Effects of axions on Nucleosynthesis in massive stars

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We investigate the effect of the axion cooling on the nucleosynthesis in a massive star with 16$M_{\odot}$ by standard stellar evolution calculation. We find that the axion cooling suppresses the 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 the 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.

I. INTRODUCTION

The standard model of particle physics (SM) well explains general properties of the results of collider experiments. For example, the lattice QCD calculation, which is the simulation based on the first principle of the quantum chromodynamics (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 the CP symmetry and involves the finite electric dipole moment (EDM) of neutron. Because this EDM has never been detected, it is generally considered that QCD has a fine tuning problem named the strong CP problem. Peccei and Quinn suggested that the existence of an undiscovered pseudo-scalar particle which is associated with another $U(1)$ symmetry for SM can solve this problem 1. This pseudo-scalar particle is named axion and have 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

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

where $C_{\gamma}$ is a model-dependent constant. For KSVZ 5,6 and DFSZ 7 scenarios, $|C_{\gamma}| = 1.9$, and 0.7, are adopted, respectively, and several constraints on them have been set (e.g. 2, 4). In addition, axions, which have a finite mass as a results of the symmetry breaking, are a candidate of the cold dark matter (e.g. 8).

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 24. 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 in a wide range of stellar mass. By comparing the photon luminosity of the sun with the nuclear reaction rate that is calibrated from the neutrino luminosity, Gondolo and Raffelt set a constraint $g_{a\gamma} < 7 \times 10^{-10}$ GeV$^{-1}$ 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 to 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 $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV$^{-1}$ 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 the Helium burning is shorten, 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 8 - 12 $M_{\odot}$, where $M_{\odot}$ is the solar mass, Friedman et al. found $g_{a\gamma} < 0.8 \times 10^{-10}$ GeV$^{-1}$ 10 with MESA 11,12, which is a public code for one-dimensional calculations of stellar evolution.

In this paper we consider the effect of axions in more massive stars. Pantziris & Kang estimated 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 synthesized during the last 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 be hardly observed. A part of the synthesized heavy nuclei are finally ejected and affects elemental abundances 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 en-
vironment of the stellar interior.

In this study, we focus on the Primakoff process \[15\], namely axions produced by the conversion from two photons (figure 1), and estimate the effects of axion cooling on the 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 §2. In §3, we compare the structure of a massive star with axions to a standard case that does not take into account axions. In §4, we discuss the effect of the axion cooling on the explosive nucleosynthesis. §5 concludes this paper.

II. SETUP

A. Axion Cooling

The axion cooling rate per unit mass \(\varepsilon_a\) in hot plasma has been derived by several authors (e.g. \[13\, 16\, 20\]). They showed that the Primakoff process plays a primary role in the axion cooling when electrons in stars are non-relativistic. In particular, if the plasma frequency \(\omega_0\) is small enough to satisfy the condition, \(\hbar \omega_0 \ll k_B T\), besides the non-relativistic and non-degenerate condition fulfilled, the emission rate can be obtained analytically as \[4\, 10\]

\[
\varepsilon_{a(NR&ND)} = \frac{g_{a\gamma}^2 T^7}{4\pi \rho} F(k_S, T) \tag{2}
\]

where \(k_S\) is the Debye-Hückel wave number which is defined in the Raffelt \[3\, 14\, 19\]. The function \(F(k_S, T)\) is defined as \[4\, 14\, 19\]

\[
F(k_S, T) = \frac{\kappa^2}{2\pi^2} \int_0^{\gamma^2} (x^2 + \kappa^2) \ln \left(1 + \frac{x^2}{\kappa^2}\right) \frac{x}{e^x - 1} dx , \tag{3}
\]

where \(x \equiv \hbar \omega / k_B T\) and \(\kappa = 2ck_S / k_B T\) \[27\]. 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 \[22\]

\[
\frac{T}{\rho^{1/3}} = \left(\frac{3cR}{4\sigma \mu}\right)^{1/3} , \tag{4}
\]

where \(\mathcal{R}\) and \(\sigma\) 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 \(T^3/\rho\) as a constant and find that \(\varepsilon_{a(NR&ND)} \propto T^4\). 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 non-degenerate \[21\, 23\]. Altherr et al. reported that the formula which is valid in the limit of the non-relativistic and non-degenerate plasma can be used to the relativistic plasma, whose temperature exceeds the rest mass of an electron \(m_e\), i.e. \(k_B T \gg m_e c^2\) \[20\]. In addition, as the plasma frequency \(\omega_0\) increases, the emission rate suffers an exponential cut-off, \(\exp(-\hbar \omega_0 / k_B T)\) (see \[10\]). Hence we adopt the following formula for the axion cooling rate

