Photon-induced reactions in the lab and under stellar conditions

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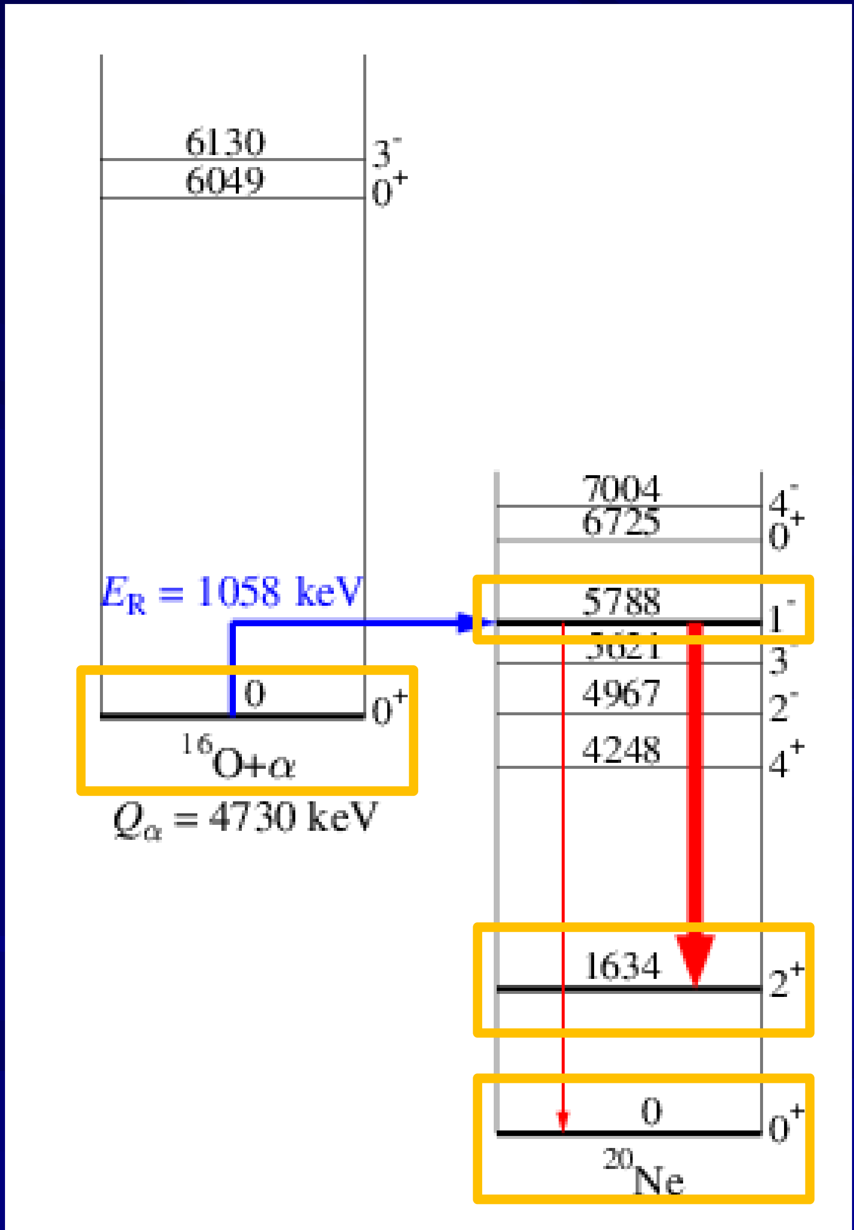
Outline of this presentation (1): formalism

- Difference between:
  $N_A < \sigma v >^*$ and $N_A < \sigma v >^{lab}$
  focus on λ^* and λ^{lab} for photon-induced reactions
- A very simple example:
  $^{16}O(\alpha,\gamma)^{20}Ne$ and $^{20}Ne(\gamma,\alpha)^{16}O$ in the lab and in stars
  P. Mohr *et al.*, EPJA **27**, s01, 75 (2006)
- ***Reciprocity*** for time-reversed ***cross sections***
  $\sigma(1+2 \leftrightarrow 3+\gamma)$
  e.g. $^{16}O_{g.s.}(\alpha_0,\gamma_1)^{20}Ne_{2+}$ and $^{20}Ne_{2+}(\gamma_1,\alpha_0)^{16}O_{g.s.}$
- ***Detailed balance*** between ***stellar reaction rates***
  for photons: $N_A < \sigma v >^*(1+2 \rightarrow 3+\gamma)$ and $\lambda^*(3+\gamma \rightarrow 1+2)$

Outline of this presentation (2): applications

- Thermalization of isomers via intermediate states: ^{180}Ta, ^{176}Lu, ^{186}Re, ^{92}Nb
  - various scenarios: s-process, p-process, ν-process
- Rate of capture reactions between light nuclei from photodisintegration
  - various scenarios: BBN, H-, He-burning
- γ-induced reactions in the p(γ)-process: (γ,n), (γ,α)
- (n,γ) rates from (γ,n) experiments
  - branching points in the s-process
- Suggestions for ELI-NP (and other photon facilities)

