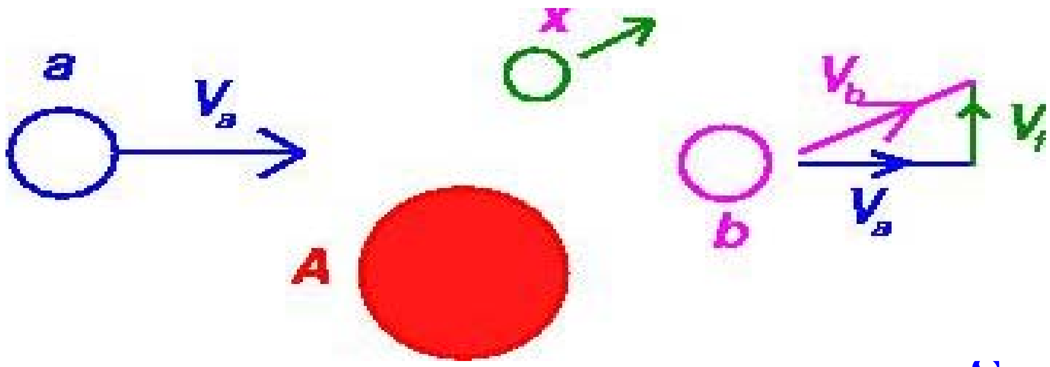
LECTURE - 3

Breakup reactions: $a + A \rightarrow b + c + A$

Two modes of breakup

- **Elastic breakup (A remains in the g.s.)**
- **Inelastic breakup (c + A can go to c + C)**

Mechanism of breakup reactions (Elastic Breakup)

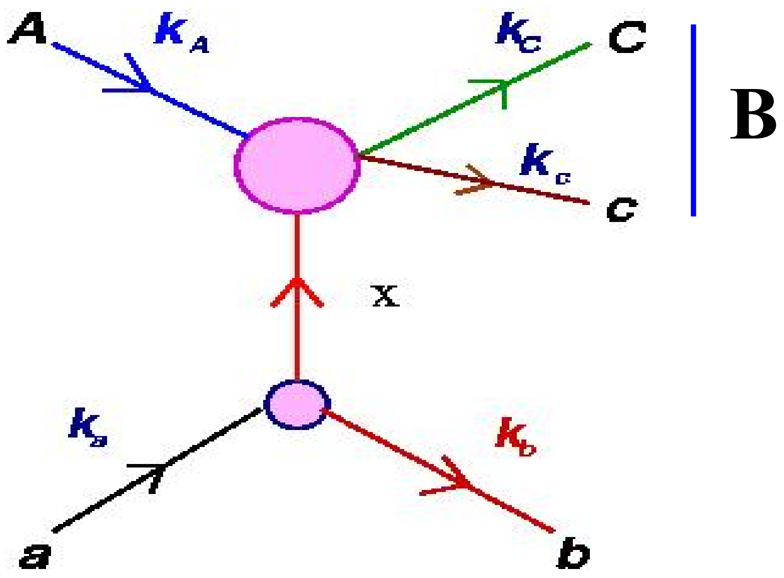


Spectator participant picture

$$T_{fi}^{(+)}(DWBA) = < \chi^{(-)}(q_c,r_{cA})\chi^{(-)}(q_b,r_{bA})|V_{bc}|\chi^{(+)}(q_a,r_{aA})\phi_a\,(r_bc) >$$

Theory of Inelastic Breakup Reactions

We want to describe the reaction a + A → b + c + C



$$T^{(+)}\,(inel) = \langle \chi^{(-)}(k_{bB})\ \psi^{(-)}(k_{Ax})\ \phi_b\,|V_x|\,\chi^{(+)}(k_{aA})\ \phi_A\ \phi_a \rangle$$

Surface approximation

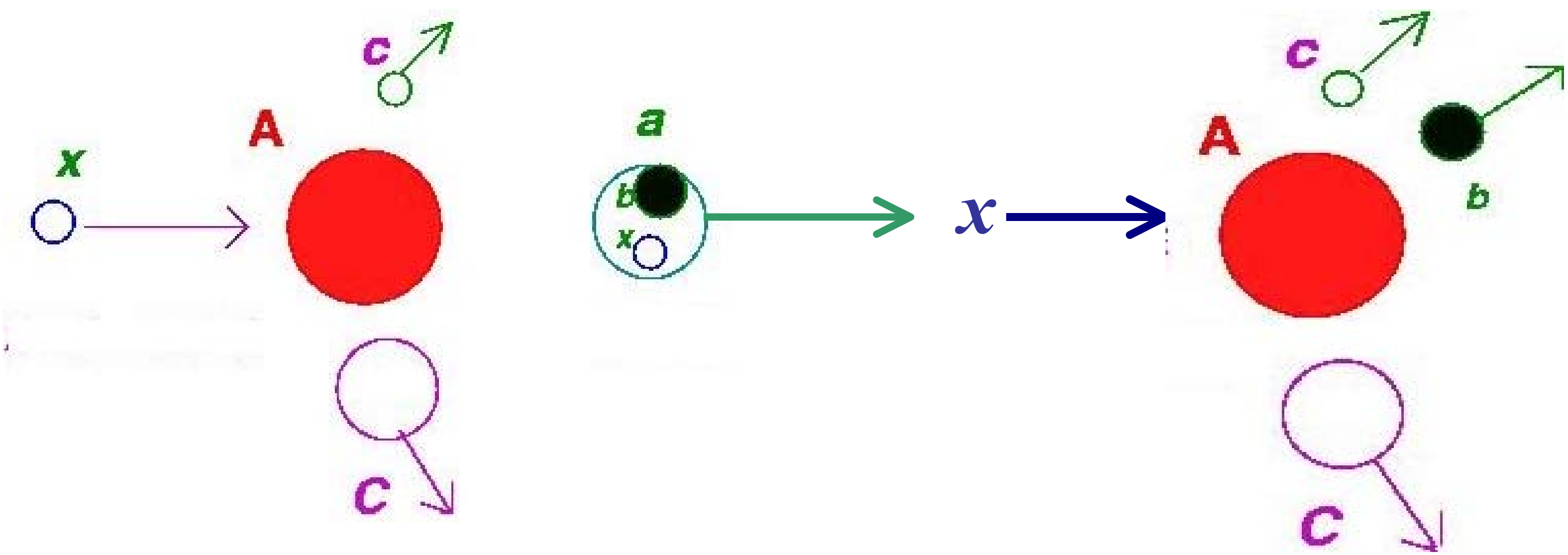
$$\int d\xi_A\ \psi^{(-)*}{}_B\ \phi_A = 4\pi\ \Sigma_{\lambda m}\ f_\lambda(r_{xA})\ Y_{\lambda m}(\Omega_{xA})\ Y^*{}_{\lambda m}(k_{cC})$$

$$f_\lambda(r_{xA}) \rightarrow \tfrac{1}{2}\ S_{\lambda c}\ h_\lambda^{(+)}(k_{Ax}\, r_{Ax})$$

