Transfer reactions: the DWBA method

A.M.Moro

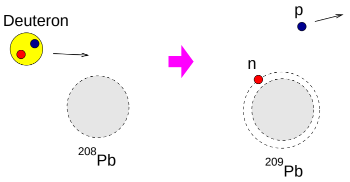
Universidad de Sevilla, Spain

April 19, 2022

Material available at: `https://github.com/ammoro/padova`

Outline

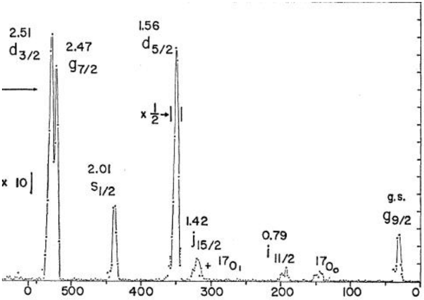
Example: d+^{208}Pb → p + ^{209}Pb

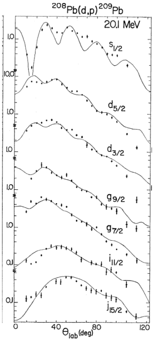


1. What do we measure in a transfer reaction?
   1. For a typical transfer reaction (e.g. d+^{208}Pb → p + ^{209}Pb), one measures the angular and energy distribution of outgoing fragments (e.g. protons).
   2. Additionally, one may collect information of decay products of ^{209}Pb (e.g. γ-rays, n, p, etc)
2. What information can we infer from a transfer reaction?
   1. Excitation energies of the residual nucleus (^{209}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}Pb → p + ^{209}Pb *Phys. Rev. 159 (1967) 1039*

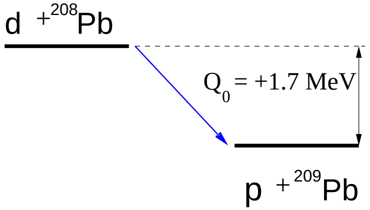




- The proton energy spectrum shows some peaks which reflect the energy spectrum of the residual nucleus (^{209}Pb).
- Each peak has a characteristic angular distribution, which depends on the structure of the associated state.
- The population probability will depend on the reaction dynamics and on the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

Transfer reactions: Q-value considerations

Example: d+^{208}Pb → p + ^{209}Pb



$$\boxed{Q_0 = M_d c^2 + M(^{208}\text{Pb})c^2 - M_p c^2 - M(^{209}\text{Pb})c^2 = +1.7\,\text{MeV}}$$

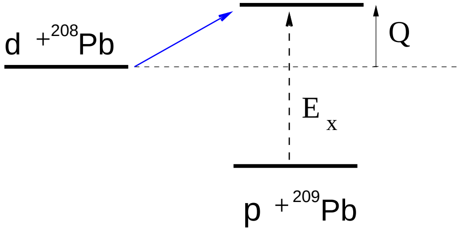
☞ $Q_0 > 0$: the outgoing proton will gain energy with respect to the incident deuteron.

N.b.: For a transfer reaction, the Q value is just the difference in binding energies of the transferred particle/cluster in the initial and final nuclei:

$$Q_0 = \varepsilon_b(f) - \varepsilon_b(i) = 3.936 - 2.224 = +1.7\,\text{MeV}$$

Transfer reactions: Q-value considerations

If the transfer leads to an excited state, the Q-value will change accordingly, and hence the kinetic energy of the outgoing nuclei.



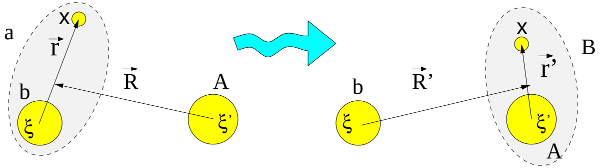
Energy balance:

$$\boxed{E^f_{\rm cm} = E^i_{\rm cm} + Q = E^i_{\rm cm} + Q_0 - E_x}$$

☞*If we know Q_0 we can infer the excitation energies (E_x) measuring the final kinetic energy of outgoing fragments.*

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

$$\underbrace{a+A}_{\alpha} \rightarrow \underbrace{b+B}_{\beta}$$

Evaluation of scattering amplitude in Born approximation (post form)

- Projectile-target interaction in post representation:

$$V_\beta(\mathbf{R}',\mathbf{r}') = V_{xb} + U_{bA} = \underbrace{U_\beta(\mathbf{R}')}_{\text{Aux. pot.}} + \underbrace{[V_{xb} + U_{bA} - U_\beta(\mathbf{R}')]}_{\text{Resid. inter.}} \equiv U_\beta(\mathbf{R}') + \Delta V_\beta$$