$^{16}O(\alpha,\gamma)^{20}Ne$: Full level scheme of ^{20}Ne (to scale)



- For simplicity:
  - discussion restricted to:

  ^{16}O: 0^+ ground state

  ^{20}Ne: 0^+ ground state

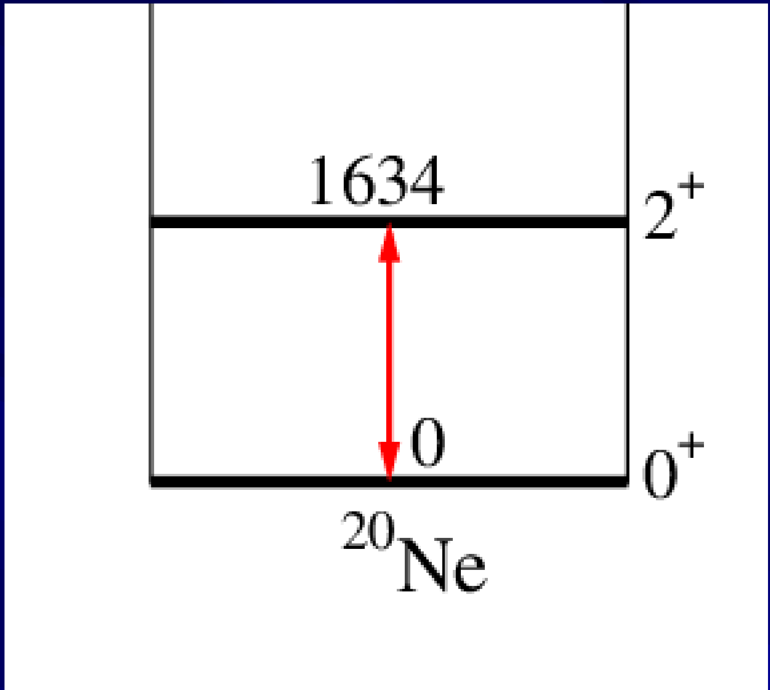
  ^{20}Ne: 2^+ state at 1634 keV

  ^{20}Ne: 1^- state at 5788 keV

  appears as resonance in $^{16}O(\alpha,\gamma)^{20}Ne$ at 1058 keV

  - partition functs. neglected: $G(^{16}O) \approx G(^{20}Ne) \approx 1.0$

Time scale for thermalization: ^{20}Ne ($0^+ \leftrightarrow 2^+$)



Fast transition between 0^+ ground state and 2^+:
$T_{1/2}$ = 0.73 ps
Γ_γ = 0.63 meV

Time scale for thermalization is essentially defined by the lifetime of the 2^+ state

First important message of this talk:
thermalization is fast, compared to typical timescales in stars
(at least for allowed intra-band transitions; isomers will require special consideration)

Some (trivial) definitions…

- Breit-Wigner cross section $\sigma(E)$ in a resonance:

$$\sigma_{BW}(E) = \frac{\pi}{k_\alpha^2} \omega \frac{\Gamma_\alpha \Gamma_\gamma}{(E - E_R^\alpha)^2 + \Gamma^2/4}$$

- Resonance strength $\omega\gamma$:

$$(\omega\gamma) = \omega \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma}$$

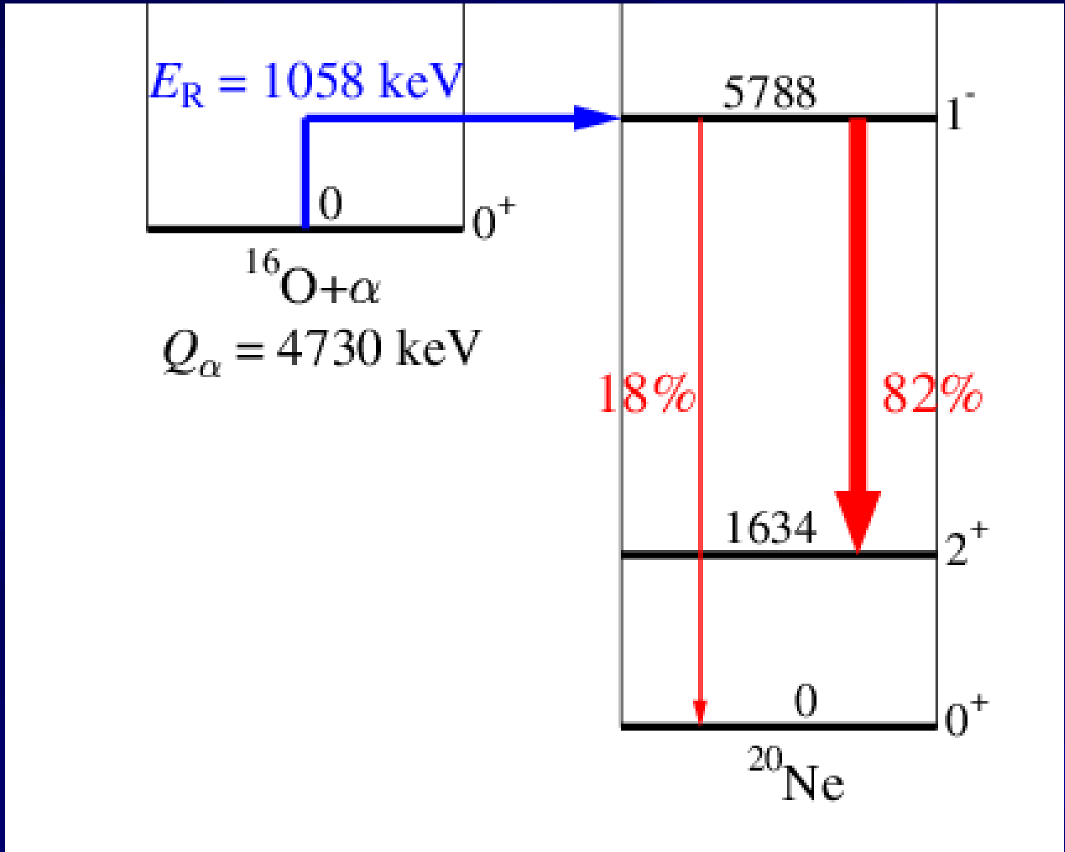
- Total and partial widths Γ, Γ_α, Γ_γ for ^{16}O(α,γ)^{20}Ne:

$$\Gamma = \Gamma_\alpha + \Gamma_\gamma \qquad \Gamma_\alpha = \Gamma_\alpha^0 \qquad \Gamma_\gamma = \Gamma_\gamma^0 + \Gamma_\gamma^{1634}$$

- γ-branching ratio:

$$B^i = \Gamma_\gamma^i / \Gamma_\gamma$$

Reaction rate of $^{16}O(\alpha,\gamma)^{20}Ne$



Stellar rate $< \sigma v >^*$ is proportional to total resonance strength $\omega\gamma$ and to $\exp(-E_R^\alpha/kT)$

0^+ ground state:
$\omega\gamma^0 = 0.18\ \omega\gamma$

2^+ excited state:
$\omega\gamma^{1634} = 0.82\ \omega\gamma$

$$\langle \sigma\, v \rangle^* = \hbar^2 \left(\frac{2\pi}{\mu k T}\right)^{3/2} (\omega\gamma)\, \exp\left(\frac{-E_R^\alpha}{kT}\right)$$

Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: formalism

- Rate λ from folding of thermal photons $n_\gamma(E,T)$ and photon-induced cross section $\sigma(E)$:

$$\lambda = c \int n_\gamma(E_\gamma, T)\, \sigma(E_\gamma)\, dE_\gamma$$

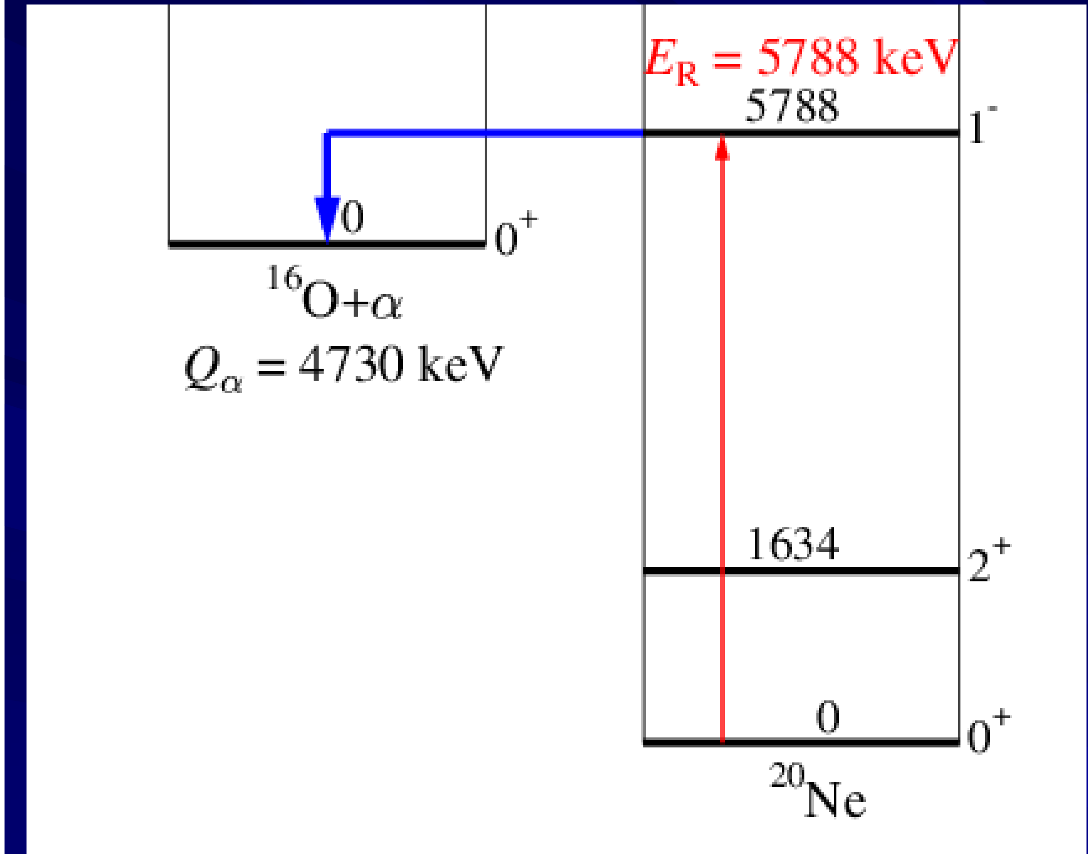
- Photon (Planck) distribution:

$$n_\gamma\,(E_\gamma, T)\, dE_\gamma = \frac{1}{\pi^2}\,\frac{1}{(\hbar c)^3}\,\frac{E_\gamma^2}{\exp\left(E_\gamma/kT\right) - 1}\, dE_\gamma$$

