LECTURE - 2

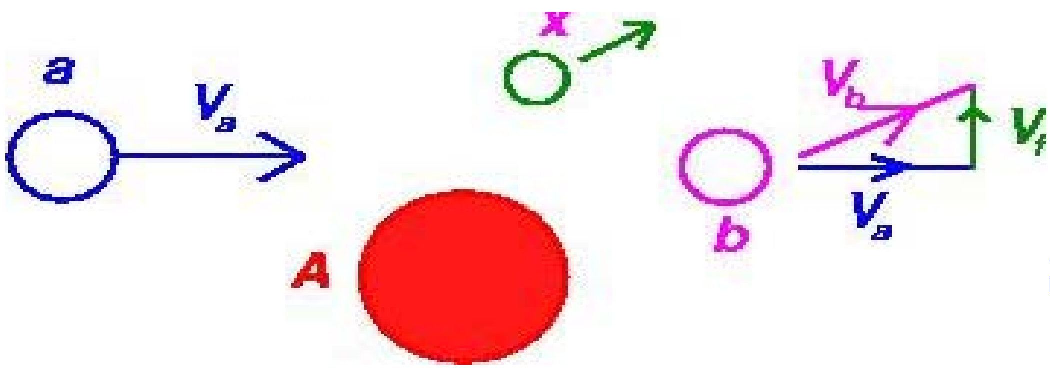
A Reminder of the Relevant Nuclear Reaction Theory

Breakup reactions: $a + A \rightarrow b + c + A$ **at least a 3-body problem**

Two modes of breakup

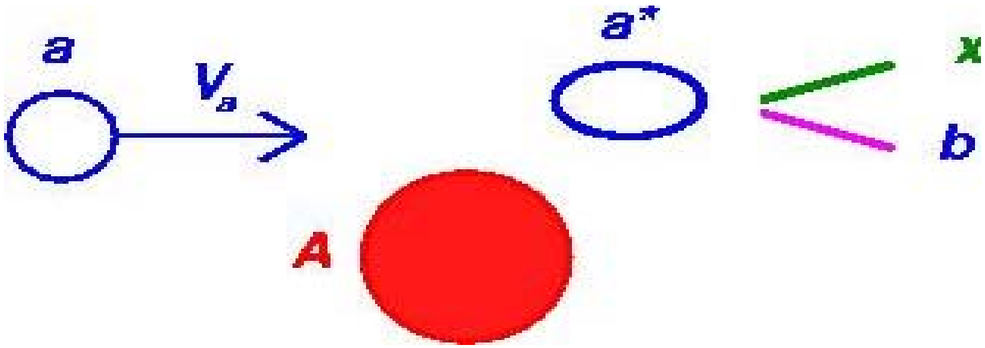
- **Elastic breakup (A remains in the g.s.)**
- **Inelastic breakup (c + A can go to c + C)**

Mechanism of breakup reactions (Elastic Breakup)



Spectator participant picture

$$T_{fi}^{(+)}(DWBA) = \langle \chi^{(-)}(q_c, r_{cA})\chi^{(-)}(q_b, r_{bA})|V_{bc}|\chi^{(+)}(q_a, r_{aA})\phi_a(r_b c) \rangle$$



Mechanism of Breakup reactions

Sequential Breakup picture

Different approximation for the Final state

$$T_{fi}^{(-)}(DWBA) = \langle \chi^{(-)}(Q_f, r_{aA})\phi^{(-)}(q_f, r_{bx}) | V_{xA}+V_{bA} | \phi_a(r_{bx})\chi^{(+)}(q_a, r_{aA})\rangle$$

Numerical computations are relatively simpler

More suitable for astrophysically interesting radiative fusion reactions.

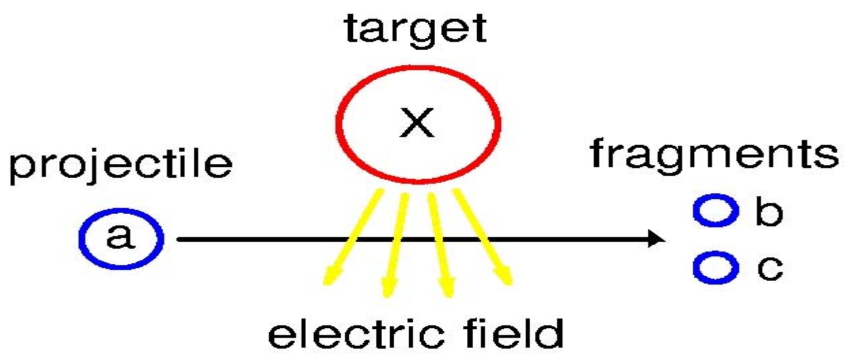
No nuclear interactions ⇒ Coulomb excitation of the projectile *a*

⇓

Semi-classical counterpart ⇒ Alder-Winther theory of Coulomb Excitation

CDCC method ⇒ relative and cm motion of the fragments are not independent

Theory of Coulomb dissociation as applied to radiative fusion



Radiative capture cross sections are related to photo-disintegration

$$\sigma(a + \gamma \rightarrow b + c) = [(2j_b + 1)(2j_c + 1) / 2(2j_a + 1)]\ (k_{CM}^2 / k_\gamma^2)\ \sigma(b + c \rightarrow a + \gamma)$$

$$\sigma(b + c \rightarrow a + \gamma) = S(E)\ E \exp(-2\pi\eta)$$

$$\sigma(a + \gamma \rightarrow b + c) = [(2j_b + 1)(2j_c + 1) / 2(2j_a + 1)]\ (k_{CM}^2 / k_\gamma^2)\ S(E)\ E \exp(-2\pi\eta)$$

