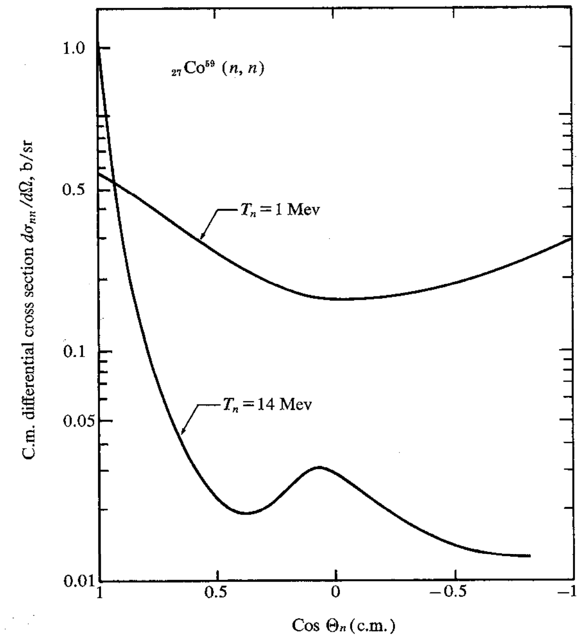
Direct Reactions

- Peripheral collision with surface nucleon.
- 1 MeV incident nucleon ▶ $\bar{\lambda} \approx$?? ▶ more likely to interact with the nucleus ▶ CN reaction.
- 20 MeV incident nucleon ▶ $\bar{\lambda} \approx$?? ▶ peripheral collision ▶ interaction with nucleons ▶ Direct reaction.
- CN and Direct (D) processes can happen at the same incident particle energy. Distinguished by:
  - ➢ D (10^{-22} s) CN (10^{-18}-10^{-16} s).

[Consider a 20 MeV deuteron on A=50 target nucleus].

  - ➢ Angular distribution.



Direct Reactions

- *(d,n)* stripping (transfer) reactions can go through both processes.
- *(d,p)* stripping (transfer) reactions prefer D rather than CN; protons do not easily evaporate (Coulomb). [*(p,d)* is a pickup reaction].
- What about *(α,n)* transfer reactions?

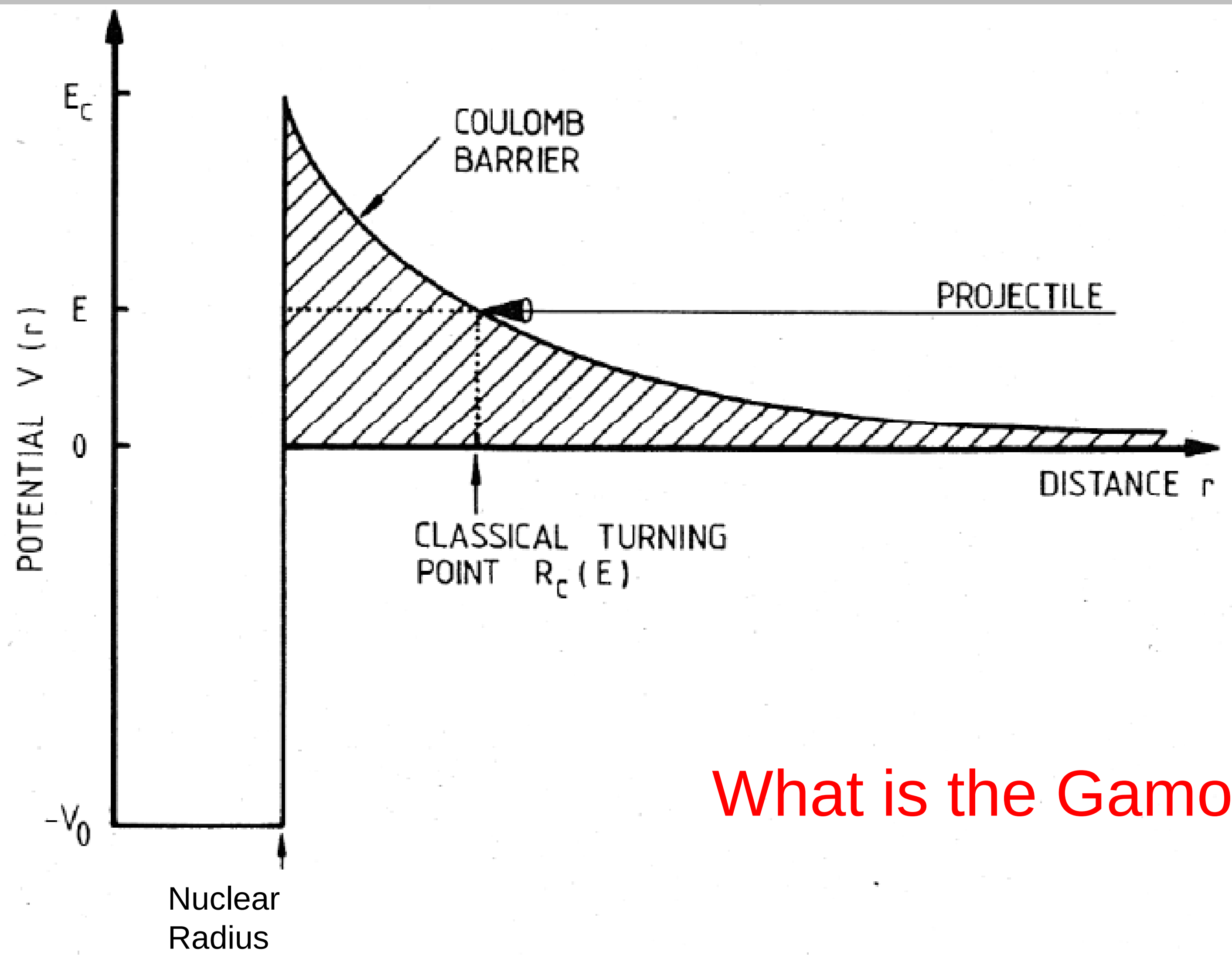
HW 15 Show that for a *(d,p)* reaction taking place on the surface of a ^{90}Zr nucleus, and with 5 MeV deuterons, the angular momentum transfer can be approximated by $l = 8\sin(\theta/2)$, where θ is the angle the outgoing proton makes with the incident deuteron direction. (Derive a general formula first).

