Transfer Reactions; Theory

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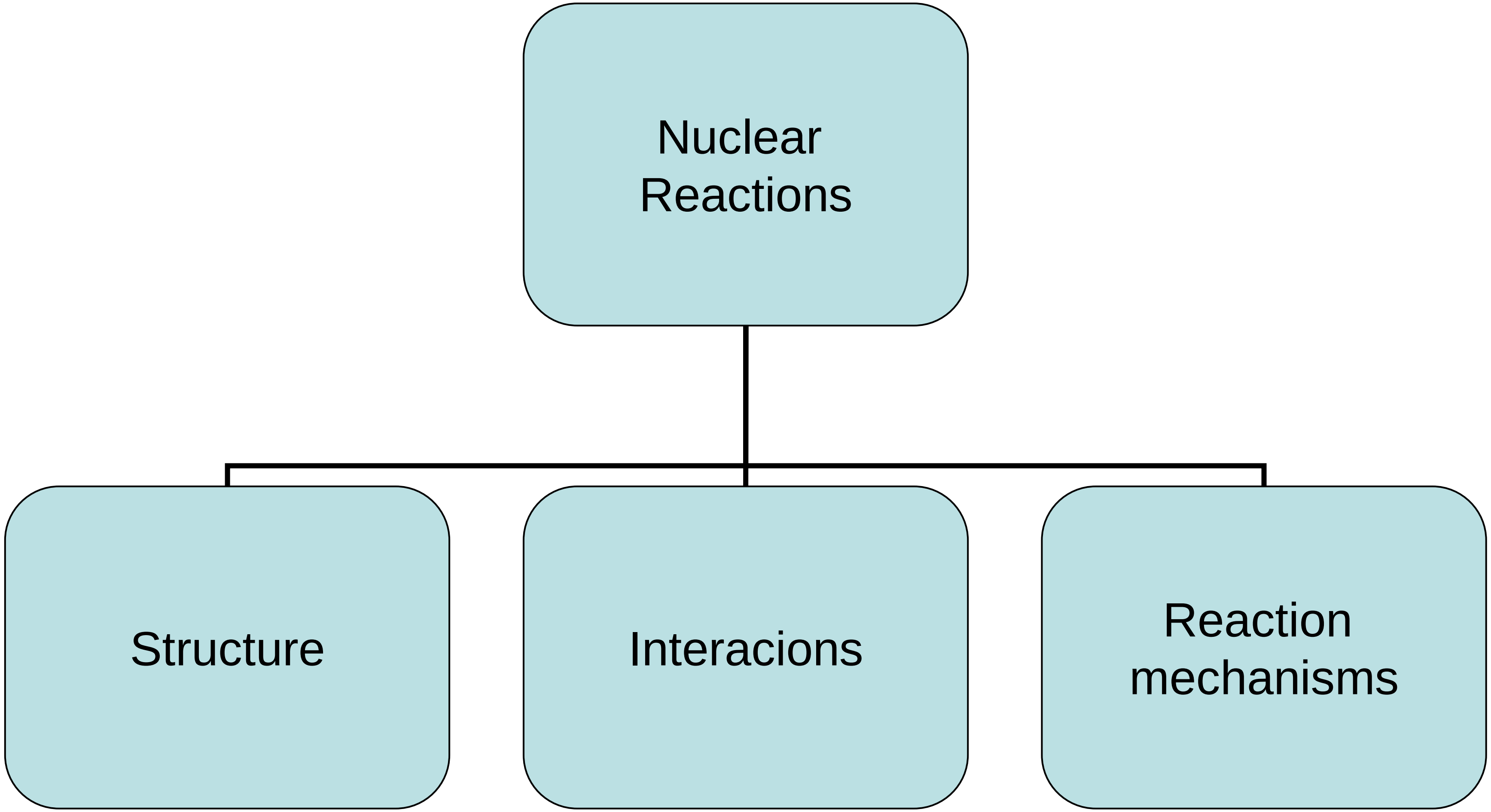
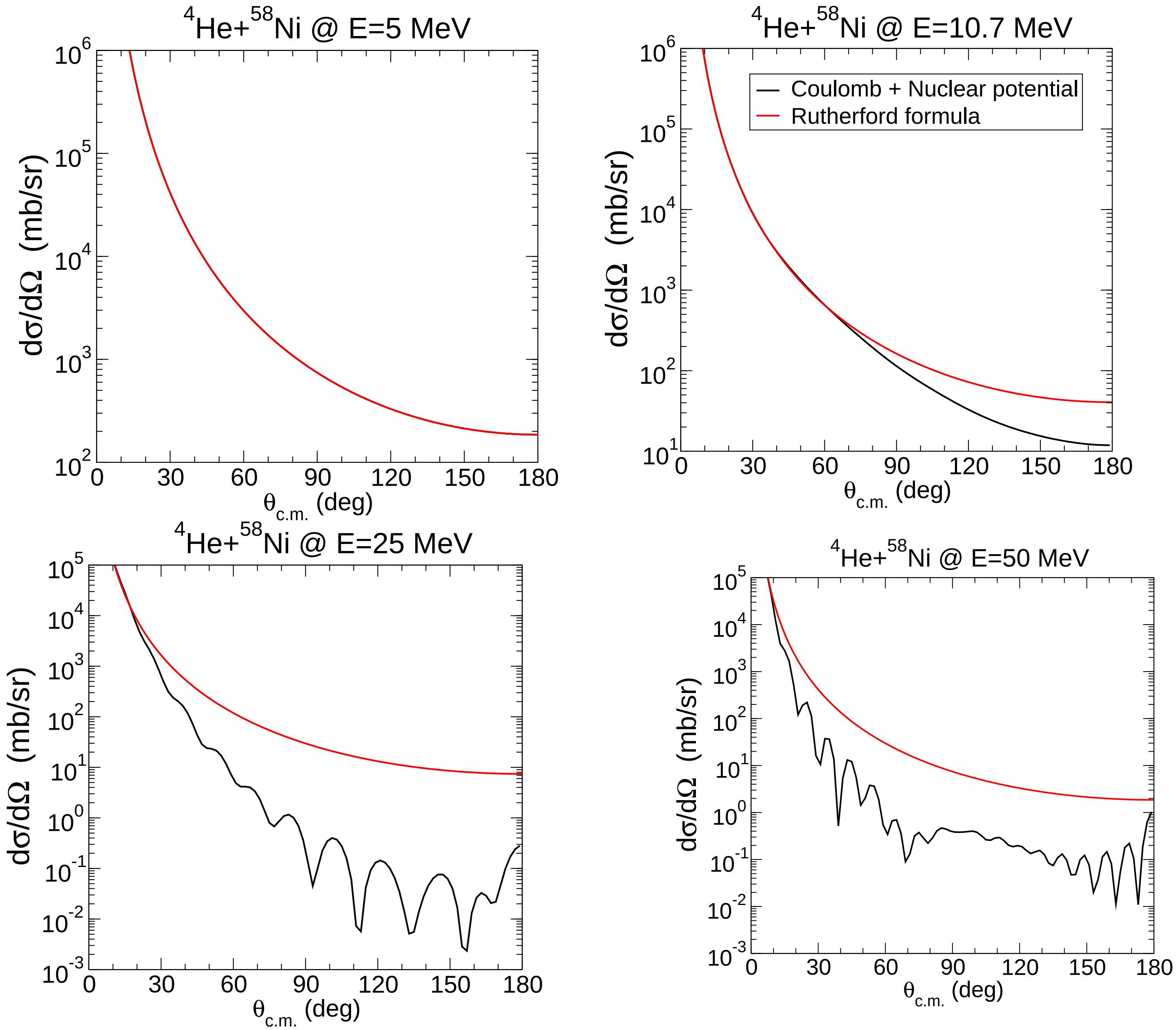
Summary

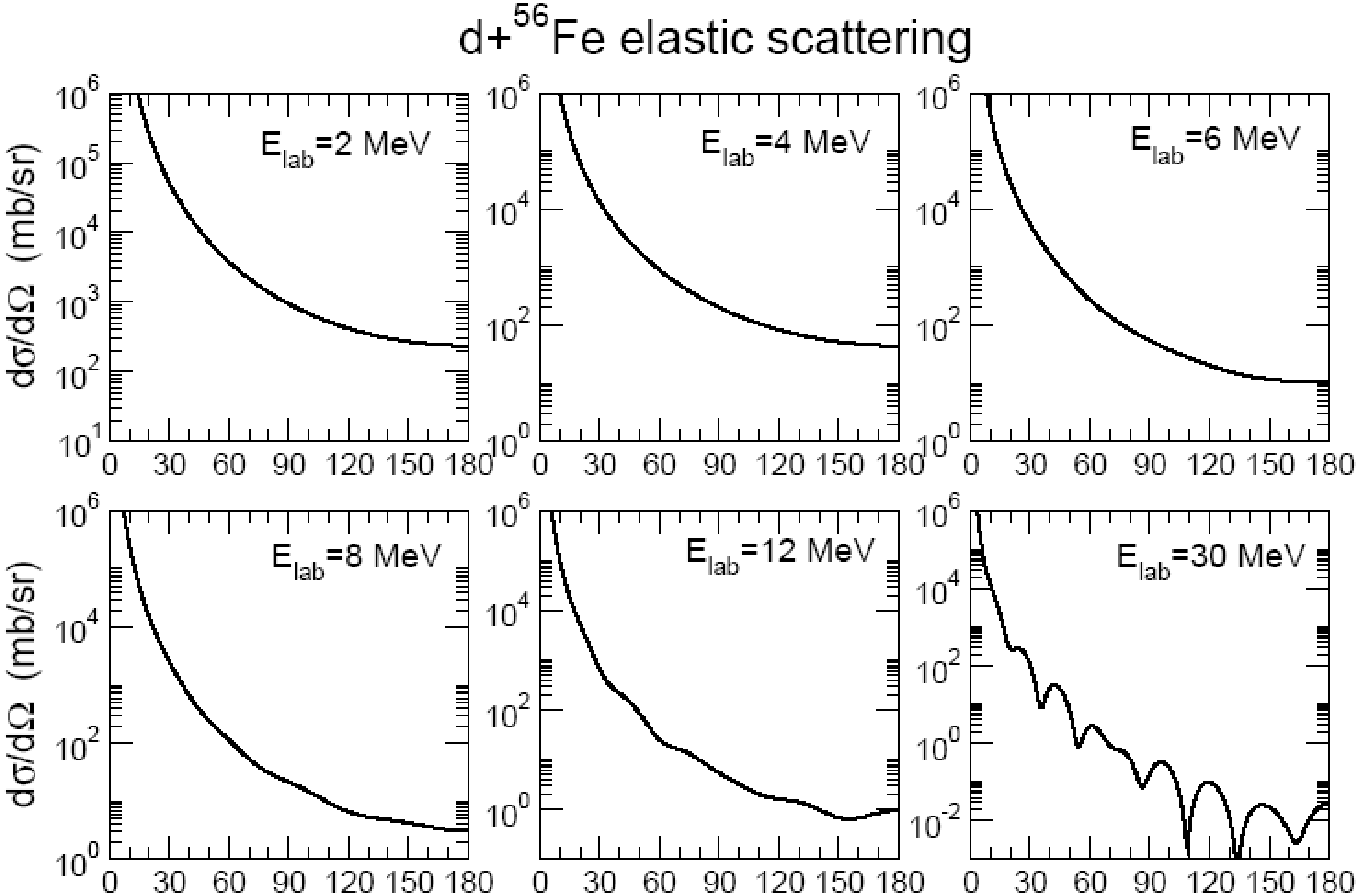
1. Transfer general concepts
2. Transfer formalism
3. Transfer to structures in the continuum

Why measure reactions?



Elastic Scattering

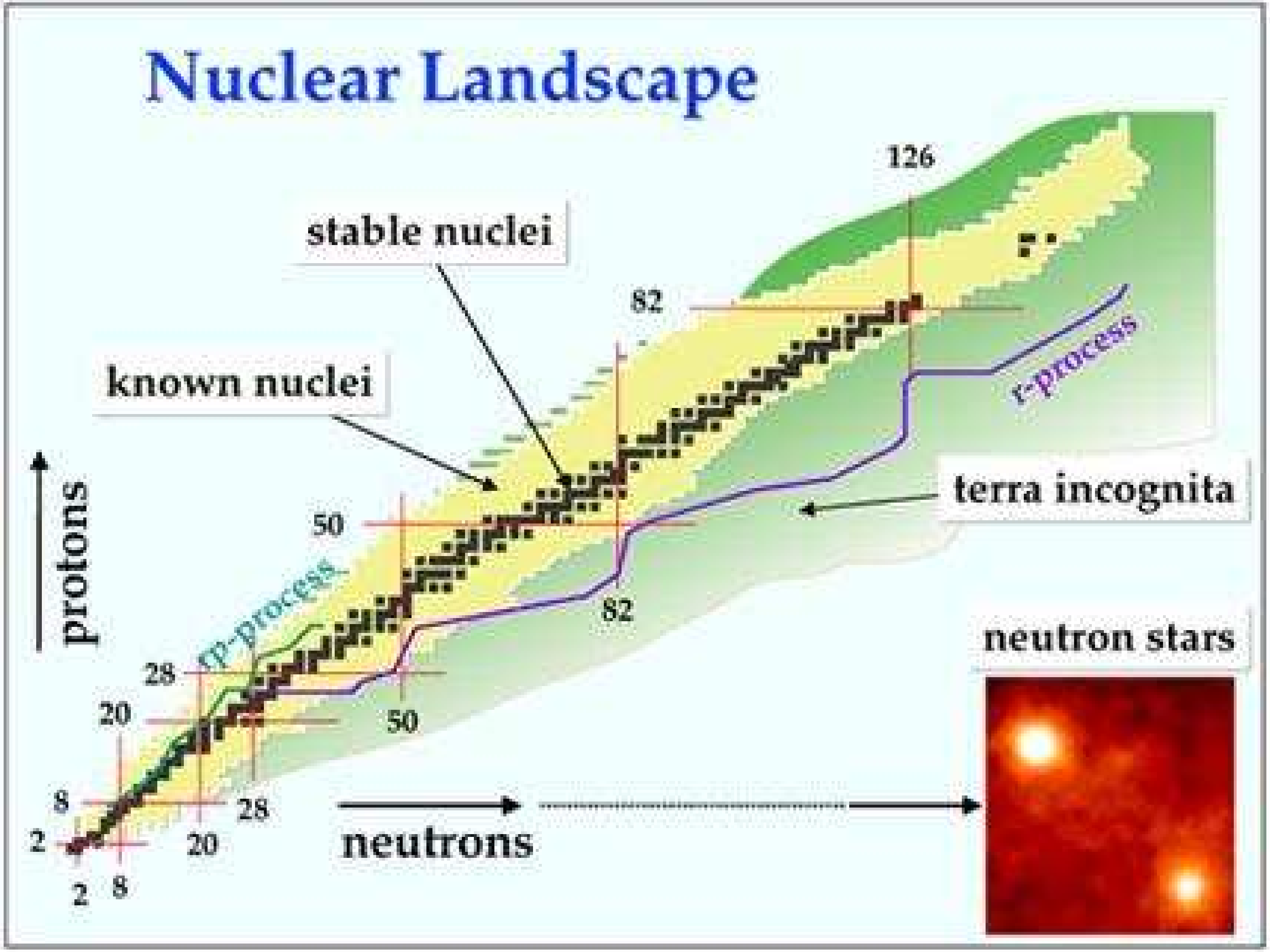




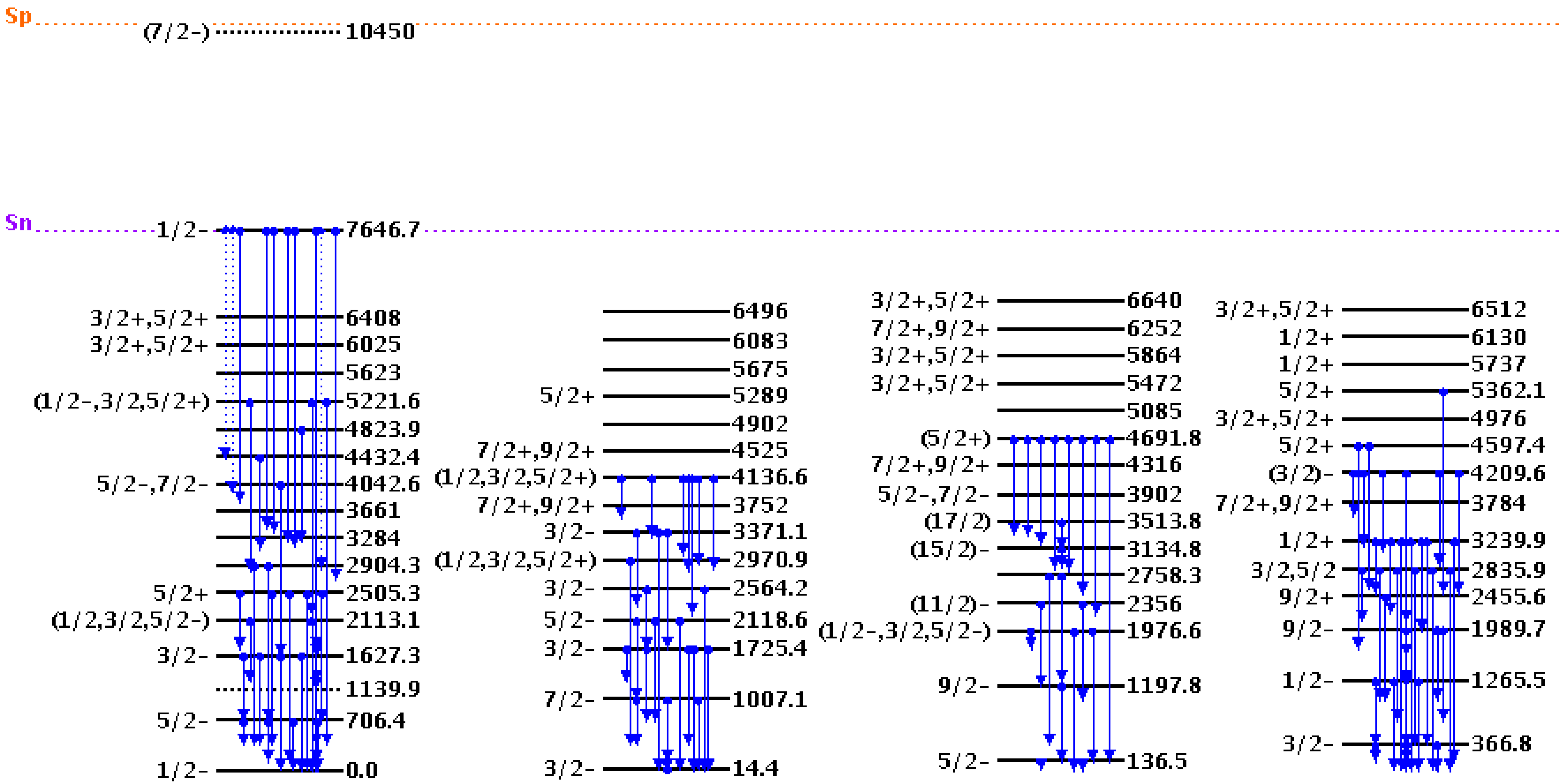
d+^{56}Fe elastic scattering
E_{lab}=2 MeV
E_{lab}=4 MeV
E_{lab}=6 MeV
E_{lab}=8 MeV
E_{lab}=12 MeV
E_{lab}=30 MeV
dσ/dΩ (mb/sr)
0 30 60 90 120 150 180

1.1 Basic concepts

- Half-distance of closest approach in a head-on collision: $a_0 = \frac{1.44 Z_1 Z_2}{2E}$.
- Strong absorption radius $R_s \simeq 1.45(A_1^{1/3} + A_2^{1/3})$ fm.
- Energy of the Coulomb Barrier $E_B \simeq \frac{1.44 Z_1 Z_2 e^2}{(R_s + 1.0)}$
- Distance of closest approach for a given angle in a Coulomb trajectory: $R_t(\theta) = a_0(1 + 1/sin(\theta/2)$.
- Rutherford differential cross section: $\frac{d\sigma}{d\Omega}_{cl} = \frac{a_0^2}{4}\frac{1}{sin^4(\theta/2)}$.