TROJAN-HORSE METHOD

G. Baur, F. Roesel, D. Trautmann, R. Shyam, Phys. Rep. 111 (1984) 333
G. Baur, Phys. Lett. B 178 (1986) 135, S. Typel, G. Baur, Ann. Phys. 305 (2003) 228

For any charged particle induced reaction at astrophysical energies



$x + A \rightarrow c + C$

$a\ (b+x) + A \rightarrow b + c + C$

Hindered at lower energies

Can proceed as *a* can have larger energy.

***x* is brought in the reaction zone of target *A* hidden inside the projectile .**

$$d^3\sigma / d\Omega_b d\Omega_c dE_b = \rho(\text{phase space})\, |\Sigma_{\lambda m} T_{\lambda m}(k_a,k_b,k_x)\, S_{\lambda c}\, Y_{\lambda m}(\Omega_c)|^2$$

$$T_{\lambda m}(k_a,k_b,k_x) = \langle \chi^{(-)}(k_b)\, Y_{\lambda m}(k_x) f_\lambda |\, V_{bx} |\, \chi^{(+)}(k_a) \phi_{bx} \rangle$$

Advantages

A – a **energy can be well above the Coulomb barrier**

Cross sections are larger

Low A **-** x **energies are accessible,** $E_a = E_b + E_x - Q$

BUT

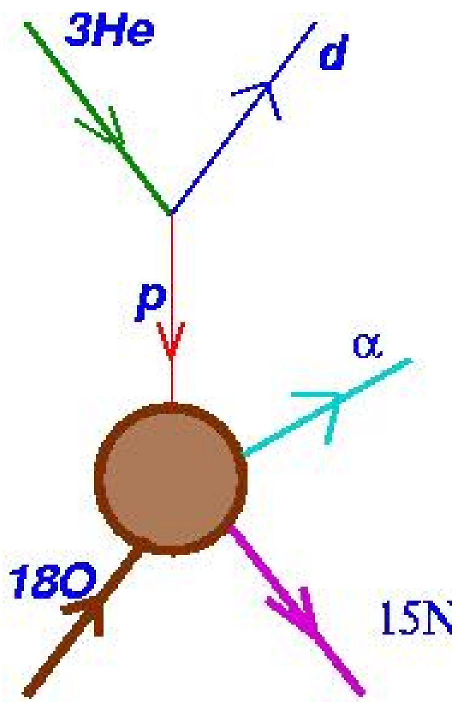
Calculation of $T_{\lambda m}(k_a,k_b,k_x)$ **must be done as accurately as possible**

The Trojan - Horse Method

Example

p + ^{18}O $\rightarrow \alpha$ + ^{15}N CNO cycle Gammow peak ; 30 keV

We study this reaction by $^{3}He + {}^{18}O \rightarrow d + \alpha + {}^{15}N$



The information about the cross section

$$\sigma(p + {}^{18}O \rightarrow \alpha + {}^{15}N) = (\pi/k_x^2)\, \Sigma\, (2\lambda+1)\, |S_{\lambda c}|^2$$

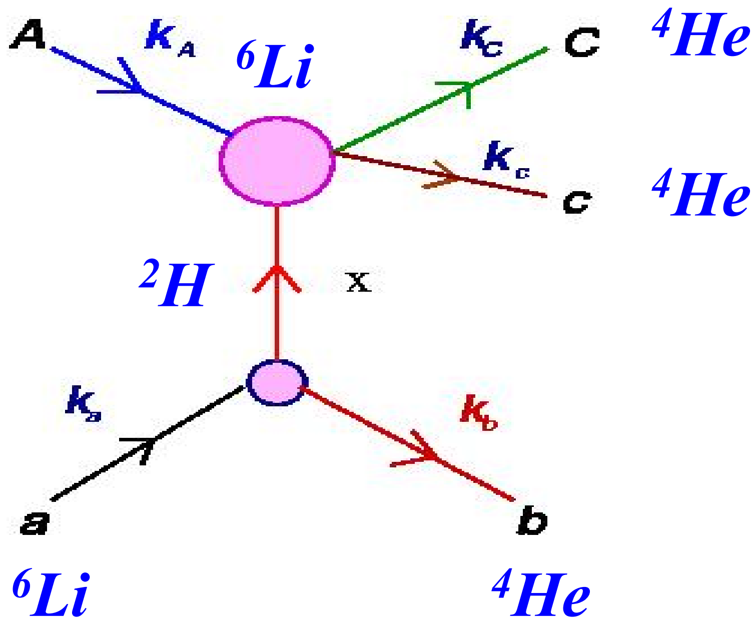
from the experimentally determined $d^3\sigma / d\Omega_d\, d\Omega_\alpha\, dE_d$

