**CNO cycle notes**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 12 6C | + | 1 1H | → | 13 7N | + | [γ](https://en.wikipedia.org/wiki/Gamma_ray) |  |  | + | 1.95 [MeV](https://en.wikipedia.org/wiki/Electron_volt) |
| 13 7N |  |  | → | 13 6C | + | [e+](https://en.wikipedia.org/wiki/Positron) | + | [ν e](https://en.wikipedia.org/wiki/Electron_neutrino) | + | 1.20 MeV | ([half-life](https://en.wikipedia.org/wiki/Half-life) of 9.965 minutes[[16]](https://en.wikipedia.org/wiki/CNO_cycle#cite_note-half-life-cn-16)) |
| 13 6C | + | 1 1H | → | 14 7N | + | γ |  |  | + | 7.54 MeV |  |
| 14 7N | + | 1 1H | → | 15 8O | + | γ |  |  | + | 7.35 MeV |  |
| 15 8O |  |  | → | 15 7N | + | e+ | + | ν e | + | 1.73 MeV | (half-life of 2.034 minutes[[16]](https://en.wikipedia.org/wiki/CNO_cycle#cite_note-half-life-cn-16)) |
| 15 7N | + | 1 1H | → | 12 6C | + | 4 2He |  |  | + | 4.96 MeV |  |

* Is a catalytic cycle, protons react with C, N and O which are catalysts (each one is consumed at one step but re-generated at a later step).
* Starting point is the 12C reaction with a proton to create 13N
* 13N undergoes B+ decay to form 13C which then reacts with a proton to form 14N, this reaction plays a key role for the nuclear energy production in massive stars
* The next reaction is 14N reacting with a proton to create 15O. This is the slowest reaction in the cycle and therefore controls energy production.
* 15O then undergoes beta+ to form 15N which then reacts with a proton to form 12C and 42He
* Hydrogen goes into the cycle, Helium comes out with 12C to restart the cycle.
* The end product is 1 alpha particle (He), two e+ and two electron neutrinos but the e+ will instantly annihilate with e- which will release gamma rays and 2MeV.
* Total energy generation is 26.7MeV (24.7MeV from reactions + 2MeV from annihilation)
* The neutrinos escape from the star carrying away energy
* The cycle allows massive stars to produce heavy elements which are scattered during the star’s death

“we find that a star with a mass larger than ∼ 1.3 M⊙ or having a central temperature greater than ∼ 1.7 × 107 K has its energy generation dominated by the CNO bi-cycle”[2]

There are multiple cycles much like P-P reactions:

**CNO-II**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 15 7N | + | 1 1H | → | 16 8O | + | γ |  |  | + | 12.13 MeV |
| 16 8O | + | 1 1H | → | 17 9F | + | γ |  |  | + | 0.60 MeV |
| 17 9F |  |  | → | 17 8O | + | e+ | + | ν e | + | 2.76 MeV | (half-life of 64.49 seconds) |
| 17 8O | + | 1 1H | → | 14 7N | + | 4 2He |  |  | + | 1.19 MeV |  |
| 14 7N | + | 1 1H | → | 15 8O | + | γ |  |  | + | 7.35 MeV |  |
| 15 8O |  |  | → | 15 7N | + | e+ | + | ν e | + | 2.75 MeV | (half-life of 122.24 seconds) |

The Fluorine produced in this minor branch is an intermediate product meaning at steady state it does not accumulate in the star

**CNO-III**

Significant only in massive stars, reactions start when reaction step 4 in CNO-II results in 18F and gamma ray instead of 14N and 4He:

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 17 8O | + | 1 1H | → | 18 9F | + | γ |  |  | + | 5.61 MeV |
| 18 9F |  |  | → | 18 8O | + | e+ | + | ν e | + | 1.656 MeV | (half-life of 109.771 minutes) |
| 18 8O | + | 1 1H | → | 15 7N | + | 4 2He |  |  | + | 3.98 MeV |  |
| 15 7N | + | 1 1H | → | 16 8O | + | γ |  |  | + | 12.13 MeV |  |
| 16 8O | + | 1 1H | → | 17 9F | + | γ |  |  | + | 0.60 MeV |  |
| 17 9F |  |  | → | 17 8O | + | e+ | + | ν e | + | 2.76 MeV | (half-life of 64.49 seconds) |

**CNO-IV**

Only significant in massive stars, reactions start when step 3 in CNO-III results in 19F and a gamma ray instead of 15N and 4He