\[
\varepsilon_a = \varepsilon_{a(NR&ND)} \exp \left(-\frac{\hbar \omega_0}{k_B T}\right) \tag{5}
\]

\[
= 27.2g_{a\gamma 10}^2 T_8^7 \rho_3^{-1} F(k_s, T) \exp \left(-\frac{\hbar \omega_0}{k_B T}\right) \text{[erg/g/sec]} ,
\]

where \(g_{a\gamma 10} \equiv g_{a\gamma}/10^{-10}\ \text{GeV}^{-1}\). \(T_8\) and \(\rho_3\) are temperature normalized by \(10^8\ \text{K}\) and density normalized by \(10^3\ \text{g/cm}^3\), respectively.

B. Stellar Evolution

We include the cooling by axions, eq. (5), in the stellar evolution code MESA. We add the extra term for the axion cooling in the energy transfer equation that is one of the basic equations governing the evolution of the stellar structure. 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.

We calculate the evolution of a star with \(M = 16M_\odot\), with the solar elemental abundances 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 \[24\]. We follow the time evolution until the gravitational core-collapse sets in just before the supernova explosion. In addition to the cases with the axion cooling, we also calculate the standard case that does not include the effect of axions for comparison.
We compare abundances of alpha elements, oxygen \((^{16}\text{O})\), neon \((^{20}\text{Ne})\), magnesium \((^{24}\text{Mg})\), and silicon \((^{28}\text{Si})\), in addition to iron \((^{56}\text{Fe})\) of the star with different \(g_{a\gamma}\) and initial mass of \(M = 16 \text{M}_\odot\) in figure 3.
The abundance of $^{20}\text{Ne}$ and $^{24}\text{Mg}$ are enhanced for large $g_{a\gamma}$ near $M_c \approx 2M_\odot$, whereas the behaviors are complicated. On the other hand, the abundance of $^{28}\text{Si}$ shows the opposite trend. The produced amount of $^{56}\text{Fe}$ is not influenced significantly by the axion cooling even with large $g_{a\gamma} \gtrsim 10^{-12}\text{ GeV}^{-1}$.

In figure 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 $^{24}\text{Mg}$ are converted to iron-group elements during the explosive nucleosynthesis just after the explosion [23]. Hence, as for the heavy elements from $^{28}\text{Si}$ to $^{56}\text{Ni}$, we consider the total amount of them.

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The amount of $^{20}\text{Ne}$ is considerably increased for large $g_{a\gamma}$; in the case with $g_{a\gamma} = 10^{-11}$ the amount is enhanced more than three times. This trend is also weakly seen in the amount of $^{24}\text{Mg}$. On the other hand, the total amount of the heavier elements is smaller for larger $g_{a\gamma}$.

To understand these results, we plot in figure 5 the time evolution of both the total energy generation rate and the axion emission rate at the center from the ZAMS to the core collapse. In the weak coupling cases with $g_{a\gamma} \lesssim 10^{-10}\text{ GeV}^{-1}$ we are considering, the axion cooling does not change the lifetime of the star. In such circumstances, the effect of axion cooling is simply the extraction of the thermal energy of the star, which slows down the nuclear reactions [23]. Our calculation shows that the temperature at the central region with $g_{a\gamma} = 10^{-11}$ GeV$^{-1}$ is 1 % lower than the standard case without axion cooling at the time of the termination of the Silicon burning at the center. In general, nuclear reaction rates strongly depend on temperature (e.g. [14, 23]) and the small decrease of the temperature considerably slows down the nuclear reactions. In fact, the peak value of the nuclear reaction rate is suppressed by half due to the axion cooling at that time.

One can find in figure 5 that the axion cooling rate increases monotonically over time at the central region. Therefore, the nuclear reactions in later phases such as carbon, oxygen and silicon burning phases are suppressed by the axion cooling and the larger amount of $^{20}\text{Ne}$ and $^{24}\text{Mg}$ is left, avoiding nuclear burning to synthesize heavier elements. Hence, the abundance of these elements, which are synthesized during these phases, are enhanced by the axion cooling as a result of the inactivation of the nucleosynthesis. Since these elements are not so affected by the later explosive nucleosynthesis [23], the ejected mass would be also larger for larger $g_{a\gamma}$ to possibly affect the chemical evolution of galaxies.