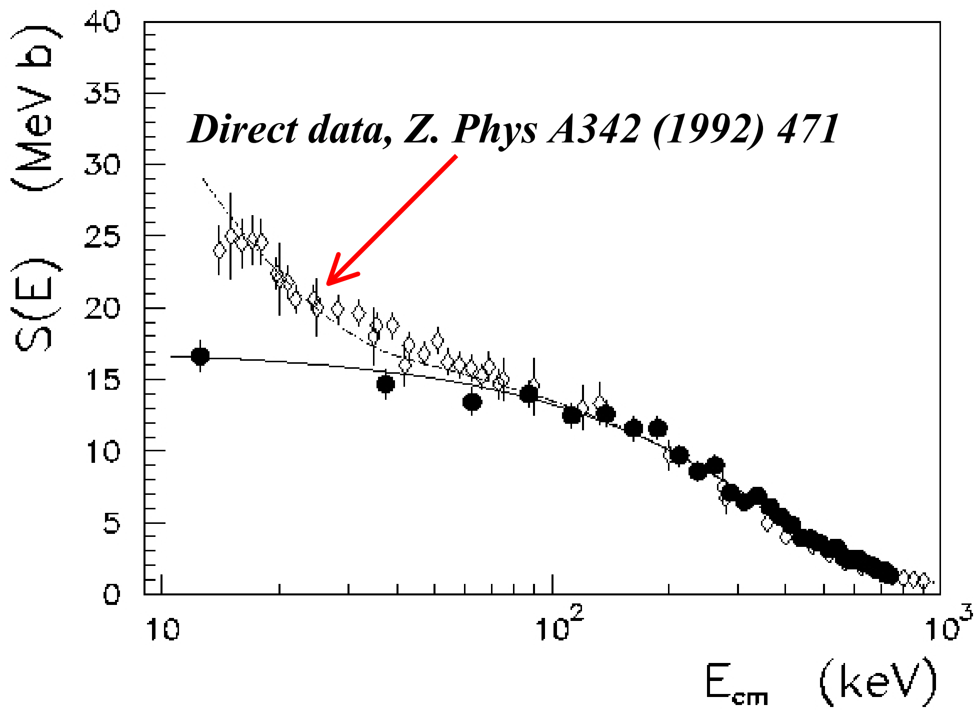
$$d^3\sigma / d\Omega_d\, d\Omega_\alpha\, dE_d = (phase\ space)\, |\Sigma_{\lambda m}\, T_{\lambda m}\, S_{\lambda c}\, Y_{\lambda m}(\Omega_\alpha)|^2$$

DWBA THEORY OF INELASTIC BREAKUP REACTIONS

Applications of Trojan-Horse Method

$^2H\ (^6Li,\alpha)\ ^4He$ **Big Bang Nucleosynthesis**





$^6Li\ (^6Li,\alpha\ \alpha)\ ^4He$ **E (beam)= 6 MeV**

Catania/Zagreb experiment, Spitaleri et al., PRC 63 (2001) 055801

Direct (corrected for electron screening) and Trojan-horse methods gave similar astrophysical S-factor

Other applications of Trojan-Horse Method

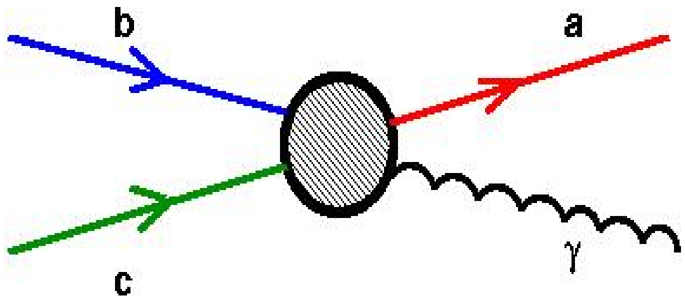
Reaction	Trojan-Horse Reaction	E_{proj} (MeV)	Ref.
$^{1}H(^{7}Li,\alpha)\,^{4}He$	$^{2}H(^{7}Li,\alpha\,\alpha)\,n$	*19-21*	*Ap. J 562 (2001)1076*
$^{6}Li(p,\,^{3}He)\,^{4}He$	$^{2}H(^{6}Li,\,^{3}He\alpha)\,n$	*25.0*	*preprint*

BUT BEWARE

Calculations as yet use simplified approximation of PW.
Absolute cross sections are unreliable
TH results are normalized to the directly measured cross sections

More work on theory side is required: (include distorted waves in the description)

Direct capture reaction $b + c \rightarrow a + \gamma$



$$\sigma \propto |M|^2$$

$$M = \langle \varphi_a(\xi_b, \xi_b, r_{bc}) | O(r_{bc}) | \varphi_b(\xi_b) \varphi_c(\xi_c) \psi_i(r_{bc}) \rangle$$

$$I_{bc}^{A}(r_{bc}) = \langle \varphi_a(\xi_b, \xi_b, r_{bc}) | \varphi_b(\xi_b) \varphi_c(\xi_c) \rangle$$

$$= C_{\lambda j} f_{\lambda j}(r_{bc}) Y_{\lambda m}(\Omega)$$

$$r_{bc} ? R_N, \; f_{\lambda j}(r_{bc}) = C_{\lambda j} W_{\lambda + 1/2}(2kr_{bc})/r_{bc}$$

At low energies

$\psi_i(r_{bc}) \rightarrow$ regular Coulomb wave functions.

$O(r_{bc}) \rightarrow$ Electromagnetic operator

So if the reaction is peripheral then the

$$|M|^2 \propto C_{\lambda j}^2$$

Capture amplitude is completely determined by $C_{\lambda j}$

Methods for the determination of ANC

- **Single particle potential model for a (b+c)**

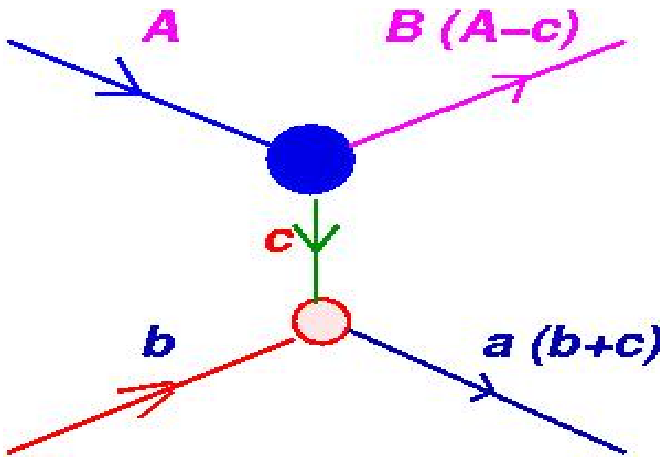
Assume b+c are bound together by a potential having a Woods-Saxon form. Its depth is adjusted to the b + c separation energy.