- $\sigma(E)$ from (narrow) B-W resonance (using reciprocity):

$$\lambda^b = \frac{1}{\hbar}\,\frac{(2J_1+1)(2J_2+1)}{(2J_3+1)}\, B^b\left(\omega\gamma\right)\, \exp\left(\frac{-E_R^\gamma}{kT}\right)$$

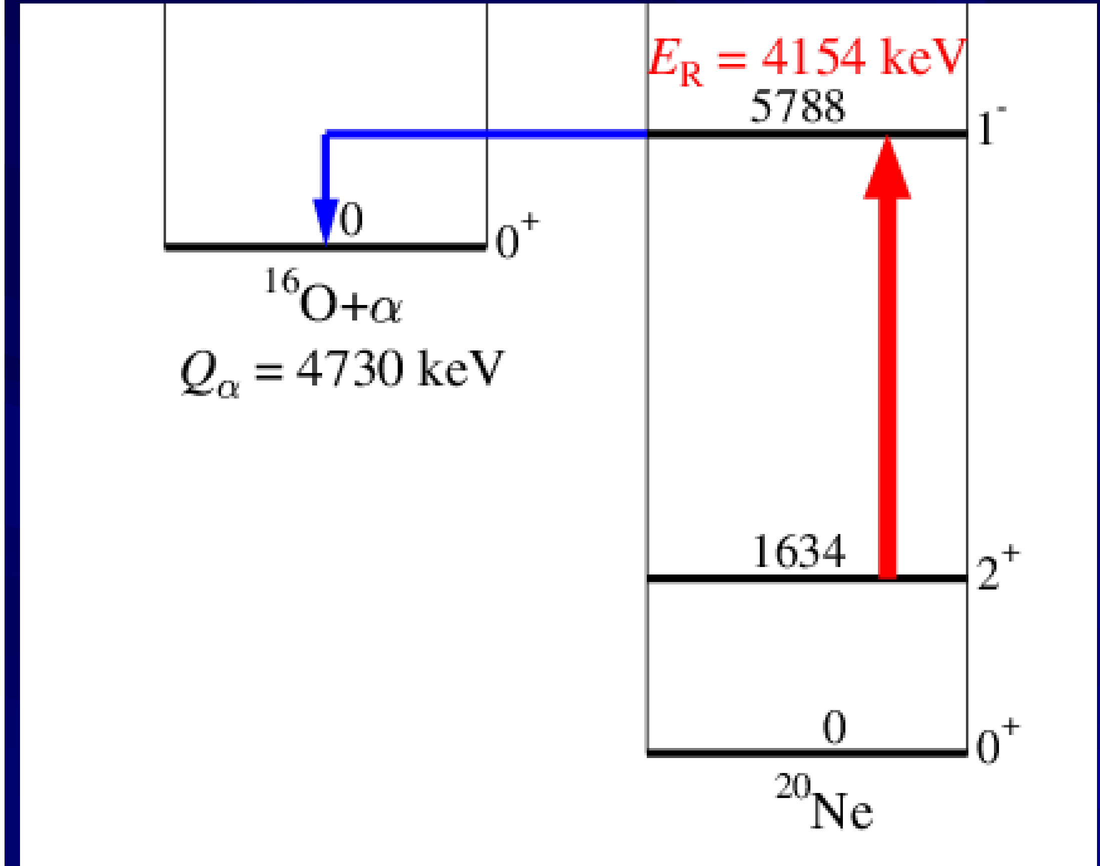
Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: (a) 0^+ ground state



Rate from 0^+ g.s.: proportional to partial resonance strength $\omega\gamma^0$ and to $\exp(-E_R^\gamma/kT)$

$$\lambda^0 = \frac{1}{\hbar} B^0 (\omega\gamma) \exp\left(\frac{-E_R^\gamma}{kT}\right)$$