- In DWBA, the scattering amplitude is $f_{\beta\alpha}(\theta) = -(\mu_\beta/2\pi\hbar^2)\mathcal{T}_{\beta,\alpha}$ with

$$\boxed{\mathcal{T}_{\beta,\alpha}(\theta) = \int \underbrace{\chi_\beta^{(-)*}(\mathbf{K}_\beta,\mathbf{R}')\,\Phi_\beta^*(\xi_\beta)}_{\text{final state}}\ \Delta V_\beta\ \underbrace{\chi_\alpha^{(+)}(\mathbf{K}_\alpha,\mathbf{R})\,\Phi_\alpha(\xi_\alpha)}_{\text{initial state}}\ \underbrace{d\xi_\beta\, d\mathbf{R}'}_{\text{(all coordinates)}}}$$

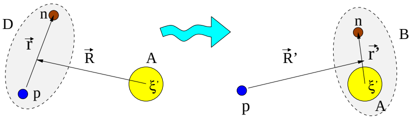
- Initial and final internal states:

$$\text{Initial state: } \Phi_\alpha(\xi_\alpha) = \varphi_a(\xi,\mathbf{r})\Phi_A(\xi') \qquad \xi_\alpha \equiv \{\xi,\xi',\mathbf{r}\}$$

$$\text{Final state: } \Phi_\beta(\xi_\beta) = \varphi_b(\xi)\Phi_B(\xi',\mathbf{r}') \qquad \xi_\beta \equiv \{\xi,\xi',\mathbf{r}'\}$$

- $\chi_{\alpha,\beta}^{(\pm)}$ are distorted waves for entrance and exit channels, obtained with appropriate optical potentials $U_\alpha(\mathbf{R})$, $U_\beta(\mathbf{R}')$

The important (d,p) case



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

$$\Phi_\alpha^{(0)}(\xi_\alpha) = \varphi_d(\mathbf{r})\phi_A(\xi') \qquad \xi_\alpha = \{\xi', \mathbf{r}\}$$

$$\Phi_\beta(\xi_\beta) = \Phi_B(\xi', \mathbf{r}') \qquad \xi_\beta = \{\xi', \mathbf{r}'\}$$

- Post-form DWBA transition amplitude:

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

- 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

➩ We need to evaluate the overlap integral

$$\int d\xi' \; \phi_B^*(\xi', \mathbf{r}')\phi_A(\xi') \equiv \langle \phi_B | \phi_A \rangle$$

➩ Use the parentage decomposition of $B \to A + n$

$$\boxed{\Phi_B(\xi', \mathbf{r}') = \mathcal{A}_{BA}^{\ell j} \underbrace{\phi_A(\xi')\varphi_{nA}^{\ell j}(\mathbf{r}')}_{\text{A g.s.}} + \sum_{A' \neq A} \mathcal{A}_{BA'}^{\ell' j'} \phi_{A'}(\xi')\varphi_{nA}^{\ell' j'}(\mathbf{r}')}$$

$$\Rightarrow \langle \phi_B | \phi_A \rangle = \mathcal{A}_{BA}^{\ell j} \varphi_{nA}^{\ell j}(\mathbf{r}')$$

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

☞ *The spectroscopic factor quantifies the single-particle content of a given physical state B, when described as A + n, with A in some specific state.*

Examples of parentage decomposition

1. Double-magic nucleus plus a single nucleon:

$$|{}^{209}\mathrm{Bi(g.s.)}\rangle_{9/2^-} \approx \left[|{}^{208}\mathrm{Pb}(0^+)\rangle \otimes |\pi 1h_{9/2}\rangle\right]_{9/2^-}$$

☞ *almost* single-particle configuration ($S_{IJ}^{\ell sj} \approx 1$).

2. Deformed core plus an extra nucleon:

$$|{}^{11}\mathrm{Be(gs)}\rangle_{1/2^+} = \alpha\left[|{}^{10}\mathrm{Be}(0^+)\rangle \otimes |\nu 2s_{1/2}\rangle\right]_{1/2^+} + \beta\left[|{}^{10}\mathrm{Be}(2^+)\rangle \otimes |\nu 1d_{5/2}\rangle\right]_{1/2^+} + \ldots$$

with $|\alpha|^2 + |\beta|^2 + \ldots \approx 1$

3. Due to indistinguishability of neutrons (or protons) the SF can be even larger than 1!

Scattering amplitude and cross sections

➩ In post form:

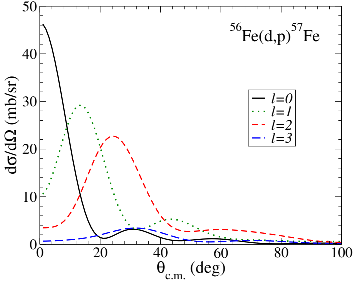
$$\boxed{\mathcal{T}^{\rm DWBA}_{d,p} = \mathcal{A}^{\ell j}_{BA} \int\int \chi^{(-)*}_p(\mathbf{K}_p, \mathbf{R}')\varphi^{\ell j,*}_{nA}(\mathbf{r}')\, V_{pn}(\mathbf{r})\, \chi^{(+)}_d(\mathbf{K}_d, \mathbf{R})\varphi_d(\mathbf{r}) d\mathbf{r}' d\mathbf{R}'}$$

