Role of the CNO cycles in stars

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Borexino has recently observed CNO solar neutrinos. This measurement confirms an energy production mechanism in stars predicted about a century ago. The CNO cycle in the Sun is sub-dominant with respect to the pp-chain energy production. However, it is definitely important in more massive stars. We describe the main characteristics of the CNO cycle in the Sun and in massive stars.

Keywords: Solar neutrinos; CNO cycle; stars; energy production in stars.

1. Energy production in stars and the role of the CNO bi-cycle

The fundamental paradigm for energy production in the Sun and similar stars is the transformation of hydrogen into helium through the process: $4p \to^4 He + 2e^+ + 2\nu_e + 26.73\,\mathrm{MeV}$.[1] This mechanism makes electron neutrinos of mainly sub-MeV energy. Due to the fact that neutrinos can travel through matter affected only by weak interactions, the observation of solar neutrinos allows to probe the interior of the Sun. Therefore, the Sun becomes a laboratory to understand the physics in stars. Solar neutrino measurements have been carried out since 1968.[2]

The main source of energy in the Sun is the so-called pp-chain shown in Figure 1. The pp-chain has three terminations. Each termination produces 26.2 MeV effective thermal energy and it burns 3.7×10^{38} hydrogen/sec, which corresponds to 612 ton/sec. Therefore, assuming 10% of solar mass involved in energy production, the timescale of the pp-chain for the Sun is of the order of 10^{10} years. This mechanism is dominant in first generation stars. In second or third generation stars a different mechanism is also at work. This latter involves light elements, such as carbon and nitrogen, generated after the production of helium. The idea of a second energy production mechanism was independently introduced by von Weizsaker and Bethe between 1937[3] and 1939.[4] Second and third generation stars contain some "heavy" elements, such as nitrogen and carbon. These elements allow the transformation of hydrogen into helium. The process can start from the reaction $p + {}^{12}_{6}\mathrm{C} \to {}^{13}_{7}\mathrm{N} + \gamma$, which is followed by the beta decay of ${}^{13}_{7}\mathrm{N}$ to ${}^{13}_{6}\mathrm{C}$ accompanied with the emission of an electron neutrino of maximum energy equal to 1.2 MeV. Afterward ${}^{14}_{7}\mathrm{N}$ is formed by $p + {}^{13}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + \gamma$. ${}^{14}_{7}\mathrm{N}$ allows the production of ${}^{15}_{8}\mathrm{O}$, which decays beta to ${}^{15}_{7}\mathrm{N}$ with the emission of another electron neutrino of maximum energy equal to 1.7 MeV. At this point ${}^{15}_{7}\mathrm{N}$ allows the production of ${}^{12}_{6}\mathrm{C}$ through the process

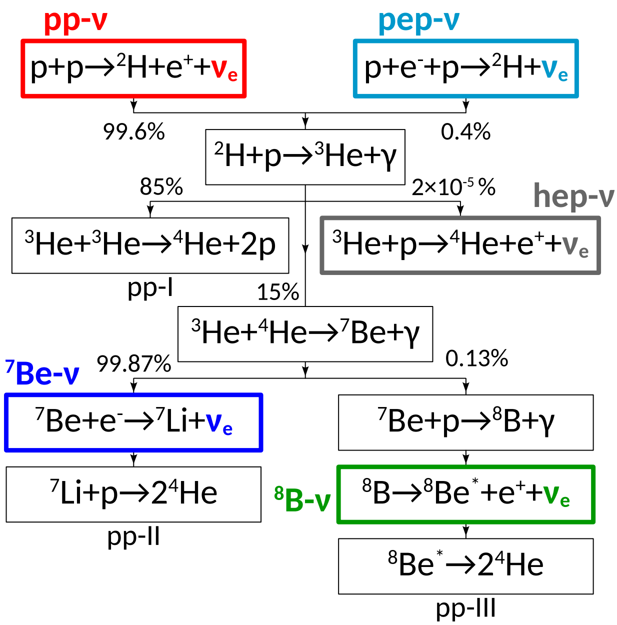

Fig. 1. Set of reactions in the pp-chain, which is the main source of energy in the Sun and in low mass H-burning stars with mass smaller than $1.3M_\odot$.

