Nuclear Astrophysics Experiments Deep Underground at LUNA

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XVI Nuclei in the Cosmos School – September 2021

Lecture 1

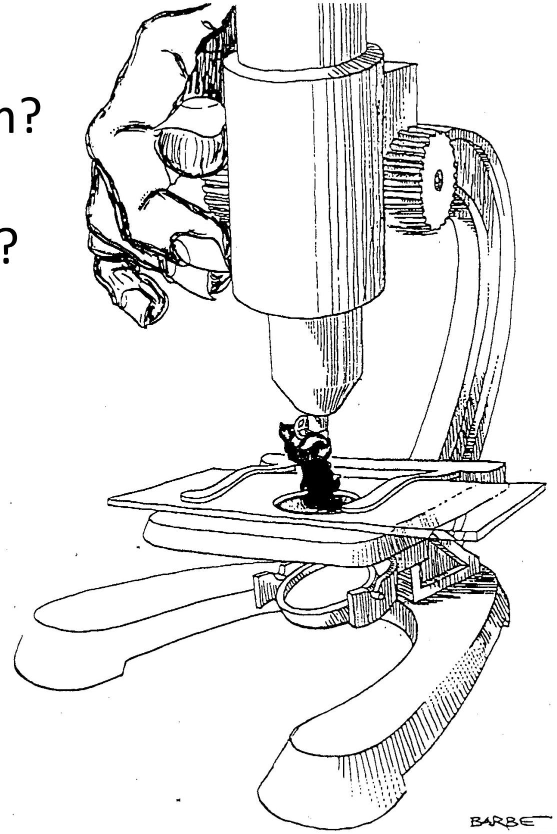
- brief overview of Nuclear Astrophysics
- thermonuclear reactions in stars
  - non-resonant and resonant reactions
  - reaction rates, cross sections and yields
- stellar reactions in the lab
  - challenges and requirements
  - why underground

Lecture 2

- the LUNA laboratory: past successes and recent studies
  - gamma-ray, charged-particle, and neutron- detection
- future opportunities

Nuclear Astrophysics

- Where do all chemical elements come from?
- How do stars and galaxies form and evolve?



Courtesy: M. Arnould

Nuclear Physics plays a key role:

intimate connection between

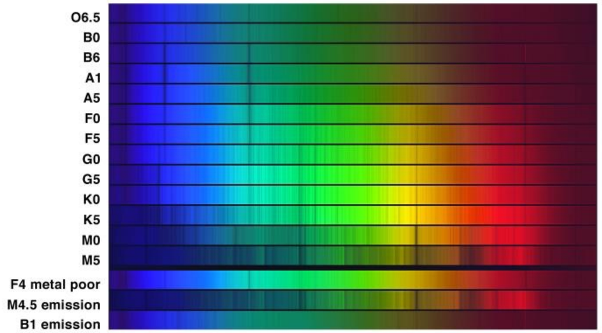
MICRO COSMOS

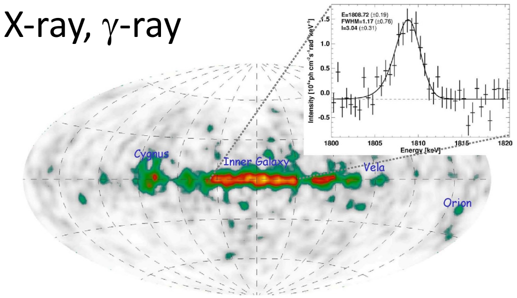
and

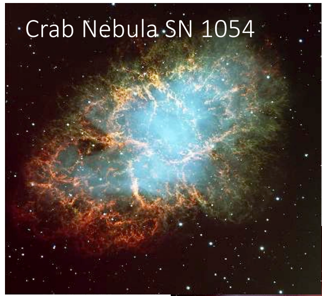
MACRO COSMOS

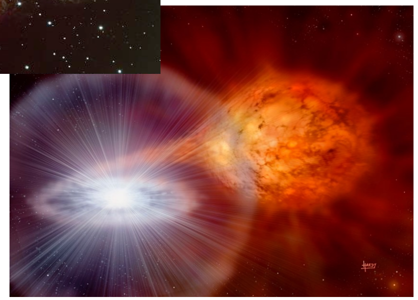
electromagnetic emissions

radio, microwave, infrared, optical, X-ray, γ-ray



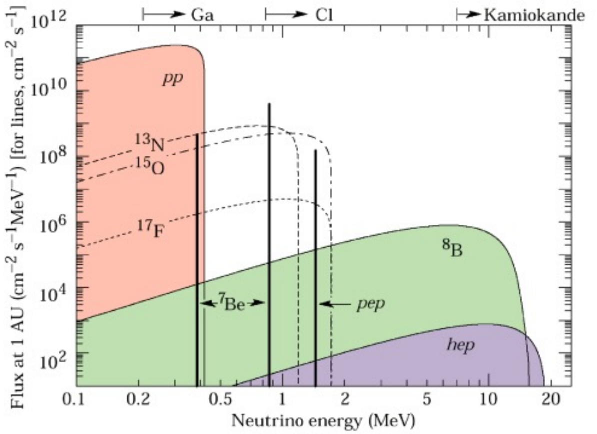


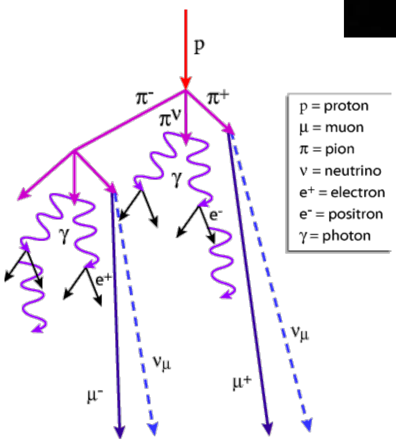




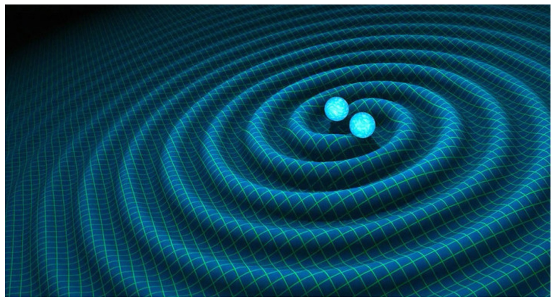
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …





gravitational waves



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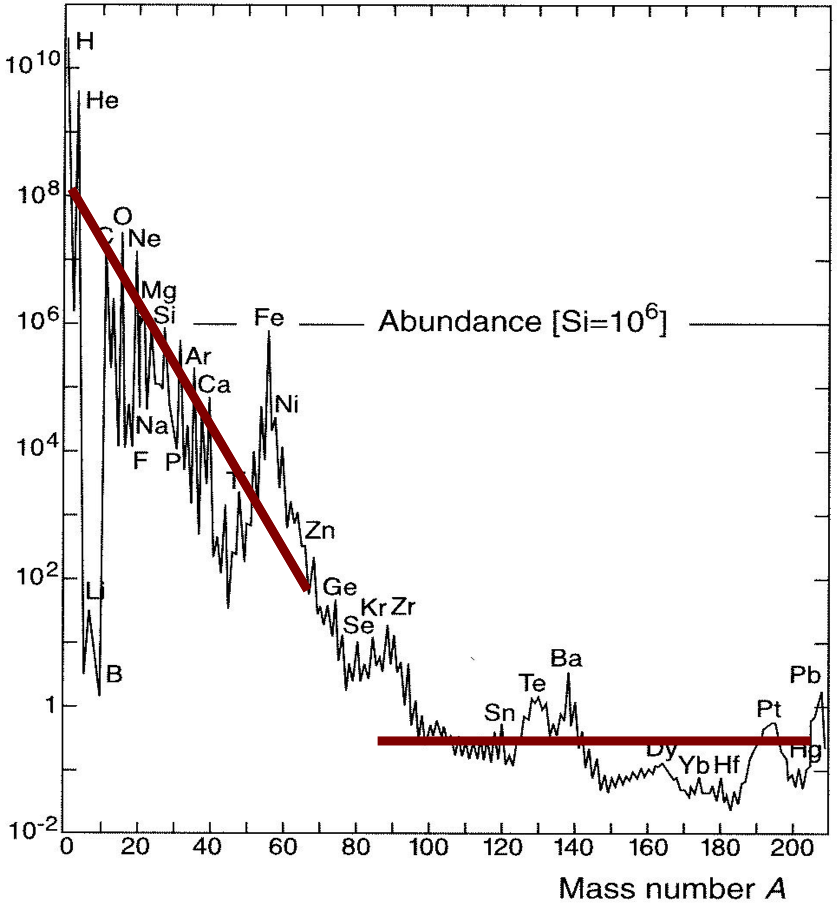
(Solar) Abundance Distribution



