PHYSICAL REVIEW D **92,** 063016 (2015)

Effects of axions on nucleosynthesis in massive stars

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(Received 12 December 2014; revised manuscript received 2 August 2015; published 22 September 2015)

We investigate the effect of axion cooling on nucleosynthesis in a massive star with $16M_{\odot}$ by a standard stellar evolution calculation. We find that axion cooling suppresses nuclear reactions in carbon, oxygen, and silicon burning phases because of the extraction of the energy. As a result, larger amounts of the already synthesized neon and magnesium remain without being consumed to produce further, heavier elements. Even in the case with axion-photon coupling constant $g_{a\gamma} = 10^{-11}$ GeV^{-1}, which is six times smaller than the current upper limit, the amount of neon and magnesium that remain just before the core-collapse supernova explosion is considerably larger than the standard value. This implies that we could give a more stringent constraint on $g_{a\gamma}$ from the nucleosynthesis of heavy elements in massive stars.

DOI: 10.1103/PhysRevD.92.063016 PACS numbers: 97.60.Bw, 97.60.Jd, 26.30.-k

I. INTRODUCTION

The standard model (SM) of particle physics well explains general properties of the results of collider experiments. For example, a lattice quantum chromodynamics (QCD) calculation, which is a simulation based on the first principle of QCD, can predict the mass of baryons and mesons only from a few input parameters. On the other hand, the Lagrangian density of QCD has a term which violates *CP* symmetry and involves the finite electric dipole moment (EDM) of a neutron. Because this EDM has never been detected, QCD is generally considered to have a fine-tuning problem referred to as the strong *CP* problem. Peccei and Quinn suggested that the existence of an undiscovered pseudoscalar particle which is associated with another $U_{\mathrm{A}}(1)$ symmetry in the SM can solve this problem [1]. This pseudoscalar particle is named axion and has interactions with baryons, leptons, and photons (see, e.g., [2–4]). The coupling constant $g_{a\gamma}$ of axions to photons is related to the energy scale of the symmetry breaking f_a as

$$g_{a\gamma} = \frac{\alpha C_{\gamma}}{2\pi f_a}, \tag{1}$$

where C_{γ} is a model-dependent constant. In the KSVZ [5,6] and DFSZ [7] scenarios, $|C_{\gamma}| = 1.9$ and 0.7, respectively, are adopted, and several constraints on them have been set (e.g., [2,4]). In addition, axions, which have a finite mass as a result of the symmetry breaking, are a candidate for cold dark matter (e.g., [3]). Throughout this paper, we frequently use the notation $g_{10} \equiv g_{a\gamma}/10^{-10}$ GeV^{-1} for convenience.

The interaction of axions with photons is supposed to affect the structure and the evolution of a star. Because the predicted mass of an axion is smaller than the typical temperature of the stellar interior, axions are expected to be easily produced in stars through the interaction with photons. The conversion from photons to axions removes the heat in the stellar interior, which possibly gives an impact on the stellar structure, whereas its reaction rate strongly depends on temperature.

Various possibilities concerning axions in the stellar interior have been explored for a wide range of stellar masses. By comparing the photon luminosity of the Sun with the nuclear reaction rate that is calibrated from neutrino luminosity, Gondolo and Raffelt set the constraint $g_{10} < 7$ [8]. Tighter constraints can be obtained for stars in later evolutionary stages because the temperature in the interior is higher than the temperature in main sequence stars—e.g., the Sun—and the production rate of axions is larger as well. For example, a constraint is derived from number counts of horizontal branch stars; the generation of axions tends to shorten the duration of the horizontal branch phase, which contradicts the standard stellar model without the effect of axions that reproduces the observed distribution of horizontal branch stars within 10% accuracy. From this observational requirement, Ayala gives $g_{10} < 0.66$ [9]. Massive stars also give tight constraints on $g_{a\gamma}$ since the interior temperature is suitable for the generation of axions. If one takes into account axions, the duration of Helium burning is shortened, which would erase the blue loop stage in the Hertzsprung-Russell (HR) diagram required for observed Cepheid variable stars. By considering this effect for stars with $8M_{\odot}$–$12M_{\odot}$, where $M_{\odot}$ is the solar mass, Friedland *et al.* found $g_{10} < 0.8$ [10] with MESA [11,12], a public code for one-dimensional calculations of stellar evolution.

