) \otimes \chi_s]_{jm}$$

$$\epsilon = \frac{\hbar^2 k^2}{2\mu}$$

Unbound states are not suitable for CC calculations:

- ⇒ They have a continuous (infinite) distribution in energy.
- ⇒ Non-normalizable:  $\langle u_{k,\ell sj}(r) | u_{k',\ell sj}(r) \rangle \propto \delta(k - k')$

**SOLUTION ⇒ continuum discretization**



# The origins of CDCC

- ⇒ Continuum discretization method proposed by G.H. Rawitscher [PRC9, 2210 (1974)] and Farrell, Vincent and Austern [Ann.Phys.(New York) 96, 333 (1976)] to describe deuteron scattering as an effective three-body problem  $p + n + A$ .

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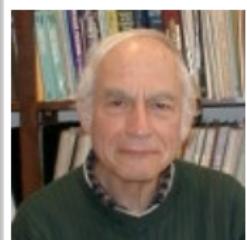
JUNE 1974

## Effect of deuteron breakup on elastic deuteron-nucleus scattering

George H. Rawitscher\*

*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,<sup>†</sup>  
and Department of Physics, University of Surrey, Guildford, Surrey, England  
(Received 1 October 1973; revised manuscript received 4 March 1974)*

The properties of the transition matrix elements  $V_{ab}(R)$  of the breakup potential  $V_N$  taken between states  $\phi_a(\vec{r})$  and  $\phi_b(r)$  are examined. Here  $\phi_a(\vec{r})$  are eigenstates of the neutron-proton relative-motion Hamiltonian, and the eigenvalues of the energy  $\epsilon_a$  are positive (continuum states) or negative (bound deuteron);  $V_N(\vec{r}, \vec{R})$  is the sum of the phenomenological proton-nucleus  $V_{p-A}(\vec{R} - \frac{1}{2}\vec{r})$  and neutron nucleus  $V_{n-A}(\vec{R} + \frac{1}{2}\vec{r})$  optical potentials evaluated for nucleon energies equal to half the incident deuteron energy. The bound-to-continuum transition matrix element for relative neutron-proton angular momenta  $l=2$  are found to be comparable in magnitude to the ones for  $l=0$  for values of  $\epsilon_a$  larger than about 3 MeV, and both decrease only slowly with  $\epsilon_a$ , suggesting that a large breakup spectrum is involved in deuteron-nucleus collisions. The effect of the various breakup transitions on the elastic phase shifts is estimated by numerically solving a set of coupled equations. These equations couple the functions  $\chi_a(\vec{R})$  which are the coefficients of the expansion of the neutron-proton-nucleus wave function in a set of the  $\phi_b(\vec{r})$ 's. The equations are rendered manageable by performing a (rather crude) discretization in the neutron-proton relative-momentum variable  $k_a$ . Numer-

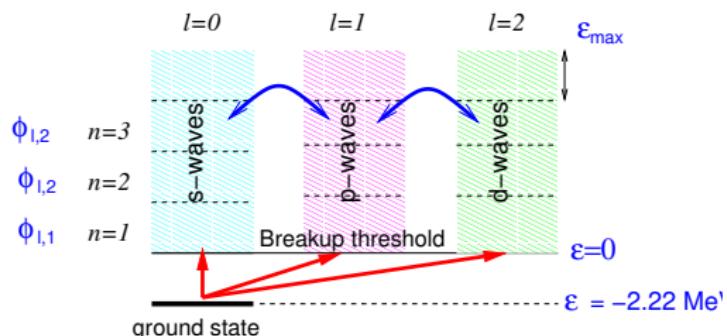


George Rawitscher  
(1928-2018)

- ⇒ Full numerical implementation by Kyushu group (Sakuragi, Yahiro, Kamimura, and co.):  
Prog. Theor. Phys.(Kyoto) 68, 322 (1982)



## Continuum discretization for deuteron scattering



- ⇒ Select a number of angular momenta ( $\ell = 0, \dots, \ell_{\max}$ ).
- ⇒ For each  $\ell$ , set a maximum excitation energy  $\epsilon_{\max}$ .
- ⇒ Divide the interval  $\epsilon = 0 - \epsilon_{\max}$  in a set of sub-intervals (*bins*).
- ⇒ For each *bin*, calculate a representative wavefunction.



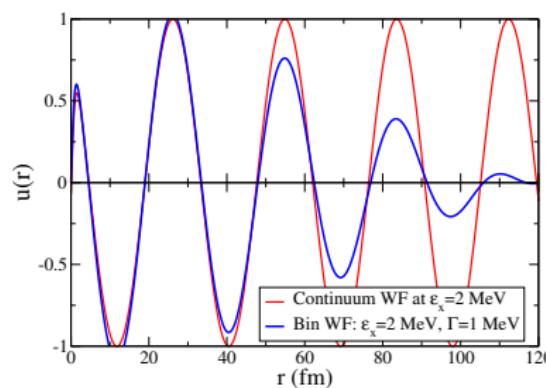
## CDCC formalism: construction of the bin wavefunctions

### Bin wavefunction:

$$\phi_{\ell jm}^{[k_1, k_2]}(\mathbf{r}) = \frac{u_{\ell j}^{[k_1, k_2]}(r)}{r} [Y_{\ell}(\hat{\mathbf{r}}) \otimes \chi_s]_{jm} \quad [k_1, k_2] = \text{bin interval}$$

$$u_{\ell sjm}^{[k_1, k_2]}(r) = \sqrt{\frac{2}{\pi N}} \int_{k_1}^{k_2} w(k) u_{k, \ell sj}(r) dk$$

- ⇒  $k$ : linear momentum
- ⇒  $u_{k, \ell sj}(r)$ : scattering states (radial part)
- ⇒  $w(k)$ : weight function



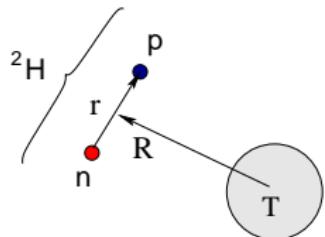


## CDCC formalism for deuteron scattering

- ⇒ Hamiltonian:  $H = T_{\mathbf{R}} + h_r(\mathbf{r}) + V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt})$
- ⇒ Model wavefunction:

$$\Psi^{(+)}(\mathbf{R}, \mathbf{r}) = \phi_{gs}(\mathbf{r})\chi_0(\mathbf{R}) + \sum_{n>0}^N \phi_n(\mathbf{r})\chi_n(\mathbf{R})$$

- ⇒ Coupled equations:  $[H - E]\Psi(\mathbf{R}, \mathbf{r}) = 0$



$$[E - \varepsilon_n - T_R - V_{n,n}(\mathbf{R})]\chi_n(\mathbf{R}) = \sum_{n' \neq n} V_{n,n'}(\mathbf{R})\chi_{n'}(\mathbf{R})$$

- ⇒ Transition potentials:

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n^*(\mathbf{r}) \left[ V_{pt}(\mathbf{R} + \frac{\mathbf{r}}{2}) + V_{nt}(\mathbf{R} - \frac{\mathbf{r}}{2}) \right] \phi_{n'}(\mathbf{r})$$



## Partial-wave decomposition of CDCC wavefunction

- ⇒ In practical calculations, the CDCC wf is expanded in the so-called **channel basis**

$$\langle \hat{R}, \mathbf{r}, |\beta; J_T \rangle = \left[ Y_L(\hat{R}) \otimes \phi_{n, J_p}(\mathbf{r}) \right]_{J_T}$$

$$\Psi_{\beta_0, J_T, M_T}(\vec{R}, \vec{r}, \xi) = \sum_{\beta} \frac{\chi_{\beta, \beta_0}^{J_T}(R)}{R} |\beta; J_T \rangle \quad \beta \equiv \{L, J_p, n\}$$

- ⇒ The radial coefficients verify

$$\left( -\frac{\hbar^2}{2\mu} \frac{d^2}{dR^2} + \frac{\hbar^2 L(L+1)}{2\mu R^2} + \varepsilon_n - E \right) \chi_{\beta, \beta_0}^{J_T}(R) + \sum_{\beta'} V_{\beta, \beta'}^{J_T}(R) \chi_{\beta'}^{J_T}(R) = 0$$

with the coupling potentials:

$$V_{\beta, \beta'}^{J_T}(R) = \langle \beta; J_T | V_1(\vec{R}, \vec{r}) + V_2(\vec{R}, \vec{r}) | \beta'; J_T \rangle$$

- ⇒ Boundary conditions:

$$\chi_{\beta, \beta_0}^{J_T}(R) \rightarrow e^{i\sigma_L} \frac{i}{2} \left[ H_L^{(-)}(K_{\beta} R) \delta_{\beta_0, \beta} - S_{\beta, \beta_0}^{J_T} H_L^{(+)}(K_{\beta} R) \right]$$



## Trivially equivalent local equivalent potential (TELP)

- From the elastic channel equation, a TELP can be defined as follows:

$$\left[ E - \varepsilon_0 - \hat{T}_{\mathbf{R}} - V_{0,0}(\mathbf{R}) \right] \chi_0(\mathbf{R}) = \sum_{i \neq 0} V_{i,0}(\mathbf{R}) \chi_i(\mathbf{R}) \equiv U_{\text{TELP}}(\mathbf{R}) \chi_0(\mathbf{R}).$$

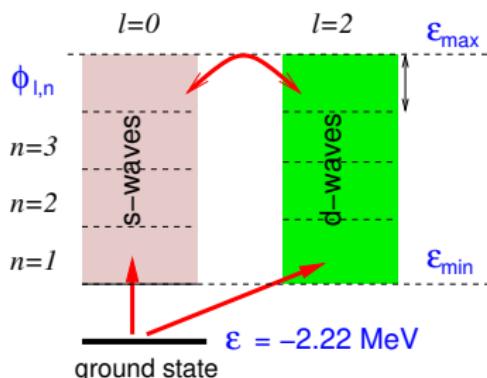
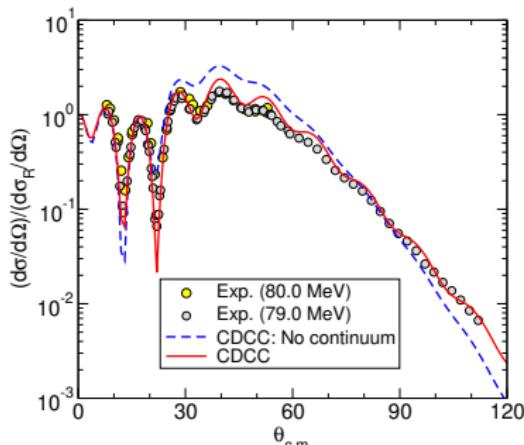
- In actual calculations,  $U_{\text{TELP}}(\mathbf{R})$  will depend on the total angular momentum, but a weighted average can be performed to obtain an approximate angular-momentum independent polarization potential
- A single channel calculation with the potential  $U(\mathbf{R}) = V_{0,0}(\mathbf{R}) + U_{\text{TELP}}(\mathbf{R})$  should reproduce approximately the elastic scattering cross section.



## Applications of the CDCC formalism: d+<sup>58</sup>Ni

Coupling to continuum states produce:

- ⇒ Polarization of the projectile (modification of real part)
- ⇒ Flux removal (absorption) from the elastic channel (imaginary part)

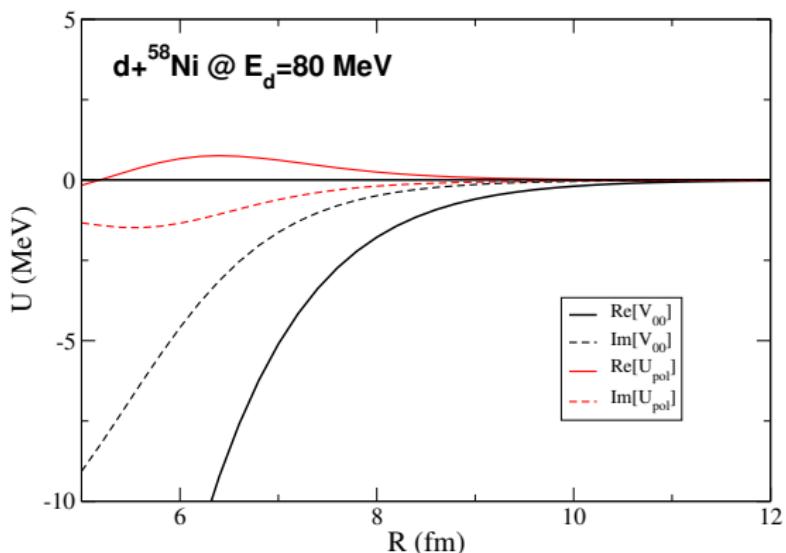


- ⇒ No continuum ⇒ retain only the Watanabe potential:

$$V_{00}(\mathbf{R}) = \int d\mathbf{r} \phi_{gs}(\mathbf{r}) (V_{pt} + V_{nt}) \phi_{gs}(\mathbf{r})$$



## Trivially equivalent local equivalent potential for d+<sup>58</sup>Ni @ 80 MeV



For this reaction, the TELP is complex:

- ⇒ The real part is **repulsive**
- ⇒ The imaginary part is **absorptive** (flux removal)



## Two- and three-body breakup observables

- CDCC scattering amplitudes readily provide **two-body breakup** observables:

$$\frac{d\sigma_n}{d\Omega_{\text{c.m.}}} = |f_{0,n}(\theta)|^2 \Rightarrow \frac{d^2\sigma}{d\Omega_{\text{c.m.}} d\epsilon_{pn}} \simeq \frac{1}{\Delta_n} \frac{d\sigma_n}{d\Omega_{\text{c.m.}}}$$

with:

- $\Delta_n$ =width of the bin containing the relative energy  $\epsilon_{pn}$
- $\Omega_{\text{c.m.}}$ =C.M. scattering angle of the projectile c.m. (not easy to measure!)

- Three-body observables** can be also calculated using a suitable combination of the scattering amplitudes and appropriate kinematical transformations ([Tostevin, PRC63, 024617 \(2001\)](#)):

$$\frac{d^3\sigma}{d\Omega_n d\Omega_p dE_p}$$

- N.b.:** These 3-body observables are not directly provided by FRESCO. They must be computed separately from the calculated amplitudes.

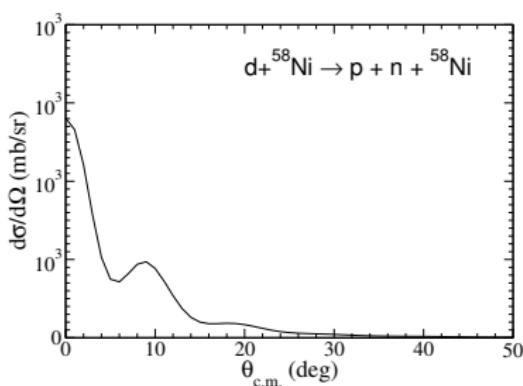


## Two-body breakup observables: $d + {}^{58}\text{Ni} \rightarrow p + n + {}^{58}\text{Ni}$

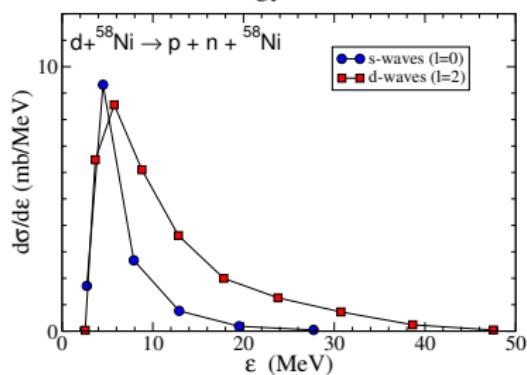
CDCC calculations for  $d + {}^{58}\text{Ni}$  at 80 MeV :

- ⇒ Continuum states with  $\ell = 0, 2$ .
- ⇒ Proton and neutron intrinsic spins ignored.
- ⇒  $p/n + {}^{58}\text{Ni}$  from global optical potential.
- ⇒  $p+n$  simple Gaussian interaction describing deuteron g.s.