$p + {}^{15}_{7}\mathrm{N} \to {}^{12}_{6}\mathrm{C} + \alpha$. With ${}^{12}_{6}\mathrm{C}$ the sequence of reactions can start over again. This so-called CN cycle is shown in Figure 2. ${}^{12}_{6}\mathrm{C}$ is used as a catalyst. This cycle produces two electron neutrinos, helium, and the same amount of energy produced by the pp-chain. The CN cycle till 1950 was considered the main source of energy in the Sun. The slowest reaction in the CN cycle is ${}^{14}_{7}\mathrm{N}(p,\gamma){}^{15}_{8}\mathrm{O}$, which has the highest Coulomb barrier.

The CN cycle might develop into a CNO bi-cycle as show in Figure 2. As a matter of fact, with a probability of order 10^{-3}, ${}^{16}_{8}\mathrm{O}$ can be produced by ${}^{15}_{7}\mathrm{N}(p,\gamma){}^{16}_{8}\mathrm{O}$. This second branch produces ${}^{17}_{9}\mathrm{F}$, which decays beta with the emission of an electron neutrino with maximum energy equal to 1.74 MeV. The CNO bi-cycle produces three electron neutrinos from beta decays of ${}^{13}\mathrm{N}$, ${}^{15}\mathrm{O}$ and ${}^{17}\mathrm{F}$. These are the so-called CNO solar neutrinos. The flux of these neutrinos is related to the abundance of these elements in the Sun's core. Therefore, a measurement of CNO solar neutrinos is a probe of the Sun's metallicity.

Measurements of stellar interaction rates have shown that the CN cycle is not dominant in the Sun. This information is used by the Solar Standard Model (SSM),[1] which is the theoretical framework to describe the evolution of the Sun. According to the SSM the CNO bi-cycle in the Sun is responsible for only 1% of the energy production. The CNO bi-cycle is important for the nucleosynthesis of ${}^{16}_{8}\mathrm{O}$, ${}^{17}_{8}\mathrm{O}$, and other light elements. The CNO bi-cycle is also referred to as the "cold" CNO cycle[5] with respect to the "hot" cycle which is discussed in the next Section.

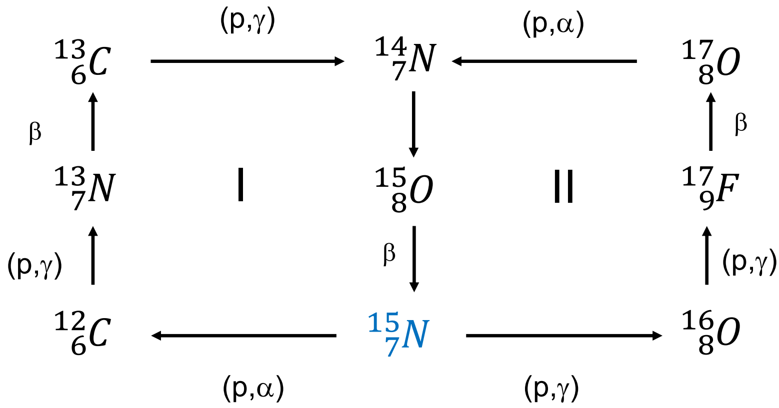

Fig. 2. The CNO bi-cycle divided in its two sub-cycles. The dominant one in the Sun is the CN cycle on the left side.

