ISOLDE Nuclear Reaction and Nuclear Structure Course

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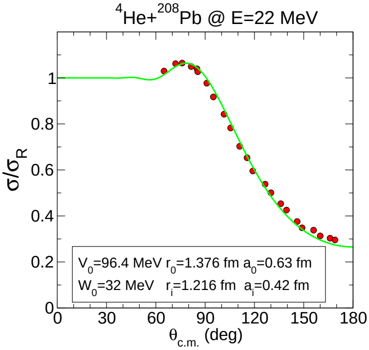
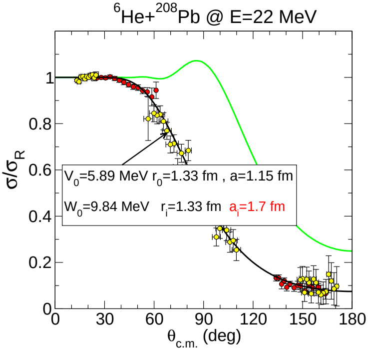
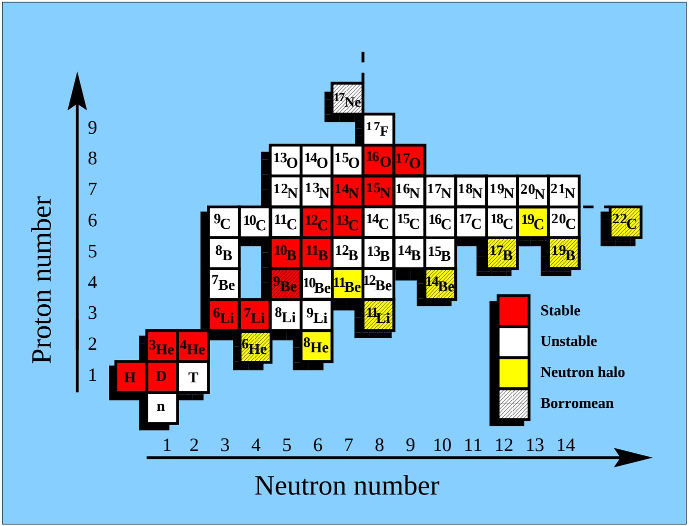
Evidences of the importance of coupling to breakup channels





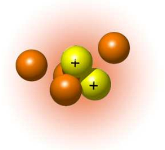
- ^{4}He+^{208}Pb shows typical Fresnel pattern → *strong absorption*
- ^{6}He+^{208}Pb shows a prominent reduction in the elastic cross section due to the flux going to other channels (mainly break-up)
- ^{6}He+^{208}Pb requires a large imaginary diffuseness → *long-range absorption*

Exotic nuclei, halo nuclei, and Borromean systems



Light exotic nuclei: halo nuclei and Borromean systems

- Radioactive nuclei: they typically decay by β emission.
  E.g.: $^6\text{He} \xrightarrow{\beta^-} {}^6\text{Li} \quad (\tau_{1/2} \simeq 807 \text{ ms})$
- Weakly bound: typical separation energies are around 1 MeV or less.
- Spatially extended
- Halo structure: one or two weakly bound nucleons (typically neutrons) with a large probability of presence beyond the range of the potential.
- Borromean nuclei: Three-body systems with no bound binary sub-systems.



Challenges found in the study of reactions with exotic beams

Experimentally:

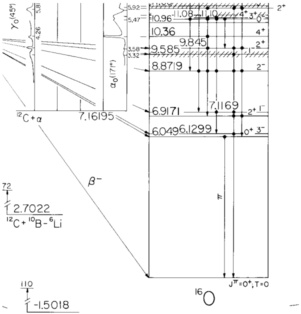
- Exotic nuclei are short-lived and difficult to produce. Beam intensities are typically small.

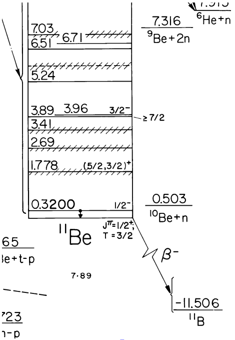
Theoretically:

- Exotic nuclei are easily broken up in nuclear collisions $\Rightarrow$ coupling to the unbound states (continuum) plays an important role.
- Effective NN interactions, level schemes, etc are different from stable nuclei.
- Many exotic nuclei exhibit complicated cluster (few-body) structure.

Inelastic scattering of weakly bound nuclei

- Single-particle (or cluster) excitations become dominant.
- Excitation to continuum states important.

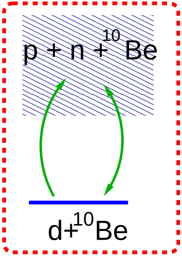




☞*Halo nuclei are weakly bound ⇒ coupling to continuum states becomes an important reaction channel*

Inclusion of breakup channels: the CDCC method

DWBA modelspace



☞*We want to include explicitly in the modelspace the breakup channels of the projectile or target, using a cluster model description of the projectile.*

Reminder of the CC method (bound states)

We need to incorporate explicitly in the Hamiltonian the internal structure of the nucleus being excited (eg. target).

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

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

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

- $V(\mathbf{R}, \xi)$: Projectile-target interaction

CC model wavefunction

We expand the total wave function in a subset of internal states (the P space):

$$\Psi^{(+)}_{\rm model}(\mathbf{R},\xi) = \phi_0(\xi)\chi_0(\mathbf{R}) + \sum_{n>0} \phi_n(\xi)\chi_n(\mathbf{R})$$

Boundary conditions for the $\chi_n(\mathbf{R})$ (unknowns):

$$\chi^{(+)}_0(\mathbf{R}) \to e^{i\mathbf{K}_0\cdot\mathbf{R}} + f_{0,0}(\theta)\frac{e^{iK_0R}}{R} \qquad \text{for n=0 (elastic)}$$

$$\chi^{(+)}_n(\mathbf{R}) \to f_{n,0}(\theta)\frac{e^{iK_nR}}{R} \qquad \text{for n>0 (non-elastic)}$$

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

- The model wavefunction must satisfy the Schrödinger equation:

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

- Projecting onto the internal states one gets a system of coupled-equations for the functions $\{\chi_n(\mathbf{R})\}$:

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

- Coupling potentials:

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

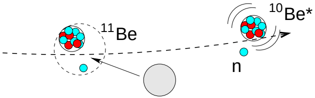
☞ *$\phi_n(\xi)$ will depend on the structure model (collective, single-particle,etc).*

Extension of the CC method to include breakup channels

- Light exotic nuclei usually present a cluster structure (recall talk by B.Jonson in this course)
- To use the CC formalism, one needs to extend the method in order to:
  - Describe the cluster (or single-particle) structure of light exotic nuclei
  - Permit the inclusion of unbound (continuum) states (breakup channels)

CC method with a cluster model

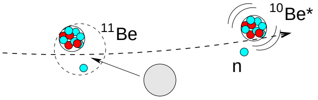
Microscopic approach



- Start from (effective) NN interaction.
- Complicated many-body scattering problem

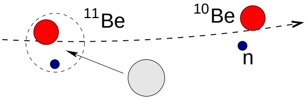
CC method with a cluster model

Microscopic approach



- Start from (effective) NN interaction.
- Complicated many-body scattering problem

Few-body approach



- Inert target approximation
- Projectile described with few-body model
- Phenomenological NA interactions

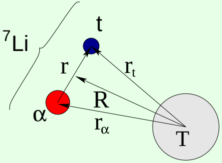
Inelastic scattering in a few-body model

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

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

Example: ^{7}Li=α+t

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



Internal states:

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

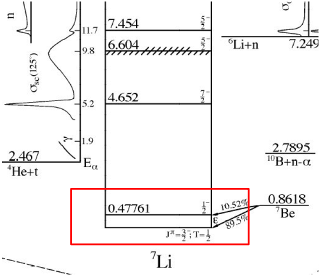
- Transition potentials:

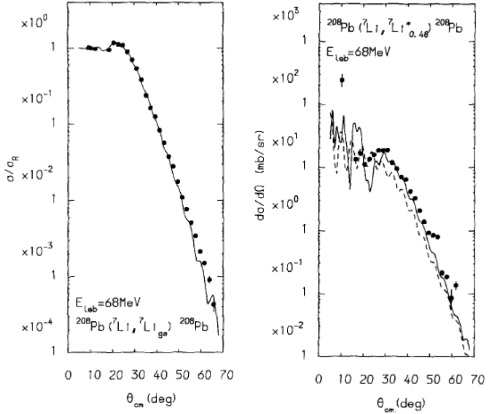
$$V_{n,n'}(\mathbf{R}) = \int d\mathbf{r}\phi^*_n(\mathbf{r})\left[U_1(\mathbf{r}_1) + U_2(\mathbf{r}_2)\right]\phi_{n'}(\mathbf{r})$$

Inelastic scattering: cluster model

Example: ^{7}Li(α+t) +^{208}Pb at 68 MeV (Phys. Lett. 139B (1984) 150):

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

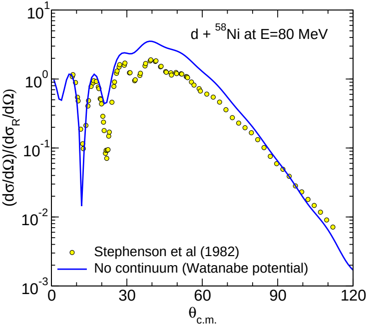


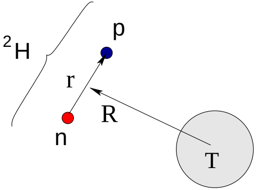


Application of the CC method to weakly-bound systems

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

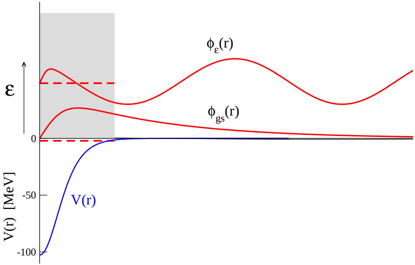
$$V_{dt}(\mathbf{R}) = \int d\mathbf{r}\phi_{gs}(\mathbf{r})\left\{V_{pt}(\mathbf{r}_{pt}) + V_{nt}(\mathbf{r}_{nt})\right\}\phi_{gs}(\mathbf{r})$$





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

Bound versus scattering states

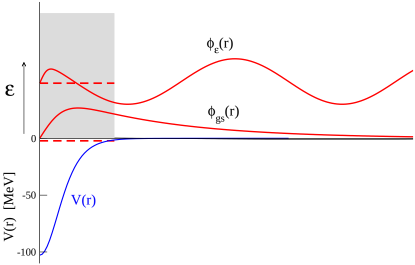


Continuum wavefunctions:

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

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

Bound versus scattering states



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

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 $\Rightarrow$ continuum discretization

The role of the continuum in the scattering of weakly bound nuclei

- Continuum discretization method proposed by G.H. Rawitscher [PRC9, 2210 (1974)] and Farrell, Vincent and Austern [Ann.Phys.(New York) 96, 333 (1976)].

PHYSICAL REVIEW C VOLUME 9, NUMBER 6 JUNE 1974

Effect of deuteron breakup on elastic deuteron-nucleus scattering

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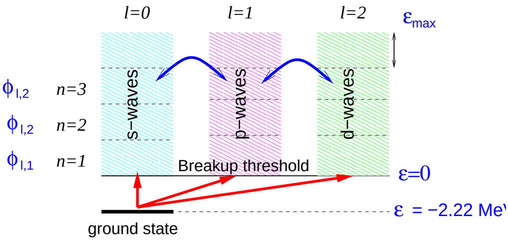
(Received 1 October 1973; revised manuscript received 4 March 1974)

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 ϵ_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 transi-

- 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 partial waves ($\ell = 0, \ldots, \ell_{\max}$).
- For each ℓ, set a maximum excitation energy $\varepsilon_{\max}$.
- Divide the interval $\varepsilon = 0 - \varepsilon_{\max}$ in a set of sub-intervals (*bins*).
- For each bin, calculate a representative wavefunction.