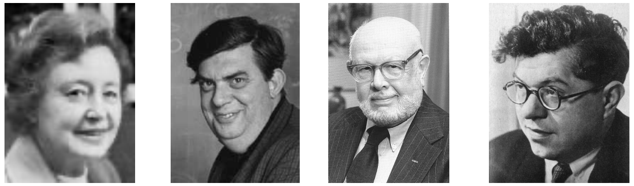
Data sources:

Earth, Moon, meteorites, cosmic rays, solar & stellar spectra…

Features:

- 12 orders-of-magnitude span
- H ~ 75%, He ~ 23%
- C → U ~ 2% (“metals”)
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- nearly flat distribution beyond Fe

Burbidge, Burbidge, Fowler & Hoyle (B^{2}FH):



Rev. Mod. Phys. 29 (1957) 547

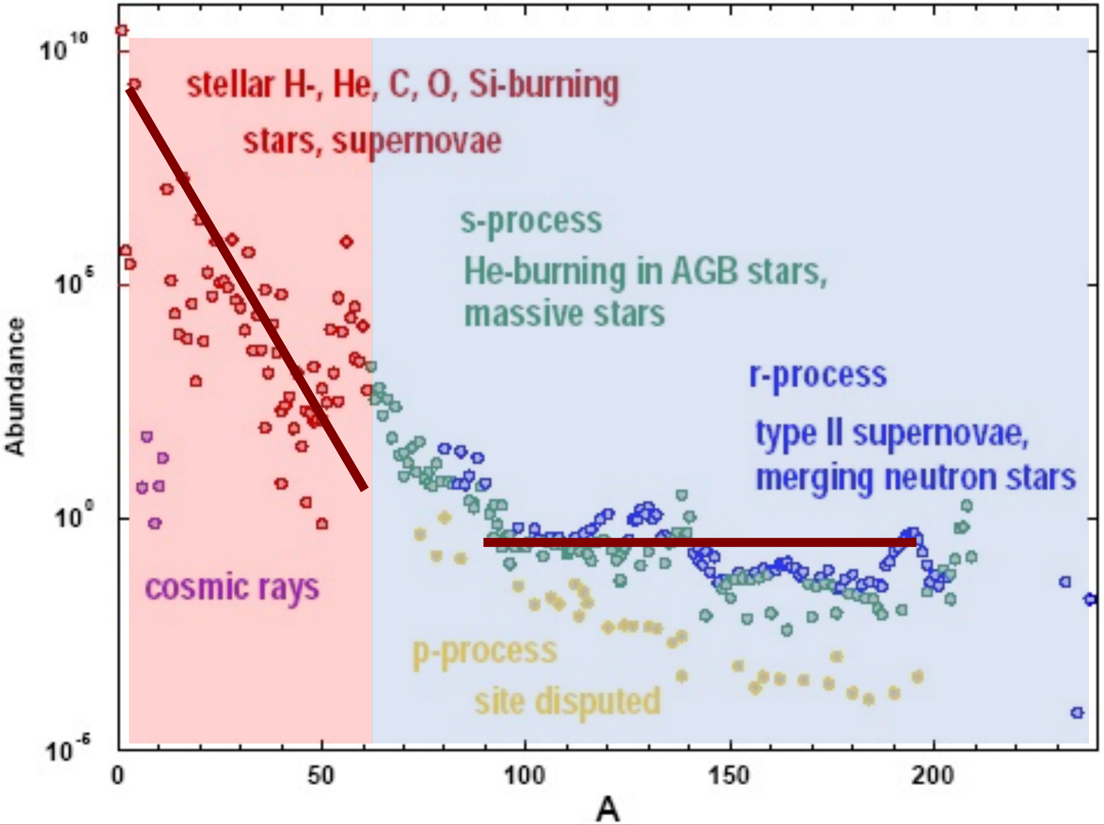
Synthesis of the Elements in Stars*

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

fusion between
charged particles

mainly **stable nuclei**



M. Wiescher, JINA lectures on Nuclear Astrophysics

neutron-capture
reactions

mainly **unstable nuclei**

Interstellar medium

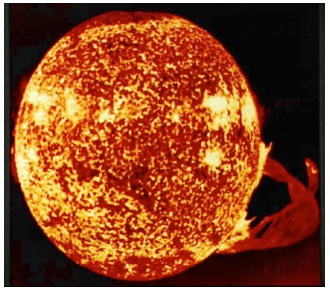
BIRTH

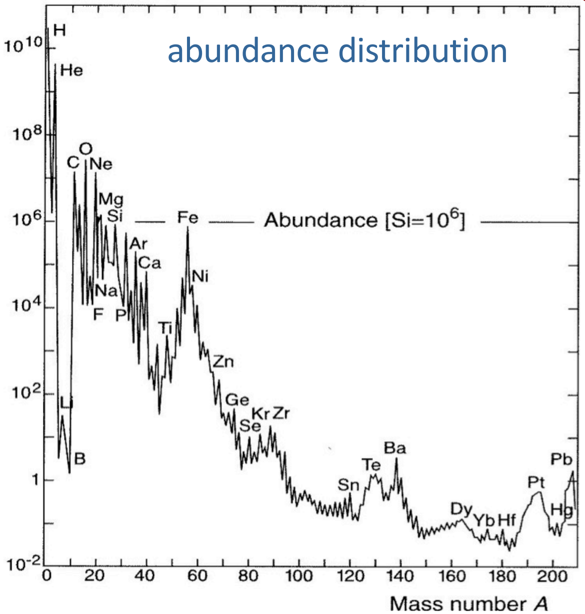
gravitational contraction

explosion ejection

DEATH

Stars





- stability against collapse
- energy production
- synthesis of “metals”

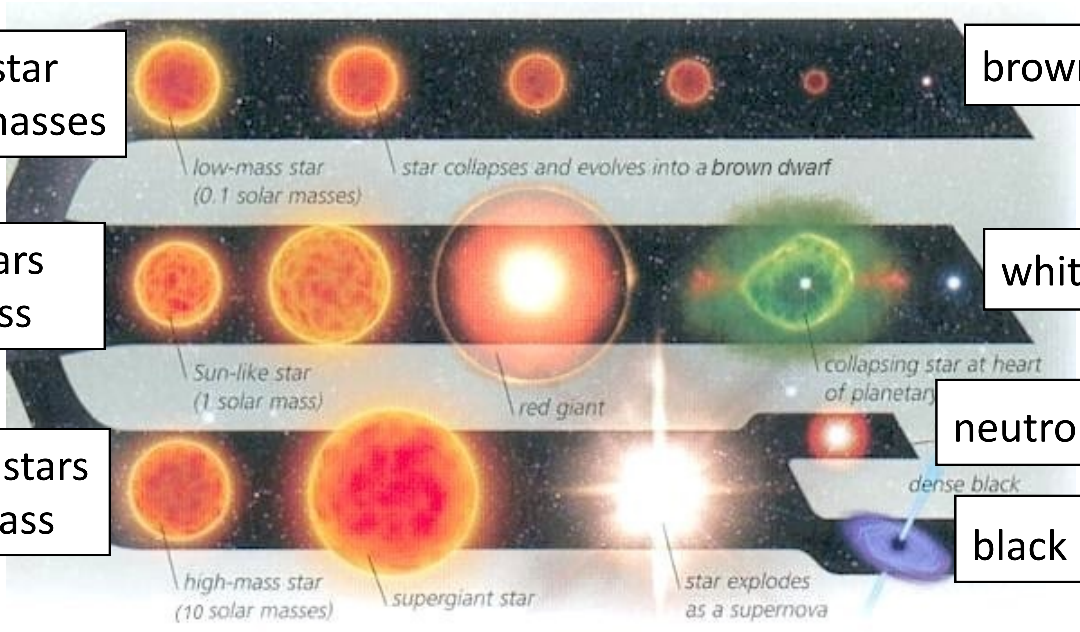
Stellar Evolutionary Paths

birth | evolution | death

low-mass star
0.1 solar masses

sun-like stars
1 solar mass

high-mass stars
10 solar mass



brown dwarf

white dwarf

neutron star

black hole

massive stars contribute to **chemical evolution** of the Universe

low-mass stars live longer → important for **evolution of life**

Key Open Questions

- Big Bang Nucleosynthesis: Li problem and the D abundance
- Core metallicity of the Sun
- Nucleosynthesis in AGB stars and galactical chemical evolution
- Fate of massive stars: supernovae or white dwarfs?
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition
- Origin of Heavy Elements
- Astrophysical site(s) for the r-process
- …

Astrophysics

Stellar evolutionary codes
nucleosynthesis calculations
astronomical observations

Nuclear Physics

experimental and
theoretical Inputs
stable and exotic nuclei

Plasma Physics

degenerate matter
electron screening
equation of state

Atomic Physics

radiation-matter interaction
energy losses, stopping powers
spectral lines
materials and detectors