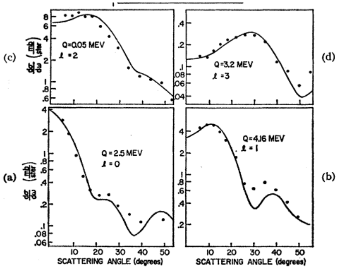
$$\boxed{\left(\frac{d\sigma}{d\Omega}\right)_{(d,p)} = \frac{\mu_\alpha\mu_\beta}{(2\pi\hbar^2)^2} S^{\ell j}_{BA} \left|\int\int \chi^{(-)*}_p(\mathbf{K}_p, \mathbf{R}')\varphi^{\ell j,*}_{nA}(\mathbf{r}')\, V_{pn}(\mathbf{r})\, \chi^{(+)}_d(\mathbf{K}_d, \mathbf{R})\varphi_d(\mathbf{r}) d\mathbf{r}'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

$$|\mathcal{A}^{\ell j}_{BA}|^2 = S^{\ell j}_{BA} = \text{spectroscopic factor}$$

☞*In DWBA, the transfer cross section is proportional to the product of the projectile and target spectroscopic factors. Comparing the data with DWBA calculations, one can extract the values of* $S^{\ell j}_{BA}$

Orbital angular momentum sensitivity





☞ *Angular distributions of transfer cross sections are very sensitive to the single-particle configuration of the transferred nucleon/s.* $\Rightarrow \varphi_{nlj}(\mathbf{r})$

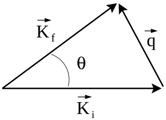
☞ From classical arguments, the angle of the first maximum appears at:

$$\theta_{\max} \approx \arcsin\left(\frac{\sqrt{\ell(\ell+1)}\hbar}{pR}\right)$$

Matching conditions

Using classical arguments, one can relate the change in the linear and final momenta to the transferred orbital angular momentum:

- Momentum transfer:



- Angular momentum transfer:

$$|(\mathbf{P}_i - \mathbf{P}_f) \times \mathbf{R}| = |\mathbf{q}\hbar \times \mathbf{R}| \simeq \ell\hbar$$

☞ *High qR values favor the population of higher spin states.*

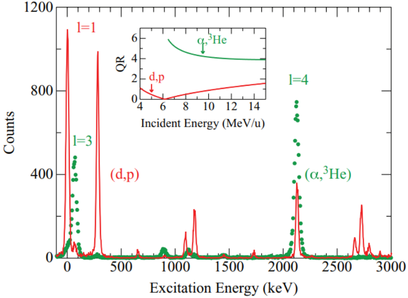


FIG. 2. (Color online) Spectra for the ^{60}Ni(d,p) and (α,^{3}He) reactions at 15° and 7°, respectively, indicating the strong enhancement of the lower ℓ values in the former reaction and the higher ones in the latter. The inset shows the reason for this: the momentum matching for the two reactions as a function of bombarding energy (deduced from a crude semiclassical picture), where the arrows show the bombarding energies used in this work, and Q is the momentum transfer and R the radius.

Schiffer et al, PRC 87, 034306 (2013)

Summary: What do we learn form a transfer experiment

1. Excitation energies of residual nucleus

➩ *The Q-value is related to the masses and excitation energies*

2. Spectroscopic factors (related to occupation numbers)

➩ In DWBA, $\sigma^{\ell j I} \propto S_{BA}^{\ell j I}$

3. Angular momentum of populated states.

➩ For heavy targets, the first maximum occurs at:

$$\theta_{\max} \approx \arcsin\left(\frac{\sqrt{\ell(\ell+1)}\hbar}{pR}\right)$$

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

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

➩ In DWBA:

$$\sigma(0^+) \propto |\alpha|^2; \quad \sigma(2^+) \propto |\beta|^2$$

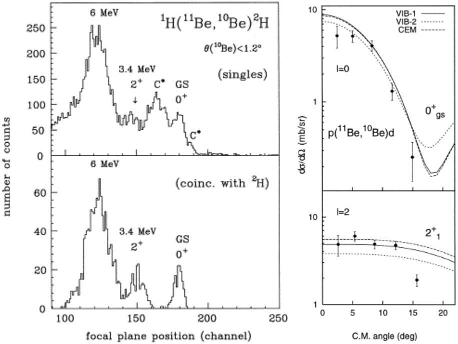
$^{1}H(^{11}Be,^{10}Be)^{2}H$ example

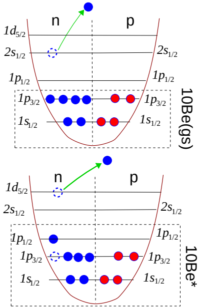
$$|^{11}\mathrm{Be}\rangle = \alpha\, |^{10}\,\mathrm{Be}(0^+) \otimes \nu 2s_{1/2}\rangle + \beta\, |^{10}\,\mathrm{Be}(2^+) \otimes \nu 1d_{5/2}\rangle + \ldots$$