$p + n$  c.m. angular distribution



Excitation energy distribution



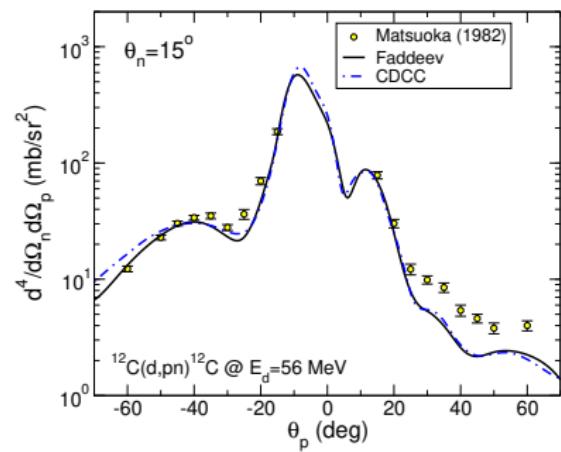
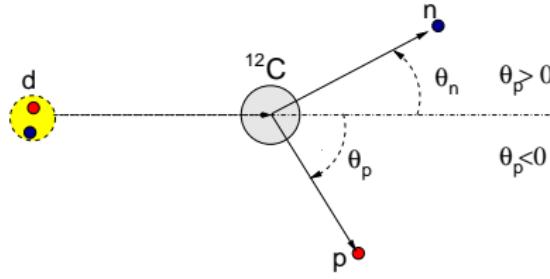


# Breakup observables with CDCC: exclusive breakup of $d + {}^{12}\text{C} \rightarrow p + n + {}^{12}\text{C}$

## CDCC calculations for $d + {}^{12}\text{C}$ at 56 MeV:

- ⇒ Continuum states with  $\ell \leq 8$  and  $\varepsilon_{\max} = 46$  MeV.
- ⇒ Proton and neutron intrinsic spins ignored
- ⇒  $p/n + {}^{58}\text{Ni}$  from Watson global optical potential
- ⇒  $p+n$  simple Gaussian interaction describing deuteron g.s.

**Data:** Matsuoka *et al.*, NPA391, 357 (1982).



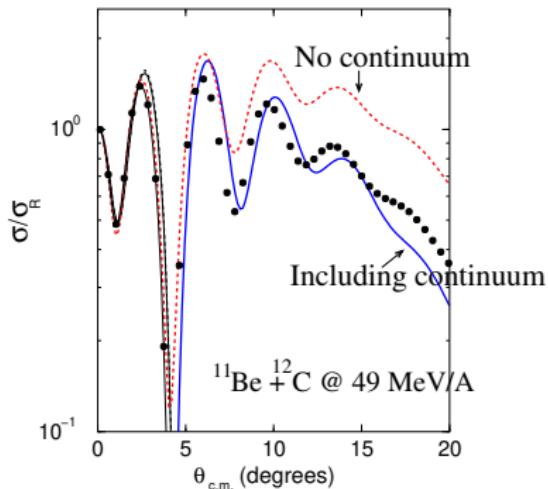
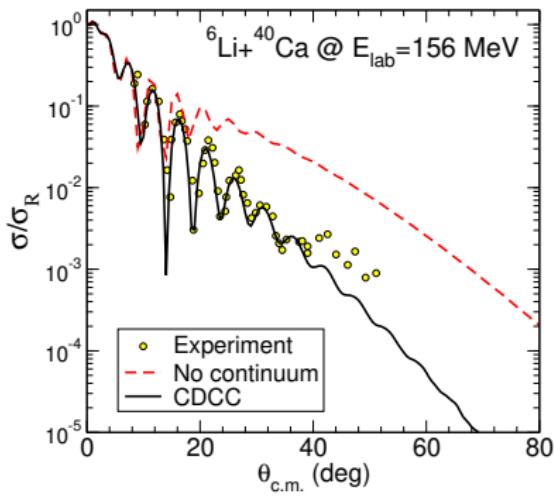
A.Deltuva, A.M.M., E.Cravo, F.M.Nunes, A.C.Fonseca, PRC 76, 064602 (2007)



## Application of the CDCC method to other weakly bound two-body nuclei

The CDCC has been also applied to nuclei with a cluster structure:

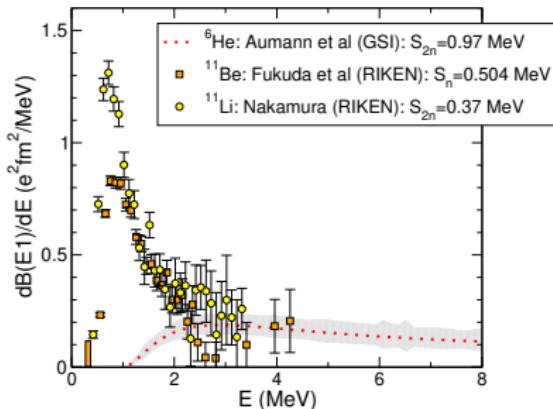
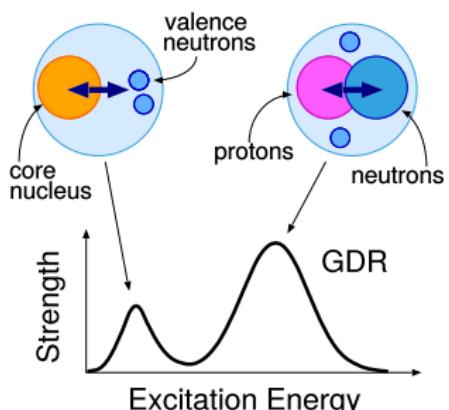
- ⇒  ${}^6\text{Li} = \alpha + \text{d}$  ( $S_{\alpha,d} = 1.47 \text{ MeV}$ )
- ⇒  ${}^{11}\text{Be} = {}^{10}\text{Be} + \text{n}$  ( $S_n = 0.504 \text{ MeV}$ )





## Exploring the continuum with breakup reactions

# Electric response of weakly-bound nuclei



- ⇒ The  $E\lambda$  response can be quantified through the  $B(E\lambda)$  probability:

$$B(E\lambda; i \rightarrow f) = \frac{1}{2I_i + 1} |\langle \Psi_f | \mathcal{M}(E\lambda) | \Psi_i \rangle|^2$$

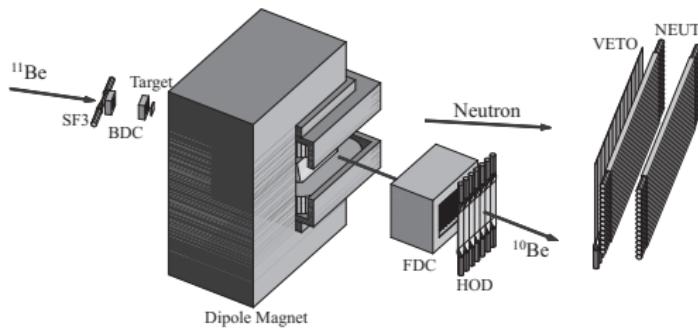
- ⇒ Neutron-halo nuclei have large  $B(E1)$  strengths near threshold



## How to probe/extract the $B(E1)$ of halo nuclei?

**Example:**  $^{11}\text{Be} + ^{208}\text{Pb} \rightarrow ^{10}\text{Be} + \text{n} + ^{208}\text{Pb}$  measured at RIKEN (69 MeV/u).

Fukuda et al, PRC70, 054606 (2004))



- 11Be excitation energy can be reconstructed from core-neutron coincidences (*invariant mass method*)

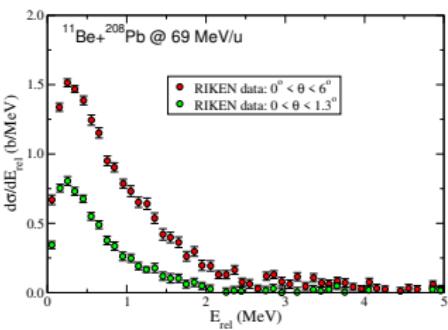
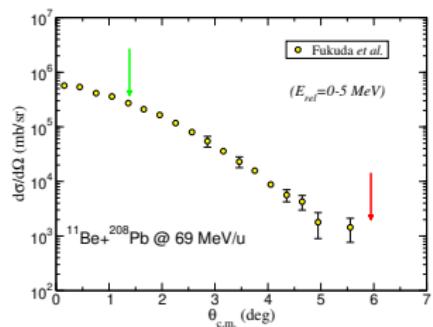


## What observables are measured in Coulomb dissociation experiments?

- ⇒ In a fully exclusive experiment, one can in principle measure the angular and relative energy distribution of the  $^{11}\text{Be}^*$  system:

$$\frac{d^2\sigma}{d\Omega dE_{\text{rel}}}$$

- ⇒ Integrating over the angle or energy, single differential cross sections are obtained:



- ⇒ In the Coulomb dominated region (i.e. small angles), the **breakup cross section** is expected to be dominated by the  $dB(E\lambda)/dE$  distribution, but we need a theory that relates both observables.



## Semiclassical 1st order E $\lambda$ excitation (Alder & Winther) (akin EPM method)

- For E $\lambda$  excitation to bound states ( $0 \rightarrow n$ ):

$$\left( \frac{d\sigma}{d\Omega} \right)_{0 \rightarrow n} = \left( \frac{Z_t e^2}{\hbar v} \right)^2 \frac{B(E\lambda, 0 \rightarrow n)}{e^2 a_0^{2\lambda-2}} f_\lambda(\theta, \xi)$$

$$\xi_{0 \rightarrow n} = \frac{(E_n - E_0)}{\hbar} \frac{a_0}{v}$$

- For continuum states (breakup):

$$\frac{d\sigma(E\lambda)}{d\Omega dE} = \left( \frac{Z_t e^2}{\hbar v} \right)^2 \frac{1}{e^2 a_0^{2\lambda-2}} \frac{dB(E\lambda)}{dE} \frac{df_\lambda(\theta, \xi)}{d\Omega}$$

- $dB(E\lambda)/dE$  can be extracted from small-angle Coulomb dissociation data.

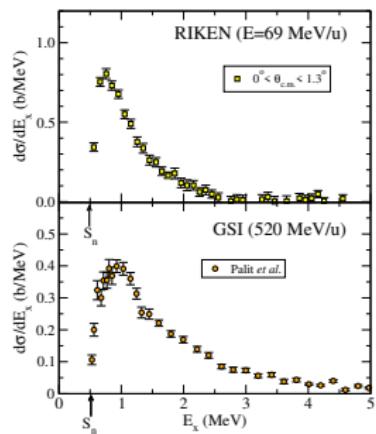
$$\frac{d\sigma}{dE}(\theta < \theta_{\max}) = \int_0^{\theta_{\max}} \frac{d\sigma(E\lambda)}{d\Omega dE} d\Omega \propto \frac{dB(E\lambda)}{dE}$$



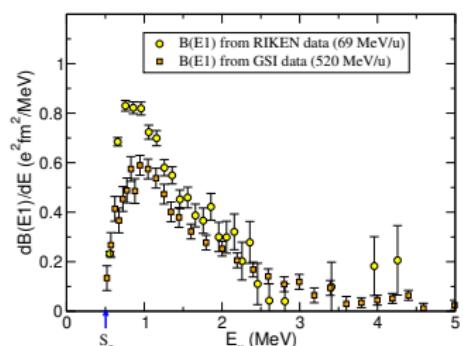
## Extracting $B(E1)$ of $^{11}\text{Be}$ from $^{11}\text{Be} + ^{208}\text{Pb}$ Coulomb dissociation

Common assumptions:

- ⇒ Breakup dominated by Coulomb excitation
- ⇒ Nuclear excitation, if present, can be estimated and added incoherently
- ⇒ If the assumptions above are fulfilled, the extracted  $dB(E\lambda)/dE$  should be independent of the incident energy and target employed, since it reflects a structure property of the projectile.



$$\frac{dB(E\lambda)}{dE} \propto \frac{d\sigma}{dE}$$



RIKEN: Fukuda et al, PRC70 (2004) 054606  
GSI: Palit et al, PRC68 (2003) 034318

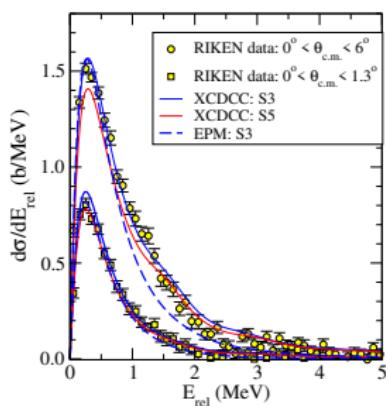
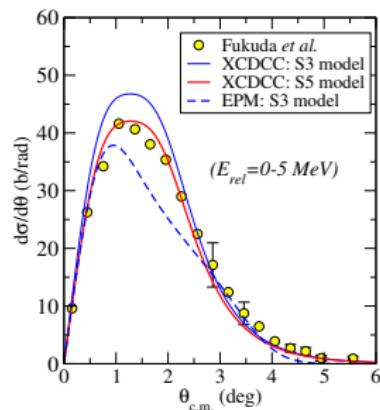
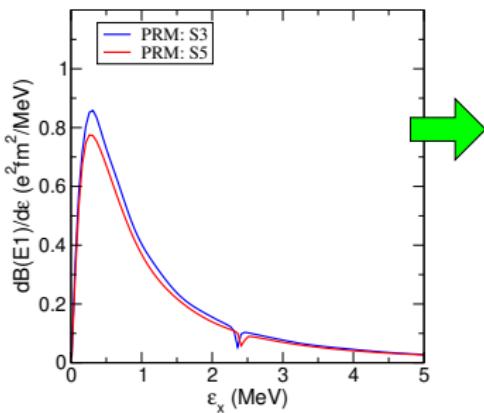
- ⇒ The extracted  $dB(E\lambda)/dE$  distributions are reasonably compatible, but with apparent differences at the peak



## CDCC analysis of Coulomb dissociation data

- ⇒ Nuclear excitation not negligible, even for small  $\theta$
- ⇒ Nuclear contribution interferes with Coulomb
- ⇒ Higher-order couplings can affect the cross sections
- ⇒ These ingredients can be naturally incorporated within the CDCC method (at the expense of more complexity!)