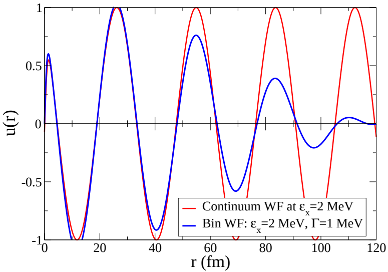
CDCC formalism: construction of the bin wavefunctions

Bin wavefunction:

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

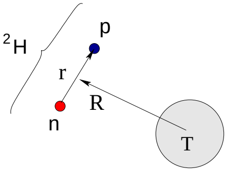
$$u^{[k_1,k_2]}_{\ell sjm}(r) = \sqrt{\frac{2}{\pi N}} \int_{k_1}^{k_2} w(k) u_{k,\ell sj}(r) dk$$

- 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:

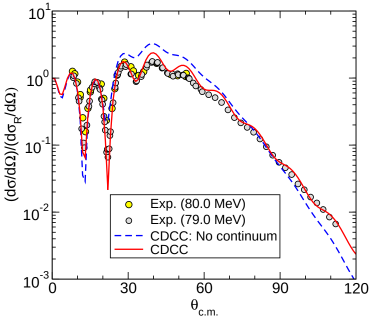
$$V_{n;n'}(\mathbf{R}) = \int d\mathbf{r}\phi_n(\mathbf{r})^* \left[V_{pt}(\mathbf{R} + \frac{\mathbf{r}}{2}) + V_{nt}(\mathbf{R} - \frac{\mathbf{r}}{2}) \right] \phi_{n'}(\mathbf{r})$$

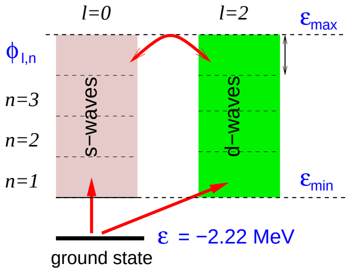
Application of the CDCC formalism: d+ ^{58}Ni

Coupled-Channels + Continuum discretization

$\Downarrow$

Continuum-Discretized Coupled-Channels (CDCC)



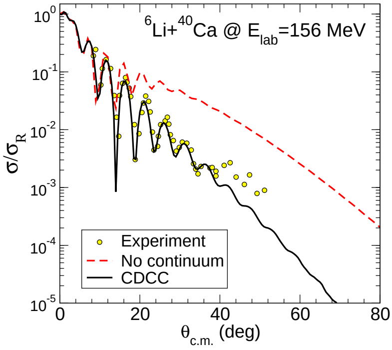


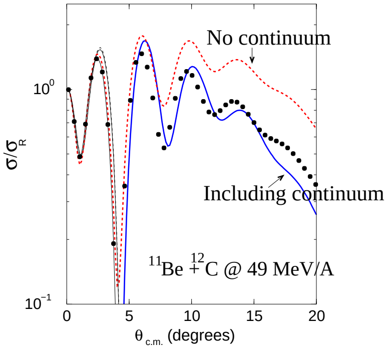
☞*Coupling to breakup channels has a important effect on the reaction dynamics*

Application of the CDCC method: ^{6}Li and ^{6}He scattering

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

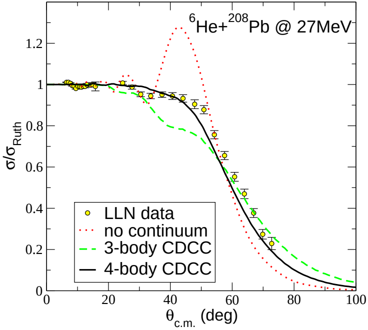
- ^{6}Li=α + d
- ^{11}Be=^{10}Be + n

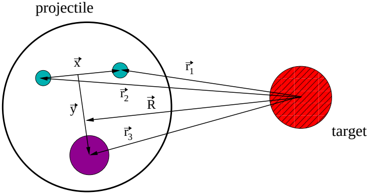




Extension to 3-body projectiles

Eg: ^{6}He=α + n + n



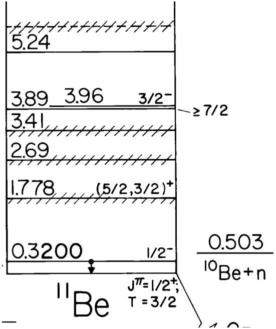


M.Rodríguez-Gallardo et al, PRC 77, 064609 (2008)

Exploring structures in the continuum

The continuum spectrum is not “homogeneus”; it contains in general energy regions with special structures:

- Resonances
- Virtual states



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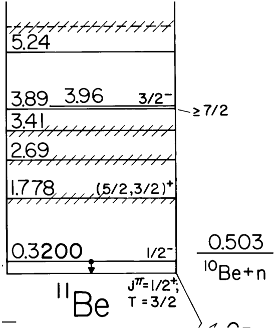


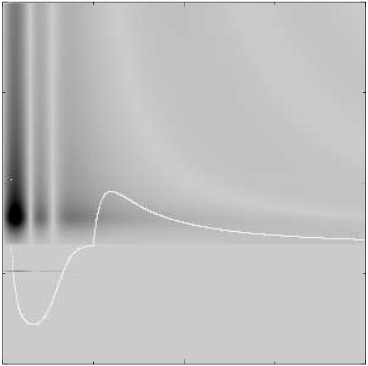
☞ *These structures may (or may not!) show up in reaction observables*

What is a resonance?

- 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 have a large probability of being in the radial range of the potential.
- The continuum wavefunctions are not square normalizable. However, a normalized "bin" of wavefunctions can be constructed to represent the resonance.