In this paper we consider the effect of axions in more massive stars. Pantziris and Kang estimate a constraint on the axion cooling rate for such massive stars by using a simple one-zone model instead of realistic stellar structure [13]. In contrast, we focus on the effect of axions on the nucleosynthesis of heavy nuclei at the very late phase of the stellar evolution just before the core-collapse supernovae. Heavy elements such as silicon, sulfur, and iron are

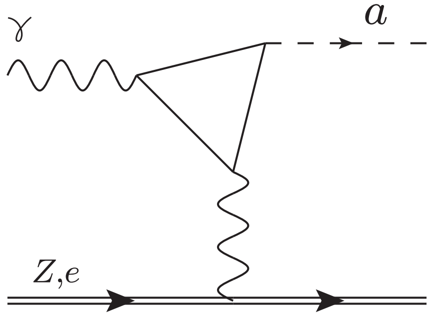

FIG. 1. Feynman diagram of the Primakoff process. Z, e represent the ions and the electron which provide a photon via the magnetic field.

synthesized over a period of a few months (see [14]). Because of the considerably short duration of the nucleosynthesis of these elements, the photons generated through the nuclear reactions, which do not have enough time to travel to the stellar surface, can hardly be observed. Part of the synthesized heavy nuclei is finally ejected and affects the elemental abundance of next generation stars and the chemical evolution of galaxies. The produced amounts of these heavy metals have the information of the high-temperature and high-density environment of the stellar interior.

In this study, we focus on the Primakoff process [15], namely, axions produced by the conversion from two photons (Fig. 1), and we estimate the effects of axion cooling on nucleosynthesis at the late phase of massive stars with the MESA code. This paper is organized as follows. Our treatment of the axion cooling in the stellar evolution code is shown in Sec. II. In Sec. III, we show results focusing particularly on the effect of axion cooling on nucleosynthesis. Section IV concludes this paper. We also briefly discuss the effect of axion cooling by Primakoff-type bremsstrahlung in Sec. IV.

II. SETUP

A. Axion cooling

The axion cooling rate per unit mass ε_a in hot plasma has been derived by several authors (e.g., [13,16–21]). They showed that the Primakoff process plays a primary role in axion cooling when electrons in stars are nonrelativistic. Specifically, if the plasma frequency ω_0 is small enough to satisfy the condition $h\omega_0 \ll k_\mathrm{B}T$ besides the nonrelativistic and nondegenerate condition fulfilled, the emission rate can be obtained analytically as [4,19]

$$\varepsilon_{a(\mathrm{NR\&ND})} = \frac{g_{a\gamma}^2 T^7}{4\pi\rho} F(k_\mathrm{S}, T), \tag{2}$$

where k_S is the Debye-Hückel wave number which is defined by Raffelt [4,19,22]. The function $F(k_\mathrm{S}, T)$ is defined as [4,17,19]

$$F(k_\mathrm{S}, T) = \frac{\kappa^2}{2\pi^2}\int_0^{+\infty} (x^2+\kappa^2)\ln\left(1+\frac{x^2}{\kappa^2}\right)\frac{x}{e^x-1}dx, \tag{3}$$

where $x \equiv \hbar\omega/k_\mathrm{B}T$ and $\kappa = 2ck_\mathrm{S}/\hbar k_\mathrm{B}T$ [23]. Although the lower bound of the integration of Eq. (3) should be $x \equiv \hbar\omega_0/k_\mathrm{B}T$ in the strict sense, we can safely approximate it to be 0 for our conditions (see [24]). In horizontal branch stars and oxygen burning stars, $\kappa^2 = 2.5$. In the region where the radiation pressure dominates, since the radiation pressure is proportional to T^4, one can find [25]

$$\frac{T}{\rho^{1/3}} = \left(\frac{3c\mathcal{R}}{4\sigma\mu}\right)^{1/3}, \tag{4}$$

where $\mathcal{R}$ and σ are the gas constant and the Stefan-Boltzmann constant, respectively. Because the value of the right-hand side is almost stationary in the stellar evolution, one can regard T^3/ρ as a constant and can find that $\varepsilon_{a(\mathrm{NR\&ND})} \propto T^4$. This dependence is mentioned by several authors (e.g., [13,16,17]).