The corresponding single particle wave function is $u_{\lambda j}$.

$$f(r_{bc}) = S_{\lambda j}^{1/2}\, u_{\lambda j}(r_{bc}) = \underline{S_{\lambda j}^{1/2}\, b_{\lambda j}}\, W_{\lambda+1/2}(2kr_{bc})$$

↓ **Spectroscopic factor** ↓ $C_{\lambda j}$

From the transfer reaction b(A,B)a



$$d\sigma/d\Omega = |< \chi_{a\text{-}B}\, \phi_B \phi_a\, | V_{B\text{-}c} |\, \phi_A \phi_b\, \chi_{b\text{-}A} >|^2$$

$$= |< \chi_{a\text{-}B}\, I_{ba}\, \underline{\phi_B\, | V_{B\text{-}c} |\, \phi_A}\, \chi_{b\text{-}A} >|^2$$

→ **Second vertex**

$$|I_{ba}|^2 = S_{\lambda j} |u_{\lambda j}|^2$$

$$= S_{\lambda j} b^2_{\lambda j} |W_{\lambda+1/2}|^2$$

Single particle potential model

If the transfer is peripheral

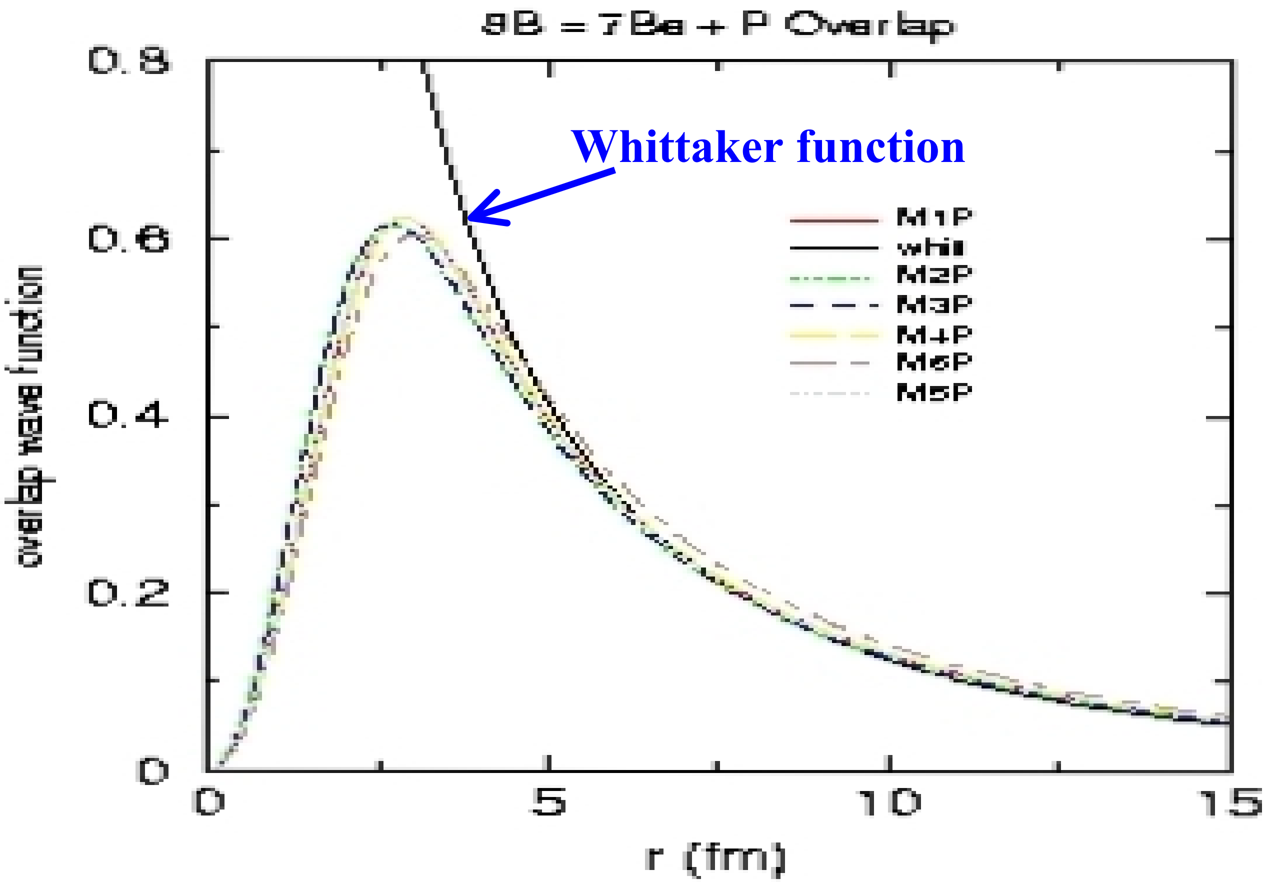
ANC from Transfer Reactions

Conditions to be satisfied

- **Transfer reaction must be peripheral**
- **Single step transfer mechanism must dominate**
- **Compound nuclear contribution should be negligible**
- **Optical model potentials must be known with great accuracy**
- **Second vertex should be known accurately**