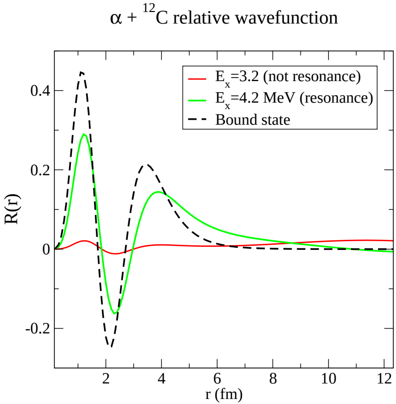
Distinctive features of a resonance

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



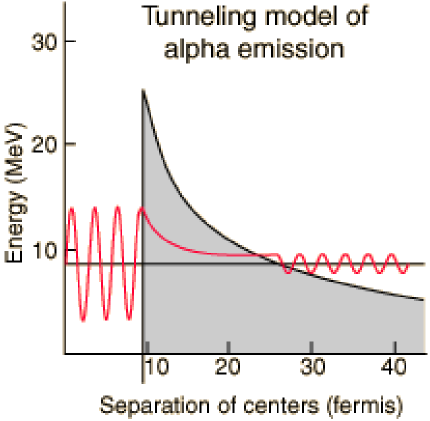
Cuts and areas ordered by size

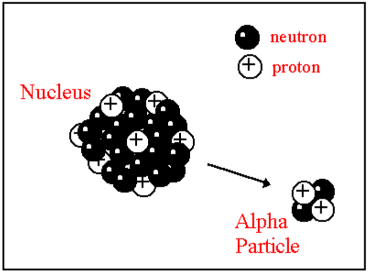
(Courtesy of C. Dasso)



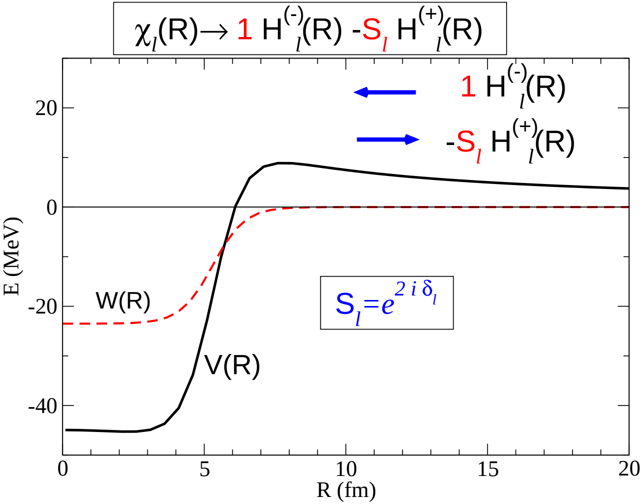
Distinctive features of a resonance

The decay of the resonance is also behind the α decay phenomenon:





Resonances and phase-shifts

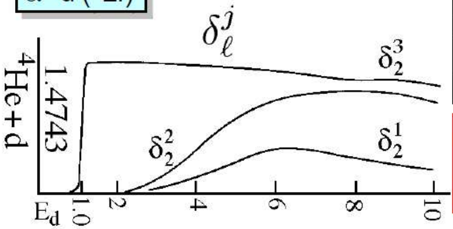


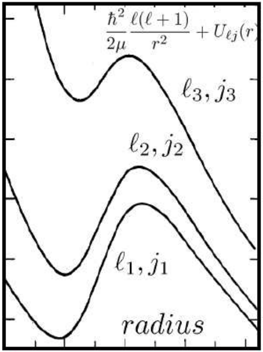
Resonances and phase-shifts

Potential pockets can lead to resonant behaviour – the system being able to trapped in the pocket for some (life)time τ.

A signal is the rise of the phase shift through 90 degrees.

α+d (^{6}Li)

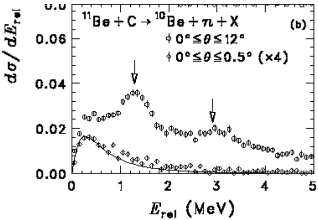


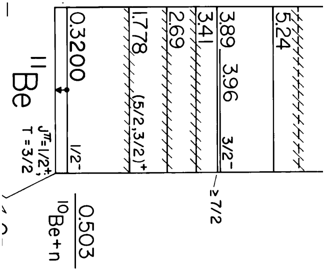


Potential parameters should describe any known resonances

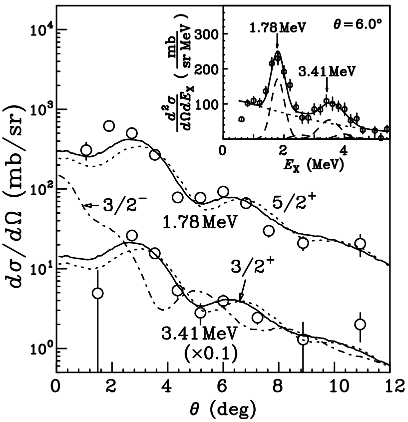
Populating resonances by "inelastic scattering": ^{11}Be+^{12}C

^{11}Be+^{12}C $\rightarrow$ (^{10}Be+n) + ^{12}C   Fukuda et al, Phys. Rev. C70 (2004) 054606)

