

Fine-tuning the basic forces of nature through the triple-alpha process in red giant stars*

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We show that the synthesis of carbon and oxygen through the triple-alpha process in red giant stars is extremely sensitive to the fine details of the nucleon-nucleon (N-N) interaction. A $\pm 0.5\%$ change in the strength of the N-N force would reduce either the carbon or oxygen abundance by as much as a factor of 30–1000. This result may be used to constrain some fundamental parameters of the Standard Model.

1. INTRODUCTION

Almost all the carbon in the Universe is produced through the triple-alpha process [1]. Although the ^8Be nucleus, formed in the collision of two alpha particles (^4He), is unbound, it lives long enough to allow the possibility of capturing a third alpha particle to form stable ^{12}C . However, in order to produce enough carbon, this second reaction must be resonant [2]. The 0_2^+ state of ^{12}C , lying at 380 keV, relative to the 3α threshold, therefore plays a key role in the synthesis of carbon. As both steps of the triple-alpha process are governed by narrow resonances, the reaction rate is given as [1]

$$r_{3\alpha} \approx 3^{\frac{3}{2}} N_\alpha^3 \left(\frac{2\pi\hbar^2}{M_\alpha k_B T} \right)^3 \frac{\Gamma_\gamma}{\hbar} \exp\left(-\frac{E_{\text{res}}}{k_B T}\right), \quad (1)$$

where M_α and N_α are the mass and the number density of the alpha particles, respectively, E_{res} and Γ_γ are the resonance energy and radiative width of the 0_2^+ state of ^{12}C , respectively, and T is the stellar plasma temperature.

2. TRIPLE-ALPHA RATE AND N-N INTERACTION STRENGTH

As the rate of the triple-alpha process is exponentially sensitive to the resonance energy, even small changes in E_{res} can lead to big changes in $r_{3\alpha}$. We studied how much E_{res} can

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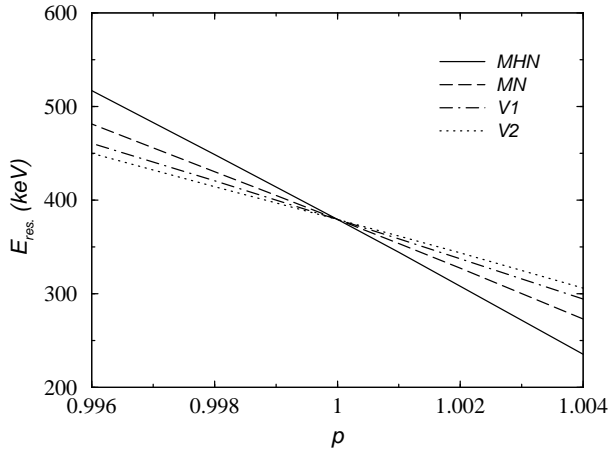


Figure 1. Resonance energy of the 0_2^+ state of ^{12}C as a function of the strength parameter of the N-N forces.

change if the strength of the N-N force is varied by a small amount. For this purpose we used a cluster-model description of ^{12}C [3]. We performed calculations using four different N-N forces, MHN, MN, V1, and V2 [4]. Each force was tuned to give the experimental value for E_{res} . Then the strengths of the forces were multiplied by a factor p , which varied from 0.996 to 1.004. Thus $p = 1.0$ gives back the experimental resonance energy. The E_{res} energies as functions of p are shown in Fig. 1. One can see that small changes (less than 1%) in the interaction strength lead to orders of magnitude bigger changes in the resonance energy. This effect is caused by the fact that the 0_2^+ state lies close to the breakup threshold, effectively behaving as a nonlinear quantum amplifier [5].

As one can see in Fig. 1, the relation between E_{res} and p has a force dependence. Its origin can be traced back to the fact that the different interactions lead to different residual alpha-alpha forces, which is the key quantity in the nonlinear amplification phenomenon [5]. If the 0_2^+ state of ^{12}C is correctly reproduced, then the resonance in the ^8Be subsystem is underbound by the MHN force, while it is successively more and more overbound by MN, V1, and V2. This means that from the viewpoint of the ^{12}C state, the residual $\alpha - \alpha$ force is too strong for MHN, and increasingly too weak for MN, V1, and V2 (e.g., in the case of an MHN force which reproduces the correct ^8Be energy, the ^{12}C state would be overbound). This implies that the true behavior of E_{res} as a function of p is expected to be somewhere between the predictions of the MHN and MN forces.

Using the predictions of the MHN and MN forces, we calculated the $r_{3\alpha}$ rates for the modified interactions, and used these rates in a stellar model [6] in order to estimate the carbon and oxygen abundances [3]. The results are shown in Fig. 2. As one can see, the amount of carbon (oxygen) synthesized in any star is strongly reduced if the N-N force is weaker (stronger) than the standard case.

3. CONCLUSION

One can see in Fig. 2 that a 0.5% change in the N-N interaction strength would lead to a Universe which does not contain an appreciable amount of carbon or oxygen. This would make the existence of carbon-based life highly unlikely. This very strong fine-tuning effect gives us a possibility to try to constrain the possible values of some fundamental

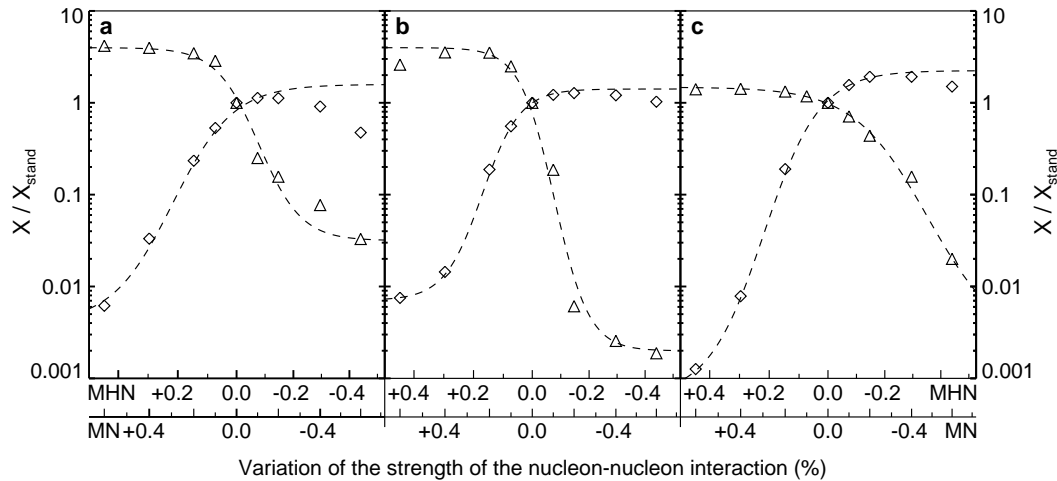


Figure 2. The change of the carbon (Δ) and oxygen (\diamond) mass abundances (X) through variations of the strength of the strong interaction. They are shown in panels a, b, and c for stars with masses of 20 , 5 , and $1.3M_{\odot}$, respectively, in units of the standard values X_{stand} . The variations of the strength of the strong interaction are given for the two effective N-N forces MHN and MN. The dashed curves are drawn to guide the eye.

constants in the Standard Model. For example, if one assumes a pion-exchange model of the strong force, then the a smaller (larger) pion mass means a stronger (weaker) force. More detailed analyses show that our result on the fine-tuning of carbon and oxygen production can be used to give constraints on the possible values of the sum of the light quark masses and the vacuum expectation value of the Higgs field at the 1% level [7].

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