2. The CNO cycle in massive stars

The Sun's core temperature is 15×10^6 K, which we write as $15T_6$. As predicted by the SSM at this temperature the energy production for the pp-chain and the CNO bi-cycle scales as $\propto T^4$ and $\propto T^8$, respectively. For stellar masses smaller than $1.3M_\odot$, the pp-chain dominates the energy production. In more massive stars with a higher core temperature, the CNO cycle is by far the dominant source of energy. In this case one has to take into account two competing processes, namely $^{17}_{8}\mathrm{O}(p,\alpha)^{14}_{7}\mathrm{N}$ and $^{17}_{8}\mathrm{O}(p,\gamma)^{18}_{9}\mathrm{F}$. For some temperature ranges the reaction rates for these processes are comparable.[6] In this case the CNO cycle is tri-cycling as shown in Figure 3.[7] In addition, for temperature ranging up to 10^{10} K the interaction rate for $^{18}_{8}\mathrm{O}(p,\alpha)^{15}_{7}\mathrm{N}$ and $^{18}_{8}\mathrm{O}(p,\gamma)^{19}_{9}\mathrm{F}$ is of order 100 with a flat minimum between T_9 and $7T_9$.[5] Therefore, with a probability of order 1% a fourth CNO cycle can develop. This fourth cycle is also shown in Figure 3. The third and fourth CNO cycles are referred to as the "hot" CNO cycles. It turns out that when $^{19}_{9}\mathrm{F}(p,\gamma)^{20}_{10}\mathrm{Ne}$ is dominat the CNO catalytic cycling stops.

One fundamental empirical properties of stars is the relationship between their total mass and surface luminosity:[8] $L/L_\odot = (M/M_\odot)^\alpha$, with $3 \lesssim \alpha \lesssim 4$[9] and $L_\odot$ and $M_\odot$ the solar surface luminosity and mass, respectively. This property is confirmed by basic stellar theory. One can make some general arguments for the role of the CNO cycle in stars in the rage of masses $[1,10]M_\odot$. In this range it turns out that the luminosity scales as $\propto M^{\sim 4}$.[9] This implies that more massive stars have a smaller lifetime, for the lifetime scales as $\propto M^{-3}$. In addition, considering that the stars number density scales as $\propto M^{-2.5}$,[10] the energy production in a given bin of mass $[M_i, M_{i+1}]$ is written as:

$$\epsilon \propto \int_{M_i}^{M_{i+1}} M^{1.5} dM \qquad (1)$$

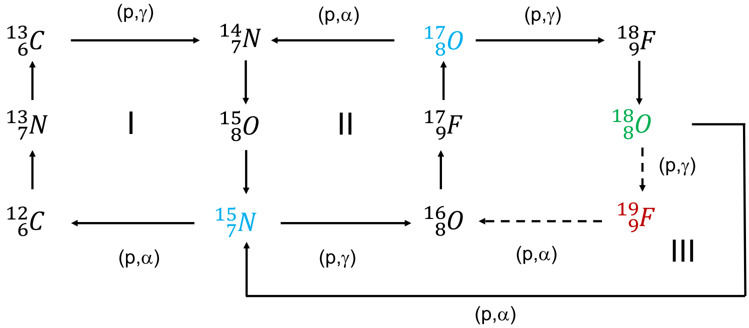

Fig. 3. The CNO tri-cycle in massive stars.

This implies that stars where the CNO energy production is dominant, namely $M > 1.3M_{\odot}$, are producing about 100 times more energy in a much shorter timescale.

3. The role of Borexino

In 2020 Borexino has reported the first ever observation of CNO neutrinos from the Sun.[11] The null hypothesis (no CNO neutrinos) has been rejected at 5σ level. Indeed, Borexino has shown that this energy production mechanism predicted about a century ago is at work in stars. Although the accuracy of the measurement at present is still large ($\sim 35\%$), this measurement allows to probe the SSM in terms of neutrino emission, metallicity, and energy production. The solar luminosity, $L_{\odot}$ can be related to the solar neutrino fluxes:[12,13]

$$\frac{L_{\odot}}{4\pi AU^2} = \sum_i \alpha_i \phi_i \tag{2}$$

where AU is one astronomical unit, ϕ_i are the neutrino fluxes, and α_i are coefficients related to the energy production in the reactions taking place in the pp-chain and CNO bi-cycle, respectively. The Borexino measurement implies that:

$$\frac{L_{CNO}}{L_{\odot}} = 1.0^{+0.4}_{-0.3}\% \tag{3}$$

This is an important confirmation of the SSM prediction. Previously Borexino had measured all the main neutrinos produced by the pp-chain,[14] proving that this mechanism is the main energy production in the Sun with an experimental accuracy of the order of 10%. Therefore, at present, solar neutrino observations have demonstrated that the pp-chain and the CNO bi-cycle are producing energy in stars as it was predicted about a century ago.

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