E.g.: CDCC analysis based on two-body  $^{10}\text{Be} + \text{n}$  model:



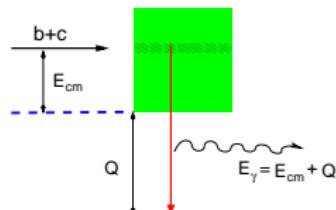
PLB 811 (2020) 135959

- ⇒ Different structure models yield different  $B(E1)$  strengths and hence different breakup cross sections
- ⇒ Comparison with the angular distribution evidences the deficiencies of the semiclassical EPM model

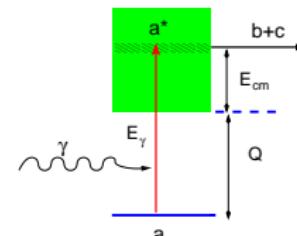


## Application to radiative capture reactions

Radiative capture:  $b + c \rightarrow a + \gamma$



Photodissociation:  $a + \gamma \rightarrow b + c$



⇒ Related by detailed balance:

$$\sigma_{E\lambda}^{(rc)} = \frac{2(2J_a + 1)}{(2J_b + 1)(2J_c + 1)} \frac{k_\gamma^2}{k^2} \sigma_{E\lambda}^{(phot)} \quad (\hbar k_\gamma = E_\gamma/c)$$

⇒ Astrophysical S-factor:

$$S(E_{c.m.}) = E_{c.m.} \sigma_{E\lambda}^{(rc)} \exp[2\pi\eta(E_{c.m.})]$$

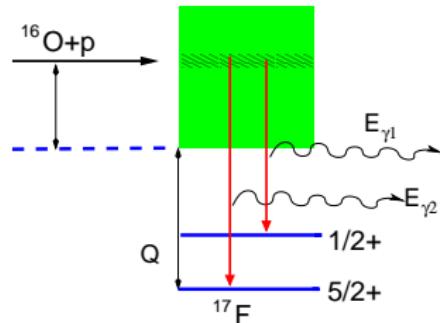
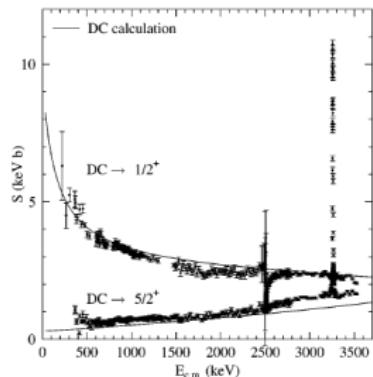
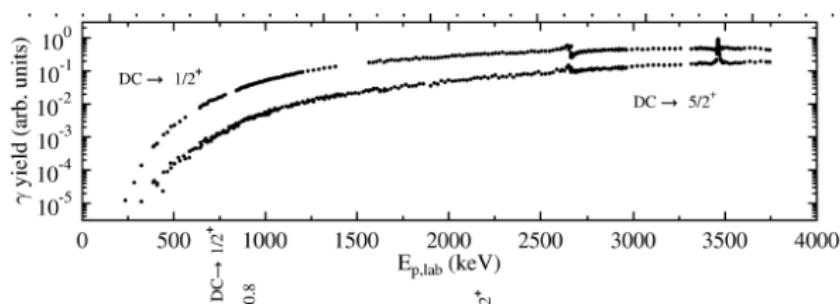
⇒ Capture cross sections are difficult to measure because they are very small at relevant astrophysical energies.



# Direct determination of radiative capture cross sections

**Example:**  $p + {}^{16}\text{O} \rightarrow {}^{17}\text{F} + \gamma$

Morlock, PRL79, 3837 (1997)





## Indirect determination of radiative capture from Coulomb breakup

⇒ The photodissociation ( $\gamma + a \rightarrow b + c$ ) cross section is related to the  $B(E\lambda)$

$$\sigma_{E\lambda}^{\text{photo}} = \frac{(2\pi)^3(\lambda + 1)}{\lambda[(2\lambda + 1)!!]^2} \left( \frac{E_\gamma}{\hbar c} \right)^{2\lambda-1} \frac{dB(E\lambda)}{dE}$$

⇒ Then, in 1st order semiclassical limit, the Coulomb breakup x-section is proportional to photodissociation x-section:

$$\boxed{\frac{d\sigma(E\lambda)}{d\Omega dE_\gamma} = \frac{1}{E_\gamma} \frac{dn_{E\lambda}}{d\Omega} \sigma_{E\lambda}^{\text{photo}}} \quad (\text{Equivalent Photon Method})$$

with the virtual photon number

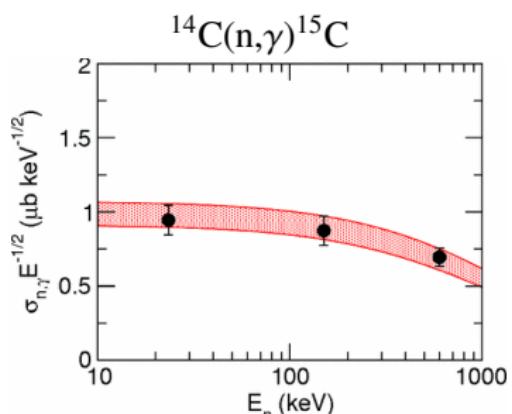
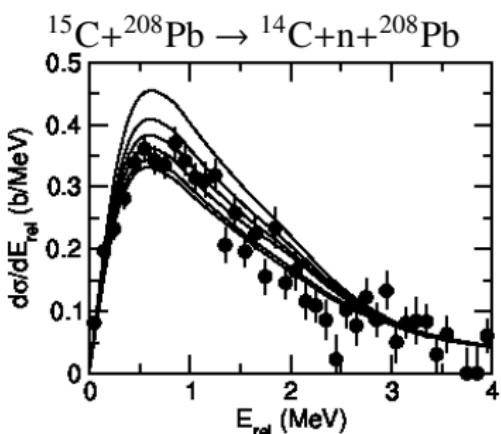
$$\frac{dn_{E\lambda}}{d\Omega} = Z_t^2 \alpha \frac{\lambda[(2\lambda + 1)!!]^2}{(2\pi)^3(\lambda + 1)} \xi^{2(1-\lambda)} \left( \frac{c}{v} \right)^{2\lambda} \frac{df_{E\lambda}}{d\Omega}$$



## Radiative capture from Coulomb dissociation experiments

- Capture reactions have typically small cross sections
- As an alternative, one can indirectly obtain the capture cross sections from Coulomb dissociation experiments involving the same two-body projectile:

$$\frac{d\sigma}{d\Omega dE_{c.m.}} \rightarrow \sigma_{E\lambda}^{(\text{phot})} \rightarrow \sigma_{E\lambda}^{(rc)} \rightarrow S(E_{\text{c.m.}})$$

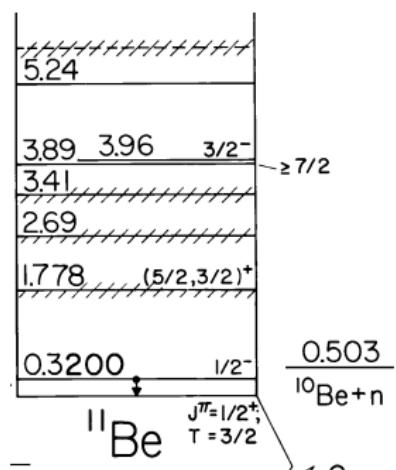


(dots: direct; shaded region: from Coulomb breakup)  
Summers and Nunes, PRC 78, 011601(R), 2008



## Exploring structures in the continuum

The continuum spectrum is not “homogeneous”; it contains in general energy regions with special structures, such as resonances and virtual states





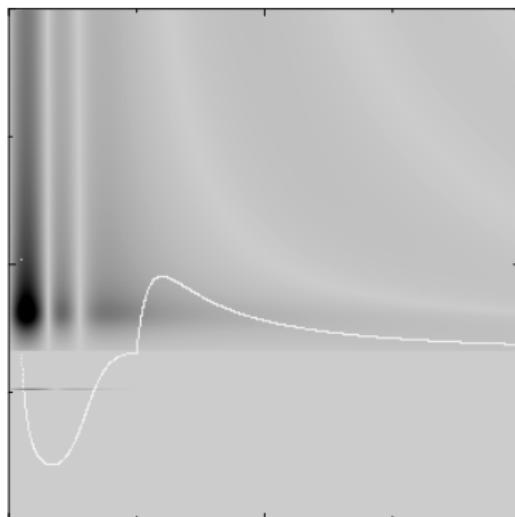
## What is a resonance?

- ⇒ It is a **pole** of the S-matrix in the complex energy plane.
- ⇒ It is a structure on the continuum which may, or may not, produce a **maximum in the cross section**, depending on the reaction mechanism and the phase space available.
- ⇒ The resonance occurs in the range of energies for which the **phase shift is close to  $\pi/2$** .
- ⇒ In this range of energies, **the continuum wavefunctions is largely localized** within the radial range of the potential.
- ⇒ The continuum wavefunctions are **not square normalizable**. For practical reasons, a normalized wave-packet (or “bin”) can be constructed to represent the resonance.



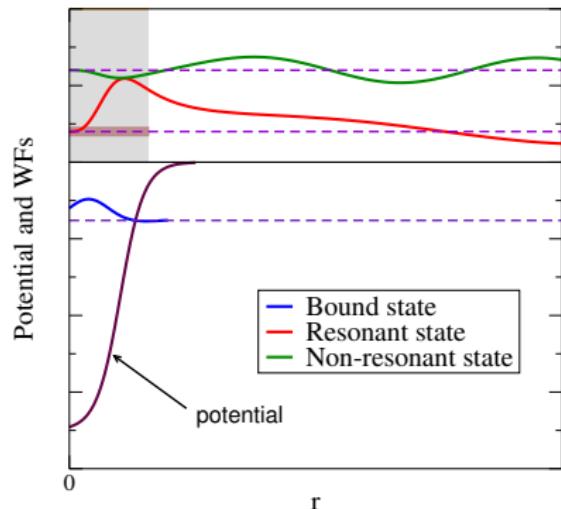
## Distinctive features of a resonance

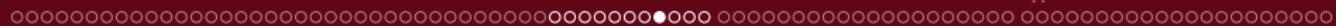
In the energy range of the resonance, the continuum wavefunctions have a large probability of being within the range of the potential.



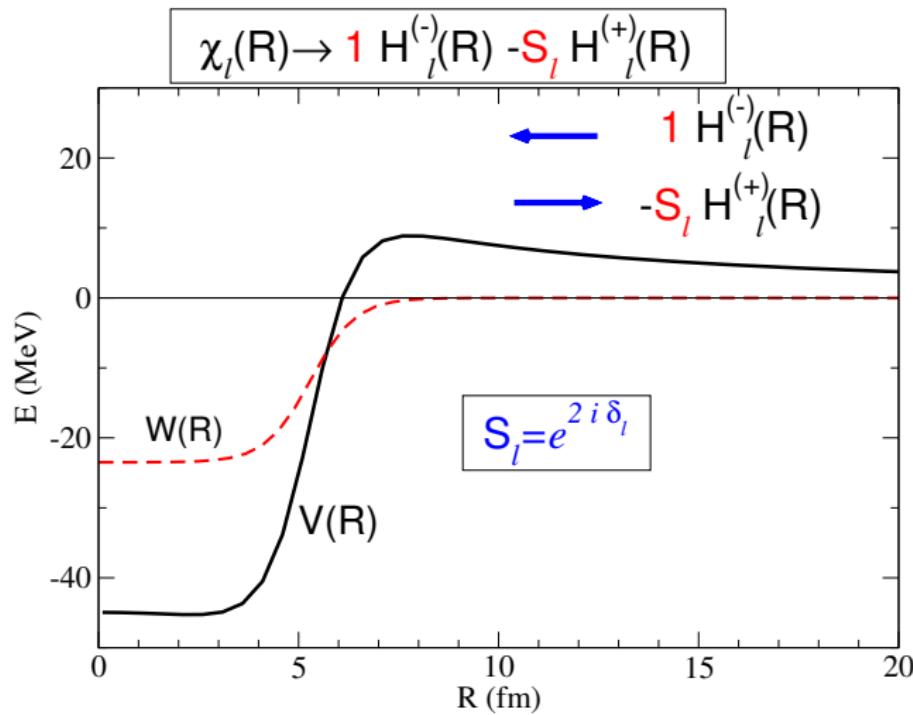
Cuts and areas ordered by size

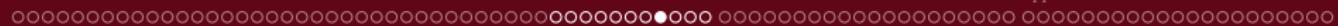
(Courtesy of C. Dasso)



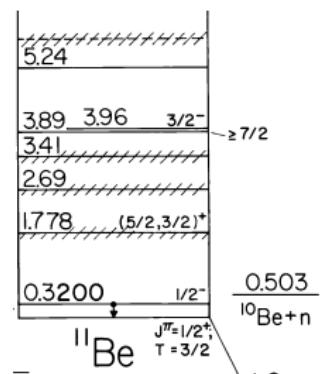
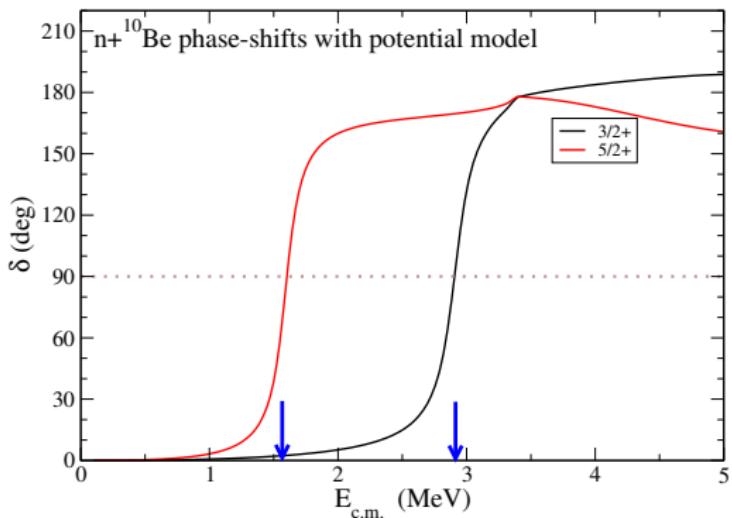


## Resonances and phase-shifts



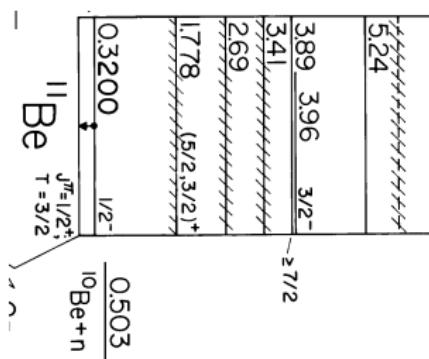
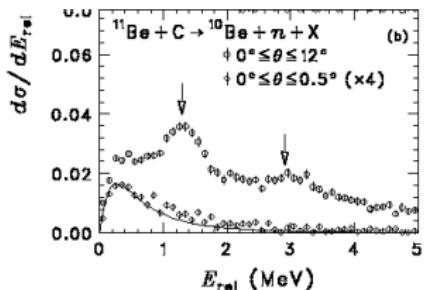


## Resonances and phase-shifts

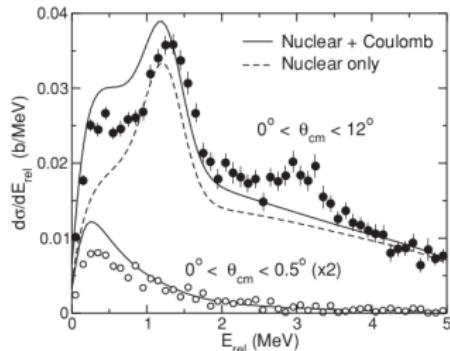
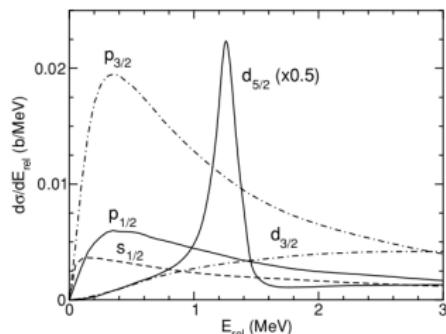


Studying resonances in nuclear breakup experiments

RIKEN data



CDCC analysis





## Proposed exercise

Consider a simple two-body model for a one-neutron halo nucleus. For E1 transitions, the electric transition probability is given by

$$\frac{dB(E1)}{dE_c} = \left( \frac{4\pi}{k} \right)^2 \frac{\mu k}{(2\pi)^3 \hbar^2} \frac{3}{4\pi} \left( \frac{Ze}{A} \right)^2 \left| \langle \ell_i 010 | \ell_f 0 \rangle \int dr r^2 \phi_f(k, r) \phi_i(r) \right|^2$$

where  $\mu$  is the reduced mass of the two-body system,  $\phi_i(r)$  is the radial part of the ground-state wavefunction and  $\phi_f(k, r)$  is the radial part of the positive-energy state with energy  $E_c = \hbar^2 k^2 / 2\mu$  and asymptotic behaviour  $\phi_f(k, r) \xrightarrow{r \gg} (kr) j_\ell(kr)$

- ⇒ Show that, in the special case in which the final states are approximated by plane waves, the  $B(E1)$  distribution is related to the Fourier transform of the ground state wavefunction. Give arguments to justify that, in the case of weakly bound systems, the  $B(E1)$  distribution is concentrated at low excitation energies.