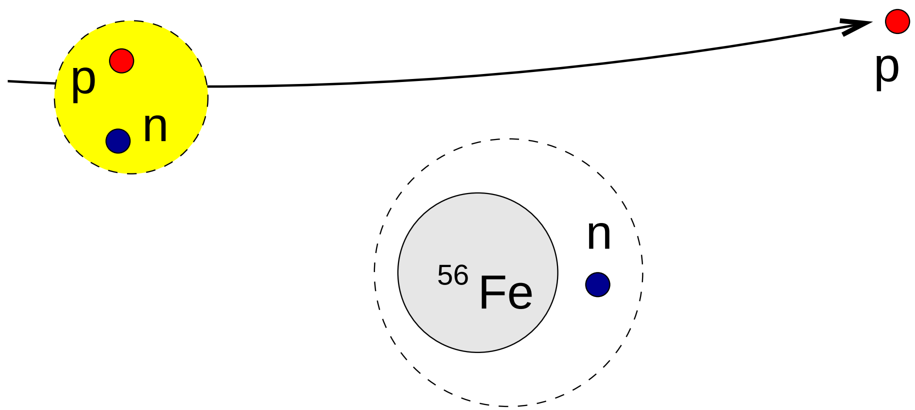

Nuclear Landscape
126
stable nuclei
82
known nuclei
r-process
terra incognita
protons
50
rp-process
82
neutron stars
28
20
50
8
28
2
20
neutrons
2
8

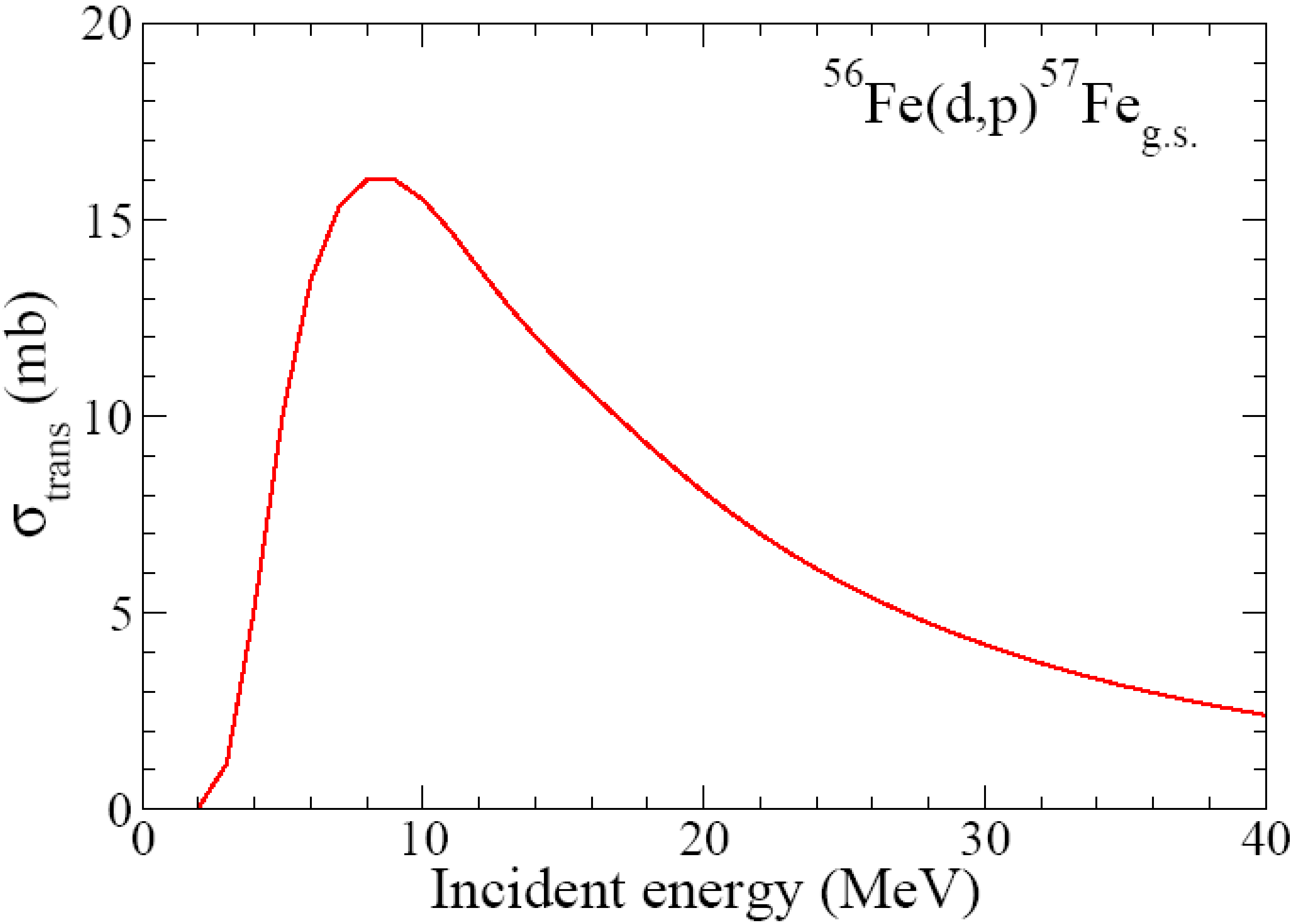
57Fe



Sp
(7/2-) 10450
Sn
1/2- 7646.7
3/2+,5/2+ 6408
3/2+,5/2+ 6025
5623
(1/2-,3/2,5/2+) 5221.6
4823.9
4432.4
5/2-,7/2- 4042.6
3661
3284
2904.3
5/2+ 2505.3
(1/2,3/2,5/2-) 2113.1
3/2- 1627.3
1139.9
5/2- 706.4
1/2- 0.0
6496
6083
5675
5/2+ 5289
4902
7/2+,9/2+ 4525
(1/2,3/2,5/2+) 4136.6
7/2+,9/2+ 3752
3/2- 3371.1
(1/2,3/2,5/2+) 2970.9
3/2- 2564.2
5/2- 2118.6
3/2- 1725.4
7/2- 1007.1
3/2- 14.4
3/2+,5/2+ 6640
7/2+,9/2+ 6252
3/2+,5/2+ 5864
3/2+,5/2+ 5472
5085
(5/2+) 4691.8
7/2+,9/2+ 4316
5/2-,7/2- 3902
(17/2) 3513.8
(15/2)- 3134.8
2758.3
(11/2)- 2356
(1/2-,3/2,5/2-) 1976.6
9/2- 1197.8
5/2- 136.5
3/2+,5/2+ 6512
1/2+ 6130
1/2+ 5737
5/2+ 5362.1
3/2+,5/2+ 4976
5/2+ 4597.4
(3/2)- 4209.6
7/2+,9/2+ 3784
1/2+ 3239.9
3/2,5/2 2835.9
9/2+ 2455.6
9/2- 1989.7
1/2- 1265.5
3/2- 366.8

Transfer Reactions





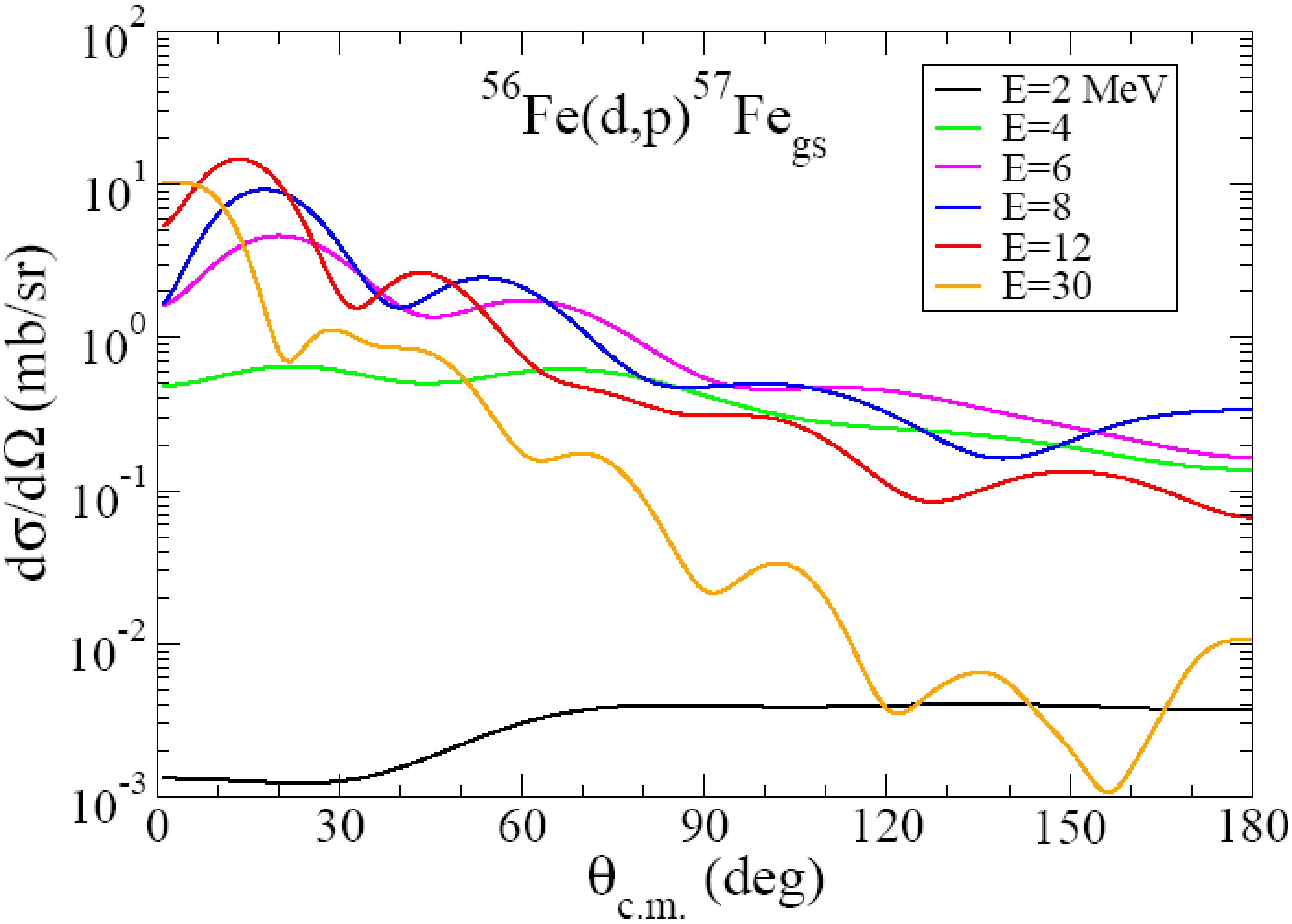
^{56}Fe(d,p)^{57}Fe$_{g.s.}$
σ$_{trans}$ (mb)
Incident energy (MeV)
0
5
10
15
20
0
10
20
30
40

1.2 Scattering energy dependence

- Below the barrier, transfer decreases exponentially with energy.
- At high energies, transfer decreases.
- Transfer has an energy window, which is determined by matching the initial and final velocity components of the transferred particle, in the forward direction.

$$E_p/A_p = 1/2mv_i^2 \simeq 1/2mv_f^2 = E_F/3$$

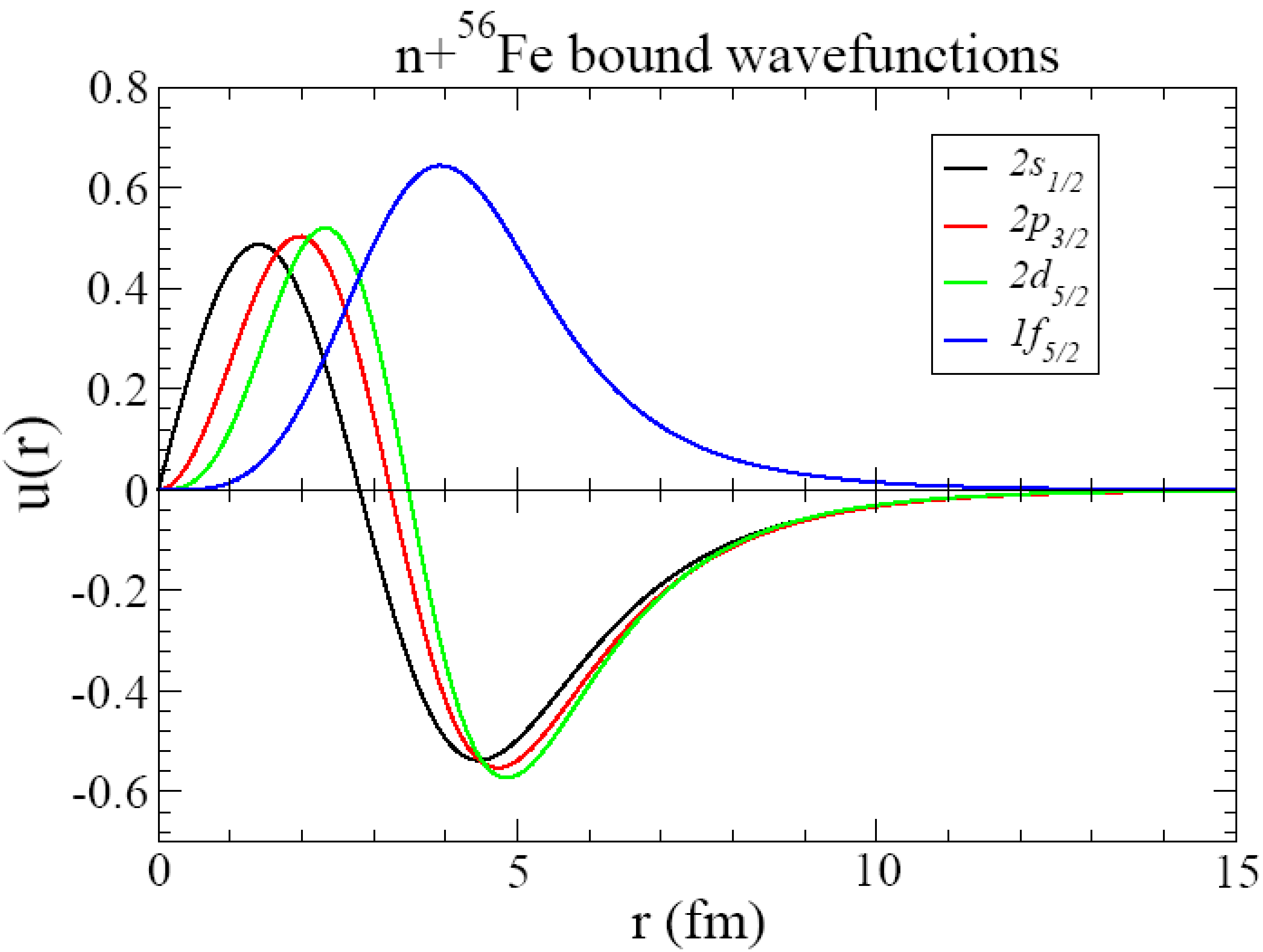
E_F is the Fermi energy, which is about 38 MeV, for stable nuclei.



$^{56}Fe(d,p)^{57}Fe_{gs}$
E=2 MeV
E=4
E=6
E=8
E=12
E=30
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$ (deg)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
30
60
90
120
150
180

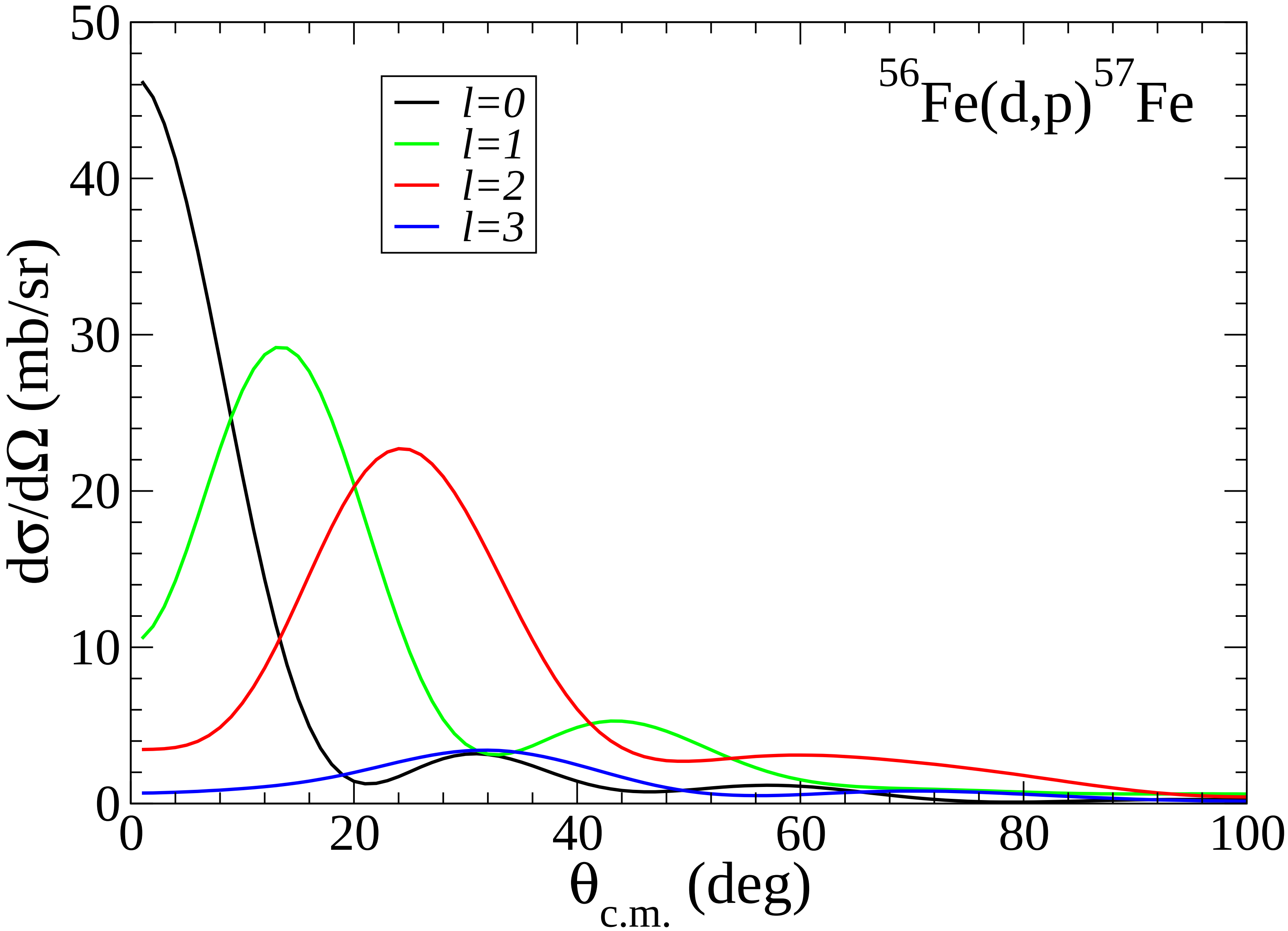
1.3 Scattering angle dependence

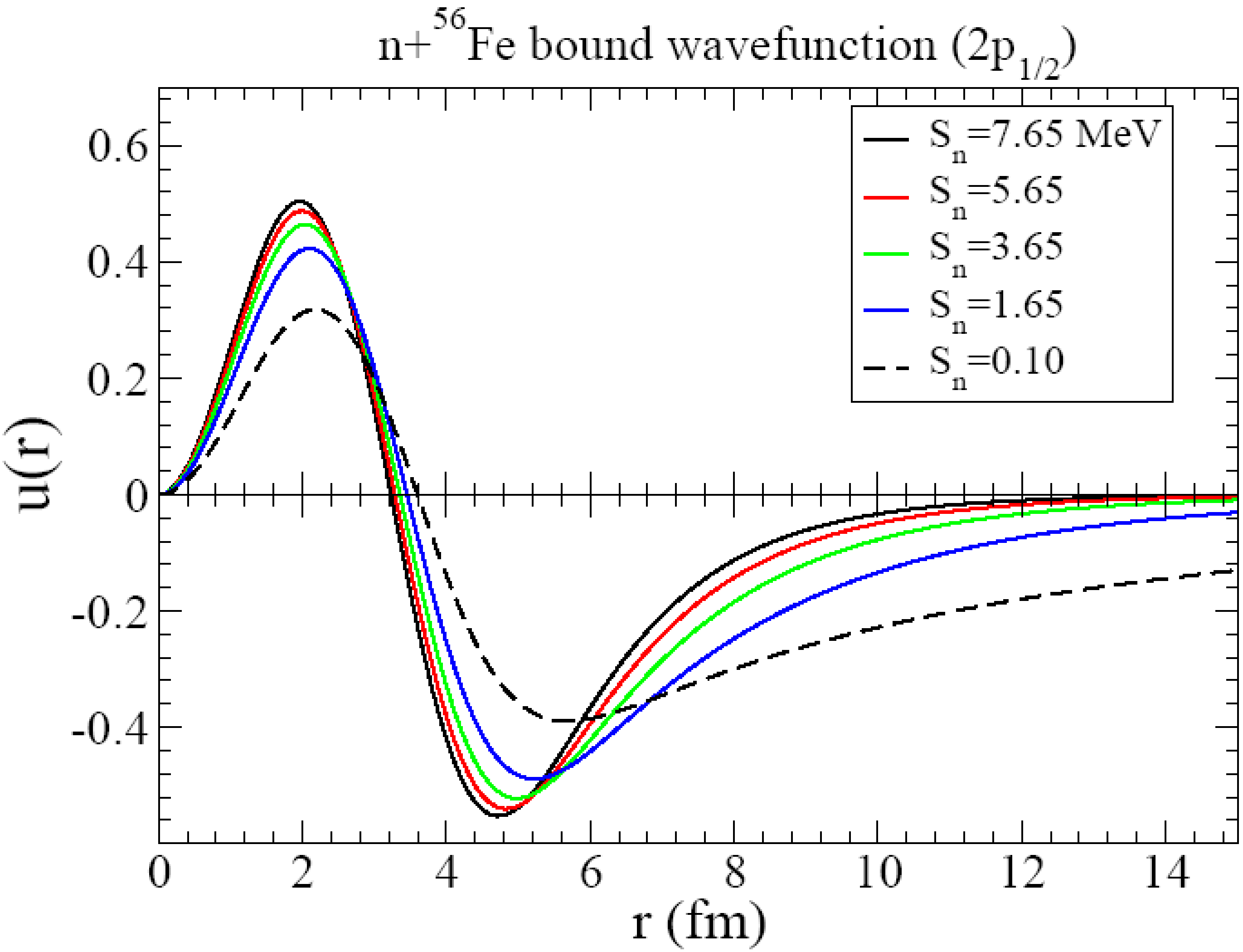
- Transfer differential cross sections: mb/sr (at best).
- Below the Coulomb Barrier transfer is maximum at backward angles. No angular structure.
- Above the barrier transfer is maximum around the grazing angle. There is angular structure.
- At larger energies, the angular structure becomes more acute, transfer moves to forward angles with the grazing angle, but cross sections diminish.