$J^{\pi}(^{90}Zr_{gs}) = 0^{+}$ Fig. 11.23 in Krane.

$J(^{91}Zr) = l \pm ½$, $\pi = (-1)^{l}$

l	0	1	2	3
θ	0º	14.4º	29º	44º

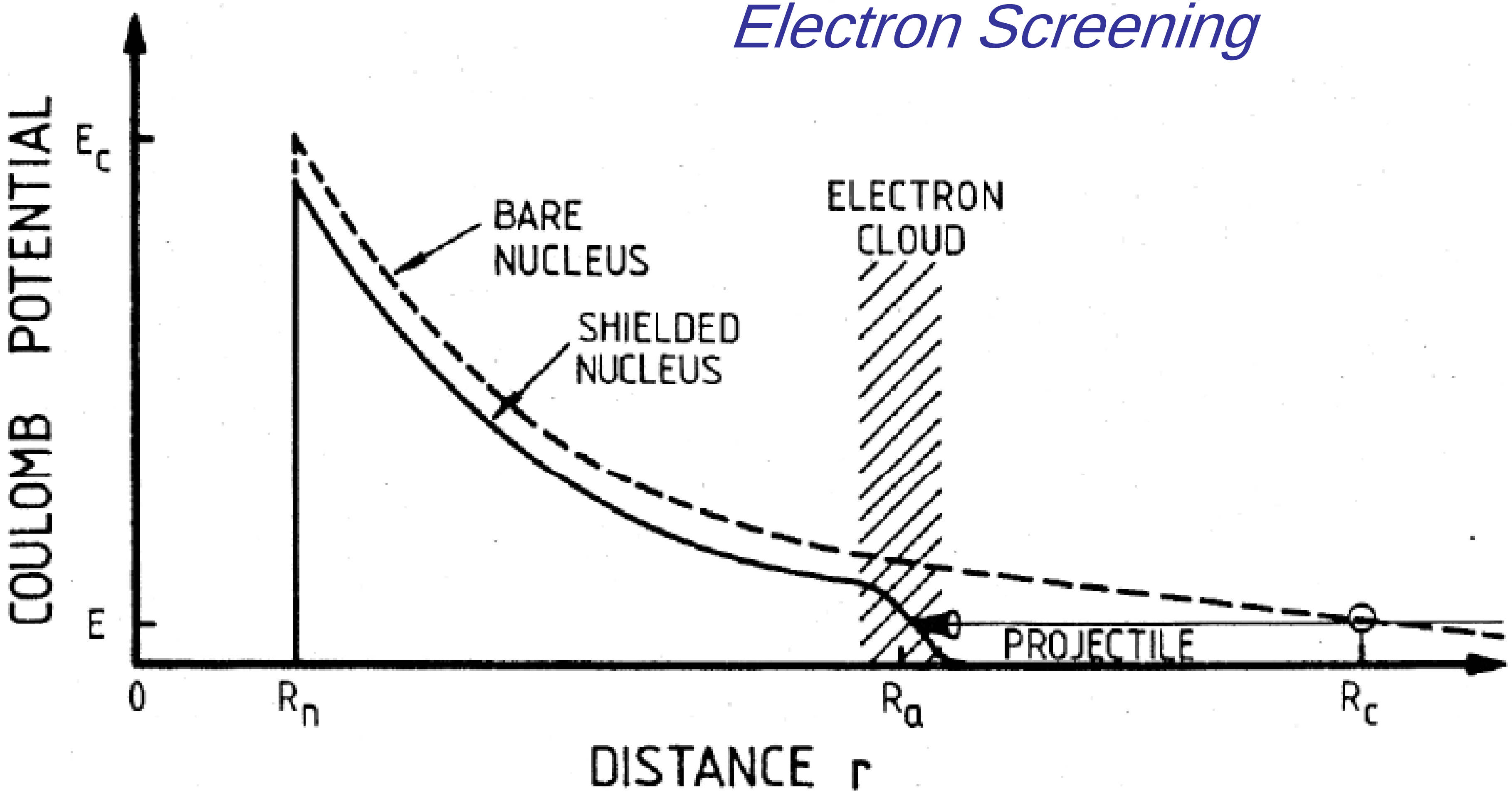
Charged Particle Reactions



What is the Gamow Peak?

Charged Particle Reactions

Electron Screening



Charged Particle Reactions

HW 16

e^2 = 1.44x10^{-12} keV.m

Tunneling probability: $P \cong e^{-2\pi\eta}$ (Gamow factor)

$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$ (Sommerfeld parameter)

In numerical units: $2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\frac{\mu(u)}{E^{CM}(keV)}}$