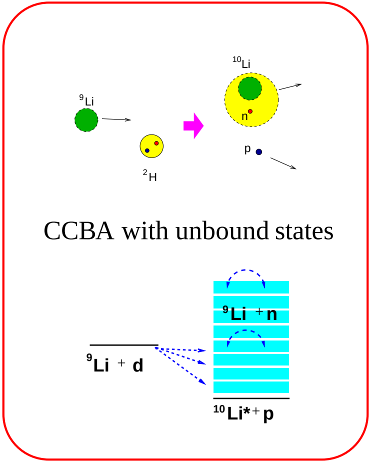




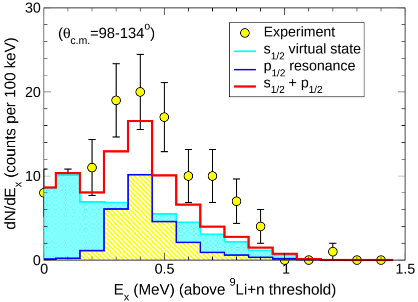
DWBA calculations



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

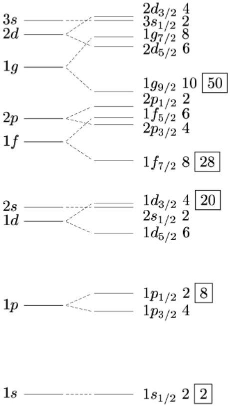


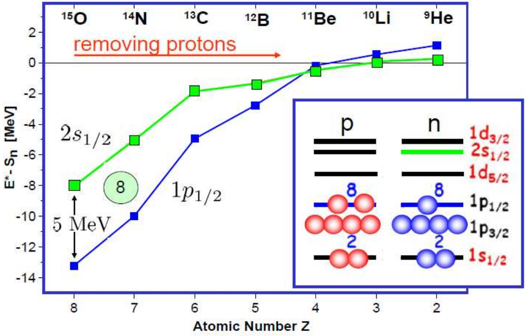
HP.Jeppesen et al, PLB642 (2006) 449



Shell evolution with neutron/proton asymmetry

Shell-evolution for N=7 isotones



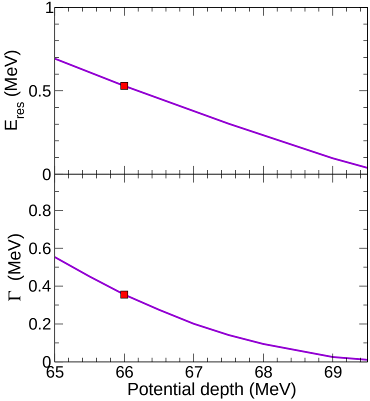


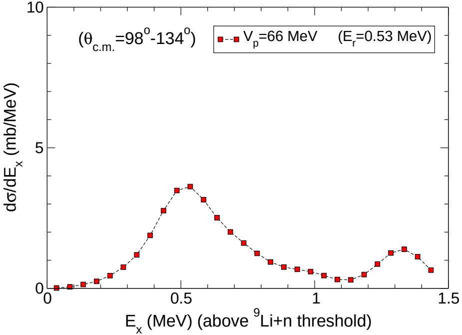
From: P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

Spectroscopy to unbound states: ^{9}Li(d,p)^{10}Li case

Structure: $p_{1/2}$ resonance → Reaction

$$V_{nc}^{(p)}(r) = -V_p \exp(-r^2/a^2) \quad (a = 2 \text{ fm})$$





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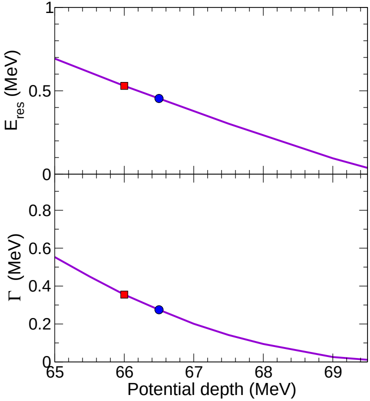

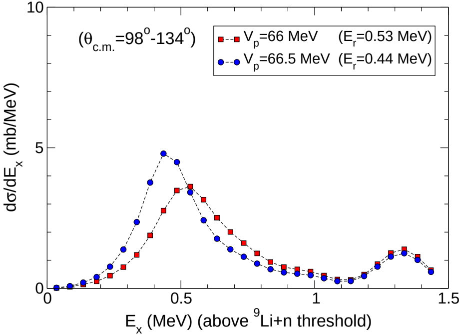

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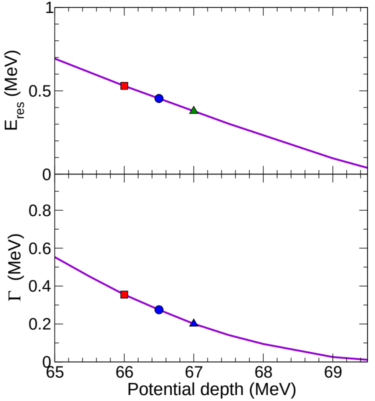
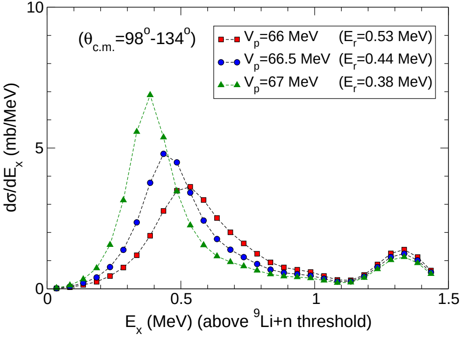
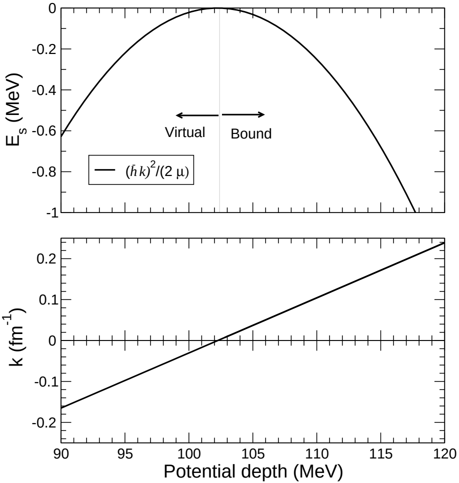
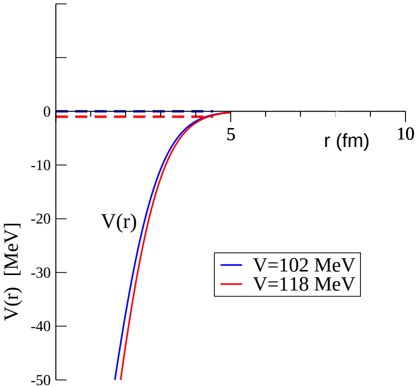


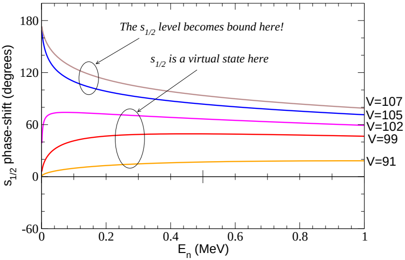


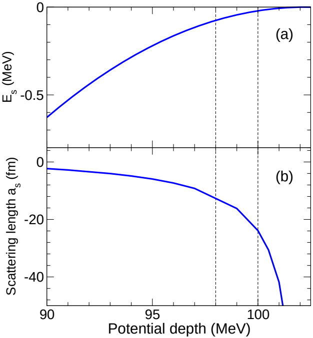
Appearance of a virtual state in ^{10}Li=^{9}Li+n:





Virtual state in ^{10}Li





Scattering length:

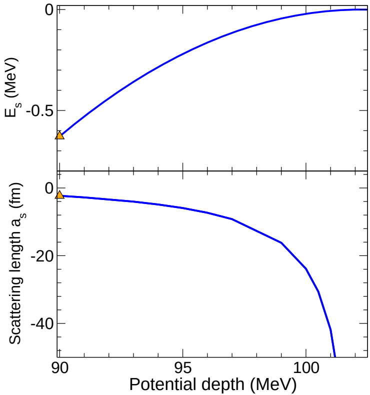
$$a_s = -\lim_{k\to 0} \tan \frac{\delta(k)}{k}$$

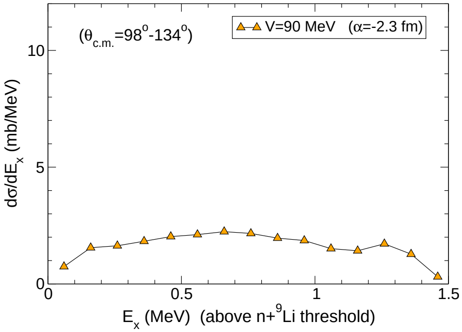
.

Spectroscopy to unbound states: ^{9}Li(d,p)^{10}Li case

Structure: $s_{1/2}$ virtual state → **Reaction**

$$V_{nc}^{(s)}(r) = -V_s \exp(-r^2/a^2) \quad (a = 2\text{ fm})$$





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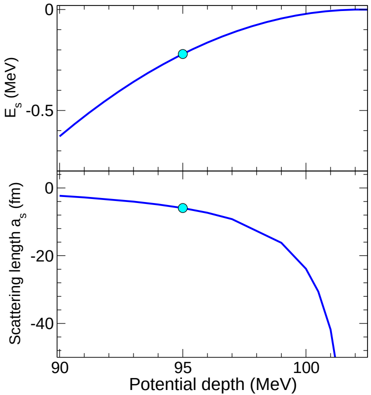

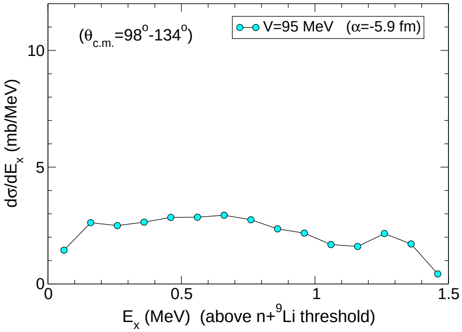

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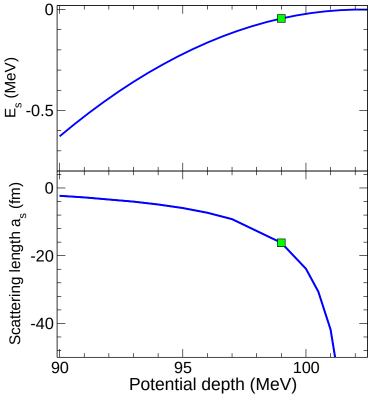

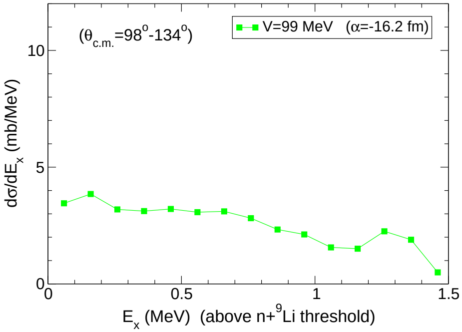

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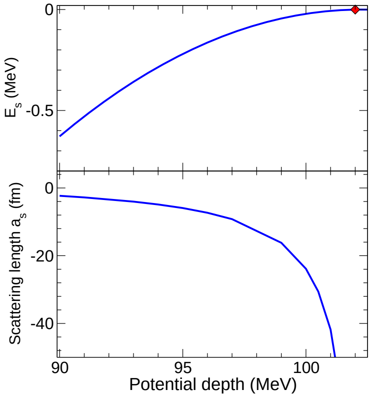

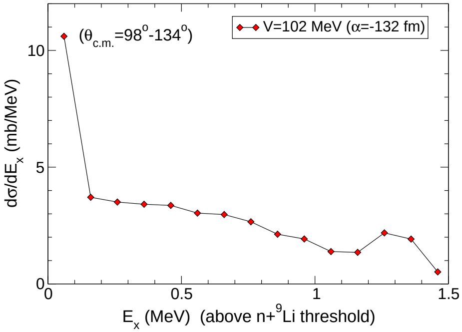

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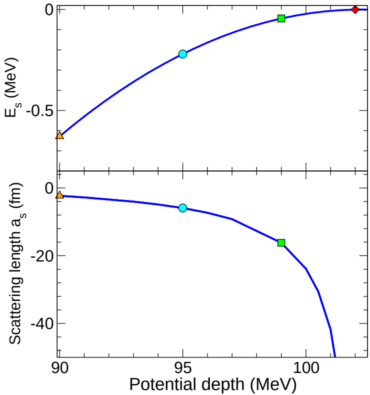
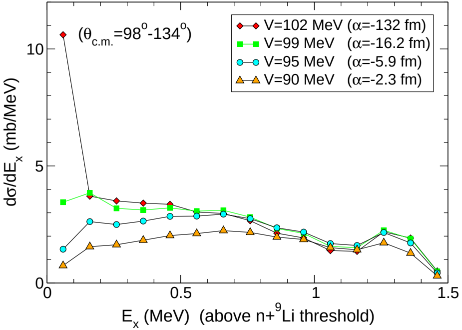
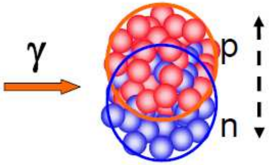