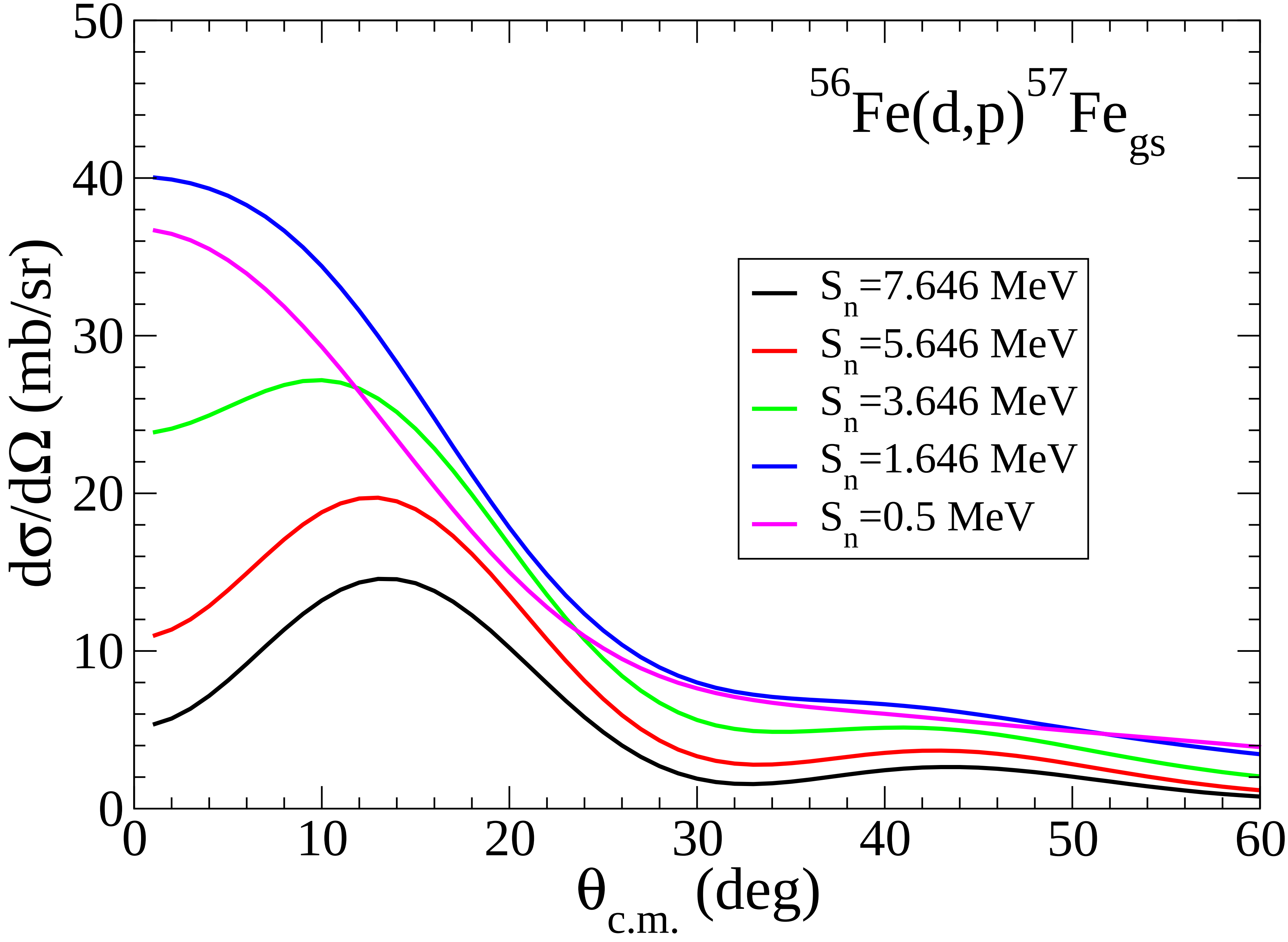
n+56Fe bound wavefunctions
u(r)
r (fm)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
5
10
15
2s1/2
2p3/2
2d5/2
1f5/2

Angular momentum dependence





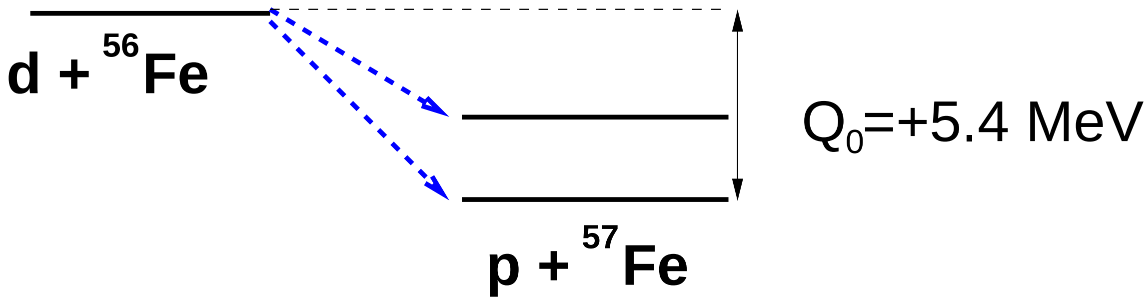
n+56Fe bound wavefunction (2p1/2)
0.6
0.4
0.2
0
-0.2
-0.4
u(r)
0
2
4
6
8
10
12
14
r (fm)
Sn=7.65 MeV
Sn=5.65
Sn=3.65
Sn=1.65
Sn=0.10

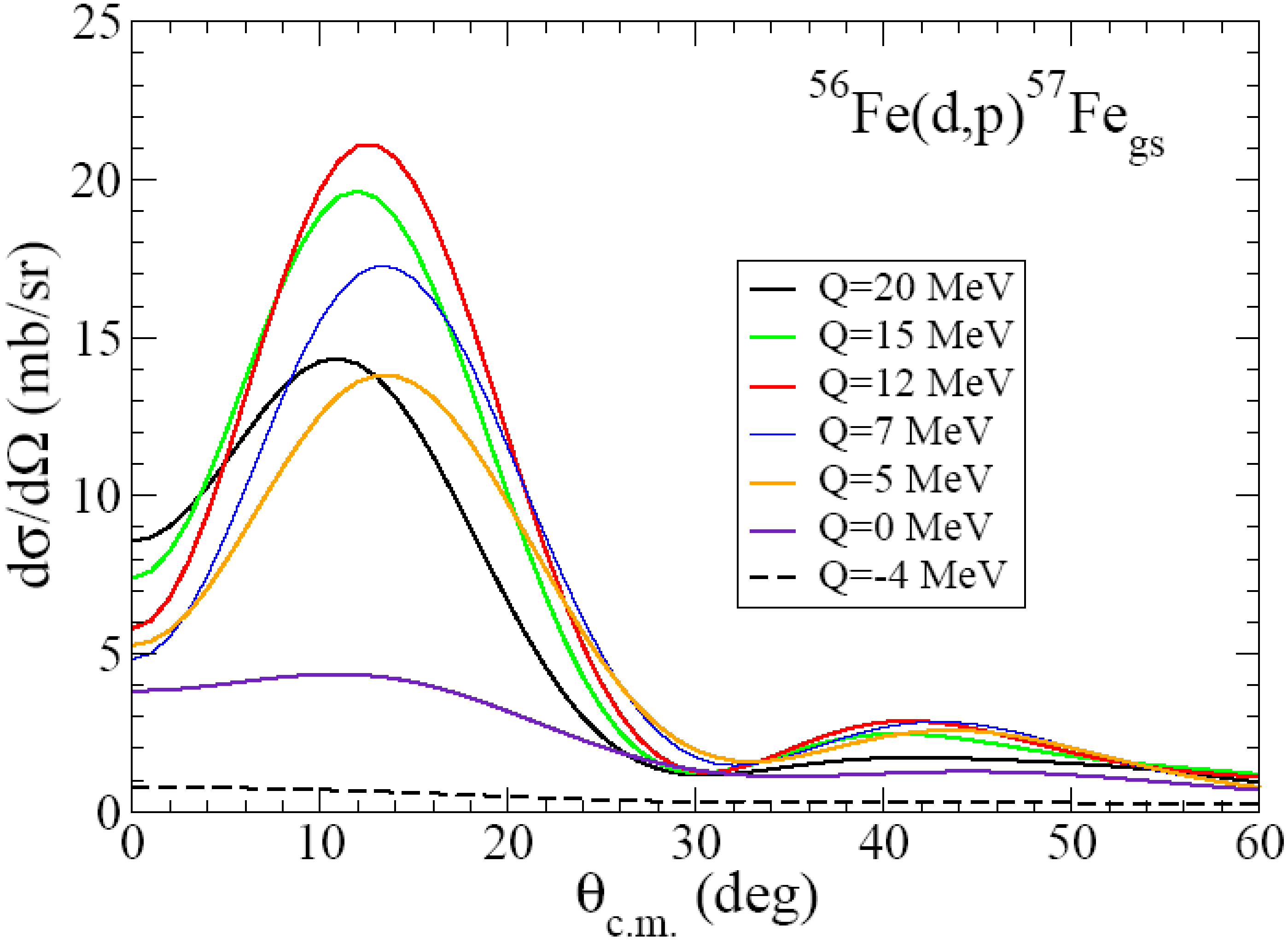


$^{56}Fe(d,p)^{57}Fe_{gs}$
S_n=7.646 MeV
S_n=5.646 MeV
S_n=3.646 MeV
S_n=1.646 MeV
S_n=0.5 MeV
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$ (deg)
0
10
20
30
40
50
60

1.4 Bound state dependence

- Angular dependence depends on the angular momentum of the bound state.
- The angle for which cross sections are larger depends on the angular momentum transferred.
- Transfer is larger for weakly bound states (specially below the Coulomb barrier).
- Angular structure is lost for weakly bound states.


d + 56Fe
Q0=+5.4 MeV
p + 57Fe



56Fe(d,p)57Fegs
dσ/dΩ (mb/sr)
θc.m. (deg)
Q=20 MeV
Q=15 MeV
Q=12 MeV
Q=7 MeV
Q=5 MeV
Q=0 MeV
Q=-4 MeV
0
5
10
15
20
25
0
10
20
30
40
50
60

1.5 Q dependence

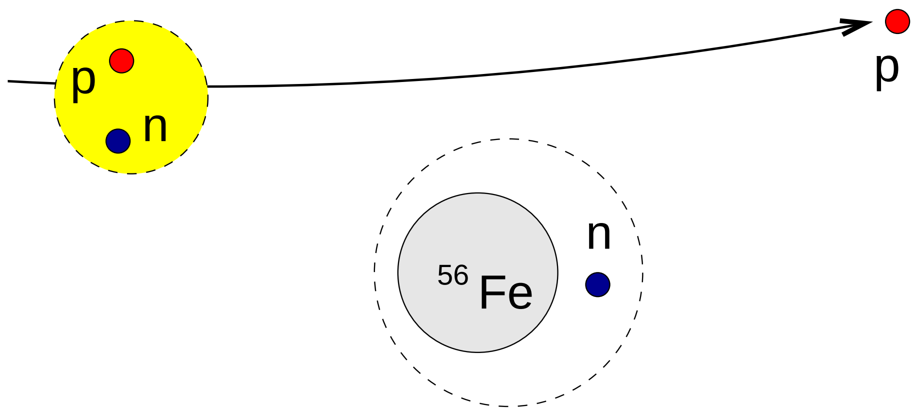
- **Transfer populates states in a range of Q-values (Q-window).**
- **(d,p) transfer favors states with high Q:**
  $E_p \simeq 2E_d \quad ; \quad k_p \simeq k_d$

1.6 Summary of Transfer general concepts

- Transfer cross sections are mb/sr (at most). Transfer is maximum when the energy per nucleon of the projectile is about 1/3 of the Fermi energy of the transferred particle.
- Transfer below the barrier is small and structureless. The maximum cross sections are at backward angles.
- Transfer above the barrier is maximum around the grazing angle. The angular structure indicates the angular momentum of the transferred particle.
- Transfer to weakly bound states is enhances, but the angular structure is smoothed.
- (d,p) transfer favors states with high Q.

Transfer: Formalism

Transfer Reactions

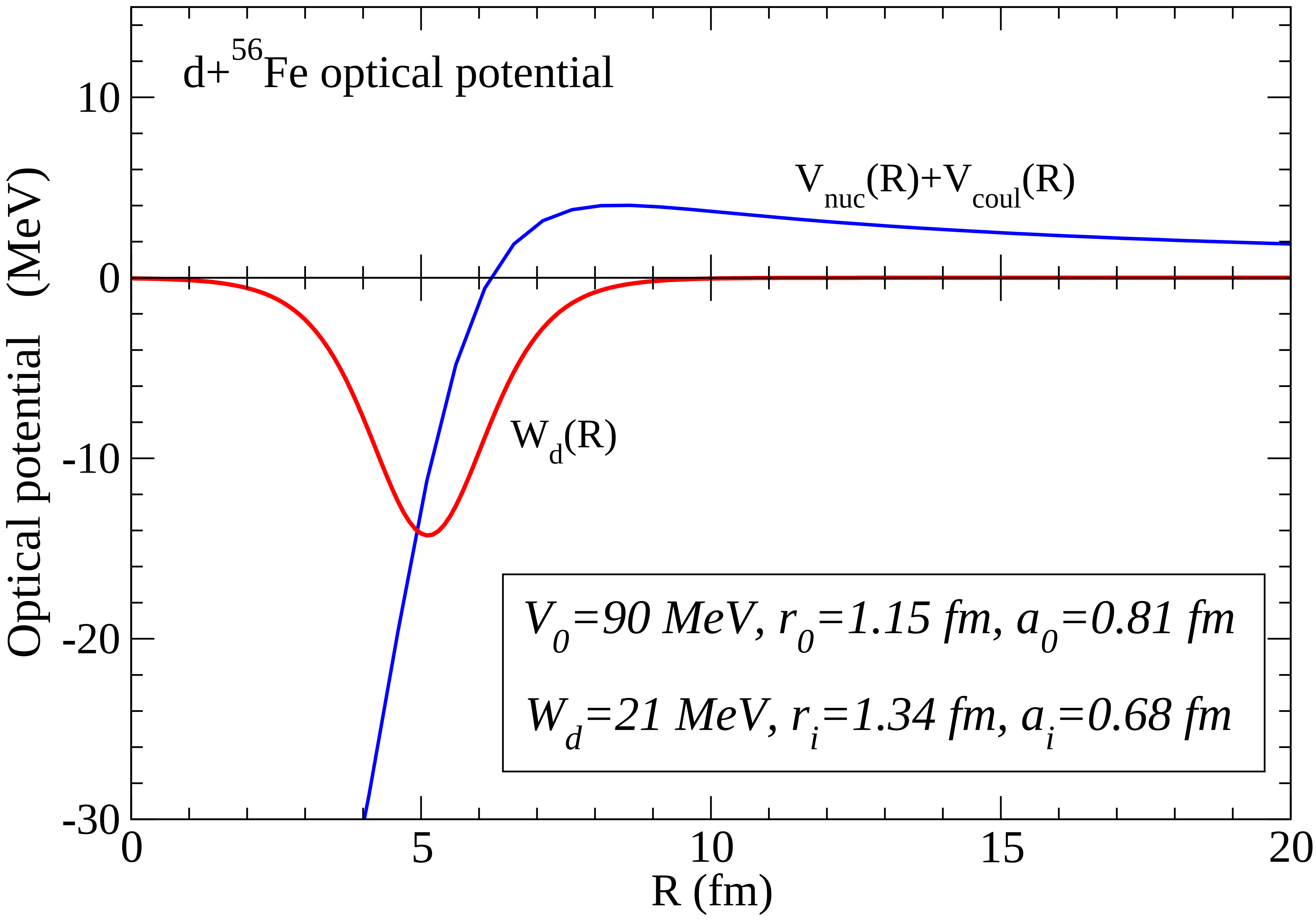


Structure

- d+56Ni= p+57Ni
- (p+n)+56Ni= p+(n+56Ni)
- Structure: Describe d as (p+n), 57Ni as (n+56Ni)
  - Binding energy (p,n); (n,56Fe)
  - L-value (p,n); (n,56Fe)
  - Single-particle wavefunction (p,n);(n,56Fe)
  - Spectroscopic amplitude (d;p,n); (57Fe;56Fe,n)

Interactions

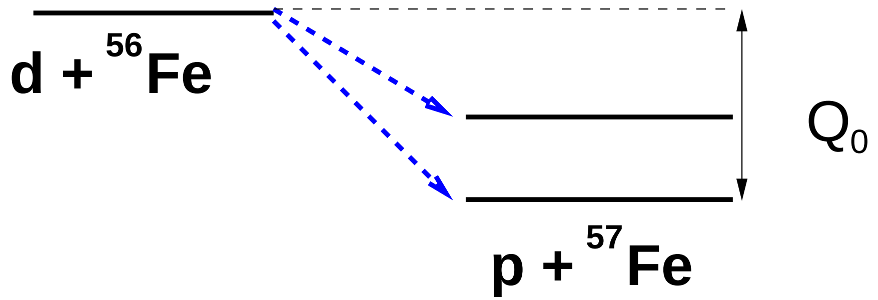
- Optical potential U(d,56Fe)
- Optical potential U(p,57Fe)
- Core-Core Optical potential V(p,56Fe)
- Binding potential V(p,n)
- Binding potential V(56Fe,n)



d+56Fe optical potential
$V_{nuc}(R)+V_{coul}(R)$
$W_d(R)$
V_0=90 MeV, r_0=1.15 fm, a_0=0.81 fm
W_d=21 MeV, r_i=1.34 fm, a_i=0.68 fm
Optical potential (MeV)
R (fm)
10
0
-10
-20
-30
0
5
10
15
20

Reaction Mechanism

- DWBA



2.1 DWBA

- Separate the interaction $V(\vec{r})$ as $V_0(r)$, which can be solved exactly, and $\Delta(\vec{r})$, which will be treated in first order.
- Obtain the solutions $\chi^{(\pm)}_{DW}(\vec{k},\vec{r})$ for the potentials $V_0(r)$: Distorted waves.
- $\chi^{(+)}_{DW}(\vec{k},\vec{r})$ is a solution of Schrödinger equation with the $V_0(r)$, which behaves asymptotically as plane wave $\exp(i\vec{k}\vec{r})$ plus outgoing spherical waves.
- $\chi^{(-)}_{DW}(\vec{k},\vec{r})$ is a solution of Schrödinger equation with the $V_0(r)$, which behaves asymptotically as plane wave $\exp(i\vec{k}\vec{r})$ plus incoming spherical waves.
- The scattering amplitude is given by

$$A(\vec{k},\vec{k}') = A_0(\vec{k},\vec{k}') - \frac{2m}{\hbar^2 4\pi}\int d\vec{r}\chi^{(-)}_{DW}(\vec{k}',\vec{r})^*\Delta(\vec{r})\chi^{(+)}_{DW}(\vec{k},\vec{r}) \quad (1)$$

2.2 Transfer reactions in DWBA

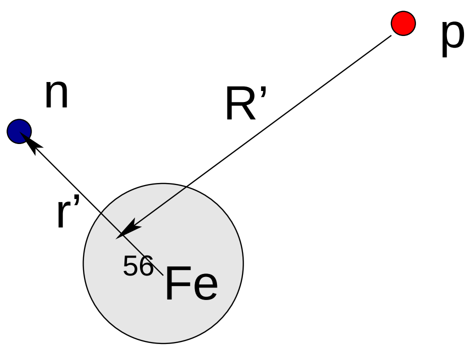
What is the quantum mechanical scattering cross sections for transfer reactions?