Theory of Coulomb dissociation as applied to radiative fusion

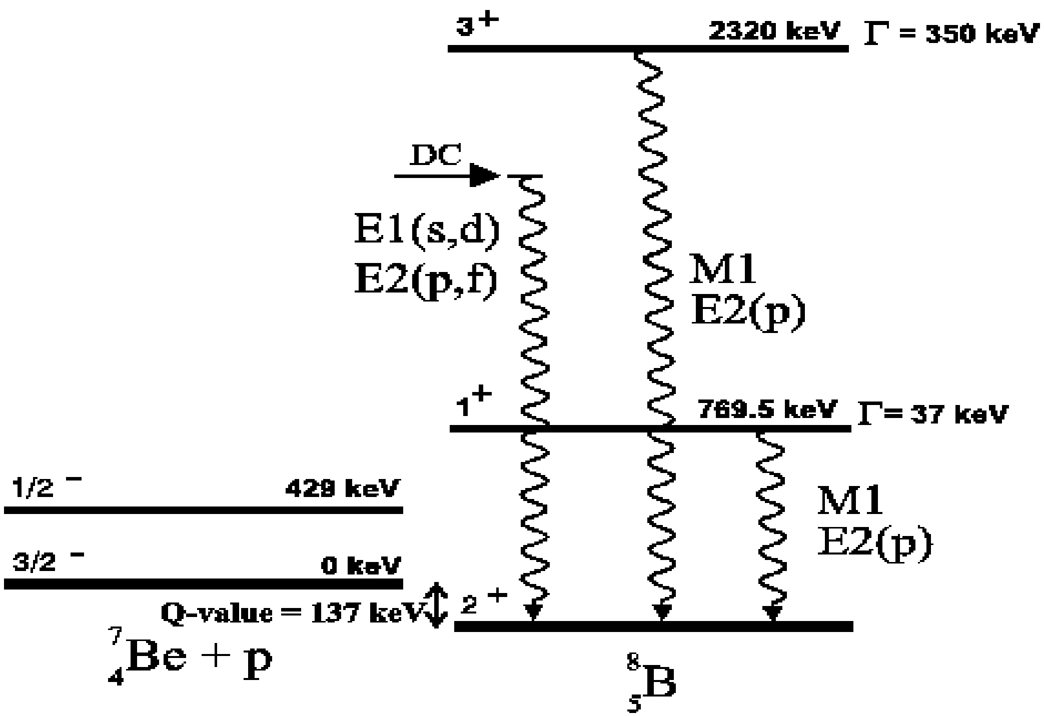
Cross section for Coulomb excitation

$$d^2\sigma/d\Omega\, dE\gamma = \Sigma_\lambda\, (1/E\gamma)\, (dn_{\pi\lambda}/d\Omega)\, \sigma(a + \gamma \rightarrow b + c)$$

$\pi \rightarrow$ E or M

$\lambda \rightarrow 1,2,\ldots.$

$$= \Sigma\lambda\, (1/E\gamma)\, (dn_{\pi\lambda}/d\Omega)\, [(2j_b + 1)(2j_c + 1) / 2(2j_a + 1)]\, (k_{CM}^2 / k_\gamma^2)\, S(E)/E\, \exp(-2\pi\eta)$$



$(dn_{\pi\lambda}/d\Omega)$ = equivalent photon number, purely kinematical quantity

$d^2\sigma/d\Omega\, dE\gamma = \Sigma\lambda\ (1/E\gamma)\ (dn_{\pi\lambda}/d\Omega)$ (phase space factors) $S(E)/E\ \exp(-2\pi\eta)$

↓

Measured CE cross section

S(E) can be extracted from the measured Coulomb excitation cross sections if

Projectile excitation is dominated by single multipolarity

Application of the first order theory is of sufficient accuracy

The point like projectile approximation is valid (we may have nuclei with large R)

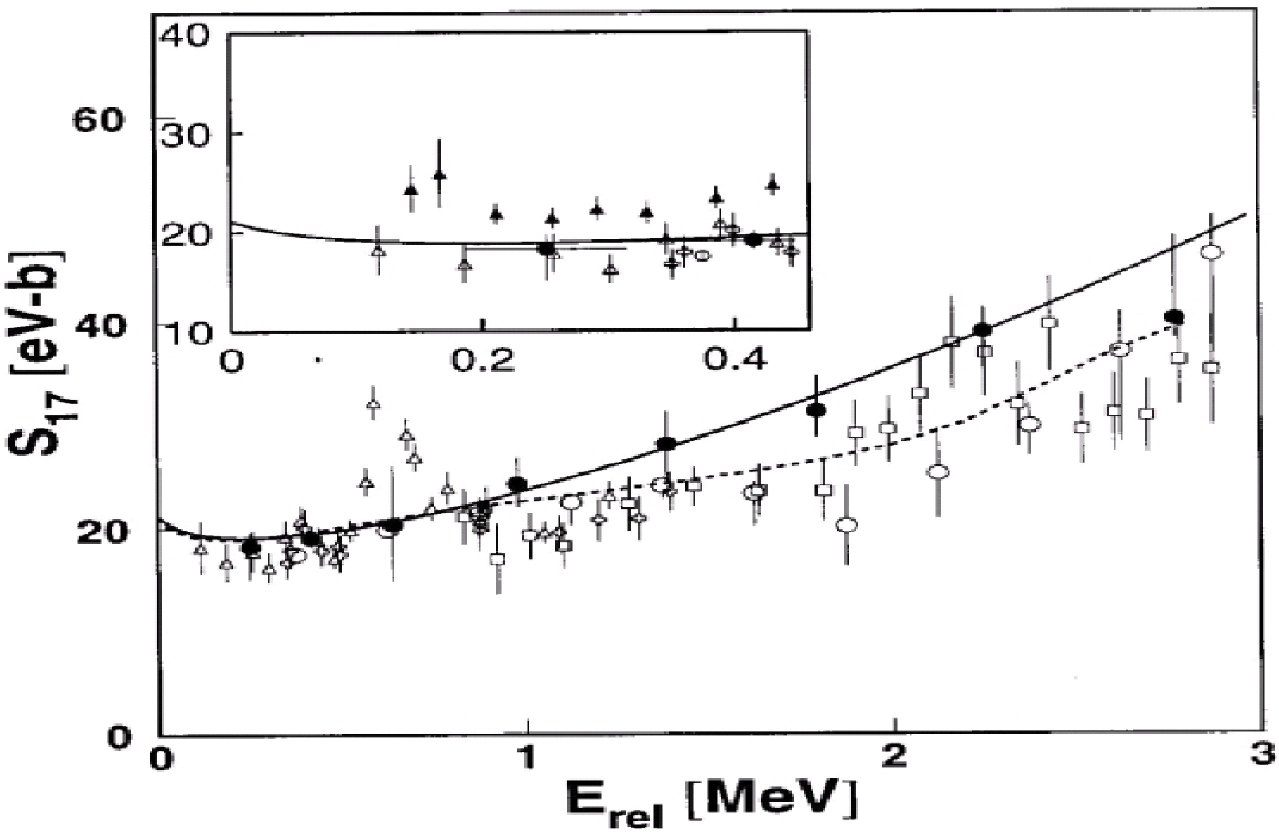
Influence of the strong nuclear field on the excitation process is negligible

Check by performing full quantal calculations

Applications of the Coulomb Dissociation Method

Radiative fusion reaction: $p + {}^7Be \rightarrow {}^8B + \gamma$

Solar neutrino problem. Determines absolute values of the calculated ${}^8B$ ν flux.



