Nuclear astrophysics (fusion up to Fe, s-, p-, r- processes)

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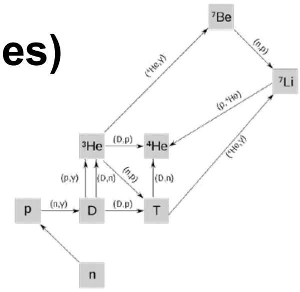


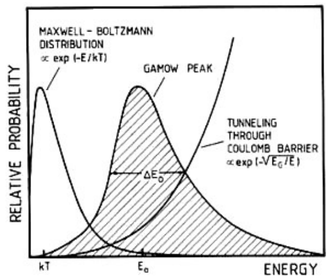
Primordial Nucleosynthesis

$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$
$$\nu_e + n \longleftrightarrow p + e^-$$
$$e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

- 10^{-30}s: 10^{25}K, quark gluon plasma
- 10^{-6} s: 10^{13} K, proton/neutron pair production
- 10^{-4} s: 10^{12}, pair production stops, free p/n annihilate
- 10^{-2} s: 10^{11} K, p↔n equilibrium, neutrino production
- 1 s; 10^{10} K, freeze out n:p=1:7, neutrino decouple from baryonic matter, cosmic ν background
- 10-1000 s: 10^{9} -10^{7} K: d production, ^{4}He formation, also ^{6,7}Li, ^{2,3}H, ^{3}He, ^{7,8}Be. H:He=3:1
- 380 000 y: 4000 K: gravity> photon radiation, atoms form, universe transparent, cosmic microwave background radiation, no further absorption/emission = dark age
- 1 mio y: gravity instabilities in dark matter: gravity sinks for baryonic, larger structures form

Nuklear Fusion

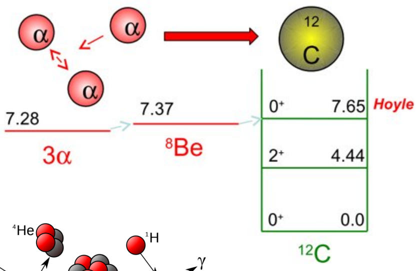
$$G = \int_R^{r_E} \mathrm{d}r \frac{\sqrt{2m_\alpha(V(r)-E)}}{\hbar}$$



- Coulomb potential repulses: barrier
- Thermal Energy (Maxwell Boltzmann distribution)
- Quantum tunnelling through barrier
- Overlap form Gamow area, Gamow Factor probability of Fusion

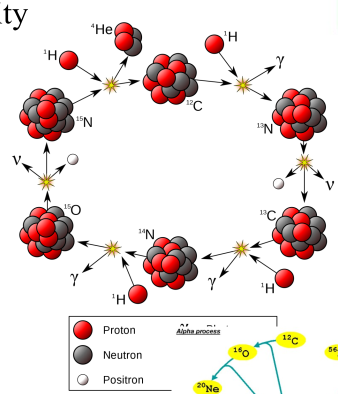
H Burning

- P-p-I chain 4 ^{1}H → ^{4}He + 2e$^+$ + 2ν_e + 2γ + 26.2 MeV
- M > 0.08 $M_\odot$, ρ > 10 g/cm³, dominates if M < 1.2 $M_\odot$,
- Our sun: P-p-I: 91 %, p-p-II: 9 %, p-p-III: 0.1 %



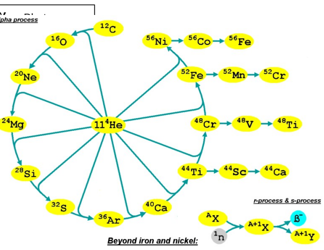
He Burning

- 3α process for ^{12}C: ^{8}Be unstable, so 3 ^{4}He needed
- T > 10^8 K, M > 0.08 $M_\odot$
- Exciteded hoyle state ^{12}C* decays to base state 0.41 % probability
- Bottleneck for larger elements



CNO cycle

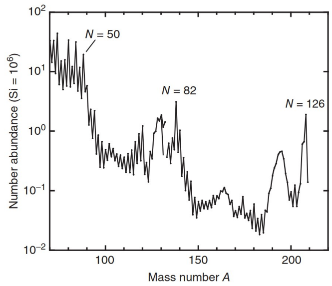
- catalysts cycled: ^{13}N, ^{14}N, ^{15}N, ^{12}C, ^{13}C, ^{15}O
- $4\ {}^1\mathrm{H} + 2\mathrm{e}^- \rightarrow\ {}^4\mathrm{He} + 2\nu_\mathrm{e} + 7\gamma + 26.7\ \mathrm{MeV}$
- Starts 15·10^6 K, dominant M > 1.3 M⊙, T > 17·10^6 K
- Our sun: 1.7% of He from CNO
- ^{12}C/^{13}C=3.5