A three-body problem:

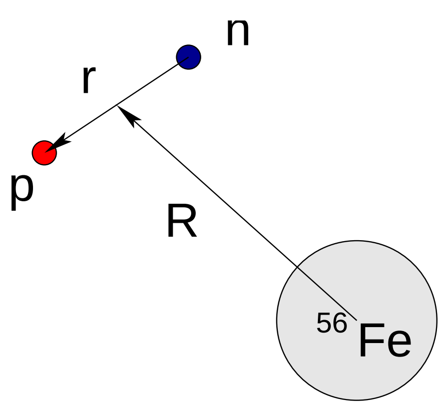
$$H = T(AC, B) + T(A, C) + V(A, C) + V(B, C) + V(A, B)$$

Post-Prior

Post



Prior



2.3 PRIOR

- **Initially, fragments $A + C$ are bound.**
- **An approximation to the Hamiltonian is:**
  $H_i = T(AC, B) + T(A, C) + V(A, C) + U(AC, B)$.
- **An approximation to the wave function is:**
  $\psi_i(\vec{r}, \vec{r}_{AC}) = \chi^{(+)}(\vec{k}_i, \vec{r}) c_i \phi_i(\vec{r}_{AC})$.
- **The bound state of (AC) is described by the wavefunction** $\phi_i(\vec{r}_{AC})$ **which is the solution of**

$$(T(A, C) + V(AC))\phi_i(\vec{r}_{AC}) = e_{AC}\phi_i(\vec{r}_{AC})$$

- **The relative motion of (AC) with respect to B is described by the distorted wave**

$$(T(AC, B) + U(AC, B))\chi^{(+)}(\vec{k}_i, \vec{r}) = (E - e_{AC})\chi^{(+)}(\vec{k}_i, \vec{r})$$

- **The term that one is not considering is**
  $\Delta(\textbf{PRIOR}) = H - H_i = V(B, C) + V(A, B) - U(AC, B)$.

2.4 POST

- **Finally, fragments $B + C$ are bound.**
- **An approximation to the Hamiltonian is:**
  $H_f = T(BC, A) + T(B, C) + V(B, C) + U(BC, A)$.
- **An approximation to the wave function is:**
  $\psi_f(\vec{r}', \vec{r}_{BC}) = \chi^{(-)}(\vec{k}_f, \vec{r}')c_f\phi_f(\vec{r}_{BC})$
- **The bound state of (BC) is described by the wavefunction $\phi_i(\vec{r}_{BC})$ which is the solution of**

$$(T(B, C) + V(BC))\phi_i(\vec{r}_{BC}) = e_{BC}\phi_f(\vec{r}_{BC})$$

- **The relative motion of (BC) with respect to A is described by the distorted wave**

$$(T(BC, A) - U(BC, A))\chi^{(-)}(\vec{k}_f, \vec{r}) = (E - e_{BC})\chi^{(-)}(\vec{k}_f, \vec{r})$$

- **The term that one is not considering is**
  $\Delta(\mathbf{POST}) = H - H_f = V(A, C) + V(A, B) - U(BC, A)$

2.5 Transfer Scattering amplitude

$$
\begin{aligned}
A^{POST}(\vec{k}_i,\vec{k}_f)_{if} &= -\frac{2m}{\hbar^2 4\pi}\int d\vec{r}' d\vec{r}_{BC}\psi_f(\vec{r}',\vec{r}_{BC})^*\Delta(\mathbf{POST})\psi_i(\vec{r},\vec{r}_{AC}) \\
&= -\frac{2mc_f^* c_i}{\hbar^2 4\pi}\int d\vec{r}' d\vec{r}_{BC}\chi^{(-)*}(\vec{k}_f,\vec{r}')\phi_f^*(\vec{r}_{BC}) \\
& \quad \Delta(\mathbf{POST})\chi^{(+)}(\vec{k}_i,\vec{r})\phi_i(\vec{r}_{AC}) \\
A^{PRIOR}(\vec{k}_i,\vec{k}_f)_{if} &= -\frac{2m}{\hbar^2 4\pi}\int d\vec{r}' d\vec{r}_{BC}\psi_f(\vec{r}',\vec{r}_{BC})^*\Delta(\mathbf{PRIOR})\psi_i(\vec{r},\vec{r}_{AC}) \\
&= -\frac{2mc_f^* c_i}{\hbar^2 4\pi}\int d\vec{r}' d\vec{r}_{BC}\chi^{(-)^*}(\vec{k}_f,\vec{r}')\phi_f^*(\vec{r}_{BC}) \\
& \quad \Delta(\mathbf{PRIOR})\chi^{(+)}(\vec{k}_i,\vec{r})\phi_i(\vec{r}_{AC})
\end{aligned}
$$

DWBA expression

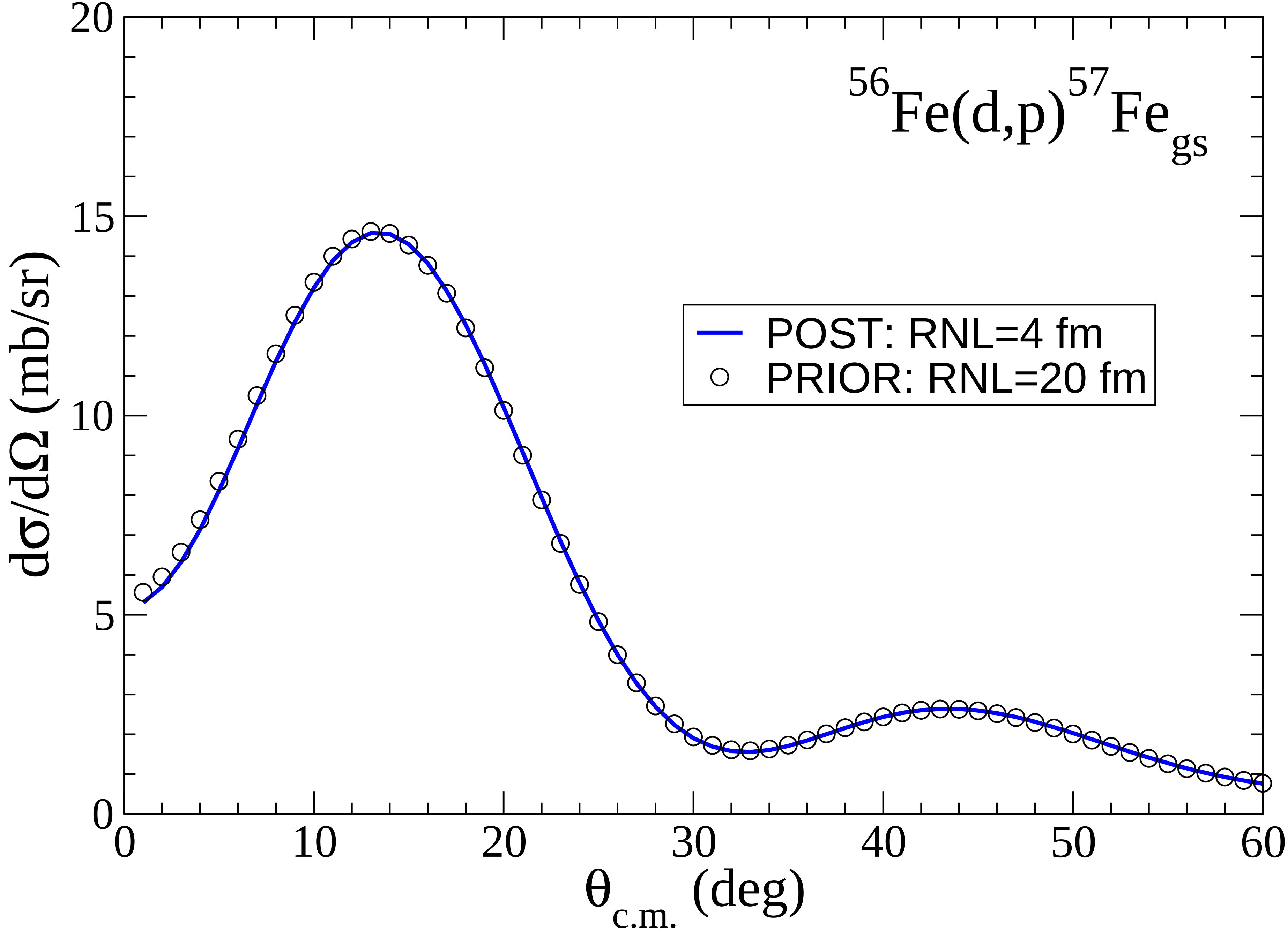
- Below the barrier: No oscillation WF- no interference
- Above the barrier; Oscillations WF – interference
- E-matching, Q-Matching: Constructive oscillations in incoming and outgoing waves.
- Binding energy dependence: Extension of wavefunction

POST-PRIOR equivalence theorem:

$$A^{PRIOR}(\vec{k}_i, \vec{k}_f)_{if} = A^{POST}(\vec{k}_i, \vec{k}_f)_{if}$$

Problem: Demonstrate the post-prior equivalence

Hint: Consider the equations satisfied by the distorted waves



$^{56}Fe(d,p)^{57}Fe_{gs}$
POST: RNL=4 fm
PRIOR: RNL=20 fm
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$ (deg)
0
5
10
15
20
0
10
20
30
40
50
60

Choice of potentials

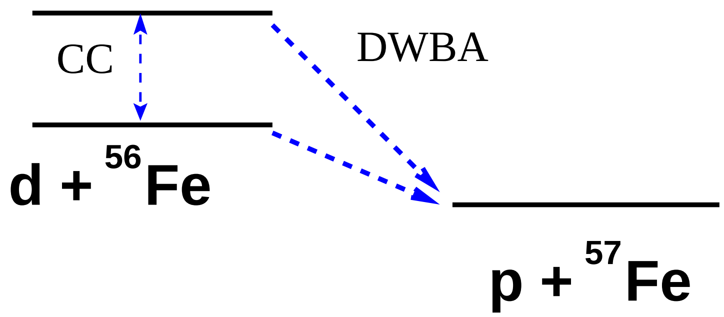
- Binding potentials V(p,n); V(n,56Ni): Real. Reproduce the binding energy.
- Core-Core Potential V(p,56Ni): Complex. Reproduce p-56Ni elastic scattering.
- Auxiliary potentials U(p,57Ni), U(d,56Ni)
  - Use potentials that describe the elastic data
  - Use single folding (to minimize D)
  - Use Johnson-Soper

2.6 What do we learn by measuring transfer reactions?

- Structure: Populate $C+B$ states. Energy. Angular momentum. Spectroscopic factors c_i, c_f.
- Interactions: Distorting optical potentials in the entrance and outgoing channels. $U(AC,B), U(A,BC)$. Inter-cluster interactions $V(AB)$.Binding interactions V_{AC}, V_{BC}.
- Reaction mechanism: DWBA as first order mechanism.

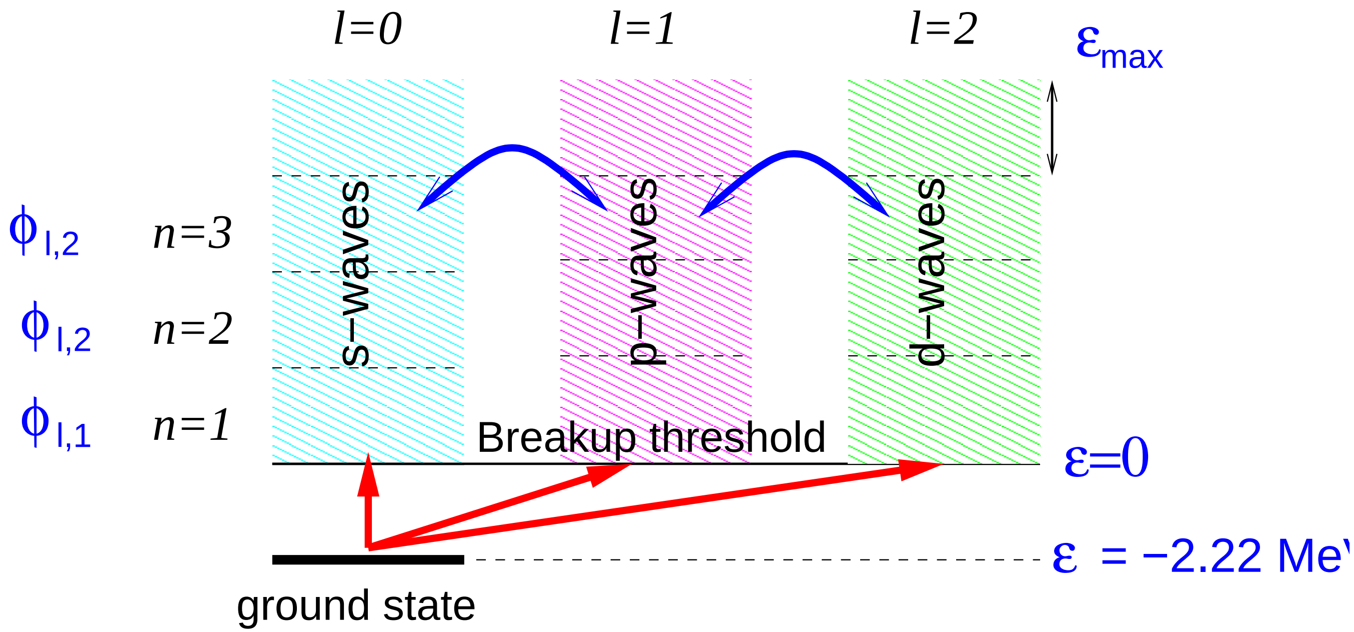
2.7 Beyond DWBA

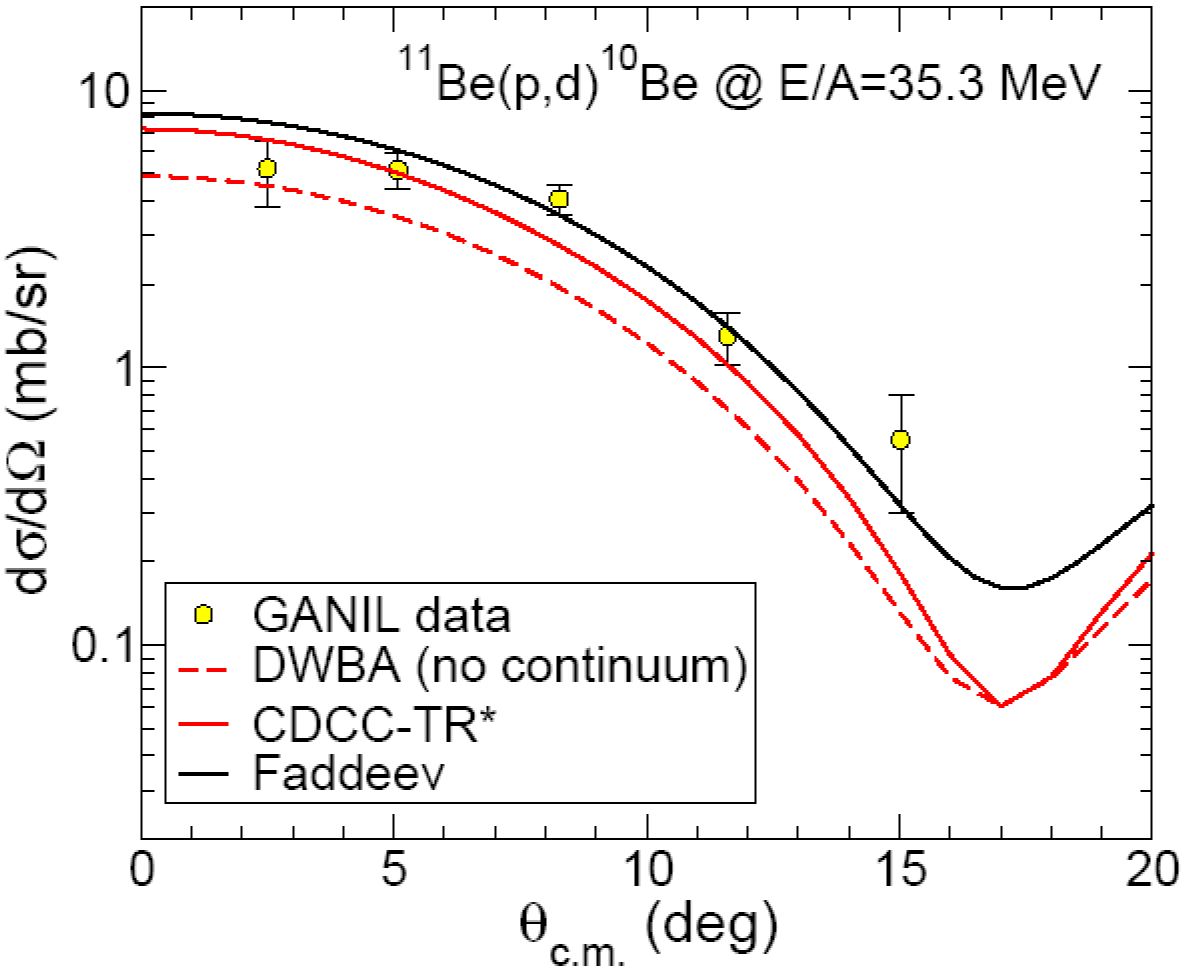
- CCBA: Coupled Channels Born Approximation: Include coupling to inelastic states in projectile or target. Relevant for nuclei with collective excitation (deformed, vibrational).
- CRC: Coupled Reaction Channels: Include back and forth transfer to all orders. Relevant for transfer around the Coulomb barrier. Keeley et al.
- Continuum effects: Include the coupling to break-up states.
  - Adiabatic approximation: Johnson, Tostevin ...
  - Faddeev Calculations: A. Fonseca et al.
  - Continuum Discretization: Thompson, Nunes, Moro ...