⇨ In DWBA:

$$\sigma(0^+) \propto |\alpha|^2; \quad \sigma(2^+) \propto |\beta|^2$$

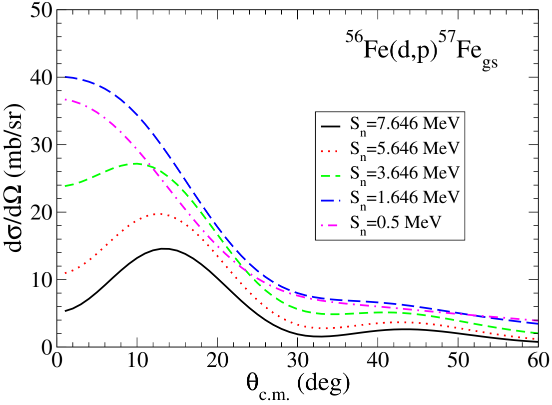
Fortier et al, PLB461, 22 (1999)





Transfer example: ^{56}Fe(d,p)^{57}Fe

Dependence with binding energy:



Peripherality of transfer reactions: the ANC

- Recall the overlap function: $\langle \phi_B | \phi_A \rangle = \mathcal{A}^{\ell j}_{BA} \varphi^{\ell j}_{nA}(\mathbf{r}')$
- Outside the range of the nuclear potential:

$$\varphi^{\ell j}_{nA}(\mathbf{r}') \to b_{\ell,j} \frac{W_{-\eta,\ell+1/2}(2kr)}{r} \approx b_{\ell,j} e^{-kr} \qquad k = \sqrt{2\mu\epsilon_b}/\hbar$$

where $b_{\ell,j}$ is the single-particle asymptotic normalization coefficient.

- Then, outside the range of the nuclear potential:

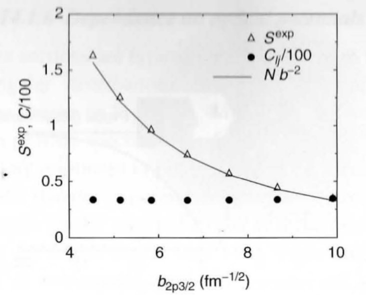
$$\langle \phi_B | \phi_A \rangle = \mathcal{A}^{\ell j}_{BA} b_{\ell,j} \frac{W_{-\eta,\ell+1/2}(2kr)}{r} \equiv C^{\ell j}_{BA} \frac{W_{-\eta,\ell+1/2}(2kr)}{r}$$

where $C^{\ell j}_{BA} = \mathcal{A}^{\ell j}_{BA} b_{\ell,j}$ is the asymptotic normalization coefficient of the $\langle \phi_B | \phi_A \rangle$ overlap.

☞ *Thus, outside the range of the nuclear potential, the overlap function is sensitive to the ANC $C^{\ell j}_{BA}$ rather than to the spectroscopic amplitude $\mathcal{A}^{\ell j}_{BA}$*

Peripherality of transfer reactions: the ANC

- For a peripheral transfer reaction, $d\sigma/d\Omega \propto |C^{\ell j}_{BA}|^2$.
- In DWBA, the ratio of the experimental and calculated cross sections will provide the quantity $|C^{\ell j}_{BA}|^2$.
- Since $|C^{\ell j}_{BA}|^2 = S^{\ell j}_{BA} b^2_{\ell,j}$, varying the parameters of the single-particle potential used to generate $\varphi^{\ell j}_{nA}(\mathbf{r}')$, will modify $b_{\ell,j}$ and also $S^{\ell j}_{BA}$ but their product ($|C^{\ell j}_{BA}|^2$) will remain roughly constant.

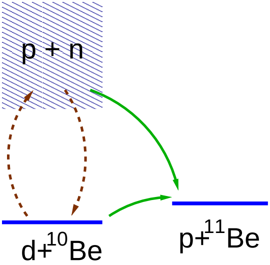


Quoted from Fig. 14.4 of Thompson and Nunes book

Transfer reactions with weakly bound nuclei

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)