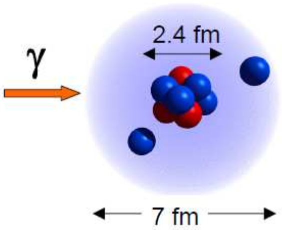


Coulomb dissociation

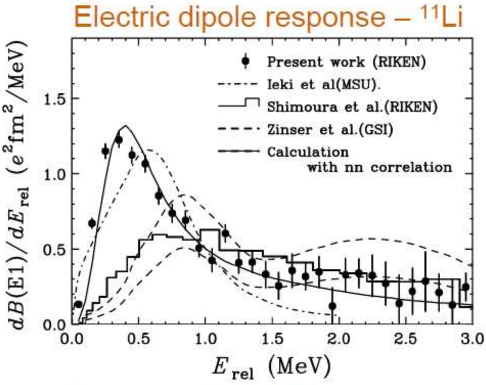
Strong response to electric fields



(Giant) electric Dipole excitation → 10-20 MeV



^{6}He (2n,1 MeV) ^{11}Be (1n,0.5 MeV)
^{11}Li (2n,0.5 MeV) ^{14}Be (2n,~1 MeV)



T. Nakamura et al., PRL (2006) in press

Application to Coulomb dissociation of halo nuclei

- First-order semiclassical cross section for a $0 \rightarrow n$ excitation:

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

- Halo nuclei are weakly bound $\Rightarrow$ excitation occurs to unbound (continuum) states

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

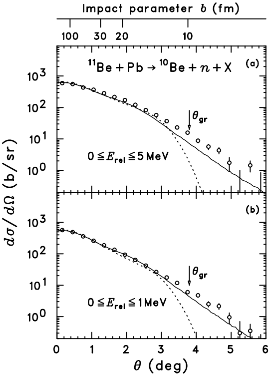
Application a CD of 1n-halo nuclei

- Halo nuclei are weakly bound $\Rightarrow$ the systems are easily polarized in strong electric field (large E1 response)
- Large Coulomb dissociation probability with heavy targets
- At small-angles (large impact parameters) the dissociation is Coulomb dominated and hence can be used to extract the $E1$ transition probability using:

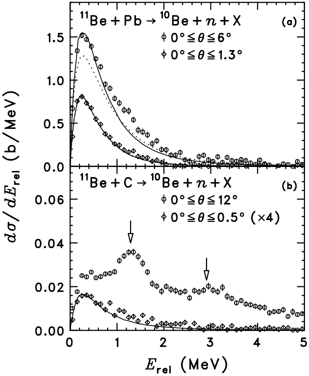
$$\frac{d\sigma}{dE_x}(\theta \ll) \propto \frac{dB(E1)}{dE_x}$$

Example: ^{11}Be dissociation

$$^{11}\mathrm{Be}+{}^{208}\mathrm{Pb} \rightarrow {}^{10}\mathrm{Be}+\mathrm{n}+{}^{208}\mathrm{Pb} \text{ @ } 69 \text{ MeV/u}$$



Fukuda, 2004



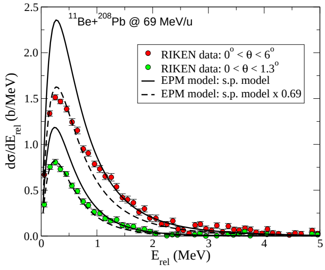
Core excitation in Coulomb breakup: $B(E1)$ response of ^{11}Be

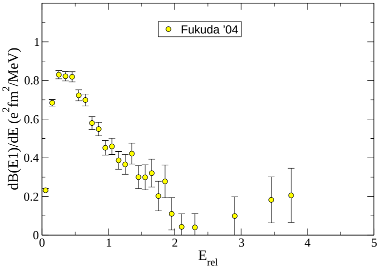
$B(E1)$ extracted in a model-dependent way $\Rightarrow$ compare directly cross sections

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

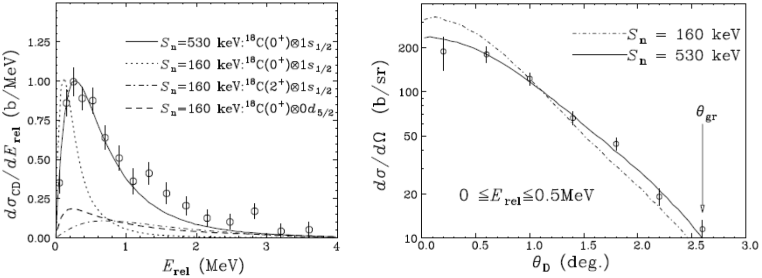
(Semiclassical 1st order)

Eg: ^{11}Be+^{208}Pb at RIKEN *Fukuda et al, PRC70, 054606 (2004))*





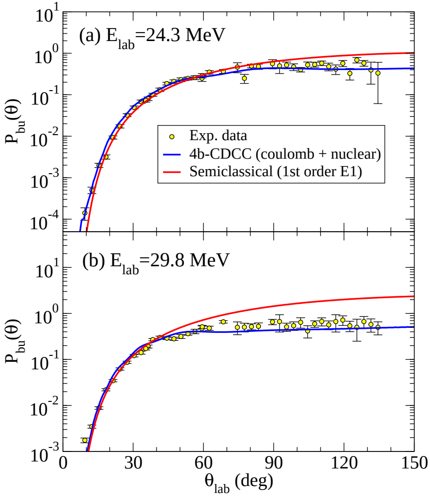
$^{11}Be+^{208}Pb$ at RIKEN



Nakamura et al, Phys. Rev. Lett. 83 1112 (1999)

Comparison of 1st order with full quantum-mechanical calculation

Eg: ^{11}Li+^{208}Pb at Coulomb barrier energies



- $E_{lab} \sim V_b \Rightarrow$ Coulomb important
- At small angles, breakup dominated by E1 Coulomb