WORLD DATA

Hammache et al. PRL 80 (1998) — $p + {}^7Be$ $S_{17} = 18.5 \pm 2.4$ eV b 118 -186 keV

A.R. Junghans et al. PRL 88 (2003) — $p + {}^7Be$ $S_{17} = 22.3 \pm 1.2$ eV b 186-1200 keV

L.T. Baby et al. PRL 90 (2003) — $p + {}^7Be$ $S_{17} = 21.2 \pm 0.7$ eV b 302-1078 keV

"^{8}B plays a crucial role in the interpretation of SNO experiments. Unfortunately the predicted value of ^{8}B flux normalization is quite uncertain, mainly due to the poorly known nuclear cross sections at low energies.",
V. Bargerner, D. Marfatia and K. Whisnant, PRL 88 (2002).

Improved (^{8}B) production rate predictions are very important for limiting the allowed neutrino mixing parameters. The astrophyical S factor for this reaction must be known to ± 5% in order that this uncertainty not To the dominant error in prediction of the Solar electron ν flux.

Home page of late John Bahcall, http:/www.sns.ias.edu/~jnb/

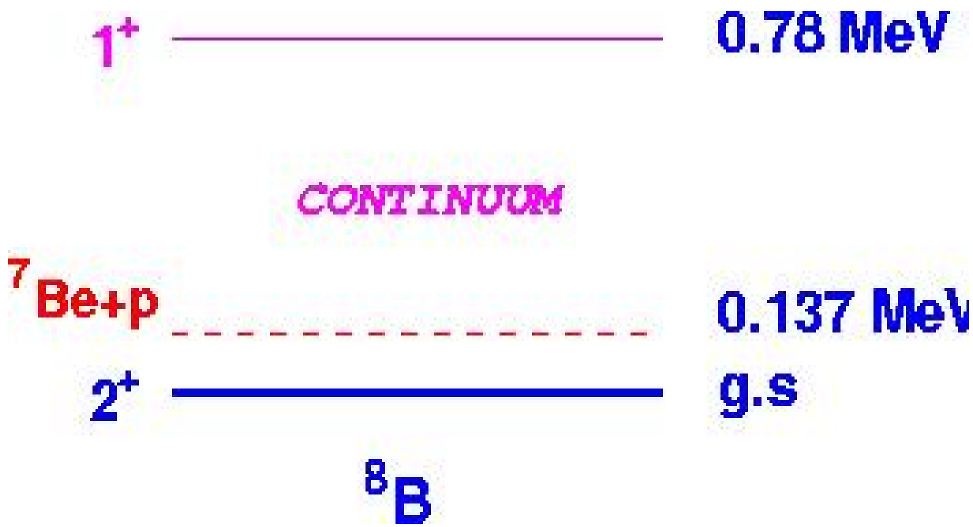
Coulomb Dissociation of ^{8}B

Determine the rate of the reaction $p + {}^{7}Be \rightarrow {}^{8}B + \gamma$ from the Coulomb dissociation of ^{8}B on a heavy target.

$$^{8}B + {}^{208}Pb \rightarrow {}^{8}B^{*} + {}^{208}Pb$$

] $p + {}^{7}Be$

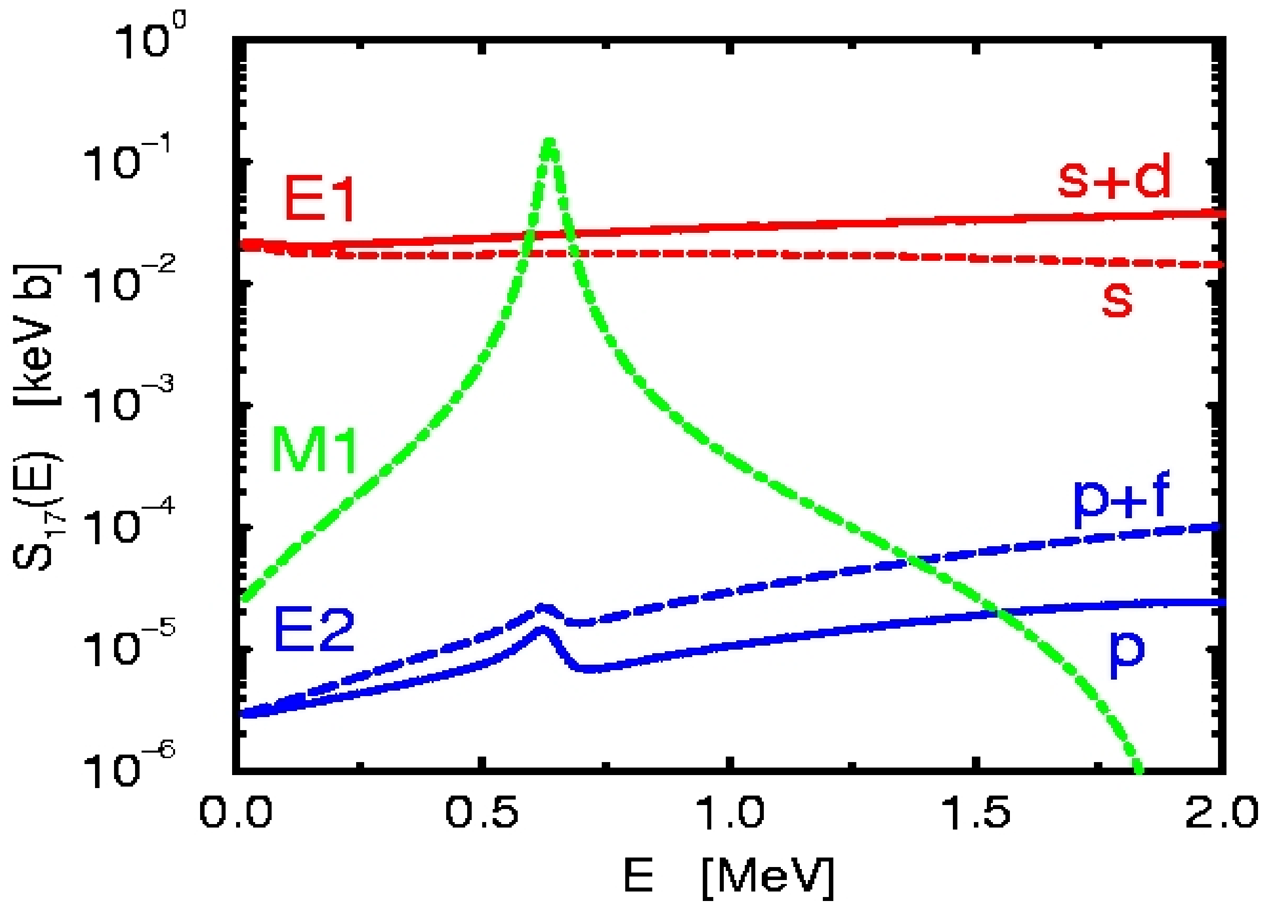
In the Coulomb excitation of ^{8}B, E1, E2, and M1 multipoles can contribute.