CC
DWBA
d + 56Fe
p + 57Fe

Continuum discretization in the deuteron





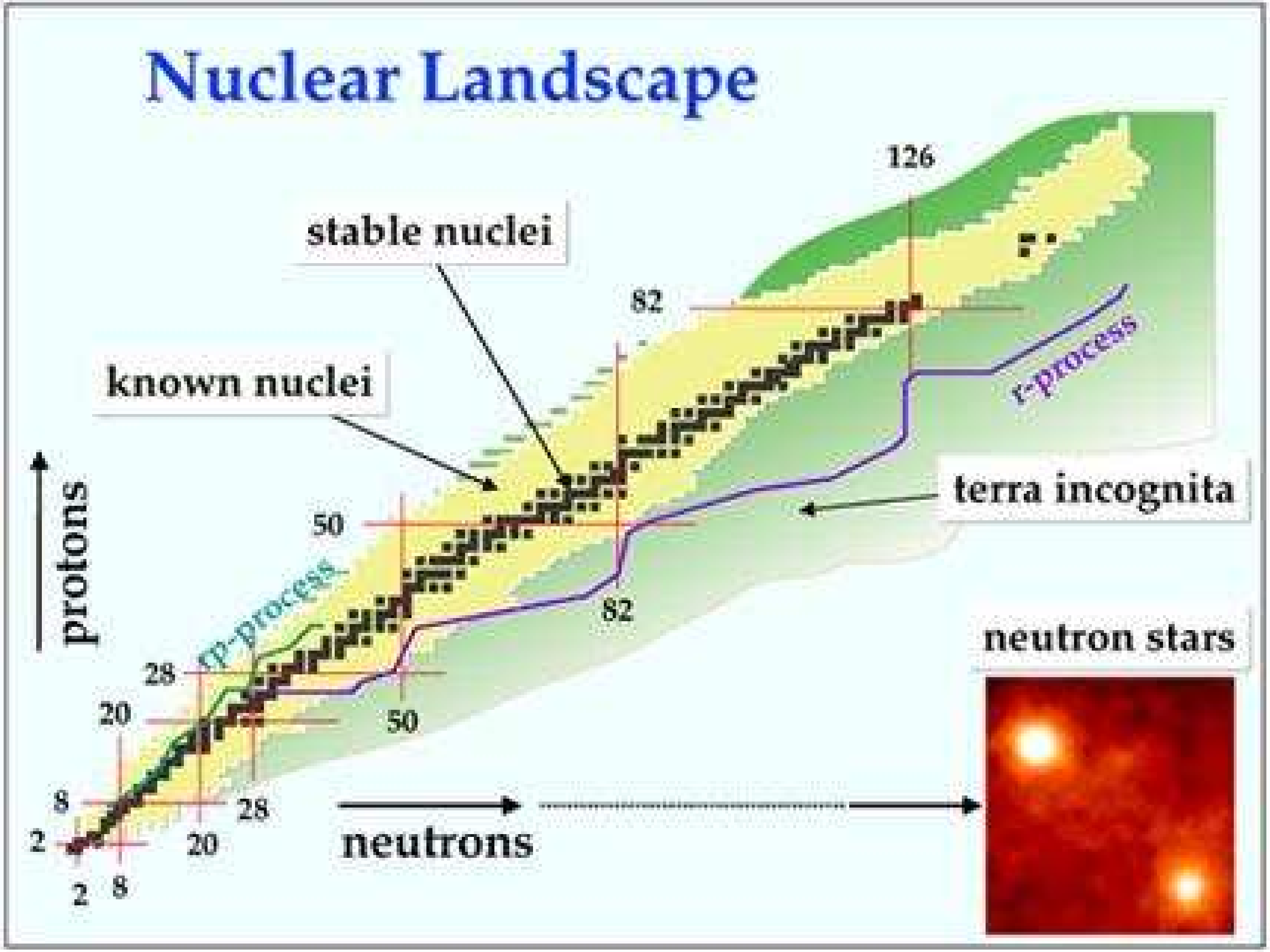
^{11}Be(p,d)^{10}Be @ E/A=35.3 MeV
dσ/dΩ (mb/sr)
θ$_{c.m.}$ (deg)
GANIL data
DWBA (no continuum)
CDCC-TR*
Faddeev
10
1
0.1
0
5
10
15
20

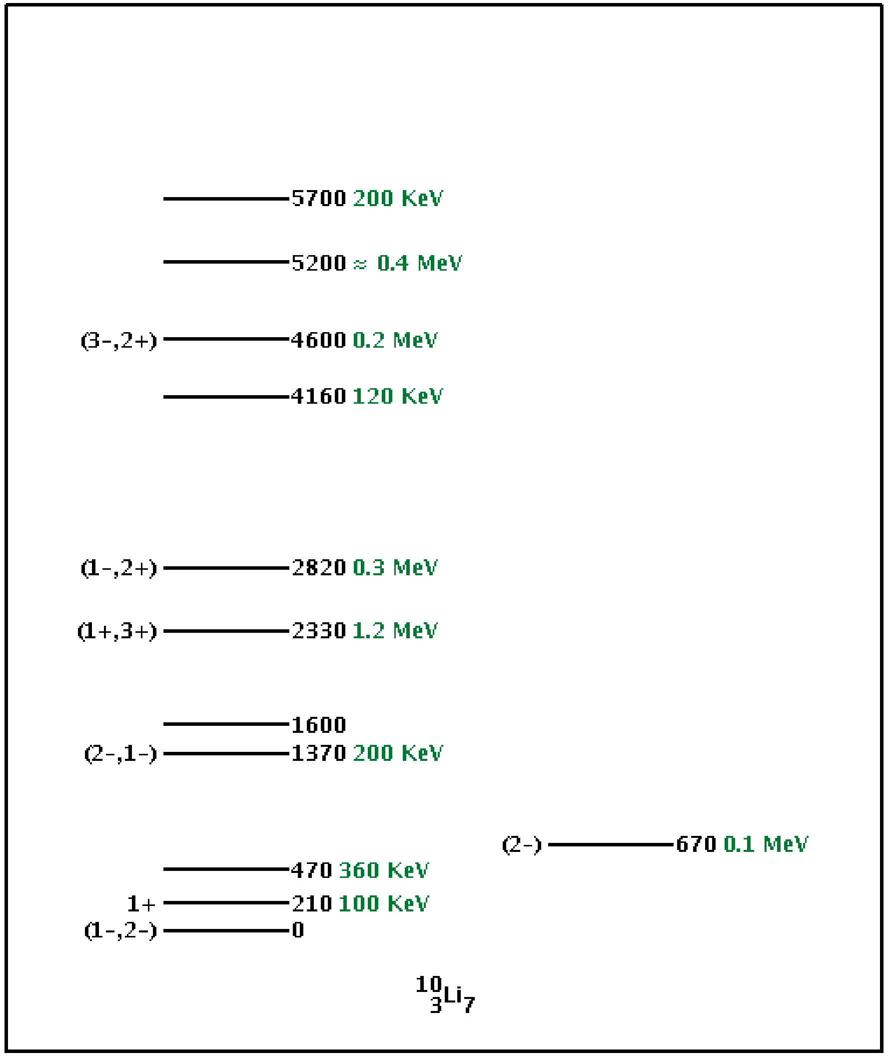
2.8 Summary of Transfer formalism

- Transfer is a 3-body quantum mechanical process. The simplest meaningful description of transfer is DWBA.
- Describing transfer in DWBA requires knowledge of structure (spectroscopic amplitudes, bound wavefunctions), interactions (binding potentials, intercluster interactions, auxiliary potentials), and reaction mechanism (DWBA).
- Transfer in DWBA can be formulated in Post or Prior forms. Both should give identical results, but one or the other is more convenient computationally.
- In DWBA, transfer cross sections are proportional to the spectroscopic factor of the final state.
- DWBA has been widely used to obtain spectroscopic factors, from the comparison of experimental transfer cross sections with DWBA calculations.

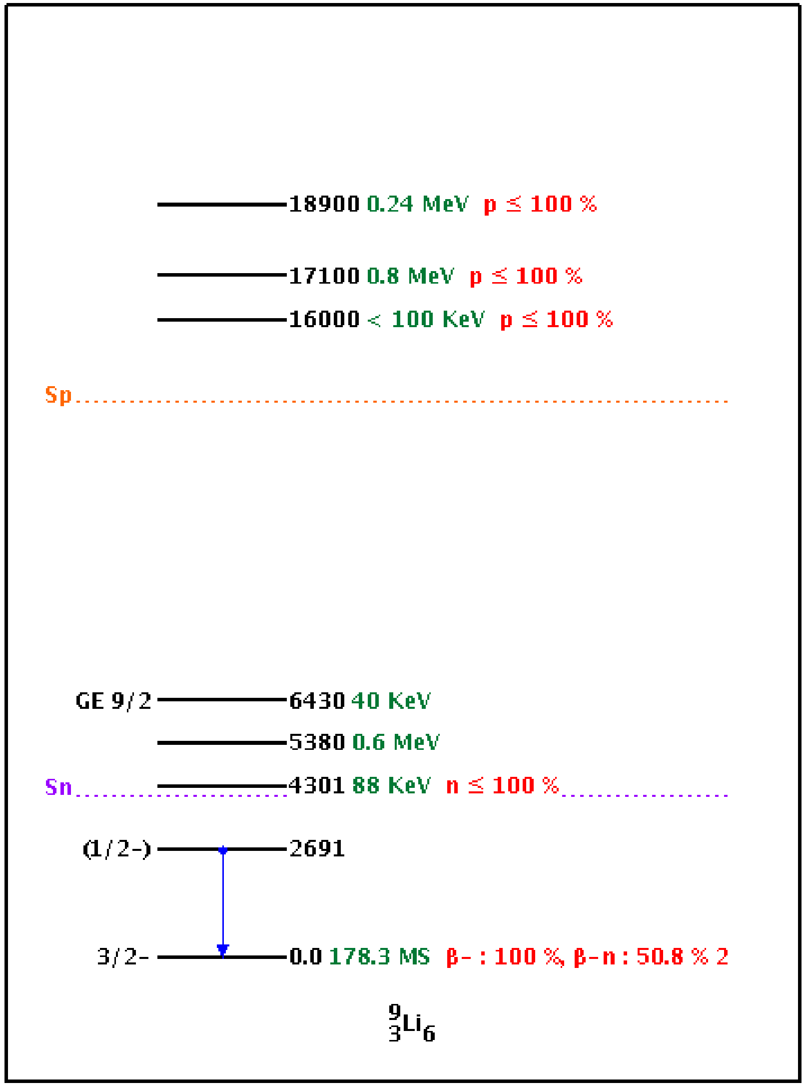
- The accuracy of DWBA is questionable. The effect of coupling to the continuum is very important for weakly bound nuclei (Including the deuteron!).
- Nuclear reaction theory needs to be improved to describe continuum effects in transfer more accurately, to measure structure properties of weakly bound exotic nuclei.

Transfer: Continuum structures


Nuclear Landscape
126
stable nuclei
82
known nuclei
r-process
protons
terra incognita
50
rp-process
82
neutron stars
28
20
50
8
28
2
20
neutrons
2
8



5700 200 KeV
5200 ≈ 0.4 MeV
(3-,2+) 4600 0.2 MeV
4160 120 KeV
(1-,2+) 2820 0.3 MeV
(1+,3+) 2330 1.2 MeV
1600
(2-,1-) 1370 200 KeV
(2-) 670 0.1 MeV
470 360 KeV
1+ 210 100 KeV
(1-,2-) 0
$^{10}_{3}Li_{7}$



18900 0.24 MeV p ≲ 100 %
17100 0.8 MeV p ≲ 100 %
16000 < 100 KeV p ≲ 100 %
Sp
GE 9/2 6430 40 KeV
5380 0.6 MeV
Sn
4301 88 KeV n ≲ 100 %
(1/2-) 2691
3/2- 0.0 178.3 MS β- : 100 %, β-n : 50.8 % 2
$^{9}_{3}Li_{6}$

Bound Vs Continuum states

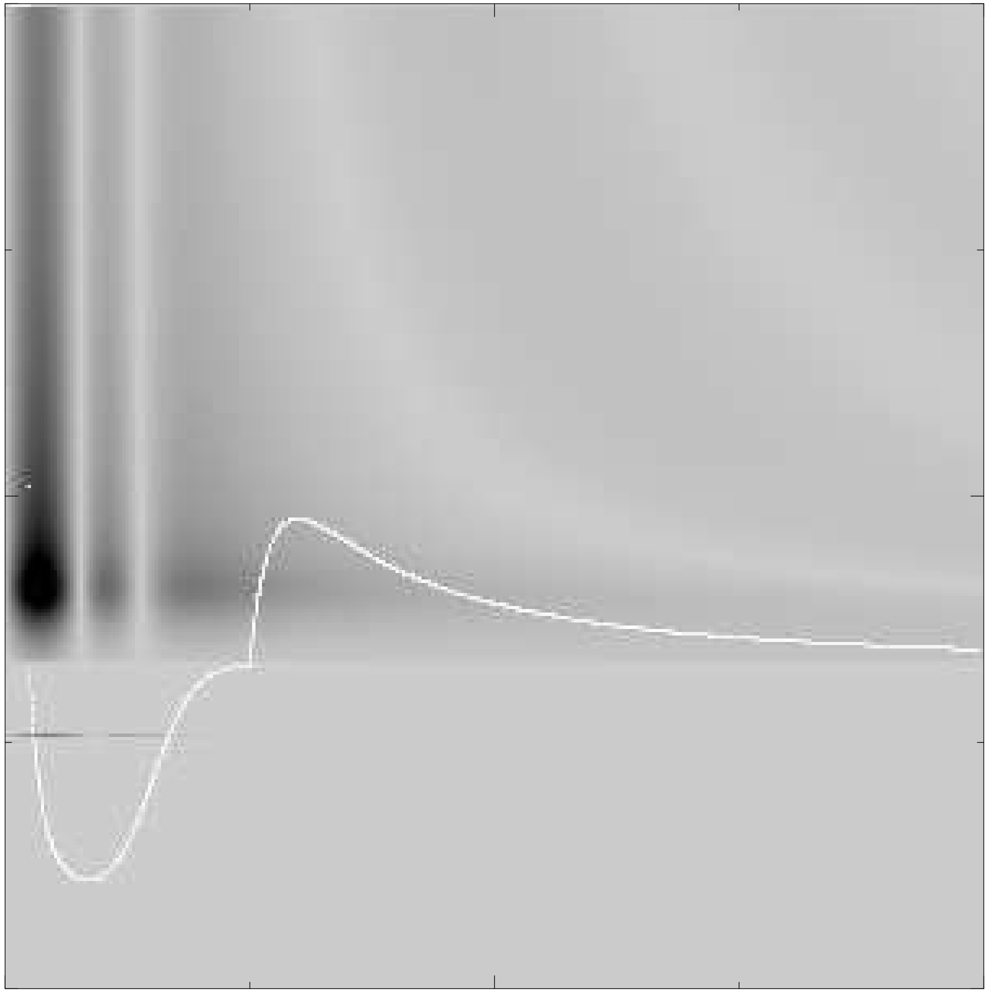
Energy

Continuum

E>0

Bound

E<0



Distance

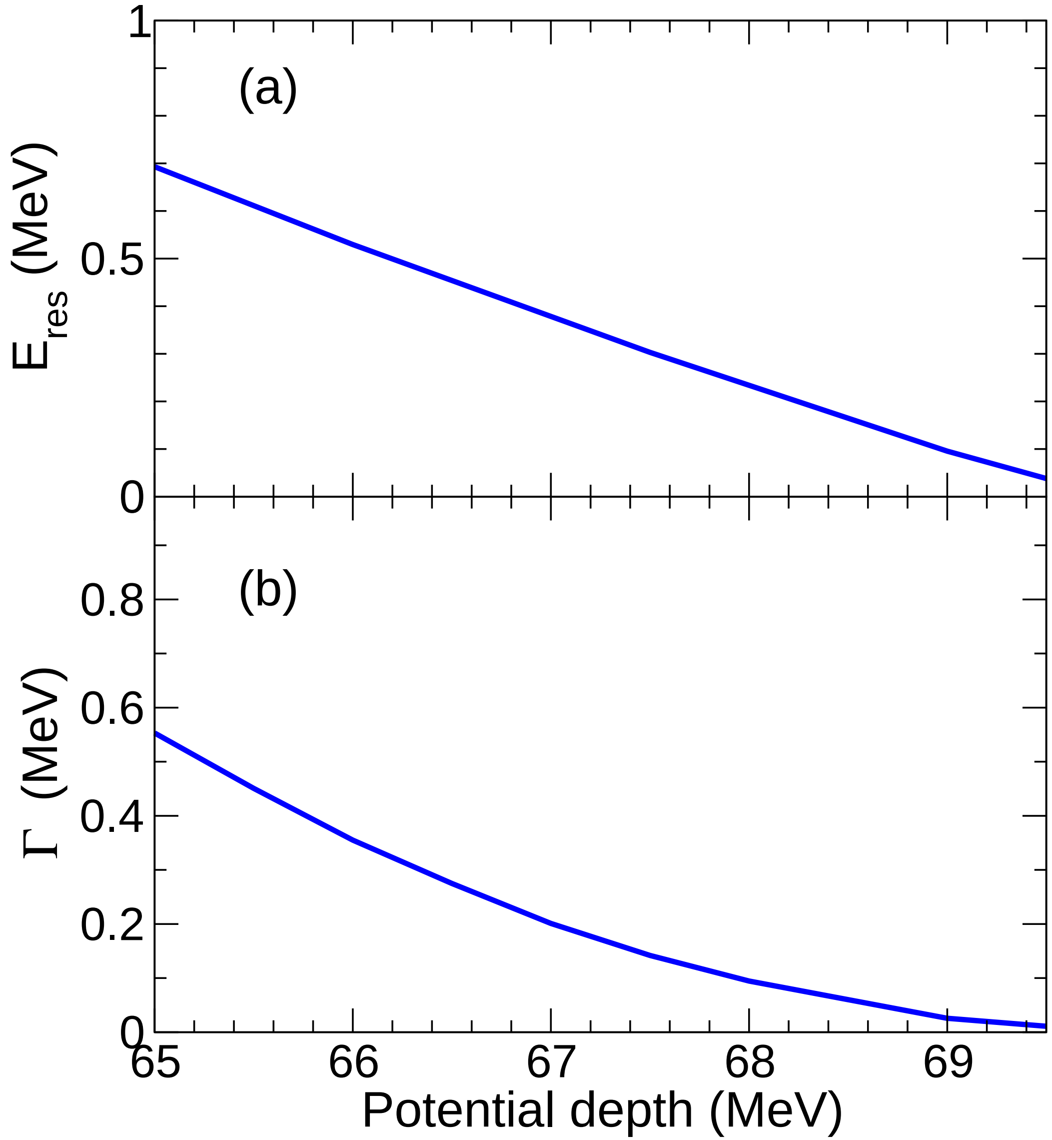
Cuts and areas ordered by size

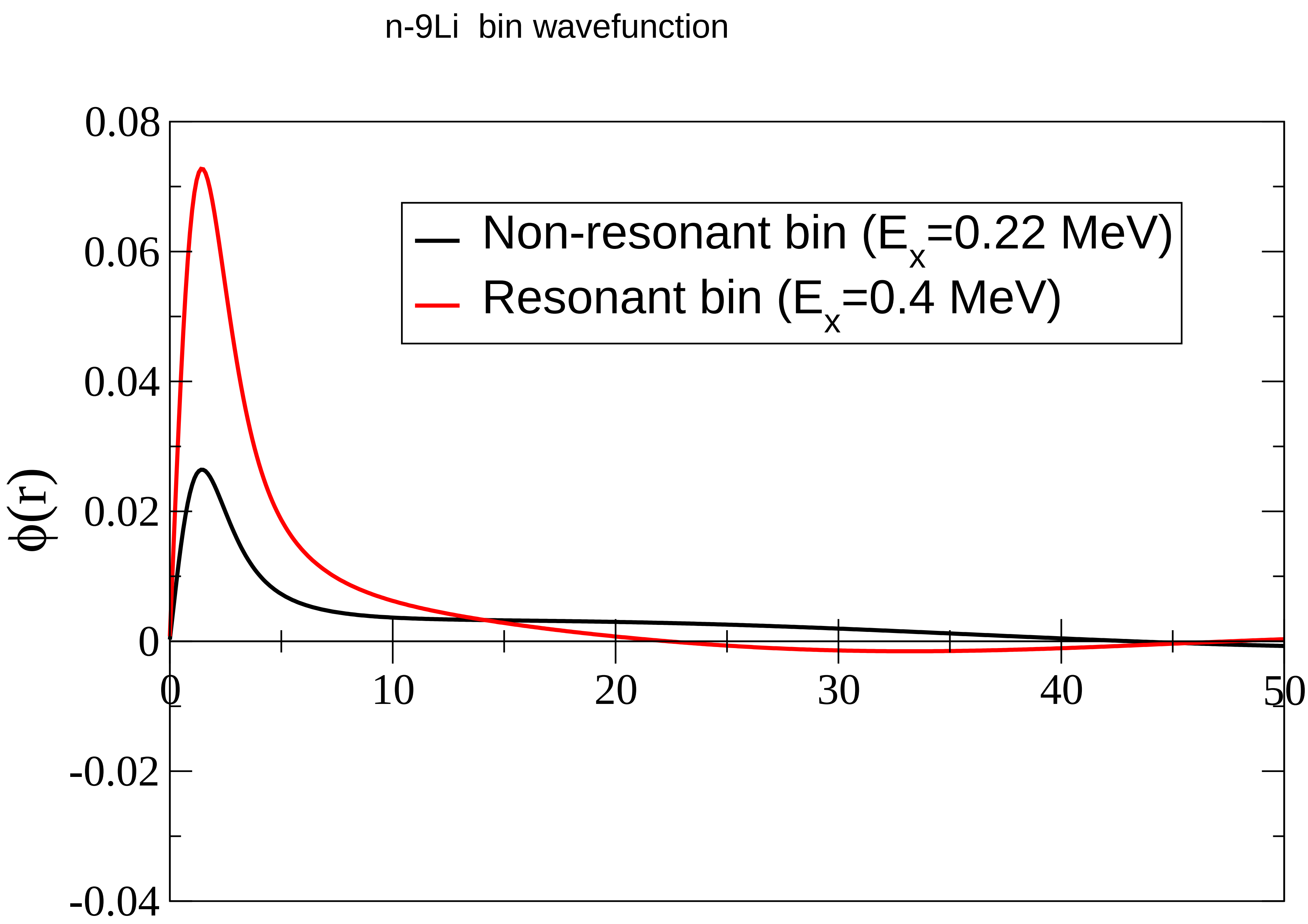
3.1 Resonances

- Resonances are structures in the continuum.
- Resonances appear in Quantum Theory as non-normalizable complex energy solutions of the hamiltonian $E_r - i\Gamma/2$.
- Continuum states around the resonance energy $E_r - \Gamma \le E \le E_r + \Gamma$, display larger probability of presence at short distances.
- Phase shifts cross 90 degrees at the resonance energy.
- Resonances appear when there is some effective barrier (not s-wave neutrons)
- Transfer cross sections are usually larger around the resonance energy.