For γ-ray emission: $\Gamma_L(E_\gamma) = \alpha_L E_\gamma^{2L+1}$

$\Gamma_{Dipole}(E_\gamma) = \alpha_1 E_\gamma^3$

Multipolarity

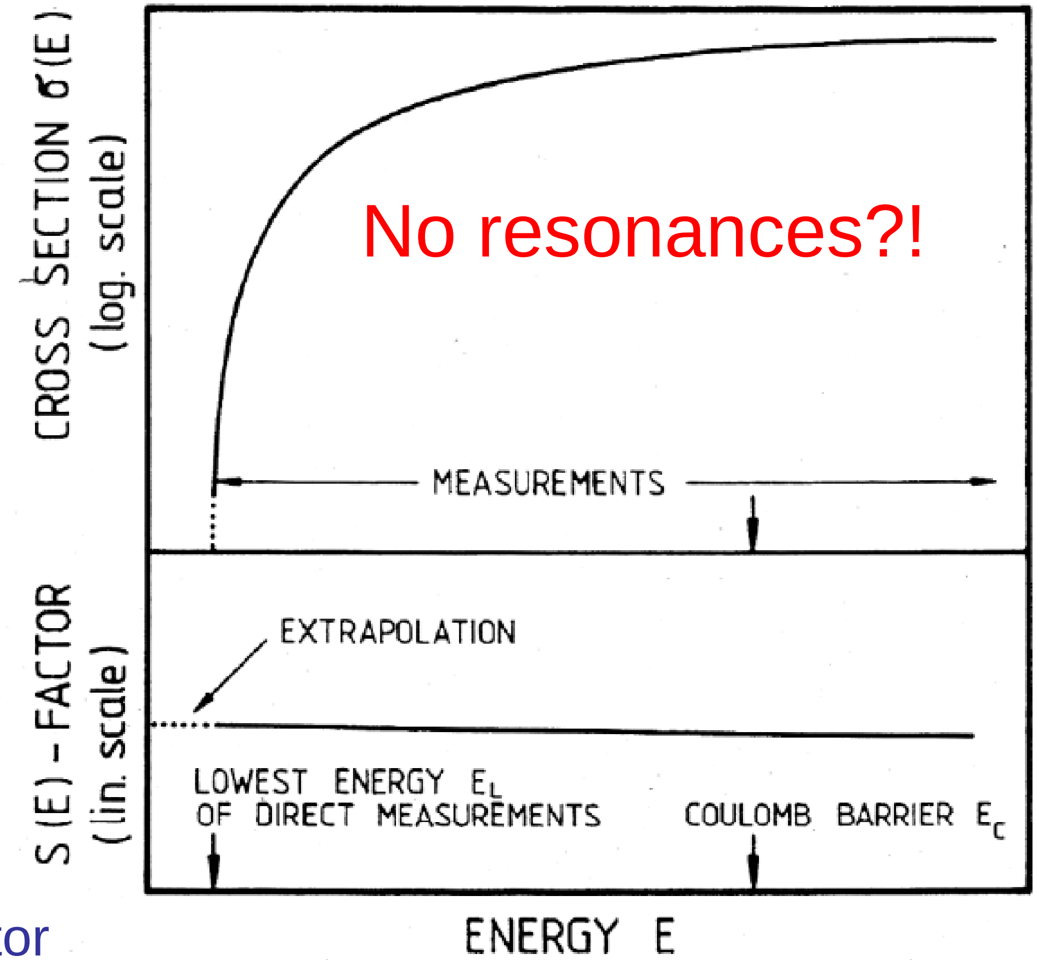
Charged Particle Reactions

$$\sigma(E) \propto e^{-2\pi\eta}$$

$$\sigma(E) \propto \pi\lambda\!\!\!^{-2} \propto \frac{1}{E}$$

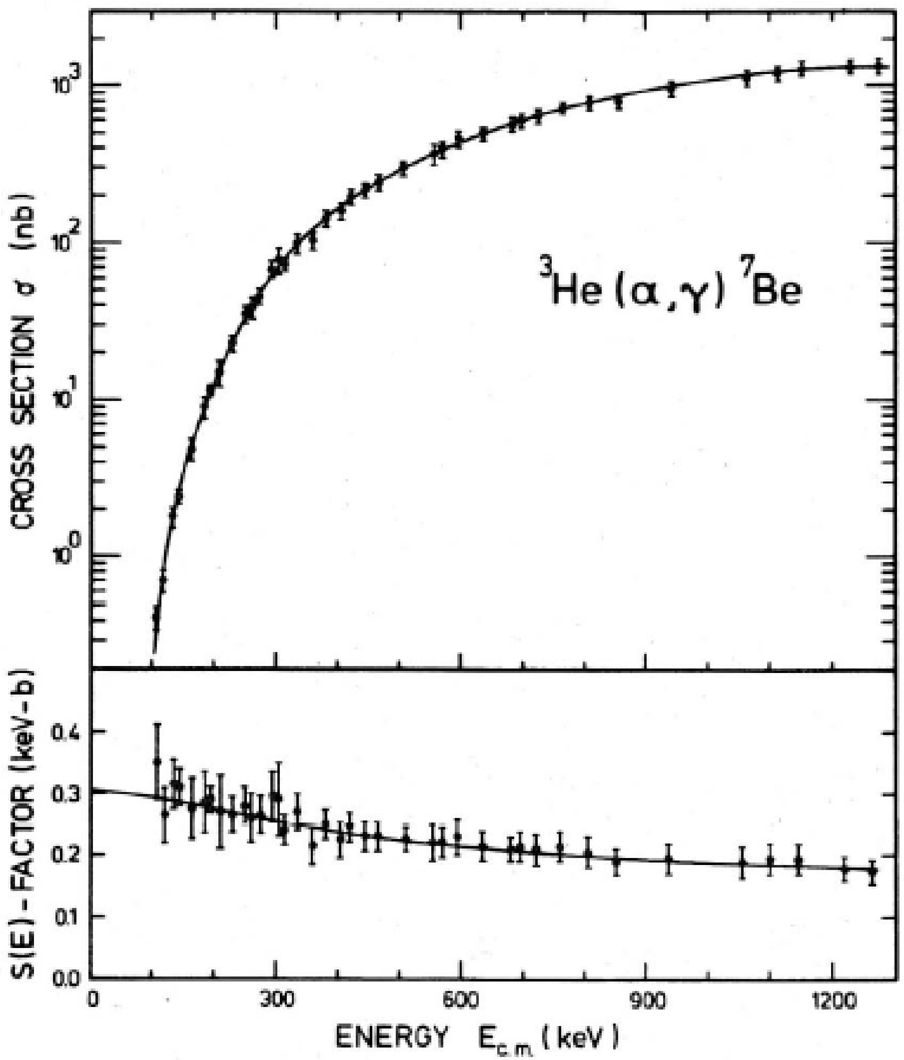
$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