^{8}B may have an extended size. QM calculations.

Nuclear interactions effects

Direct Capture Cross sections for $p + {}^{7}Be \rightarrow {}^{8}B + \gamma$
E1 multipolarity dominates

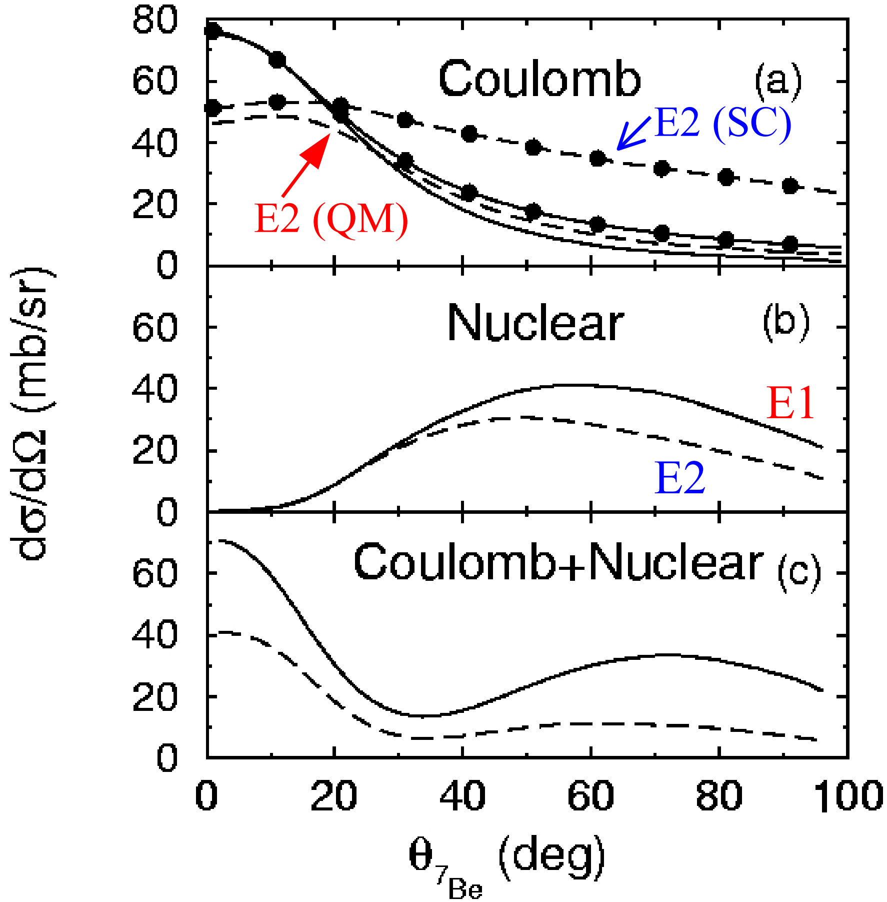


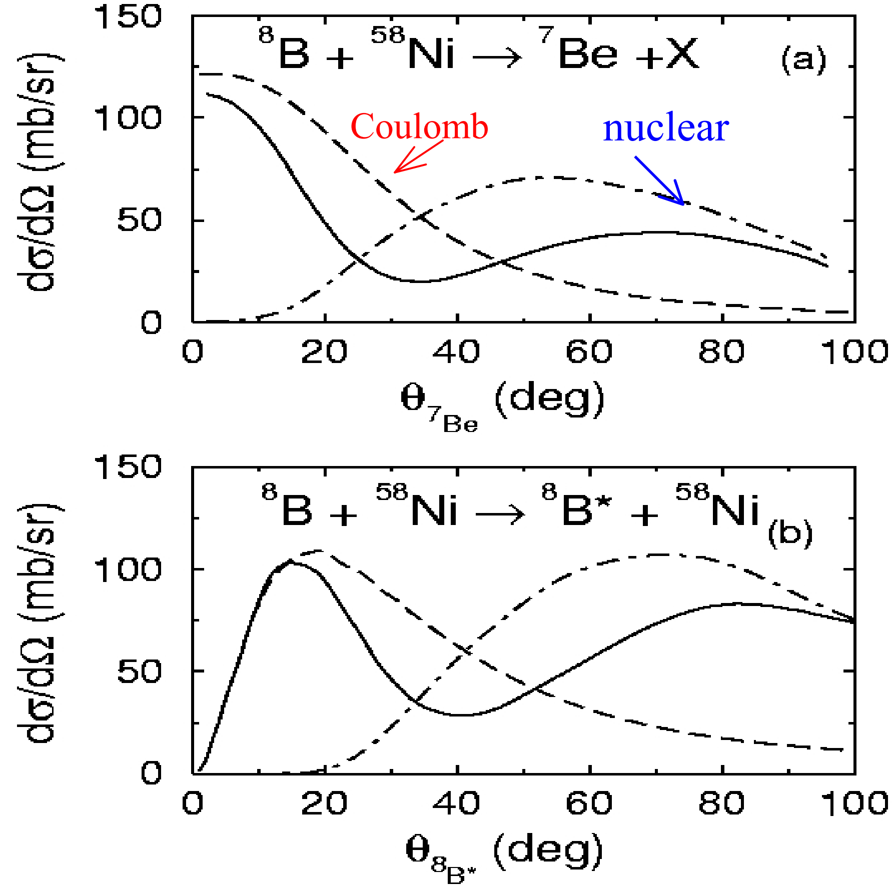
Coulomb Dissociation of ^{8}B

Shyam, Thompson, PRC 59(1999)