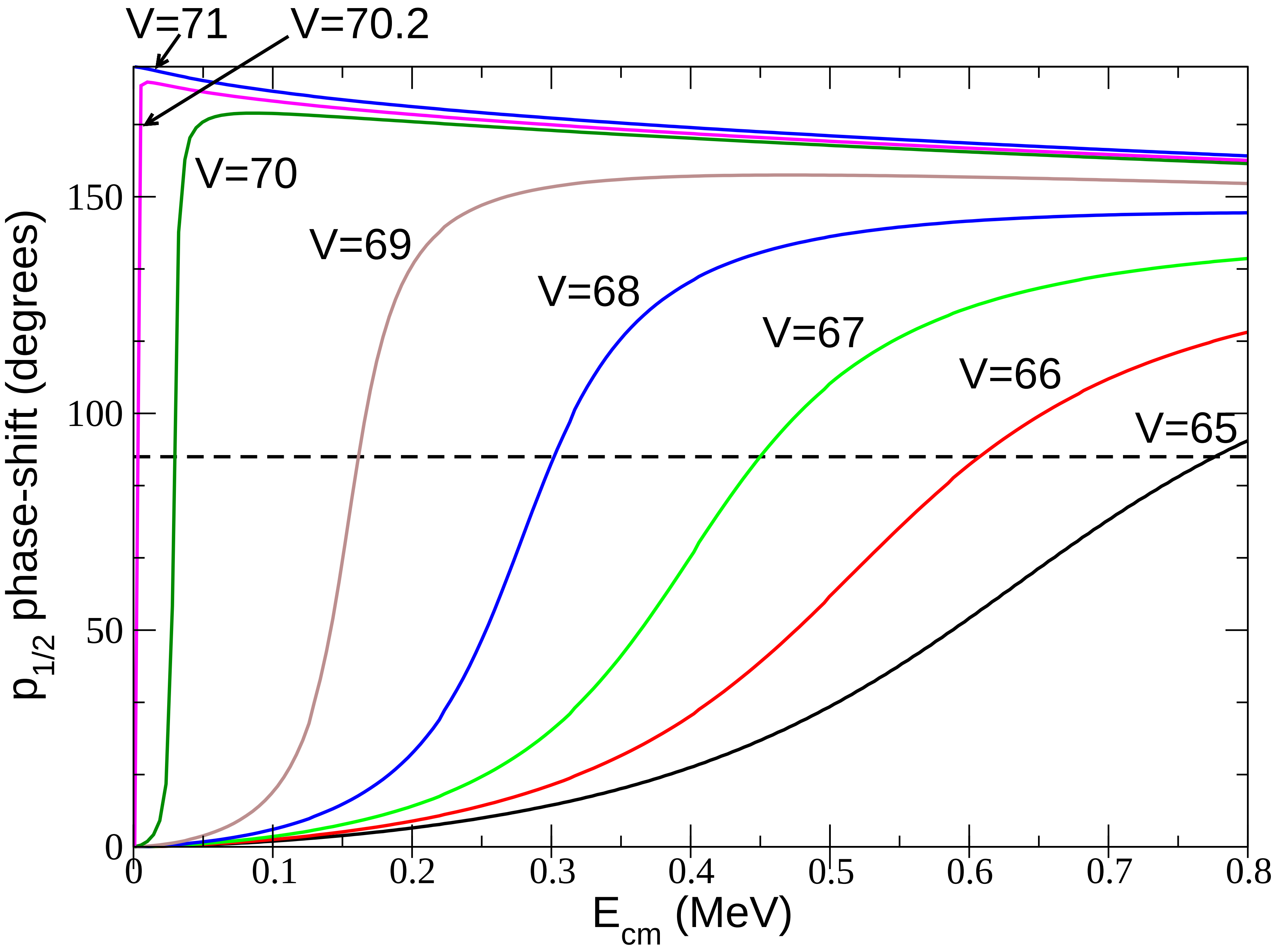
10Li=n+9Li

p1/2
resonance



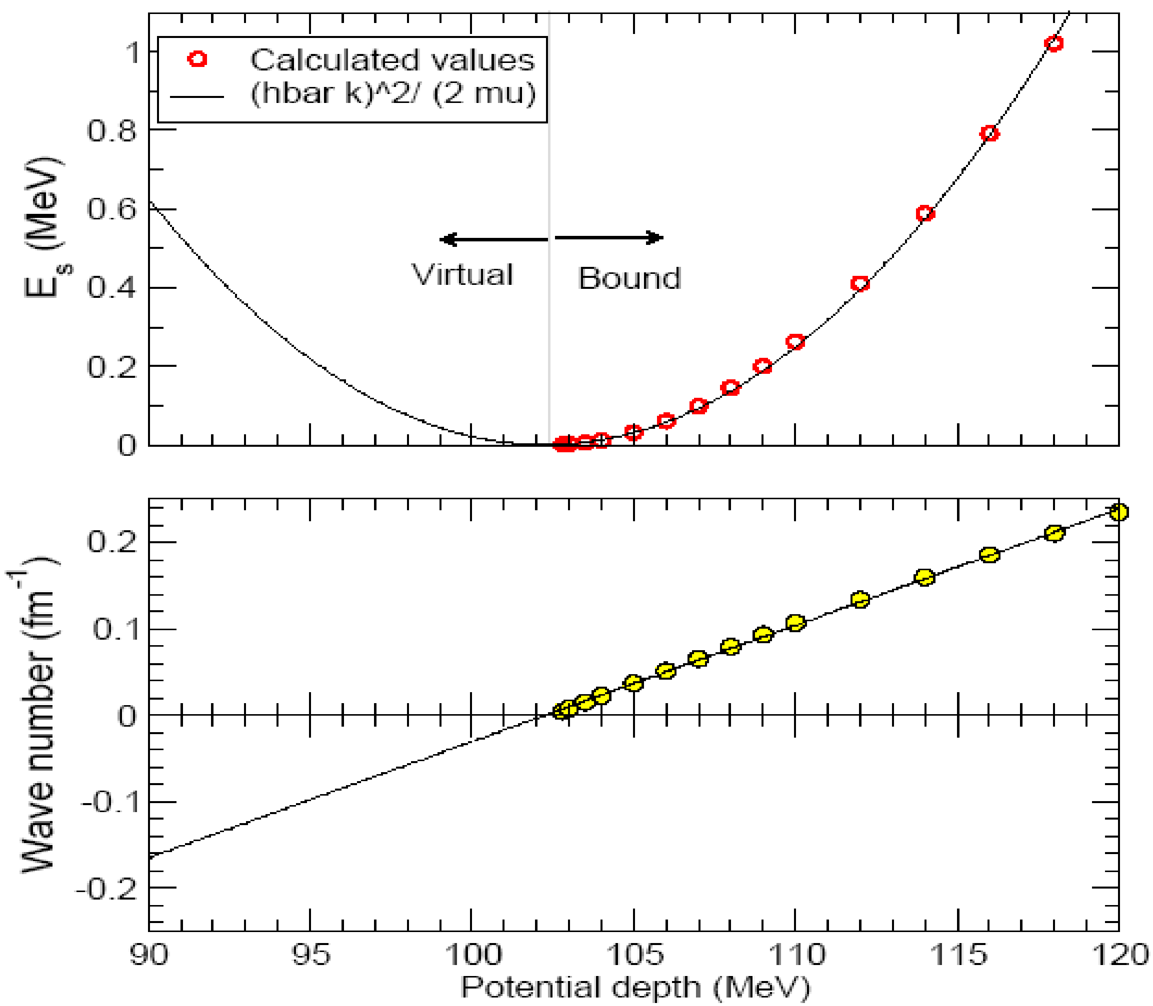


n-9Li bin wavefunction
Non-resonant bin (Ex=0.22 MeV)
Resonant bin (Ex=0.4 MeV)
φ(r)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
10
20
30
40
50

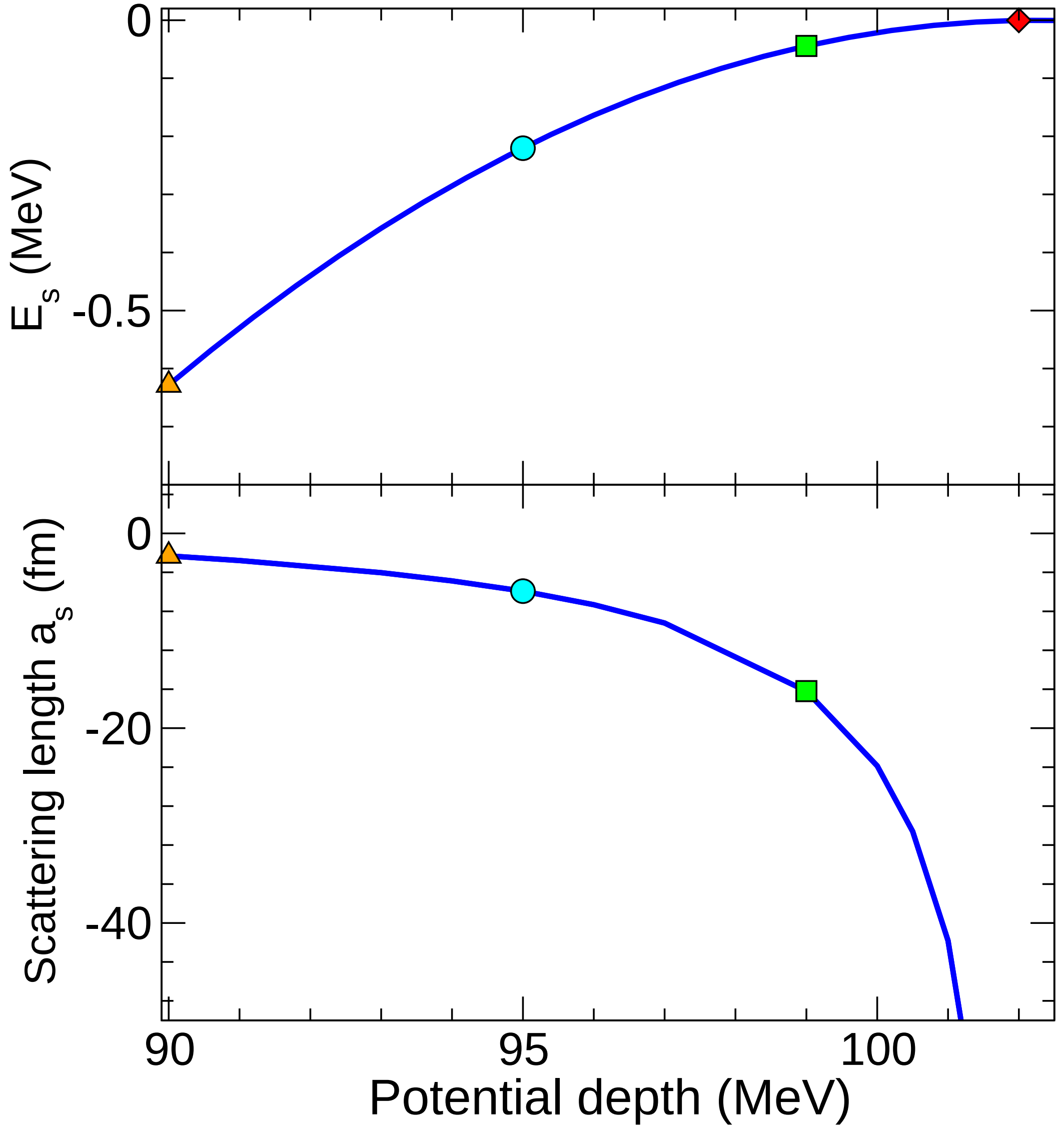

V=71
V=70.2
V=70
V=69
V=68
V=67
V=66
V=65
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$p_{1/2}$ phase-shift (degrees)
E_{cm} (MeV)

3.2 Virtual States

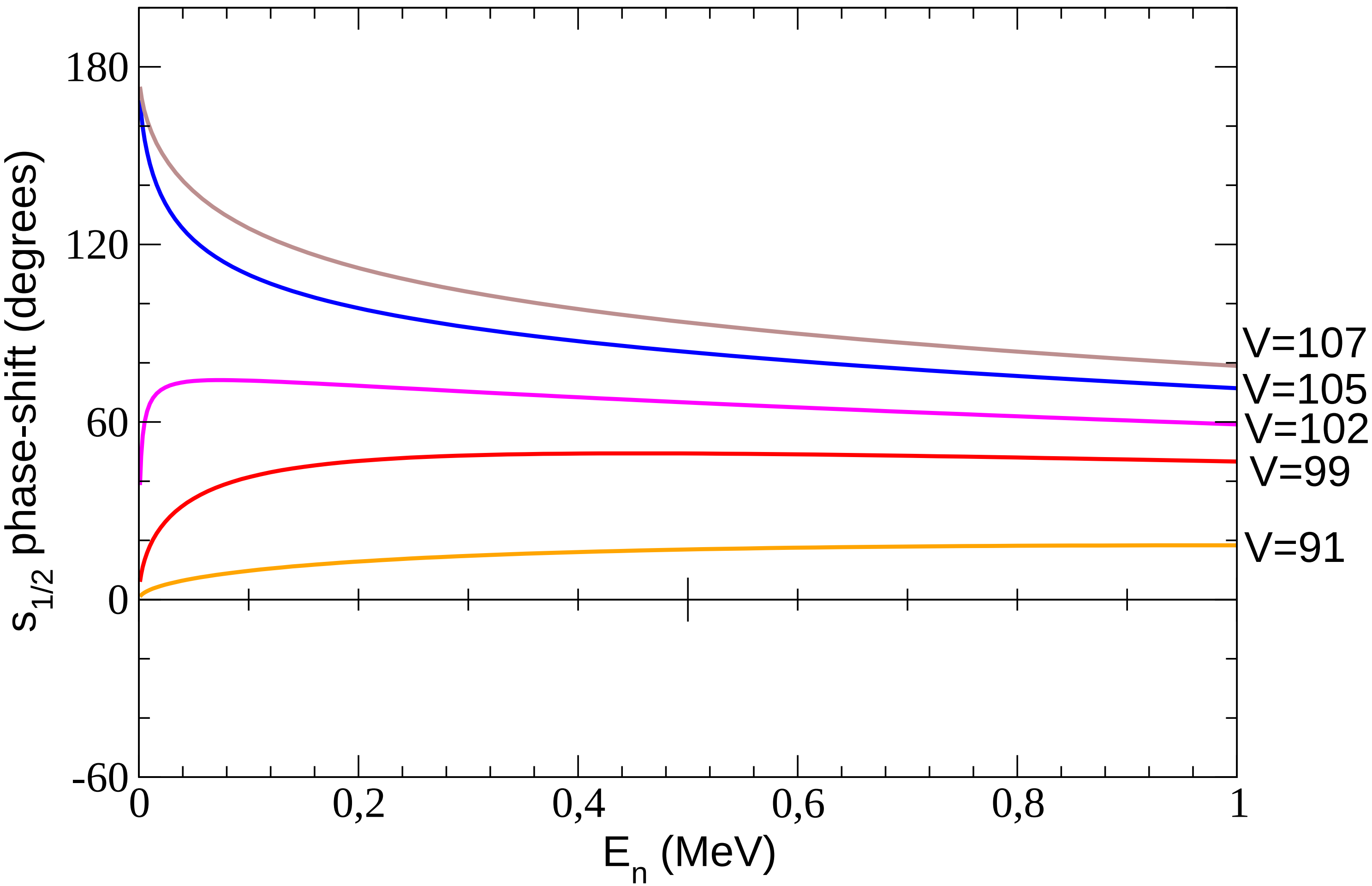
- Virtual states are structures in the continuum.
- Virtual states appear in Quantum Theory as non-normalizable (exponentially increasing) negative energy solutions of the hamiltonian $E_v < 0$.
- Continuum states at small positive energies $0 \leq E \leq |E_v|$ display a larger probability of presence at short distances of continuum states is larger.
- When the energy of a virtual state is close to the threshold, the scattering length is very large. Phase shifts depend strongly on energy.
- Virtual states appear when there is no barrier (s-wave).
- The presence of virtual states enhances the transfer cross sections at energies just above the threshold.