Thermonuclear Reactions in Stars

Consider reaction: $1 + 2 \rightarrow 3 + 4$ $Q_{12} > 0$ ($\Leftarrow$ known from atomic mass tables)

Reaction cross section σ $\Rightarrow$ probability for a reaction to occur

Dimension: area Unit: barn (b) = 10^{-24} cm^2

In general: not possible to determine reaction cross section from first principles

However: 1. cross sections depend on nature of force involved

Reaction	Force	σ (barn)	E_{proj} (MeV)
$^{15}N(p,\alpha)^{12}C$	strong	0.5	2.0
$^{3}He(\alpha,\gamma)^{7}Be$	electromagnetic	10^{-6}	2.0
$p(p,e^{+}\nu)d$	weak	10^{-20}	2.0

2. cross sections are energy (i.e. velocity) dependent

Reaction rate: $r = N_1 N_2 \, v\sigma(v)$

In stellar plasma: velocity of particles varies over wide range

Reaction rate per particle pair: $\langle\sigma v\rangle_{12} = \int_0^\infty v\sigma(v)\phi(v)dv$ $\phi(v)$ velocity distribution

Quiescent stellar burning:

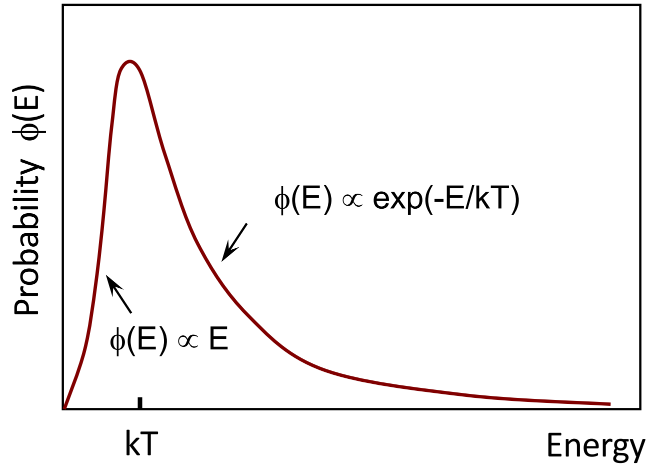
non-relativistic, non-degenerate gas in thermodynamic equilibrium at temperature T

Maxwell-Boltzmann distribution

$$\phi(v) \propto \exp\left(-\frac{\mu v^2}{2kT}\right) = \exp\left(-\frac{E}{kT}\right)$$

μ = reduced mass

v = relative velocity



$$\langle\sigma v\rangle_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) \exp\left(-\frac{E}{kT}\right) E\, dE$$

Total reaction rate: $R_{12} = (1+\delta_{12})^{-1} N_1 N_2 <\sigma v>_{12}$ reactions $cm^{-3}\ s^{-1}$

N_i = number density

Energy production rate: $\varepsilon_{12} = R_{12}\, Q_{12}$

Mean lifetime of nuclei X against destruction by nuclei a

$$\tau_a(X) = \frac{1}{N_a < \sigma v >}$$

energy production as star evolves ⇐ $<\sigma v>$ = KEY quantity ⇒ change in abundance of nuclei X

⇓

to be determined from experiments and/or theoretical considerations

as star evolves, T changes $\Rightarrow$ evaluate $<\sigma v>$ for each temperature

⇓

NEED ANAYLITICAL EXPRESSION FOR σ!

Reaction Mechanisms

I. direct (non-resonant) reactions

II. resonant reactions

Cross Section for Non-Resonant Reactions

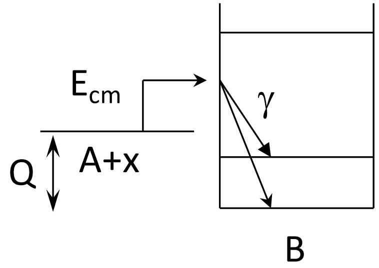
- reactions with charged particles
- reactions with neutrons (see Lectures by Prof Artemis Spyrou)

Direct (non-resonant) Reactions

one-step process

direct transition into a bound state

example: radiative capture $A(x,\gamma)B$

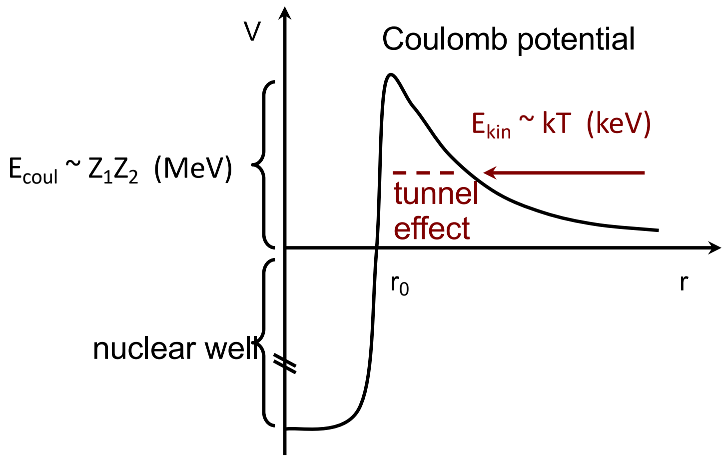


$$\sigma_\gamma \propto \left| \langle B | H_\gamma | A + x \rangle \right|^2$$

H_γ = electromagnetic operator describing the transition

- reaction cross section proportional to single matrix element
- can occur at all projectile energies
- smooth energy dependence of cross section

other direct processes: stripping, pickup, charge exchange, Coulomb excitation charged particles ➜ Coulomb barrier



energy available to initiate reaction comes from thermal motion

$$kT \sim 8.6 \times 10^{-8}\ T[K]\ \text{keV}$$

T ~ 15×10^6 K (e.g. our Sun) $\Rightarrow$ kT ~ 1 keV

T ~ 10^{10} K (Big Bang) $\Rightarrow$ kT ~ 2 MeV

during quiescent burnings: $kT \ll E_c$ ➜ reactions occur through TUNNEL EFFECT non-zero probability of tunnelling through Coulomb barrier at energies $E << V_{coul}$

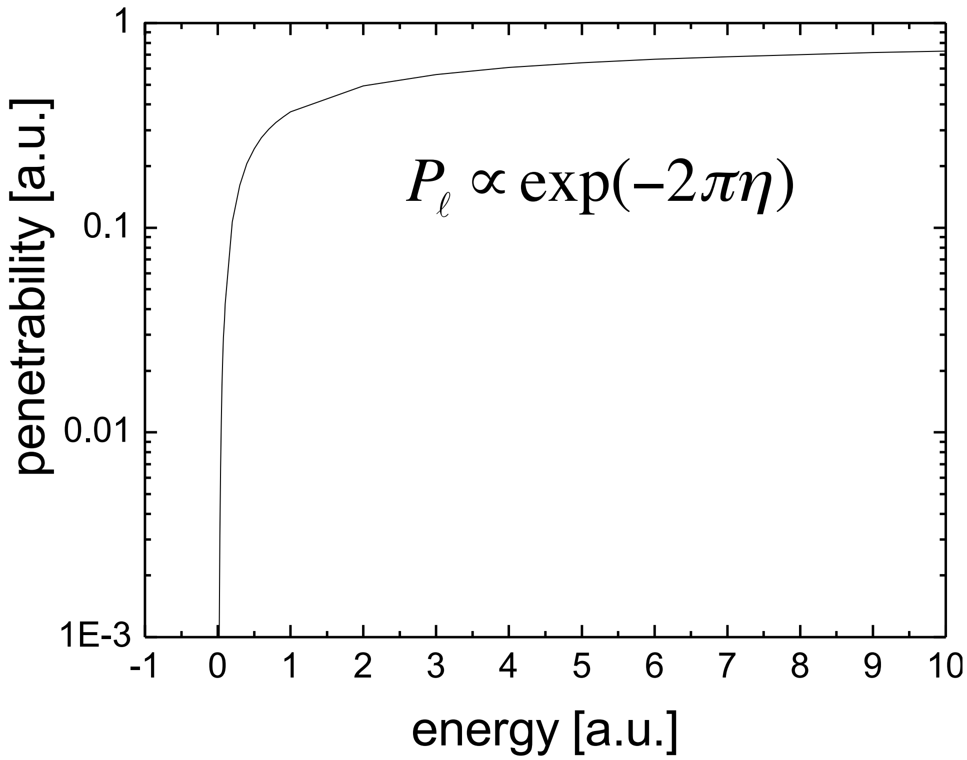
assuming full ion charges and zero orbital angular momentum:

$$\boxed{P_\ell \propto \exp(-2\pi\eta) = \exp\left(-\frac{b}{\sqrt{E}}\right)}$$

$$\eta = \sqrt{\frac{\mu}{2E}} \frac{Z_1 Z_2 e^2}{\hbar}$$ Sommerfeld parameter

$$\boxed{2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{1/2}}$$ GAMOW factor

μ in amu and E_{cm} in keV



determines exponential drop in abundance curve!