Experiment – I: University of Notre Dame, J von Schwarzenberg, PRC53 (1996)

Reaction: $^{8}B + ^{58}Ni \rightarrow ^{7}Be + ^{58}Ni$ **E = 25.8 MeV**





Semiclassical approximation is not valid for $\geq 20^{0}$

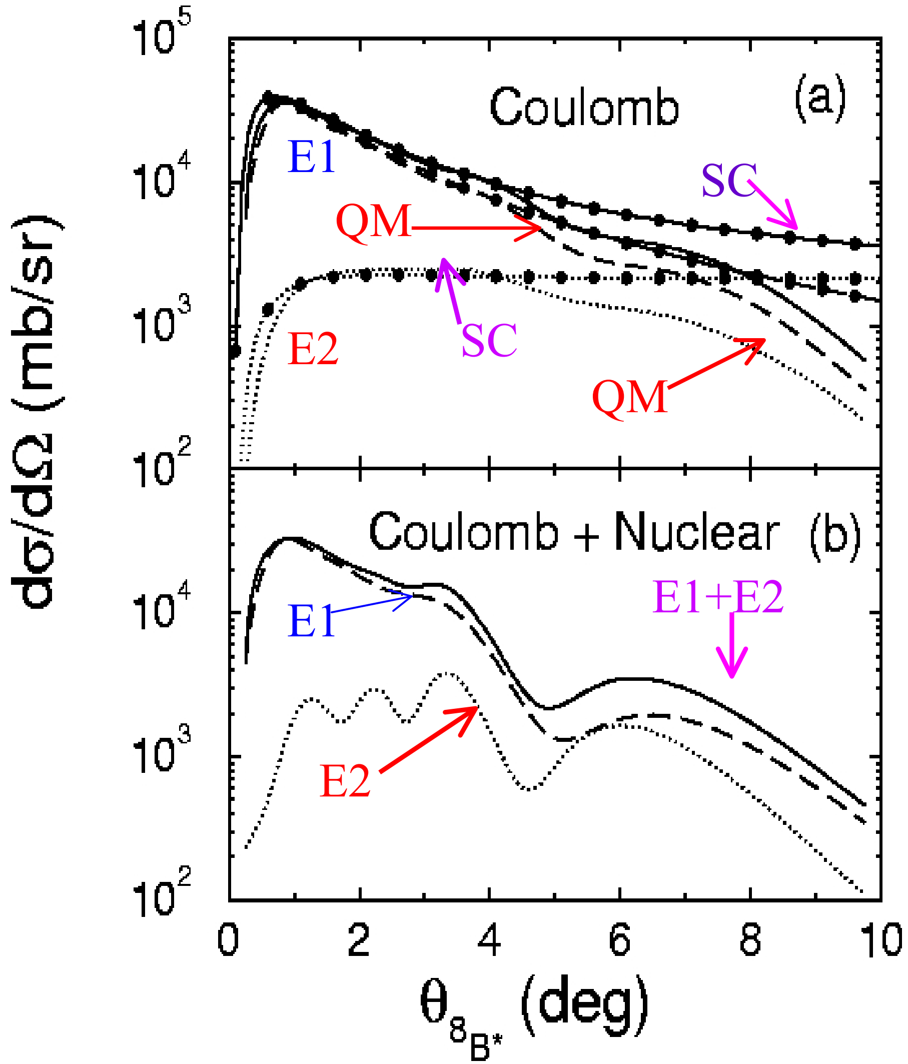
E2 and nuclear breakup Effects are quite large

Angular distributions of ^{7}Be and $^{8}B^{*}$ are not the same

Coulomb Dissociation of ^{8}B

Experiment –II: RIKEN, Japan, T. Kikuchi et al., Phys. Lett B391(1997)

Reaction: $^{8}B + ^{208}Pb \rightarrow ^{8}B^{*}$ (^{7}Be-p) + ^{208}Pb, E = 51.2 MeV/nucleon



For $\theta_{8B^*} \leq 4$ deg, conditions for the applicability of the CD method are satisfied.

E1 mulipolarity dominates
E2 and nuclear excitation effects are negligible.
Semiclassical approximation is valid.

Data in this regime can be used for the extraction of S-factor using the SC theory.