Reaction rate of ^{20}Ne(γ,α)^{16}O: (b) 2^+ excited state

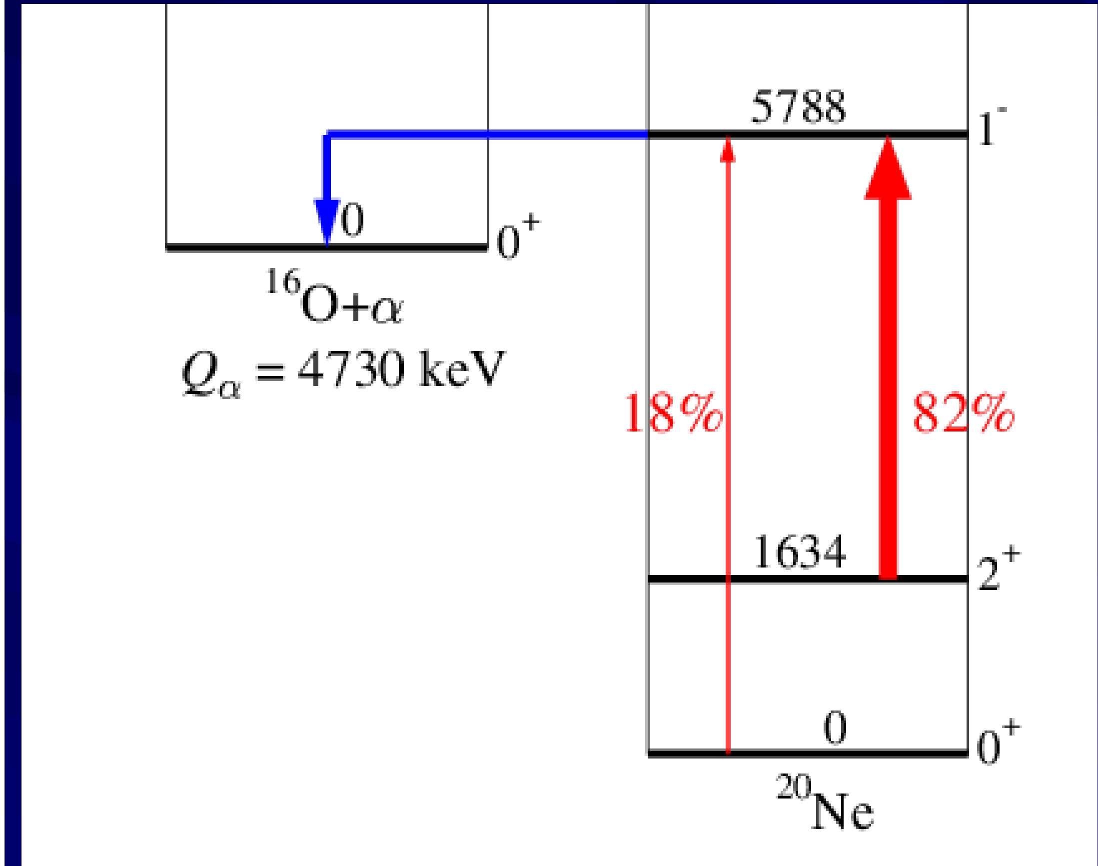


Rate from excited 2^+: proportional to partial res. strength $\omega\gamma^{1634}$ and to $\exp[-(E_R^{\gamma}-E_x)/kT]$

enhancement by factor $\exp(+E_x/kT)$ for excited state because of lower transition energy $E_R^{\gamma}-E_x$!

$$\lambda^{1634} = \frac{1}{\hbar}\,\frac{1}{5}\,B^{1634}\,(\omega\gamma)\,\exp\left(\frac{-(E_R^{\gamma}-E_x^{1634})}{kT}\right)$$

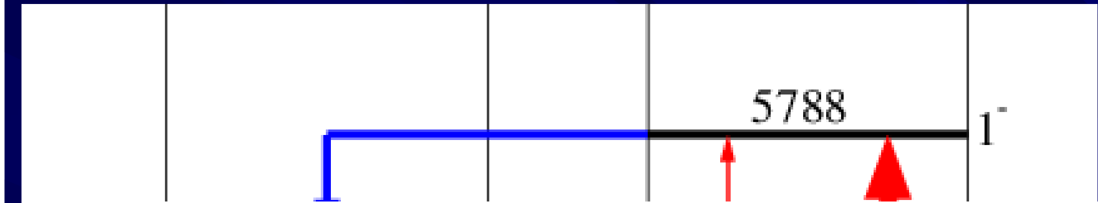
Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: (c) stellar rate λ^*



Stellar rate λ^* from weighted summation (Boltzmann factors):

$$n^{1634}/n^0 = \frac{(2J^{1634}+1)}{(2J^0+1)} \exp\left(\frac{-E_x^{1634}}{kT}\right)$$

Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: (c) stellar rate λ^*



Stellar rate λ^* from weighted summation

$$\lambda^\star \approx \frac{1}{\hbar}(\omega\gamma)\left[B^0 \exp\left(\frac{-E_R^\gamma}{kT}\right) + \right.$$

← 0^+ g.s.