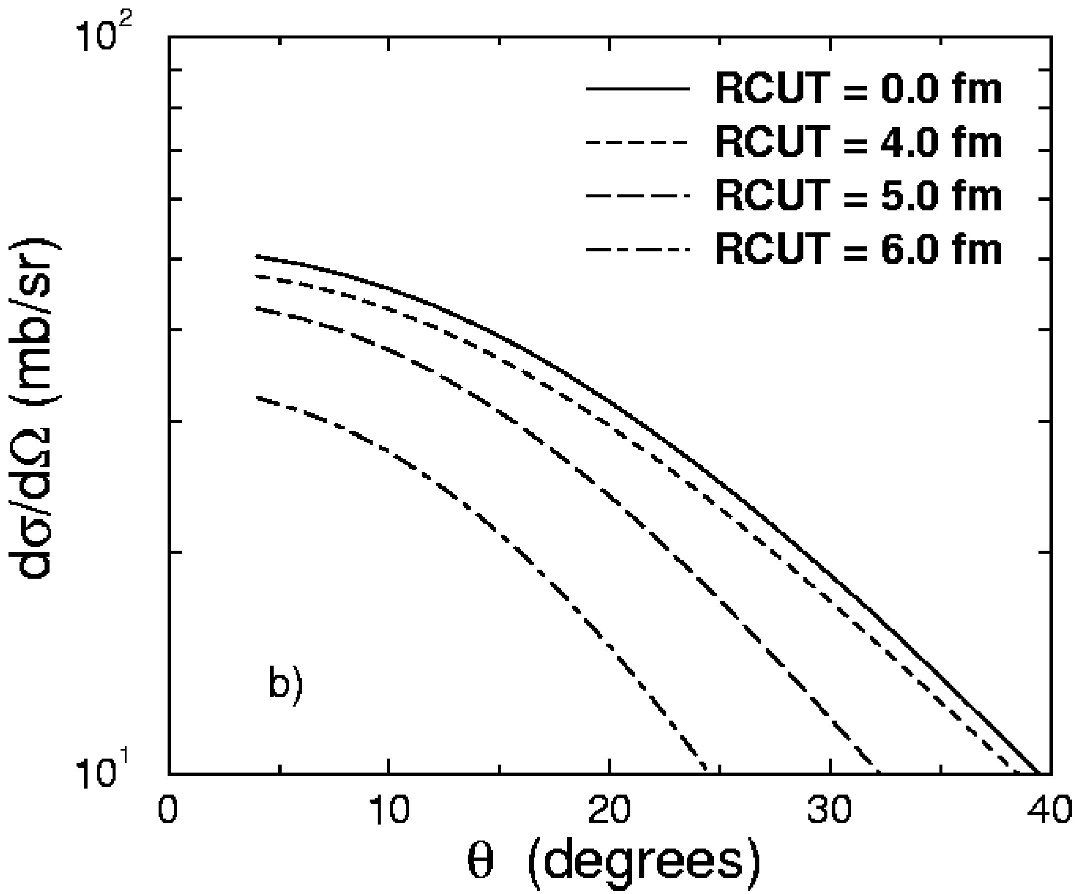
Study of the $p + {}^7Be \rightarrow {}^8B + \gamma$ reaction

Whittaker function describes the asymptotics of the ^8B well.



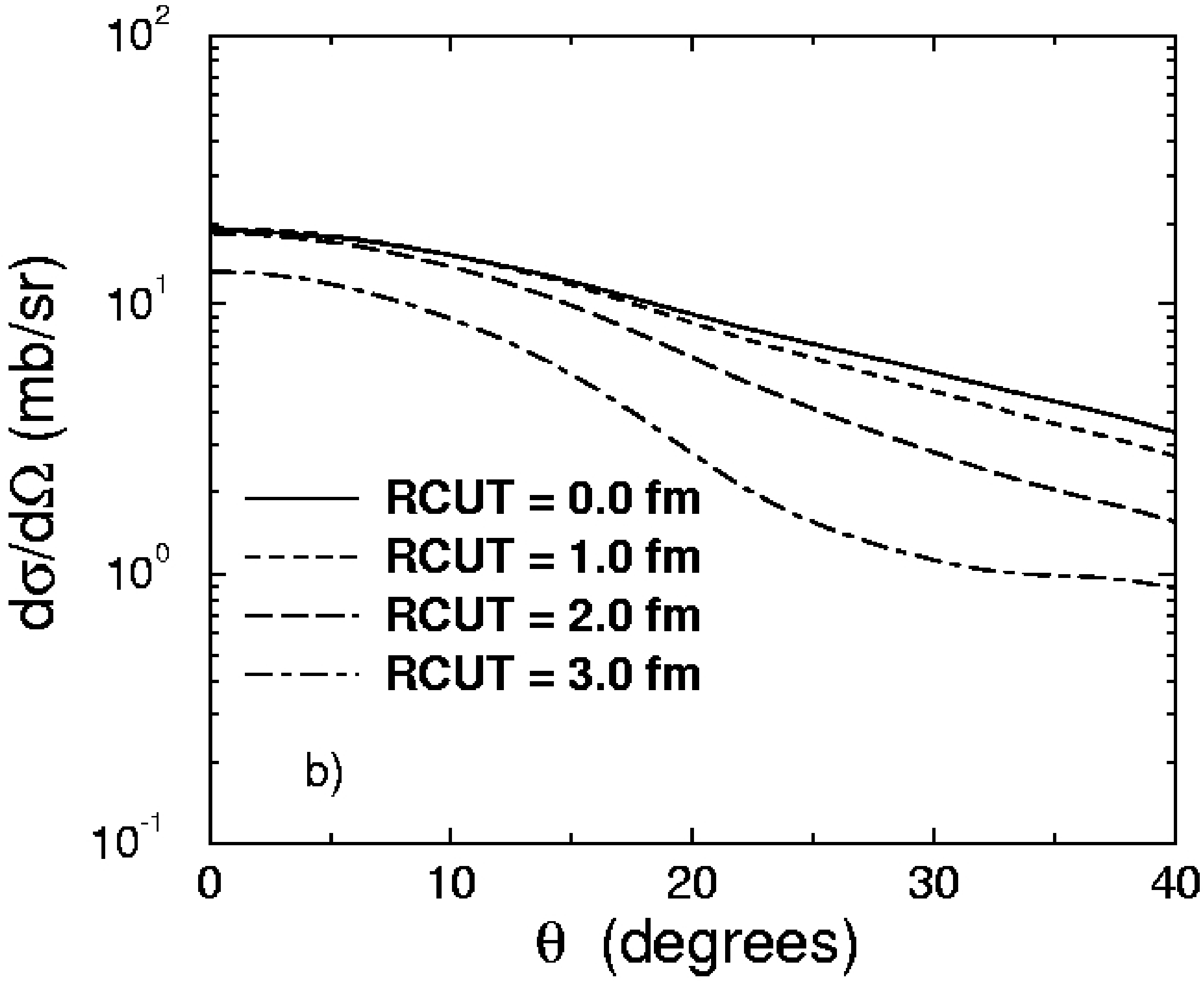
S-factor of $p + {}^7Be \rightarrow {}^8B + \gamma$ reaction via study of ${}^7Be\,(d,n)\,{}^8B$