Nuclear (or astrophysical) *S*-factor

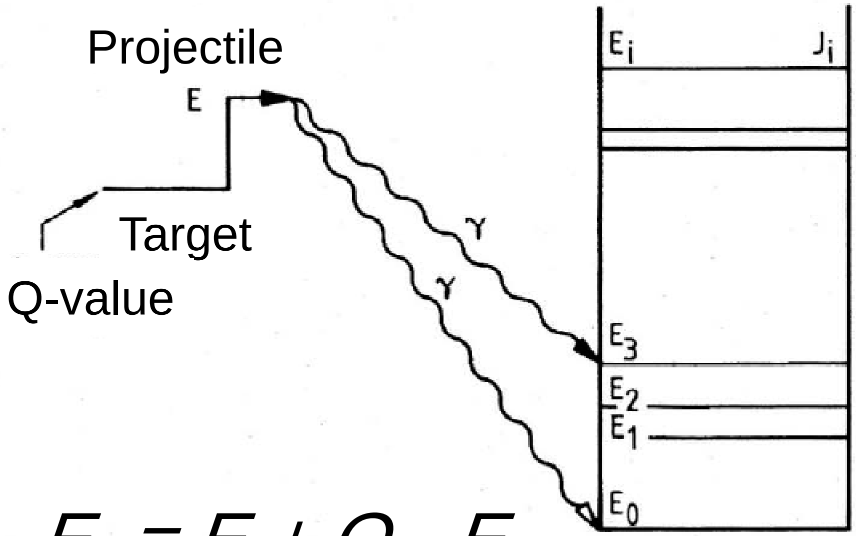


Charged Particle Reactions

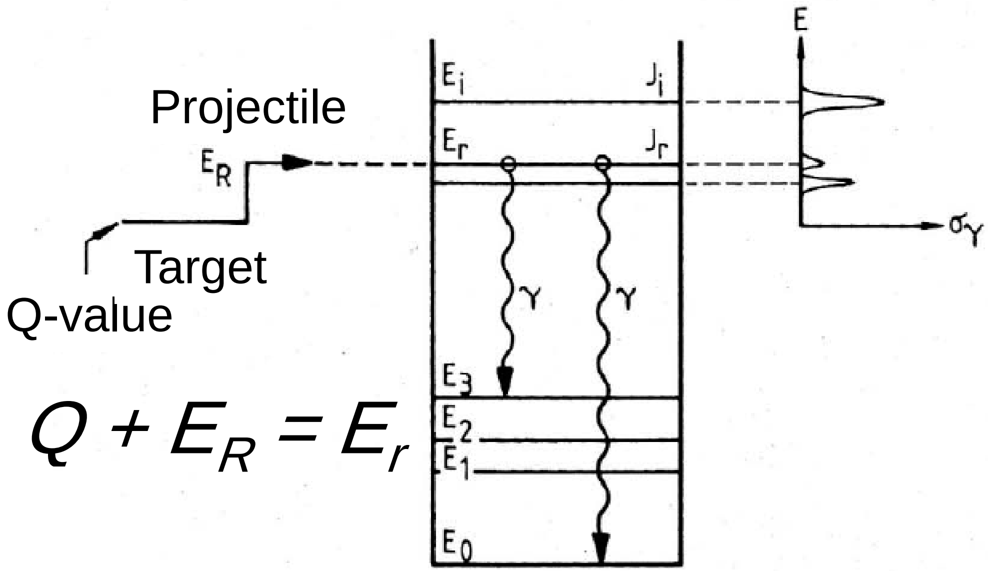
$E_C = ??$



Resonance Reactions



$$E_\gamma = E + Q - E_{ex}$$



$$Q + E_R = E_r$$

Non-resonant Capture
(all energies)

Resonant Capture
(selected energies with large X-section)

$$\sigma_\gamma \propto \left|\langle Y | H_\gamma | a + X \rangle\right|^2$$

$$\sigma_\gamma \propto \left|\langle E_f | H_\gamma | E_r \rangle\right|^2 \left|\langle E_r | H_{CN} | a + X \rangle\right|^2$$

$$\sigma_\gamma \propto \Gamma_a \Gamma_b$$

Resonance Reactions

322 *S.O.F. Dababneh et al. / The reaction $^{19}F(p,\alpha\gamma)^{16}O$*

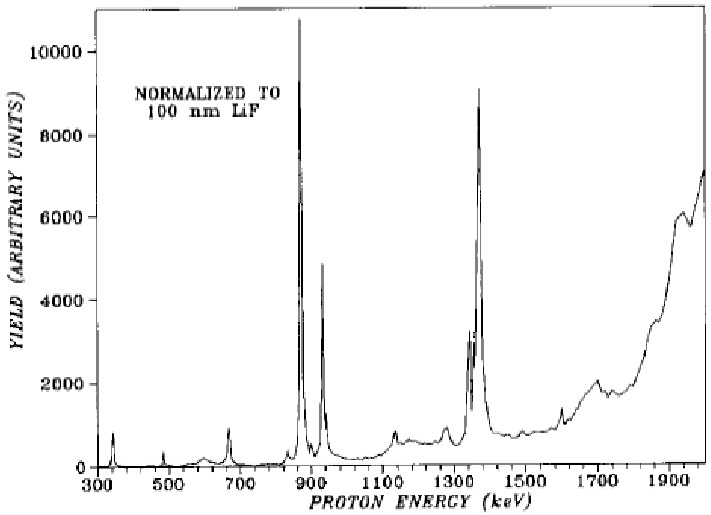


Fig. 1. Overview of the excitation curve from $E_p = 0.3–2.0$ MeV, where isolated and narrow resonances are found.