2^+ (1634) →

$$\left. \frac{1}{5} B^{1634} \exp\left(\frac{-(E_R^\gamma - E_x^{1634})}{kT}\right) 5 \exp\left(\frac{-E_x^{1634}}{kT}\right)\right]$$

$$= \frac{1}{\hbar}(\omega\gamma)\,(B \ldots) \exp\left(\frac{\ldots}{kT}\right)$$

E_γ enhancement

Boltzmann suppression

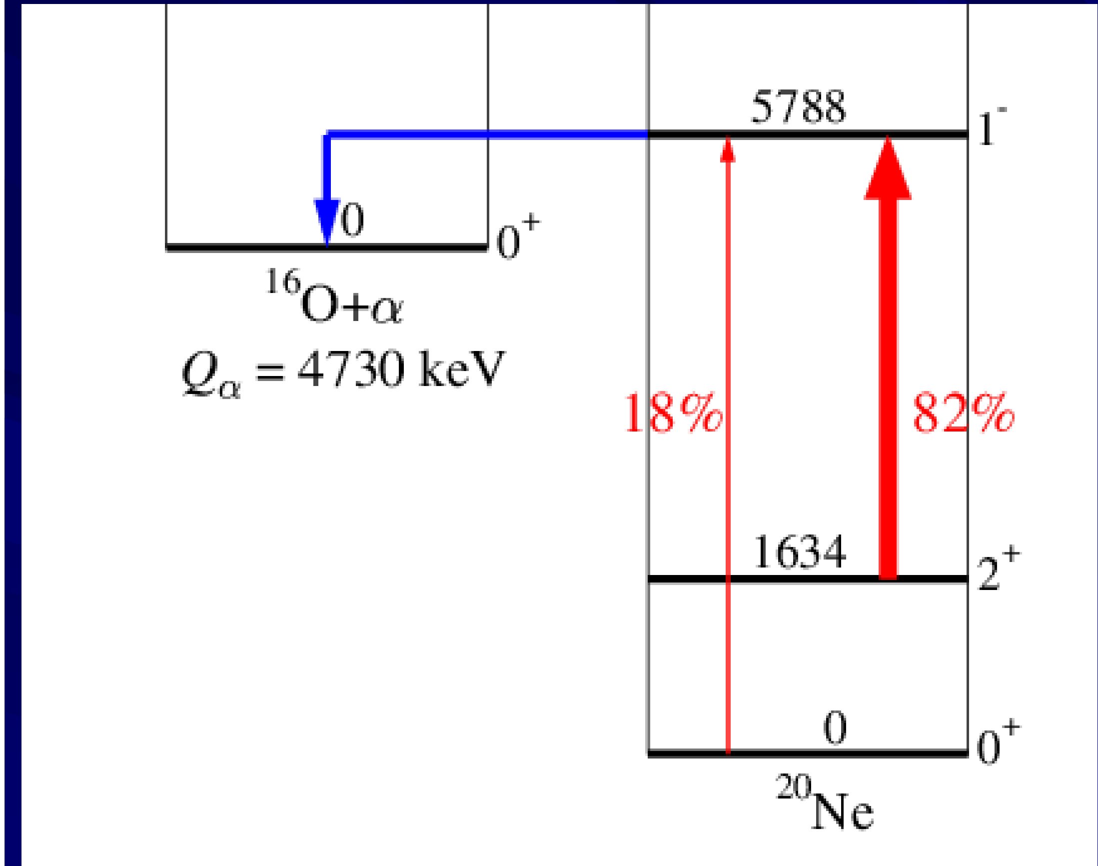
$$= \frac{1}{\hbar}(\omega\gamma)\exp\left(\frac{-E_R^\gamma}{kT}\right)$$

proportional to total $\omega\gamma$ and exp(-5788 keV/kT)

exactly cancel each other!

$$r \ldots = \frac{1}{\hbar}(\omega\gamma)\exp\left(\frac{-E_R^\alpha}{kT}\right)\exp\left(\frac{-Q}{kT}\right)$$

Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: (c) stellar rate λ^*



Stellar rate $\lambda^* \geq \lambda^{lab}$

proportional to total resonance strength $\omega\gamma$ and to $\exp(-E_R^{\gamma}/kT)$