## Exercises

- ⇒ In the situation above, the ground state wavefunction can be approximated by its asymptotic form which, for a  $s$ -wave configuration, can be written as

$$\phi_i(r) \simeq \sqrt{2k_0} e^{-k_0 r} / r.$$

Give the expression for  $k_0$  in terms of the neutron separation energy ( $S_n$ ) and the reduced mass of the neutron-core system. Compute it numerically for the  $^{11}\text{Be}$  ( $^{10}\text{Be} + n$ ) case.

- ⇒ Show that, under these approximations, the  $B(E1)$  distribution is given by

$$\frac{dB(E1)}{dE_c} = \frac{3\hbar^2}{\pi^2 \mu} \left( \frac{Ze}{A} \right)^2 \frac{\sqrt{S_n} E_c^{3/2}}{(E_c + S_n)^4}.$$

**Hint:**  $\int_0^\infty dr r^2 j_1(br) e^{-ar} = 2b/(a^2 + b^2)^2$

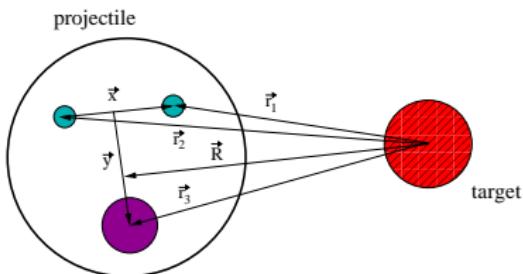
- ⇒ Show that the maximum of this  $B(E1)$  distribution is located at  $E_c = \frac{3}{5} S_n$ .



## Advanced CDCC applications



## Extension to 3-body projectiles



To extend the CDCC formalism, one needs to evaluate the new coupling potentials:

$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r} \phi_n^*(\mathbf{x}, \mathbf{y}) \{V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{at}(\mathbf{r}_3)\} \phi_{n'}(\mathbf{x}, \mathbf{y})$$

- ☞  $\phi_n(\mathbf{x}, \mathbf{y})$  three-body WFs for bound and continuum states: hyperspherical coordinates, Faddeev, etc (difficult to calculate!)



## Calculation of three-body states in the HH formalism

$$\Psi^{j\mu}(\rho, \Omega) = \rho^{-5/2} \sum_{\beta} \chi_{\beta}^j(\rho) \mathcal{Y}_{\beta}^{j\mu}(\Omega) \quad \beta \equiv \{K, l_x, l_y, l, S_x, J; I\}$$

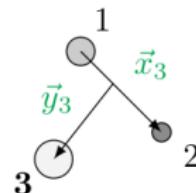
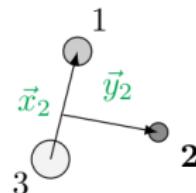
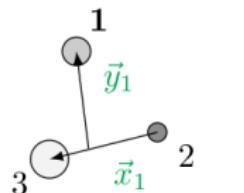
Hyperspherical Harmonics (HH) expansion

hypermomentum  $\hat{K}$

$$\mathcal{Y}_{\beta}^{j\mu}(\Omega) = \left[ \left( \Upsilon_{Klm_l}^{l_x l_y}(\Omega) \otimes \kappa_{S_x} \right)_J \otimes \phi_I \right]_{j\mu}$$

$$\Upsilon_{Klm_l}^{l_x l_y}(\Omega) = \varphi_K^{l_x l_y}(\alpha) [Y_{l_x}(\hat{x}) \otimes Y_{l_y}(\hat{y})]_{lm_l}$$

$$\varphi_K^{l_x l_y}(\alpha) = N_K^{l_x l_y} (\sin \alpha)^{l_x} (\cos \alpha)^{l_y} P_n^{l_x + \frac{1}{2}, l_y + \frac{1}{2}}(\cos 2\alpha)$$



**Jacobi  
coordinates**  
 $\{x, y, \hat{x}, \hat{y}\}$

**Hyperspherical  
coordinates**

$$\{\rho, \alpha, \hat{x}, \hat{y}\}$$

$$\rho = \sqrt{x^2 + y^2}$$

$$\alpha = \arctan \frac{x}{y}$$



## Calculation of three-body states in the HH formalism

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Hyperspherical Harmonics (HH) expansion

hypermomentum  $\hat{K}$

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$$\varphi_K^{l_x l_y}(\alpha) = N_K^{l_x l_y} (\sin \alpha)^{l_x} (\cos \alpha)^{l_y} P_n^{l_x + \frac{1}{2}, l_y + \frac{1}{2}} (\cos 2\alpha)$$

Hyperradial functions are the solution of the coupled equations:

$$\left[ -\frac{\hbar^2}{2m} \left( \frac{d^2}{d\rho^2} - \frac{15/4 + K(K+4)}{\rho^2} \right) - \varepsilon \right] \chi_{\beta}^j(\rho) + \sum_{\beta'} V_{\beta' \beta}^{j\mu}(\rho) \chi_{\beta'}^j(\rho) = 0$$

with coupling potentials  $V_{\beta' \beta}^{j\mu}(\rho)$ . Model space defined by a given  $K_{max}$



## Calculation of three-body states in the HH formalism

$$V_{\beta'\beta}^{j\mu}(\rho) = \left\langle \mathcal{Y}_{\beta}^{j\mu}(\Omega) \middle| V_{12} + V_{13} + V_{23} \middle| \mathcal{Y}_{\beta'}^{j\mu}(\Omega) \right\rangle + \delta_{\beta\beta'} V_{3b}(\rho)$$

- $V_{ij}$  interaction between pairs  
central, spin-orbit, spin-spin, tensor. To reproduce binary subsystem
- $V_{3b}$  phenomenological three-body force  
diagonal term. Fixed to fine-tune the three-body energies

### Pseudo-State (PS) method

$$\chi_{\beta}^j(\rho) = \sum_{i=0}^N C_{i\beta}^j U_{i\beta}(\rho) \quad \text{expanded in } \mathcal{L}^2 \text{ basis}$$

$N$ : number of hyperradial excitations included

$$\mathcal{H}\Psi_n^{j\mu} = \varepsilon_n \Psi_n^{j\mu}$$

- $\varepsilon_n < 0$  **bound states**
- $\varepsilon_n > 0$  **discretized continuum**

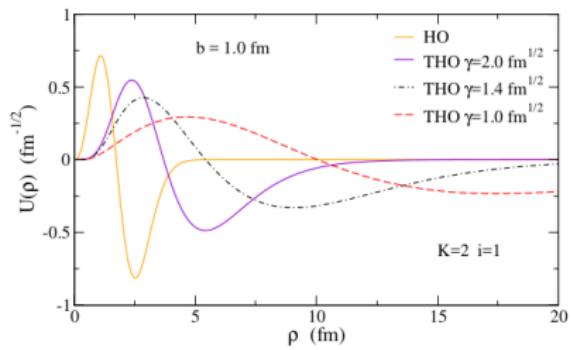


# Calculation of three-body states in the HH formalism

## Analytical Transformed Harmonic Oscillator (THO) basis

$$U_{i\beta}^{\text{THO}}(\rho) = \sqrt{\frac{ds}{d\rho}} U_{iK}^{\text{HO}}[s(\rho)]$$

$$s(\rho) = \frac{1}{\sqrt{2}b} \left[ \frac{1}{\left(\frac{1}{\rho}\right)^4 + \left(\frac{1}{\gamma\sqrt{\rho}}\right)^4} \right]^{\frac{1}{4}}$$

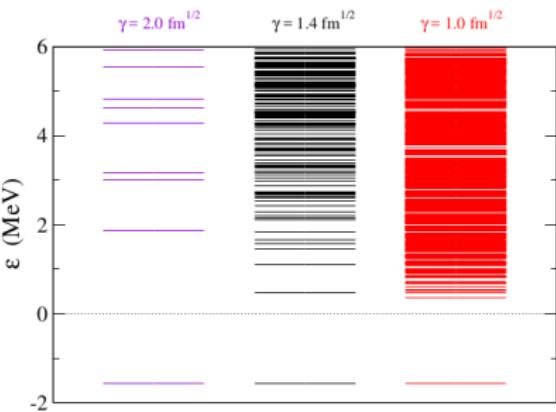


[PRC88(2013)014327]

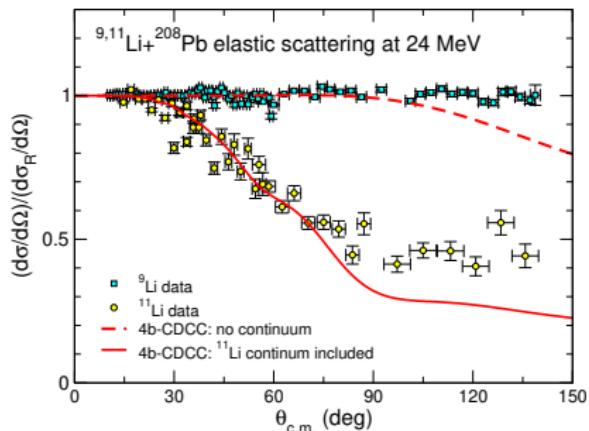
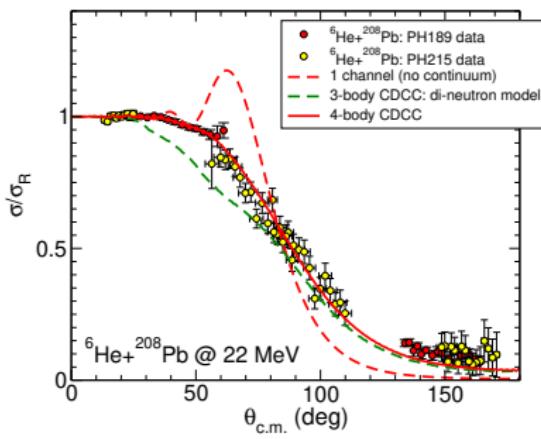
Example:

$\Psi_n^{j\mu}(\rho, \Omega)$  PS spectra,  $\varepsilon_n$   
 $b = 0.7$  fm

The ratio  $\gamma/b$  controls the density  
 of PS as a function of the energy.



# Four-body CDCC calculations for $^6\text{He}$ and $^{11}\text{Li}$ scattering



Data (LLN): NPA803, 30 (2008); PRC 84, 044604 (2011)

M Cubero et al, PRL109, 262701 (2012)

Calculations: PRC 80, 051601 (2009)

N.b.: 1-channel potential considers only g.s.  $\rightarrow$  g.s. coupling potential:

$$V_{00}(\mathbf{R}) = \int d\mathbf{r} \phi_{g.s.}^*(\mathbf{x}, \mathbf{y}) \{ V_{nt}(\mathbf{r}_1) + V_{nt}(\mathbf{r}_2) + V_{ct}(\mathbf{r}_3) \} \phi_{g.s.}(\mathbf{x}, \mathbf{y})$$

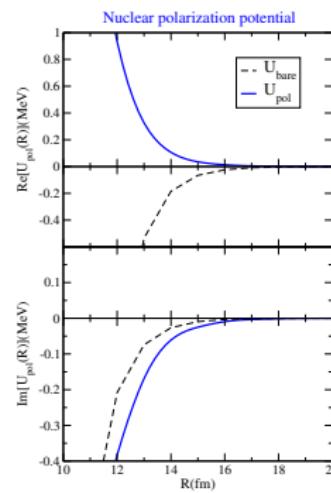
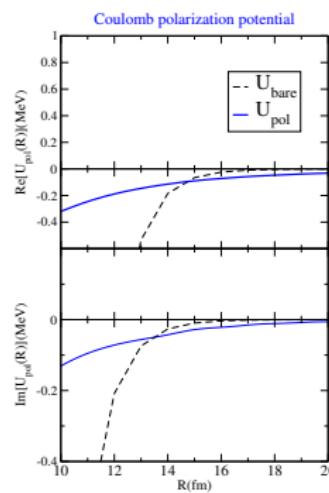


## Polarization potential for ${}^6\text{He} + {}^{208}\text{Pb}$ : long-range effect

Trivially Equivalent Local Polarization potential (TELP):

$$[E - \varepsilon_0 - \hat{T}_{\mathbf{R}} - V_{0,0}(\mathbf{R})] \chi_0(\mathbf{R}) = \sum_{i \neq 0} V_{i,0}(\mathbf{R}) \chi_i(\mathbf{R}) \equiv U_{\text{TELP}}(\mathbf{R}) \chi_0(\mathbf{R}).$$

Application to  ${}^6\text{He} + {}^{208}\text{Pb}$  at 22 MeV

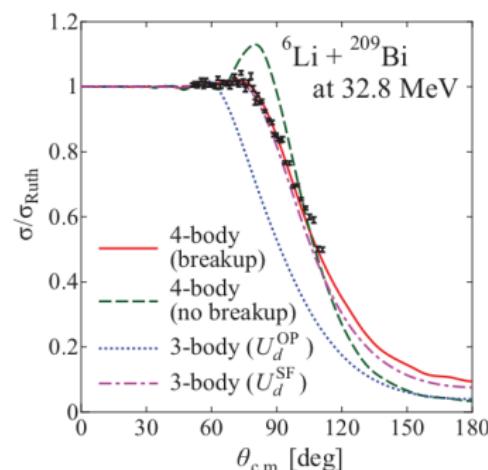
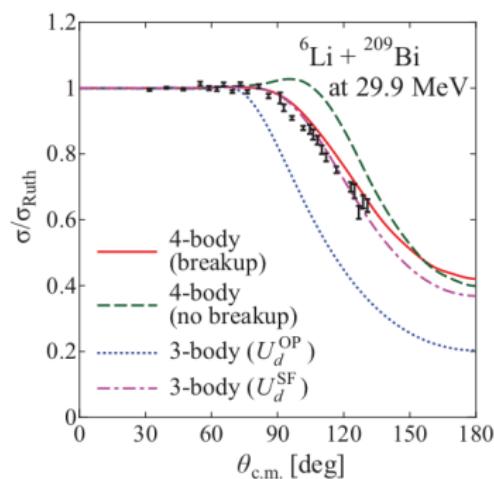


- ⇒ Imaginary part of TELP is long-ranged and absorptive (explains the need for large imaginary diffuseness parameter in OM analysis)
- ⇒ Real part is attractive for the Coulomb potential and repulsive for the nuclear couplings.

## Application to ${}^6\text{Li}$ scattering

**Example:**  ${}^6\text{Li} + {}^{209}\text{Bi}$  around Coulomb barrier

- ⇒ 4-body CDCC:  ${}^6\text{Li} = \alpha + p + n$
- ⇒ 3-body CDCC:  ${}^6\text{Li} = \alpha + d$

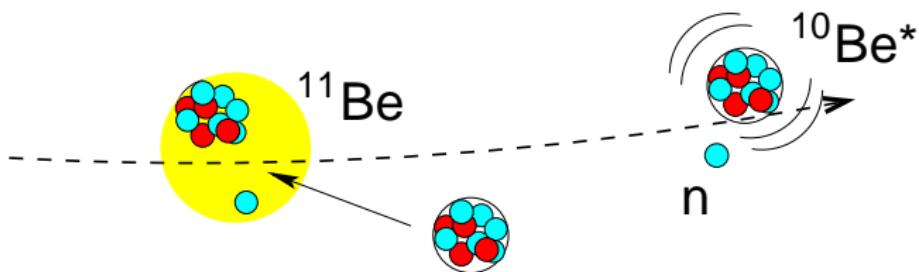


Watanabe *et al*, PRC 86, 031601(R) (2012)



## Beyond the strict few-body picture: the effect of core excitation

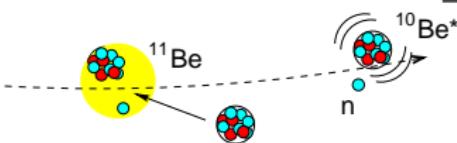
To what extent can one ignore the dynamics of the core?