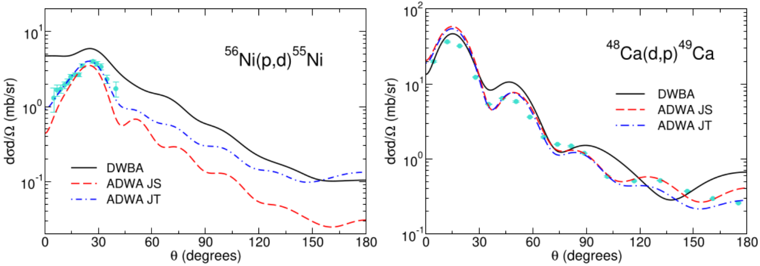
- $\chi_d^{(+)}(\mathbf{K}_d, \mathbf{R})$ describes deuteron elastic scattering but, for the (d,p) transfer matrix element, we need only $\Psi^{(+)}_{\mathbf{K}_d}(\mathbf{R}, \mathbf{r})$ for small $|\mathbf{r}|$
- R.C. Johnson and col. have derived an approximation of $\Psi^{(+)}_{\mathbf{K}_d}(\mathbf{R}, \mathbf{r})$ valid for $r \approx 0$, which includes the effect of deuteron breakup effectively (adiabatic approx.):
  1. Zero-range approximation (Johnson-Soper):[(Johnson,Soper,PRC1, 976 (1970)]

     $$\boxed{U^{JS}(R) = U_{pA}(R) + U_{nA}(R)} \quad \Rightarrow \chi_d^{JS}(\mathbf{R})$$

  2. Finite-range version (Johnson–Tandy): [Johnson & Tandy, NPA235 (1974) 56]

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

DWBA vs ADWA



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

CDCC-BA approximation

- Exact transition amplitude for a general $A(d,p)B$ process:

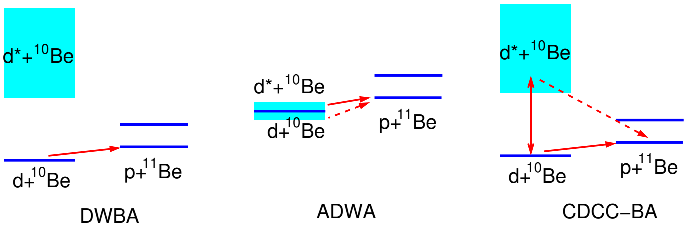
$$\boxed{\mathcal{T}^{\rm CDCC}_{d,p} = C^{\ell j}_{BA} \int\int \chi^{(-)*}_p(\mathbf{K}_p, \mathbf{R}')\varphi^{\ell j,*}_{nA}(\mathbf{r}')\; V_{pn}(\mathbf{r})\; \underbrace{\Psi^{(+)}_{\mathbf{K}_\alpha}(\mathbf{R}_\alpha, \xi_\alpha)}\, d\mathbf{r}'\, d\mathbf{R}'}$$

- Use CDCC approximation for $\Psi^{(+)}_{\mathbf{K}_\alpha}$:

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

- Unlike the DWBA and ADWA methods, coupling to deuteron breakup states is included explicitly.

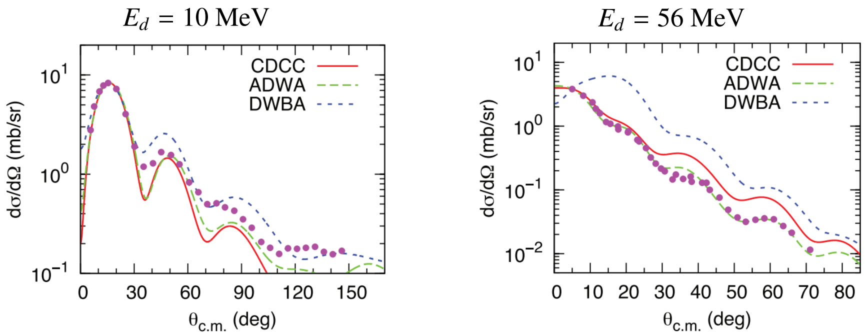
DWBA, ADWA and CDCC-BA compared



Gómez-Camacho and A.M.M., *A Pedestrian Approach to the Theory of Transfer Reactions: Application to Weakly-Bound and Unbound Exotic Nuclei*, Lecture Notes in Physics, vol 879.

DWBA vs ADWA vs CDCC

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



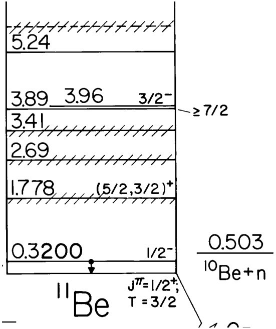
☞*CDCC and ADWA provide better description of the data and lead also to more realistic spectroscopic information (e.g. spectroscopic factors)*

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

Transfer reactions populating unbound states: resonances

Continuum resonances

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

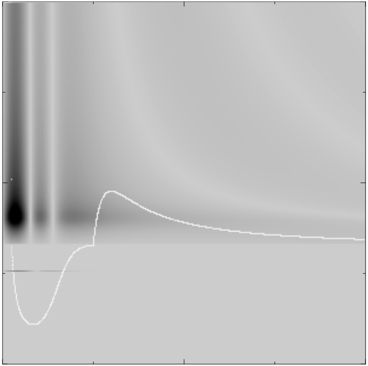


What is a resonance?