Cross section for Non-resonant Reactions

$$\sigma \propto \pi\lambda^2 \cdot P_\ell(E) \cdot \left|\langle b+Y|H|a+X\rangle\right|^2$$

geometrical factor
(particle's de Broglie wavelength)

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

penetrability probability
depends on projectile's
angular momentum ℓ and energy E

interaction matrix element

$$\boxed{\sigma(E) = \underbrace{\frac{1}{E}\exp(-2\pi\eta)}_{\text{non-nuclear origin}}\ \underbrace{S(E)}_{\text{nuclear origin}}}$$

(for s-waves only!)

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

Above relation defines ASTROPHYSICAL S(E)-FACTOR (units: keV barn, MeV barn, …)

N.B.
If angular momentum is non zero
$\Rightarrow$ centrifugal barrier $V_\ell = \dfrac{\ell(\ell+1)\hbar^2}{2\mu r^2}$ must also be taken into account

reaction rate: $\langle \sigma v \rangle = \int \sigma(v)\phi(v) v\,dv = \int \sigma(E) \exp(-E/kT) E\,dE$

and substituting for σ: $\langle \sigma v \rangle \propto \int S(E) \exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E}}\right) dE$

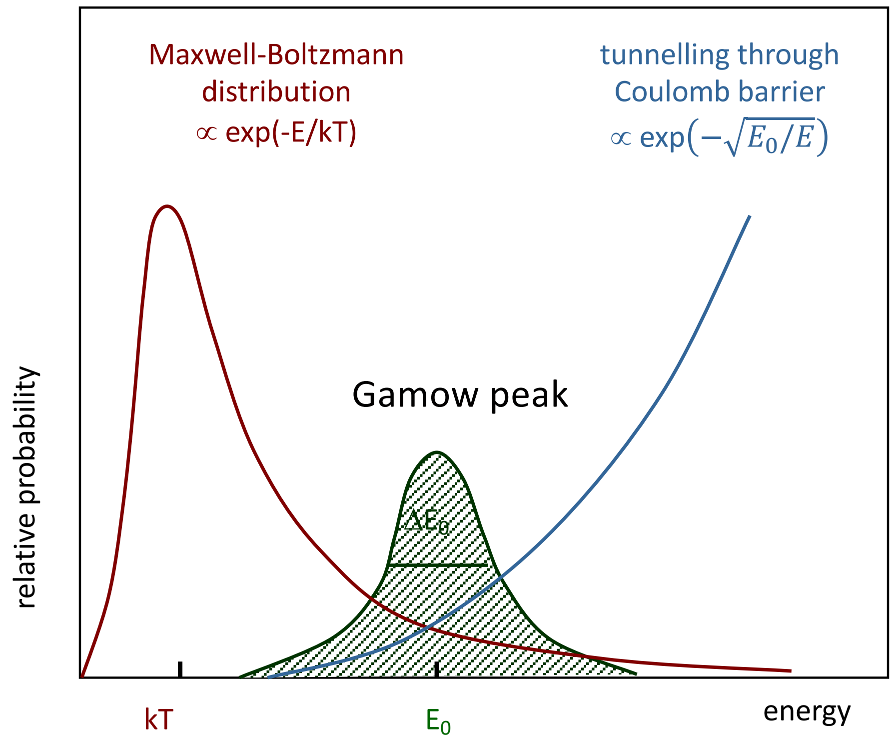
maximum reaction rate at E_0:

$$\frac{d}{dE}\left[\exp\left(-\frac{E}{kT} - \frac{b}{\sqrt{E}}\right)\right] = 0$$

$E_0 = (bkT/2)^{2/3} = (Z_1^2 Z_2^2 \mu T_9^2)^{1/3}$ MeV

$\Delta E = \frac{4}{\sqrt{3}}\sqrt{E_0 kT} = 0.237\left(Z_1^2 Z_2^2 A\right)^{1/6} T_9^{5/6}$ MeV

GAMOW Peak



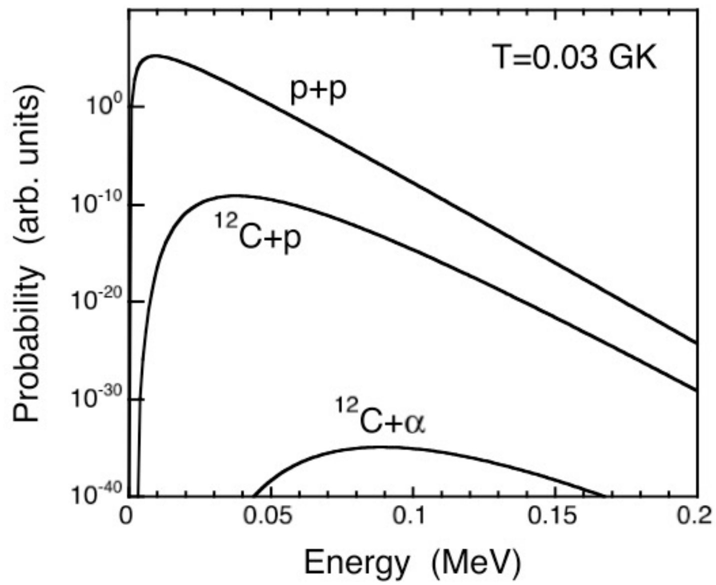
Gamow peak: $E_0 \pm \Delta E_0/2$

energy window of astrophysical interest

$E_0 = f(Z_1, Z_2, T)$

⬇

varies depending on reaction and/or temperature



Iliadis, Nuclear Physics of Stars, 2007

Examples: $T \sim 15 \times 10^6$ K ($T_6 = 15$)

reaction	Coulomb barrier (MeV)	E_0 (keV)	area under Gamow peak ~ $<\sigma v>$
p + p	0.55	5.9	7.0×10^{-6}
α + ^{12}C	3.43	56	5.9×10^{-56}
^{16}O + ^{16}O	14.07	237	2.5×10^{-237}

STRONG sensitivity to Coulomb barrier

⬇

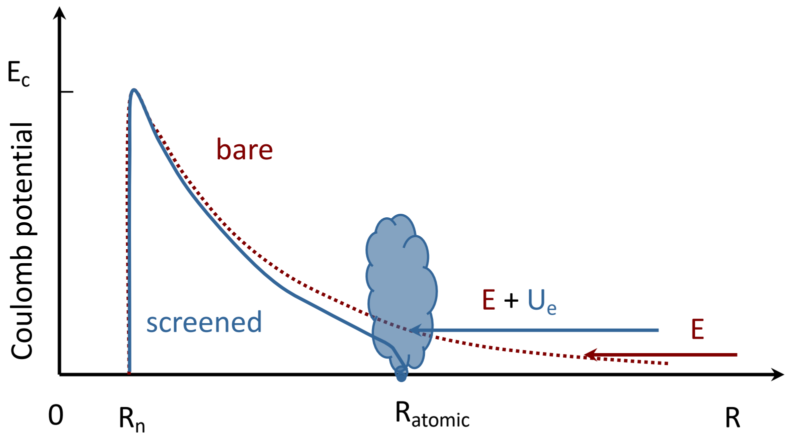
separate stages: H-burning
He-burning
C/O-burning …

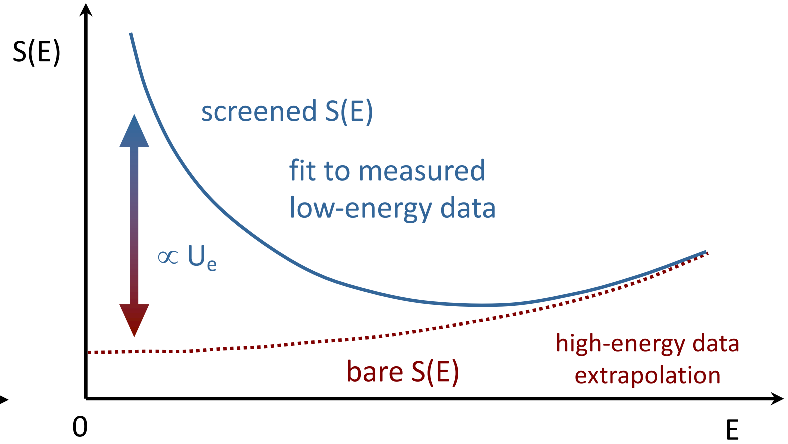
Electron Screening

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

assumption: $2\pi\eta \sim Z_1 Z_2 (\mu/E)^{1/2}$
bare nuclei

$$f_{lab}(E) = \frac{S_{screen}(E)}{S_{bare}(E)} \sim \exp(\pi\eta U_e/E)$$





in the lab and in stellar plasmas

interaction affected by electrons

SCREENING POTENTIAL U_e

typically tiny amount (~ 10-100 eV)