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 18 8O | + | 1 1H | → | 19 9F | + | γ |  |  | + | 7.994 MeV |
| 19 9F | + | 1 1H | → | 16 8O | + | 4 2He |  |  | + | 8.114 MeV |
| 16 8O | + | 1 1H | → | 17 9F | + | γ |  |  | + | 0.60 MeV |
| 17 9F |  |  | → | 17 8O | + | e+ | + | ν e | + | 2.76 MeV | (half-life of 64.49 seconds) |
| 17 8O | + | 1 1H | → | 18 9F | + | γ |  |  | + | 5.61 MeV |  |
| 18 9F |  |  | → | 18 8O | + | e+ | + | ν e | + | 1.656 MeV | (half-life of 109.771 minutes) |

**Radiation pressure**

Most important for high-mass stars

**a = the radiation constant =**

O and B type stars have no convective envelope, energy generation (from the CNO cycle) becomes dependent on depth which produces a steep temperature gradient and a large convective core. The majority of energy transfer in O and B type stars is therefore radiative transfer.

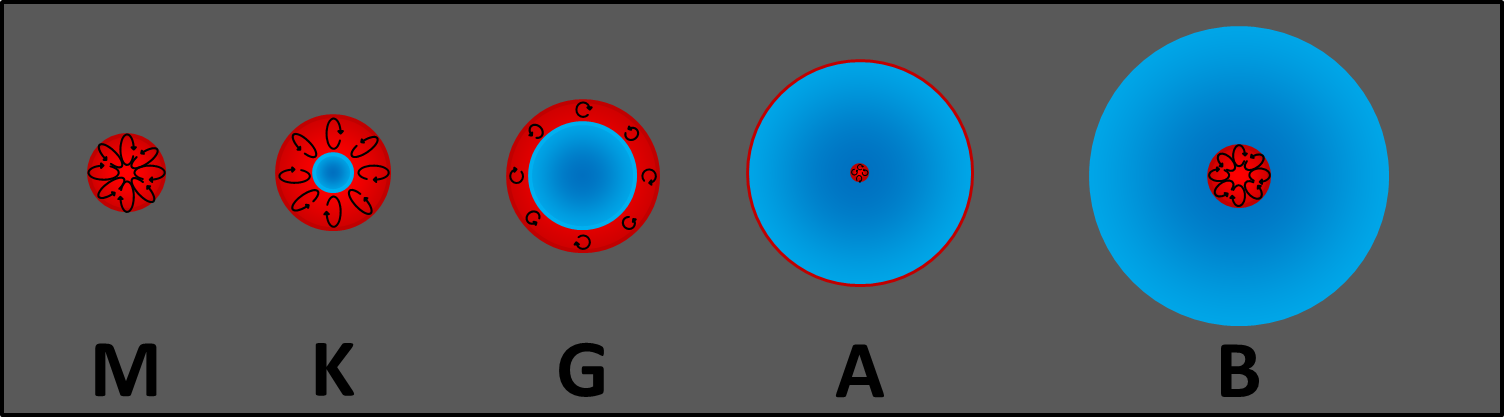


Figure 1: Convective zones of different star types [5]

**Compared to the Sun**

The sun is a G type star so has a radiative zone surrounding the core, radiative transfer is the more effective form of energy transfer at this stage. But optical depth rapidly falls as the surface is approached so temperature and density decrease outwards from the core. As the temperature decreases atoms recombine with electrons, opacity increases and therefore radiation becomes less effective as distance from the core increases. At the tachocline (bottom of the convection zone) is where energy transfer changes from radiative to convective due to the latter being more efficient at this depth, T=2MK. Convection account for around 30% of energy transfer in the Sun [6]

Higher-mass stars have bigger radiative zones and smaller convective zones

[1] Le Anh, N. and Minh Loc, B., 2021. *Bound-to-continuum potential model for the (p, γ ) reactions of the CNO cycle*. [ebook] Ho Chi Minh City. Available at: <https://arxiv.org/pdf/2101.00199.pdf> [Accessed 5 February 2021].

[2] C. Schuler, S., R. King, J. and The, L., 2009. *STELLAR NUCLEOSYNTHESIS IN THE HYADES OPEN CLUSTER*. [ebook] Cornell: The astrophysics journal. Available at: *<https://arxiv.org/pdf/0906.4812.pdf> [Accessed 5 February 2021].*

*[3]* Bethe, H., 1939. Energy Production in Stars. *Physical Review*, [online] 55(1), pp.103-103. Available at: <https://journals.aps.org/pr/abstract/10.1103/PhysRev.55.103> [Accessed 5 February 2021].

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[5] Solarcyclescience.com. 2017. *Discover the Sun!*. [online] Available at: <http://solarcyclescience.com/basics.html> [Accessed 5 February 2021].

[6] Antolin, p., 2020. *Introduction to the Sun*. Northumbria university , pp.7-8.