- 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, continuum wavefunctions have a large probability of being in the radial range of the potential.
- The continuum wavefunctions are not square normalizable. For practical applications, a normalized wavepacket (or "bin") can be constructed to represent the resonance.

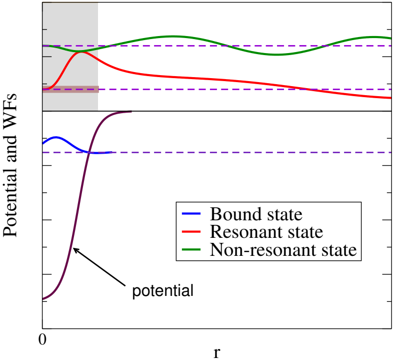
Distinctive features of a resonance

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



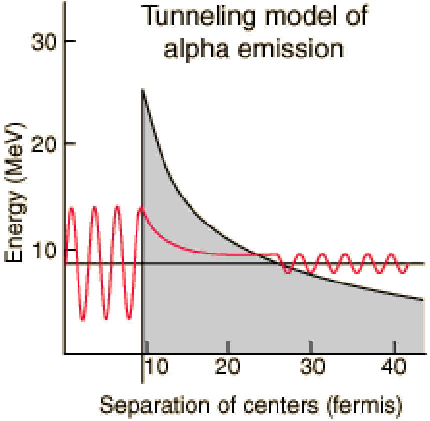
Cuts and areas ordered by size

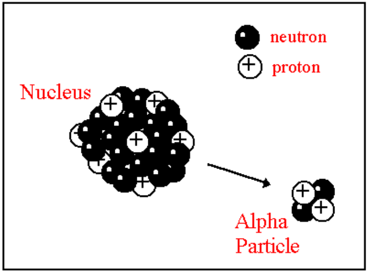
(Courtesy of C. Dasso)



Distinctive features of a resonance

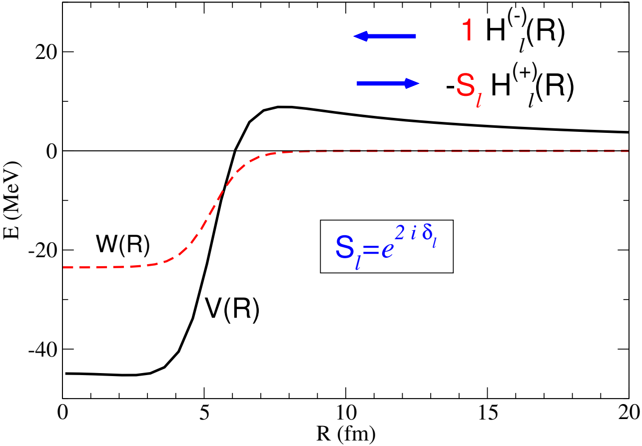
The decay of the resonance is also behind the α-decay phenomenon:



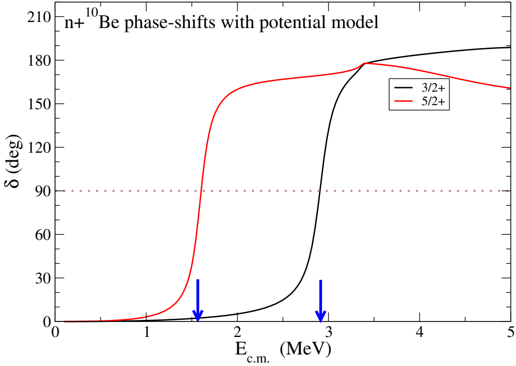


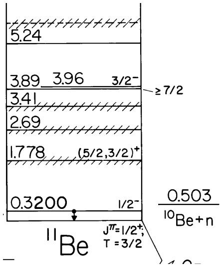
Resonances and phase-shifts

$$\chi_l(R) \rightarrow 1\, H^{(-)}_l(R) - S_l\, H^{(+)}_l(R)$$



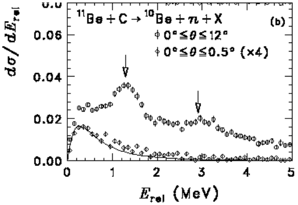
Resonances and phase-shifts

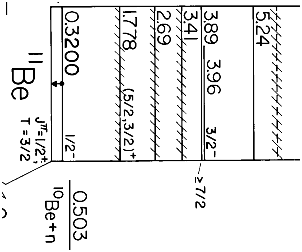




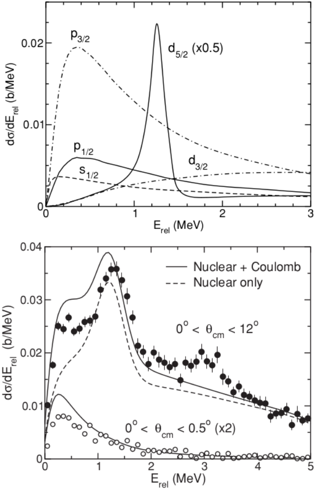
Studying resonances in nuclear breakup experiments