On the other hand, when one considers the nucleosynthesis of heavy elements, the temperature is so high that the relativistic effect needs to be taken into account, although the electrons are still nondegenerate [21,25]. Altherr *et al.* reported that the formula which is valid in the limit of nonrelativistic and nondegenerate plasma can be used with relativistic plasma, whose temperature exceeds the rest mass of an electron m_e, i.e., $k_\mathrm{B}T \gg m_\mathrm{e}c^2$ [20]. In addition, as the plasma frequency ω_0 increases, the emission rate suffers an exponential damping, $\propto \exp(-\hbar\omega_0/k_\mathrm{B}T)$ (see [16]). Hence we adopt the following formula for the axion cooling rate:

$$\begin{aligned}\varepsilon_a &= \varepsilon_{a(\mathrm{NR\&ND})}\exp\left(-\frac{\hbar\omega_0}{k_\mathrm{B}T}\right)\\ &= 27.2 {g_{10}}^2 T_8^7 \rho_3^{-1} F(k_\mathrm{S}, T)\exp\left(-\frac{\hbar\omega_0}{k_\mathrm{B}T}\right)[\mathrm{erg/g/\,sec}].\end{aligned} \tag{5}$$

T_8 and ρ_3 are the temperature normalized by 10^8 K and the density normalized by 10^3 g/cm^3, respectively.

B. Stellar evolution

We include the cooling by axions, Eq. (5), in the stellar evolution code MESA. We add the extra term for axion cooling to the energy transfer equation that is one of the basic equations governing the evolution of the stellar structure. The axion cooling works as an extra energy loss in addition to the neutrino emission. The axion cooling term simply removes the luminosity carried by the photons emitted as a result of the nuclear reactions in the stellar interior. Therefore, it reduces the radiation pressure by these photons to modify the momentum balance and, accordingly, changes the stellar structure if the effect is not negligible. This treatment of axion cooling is applicable not only to the QCD axions which we focus on in this paper but also to generic axionlike particles which couple with photons since this can be treated as the simple energy loss in the stellar evolution calculation.

We calculate the evolution of a star with $M = 16M_\odot$, with the solar elemental abundance from the zero-age main sequence phase when the hydrogen burning reaction is ignited at the center of the star. We take into account the mass loss by radiation pressure-driven stellar wind with an empirical mass loss rate [26]. We follow the time evolution until the gravitational core collapse sets in just before the supernova explosion. In addition to the cases with axion cooling, we also calculate, for comparison, a standard case that does not include the effect of axions.

III. RESULTS

A. Overview of stellar evolution

A star changes its luminosity and surface temperature over time. After the exhaustion of hydrogen in the central core, a star evolves to a red giant and the helium burning eventually sets in to synthesize heavier elements. Massive stars with $M \gtrsim 10M_\odot$ continue through the oxygen burning to the silicon burning phase, with their core being non-degenerated. Iron-group elements dominate the core finally before the core-collapse supernova (see [14]). With the stellar evolution, the star with the initial mass of $16M_\odot$ lost $\approx 2M_\odot$ during its lifetime by radiation pressure-driven stellar wind (see [25]).

We study the effect of axion cooling in the HR diagram. In Fig. 2, we plot evolutionary tracks of cases with $g_{10} = 1$ and 0.1 for comparison with the case without axion cooling. The evolutionary track with $g_{10} = 1$ differs from the other two cases. This is because energy leakage by axions leads to a higher temperature in the self-gravitating system, with negative gravothermal specific heat. The energy loss also leads to a faster nuclear reaction and the lifetime of this case is shorter by ≈10%. However, this large $g_{10} = 1$ is already excluded [9,10], and we do not study this case further in this paper.