Validity of the peripheral approximation



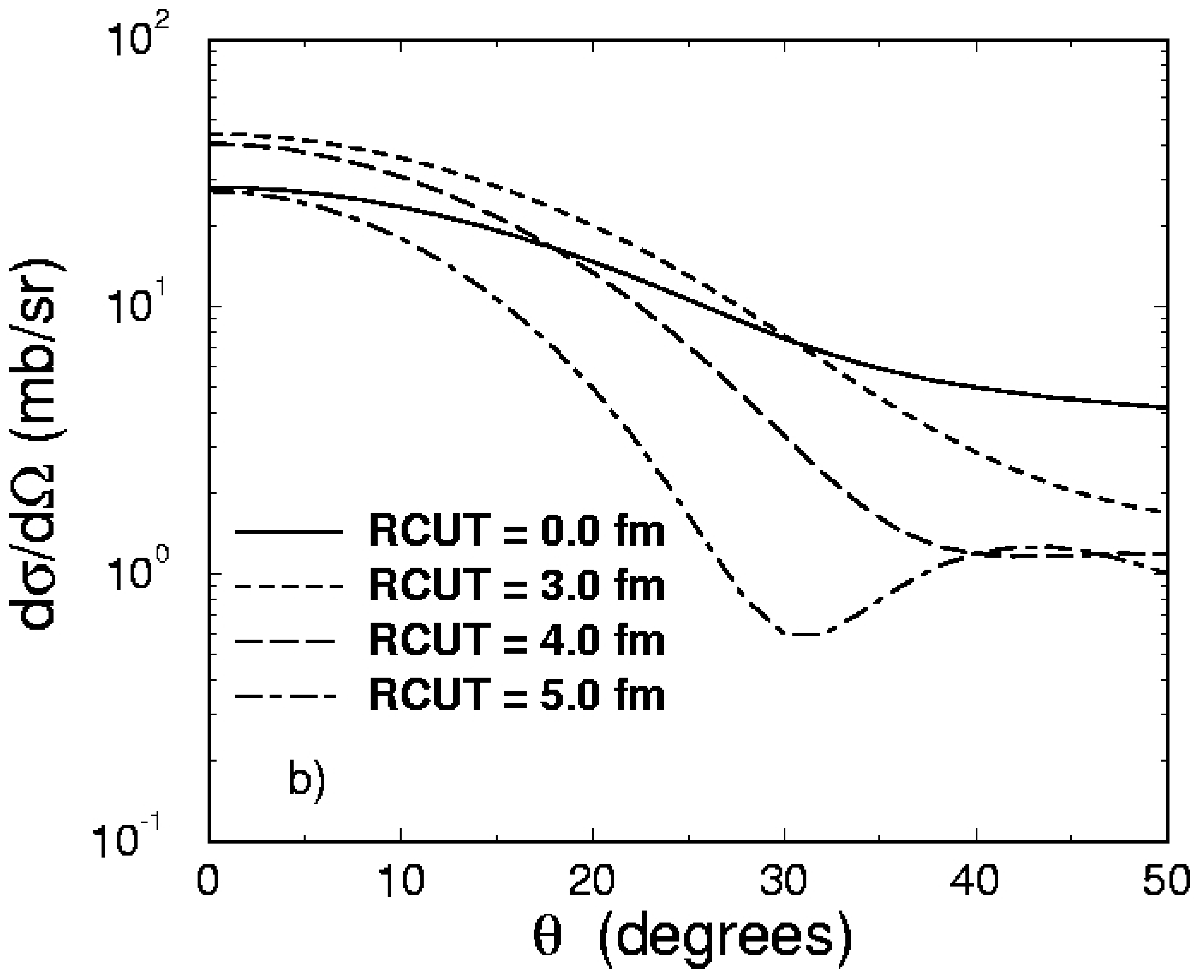
E_{cm} = 5.8 MeV

Validity of the peripheral approximation



E_{cm} = 15.6 MeV

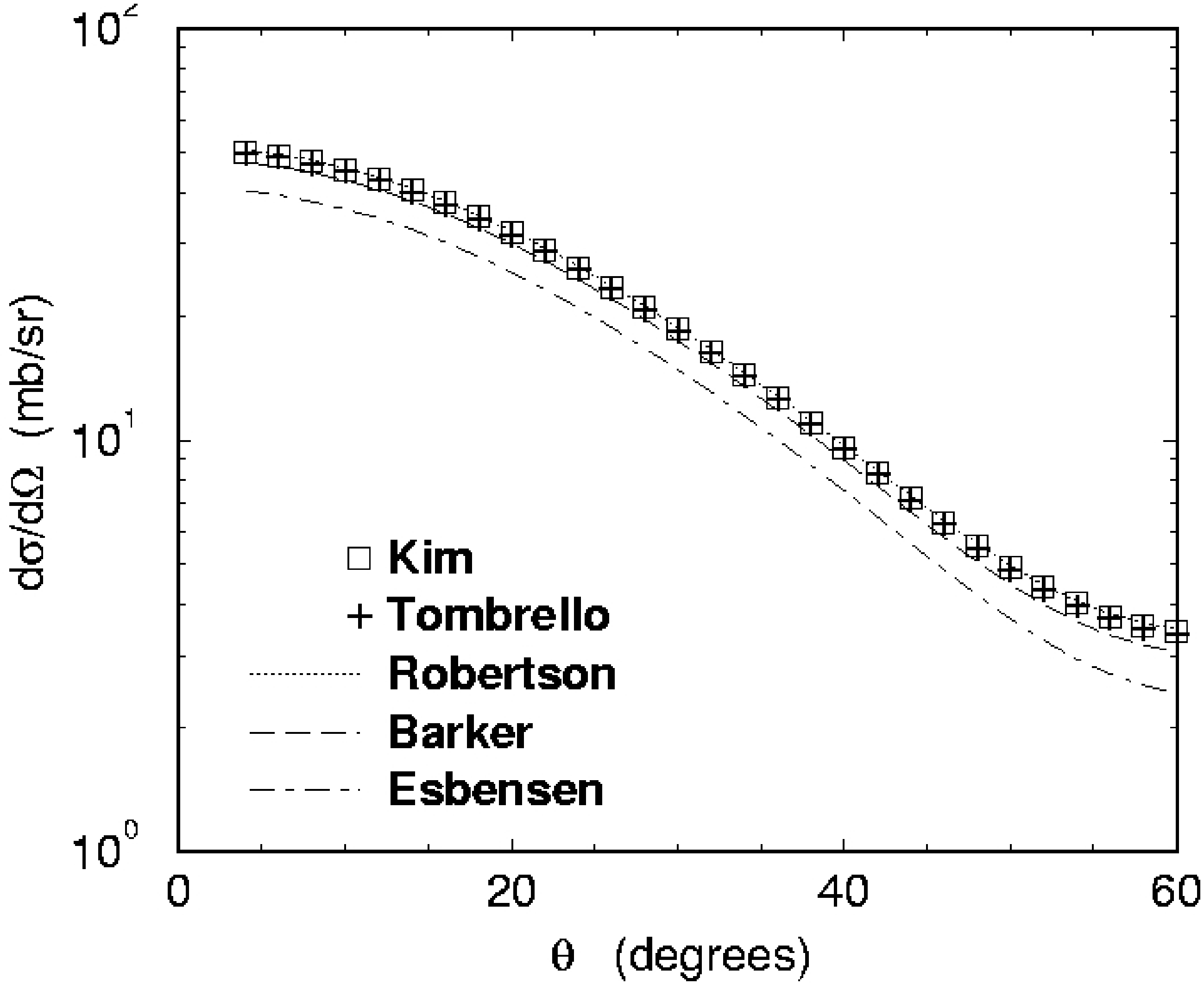
Validity of the peripheral approximation