## Few-body versus Microscopic

### Microscopic models

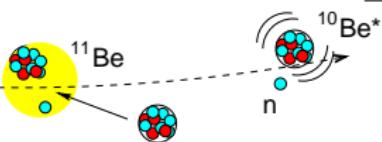


- ✓ Fragments described microscopically
- ✓ Realistic NN interactions (Pauli properly accounted for)
- ✗ Numerically demanding / not simple interpretation.



## Few-body versus Microscopic

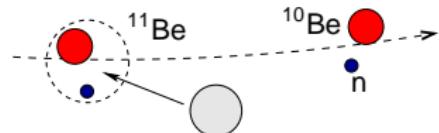
### Microscopic models



- ✓ Fragments described microscopically
- ✓ Realistic NN interactions (Pauli properly accounted for)
- ✗ Numerically demanding / not simple interpretation.

Many-body  
↑  
Few-body

### Inert cluster models

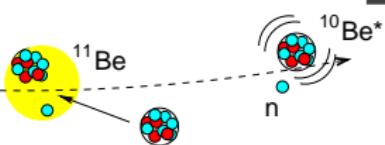


- ✗ Ignores cluster excitations (only few-body d.o.f.).
- ✗ Phenomenological inter-cluster interactions (aprox. Pauli).
- ✓ Exactly solvable (in some cases).
- ✓ Achieved for 3-body and 4-body (eg. coupled-channels, Faddeev).



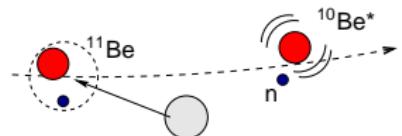
# Few-body versus Microscopic

## Microscopic models



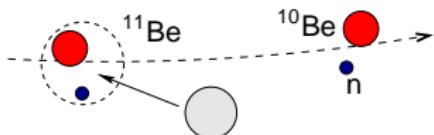
- ✓ Fragments described microscopically
- ✓ Realistic NN interactions (Pauli properly accounted for)
- ✗ Numerically demanding / not simple interpretation.

## Non-inert-core few-body models



- ✓ Few-body + some relevant collective d.o.f.
- ✓ Pauli approximately accounted for.
- ✓ Achieved for 3-body problems (coupled-channels, Faddeev).

## Inert cluster models



- ✗ Ignores cluster excitations (only few-body d.o.f.).
- ✗ Phenomenological inter-cluster interactions (aprox. Pauli).
- ✓ Exactly solvable (in some cases).
- ✓ Achieved for 3-body and 4-body (eg. coupled-channels, Faddeev).

Many-body ↑  
↓ Few-body



## Effect of core excitation in scattering observables

- ⇒ **Elastic** scattering (adiabatic recoil model): K. Horii *et al*, PRC81 (2010) 061602
  - ⇒ Some effects found in  ${}^8\text{B} + {}^{12}\text{C}$ .
- ⇒ Transfer (DWBA, CCBA, Faddeev): Winfield *et al*, NPA 683 (2001) 48, Fortier *et al*, PLB 461 (1999) 22, Deltuva, Phys.Rev. C 88, 011601 (2013)
- ⇒ Knock-out: Batham et al, PRC71, 064608 (2005)
  - ⇒ Small effect on stripping; large effect on diffraction
- ⇒ Breakup
  - DWBA: Crespo *et al*, PRC83, 044622 (2011), A.M.M. *et al* PRC85, 054613 (2012), A.M.M. and J.A. Lay, PRL109, 232502 (2012)
  - CDCC: Summers *et al*, PRC74, 014606(2006), PRC76,014611 (2007), De Diego *et al*, PRC89, 064609 (2014), PRC 95, 044611 (2017)

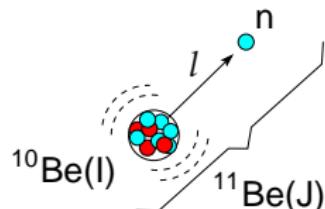


## How do core excitations affect the breakup of weakly-bound nuclei?

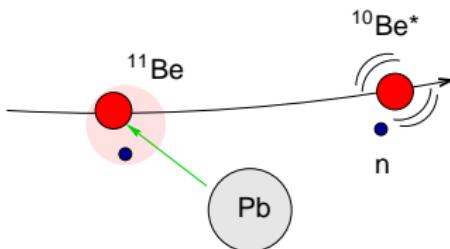
Core excitations will affect:

- ① the **structure** of the projectile  $\Rightarrow$  core-excited admixtures

$$\Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} [\varphi_{\ell,j,I}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$



- ② the **dynamics**  $\Rightarrow$  collective excitations of the  $^{10}\text{Be}$  during the collision compete with halo (single-particle) excitations.



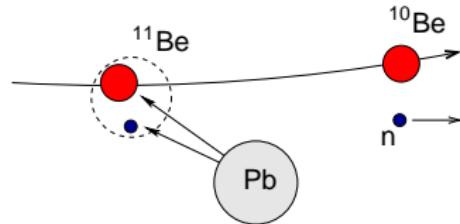
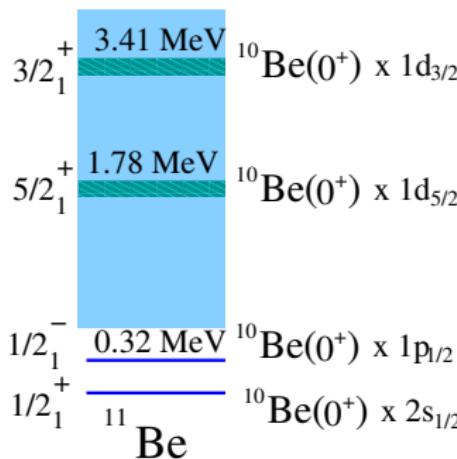
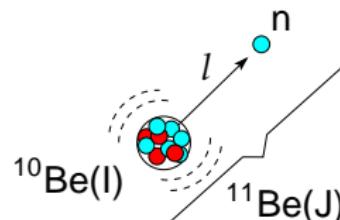
$\Rightarrow$  Both effects have been recently implemented in an extended version of the CDCC formalism (CDCC): Summers *et al*, PRC74 (2006) 014606, R. de Diego *et al*, PRC 89, 064609 (2014)



## Core excitation in reactions: *frozen-halo* picture

$$\Psi_{JM}(\vec{r}, \xi) = [\varphi_{\ell,j}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$

- ⇒  $\varphi_{\ell,j}^J(\vec{r})$ = valence particle wavefunction
- ⇒  $\Phi_I(\xi)$ = core wavefunction (*frozen*)

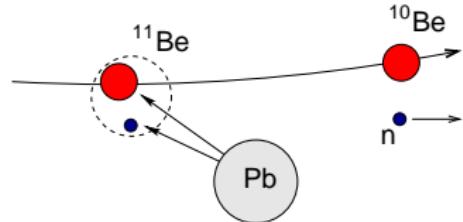
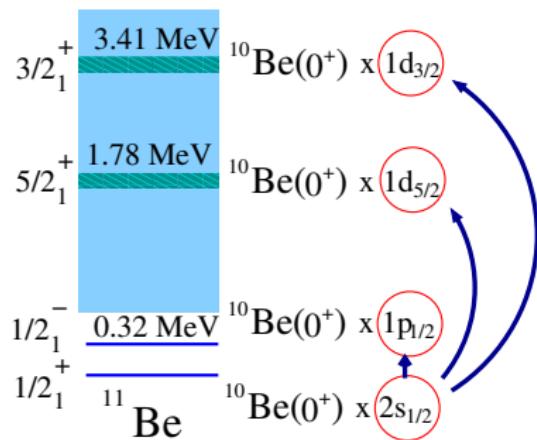
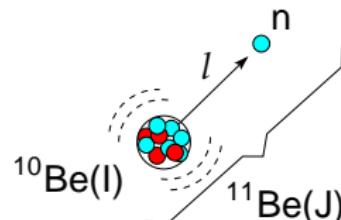




## Core excitation in reactions: *frozen-halo* picture

$$\Psi_{JM}(\vec{r}, \xi) = [\varphi_{\ell,j}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$

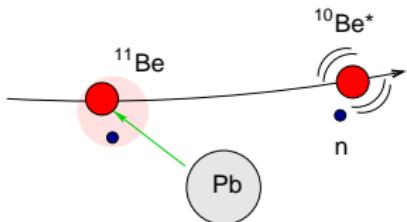
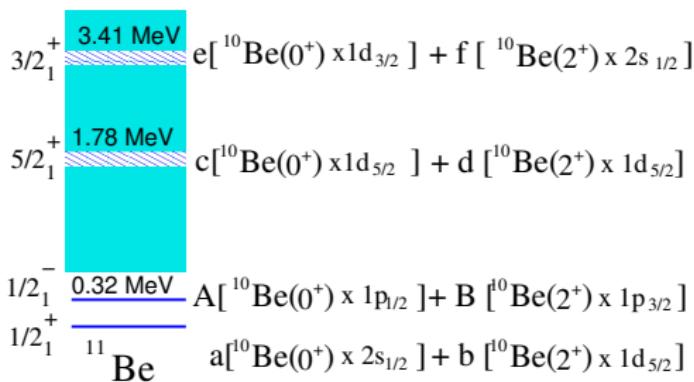
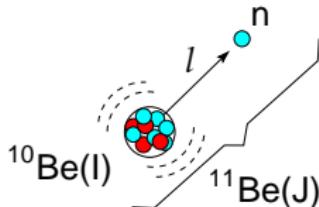
- ⇒  $\varphi_{\ell,j}^J(\vec{r})$ = valence particle wavefunction
- ⇒  $\Phi_I(\xi)$ = core wavefunction (*frozen*)





## Core excitation mechanism in breakup

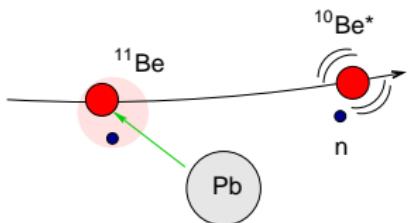
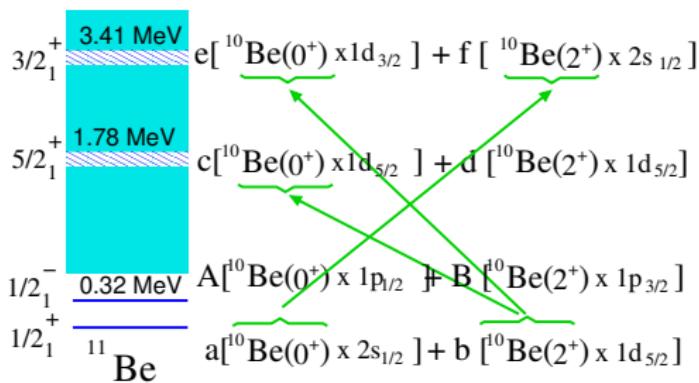
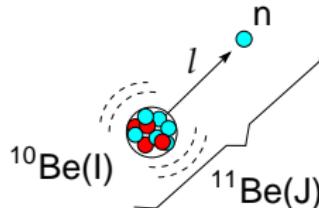
$$\Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} [\varphi_{\ell,j,I}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$





## Core excitation mechanism in breakup

$$\Psi_{JM}(\vec{r}, \xi) = \sum_{\ell,j,I} [\varphi_{\ell,j,I}^J(\vec{r}) \otimes \Phi_I(\xi)]_{JM}$$



☞ Dynamic core excitation contributes to the inelastic/breakup probabilities



## Extending CDCC to include core excitations

⇒ Standard CDCC ⇒ use coupling potentials:

$$V_{\alpha;\alpha'}(\mathbf{R}) = \langle \Psi_{J'M'}^{\alpha'}(\vec{r}) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}) | \Psi_{JM}^{\alpha}(\vec{r}) \rangle$$

⇒ Extended CDCC (XCDCC) ⇒ use generalized coupling potentials

$$V_{\alpha;\alpha'}(\mathbf{R}) = \langle \Psi_{J'M'}^{\alpha'}(\vec{r}, \xi) | V_{vt}(r_{vt}) + V_{ct}(r_{ct}, \xi) | \Psi_{JM}^{\alpha}(\vec{r}, \xi) \rangle$$

- ☞  $\Psi_{JM}^{\alpha}(\vec{r}, \xi)$ : projectile WFs involving core-excited admixtures (**structure**).
- ☞  $V_{ct}(r_{ct}, \xi)$ : non-central potential allowing for core excitations/de-exitations (**dynamic** core excitation).

- Summers *et al*, PRC74 (2006) 014606 (bins)
- R. de Diego *et al*, PRC 89, 064609 (2014) (THO pseudo-states)



## Evidences of core excitation in nuclear breakup



## Structure part: particle-core model

- ⇒ Particle-plus-core Hamiltonian:

$$H_{\text{proj}} = T_r + h_{\text{core}}(\xi) + V_{vc}(\vec{r}, \xi)$$

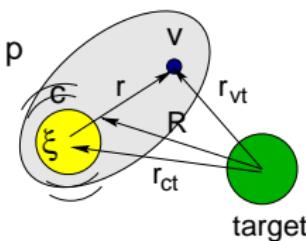
- ⇒ Projectile states expanded in  $|\alpha; JM\rangle \equiv |(\ell s)j, I; JM\rangle$  basis:

$$\Psi_{JM}(\vec{r}, \xi) = \sum_{\ell, j, I} R_{\ell, j, I}^J(r) \left[ [Y_\ell(\hat{r}) \otimes \chi_s]_j \otimes \Phi_I(\xi) \right]_{JM}$$

- ⇒ The unknowns  $R_{\ell, j, I}^J(r)$  can be obtained by direct integration of the Schrödinger equation or by diagonalization in a suitable discrete basis (pseudo-state method).



## Valence-core and core-target interactions in a simple collective model



⇒ Valence-core:

$$V_{vc}(\vec{r}, \xi) \simeq V_{vc}^{(0)}(r) - \delta_2 \frac{dV_{vc}^{(0)}}{dr} Y_{20}(\hat{r})$$

⇒ Core-target:

$$V_{ct}(\vec{r}_{ct}, \xi) \simeq \underbrace{V_{ct}^{(0)}(r_{ct})}_{\text{Valence excitation}} - \underbrace{\delta_2 \frac{dV_{ct}^{(0)}}{dr} Y_{20}(\hat{r}_{ct})}_{\text{Core excitation}}$$

$$\delta_2 = \beta_2 R_0 = \text{deformation length}$$

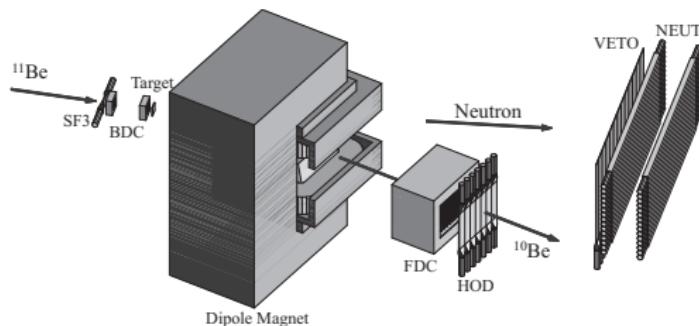
⇒ More sophisticated models for the projectile structure and core-target interaction are possible!