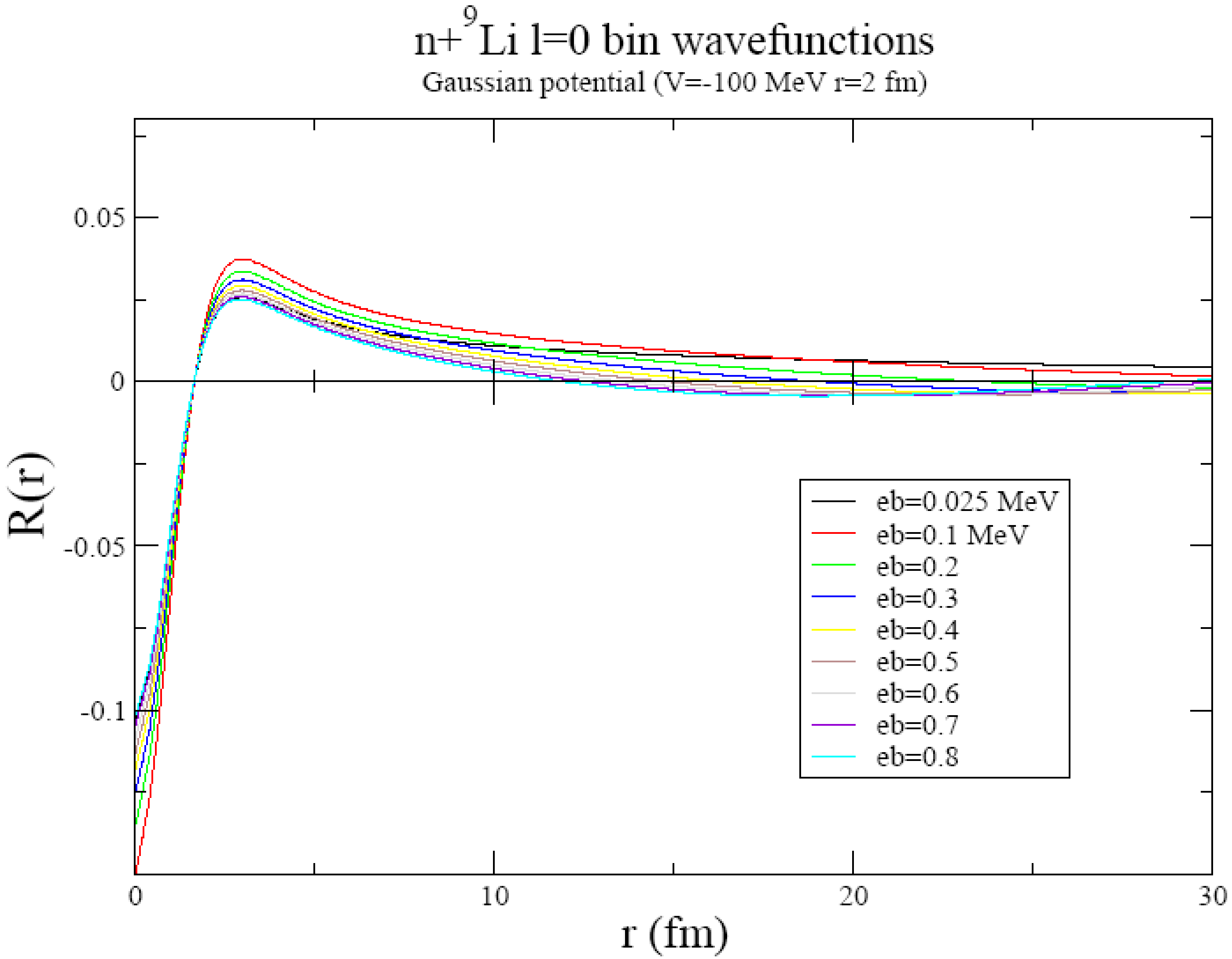
Calculated values
(hbar k)^2/ (2 mu)
Virtual
Bound
E_s (MeV)
Wave number (fm^{-1})
Potential depth (MeV)

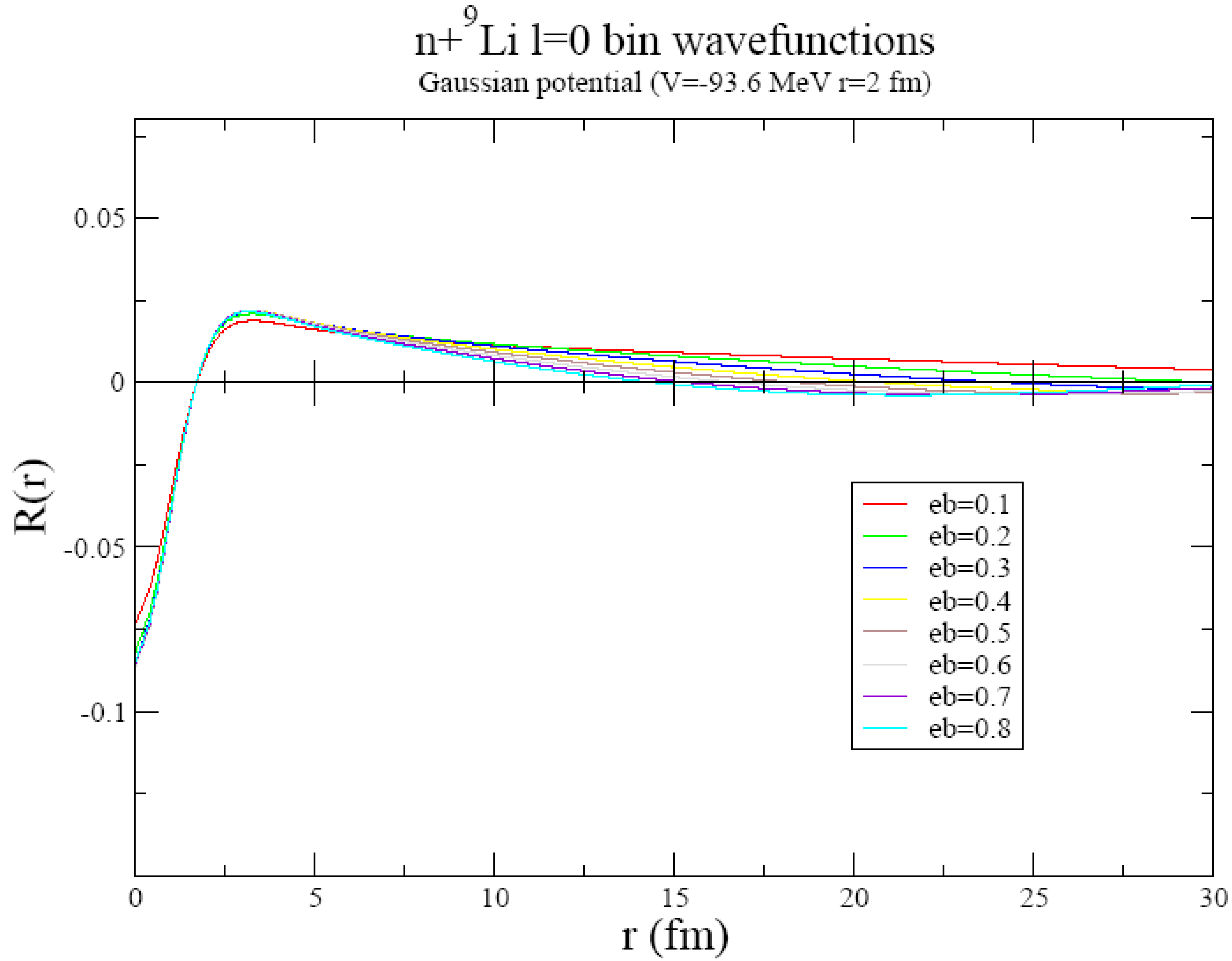


0
-0.5
E_s (MeV)
0
-20
-40
Scattering length a_s (fm)
90
95
100
Potential depth (MeV)



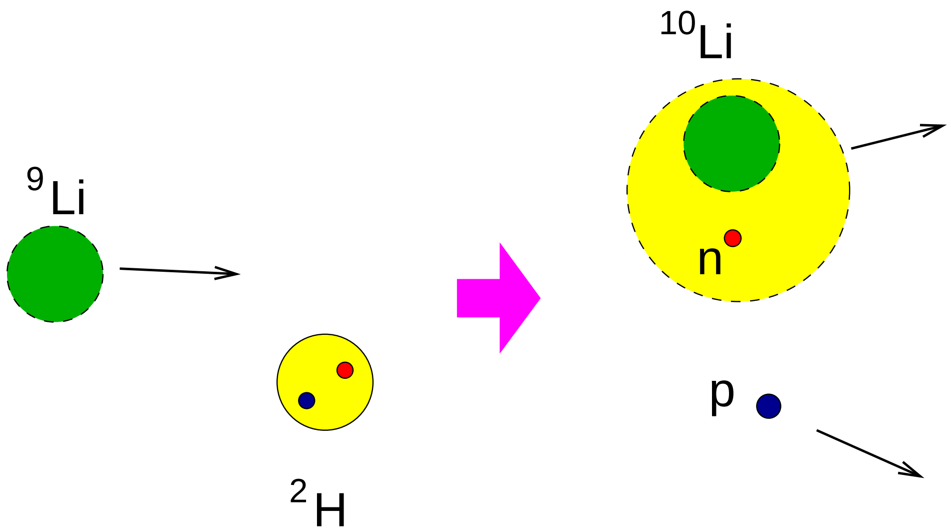
180
120
60
0
-60
0
0,2
0,4
0,6
0,8
1
$s_{1/2}$ phase-shift (degrees)
E_n (MeV)
V=107
V=105
V=102
V=99
V=91


n+^{9}Li l=0 bin wavefunctions
Gaussian potential (V=-100 MeV r=2 fm)
R(r)
r (fm)
0.05
0
-0.05
-0.1
0
10
20
30
eb=0.025 MeV
eb=0.1 MeV
eb=0.2
eb=0.3
eb=0.4
eb=0.5
eb=0.6
eb=0.7
eb=0.8


n+^{9}Li l=0 bin wavefunctions
Gaussian potential (V=-93.6 MeV r=2 fm)
0.05
0
-0.05
-0.1
R(r)
0
5
10
15
20
25
30
r (fm)
eb=0.1
eb=0.2
eb=0.3
eb=0.4
eb=0.5
eb=0.6
eb=0.7
eb=0.8

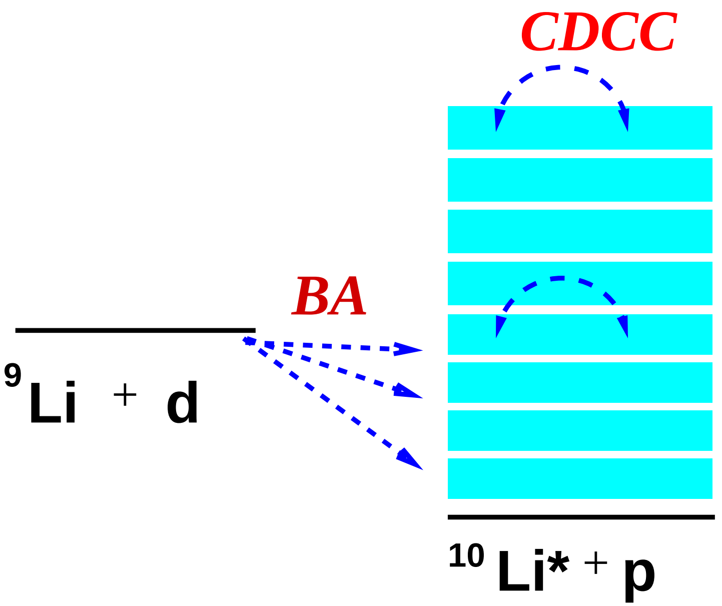
3.3 Transfer to structures in the continuum

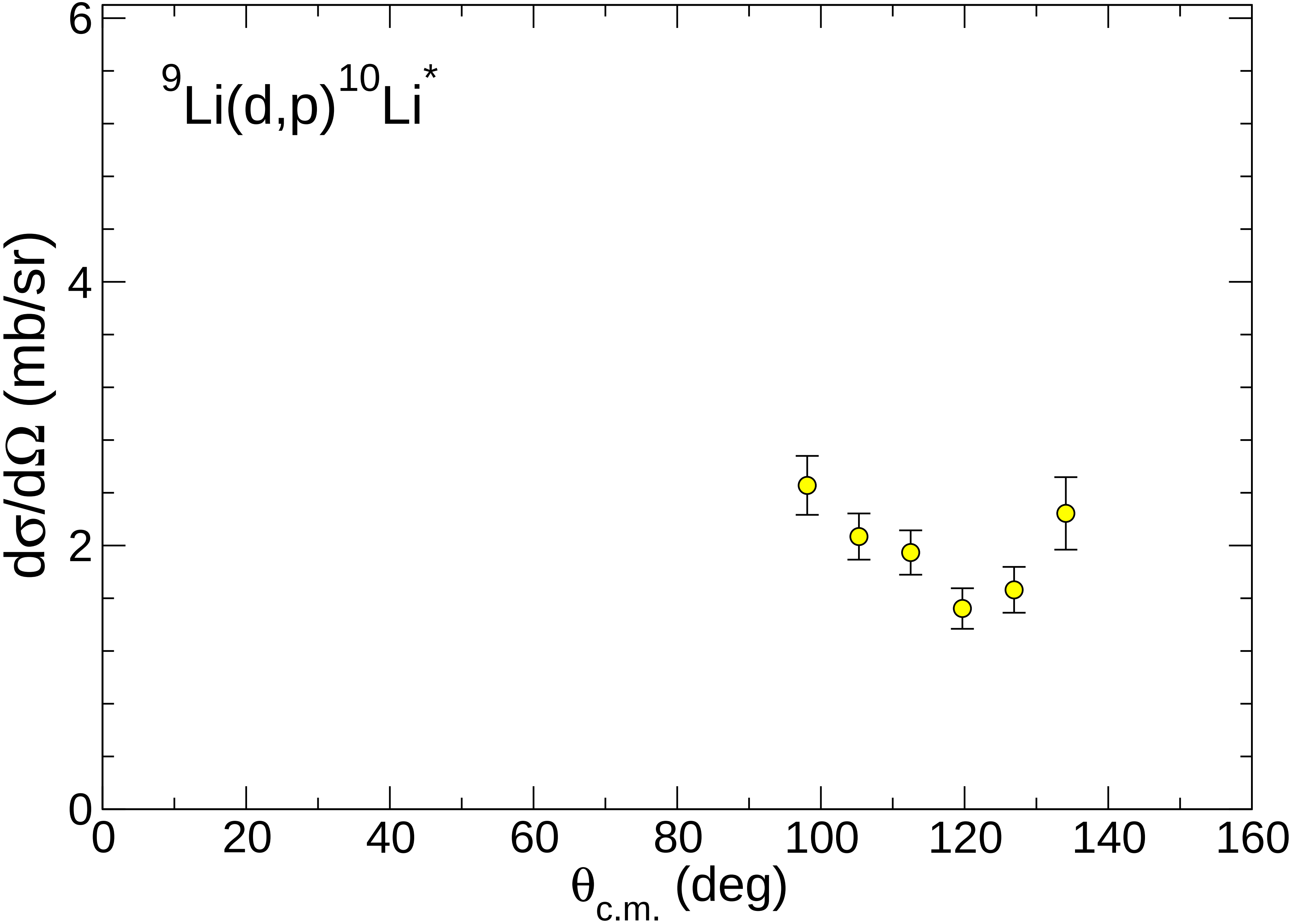
- Structure: All $L = 0$ and $L = 1$ continuum states in ^{10}Li as $^{9}Li(gs) + n$ considered.
- Interactions: $U(p, 9Li)$, $U(d + 9Li)$ from elastic scattering. $V(n, 9Li)$ adjusted to reproduce cross sections.
- Reaction mechanism: CDCC-BA. Born approximation for transfer, Coupling to the $^{9}Li + n$ continuum to all orders.
- Cross sections are extremely sensitive to the $V(n, 9Li)$ interaction. A careful analysis allows to obtain accurately the energy and width of the $l = 1$ resonance, as well as the energy of the $l = 0$ virtual state.