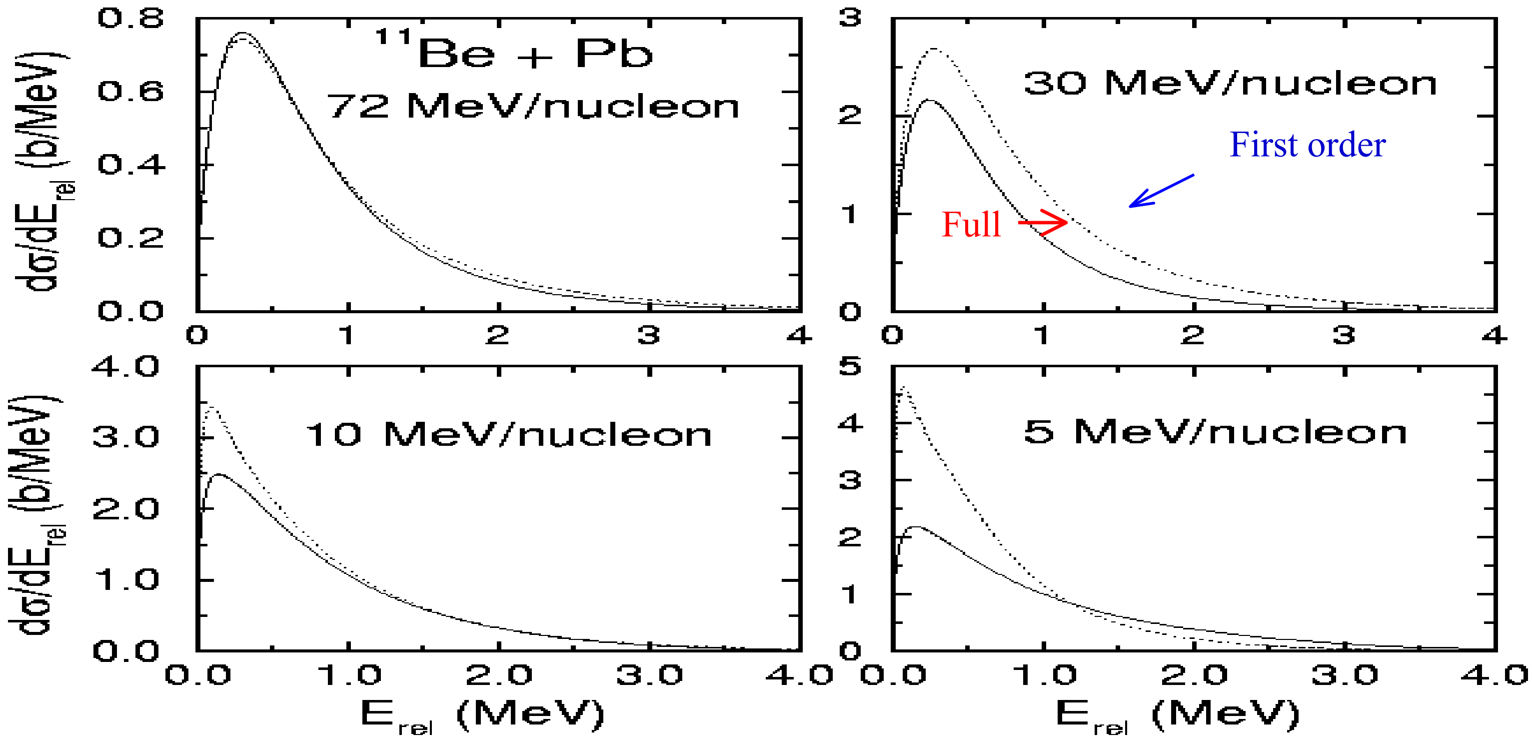
Shyam, Thompson, PRC 59 (1999)
Banerjee, Shyam, PRC 62 (2000)

Role of the Postacceleration Effects

In a reaction $a + A \rightarrow b + c + A$, $Z_b \neq Z_c$ then $E_b \geq E_b$ (allowed by the mass ratio).

Affects the rel. energy spectrum of the fragments.

This Effect is not included in the first order theory.

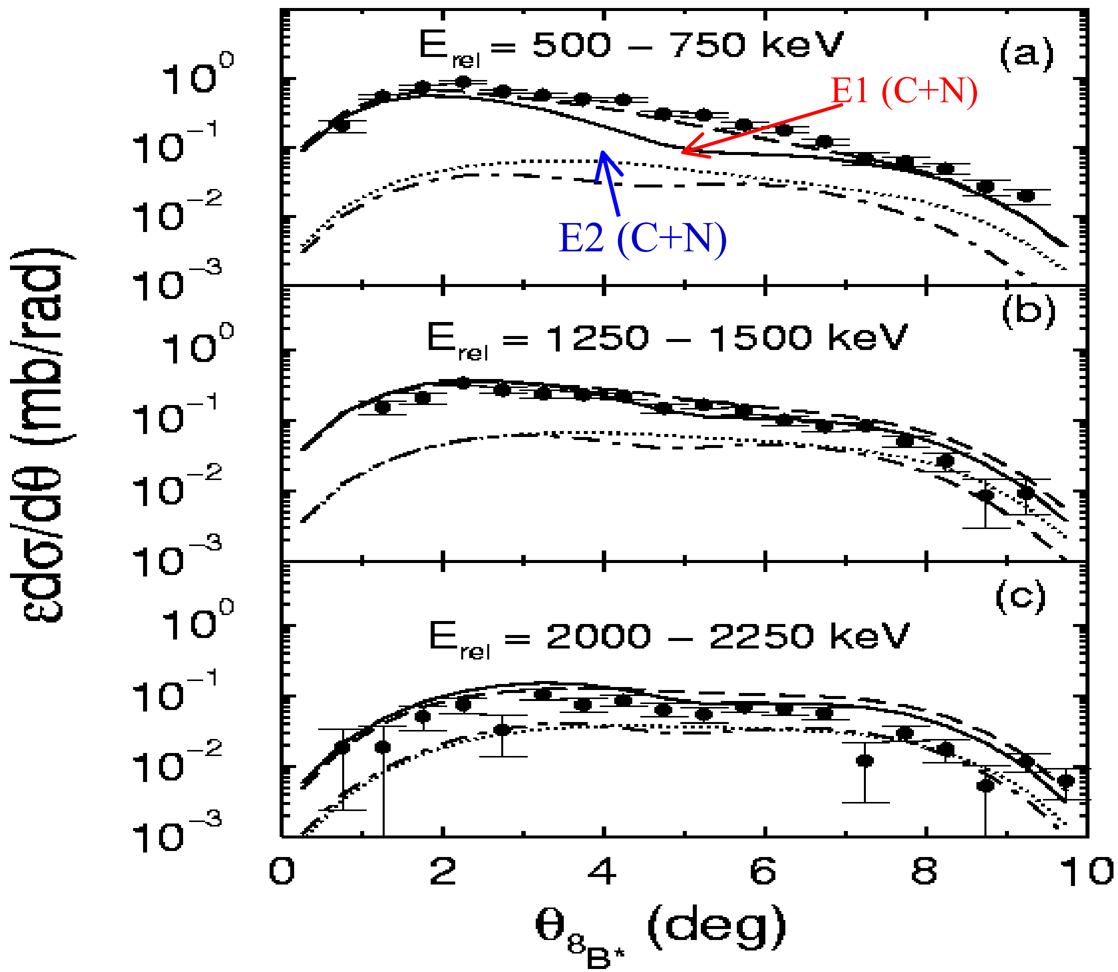


Postacceleration effects not important at higher Beam Energies.