⇒ corrections typically negligible

⇒ except for ultra-low energies

typically, experimental investigations

⬇

U_e in excess of theoretical limit !

electron screening puzzle

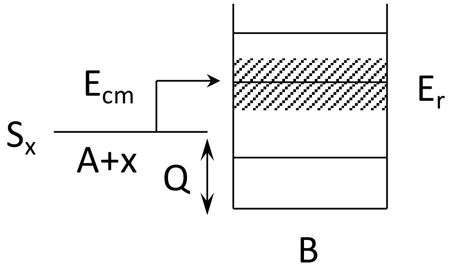
Cross Section for Resonant Reactions

reactions with either neutrons or charged particles

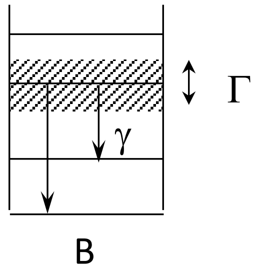
two-step process

example: **resonant radiative capture A(x,γ)B**

1. **Formation of a compound nucleus** (into an unbound, excited state)



2. **Decay of compound nucleus** (to lower excited states)



$$\sigma_\gamma \propto \underbrace{\left|\langle E_f | H_\gamma | E_r \rangle\right|}_{\text{compound decay}} \; \underbrace{\left|\langle E_r | H_B | A + x \rangle\right|}_{\text{compound formation}}$$

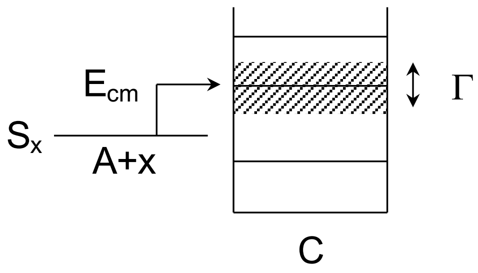
compound decay probability $\propto \Gamma_\gamma$

compound formation probability $\propto \Gamma_x$

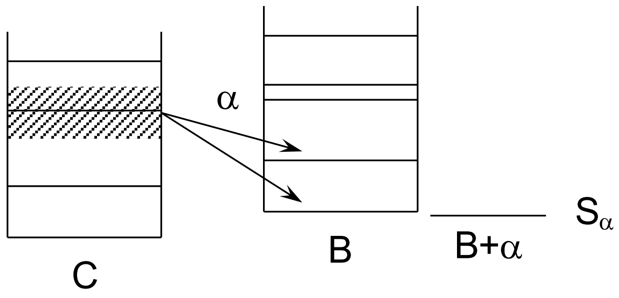
- reaction cross section proportional to two matrix elements
- only occurs at energies $E_{cm} \sim E_r - Q$
- strong energy dependence of cross section

N. B. energy in entrance channel ($Q+E_{cm}$) has to match excitation energy E_r of resonant state, however all excited states have a width $\Rightarrow$ there is always some cross section through tails example: **resonant reaction A(x,α)B**

1. Compound nucleus formation
   (into an unbound state)



2. Compound nucleus decay
   (by particle emission)



$$\sigma_\gamma \propto \underbrace{\left|\langle B+\alpha|H_\alpha|E_r\rangle\right|}_{\text{compound decay}} \; \underbrace{\left|\langle E_r|H_x|A+x\rangle\right|}_{\text{compound formation}}$$

compound decay probability $\propto \Gamma_\alpha$

compound formation probability $\propto \Gamma_x$

N. B. energy in entrance channel (S_x+E_{cm}) has to match excitation energy E_r of resonant state, however all excited states have a width $\Rightarrow$ there is always some cross section through tails

Breit-Wigner Cross Section

for a single isolated resonance:

resonant cross section given by **Breit-Wigner expression**

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1 \Gamma_2}{(E-E_R)^2 + (\Gamma/2)^2}$$

for reaction: 1 + T → C → F + 2

geometrical factor

$\propto$ 1/E

spin factor ω

J = spin of CN's state

J_1 = spin of projectile

J_T = spin of target

strongly energy-dependent term

Γ_1 = partial width for decay via emission of particle 1

= probability of compound formation via entrance channel

Γ_2 = partial width for decay via emission of particle 2

= probability of compound decay via exit channel

Γ = total width of compound's excited state

$= \Gamma_1 + \Gamma_2 + \Gamma_\gamma + \ldots$

E_R = resonance energy

what about penetrability considerations? $\Rightarrow$ look for energy dependence in partial widths!

partial widths are NOT constant but energy dependent!

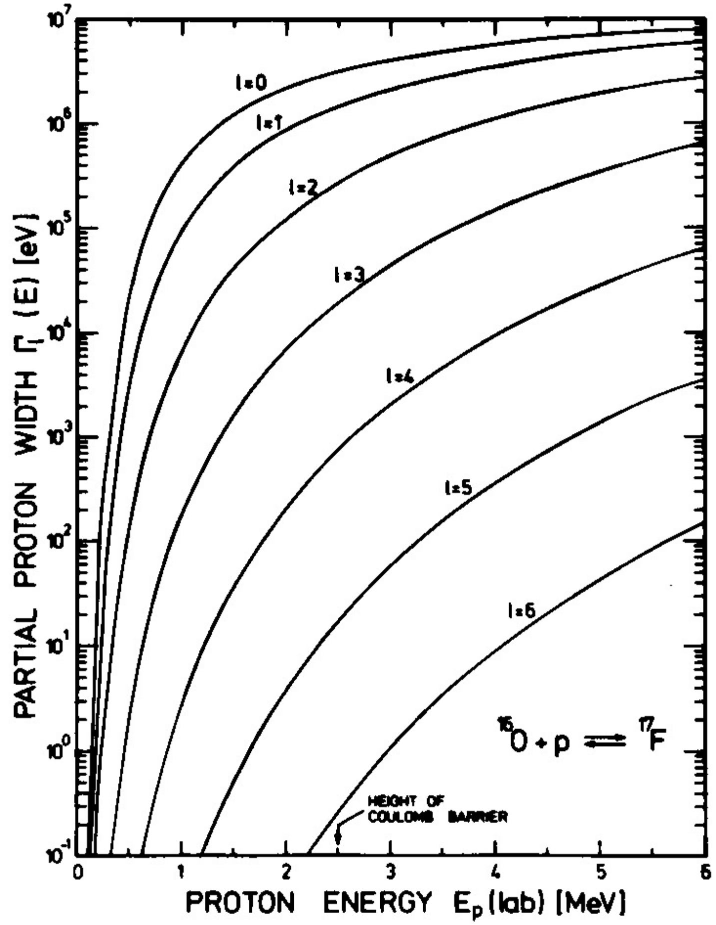
particle widths

$$\boxed{\Gamma_l = \frac{2\hbar}{R} P_\ell(E_l)\,\theta_\ell^2}$$

θ_l = "reduced width" (contains nuclear physics info)
P_ℓ gives strong energy dependence

example: $^{16}O(p,\gamma)^{17}F$

energy dependence of proton partial width Γ_p as function of ℓ



particle partial widths have approximately same energy dependence as penetrability function seen in direct reaction processes reaction rate: $\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv = \int \sigma(E) \exp(-E/kT) E dE$

$\downarrow$

here Breit-Wigner cross section

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1 \Gamma_2}{(E-E_r)^2 + (\Gamma/2)^2}$$

integrate over appropriate energy region

if compound nucleus has an exited state (or its wing) in this energy range

$\Rightarrow$ RESONANT contribution to reaction rate (if allowed by selection rules)

typically:

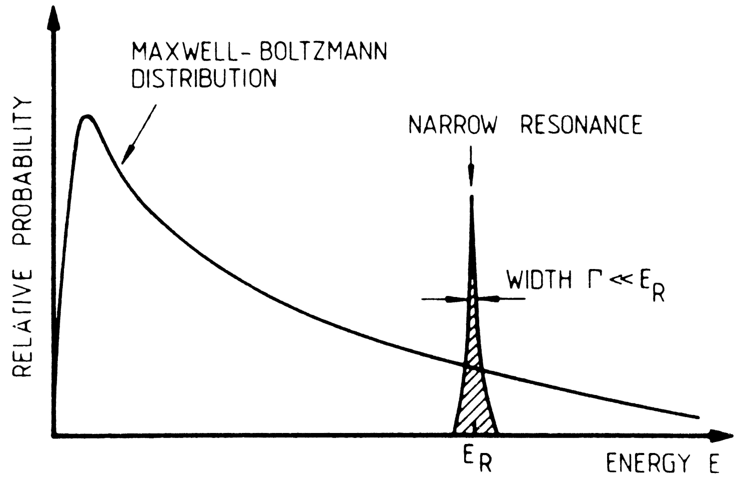
- resonant contributions dominate reaction rate
- reaction rate critically depends on resonant state properties