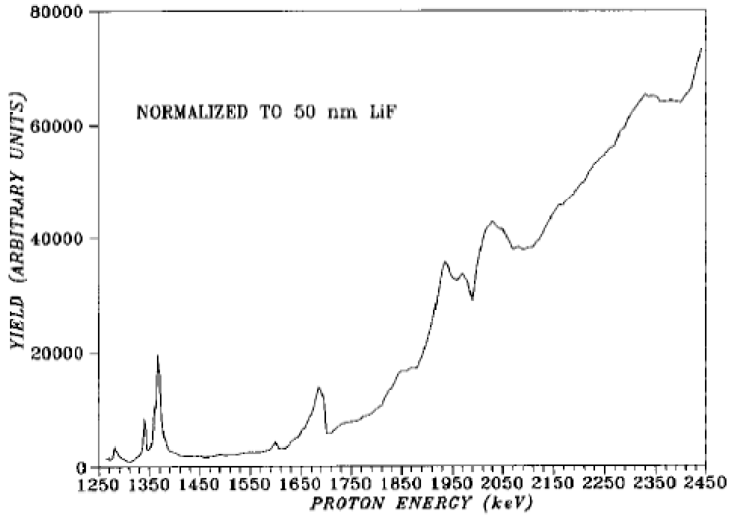


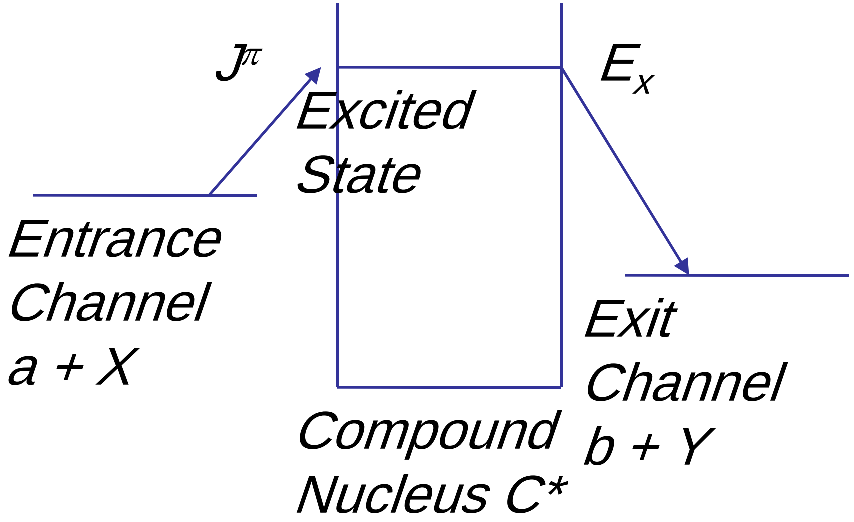
Fig. 2. Excitation function in the proton energy region from 1.25 to 2.45 MeV, including the last narrow resonances, and the beginning of the continuum.

$\Delta E \Leftrightarrow \Delta t$

CN ▶ particle emission ▶ ΔE↑ ▶ ΔE > spacing between virtual states ▶ continuum.

Lower part ▶ larger spacing ▶ isolated resonances.

Resonance Reactions



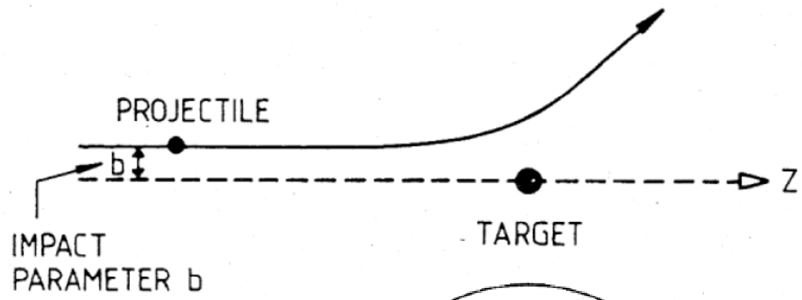
HW 17

In the $^{19}F(p,\alpha\gamma)$ reaction:

- The Q-value is 8.??? MeV.
- The Q-value for the formation of the C.N. is 12.??? MeV.
- For a proton resonance at 668 keV in the lab system, the corresponding energy level in the C.N. is at 13.??? MeV.
- If for this resonance the observed gamma energy is 6.13 MeV, what is the corresponding alpha particle energy?
- If for this resonance there has been no gamma emission observed, what would then be the alpha particle energy?

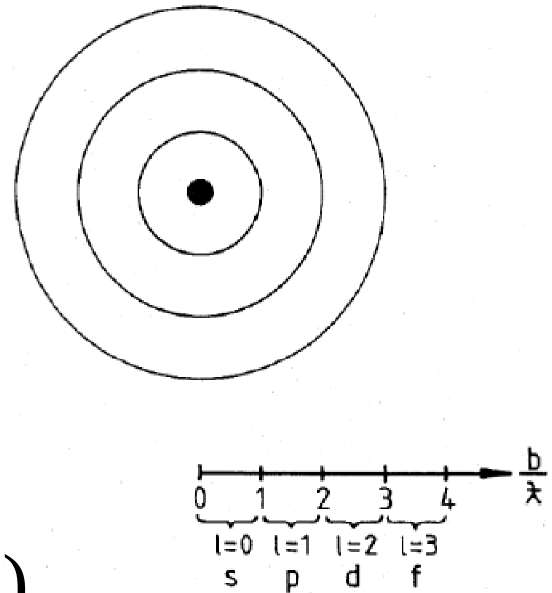
Resonance Reactions

$$L = l\hbar = bp = b\frac{\hbar}{\lambda\!\!\!^{-}}$$



$$b = l\lambda\!\!\!^{-}$$

$$\sigma_{l,\max} = \pi b_{l+1}^2 - \pi b_l^2 = (2l+1)\pi\lambda\!\!\!^{-\,2}$$



HW 18 $$\pi\lambda\!\!\!^{-\,2}(b) = \frac{656.7}{\mu(u)E^{CM}(keV)}$$

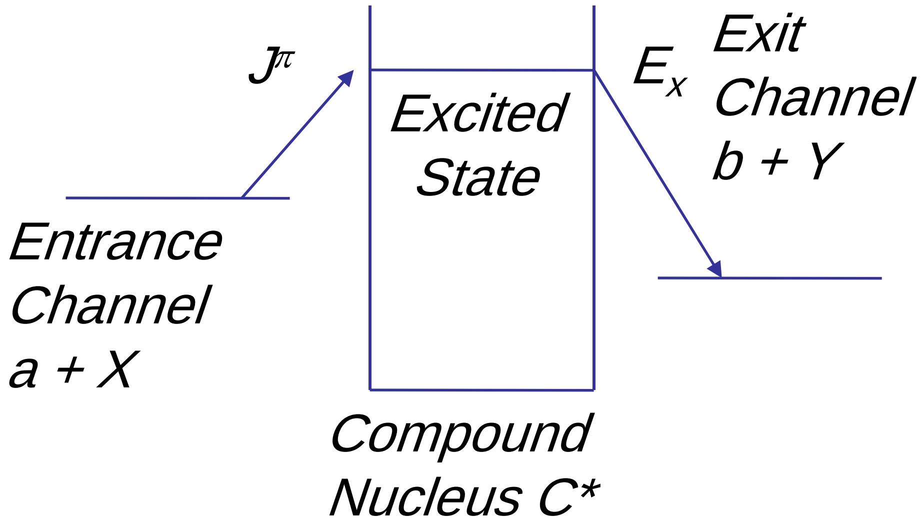
$$\sigma_{\max} = \pi\lambda\!\!\!^{-}_{aX}{}^{2}\underbrace{\frac{2J+1}{(2J_a+1)(2J_X+1)}(1+\delta_{aX})}_{\omega}$$