On the other hand, the evolutionary track with $g_{10} = 0.1$ is indistinguishable from the nonaxion case. Axion cooling affects the stellar evolution at late stages during the carbon, oxygen, and silicon burning phases (see Sec. III B). However, their durations are short: $\lesssim$ several thousand years. This is much shorter than that of the thermal time scale of the star ($\sim$ a hundred thousand years) [25,27]. Namely, the effect of the nuclear reaction deep in the stellar interior is still not observable because the travel time of the photons to the stellar surface is much longer. Therefore, the effect of the axion cannot be observed in the HR diagram.

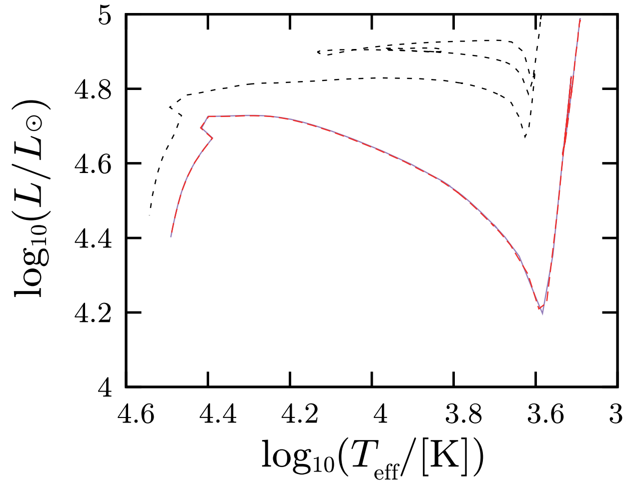

FIG. 2 (color online). Evolutionary tracks of stars with $16M_\odot$ that take into account axion cooling with different coupling constants, g_{10}, in a HR diagram. The short dashed (black) and long-dashed (red) lines represent the evolutionary tracks with $g_{10} = 1$ and 0.1, respectively. The solid (purple) line indicates the case without axion cooling.

B. Nucleosynthesis

We investigate how axion cooling affects nucleosynthesis through the evolution of a massive star.

We compare the abundance of the alpha elements oxygen (^{16}O), neon (^{20}Ne), magnesium (^{24}Mg), and silicon (^{28}Si), in addition to iron (^{56}Fe), of the star with a different $g_{a\gamma}$ and an initial mass of $M = 16M_\odot$ in Fig. 3. The abundance of ^{20}Ne and ^{24}Mg is generally enhanced for a large $g_{a\gamma}$ near $M_r \simeq 2M_\odot$, while the abundance of ^{28}Si shows the opposite trend to compensate for the increased ^{20}Ne. This implies that axion cooling suppresses the ^{20}Ne combustion to synthesize heavier elements, which we discuss further later in this section. However, if we carefully inspect the detailed profiles, one may notice that the dependence on g_{10} is not simple. For example, the ^{20}Ne abundance with $g_{10} = 10^{-3}$ is larger than that of the $g_{10} = 10^{-2}$ case, which is different from the general trend, near $M_r \approx 2.5M_\odot$, while it is smaller than that of the nonaxion case in the outer region $M_r > 3N_\odot$. ^{24}Mg also shows a similar nonmonotonic trend on g_{10}. The complexities are mainly because these elements are intermediate products on the pathway to the most stable ^{56}Fe; these elements are the product of the nucleosynthesis from lighter elements as well as the seeds for further heavier elements, and nuclear reaction rates depend sensitively on the temperature. The produced amount of ^{56}Fe is not influenced significantly by axion cooling, even with a large $g_{10} \geq 10^{-2}$.