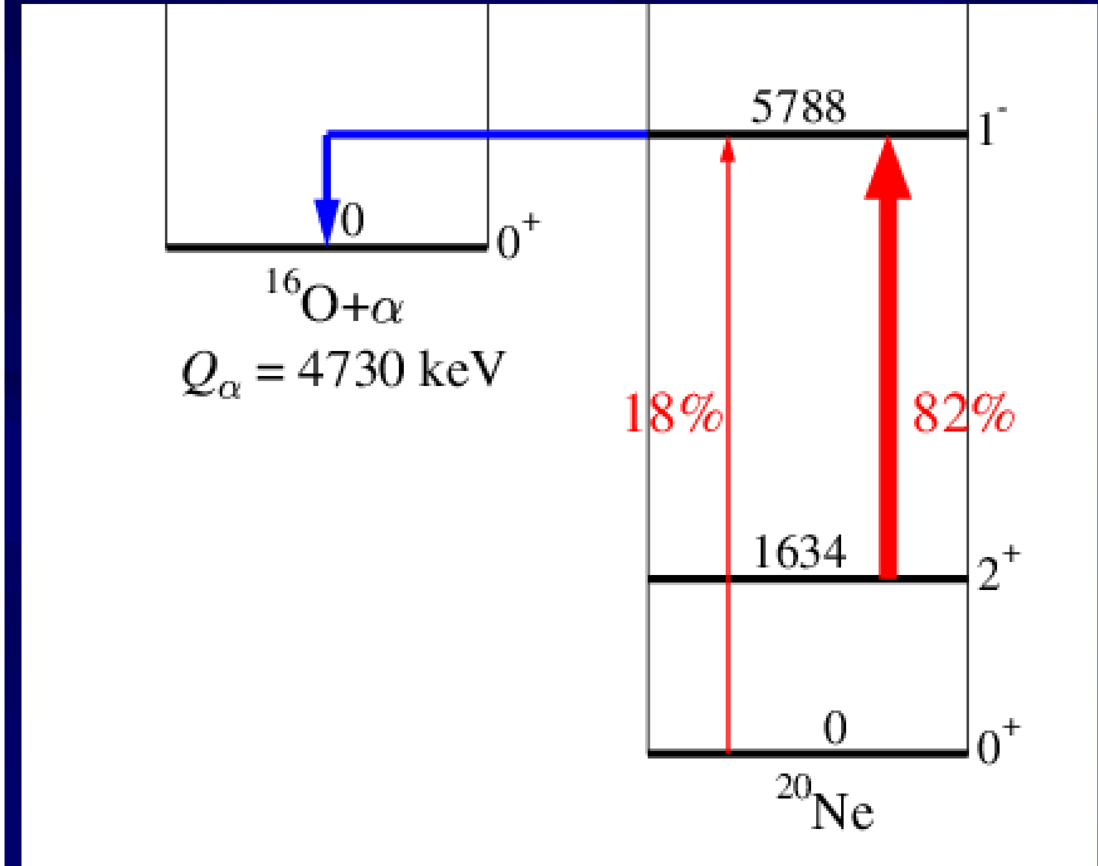
$\lambda^*/\lambda^{lab} = (\omega\gamma)/(\omega\gamma^0) \geq > 1$

exact cancellation

between enhancement from lower E_γ and Boltzmann suppression

$$\lambda^\star = \frac{1}{\hbar}(\omega\gamma)\,\exp\left(\frac{-E_R^\gamma}{kT}\right) = \frac{1}{\hbar}(\omega\gamma)\,\exp\left(\frac{-E_R^\alpha}{kT}\right)\,\exp\left(\frac{-Q}{kT}\right)$$

Reaction rate of $^{20}Ne(\gamma,\alpha)^{16}O$: (c) stellar rate λ^*



Stellar rate $\lambda^* \geq \lambda^{lab}$

proportional to total resonance strength $\omega\gamma$ and to $\exp(-E_R^\gamma/kT)$

$\lambda^*/\lambda^{lab} = (\omega\gamma)/(\omega\gamma^0) \geq 1$

ratio λ^*/λ^{lab} depends only on nuclear properties, but not on stellar temperature!

$$\lambda^\star = \frac{1}{\hbar}(\omega\gamma)\exp\left(\frac{-E_R^\gamma}{kT}\right) = \frac{1}{\hbar}(\omega\gamma)\exp\left(\frac{-E_R^\alpha}{kT}\right)\exp\left(\frac{-Q}{kT}\right)$$

Detailed balance betw. $^{16}O(\alpha,\gamma)\,^{20}Ne$ and $^{20}Ne(\gamma,\alpha)^{16}O$

- stellar $^{16}O(\alpha,\gamma)^{20}Ne$ capture rate:

$$\langle \sigma\, v \rangle^* \;=\; \hbar^2 \left(\frac{2\pi}{\mu k T} \right)^{3/2} \; (\omega\gamma) \; \exp\left(\frac{-E_R^\alpha}{kT} \right)$$

- stellar $^{20}Ne(\gamma,\alpha)^{16}O$ photodisintegration rate:

$$\lambda^\star \;=\; \frac{1}{\hbar}\,(\omega\gamma)\; \exp\left(\frac{-E_R^\gamma}{kT} \right) \;=\; \frac{1}{\hbar}\,(\omega\gamma)\; \exp\left(\frac{-E_R^\alpha}{kT} \right)\; \exp\left(\frac{-Q}{kT} \right)$$

- Detailed balance between ***stellar*** forward (α,γ) and backward (γ,α) ***rates***:

$$\frac{\lambda^\star}{\langle \sigma v \rangle^\star} \;=\; \left(\frac{\mu\, kT}{2\pi\hbar^2} \right)^{3/2} \; \exp\left(\frac{-Q}{kT} \right)$$