Resonance Reactions

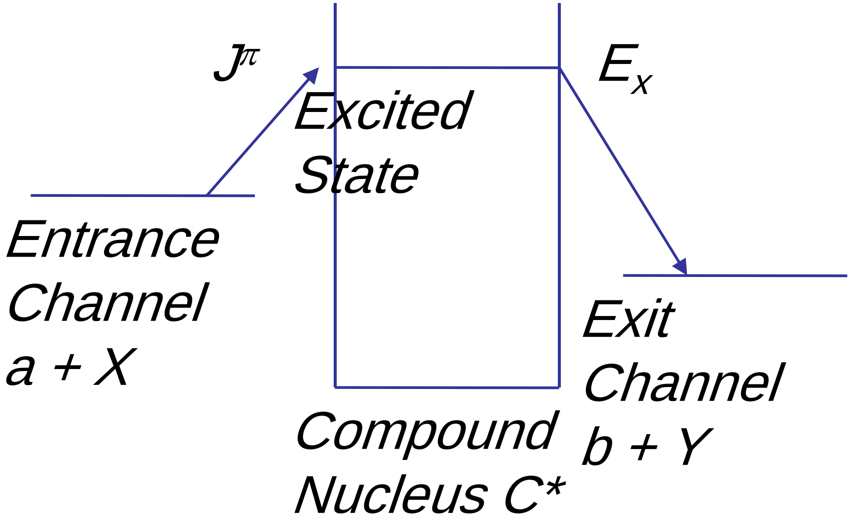
$J_a + J_X + l = J$

$(-1)^l \, \pi(J_a) \, \pi(J_X) = \pi(J)$

$(-1)^l = \pi(J)$ Natural parity.



Resonance Reactions



a + X → Y + b   Q > 0

b + Y → X + a   Q < 0

Inverse Reaction

$$\sigma_{aX} = \pi\lambda\!\!\!^{-}{}^2_{aX} \frac{2J+1}{(2J_a+1)(2J_X+1)} (1+\delta_{aX}) \left| \langle Y+b | H_{II} | C \rangle \langle C | H_I | a+X \rangle \right|^2$$

QM

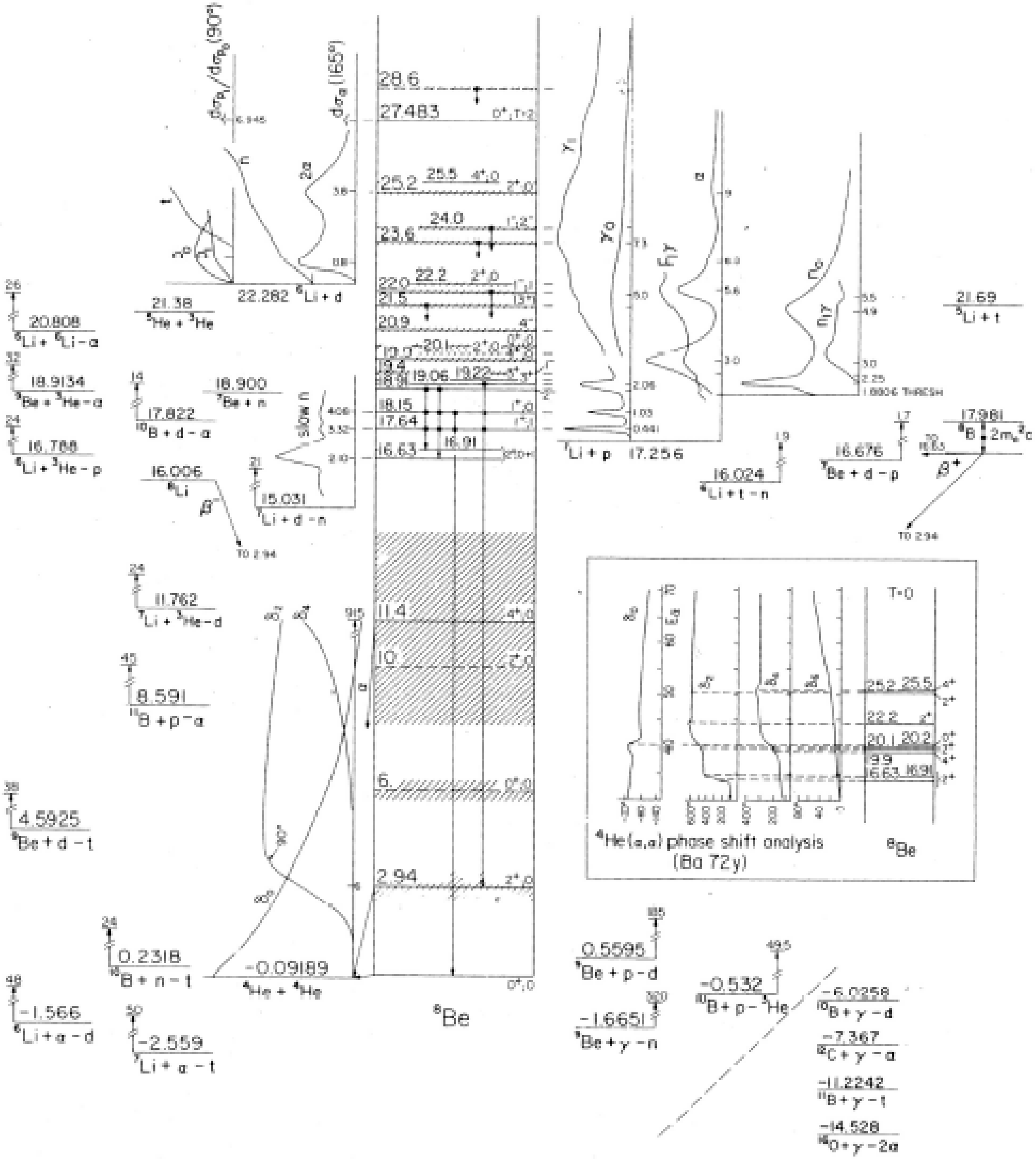
Statistical Factor (ω)