RIKEN data





CDCC analysis



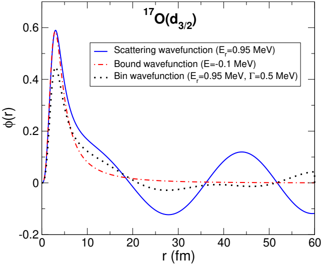
Fukuda *et al*, PRC70 (2004) 054606)

Howell *et al.*, JPG31 (2005) S1881

Exploring resonances from transfer reactions

- Calculation of transfer to unbound states in DWBA and ADWA poses numerical problems due to the oscillatory behaviour of unbound wavefunctions.
- A 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*

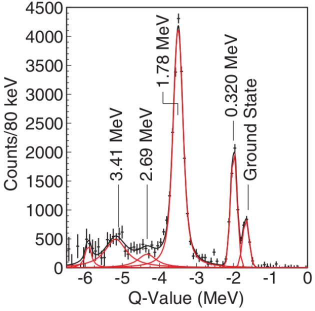
E.g.: $d_{3/2}$ resonance in ^{17}O resonance at $E_r = 0.95$ MeV



Exploring resonances from transfer reactions

- Inclusion of continuum states in DWBA poses numerical problems due to the oscillatory behaviour of unbound wavefunctions
- Regularization method must be applied, such as representing the resonance by a wavepacket (continuum *bin*, as in the CDCC method)

E.g.: ^{11}Be resonance at $E_x = 1.78$ MeV from ^{10}Be(d,p)^{11}Be   Schmitt et al, PRC88, 064612 (2013)



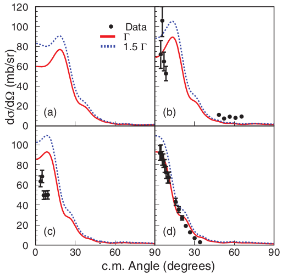
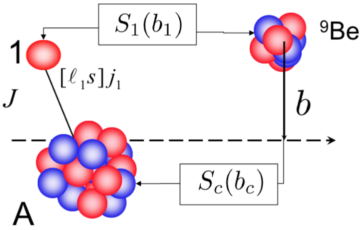


FIG. 8. (Color online) Differential cross sections are presented for transfer to the first resonance in ^{11}Be at 1.78 MeV via the ^{10}Be(d,p) reaction in inverse kinematics at deuteron energies of (a) 12 MeV, (b) 15 MeV, (c) 18 MeV, and (d) 21.4 MeV. The curves are from FR-ADWA calculations using (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 MeV the protons were too low in energy to extract an angular distribution.

Knock-out reactions

Spectroscopic from momentum distributions

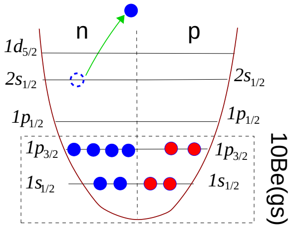
- Fast-moving projectile on a (typically) light target.
- One nucleon suddenly removed (absorbed) due to its interaction with the target.
- The remaining residue remains unchanged and is detected.
- The momentum of the core is related to that of the removed nucleon because, in the rest frame of the projectile,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

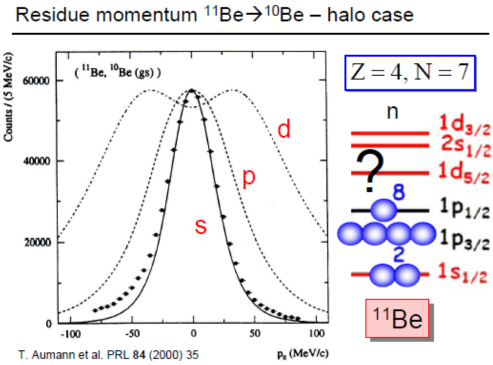


$$\boxed{\vec{P} = \vec{p}_c + \vec{p}_1 = 0}$$

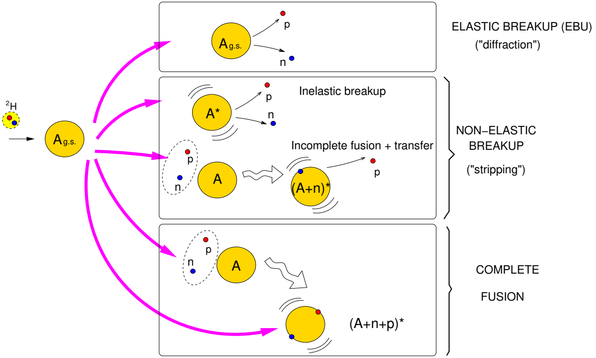
Angular momentum sensitivity of momentum distributions