Banerjee et al., PRC 65 (2003)

Extraction of S_{17} factor

$^{8}B + {}^{208}Pb \rightarrow {}^{8}B^{*}\ ({}^{7}Be\text{-}p) + {}^{208}Pb$, E = 51.2 MeV/nucleon



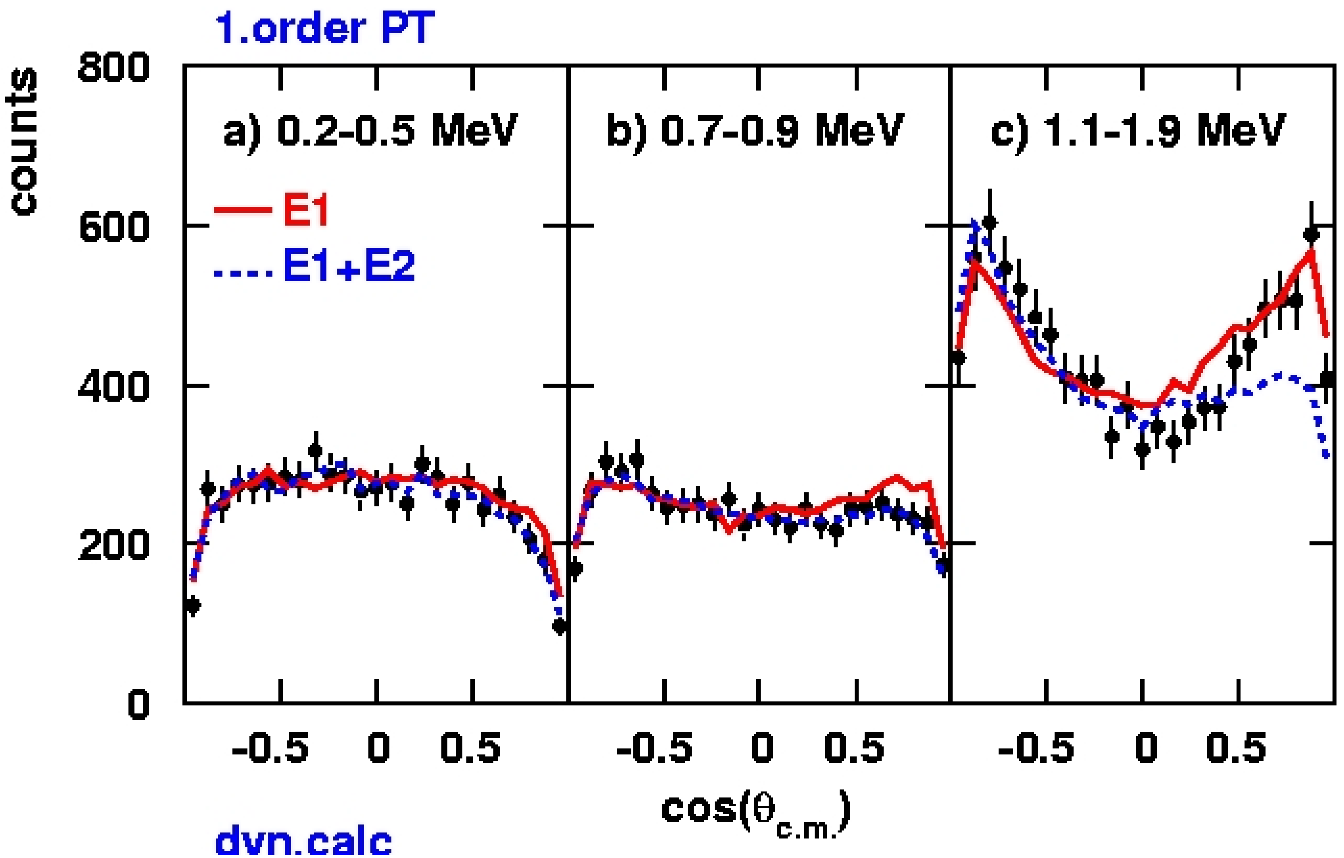
E_{rel} = 500-750 keV is suitable for the application of the CD method

S_{17} = 18.2 eV b

Coulomb Dissociation of ^{8}B

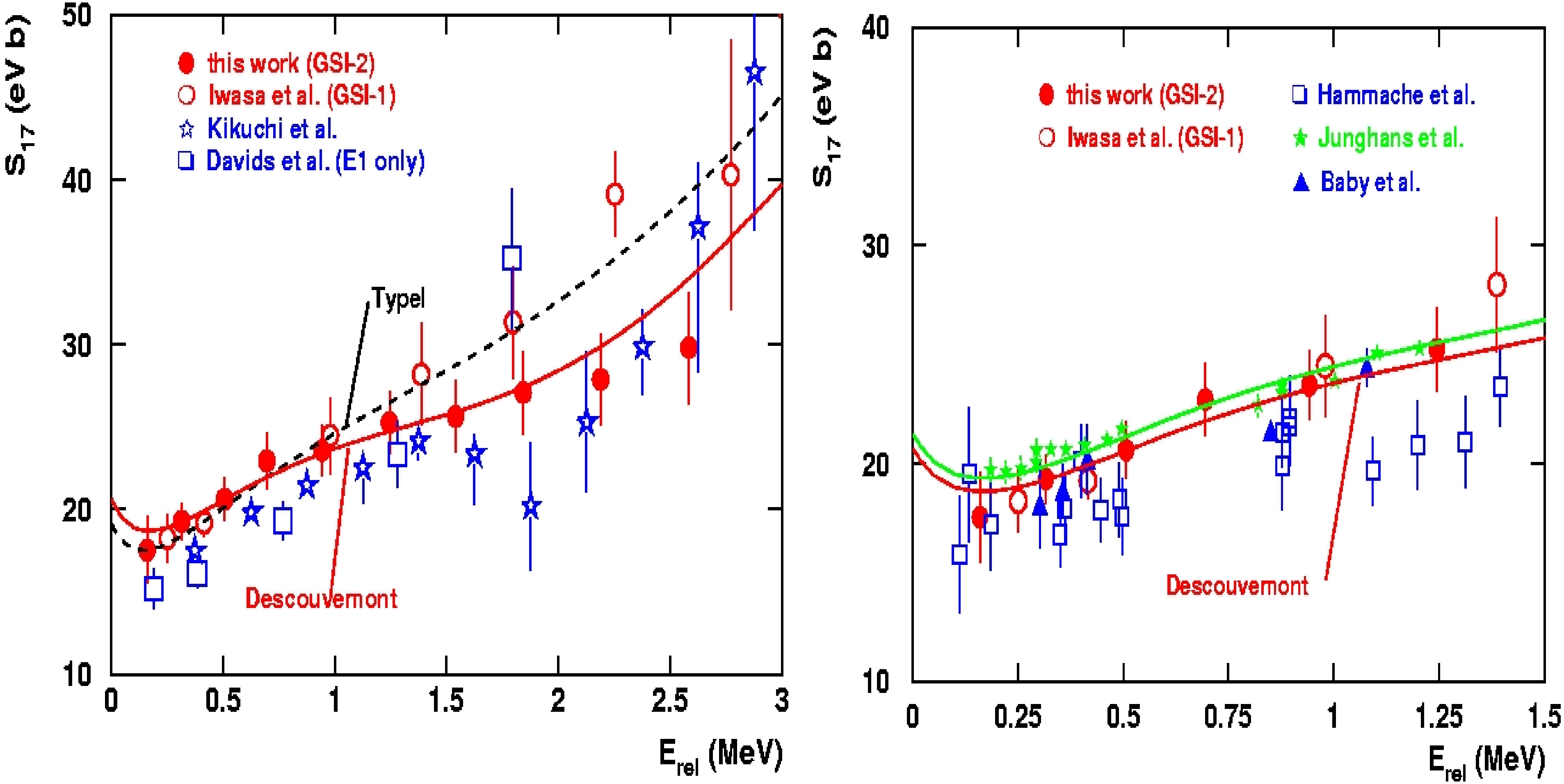
Experiment –III: GSI, Germany, , F. Schuemann PRL 90 (2003), PRC (2006)