Identical particles

- *Nature of force(s).*
- *Time-reversal invariance.*

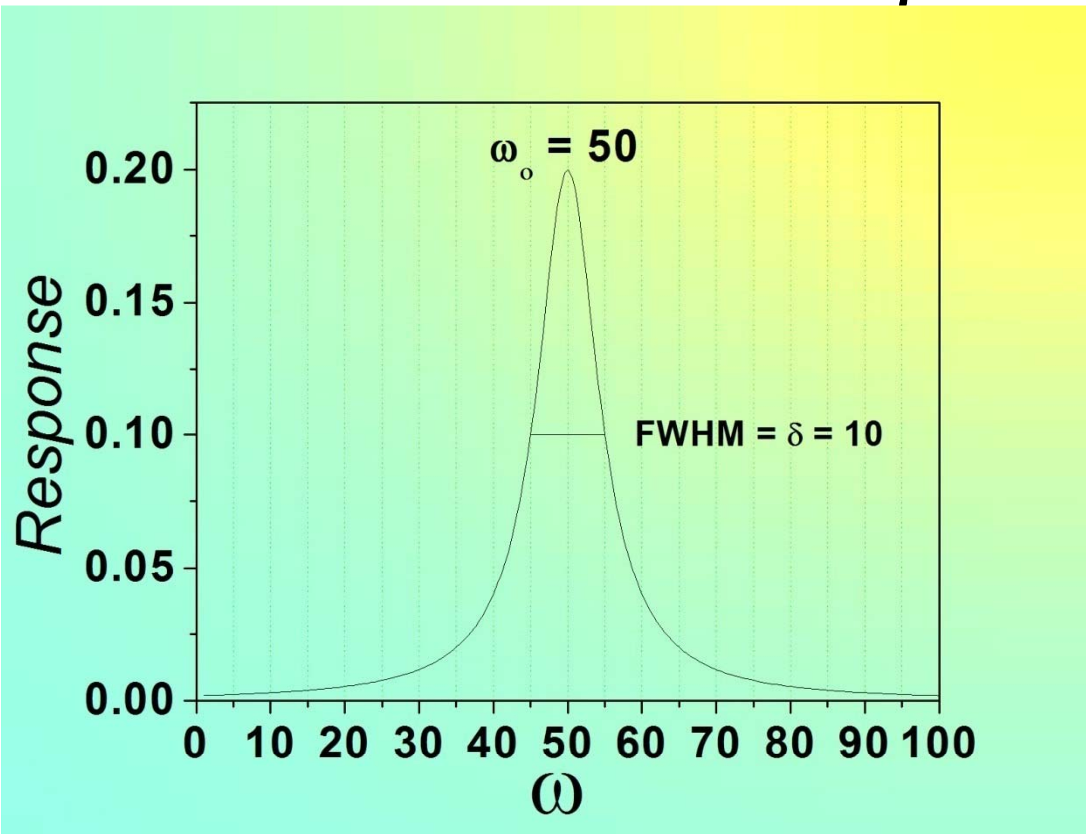
$$\sigma_{bY} = \pi\lambda\!\!\!^{-}{}^2_{bY} \frac{2J+1}{(2J_b+1)(2J_Y+1)} (1+\delta_{bY}) \left| \langle a+X | H_I | C \rangle \langle C | H_{II} | b+Y \rangle \right|^2$$

HW 19 $\frac{\sigma_{aX}}{\sigma_{bY}} = ??$


28.6
27.483
0+;T=2
25.2
25.5
4+;0
2+;0
24.0
23.6
22.0
22.2
2+;0
21.5
20.9
4-
20.1
19.9
19.4
18.9
19.06
19.22
18.15
1+;0
17.64
1+;1
16.63
16.91
11.4
4+;0
10
2+;0
6.
0+;0
2.94
2+;0
-0.09189
0+;0
^{4}He + ^{4}He
^{8}Be
22.282 ^{6}Li + d
21.38
^{3}He + ^{5}He
20.808
^{6}Li + ^{6}Li - α
18.9134
^{9}Be + ^{3}He - α
17.822
^{10}B + d - α
18.900
^{7}Be + n
16.788
^{6}Li + ^{3}He - p
16.006
^{8}Li
β-
TO 2.94
15.031
^{7}Li + d - n
11.762
^{7}Li + ^{3}He - d
8.591
^{11}B + p - α
4.5925
^{9}Be + d - t
0.2318
^{10}B + n - t
-1.566
^{6}Li + α - d
-2.559
^{7}Li + α - t
^{7}Li + p
17.256
21.69
^{5}Li + t
17.981
^{8}B
β+
TO 2.94
16.676
^{9}Be + d - p
16.024
^{6}Li + t - n
0.5595
^{9}Be + p - d
-1.6651
^{9}Be + γ - n
-0.532
^{10}B + p - ^{3}He
-6.0258
^{10}B + γ - d
-7.367
^{12}C + γ - α
-11.2242
^{11}B + γ - t
-14.528
^{16}O + γ - 2α
^{4}He(α,α) phase shift analysis
(Ba 72y)
T=0
^{8}Be

Resonance Reactions

Damped Oscillator



Oscillator strength

$$response \propto \frac{f}{(\omega - \omega_o)^2 + (\frac{\delta}{2})^2}$$

$$\delta = \frac{1}{t_0}$$

Damping factor

eigenfrequency

$$\sigma(E) \propto \frac{\Gamma_a \Gamma_b}{(E - E_R)^2 + (\frac{\Gamma}{2})^2}$$

$$\Gamma t_o = \hbar$$

Resonance Reactions

$$\sigma(E) = \pi\lambda\!\!\!^{-}{}_{aX}^{\;2} \frac{2J+1}{(2J_a+1)(2J_X+1)}(1+\delta_{aX})\frac{\Gamma_a\Gamma_b}{(E-E_R)^2+(\frac{\Gamma}{2})^2}$$

Breit-Wigner formula

$$\Gamma = \Gamma_a + \Gamma_b$$

- All quantities in CM system
- Only for isolated resonances.