Reaction Rates

I. Narrow Resonances
II. Broad Resonances
III. Sub-threshold resonances

I. Narrow resonances

$$\Gamma << E_R$$



- resonance must be **near** relevant energy range ΔE_0 to contribute to stellar rate
- MB distribution assumed **constant** over resonance region
- partial widths also **constant**, i.e. $\Gamma_i(E) \cong \Gamma_i(E_R)$

reaction rate for a single narrow resonance

$$\langle\sigma v\rangle_{12} = \left(\frac{2\pi}{\mu_{12}kT}\right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

NOTE

exponential dependence on energy means:

- rate strongly dominated by **low-energy resonances** (**$E_R \rightarrow kT$**) if any
- small uncertainties in E_R (even a few keV) imply large uncertainties in reaction rate

$$\langle\sigma v\rangle_{12} = \left(\frac{2\pi}{\mu_{12}kT}\right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

rate entirely determined by "**resonance strength**" $\omega\gamma$ and **energy of the resonance E_R**

resonance strength

(= integrated cross section over resonant region)

$$\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1\Gamma_2}{\Gamma}$$

(Γ_i values at resonant energies)

$$\Gamma = \Gamma_1 + \Gamma_2$$

often:

$$\Gamma_1 << \Gamma_2 \longrightarrow \Gamma \approx \Gamma_2 \longrightarrow \frac{\Gamma_1\Gamma_2}{\Gamma} \approx \Gamma_1$$

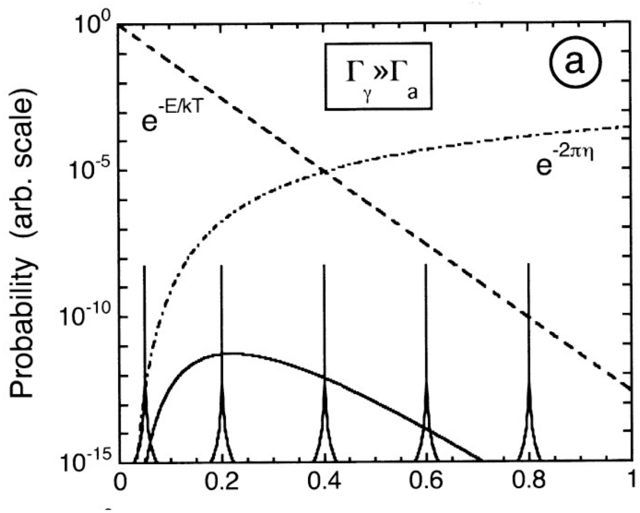
$$\Gamma_2 << \Gamma_1 \longrightarrow \Gamma \approx \Gamma_1 \longrightarrow \frac{\Gamma_1\Gamma_2}{\Gamma} \approx \Gamma_2$$

reaction rate is determined by the **smaller** width !

experimental info needed:

- partial widths Γ_i
- spin **J**
- energy E_R

note: for many unstable nuclei most of these parameters are **UNKNOWN**!



resonant strength dominated by particle width

$\omega\gamma = \omega\Gamma_\alpha$ (typically for $E_R \leq 0.5$ MeV)

- strong energy dependence through Coulomb barrier penetration
- only resonances in Gamow window are relevant to reaction rate

resonant strength dominated by gamma width

$\omega\gamma = \omega\Gamma_\gamma$ (typically for $E_R > 0.5$ MeV)

- lowest energies dominate rate because of $\exp(-E_R/kT)$ term
- no Gamow peak exists!
- effect most important at high temperatures

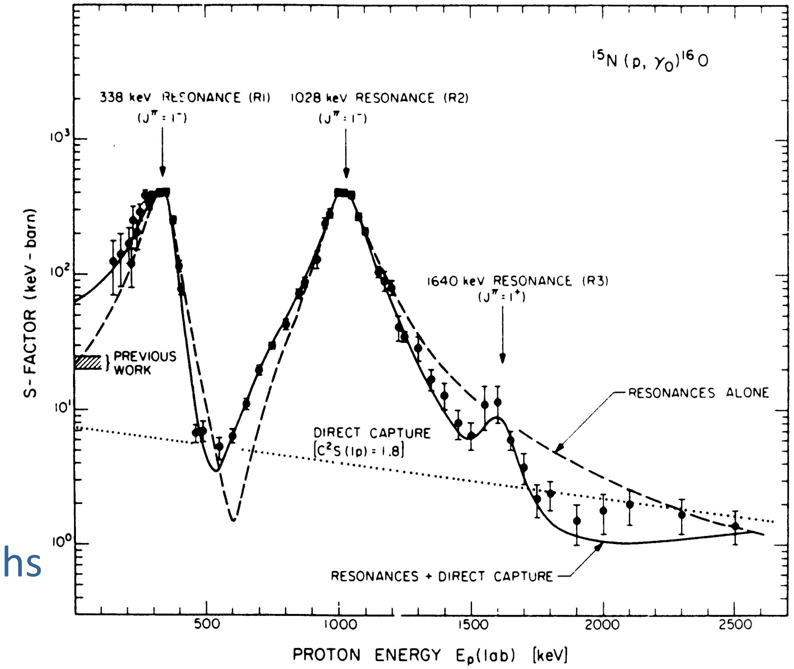
Reaction Rates

I. Narrow Resonances
II. Broad Resonances
III. Sub-threshold resonances

II. Broad resonances $\boxed{\Gamma \sim E_R}$

broader than the relevant energy window for the given temperature

resonances outside the energy range can also contribute through their wings



Breit-Wigner formula
+
energy dependence of partial and total widths

assume: Γ_2= const, Γ = const and use simplified expression

$$\boxed{\sigma(E) = \pi\lambda\!\!\!^{-2}\underbrace{\Gamma_1(E)\omega}_{\text{same energy dependence as in direct process}}\underbrace{\frac{\Gamma_2}{(E-E_R)^2+(\Gamma/2)^2}}_{\text{for } E \ll E_R \text{ very weak energy dependence}}}$$

same energy dependence as in direct process

for E << E_R very weak energy dependence

N.B. overlapping broad resonances of same $J^\pi \rightarrow$ **interference effects**

Reaction Rates

I. Narrow Resonances
II. Broad Resonances
III. Sub-threshold resonances

III. Sub-threshold resonances

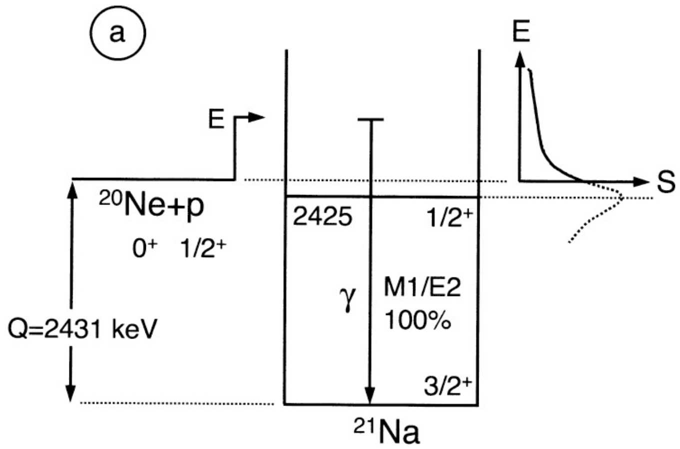
any exited state has a finite width

$\Gamma \sim h/\tau$

high energy wing can extend
above particle threshold

cross section can be entirely dominated
by contribution of sub-threshold state(s)

