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Neutrino-Induced Hydrogen Burning

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Abstract.
The principal hydrogen burning mechanisms that take place in stars have been elucidated and explored for many decades. However, the introduction of a prodigious flux of electron anti-neutrinos would significantly accelerate these mechanisms and change the path toward the production of an α particle. We discuss the nature of such changes in the hydrogen burning mechanisms, and the side effects spawned from such alterations.

Keywords: neutrinos; nuclear reactions
PACS: 25.60.Pj (fusion reactions); 13.15.+g (neutrino interactions)

INTRODUCTION

Hydrogen burning involves the conversion of four protons into an alpha particle, liberating energy in photons and neutrinos, through fast radiative proton captures and slow weak interactions. The weak interaction is necessary to transform protons into neutrons during hydrogen burning and provides the bottleneck reactions in the hydrogen burning sequence. In the proton-proton chain (pp-chain), the weak reaction $p(p,e^+\nu_e)d$ is the rate limiting step, while the CNO cycle relies on the positron decay of isotopes of oxygen. We investigate the repercussions of introducing a prodigious flux of neutrinos with large energies into the mix.

NEUTRINO-INDUCED HYDROGEN BURNING MECHANISMS

The weak reaction $p(p,e^+\nu_e)d$ provides the bottleneck in the pp-chain. A significant flux of electron anti-neutrinos allows an alternate mechanism to be favored, where anti-neutrino capture on a proton creates a neutron and positron, followed by fast radiative proton capture to form a deuteron, $p(\bar{\nu}_e,e^+)n(p,\gamma)d$. If a large $\bar{\nu}_e$-flux with high energies is introduced ($\phi_{\bar{\nu}_e} \gtrsim 10^{40}$ cm^{-2} s^{-1}, $\langle E_{\bar{\nu}_e}\rangle \gtrsim$ a few MeV), this alternate reaction path is favored in astrophysical environments where hydrogen burning would be relevant . This provides not only a new mechanism for hydrogen burning, but increases the energy generation rate by several orders of magnitude.

The positron decay of ^{14}O and ^{15}O are the rate limiting steps in the β-limited CNO cycle, with half lives of 71 s and 122 s respectively. This decay can be facilitated by anti-neutrino capture on these nuclei. Figure 1 illustrates the acceleration of the relevant weak rates as a function of total electron anti-neutrino flux. For a large enough flux, the reaction rates are proportional to the flux of electron anti-neutrinos, while at low fluxes, the decay rates of ^{14,15}O asymptote to their laboratory decay values, meaning there is no discernible effect at those levels.

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edited by S. Kubono, W. Aoki, T. Kajino, T. Motobayashi, and K. Nomoto

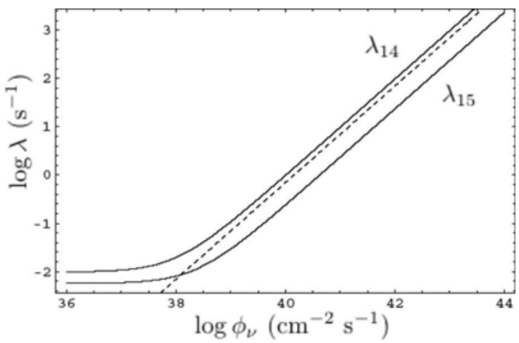

FIGURE 1. Key weak decay rates as a function of electron anti-neutrino flux, assuming a Fermi-Dirac $\bar{\nu}_e$-energy spectrum with zero chemical potential and $\langle E_{\bar{\nu}_e} \rangle = 25$ MeV. The solid lines labeled $\lambda_{14,15}$ are the decay rates of ^{14,15}O. The dashed line is the conversion of a proton to a neutron through $\bar{\nu}_e$-capture.

OTHER EFFECTS

The rationale for introducing a large $\bar{\nu}_e$-flux was to accelerate the rate limiting steps in hydrogen burning. However, a number of side effects are possible as this flux will accelerate the rates of other positron decays.