## Exclusive breakup measurements of halo nuclei

### RIKEN experiments:

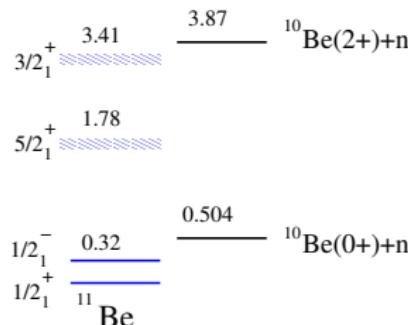
- ☞  $^{19}\text{C} + \text{p}$ : Satou et al., PLB660 (2008) 320
- ☞  $^{11}\text{Be} + ^{12}\text{C}$ : Fukuda et al, PRC70, 054606 (2004)



- ☞ Excitation energy and angular distribution of the projectile can be reconstructed from core-neutron coincidences (*invariant mass method*)



## Application to $^{11}\text{Be}$ : spectroscopic factors



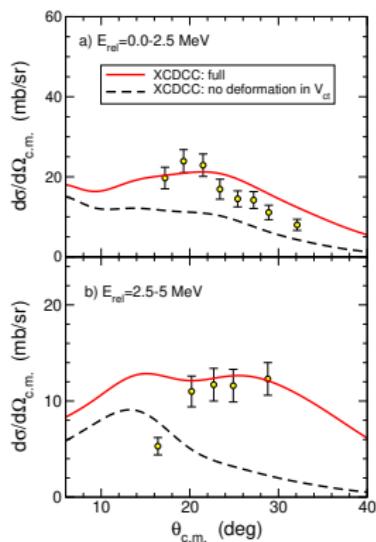
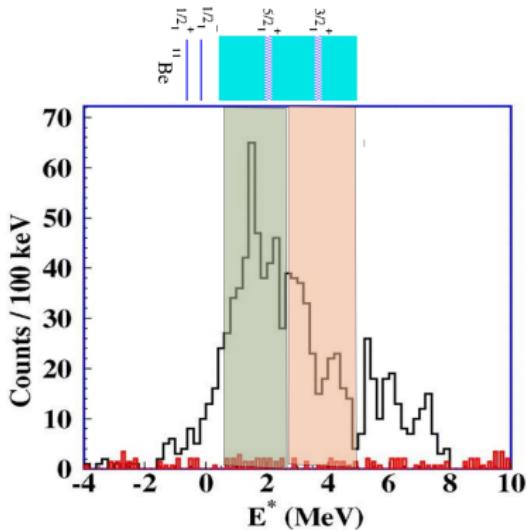
State	Model	$ 0^+ \otimes (\ell s)j\rangle$	$ 2^+ \otimes s_{1/2}\rangle$	$ 2^+ \otimes d_{5/2}\rangle$
$1/2_1^+$ (g.s.)	PRM	0.857	–	0.121
	SM (WBT)	0.76	–	0.184
$5/2_1^+$ (1.78 MeV)	PRM	0.702	0.177	0.112
	SM(WBT)	0.682	0.177	0.095
$3/2_1^+$ (3.41 MeV)	PRM	0.165	0.737	0.081
	SM(WBT)	0.068	0.534	0.167

- ⇒  $1/2_1^+, 5/2_1^+ \Rightarrow$  dominant  ${}^{10}\text{Be}(\text{gs}) \otimes nlj$  configuration
- ⇒  $3/2_1^+ \Rightarrow$  dominant  ${}^{10}\text{Be}(2^+) \otimes 2s_{1/2}$  configuration



## Evidence of *dynamical* core excitations in p( $^{11}\text{Be},\text{p}'$ ) at 64 MeV/u (MSU)

Data: Shrivastava et al, PLB596 (2004) 54 (MSU)



R.de Diego et al, PRC85, 054613 (2014)

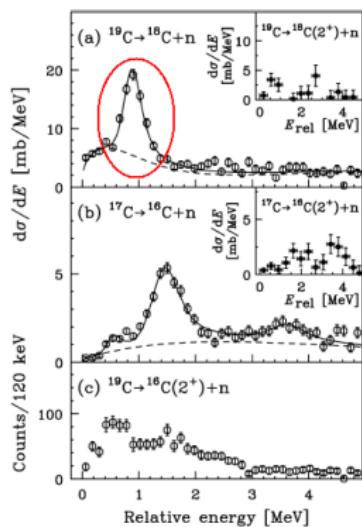
- ⇒  $E_{rel}=0\text{--}2.5$  MeV contains  $5/2^+$  resonance (expected **single-particle** mechanism)
- ⇒  $E_{rel}=2.5\text{--}5$  MeV contains  $3/2^+$  resonance (expected **core excitation** mechanism)

⇒ Dynamical core excitations give additional (and significant!) contributions to breakup

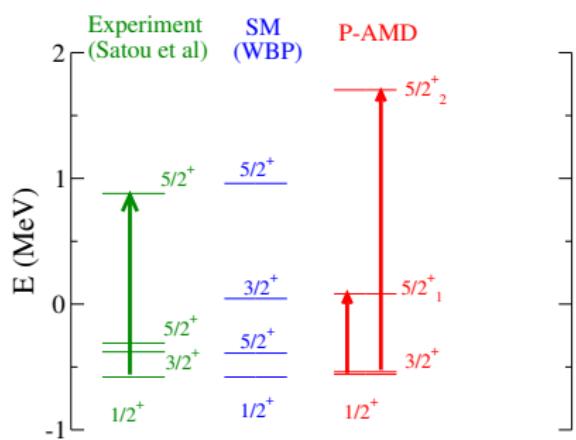


# Dominance of dynamical core excitations in $^{19}\text{C}$ resonant breakup

$^{19}\text{C} + \text{p} \rightarrow ^{18}\text{C} + \text{n} + \text{p}$  @ 70 MeV/u (RIKEN)



Satou et al, PLB660 (2008) 320

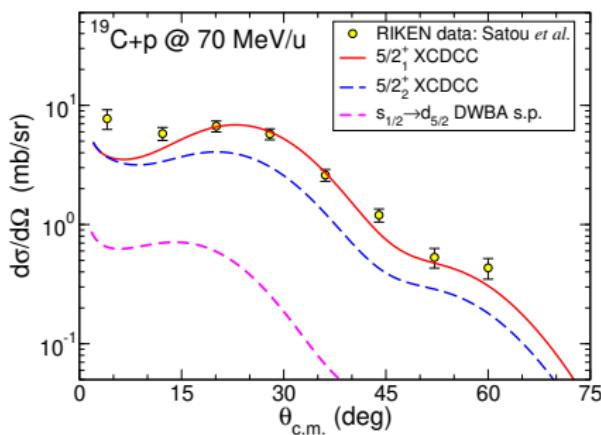
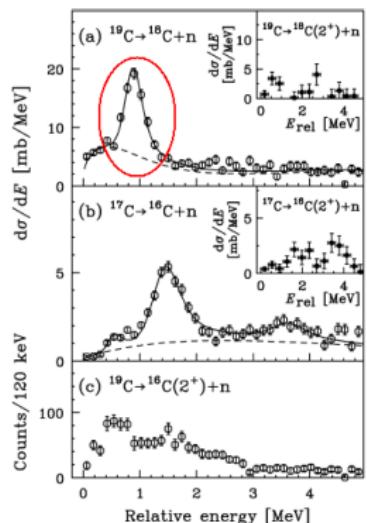


- ⇒ No general consensus about the  $^{19}\text{C}$  spectrum.
- ⇒ Resonant peak consistent with  $5/2_1^+$ ,  $5/2_2^+$  or even a combination of both.



## Dominance of *dynamical* core excitations in $^{19}\text{C}$ resonant breakup

$^{19}\text{C} + \text{p} \rightarrow ^{18}\text{C} + \text{n} + \text{p}$  @ 70 MeV/u (RIKEN)



J.A. Lay et al, PRC 94, 021602 (2016)

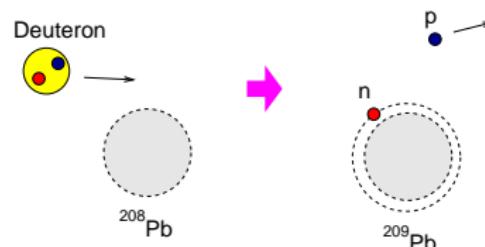
Satou et al, PLB660 (2008) 320

⇒ The core-excitation mechanism gives the dominant contribution to the cross section

## Transfer reactions



## Outline



Example:  $\text{d} + ^{208}\text{Pb} \rightarrow \text{p} + ^{209}\text{Pb}$

### ① What do we measure in a transfer reaction?

- ① For a typical transfer reaction (e.g.  $\text{d} + ^{208}\text{Pb} \rightarrow \text{p} + ^{209}\text{Pb}$ ), one measures the **angular** and **energy** distribution of outgoing fragments (e.g. protons).
- ② Additionally, one may collect information of decay products of  $^{209}\text{Pb}$  (e.g.  $\gamma$ -rays, n, p, etc)

### ② What information can we infer from a transfer reaction?

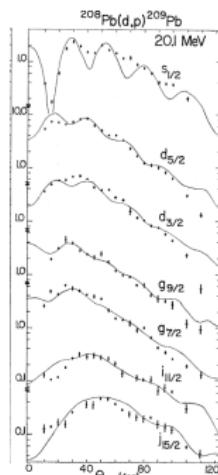
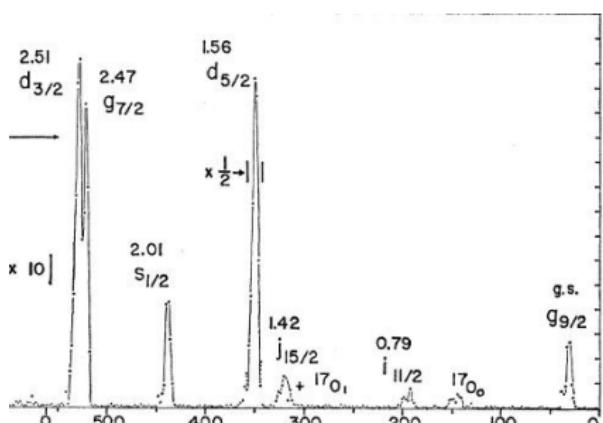
- ① **Excitation energies** of the residual nucleus ( $^{209}\text{Pb}$ ).
- ② **Angular momentum** assignment.
- ③ Single-particle content of populated states (i.e. **spectroscopic factors**).



## What do we measure in a transfer reaction?

Example:  $d + {}^{208}\text{Pb} \rightarrow p + {}^{209}\text{Pb}$

Phys. Rev. 159 (1967) 1039

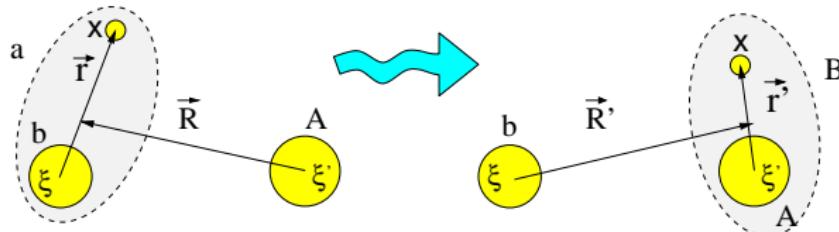


- ☞ The proton energy spectrum shows some peaks which reflect the **energy spectrum** of the residual nucleus ( ${}^{209}\text{Pb}$ ).
- ☞ Each peak has a characteristic **angular distribution**, which depends on the structure of the associated state.
- ☞ The population probability will depend on the **reaction dynamics** and on the **structure properties** of these states.

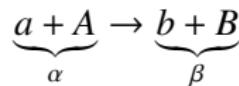


## DWBA method for transfer reactions

⇒ Transfer process:  $\underbrace{(b + x)}_a + A \rightarrow b + \underbrace{(A + x)}_B$

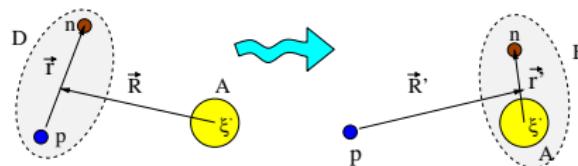


⇒ Complications arise with respect to inelastic scattering because now we have two different mass partitions involved





## The important ( $d, p$ ) case



- Introduce auxiliary potentials in entrance ( $U_\alpha(\mathbf{R})$ ) and exit ( $U_\beta(\mathbf{R}')$ ) channels.
- Projectile-target interaction:  $V_\beta = V_{pn} + U_{pA} = U_{pB}(\mathbf{R}') + \underbrace{V_{pn} + U_{pA} - U_{pB}}_{\Delta V_\beta} \equiv U_\beta(\mathbf{R}') + \Delta V_\beta$
- Post-form DWBA transition amplitude:

$$\mathcal{T}_{d,p}^{\text{DWBA}} = \int \int \underbrace{\chi_p^{(-)*}(\mathbf{K}_p, \mathbf{R}') \Phi_B(\xi', \mathbf{r}')}_{\text{Final state}} \underbrace{(V_{pn} + U_{pA} - U_{pB})}_{\Delta V_\beta} \underbrace{\chi_d^{(+)}(\mathbf{K}_d, \mathbf{R}) \varphi_d(\mathbf{r}) \phi_A(\xi') d\xi' d\mathbf{r}' d\mathbf{R}'}_{\text{Initial state}}$$

- ⇒  $\chi_{\alpha,\beta}^{(\pm)}$  are distorted waves for entrance and exit channels, obtained with the optical potentials  $U_\alpha(\mathbf{R})$ ,  $U_\beta(\mathbf{R}')$
- For medium-mass/heavy targets:  $U_{pA} \approx U_{pB} \Rightarrow V_{pn} + U_{pA} - U_{pB} \approx V_{pn}(\mathbf{r})$



## $(d, p)$ case: parentage decomposition of target nucleus

⇒ Approximation of the **overlap integral**

$$\int d\xi' \phi_B^*(\xi', \mathbf{r}') \phi_A(\xi') \approx C_{BA}^{\ell j} \varphi_{nA}^{\ell j}(\mathbf{r}')$$

- $C_{BA}^{\ell j}$  = spectroscopic amplitude
- $|C_{BA}^{\ell j}|^2 = S_{BA}^{\ell j}$  = spectroscopic factor
- $\varphi_{nA}^{\ell j}(\mathbf{r}')$  = single-particle wavefunction describing motion of  $n$  with respect to  $A$ .

$$\mathcal{T}_{d,p}^{\text{DWBA}} = C_{BA}^{\ell j} \int \int \chi_p^{(-)*}(\mathbf{K}_p, \mathbf{R}') \varphi_{nA}^{\ell j,*}(\mathbf{r}') V_{pn}(\mathbf{r}) \chi_d^{(+)}(\mathbf{K}_d, \mathbf{R}) \varphi_d(\mathbf{r}) d\mathbf{r}' d\mathbf{R}'$$

$$\left( \frac{d\sigma}{d\Omega} \right)_{\beta,\alpha} = \frac{\mu_\alpha \mu_\beta}{(2\pi\hbar^2)^2} S_{BA}^{\ell j} \left| \int \int \chi_p^{(-)*}(\mathbf{K}_p, \mathbf{R}') \varphi_{nA}^{\ell j,*}(\mathbf{r}') V_{pn}(\mathbf{r}) \chi_d^{(+)}(\mathbf{K}_d, \mathbf{R}) \varphi_d(\mathbf{r}) d\mathbf{r}' d\mathbf{R}' \right|^2$$

⇒ In DWBA, the  $(d, p)$  cross section is proportional to the spectroscopic factor. Comparing the data with DWBA calculations, one can extract the values of  $S_{BA}^{\ell j}$

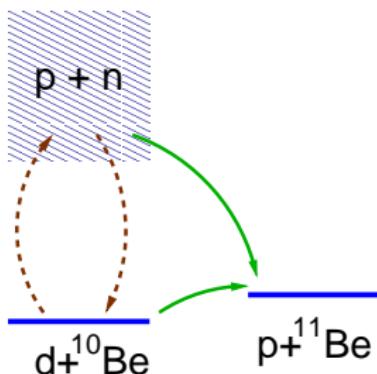


## Application of CDCC to transfer reactions



## Transfer reactions with weakly bound nuclei

- ⇒ DWBA approximates the total WF by the elastic channel and assumes that the transfer occurs in one step (Born approximation).
- ⇒ For weakly bound projectiles (eg. deuterons), breakup is an important channel and can influence the transfer process.