### IV. CONCLUSION

In this paper, we have studied the effect of the axion cooling on the nucleosynthesis in the massive star with $16M_\odot$ by using the stellar evolution code, MESA. We have found that the axion cooling suppresses the nucleosynthesis in the carbon, oxygen and silicon burning phases even...
in the weak coupling, \( g_{a\gamma} < 10^{-11} \text{ GeV}^{-1} \). As a result, the abundances of oxygen, neon and magnesium increase as the coupling constant \( g_{a\gamma} \) increases. Even in the case \( g_{a\gamma} = 10^{-11} \text{ GeV}^{-1} \), which is six times smaller than the current upper limit of \( g_{a\gamma} = 10^{-10} \), the final amount of neon is enhanced more than three times larger than the standard value that does not take into account the effect of axion cooling.

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[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977), URL http://link.aps.org/doi/10.1103/PhysRevLett.38.1440
[2] M. Kuster, G. Raffelt, and B. Beltrán, eds., Axions, vol. 741 of Lecture Notes in Physics, Berlin Springer Verlag (Springer, 2008).
[3] E. W. Kolb and M. S. Turner, The early universe, (Westview Press, 1990).
[4] G. G. Raffelt, Stars as laboratories for fundamental physics, (The University of Chicago Press, 1996).
[5] J. E. Kim, Physical Review Letters 43, 103 (1979).
[6] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nuclear Physics B 166, 493 (1980).
[7] M. Dine, W. Fischler, and M. Srednicki, Physics Letters B 104, 199 (1981).
[8] P. Gondolo and G. G. Raffelt, Phys. Rev. D 79, 107301 (2009), 0807.2926.
[9] A. Ayala, I. Dominguez, M. Giannotti, A. Mirizzi, and O. Straniero, ArXiv e-prints (2014), 1406.6053.
[10] A. Friedland, M. Giannotti, and M. Wise, Physical Review Letters 110, 061101 (2013), 1210.1271.
[11] B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, and F. Timmes, ApJS 192, 3 (2011), 1009.1622.
[12] B. Paxton, M. Cantiello, P. Arras, L. Bildsten, E. F. Brown, A. Dotter, C. Mankovich, M. H. Montgomery, D. Stello, F. X. Timmes, et al., ApJS 208, 4 (2013), 1301.0319.
[13] A. Pantziris and K. Kang, Phys. Rev. D 33, 3509 (1986).
[14] S. G. Ryan and A. J. Norton, Stellar Evolution and Nucleosynthesis (Cambridge University Press, 2010).
[15] H. Primakoff, Phys. Rev. 81, 899 (1951), URL http://link.aps.org/doi/10.1103/PhysRev.81.899
[16] M. Fukugita, S. Watamura, and M. Yoshimura, Phys. Rev. D 26, 1840 (1982).
[17] G. G. Raffelt, Phys. Rev. D 33, 897 (1986).
[18] G. G. Raffelt and D. S. P. Dearborn, Phys. Rev. D 36, 2211 (1987).
[19] G. G. Raffelt, Phys. Rep. 198, 1 (1990).
[20] T. Altherr, Zeitschrift fur Physik C Particles and Fields 47, 559 (1990).
[21] T. Altherr, E. Petitgirard, and T. del Río Gaztelurrutia, Astroparticle Physics 15, 801 (2000), hep-ph/0008190.
[22] G. G. Raffelt, Phys. Rev. D 37, 1356 (1988).
[23] R. Kippenhahn, A. Weigert, and A. Weiss, Stellar Structure and Evolution (Springer, 2013).
[24] D. Reimers, Memoires of the Societe Royale des Sciences de Liege 8, 369 (1975).
[25] S. E. Woosley and T. A. Weaver, ApJS 101, 181 (1995).
[26] Electrons, heavy ions and nucleons in stars are also expected to play an important role in the axion production process. However we focus only on axions generated by photons.
[27] \( \hbar, k_B \) and \( c \) are the reduced Planck constant, the Boltzmann constant and the speed of light, respectively.
[28] Although \( g_{a\gamma} = 10^{-10} \text{ GeV}^{-1} \) has already been excluded in a number of observations (e.g. [11, 12]), we plot this case for an illustrative purpose, in order to show the effect of the axion cooling.
[29] In general cooling increases the temperature of a star because the gravo-thermal specific heat is negative. However, in this case, the duration of the nuclear burning, \( \mathcal{O}(10^3) \) years, is much shorter than Kelvin-Helmholtz time scale of the star, \( \mathcal{O}(10^5) \) years. Therefore, the axion cooling of the star is too rapid to change the inner structure of the star, and invokes the decrease of the temperature of the star.