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





Stripping and diffraction contributions to inclusive breakup cross sections



☞*The singles (inclusive) cross section of a given fragment will contain in general diffraction and stripping components*

Stripping cross section within a semiclassical (eikonal) theory

At high energies, one can use the sudden, eikonal approximations to obtain simple formulas for the stripping and diffraction parts of the inclusive breakup cross section for a inclusive reaction of the form $a + B \rightarrow b + X$, with $a = b + x$:

Stripping:

$$\boxed{\sigma_{\rm sp}^{\rm str} = 2\pi \int b db \int d\mathbf{r}\, |\varphi_{bx}(\mathbf{r})|^2 (1 - |S_x(b_x)|)^2 |S_{bA}(b_b)|^2}$$

Diffraction:

$$\boxed{\sigma_{\rm sp}^{\rm diff} = 2\pi \int b db \left[\langle \varphi_{bx}|\, |S_b S_x|^2 |\varphi_{bx}\rangle - |\langle \varphi_{bx}| S_b S_x |\varphi_{bx}\rangle|^2 \right].}$$

- $|S_b(b_b)|^2$=probability of survival of the core.
- $1 - |S_x(b_x)|^2$=probability of absorption of the valence particle.

Extraction of SFs from knockout reactions

- Agreement theory vs experiment quantified with the reduction factor:

$$\boxed{R_s = \frac{\sigma_{\rm theor}}{\sigma_{\rm exp}}}$$

with

$$\boxed{\sigma_{\rm theor} = \sum_{n\ell j} S^{a}_{bx}(I; n\ell j)\sigma_{\rm sp}(I; n\ell j)} \qquad \boxed{\sigma_{\rm sp}(I; n\ell j) = \sigma^{\rm EBU}_{\rm sp} + \sigma^{\rm NEB}_{\rm sp}}$$

☞ $R_s < 1 \Rightarrow$ possible correlations (long-range, short-range, tensor,...) not included in $\sigma_{\rm theor}$?

☞ R_s strongly dependent on $\Delta S = S_p - S_n$.

Extraction of SFs from knockout reactions

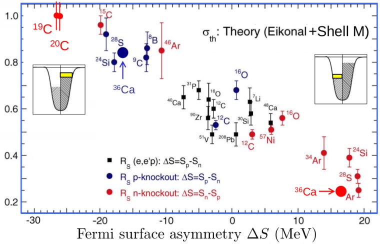
- Agreement theory vs experiment quantified with the reduction factor:

$$\boxed{R_s = \frac{\sigma_{\text{theor}}}{\sigma_{\text{exp}}}}$$

with

$$\boxed{\sigma_{\text{theor}} = \sum_{n\ell j} S^a_{bx}(I;n\ell j)\sigma_{\text{sp}}(I;n\ell j)} \qquad \boxed{\sigma_{\text{sp}}(I;n\ell j) = \sigma^{\text{EBU}}_{\text{sp}} + \sigma^{\text{NEB}}_{\text{sp}}}$$

Measurements at the two Fermi surfaces



-Gade et al, PRC 77, 044306 (2008)

Tostevin, PRC90,057602(2014)

☞ $R_s < 1 \Rightarrow$ possible correlations (long-range, short-range, tensor,...) not included in σ_{theor}?

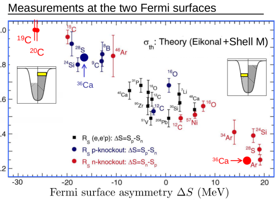
☞ R_s strongly dependent on $\Delta S = S_p - S_n$.

Extraction of SFs from knockout reactions

...however, this behaviour has not been corroborated by other probes, such as transfer or proton-induced knockout reactions (p,pN)

HI knockout (∼100 MeV/u)

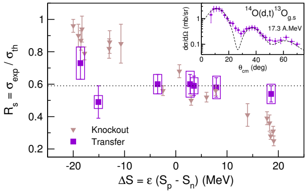
Tostevin, PRC90,057602(2014)



- Reaction model: eikonal + adiabatic
- R_s strongly dependent on $S_p - S_n$.

Low-energy transfer

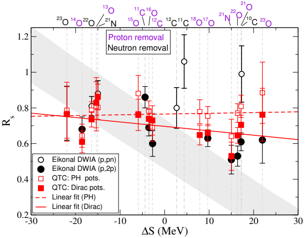
Flavigny, PRL110, 122503(2013)



- Reaction model: ADWA, DWBA, CRC
- R_s ∼ constant.

(p,pN) @ 200-400 MeV/u

Aumann, PPNP118,103847(2021)



- Reaction models: DWIA, TC
- R_s ∼ constant.

☞ Similar results from RIKEN Wakase, PTEP 021D01 (2018)

R_s from knockout disagree with those from transfer and (p,pN) ⇒ description of reaction mechanism?