- ⇒  $\Psi_{\mathbf{K}_d}^{(+)}(\mathbf{R}, \mathbf{r})$  includes breakup components, but these are lost when we make the DWBA approximation ( $\Psi^{(+)} \approx \chi_d^{(+)}(\mathbf{K}_d, \mathbf{R})\varphi_d(\mathbf{r})$ )  $\Rightarrow$  need to go beyond DWBA



## Adiabatic distorted wave approximation (ADWA)

- ⇒  $\chi_d^{(+)}(\mathbf{K}_d, \mathbf{R})$  describes deuteron elastic scattering but, for the  $(d, p)$  transfer matrix element, we need only  $\Psi_{\mathbf{K}_d}^{(+)}(\mathbf{R}, \mathbf{r})$  for small  $|\mathbf{r}|$
- ⇒ R.C. Johnson and col. have derived an approximation of  $\Psi_{\mathbf{K}_d}^{(+)}(\mathbf{R}, \mathbf{r})$  valid for  $r \approx 0$ , which includes the effect of deuteron breakup effectively (adiabatic approx.):

- ➊ Zero-range approximation (Johnson-Soper):

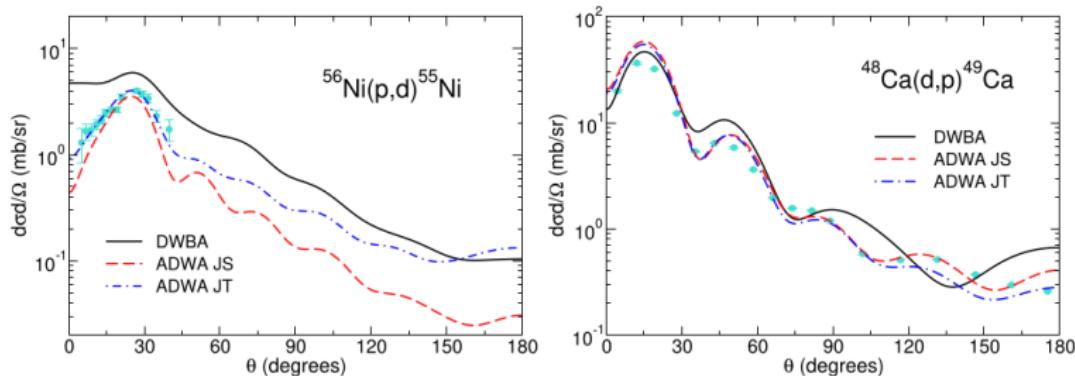
$$U^{JS}(R) = U_{pb}(R) + U_{nb}(R) \Rightarrow \chi_d^{JS}(\mathbf{R})$$

- ➋ Finite-range version (Johnson-Tandy):

$$U^{JT}(R) = \frac{\langle \varphi_{pn}(\mathbf{r}) | V_{pn} (U_{nb} + U_{pb}) | \varphi_{pn}(\mathbf{r}) \rangle}{\langle \phi_{pn}(\mathbf{r}) | V_{pn} | \phi_{pn}(\mathbf{r}) \rangle}$$



## DWBA vs ADWA



From Timofeyuk and, Progress in Particle and Nuclear Physics 111 (2020) 103738



## CDCC-BA approximation

- ⇒ Exact transition amplitude for a general  $\alpha \rightarrow \beta$  process:

$$\mathcal{T}_{d,p}^{\text{CDCC}} = C_{\text{BA}}^{\ell j} \int \int \chi_p^{(-)*}(\mathbf{K}_p, \mathbf{R}') \varphi_{nA}^{\ell j,*}(\mathbf{r}') V_{pn}(\mathbf{r}) \underbrace{\Psi_{\mathbf{K}_\alpha}^{(+)}(\mathbf{R}_\alpha, \xi_\alpha) d\mathbf{r}' d\mathbf{R}'}$$

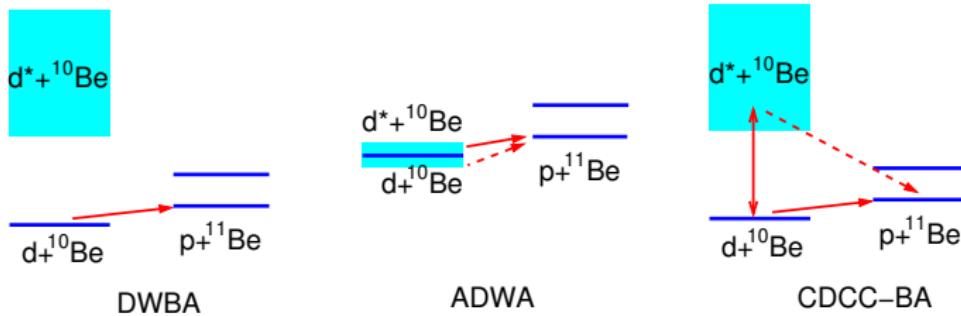
- ⇒ Use CDCC approximation for  $\Psi_{\mathbf{K}_\alpha}^{(+)}$ .

$$\Psi_{\mathbf{K}_\alpha}^{(+)} \approx \Psi^{\text{CDCC}} = \underbrace{\chi_0(\mathbf{R}) \phi_0(\mathbf{r})}_{\text{elastic}} + \sum_{n', j, \pi} \underbrace{\phi_{n'}^{j\pi}(k_{n'}, \mathbf{r}) \chi_{n' j, \pi}(\mathbf{R})}_{\text{breakup}}$$

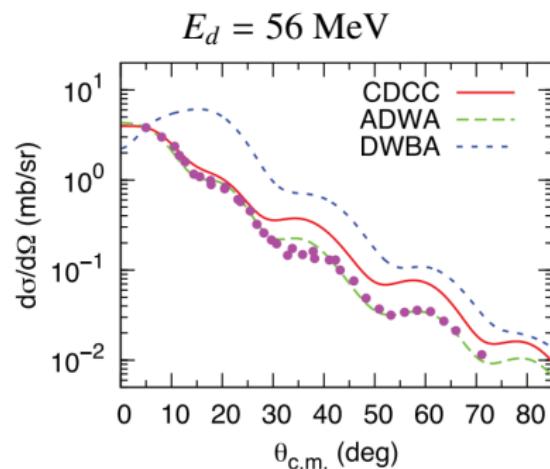
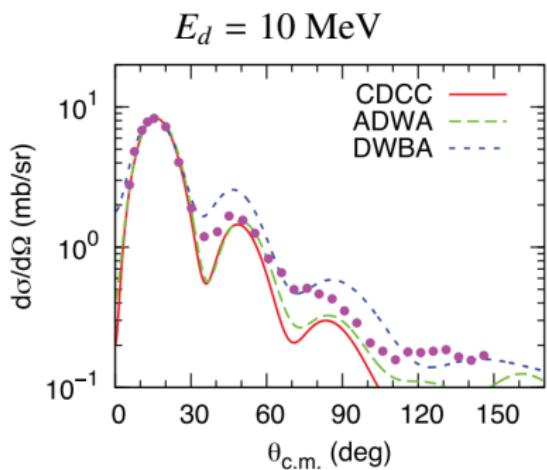
- ⇒ Coupling to deuteron breakup states included explicitly.



## DWBA, ADWA and CDCC-BA compared



## DWBA vs ADWA vs CDCC

Example:  $^{58}\text{Ni}(\text{d},\text{p})^{59}\text{Ni}$ 

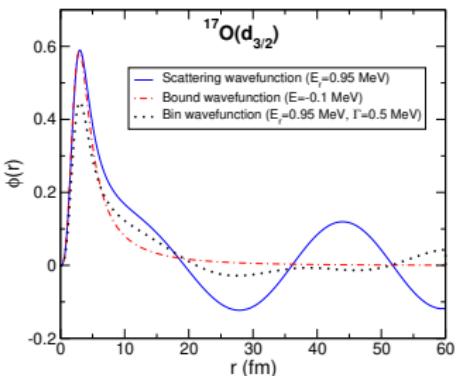
- CDCC and ADWBA provide better description of the data and lead also to more realistic spectroscopic information (e.g. spectroscopic factors)

Pang *et al*, PRC 90, 044611 (2014)

## Exploring resonances from transfer reactions

- ⇒ Inclusion of continuum states in DWBA and ADWA poses numerical problems due to oscillatory behaviour of unbound wavefunctions
- ⇒ Some regularization method must be applied:
  - Representing the resonance by a weakly bound state with the same quantum numbers
  - Vincent & Fortune contour integration in the complex radius plane ([PRC2 \(1970\) 782](#))
  - Representing the resonance by a continuum *bin*

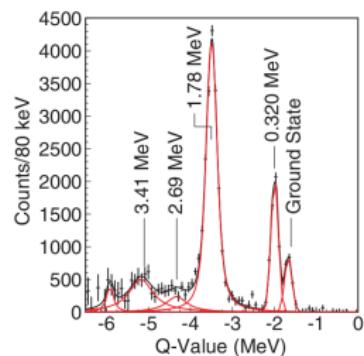
E.g.:  $d_{3/2}$  resonance in  $^{17}\text{O}$  resonance at  $E_r = 0.95 \text{ MeV}$





## Application of ADWA populating unbound states

E.g.:  $^{11}\text{Be}$  resonance at  $E_x = 1.78 \text{ MeV}$  from  $^{10}\text{Be}(\text{d},\text{p})^{11}\text{Be}$



Schmitt et al, PRC88, 064612 (2013)

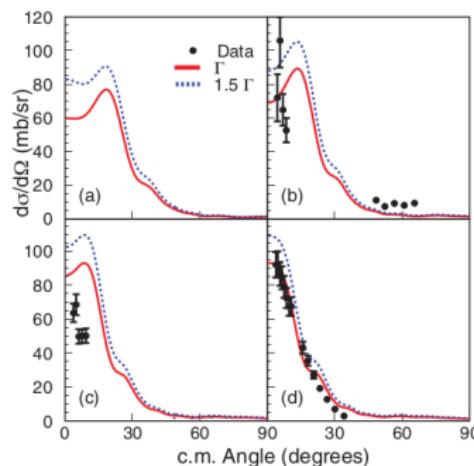


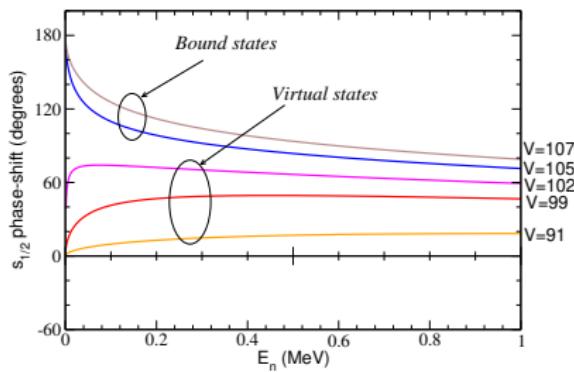
FIG. 8. (Color online) Differential cross sections are presented for transfer to the first resonance in  $^{11}\text{Be}$  at  $1.78 \text{ MeV}$  via the  $^{10}\text{Be}(\text{d},\text{p})$  reaction in inverse kinematics at deuteron energies of (a)  $12 \text{ MeV}$ , (b)  $15 \text{ MeV}$ , (c)  $18 \text{ MeV}$ , and (d)  $21.4 \text{ MeV}$ . The curves are from FR-ADWA calculations using (solid line) an energy bin that is the same width as for the resonance used in the calculation and (dotted line) with a width 1.5 times that value. At  $12 \text{ MeV}$  the protons were too low in energy to extract an angular distribution.



## Virtual states

- ⇒ Neutrons in *s*-wave cannot produce resonant states (no barrier)
- ⇒ Still, they can exhibit distinctive structures, characterized by a rapid increase of the phase-shift near zero energy (**virtual states**). This behaviour is commonly characterized in terms of the **scattering length**:

$$a_s = - \lim_{k \rightarrow 0} \tan \frac{\delta(k)}{k}$$



### Levinson theorem:

$$\delta_\ell(E_n = 0) \rightarrow n\pi$$

( $n$ =number of bound states for partial wave  $\ell$ )



## Resonances and virtual states in the complex energy/momentum plane

- ⇒ A **bound state** is a normalizable solution of the Schrödinger equation for a imaginary momentum  $+i|k|$  and (negative) energy:  $E_s = \hbar^2(+i|k|)^2/2\mu = -\hbar^2|k|^2/2\mu$ .
- ⇒ A **virtual state** is a non-normalizable solution of the Schrödinger equation for a imaginary momentum  $-i|k|$  and (negative) energy:  $E_s = \hbar^2(-i|k|)^2/2\mu = -\hbar^2|k|^2/2\mu$ .

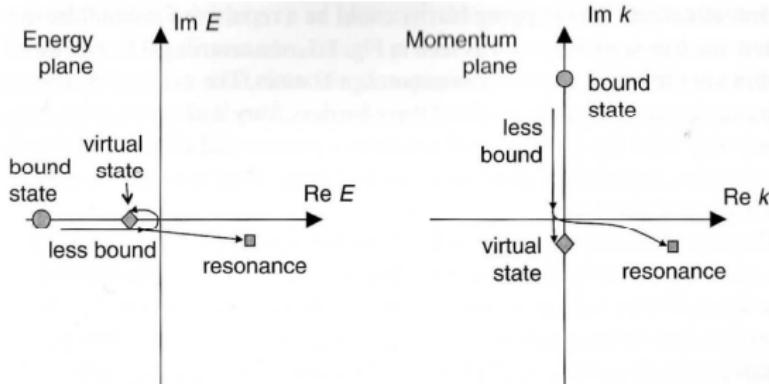
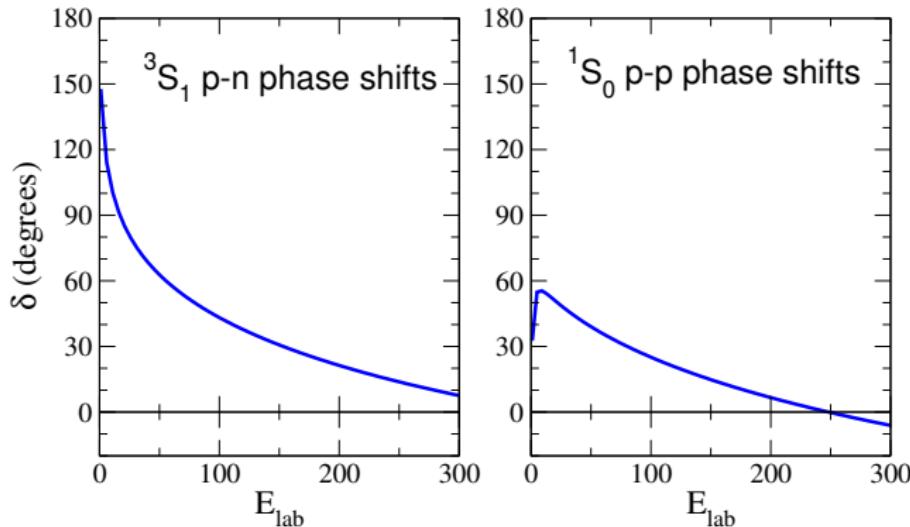


Fig. 3.4. The correspondences between the energy (left) and momentum (right) complex planes. The arrows show the trajectory of a bound state caused by a progressively weaker potential: it becomes a resonance for  $L > 0$  or when there is a Coulomb barrier, otherwise it becomes a virtual state. Because  $E \propto k^2$ , bound states on the positive imaginary  $k$  axis and virtual states on the negative imaginary axis both map onto the negative energy axis.