Reaction: $^{8}B + ^{208}Pb \rightarrow ^{8}B^{*}\ (^{7}Be\text{-}p) + ^{208}Pb$, E ; 250 MeV/nucleon



S_{17} = 20.6 ± 2.0 eV b

Comparison of Results



Latest CD S_{17} results are in good agreement with those obtained in the direct (p,γ) measurements by Junghans et al.

Also slopes of the CD and direct capture measurements are in agreement

Other Applications of the Coulomb Dissociation Method

- **Coulomb dissociation of ^{9}Li for determining the rate of the ^{8}Li (n,γ) ^{9}Li reaction**

After the production of ^{7}Li (big bang nucleosynthesis) the synthesis of ^{12}C follows the chain

$$^{7}\mathrm{Li}\ (n,\gamma)\ ^{8}\mathrm{Li}\ (\alpha,n)\ ^{11}\mathrm{B}(n,\gamma)\ ^{12}\mathrm{B}\ (\beta^{-})\ ^{12}\mathrm{C}$$

$$\downarrow$$

$$^{8}\mathrm{Li}\ (n,\gamma)\ ^{9}\mathrm{Li}\ (\beta^{-},\nu)\ ^{9}\mathrm{Be}\ (p,\alpha)\ ^{6}\mathrm{Li} \quad \Rightarrow$$ **Reaction flows back to lighter elements**

Preliminary study at Michigan State University, but detailed work is needed.

• **Coulomb dissociation of ^{15}C for determining the rate of the ^{14}C (n,γ) ^{15}C reaction**

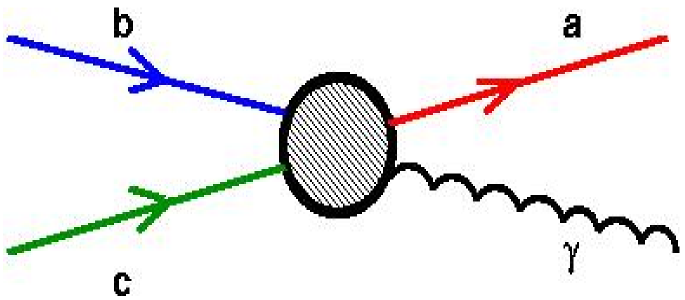
Neutrons produced in the burning zone of the 1.3M AGB stars by the ^{13}C(α, n) reaction can drive a CNO cycle in which an α particle is synthesized from neutrons

^{14}C (n,γ) ^{15}C (β^-) ^{15}N(n,γ) ^{16}N (β^-) ^{16}O (n,α) ^{14}C $\Rightarrow$ Controlling reaction is ^{14}C(n,γ) ^{15}C

• **Coulomb dissociation of ^{23}Al to study the stellar reaction ^{22}Mg (p,γ) ^{23}Al**

T. Gomi et al. Nucl. Phys. A758 (2005), and planned at GSI, Darmstadt

THE ANC METHOD



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

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

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

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

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

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

At low energies $\psi_i(r_{bc})$ is given by Coulomb wave functions. So if the reaction is peripheral then the capture cross section is determined solely By the asymptotic normalization constant $C_{\lambda j.} \Rightarrow$ ANC

Methods for the determination of ANC

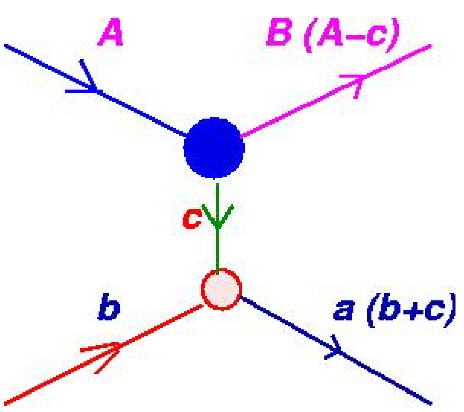
•Single particle potential model for a (b+c)

Assume b+c are bound together by a potential having a Woods-Saxon form. Its depth is adjusted to reproduce the properties of the bound state.

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

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

$S_{\lambda j}^{1/2}$ ⇓ Spectroscopic factor; $S_{\lambda j}^{1/2} b_{\lambda j}$ ↓ $C_{\lambda j}$



From the transfer reaction b (A,B) a

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

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

$$|I_{ba}|^2 = S_{\lambda j} |u_{\lambda j}|^2 = S_{\lambda j} b_{\lambda j} |W_{\lambda+1/2}|^2$$ If the transfer is peripheral

χ_s are the distorted waves in the initial and final channels

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

Applications to $p + {}^{7}Be \rightarrow {}^{8}B + \gamma$ Reaction

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

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

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

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

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

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