E_{cm} = 38.9 MeV

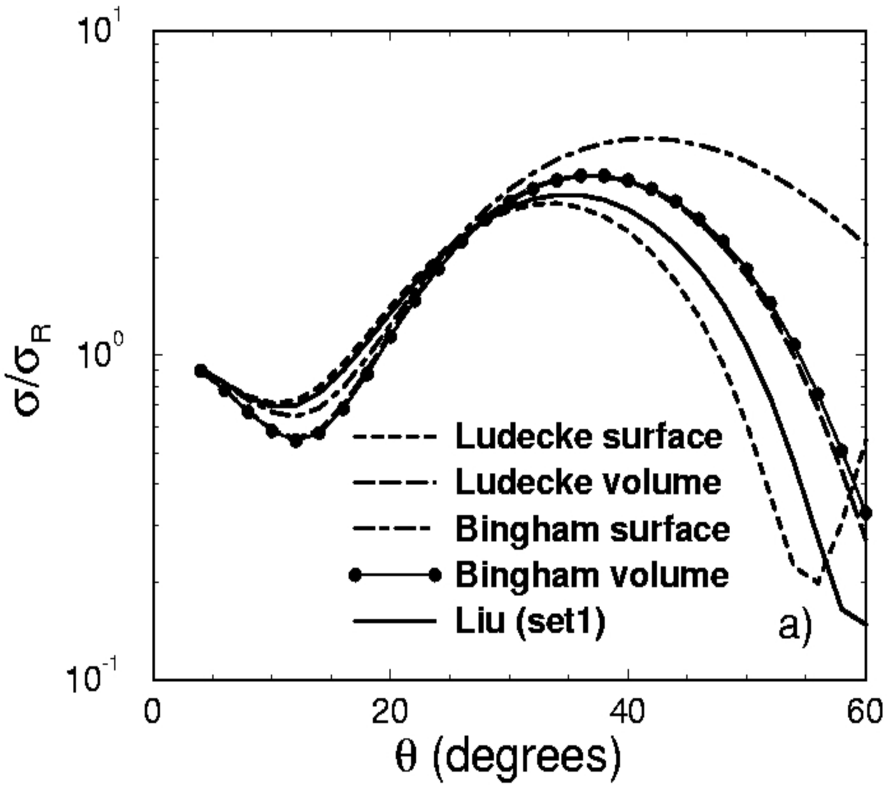
Effect of different parameters for the bound state of ^{8}B