(figure borrowed from Thompson & Nunes' book)



## Bound vs virtual (anti-bound) states in the N-N system

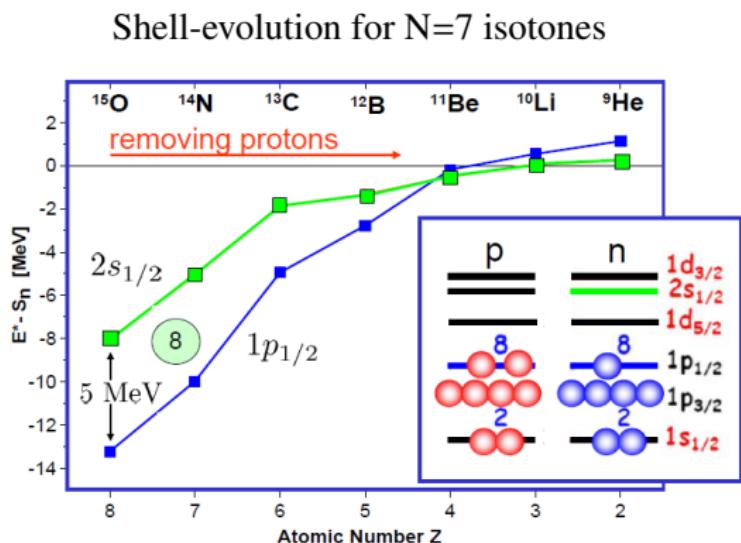
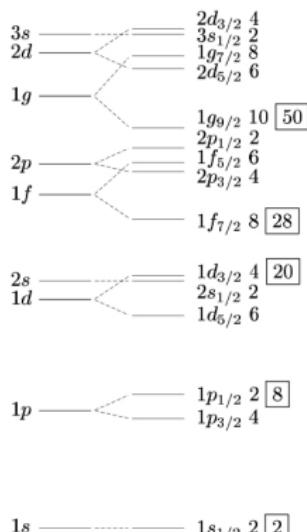


- ⇒  $p - n$ :  $\delta(E) \xrightarrow{E \rightarrow 0} \pi \Rightarrow$  one-bound state (deuteron)
- ⇒  $p - p, n - n$ : no bound states, but they do have an anti-bound (virtual) state.
- ⇒  $p - p$ :  $\delta$  becomes negative for large  $E \Rightarrow$  evidence of repulsive core!

○○○●○

# Spectroscopy in the continuum: shell evolution with neutron/proton asymmetry

⇒ Systematic studies of shell evolution requires extensions to the continuum



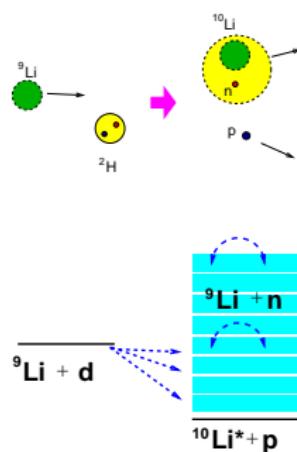
From: P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci 53 (2003) 219

SM explanation: Otsuka et al, PRL95,232502(2005)

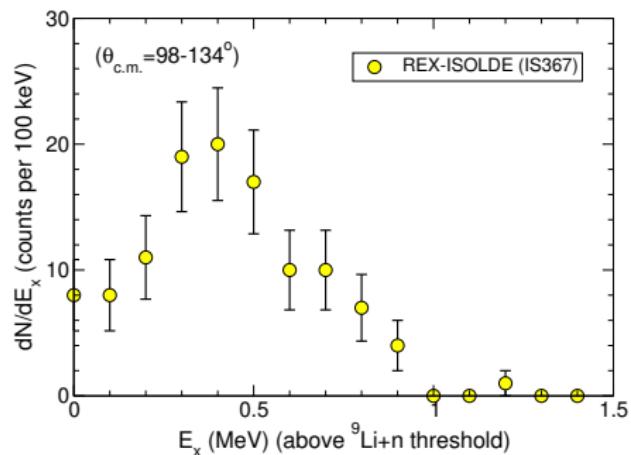


## Spectroscopy in the continuum: the ${}^{10}\text{Li}$ case

- Detected protons carry information on the  ${}^9\text{Li} + \text{n}$  excitation spectrum.



H.P. Jeppesen et al, PLB642 (2006) 449

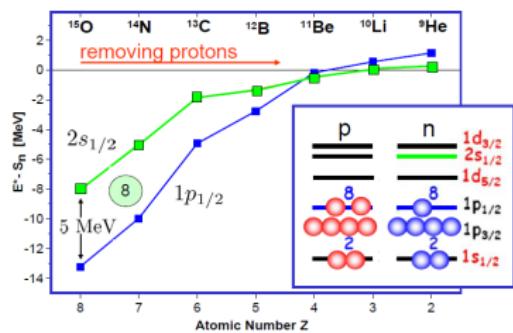


# Populating resonances via transfer reactions ${}^9\text{Li}(\text{d},\text{p}){}^{10}\text{Li}^*$

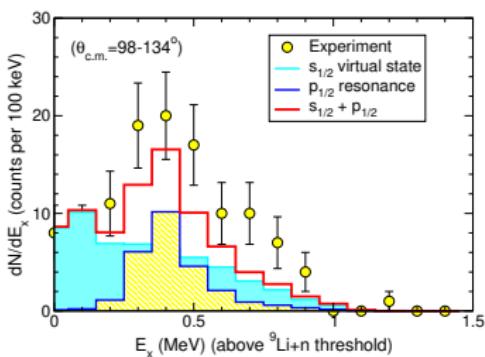
⇒ Prior form transition amplitude:

$$\mathcal{T}_{if} = \langle \Psi_f^{(-)} | V_{nA} + U_{pA} - U_{dA} | \phi_d(\vec{r}) \chi_{dA}^{(+)}(\vec{R}) \rangle$$

⇒  $\Psi_f^{(-)}$ , describing  $\text{p}+{}^{10}\text{Li}$ , approximated by a CDCC expansion in terms of  $n+{}^9\text{Li}$  states



From: P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci 53 (2003) 219



⇒  $p_{1/2}$  resonance ( $1^+$  or  $2^+$ ):  $E_r \simeq 0.38$  MeV,  $\Gamma = 0.2$  MeV

⇒  $s_{1/2}$  virtual state ( $1^-$  or  $2^-$ ):  $a_s \simeq -24$  fm

## Coupled-Reaction Channels (CRC) method

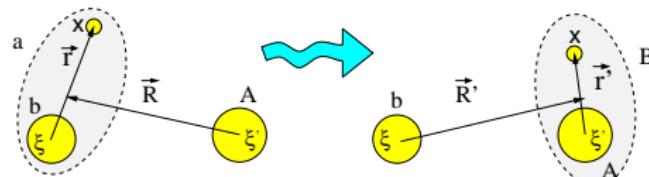


## Motivation of the CRC method

- ⇒ The DWBA method includes transfer couplings to first order in the residual interaction ( $\Delta V$ ).
- ⇒ Transfer couplings should affect the elastic channel, but this effect is not considered in DWBA
- ⇒ When couplings are strong, higher orders may be important.

## Post and prior Hamiltonians

⇒ Transfer process:  $\underbrace{(b + x) + A}_{a} \rightarrow b + \underbrace{(b + x)}_{B}$



⇒ Full Hamiltonian:

- Prior form:  $\xi_\alpha = \{\xi, \xi', \mathbf{r}\}$

$$H = \hat{T}_{\mathbf{R}} + H_\alpha(\xi_\alpha) + V_\alpha(\mathbf{R}, \mathbf{r}) = \hat{T}_{\mathbf{R}} + \underbrace{H_a(\xi, \mathbf{r}) + H_A(\xi') + V_{xA} + U_{bA}}_{H_\alpha(\xi_\alpha)} + \underbrace{V_\alpha(\mathbf{R}, \mathbf{r})}_{V_\alpha(\mathbf{R}, \mathbf{r})}$$

- Post form:  $\xi_\beta = \{\xi, \xi', \mathbf{r}'\}$

$$H = \hat{T}_{\mathbf{R}'} + H_\beta(\xi_\beta) + V_\beta(\mathbf{R}', \mathbf{r}') = \hat{T}_{\mathbf{R}'} + \underbrace{H_b(\xi) + H_B(\xi', \mathbf{r}') + V_{xb} + U_{bA}}_{H_\beta(\xi_\beta)} + \underbrace{V_\beta(\mathbf{R}', \mathbf{r}')}_{V_\beta(\mathbf{R}', \mathbf{r}')}}$$

# Coupled Reaction Channels

⇒ Trial model wavefunction:

$$\Psi = \phi_a(\xi, \mathbf{r})\phi_A(\xi')\chi_\alpha(\mathbf{R}_\alpha) + \phi_b(\xi)\phi_B(\xi', \mathbf{r}')\chi_\beta(\mathbf{R}_\beta)$$

⇒ Coupled-reaction channels (CRC) equations:  $[H - E]\Psi = 0$

$$\begin{aligned} [E - \varepsilon_\alpha - T_R - U_\alpha(\mathbf{R}_\alpha)]\chi_\alpha(\mathbf{R}_\alpha) &= \int d\mathbf{R}_\beta K_{\alpha\beta}(\mathbf{R}_\alpha, \mathbf{R}_\beta)\chi_\beta(\mathbf{R}_\beta) \\ [E - \varepsilon_\beta - T_R - U_\beta(\mathbf{R}_\beta)]\chi_\beta(\mathbf{R}_\beta) &= \int d\mathbf{R}_\alpha K_{\alpha\beta}(\mathbf{R}_\alpha, \mathbf{R}_\beta)\chi_\alpha(\mathbf{R}_\alpha) \end{aligned}$$

⇒ Non-local kernels:

$$\begin{aligned} K_{\alpha\beta}(\mathbf{R}_\beta, \mathbf{R}_\alpha) &= \int d\xi d\xi' d\mathbf{r} \phi_a^*(\xi, \mathbf{r})\phi_A^*(\xi')(H - E)\phi_b(\xi)\phi_B(\xi', \mathbf{r}') \\ &\equiv \int d\xi_\alpha \Phi_\beta^*(\xi_\beta)(H - E)\Phi_\alpha(\xi_\alpha) \end{aligned}$$

⇒ CRC equations have to be solved iteratively due to NL kernels.

## Evaluation of the non-local kernels

- ⇒ In the NL kernels,  $H$  can be replaced by either  $H^{\text{prior}}$  or  $H^{\text{post}}$
- ⇒ E.g., for  $H = H^{\text{prior}}$ :

$$K_{\alpha,\beta} = I_{\alpha,\beta}^{\text{prior}} + N_{\alpha,\beta}^{\text{post}}$$

- Interaction kernel:

$$I_{\alpha,\beta}^{\text{prior}} = J_{\alpha,\beta} \int d\xi_\alpha \Phi_\beta^*(\xi_\beta) (V_\alpha - U_\alpha) \Phi_\alpha(\xi_\alpha)$$

- Non-orthogonality kernel:

$$N_{\alpha,\beta}^{\text{post}} = J_{\alpha,\beta} [T_{\mathbf{R}} + U_\alpha - (E - \varepsilon_\alpha)] \int d\xi_\alpha \Phi_\beta^*(\xi_\beta) \Phi_\alpha(\xi_\alpha)$$

## Coupled radial equations

- As in other CC applications, the total WF is expanded in partial waves, leading to a set of coupled radial differential equations:

$$\begin{aligned} \left[ E_{\kappa p t} - T_{\kappa L}(R_\kappa) - U_\kappa(R_\kappa) \right] f_\alpha(R_\kappa) &= \sum_{\alpha', \Gamma > 0} i^{L' - L} V_{\alpha:\alpha'}^\Gamma(R_{\kappa'}) f_{\alpha'}(R_{\kappa'}) \\ &+ \sum_{\alpha', \kappa' \neq \kappa} i^{L' - L} \int_0^{R_m} V_{\alpha:\alpha'}(R_\kappa, R_{\kappa'}) f_{\alpha'}(R_{\kappa'}) dR_{\kappa'} \end{aligned}$$

- Asymptotic kinetic energies:  $E_{\kappa p t} = E + Q_\kappa - \epsilon_p - \epsilon_t$
- $R_\kappa, R_{\kappa'}$ =projectile-target radial coordinates in partitions  $k,k'$ .
- $V_{\alpha:\alpha'}^\Gamma(R_{\kappa'})$ = coupling potential of multipolarity  $\Gamma$  within partition  $k'$  (local)
- $V_{\alpha:\alpha'}(R_\kappa, R_{\kappa'})$ =transfer coupling potentials (nonlocal)

- Boundary conditions:

$$f_\alpha(R_{\kappa'}) \rightarrow \frac{i}{2} \left[ \delta_{\alpha\alpha_0} H_{L\eta_\alpha}^{(-)}(K_\alpha R_\kappa) - S_{\alpha_0\alpha} H_{L\eta_\alpha}^{(+)}(K_\alpha R_\kappa) \right]$$



## Some remarks on CRC calcultions

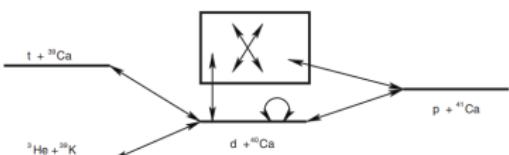
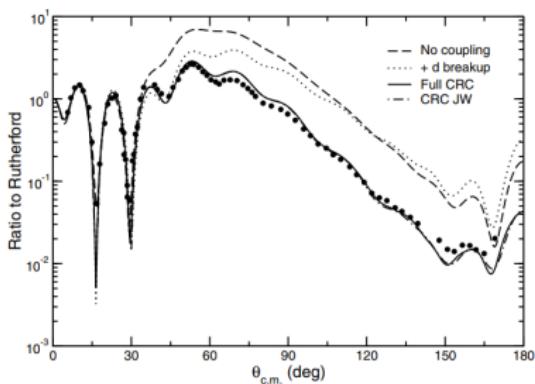


- ⇒ For each transfer coupling, we need to provide the appropriate spectroscopic amplitude. Results will depend on its phase!
- ⇒ The diagonal potential describing each channel will not coincide with the optical potential describing elastic scattering in that channel, since the effect of some channels are already taken into account explicitly.



## Comparison with data

**Example:**  $d + {}^{40}\text{Ca}$   $E_d = 58 \text{ MeV}$



- ⇒ Full CRC calculation includes coupling to deuteron breakup,  $(d, t)$  transfer and  $(d, 3\text{He})$  transfer
- ⇒ The final potential employed for the  $d + {}^{40}\text{Ca}$  differs from that used in the one-channel optical model case.

Keeley & Mackintosh, PRC77, 054603 (2008)

## DWBA approximation from CRC

⇒ Iterative solution of the CRC equations:

$$\begin{aligned}[E - \varepsilon_\alpha - T_R - U_\alpha(\mathbf{R}_\alpha)]\chi_\alpha(\mathbf{R}_\alpha) &\approx 0 \\ [E - \varepsilon_\beta - T_R - U_\beta(\mathbf{R}_\beta)]\chi_\beta(\mathbf{R}_\beta) &\approx \int d\mathbf{R}_\alpha K_{\alpha,\beta}(\mathbf{R}_\alpha, \mathbf{R}_\beta)\chi_\alpha(\mathbf{R}_\alpha)\end{aligned}$$

⇒ DWBA scattering amplitude (prior):

$$f_{\beta,\alpha}^{\text{DWBA}} = -\frac{\mu_\beta}{2\pi\hbar^2} \int \int \widetilde{\chi}_\beta^{(-)*}(\mathbf{R}_\beta)(\phi_b\phi_B|V_{\text{prior}}|\phi_a\phi_A)\widetilde{\chi}_\alpha^{(+)}(\mathbf{R}_\alpha)d\mathbf{R}_\alpha d\mathbf{r}$$

⇒ Distorted waves:

$$\begin{aligned}[E - \varepsilon_\alpha - T_R - U_\alpha(\mathbf{R}_\alpha)]\widetilde{\chi}_\alpha(\mathbf{R}_\alpha) &= 0 \\ [E - \varepsilon_\beta - T_R - U_\beta(\mathbf{R}_\beta)]\widetilde{\chi}_\beta(\mathbf{R}_\beta) &= 0\end{aligned}$$

⇒ Structure form-factor:

$$(\phi_b\phi_B|V_{\text{prior}}|\phi_a\phi_A) \equiv \int d\xi d\xi' \phi_b(\xi)\phi_B(\xi', \mathbf{r}')V_{\text{prior}}\phi_a(\xi, \mathbf{r})\phi_A(\xi')$$