Examples: $^{20}Ne(p,\gamma)^{21}Na$, $^{12}C(\alpha,\gamma)^{16}O$



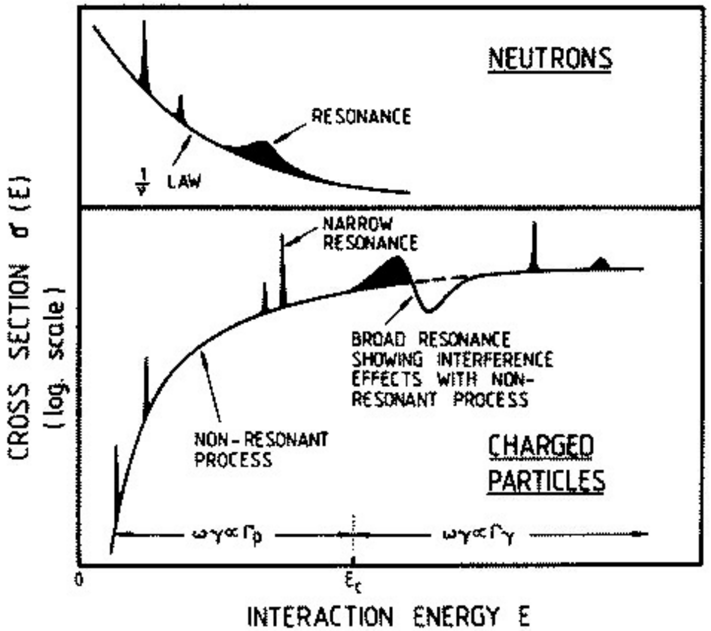
Iliadis, 2007

Total Stellar Reaction Rates

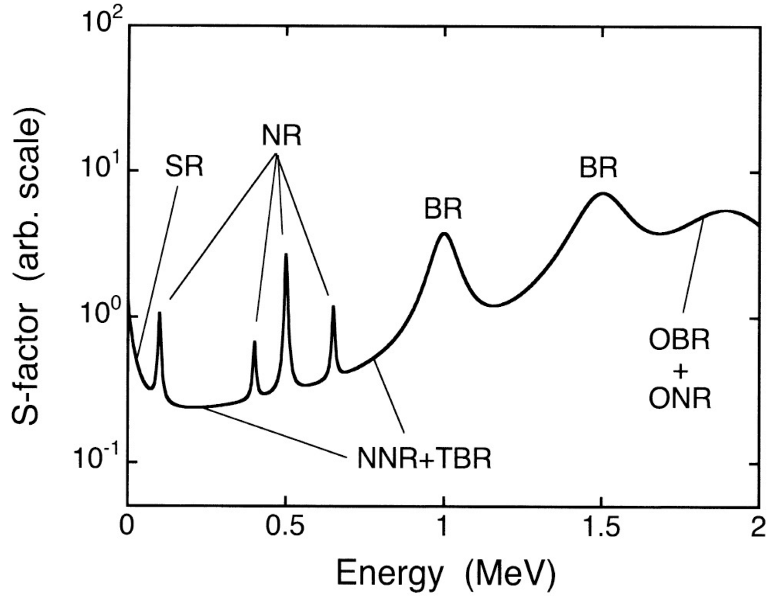
- direct (non-resonant) transitions to the various bound states
- all narrow resonances in the relevant energy window
- broad resonances (tails) e.g. from higher lying resonances
- any interference term

total rate

$$\langle \sigma v \rangle = \sum_i \langle \sigma v \rangle_{\mathrm{DCi}} + \sum_i \langle \sigma v \rangle_{\mathrm{Ri}} + \langle \sigma v \rangle_{\mathrm{tails}} + \langle \sigma v \rangle_{\mathrm{int}}$$



Rolfs, 1988



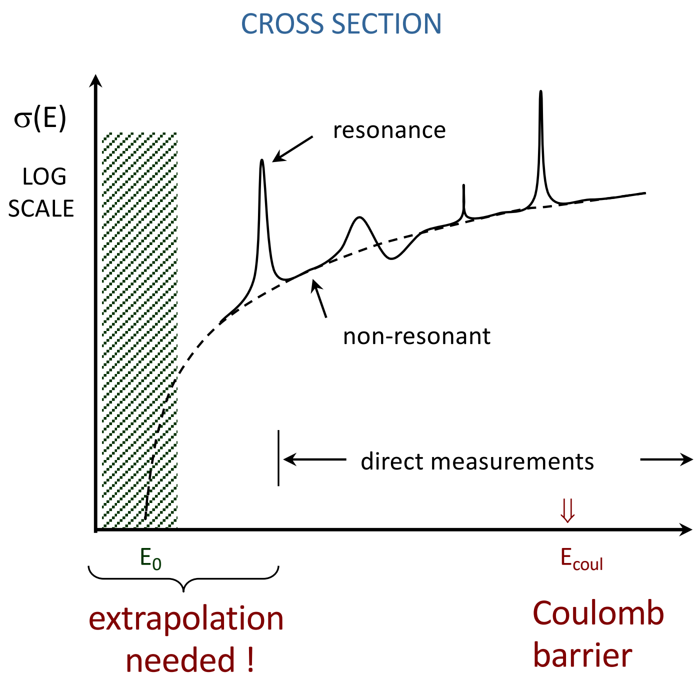
Iliadis, 2007

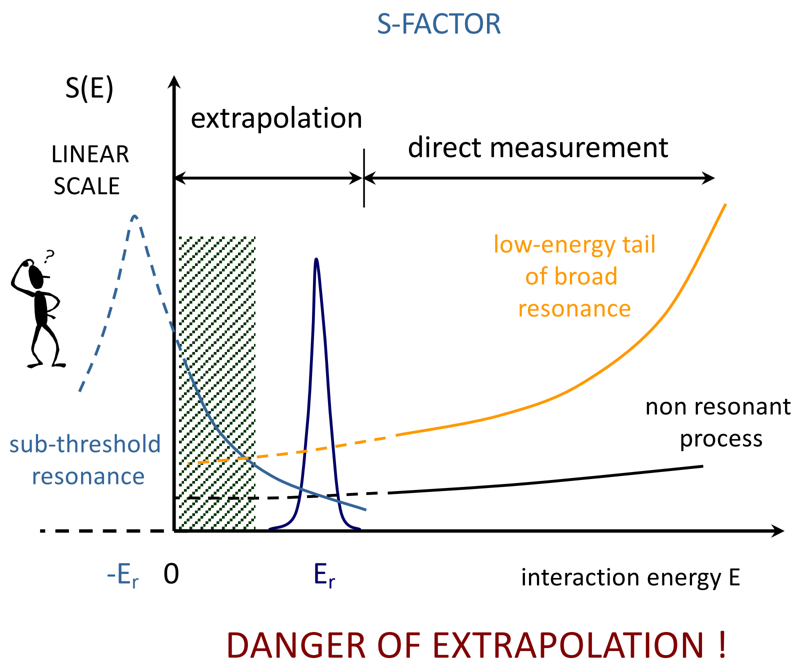
Experimental Challenges and Requirements of Direct Measurements

Gamow peak: energy window where information on nuclear processes is needed

BUT: $kT \ll E_0 \ll E_{coul}$ ➡ 10^{-18} barn < σ < 10^{-9} barn ➡ Major experimental difficulties

Procedure: measure $\sigma(E)$ over wide energy, then extrapolate down to E_0!

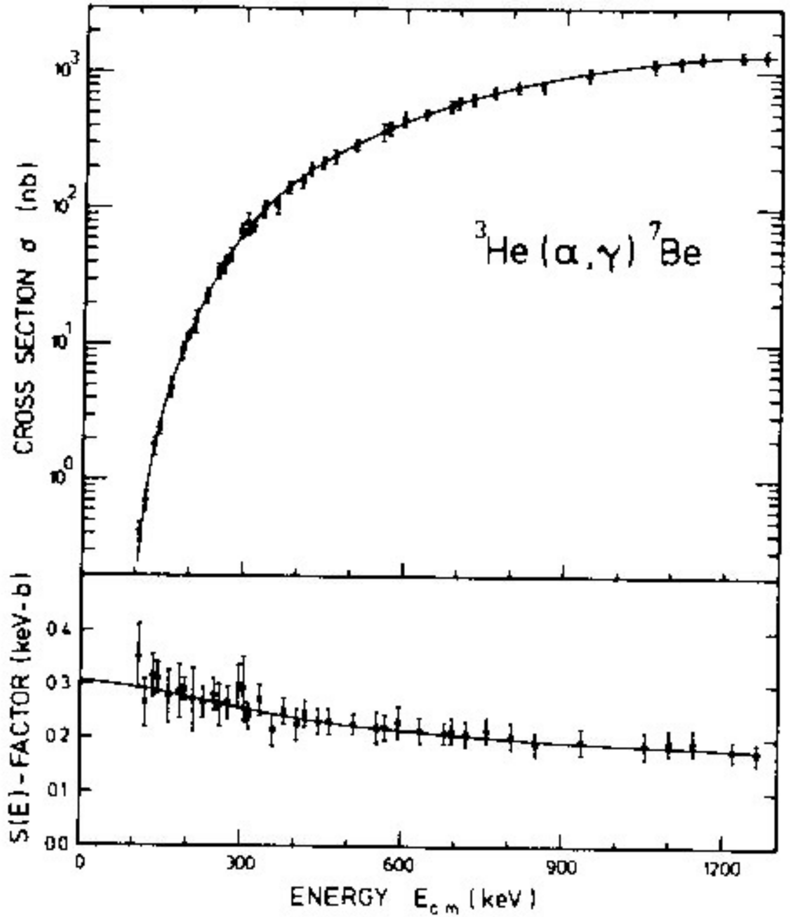




Example: $^{3}He(\alpha,\gamma)^{7}Be$

cross section

S-factor



Data EXTRAPOLATION down to astrophysical energies REQUIRED!