In Fig. 4, we present the total mass of each element left just before the core collapse (type II) supernova, where each value is normalized by that of the standard case without axion cooling. Metals heavier than ^{24}Mg are

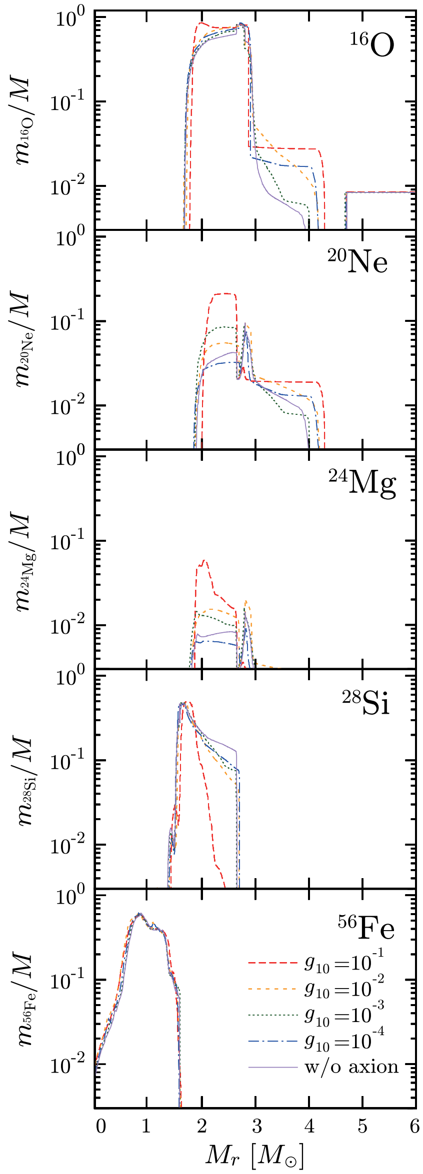

FIG. 3 (color online). The abundance of alpha elements as a function of mass radius in units of the solar mass, $M_r/M_\odot$, at the end of the silicon burning phase. Long-dashed (red), dashed (orange), dotted (dark-green), and dot-dashed (blue) lines correspond to the cases with $g_{10} = 10^{-1}, 10^{-2}, 10^{-3}$, and 10^{-4}, respectively. The solid line represents the case without axion cooling.

converted to iron-group elements during the explosive nucleosynthesis just after the explosion [28]. Hence, as for the heavy elements from ^{28}Si to ^{56}Ni, we consider the total amount of them. The amount of ^{20}Ne is considerably increased for a large $g_{a\gamma}$; in the case of $g_{10} = 0.1$, the amount is enhanced more than three times. This trend is also weakly seen in the amount of ^{24}Mg. On the other hand, the total amount of the heavier elements is smaller for a larger $g_{a\gamma}$ to compensate for the enhanced ^{20}Ne, as shown in Fig. 3.

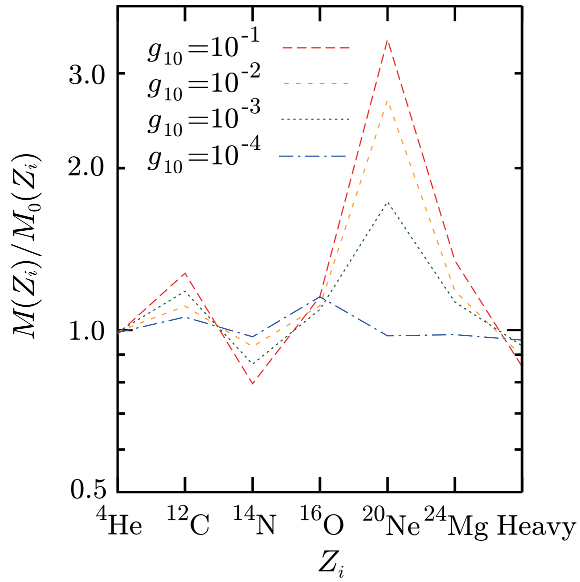

FIG. 4 (color online). The abundance of each element i $[M(Z_i)]$ normalized by that from the standard case without axion cooling $[M_0(Z_i)]$ just before the core collapse. Long-dashed (red), dashed (orange), and dotted (dark-green) lines correspond to the cases with $g_{10} = 10^{-1}, 10^{-2}, 10^{-3}$, and 10^{-4}, respectively. "Heavy" represents the total amount from ^{28}Si to ^{56}Ni.