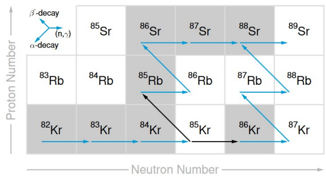
C, Ne, O, Si Burning

- Once fuel is used up: next process → layers
- Each phase is hotter, denser and has shorter duration (2 ky, 0.7 y, 2.6 y, 18 d)
- C Burning: 2 ^{12}C form ^{24}Mg*, decaying to ^{16}O, ^{24}Mg, ^{20} Ne and n
- Ne Burning: photodisintegration ^{20}Ne+γ → ^{6}O + ^{4}He, then ^{20}Ne $^{+4}$He → ^{24}Mg+γ
- O Burning: double magic nucleus. Fusion of 2 ^{16}O. 90% of final product ^{28}Si, ^{32}S
- Si Burning: a process, ^{4}He capture up to ^{56}Ni, decay to ^{56}Fe
- After Si core collapse, ^{56}Fe most abundant, binding E max and product of α-process

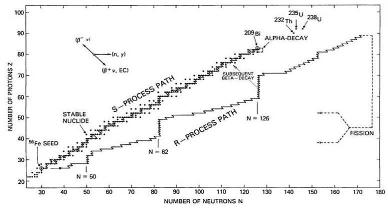
S process



- Slow neutron capture (n density 10^{6}-10^{11}/cm³, red giants)
- Captures n, decays with β-. Enough time to move along stability
- Nucleosynthesis almost 50% nuclides heavier than Fe.
- Ends in Pb, Bi, Po due to alpha decay
- Abundance proportional to 1/σ
- Magic number, closed shell energetically favourable
- Branching points where capture and decay rates similar
- Some Isotope shielded by stable nuclei from p-process
- $R = \frac{\lambda_\beta}{\lambda_n} = \frac{1}{\tau_\beta N_n \langle \sigma v \rangle_A}$ determines Neutron flux, temperature and density



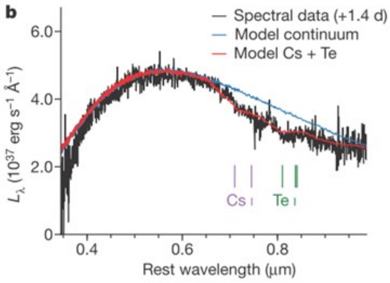
R process



- Rapid neutron capture, Timescale 0.5-30 s.
- 10^{28}/cm³, 10^{9}K, core collapse supernova, star merger, nucl. Weapons
- N capture equilibrium with photodissociation ~ 2 MeV separation energy
- Waiting points for β- decay
- At m>270 spontaneous fission, then reiteration
- Also 50% of nuclides heaver than Fe → abundance difference natural – s process
- After cooling down or neutron flux: decay to stable nuclei
- Abundance proportional to beta decay time

Event GW170817

- Gravitational wave detected in LIGO & VIRGO: two Heavy ($1M_\odot$), small object
- Also Optical spectra via Hubble a. o.: black body radiation missing Te/Cs
- Only via n capture → two neutron stars
- Detected Gold Platinum, Strontium
- Improved hubble constant, general relativity, ratio speed of light and gravity, proved neutron mergers cause short gamma ray bursts



P process

- Proton capture, p-nuclides generation
- Proton capture + β^{+} decay against coulomb barrier (less abundance)
- $T>2\cdot10^{9}$, high proton density, see nuclei form s/r, timescale 1 s
- P capture can not produce p-nuclides (photodissocation, too low N_p in core collapse supernovae)
- ~35 p-nuclides not by r/p process, maxima at magic numbers, even N, Z, only 1% abundance of s/r.
- Not yet clear how they are produced
- γ process: (γ,n), (γ,α) and (γ,p) , $T\sim2\cdot10^{9}$ K, abundance would match
- ν process: excitation via neutrino + dissociation
- rp: rapid proton capture: requires 10^{28} p/cm^{3}, $T>2\cdot10^{9}$ K (accreting neutron star)
  - Timescale 10 – 600 s, Waiting points ^{56}Ni, ^{60}Zn, ^{64}Ge, ^{68}Se
  - Stops at Sn-Sb-Te cycle (a-decay), m < 105 u
- np: skip Waiting points by neutron reactions. Unlikely in high p rich areas
- νp: neutrino generates neutron to skip waiting points. Requires high flux of p and ν