Yield Measurements and Cross Sections

$$\text{Yield} = \frac{\text{total number of reactions}}{\text{total number of incident particles}} = \sigma N_t d$$

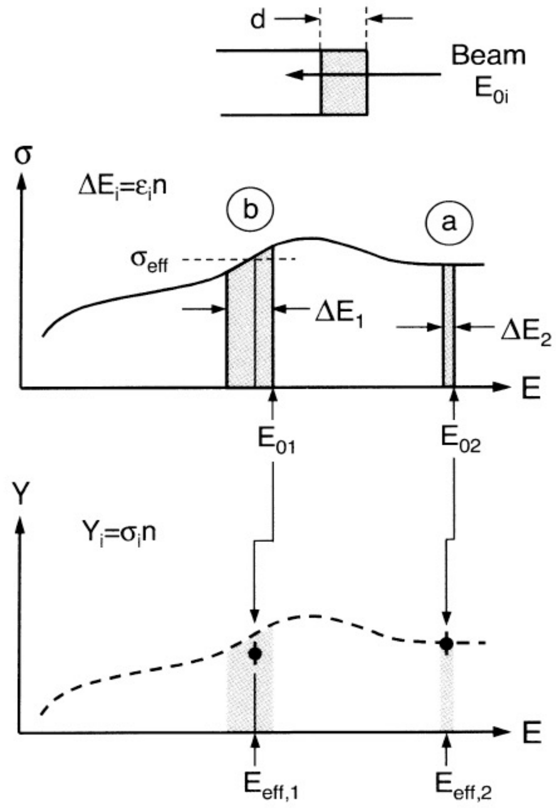
yield vs bombarding energy = *yield curve* or *excitation function*

for non-resonant reactions or for broad resonances

$$Y(E_0) = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\varepsilon(E)} dE = \frac{\sigma(E_{eff})}{\varepsilon(E_0)} \Delta E(E_0)$$

cross section and stopping power $\varepsilon(E)$ are almost constant within small energy region

E_{eff} = energy at which 50% of total yield is obtained



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for **resonant reactions:** yield depends strongly on bombarding energy and target thickness

***thin* target thickness** $\Delta E \ll \Gamma$

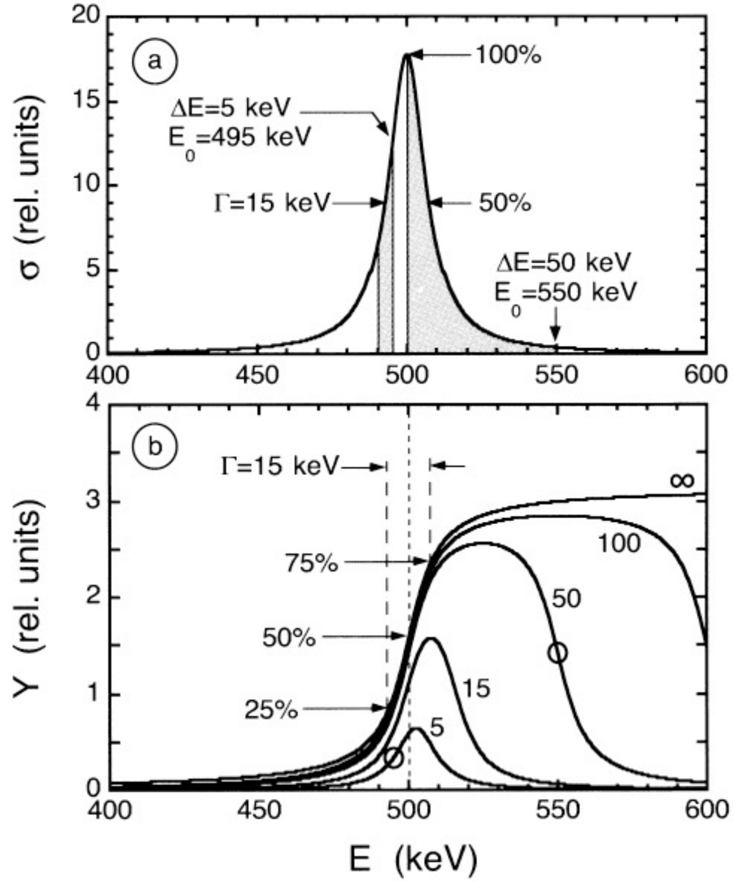
yield curve resembles cross section curve

- max yield at E_R
- FWHM ≈ Γ of resonant state

***thick* target thickness** $\Delta E \gg \Gamma$

yield approaches flat plateau

- max yield at $E_R + \Delta E/2$
- FWHM ≈ ΔE
- Γ = energy difference for $Y_{75\%}$-$Y_{25\%}$



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$\Delta E \to \infty$

$$\boxed{Y_{\max}(\infty) = \frac{\lambda^2}{2}\frac{m_p + m_T}{m_T}\frac{1}{\varepsilon}\omega\gamma}$$

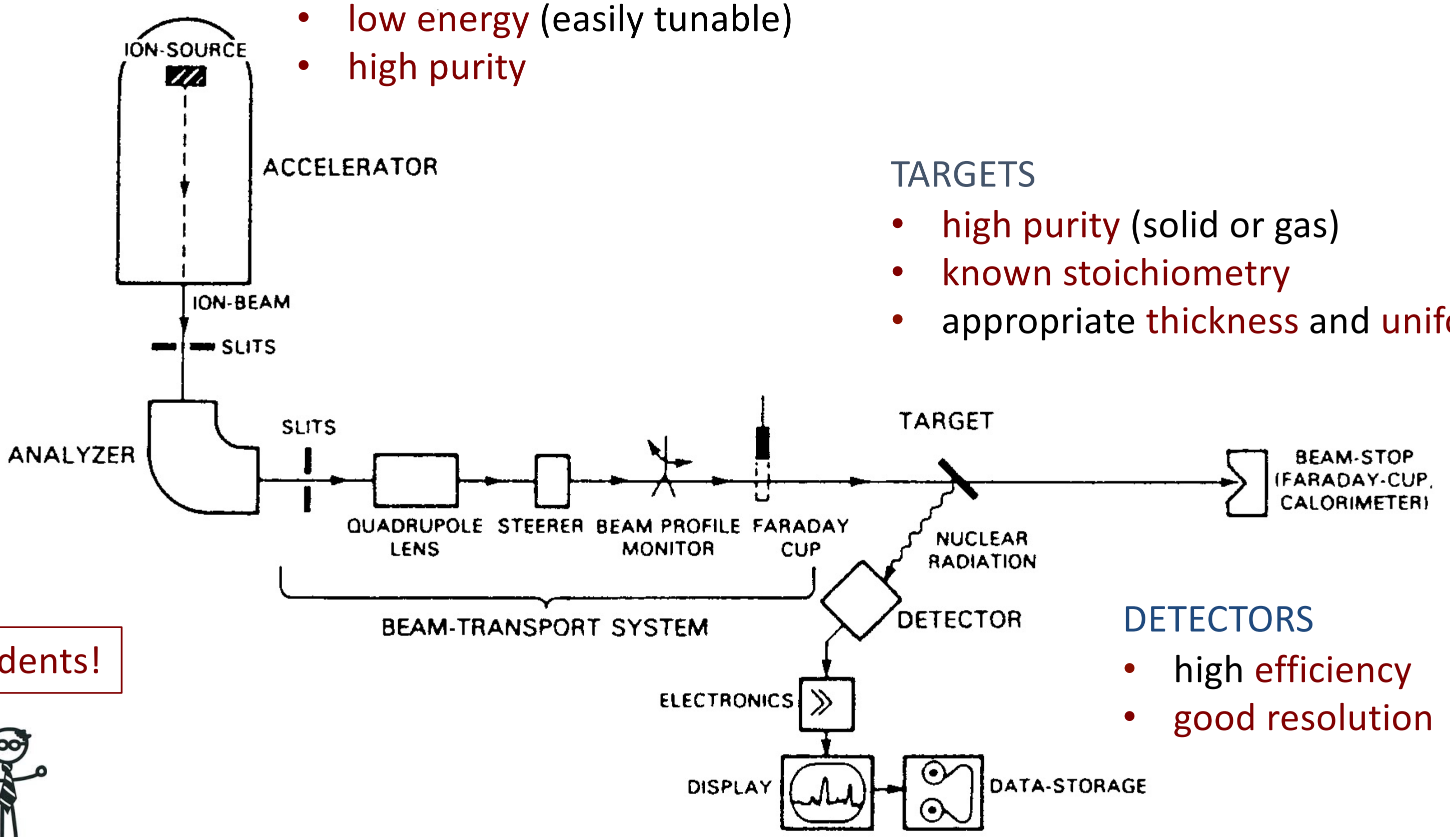
yield measurement gives **directly** $\omega\gamma$

Equipment and General Requirements

Schematic Layout for Nuclear (Astro-)Physics Experiments

BEAMS
- high beam currents
- low energy (easily tunable)
- high purity

TARGETS
- high purity (solid or gas)
- known stoichiometry
- appropriate thickness and uniformity



DETECTORS
- high efficiency
- good resolution

Excellent Students!

In my next Lecture:

- how to mitigate experimental challenges
- LUNA: the first underground laboratory for Nuclear Astrophysics studies
- past achievements and recent results
- future perspectives


THANK YOU