In the weak coupling cases with $g_{10} \leq 0.1$ that we are considering, axion cooling does not change the lifetime of the star. Axion cooling affects the nucleosynthesis at late phases. The typical time scale of the nuclear reaction for carbon and oxygen burning is shorter than the thermal adjustment (Kelvin-Helmholz) time scale. Axion cooling is then simply the extraction of thermal energy to reduce the temperature, which slows down the nuclear reactions [29]. Specifically, the process that photodisintegrates ^{20}Ne into ^{16}O, and α is affected because it strongly depends on temperature $\propto T^{50}$. We compare the temperatures of different cases at $M_r = 2.2 M_\odot$ where the ^{20}Ne reaction takes place. $T \simeq 2.72 \times 10^9$ [K] in the case with $g_{10} = 10^{-1}$, while $T \simeq 3.04 \times 10^9$ in the case without axion cooling. This ≈10% difference of the temperature gives more than 100 times the difference of the reaction rate.

As a result, a larger amount of ^{20}Ne survives, avoiding the photodisintegration in cases with a large $g_{a\gamma}$. The same argument can be applied to the photodisintegration of ^{24}Mg, which also shows the similar (but weaker) trend on $g_{a\gamma}$ (Fig. 3). In other words, the abundance of these elements is enhanced by axion cooling as a result of the inactivation of nucleosynthesis. The α particles supplied from the photodisintegration processes are the seeds for subsequent α capture reactions to synthesize heavier elements. The inactivation of the photodisintegration reduces the production of ^{28}Si and heavier elements. Since ^{20}Ne and ^{24}Mg are produced at off-center locations (Fig. 3), the amount is not as affected by the later explosive nucleosynthesis [28], the ejected mass would also be larger for a larger $g_{a\gamma}$ to possibly affect the chemical evolution of galaxies.

IV. SUMMARY AND DISCUSSION

In this paper, we have studied the effect of axion cooling on nucleosynthesis in a massive star with $16M_\odot$ by using the stellar evolution code MESA. We have found that axion cooling suppresses nucleosynthesis in the carbon, oxygen, and silicon burning phases even in the weak coupling, $g_{10} < 0.1$. As a result, the abundance of oxygen, neon, and magnesium increases as the coupling constant $g_{a\gamma}$ increases. Even in the case of $g_{10} = 0.1$, which is six times smaller than the current upper limit of $g_{10} = 0.6$, the final amount of neon is enhanced more than three times larger than the standard value, which does not take into account the effect of axion cooling. This overproduction of neon may reconcile the anomaly of the observed neon abundance (see [30]). Woosely *et al.* pointed out that the standard nucleosynthesis in massive stars is not enough to explain the observed neon abundance of the Sun by a factor of 2. Our results show that a $16M_\odot$ star with $g_{10} = 10^{-3}$–10^{-2} produces ^{20}Ne twice that of the standard model, whereas for quantitative arguments on galactic chemical evolution, we need to calculate stellar evolution with other masses because the nucleosynthesis depends sensitively on the detailed time evolution of the temperature structure.

In this paper, we have focused only on the Primakoff process for axion cooling. However, when the temperature is high enough to be comparable to to the rest mass of an electron near the center at later epochs, it is pointed out that the Primakoff-type bremsstrahlung of axions possibly plays an important role [31,32]. The cooling rate by the axion bremsstrahlung is characterized by a coupling constant, which is constrained by the observation of globular clusters [33,34]. Similar to the Primakoff process investigated in this paper, the Primakoff-type bremsstrahlung also suppresses the nucleosynthesis at later phases of the stellar evolution. We have performed the calculation of the stellar evolution by considering the Primakoff-type bremsstrahlung with the allowed upper bound for the coupling constant, and we have found that the abundance of oxygen is 70% larger than in the standard model case. On the other hand, the abundance of neon, which is considerably enhanced by the Primakoff process (Fig. 4), decreases by half. These results indicate that stellar nucleosynthesis will also be very effective in putting a constraint on Primakoff-type bremsstrahlung.

ACKNOWLEDGMENTS

This work is supported in part by a scientific research grant for research fellows from the Japan Society for the Promotion of Science through JSPS Grant No. 24009838 (S. A.).

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