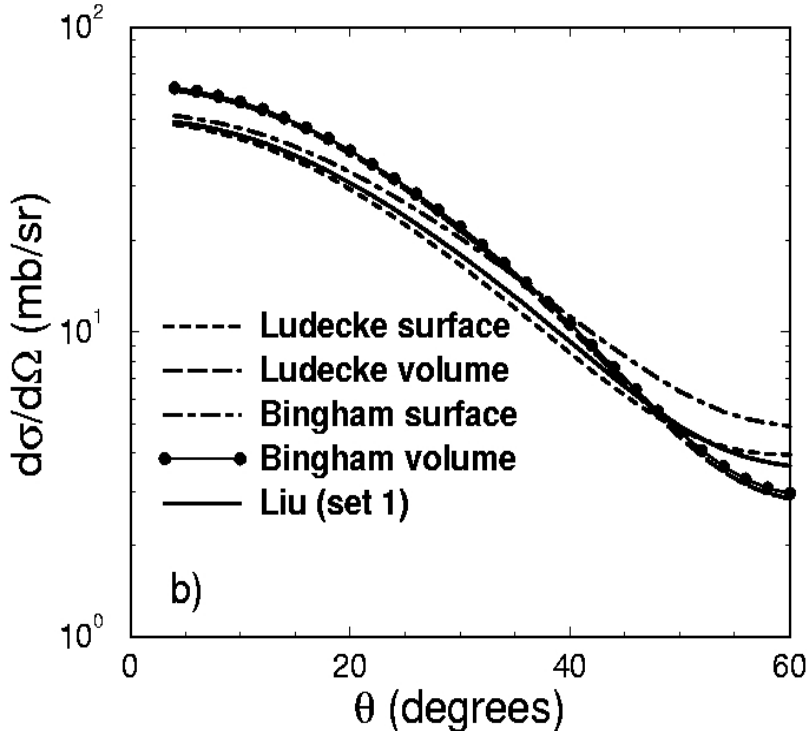
$^{7}Be(d,n)^{8}B$ $E_{cm} = 5.8$ MeV



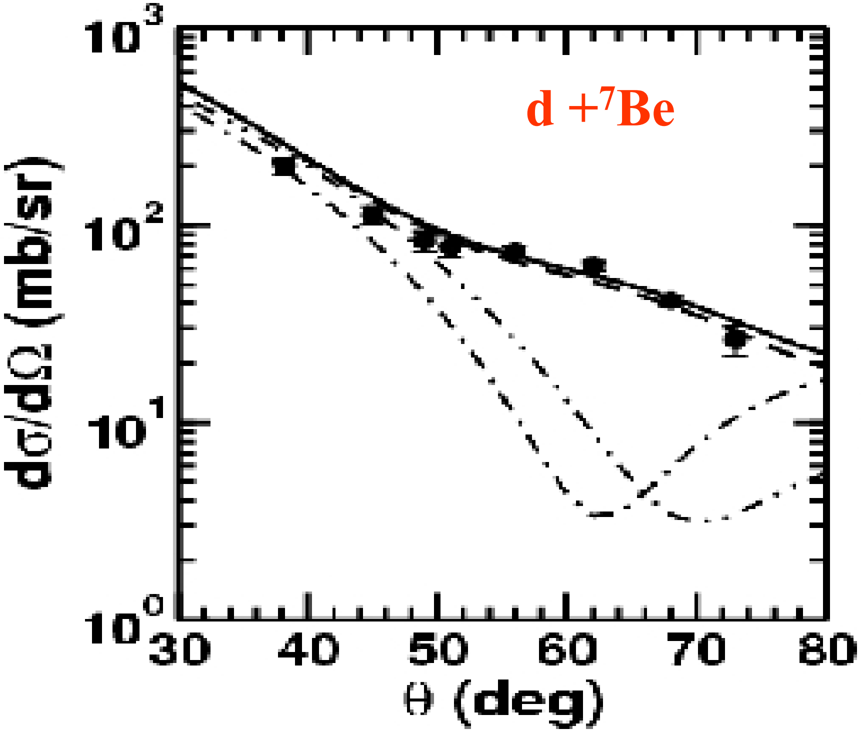
Effect of different Optical model parameters for d + ^{7}Be

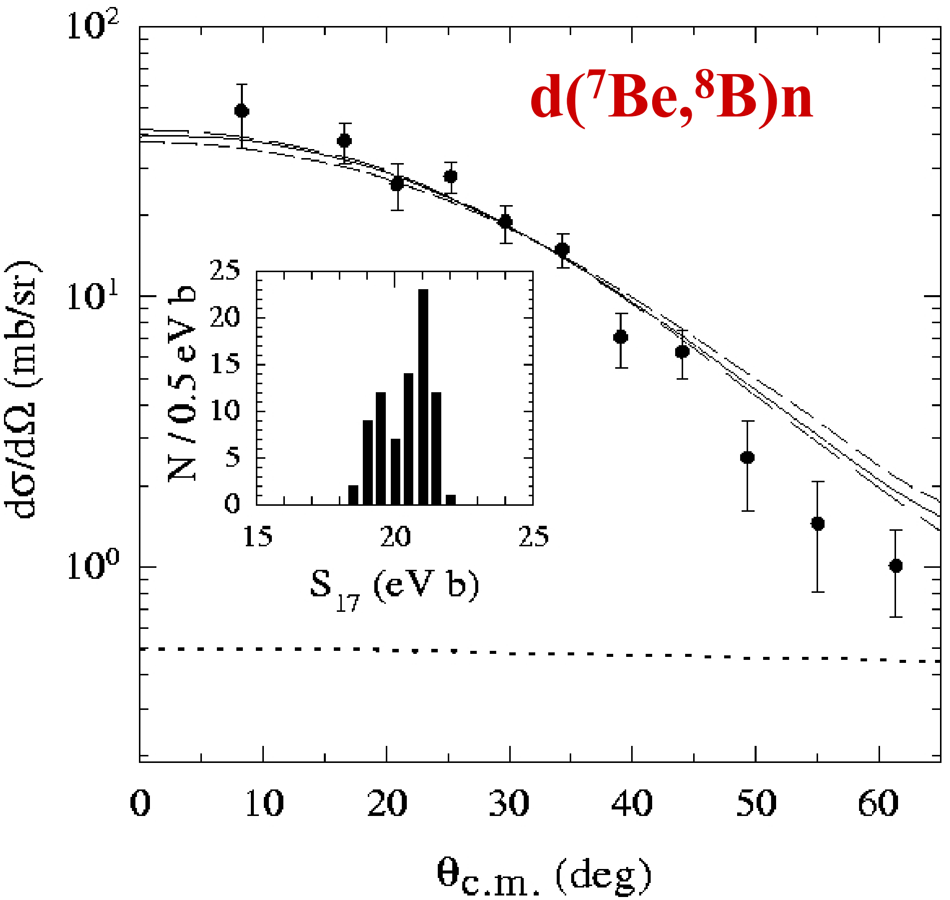
d + ^{7}Be **Ecm = 5.8 MeV** **^{7}Be (d,n) ^{8}B**





S-factor of p + ^{7}Be → ^{8}B + γ reaction via study of ^{7}Be (d,n) ^{8}B at Ecm = 4.4 MeV at IUAC (NSC), New Delhi





S_{17} = 20.7 ± 2.4 eV b,
J J Das et al., PRC (in press)

Values from Indirect and Direct methods are converging finally !!

Studies of $p + {}^7Be \rightarrow {}^8B + \gamma$ reaction from transfer reactions on heavier targets,

Texas A & M group, Tribble et al. PRC 60 (1999), PRL 82 (1999)

$^{10}B(^7Be,^8B)^9Be$, $^{14}N(^7Be,^8B)^{13}C$ transfer reactions with ^7Be beam

Elastic scattering cross section for the $^{10}B + {}^7Be$ and $^{14}N + {}^7Be$ were also measured

Peripheral nature of transfer process confirmed, but final channel OMP are uncertain

ANC approximation was used for both ($^7Be,^8B$) and (A,B) vertices.

$S_{17} = 16.6 \pm 1.9$ *eV b*, $S_{17} = 17.8 \pm 2.8$ *eV b*

ANC from Nuclear Structure Calculations

$$I_{ba}[r] = \int d\xi\ \phi_b^*(\xi,r)\,\phi_a(\xi) \Rightarrow f_{\lambda j}\, Y_{\lambda m}(\Omega_r)$$

Calculate ϕ_b and ϕ_a within some nuclear structure model

Mean field model like HF

Translational Invariance
Correct asymptotic form

Calculate σ (E) and S_{pA}

$$I_{ba}[r] = C_{\lambda j} W_{\lambda+1/2}(2kr)/r \Rightarrow S_{pA} = K \sum C_{\lambda j}^{2}$$

$S_{17} = 22.0$ *ev b*, **Chandel, Dhiman, Shyam, PRC 68 (2003) 054320**