The principal mechanism for break out into the *rp*-process is $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$. Break out into the *rp*-process occurs when proton capture on ^{19}Ne competes favorably with the decay of ^{19}Ne. For densities and temperatures that satisfy the inequality

$$\rho X \lambda_{p\gamma}(^{19}\text{Ne}) > \lambda_{e^+}(^{19}\text{Ne}), \tag{1}$$

where ρ is the density in g cm^{-3}, X is the hydrogen mass fraction, $\lambda_{e^+}(^{19}\text{Ne})$ is the decay rate of ^{19}Ne, and $\lambda_{p\gamma} = N_A \langle \sigma v \rangle_{p\gamma}$ taken from Caughlin and Fowler [1], break out into the *rp*-process will occur. [4]

A large $\bar{\nu}_e$-flux would upset the inequality (1) by increasing the decay rate of ^{19}Ne with anti-neutrino capture. This would demand higher temperatures (increasing $\lambda_{p\gamma}$) at a given density for break out into the *rp*-process to occur. Figure 2a shows how the conditions for break out into the *rp*-process are altered in the presence of a strong $\bar{\nu}_e$ flux.

Another relevant question is if the conditions are favorable to break out into the *rp*-process, what are the effects of a prodigious electron anti-neutrino flux on the subsequent nucleosynthesis? The competition between the slow capture of an α particle on ^{15}O and the faster decay of ^{15}O becomes even more lopsided in favor of nuclear material remaining in the CNO cycle rather than escaping into the *rp*-process. As a result, the total yield in *rp*-process elements will decrease with increasing neutrino flux and energy. Figure 2b shows the effects of large electron anti-neutrino fluxes on the total yield in *rp*-process elements. Notice that at large $\bar{\nu}_e$-fluxes, break out into the *rp*-process is nearly completely suppressed.

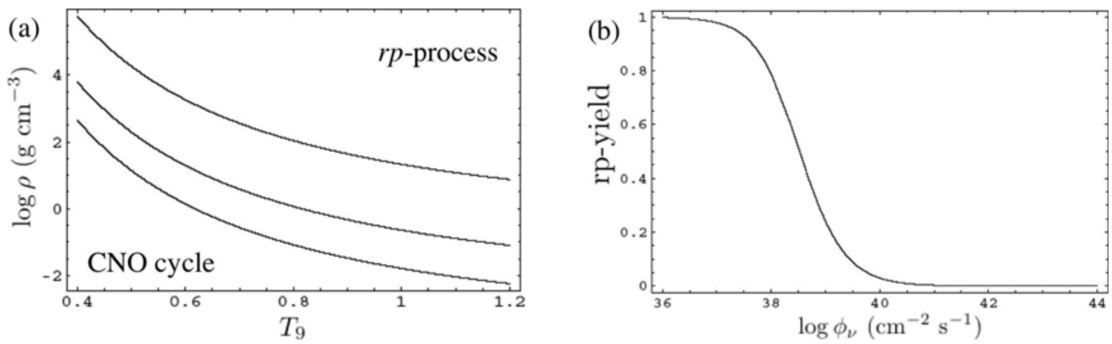

FIGURE 2. (a) Conditions required for break out into the *rp*-process. The plotted contours are for, in ascending order, $\bar{\nu}_e$-fluxes of $10^{38,40,42}$ cm^{-2} s^{-1}. Zero flux is indistinguishable from the lowest contour. (b) Ratio of the yield of *rp*-process elements with neutrinos to without neutrinos. Both figures are made assuming a Fermi-Dirac $\bar{\nu}_e$-energy spectrum with zero chemical potential and $\langle E_{\bar{\nu}_e} \rangle = 25$ MeV

DISCUSSION

We have examined the effects of a prodigious flux of electron anti-neutrinos on hydrogen burning. Large fluxes and high energies allow anti-neutrino capture to accelerate the rate limiting steps in hydrogen burning, causing a significant increase in the energy generation rates due to the pp-chain and β-limited CNO cycle. This large flux of electron anti-neutrinos would also lead to a change in the conditions necessary for break out into the *rp*-process, and suppress the expected yield in *rp*-process elements.

The next step is to find an environment where this effect may be relevant. A high entropy electron-positron plasma is an efficient engine for the production of neutrinos and anti-neutrinos of all flavors, and could provide the $\bar{\nu}_e$-flux necessary to drive this effect. Possible environments that would merit future investigations into the effects of anti-neutrino capture on hydrogen burning include high mass accretion disks and collapsing supermassive stars.

In [3], we explore these effects in supermassive stars, where in the final stages of collapse, a prodigious flux of neutrinos is emitted from the collapsing homologous core. We find that changes from current simulations may occur on the lower end of the mass spectrum. Further investigation using computer simulations would be necessary to see if this effect could be relevant and leave a possible observational signature.

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