$\sigma_R \propto \Gamma_a\Gamma_b$ ← Reaction

$\sigma_e \propto \Gamma_a\Gamma_a$ ← Elastic scattering

Usually $\Gamma_a >> \Gamma_b$.

$$\frac{\sigma_R}{\sigma_e} = \frac{\Gamma_b}{\Gamma_a}$$

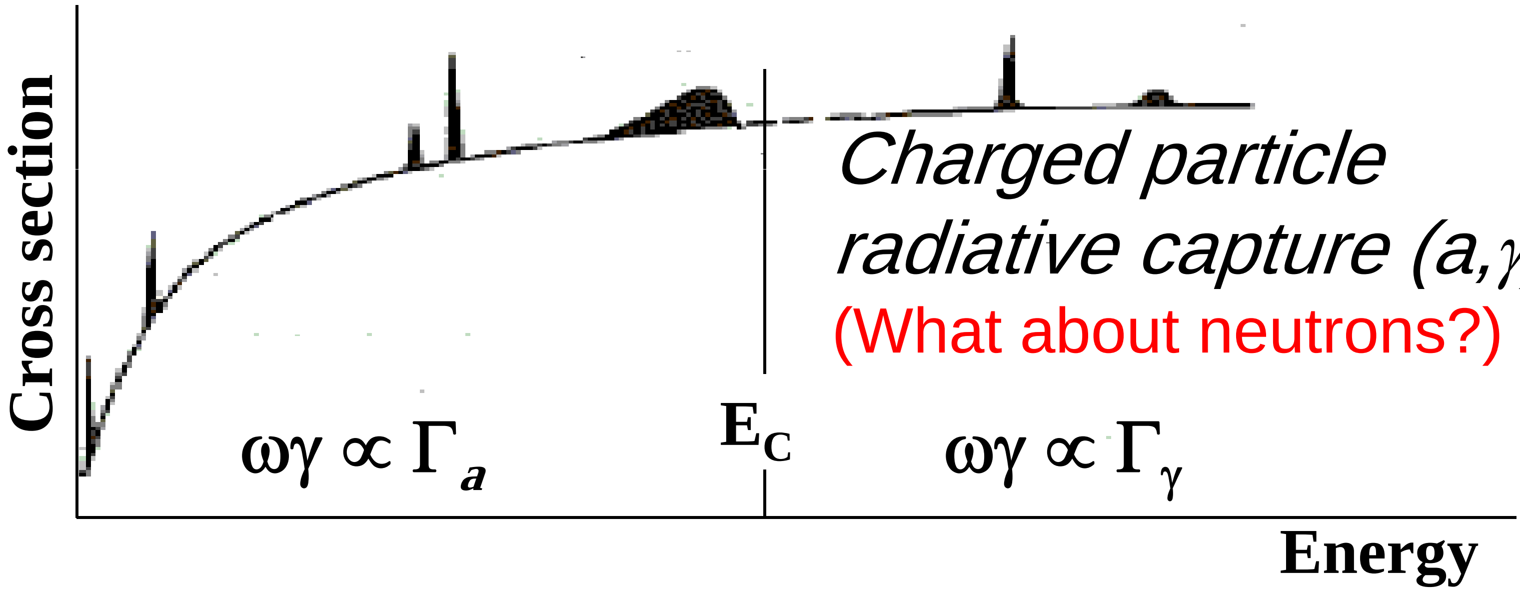
HW 20 When does σ_R take its maximum value?

Resonance Reactions

What is the "Resonance Strength" …?
What is its significance?
In what units is it measured?

HW 21

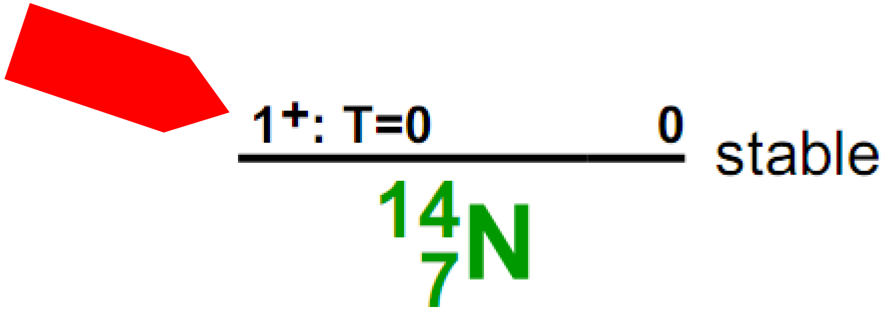
$$\omega\gamma = \frac{2J+1}{(2J_a+1)(2J_X+1)}(1+\delta_{aX})\frac{\Gamma_a\Gamma_b}{\Gamma}$$



Charged particle radiative capture (a,γ)
(What about neutrons?)

Resonance Reactions

$^{14}N(p,\gamma)$ **HW 22**



- Q = ??
- E_C = ??
- $E_R^{C.M.}$ = 2.0 MeV

  Formation via *s*-wave protons, Take $J = ½$, Γ_p = 0.1 MeV, dipole radiation E_γ = 9.3 MeV, Γ_γ = 1 eV.
  Show that $\omega\gamma$ = 0.33 eV.
- If same resonance but at E_R = 10 keV

  Γ_p = ?? E_γ = ?? Γ_γ (dipole) = ??
  Show that $\omega\gamma = 3.3\times10^{-23}$ eV.

Huge challenge to experimentalists

Neutron Resonance Reactions