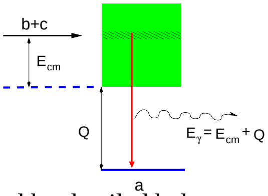
J.P. Fernandez-Garcia et al, PRL110, 142701(2013)

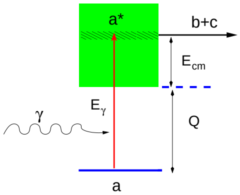
Radiative capture

Relation to radiative capture

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

Photo-absorption: $a + \gamma \longrightarrow b + c$





➪ Related by detailed balance:

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

➪ Astrophysical S-factor:

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

Photo-absorption cross section: virtual photon description

➪ Photo-absorption (not proven here): $\gamma + a \rightarrow b + c$

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

➪ 1^{st} order Coulomb breakup cross section in terms of photo-absorption:

$$\frac{d\sigma(E\lambda)}{d\Omega dE_\gamma} = \frac{1}{E_\gamma}\frac{dn_{E\lambda}}{d\Omega}\sigma^{\text{photo}}_{E\lambda}$$

(Equivalent Photon Method)

with the virtual photon number

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

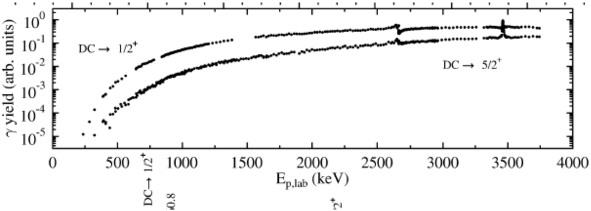
Radiative capture from Coulomb dissociation experiments

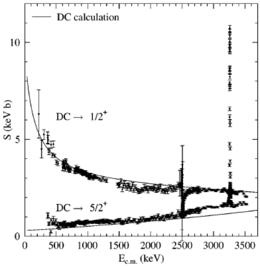
- Capture reactions have typically small cross sections
- Use breakup (Coulomb dissociation) reactions:

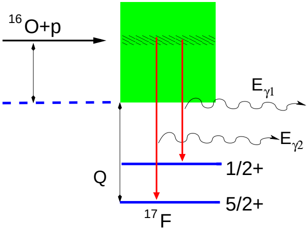
$$\frac{d\sigma}{d\Omega dE_{c.m.}} \rightarrow \sigma_{E\lambda}^{(\mathrm{phot})} \rightarrow \sigma_{E\lambda}^{(rc)} \rightarrow S(E_{\mathrm{c.m.}})$$

Example: p+^{16}O → ^{17}F + γ

Morlock, PRL79, 3837 (1997)



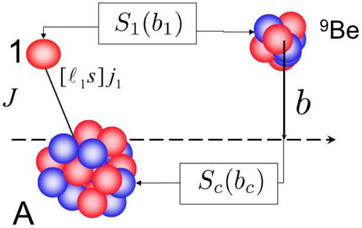




Knock-out reactions

Spectroscopic from momentum distributions

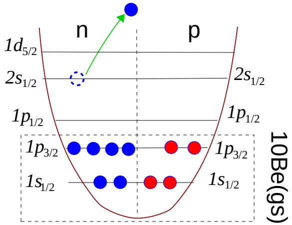
- Fast-moving projectile on a (typically) light target.
- One nucleon suddently removed (absorbed) due to its interaction with the target.
- The remaining nucleons remain unchanged and is detected.
- The momentum of the core is traced back to that of the removed nucleon because in the rest frame of the projectile $\vec{P} = 0$

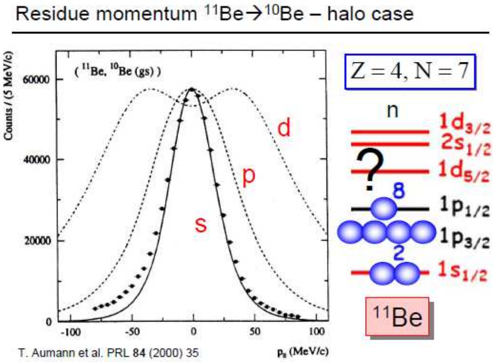


$$\vec{P} = \vec{p}_c + \vec{p}_1 = 0$$

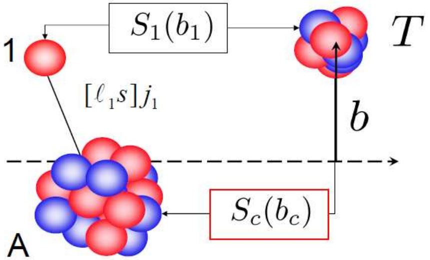
Angular momentum sensitivity of momentum distributions

- The shape is determined by the orbital angular momentum ℓ.
- The magnitude is determined by the amount of $s_{1/2}$ (spectroscopic factor)





Stripping cross section within a semiclassical (eikonal) theory



$$\sigma_{\mathrm{strip}} = \int d\mathbf{b}\ \langle \phi_0 \,|\, |S_c|^2 \,(1 - |S_1|^2) \,|\, \phi_0 \rangle$$

- $|S_c(b_c)|^2$=probability of survival of the core.
- $1 - |S_1(b_1)|^2$=probability of absorption of the neutron.

Transfer reactions with exotic nuclei

^{1}H(^{11}Be,^{10}Be)^{2}H example

$$|^{11}\mathrm{Be}\rangle = a \, |^{10}\,\mathrm{Be}(0^{+}) \otimes \nu 2s_{1/2}\rangle + b \, |^{10}\,\mathrm{Be}(2^{+}) \otimes \nu 1d_{5/2}\rangle + \ldots$$

➩ In DWBA:

$$\sigma(0^{+}) \propto |a|^{2}; \quad \sigma(2^{+}) \propto |b|^{2}$$

^{1}H(^{11}Be,^{10}Be)^{2}H example

$$|^{11}\text{Be}\rangle = a\,|^{10}\,\text{Be}(0^+) \otimes \nu 2s_{1/2}\rangle + b\,|^{10}\,\text{Be}(2^+) \otimes \nu 1d_{5/2}\rangle + \dots$$

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Fortier et al, PLB461, 22 (1999)