Summary of formalism: three important messages

1) Thermalization is fast

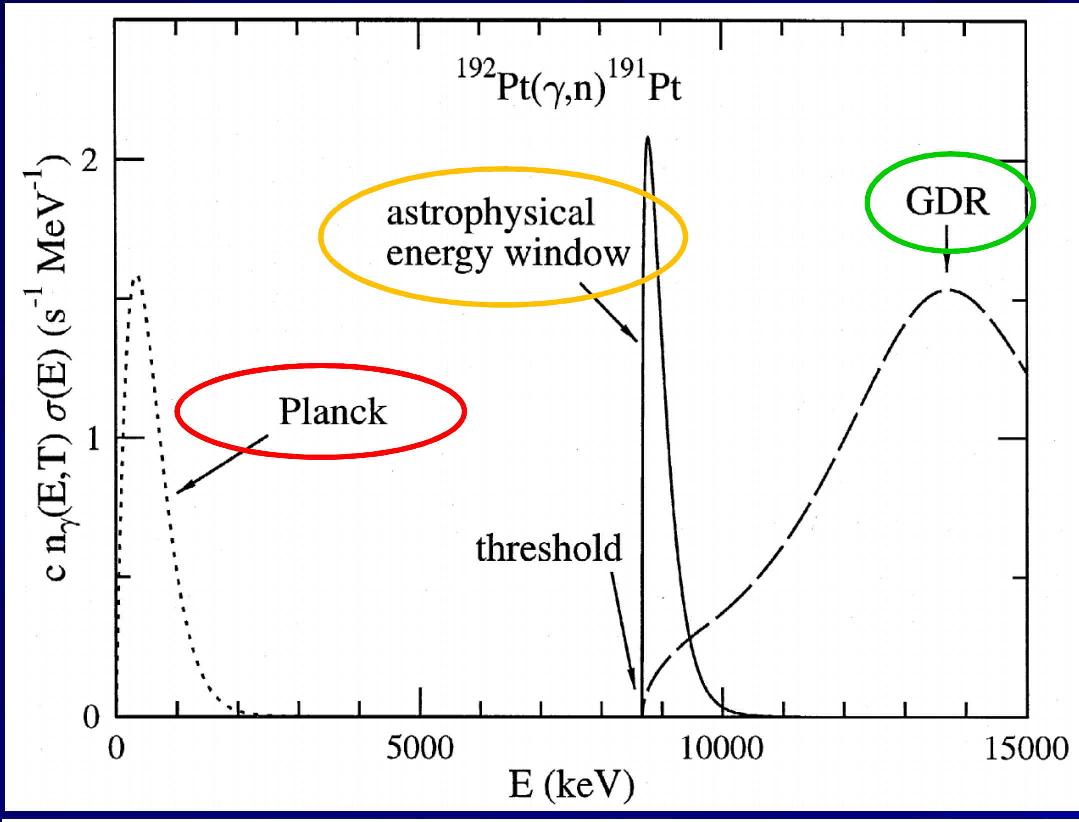
2) Detailed balance between stellar forward and backward rates (not cross sections!)

3) Significant (often: dramatic!) enhancement for stellar rates of photon-induced reactions:
$\lambda^{*}/\lambda^{lab} = (\omega\gamma)/(\omega\gamma^{0}) = 1/B^{0} \geq 1$

- lab experiments *miss contributions of excited states*
- lab experimts. *miss resonances without gs branching*

similar results for non-resonant reactions:
λ^{lab} provides only the (typically minor) ground state contribution

Gamow-like window for photon-induced reactions ?



first presentation of a Gamow-like window:
P. Mohr *et al.*,
PLB **488**, 127 (2000)

chosen example:
$^{192}Pt(\gamma,n)^{191}Pt$

similar for (γ,α) react.

$$\lambda = c \int n_\gamma(E_\gamma, T)\, \sigma(E_\gamma)\, dE_\gamma$$

Conclusion (1): Thermalization of isomers

- most important:
  intermediate states (IMS) at low excitation energies
- typically: lowest IMS for transitions between low-*K* and high-*K* states have intermediate J^{π}
- consequence: branching from IMS to ground state (with either high-*K* or small-*K*) very small (or even negligible)
- in such cases: experiments under laboratory conditions cannot provide the stellar transition rate λ^* between low-*K* and high-*K* states (e.g., ^{180}Ta)
- experimental data are very useful to analyze the structure of IMS

Conclusion (2): capture reactions

- Stellar rate of capture reactions between light nuclei can be estimated from photodisintegration
- essential prerequisite:
  dominating ground state branching in capture reaction
- alternatively:
  ground state contribution sufficiently strong and well-known from other experiments
- few good examples: $^{2}H(\alpha,\gamma)^{6}Li$, $^{3}H(\alpha,\gamma)^{7}Li$, $^{12}C(\alpha,\gamma)^{16}O$
- ground state contribution minor for many cases
- many bad examples: $^{15}N(\alpha,\gamma)^{19}F$, $^{20}Ne(\alpha,\gamma)^{24}Mg$, …

Conclusion (3): (γ,n) and (γ,α) in the γ-process

- relevant: heavy nuclei (A > 100)
- typically: ground state contribution in (n,γ) and (α,γ) reactions small or even negligible
- experimental (γ,X) data cannot provide stellar (γ,X) reaction rates
- experimental (γ,X) data are essential to constrain model parameters (gamma-ray strength function)

- above arguments also hold for (n,γ) rates from (γ,n) experiments (for branching points in the s-process)

Final conclusion

- Significant difference between (γ,X) in the lab and (γ,X) under stellar conditions
- Reason: thermally excited states in the target nucleus in the hot stellar plasma
- Bad news: determination of (γ,X) rates from (γ,X) experiments not possible in most cases
- Good news: experimental (γ,X) data are essential to constrain theoretical models

Thank you very much
for your attention!