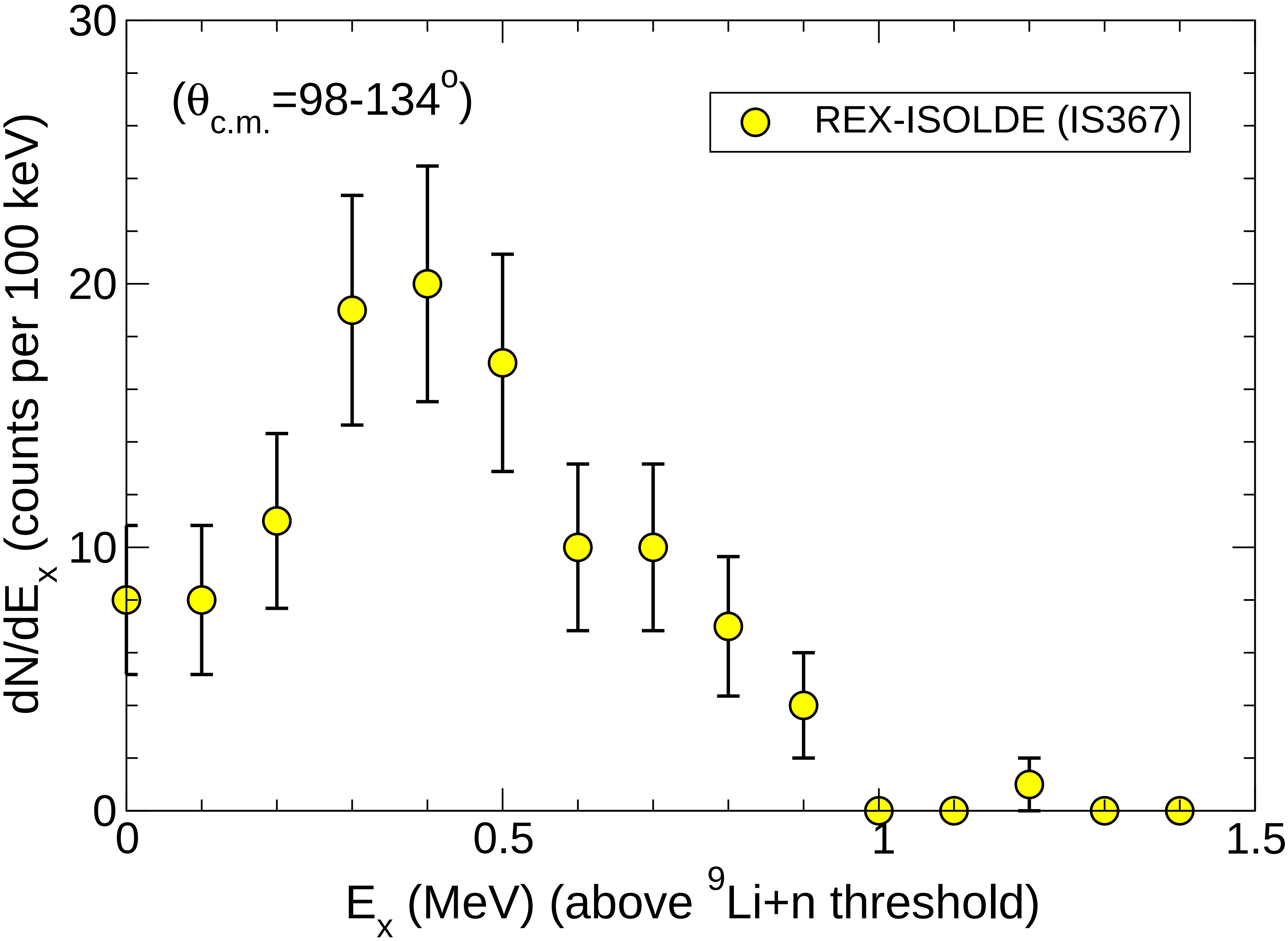
^{9}Li
^{2}H
^{10}Li
n
p

Reaction mechanism: CCBA

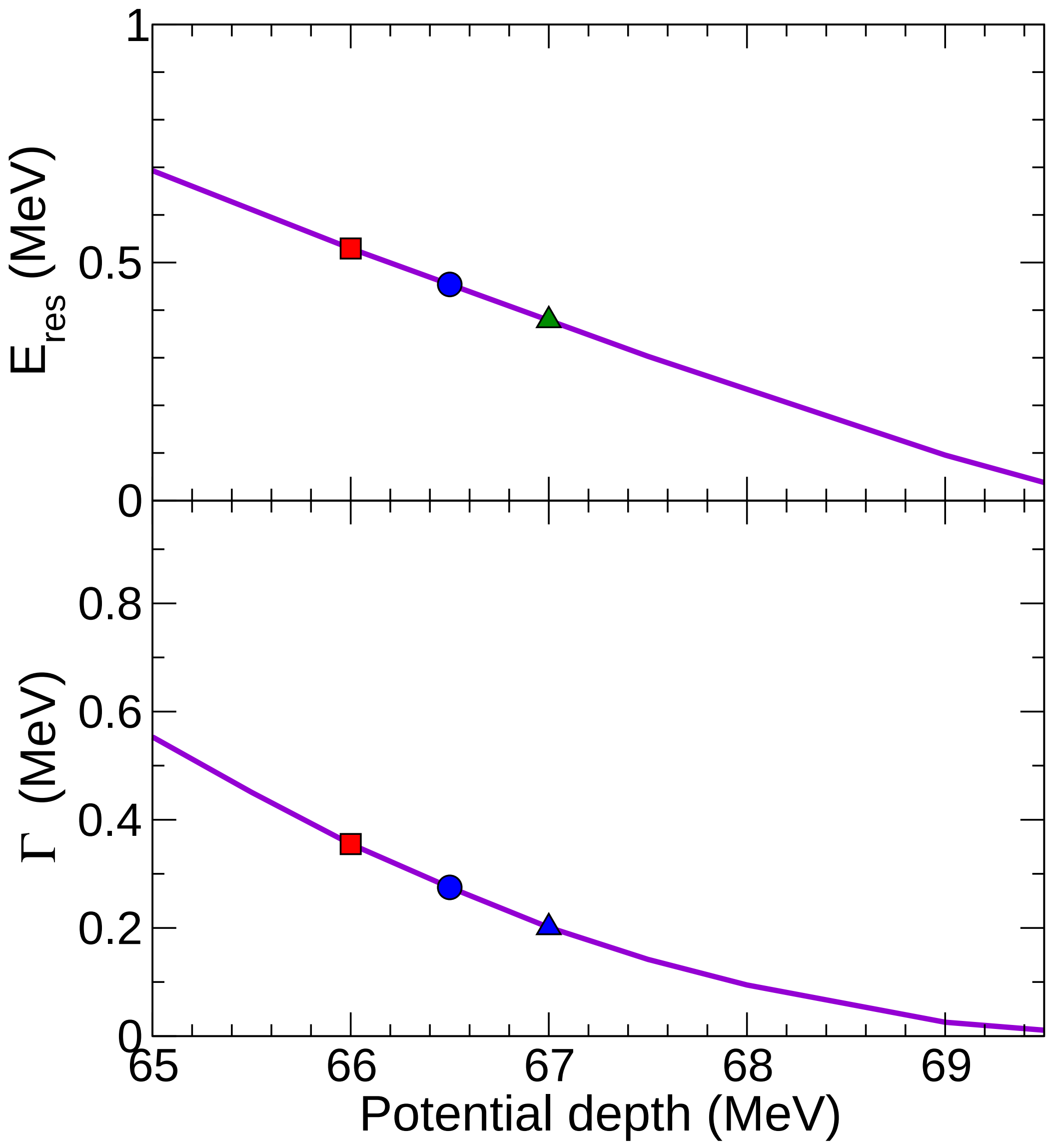




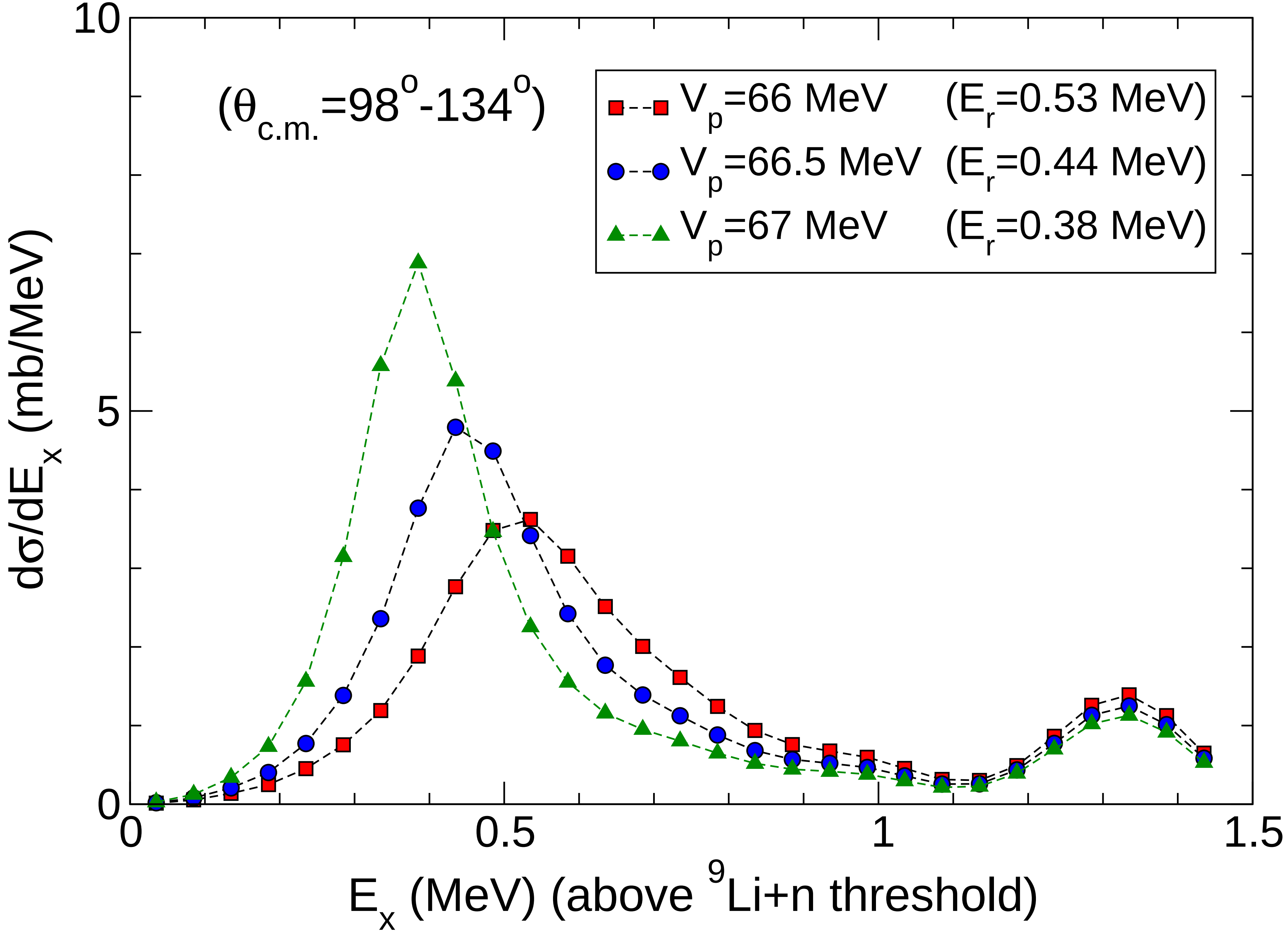
$^{9}Li(d,p)^{10}Li^{*}$
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$ (deg)
0
2
4
6
0
20
40
60
80
100
120
140
160



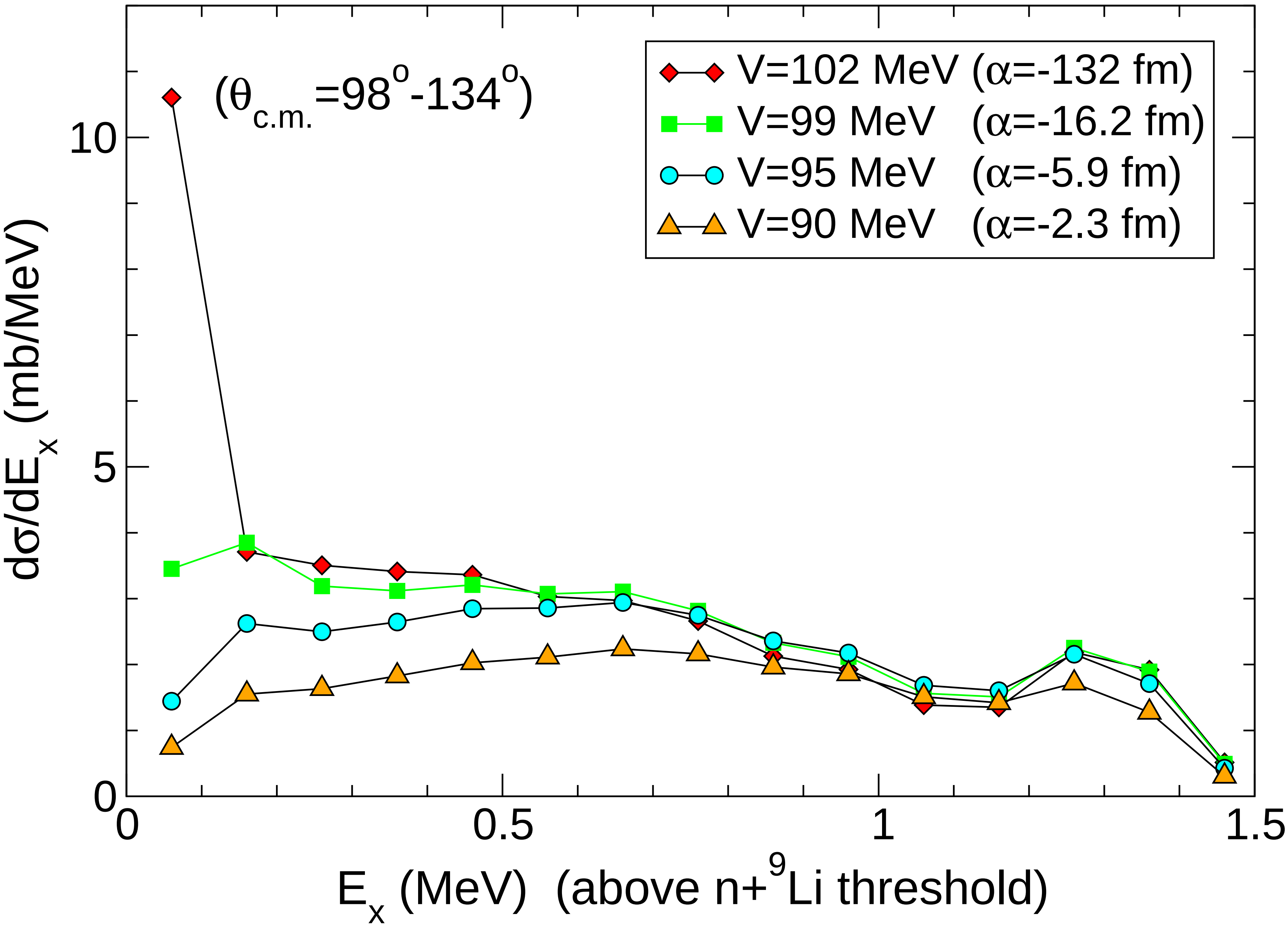
30
20
10
0
0
0.5
1
1.5
(θc.m.=98-134o)
REX-ISOLDE (IS367)
dN/dEx (counts per 100 keV)
Ex (MeV) (above 9Li+n threshold)



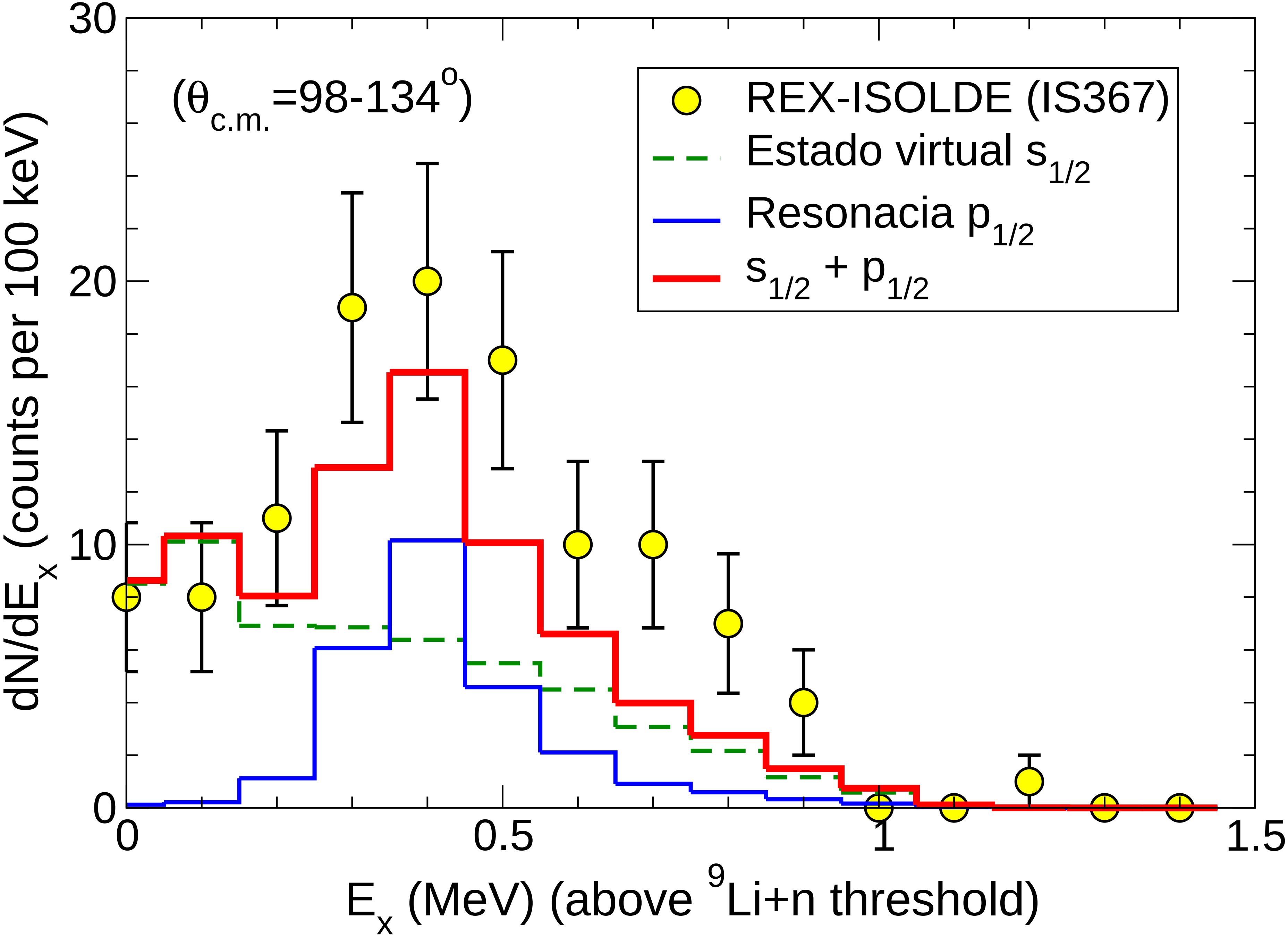
1
0.5
0
E_{res} (MeV)
0.8
0.6
0.4
0.2
0
Γ (MeV)
65
66
67
68
69
Potential depth (MeV)



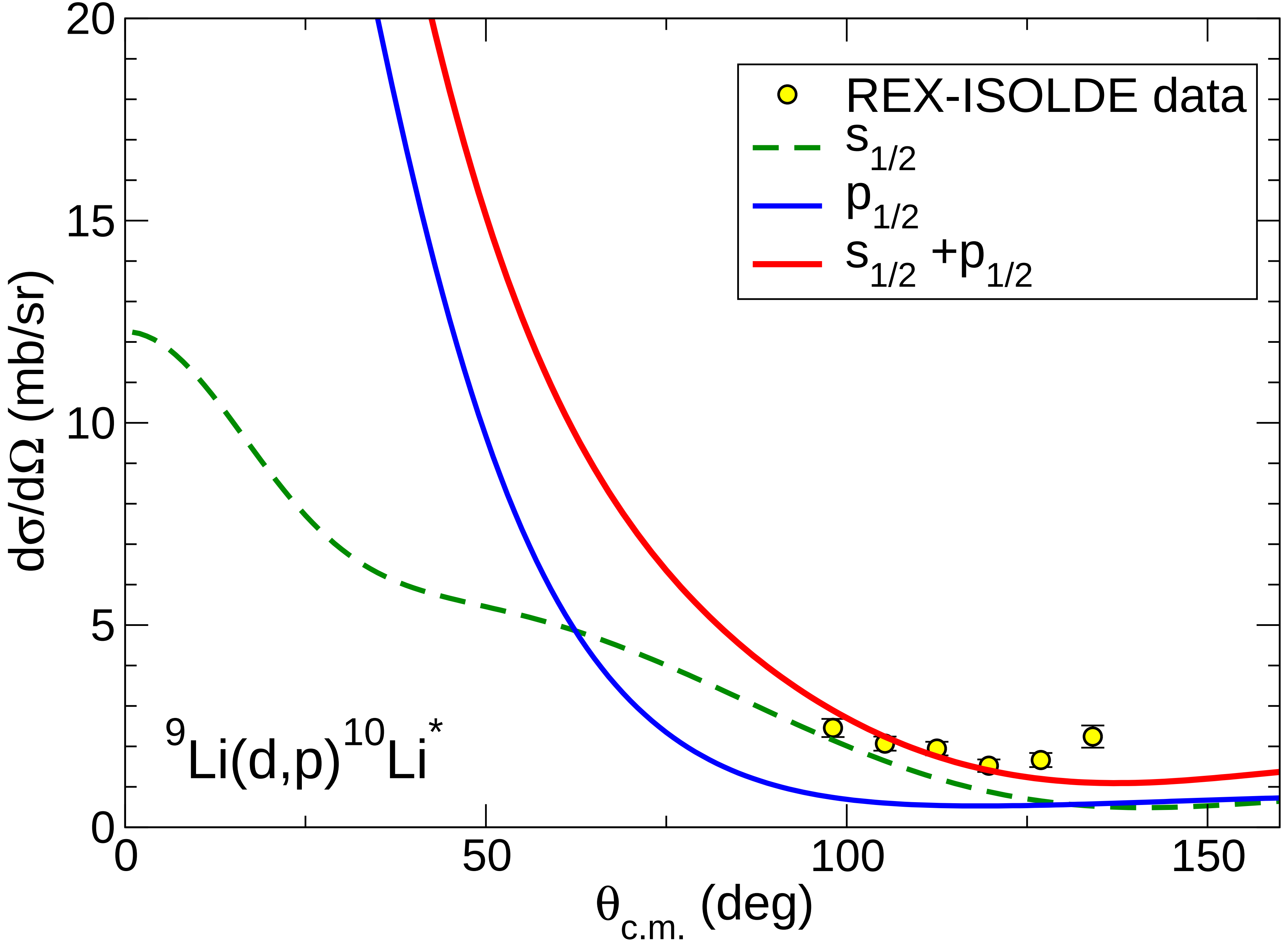
10
5
0
0
0.5
1
1.5
(θc.m.=98°-134°)
Vp=66 MeV (Er=0.53 MeV)
Vp=66.5 MeV (Er=0.44 MeV)
Vp=67 MeV (Er=0.38 MeV)
dσ/dEx (mb/MeV)
Ex (MeV) (above 9Li+n threshold)



V=102 MeV (α=-132 fm)
V=99 MeV (α=-16.2 fm)
V=95 MeV (α=-5.9 fm)
V=90 MeV (α=-2.3 fm)
(θc.m.=98o-134o)
dσ/dEx (mb/MeV)
Ex (MeV) (above n+9Li threshold)
0
5
10
0
0.5
1
1.5



30
20
10
0
0
0.5
1
1.5
dNdE_x (counts per 100 keV)
E_x (MeV) (above 9Li+n threshold)
(θc.m.=98-134o)
REX-ISOLDE (IS367)
Estado virtual s1/2
Resonacia p1/2
s1/2 + p1/2


REX-ISOLDE data
s1/2
p1/2
s1/2 +p1/2
9Li(d,p)10Li*
dσ/dΩ (mb/sr)
θc.m. (deg)
0
5
10
15
20
0
50
100
150

3.4 Summary of Transfer to Structures in the continuum

- Unbound, or weakly bound nuclei display structures in the continuum.
- Resonances are structures in the continuum associated to complex energy solutions of the hamiltonian. They require an effective barrier.
- Virtual states are structures in the continuum associated to exponentially increasing negative energy solutions of the hamiltonian. They require the absence of barriers.
- Transfer to continuum states can be calculated combining DWBA transfer with continuum discretization.

- **The analysis of $d(^9Li,p)^{10}Li$ data are consistent with the presence of a p resonance and an s virtual state in ^{10}Li.**

- **A gaussian or lorentzian fit to the cross sections is not justified and is inaccurate to determine continuum structures of weakly bound systems.**

Reactions with exotic nuclei