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THE SYNTHESIS OF ^{26}Al DURING COMBINED HYDROGEN AND HELIUM-BURNING REACTIONS

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Abstract. We have studied the synthesis of ^{26}Al during combined hydrogen and helium-burning processes in high temperature and density conditions. The possible sites for these processes are believed to be the neutron star surfaces where the density ranges from $\rho = 10^4$–10^7 g cm^{-3} and temperature range from 10^8–8×10^8 K. The screening effect which leads to an enhancement of nuclear reaction rates is taken into account whenever necessary. A detailed calculation of the abundances of ^{26}Al and ^{27}Al isotopes is presented here. Finite amounts of ^{26}Al is found to be produced at $T = 2 \times 10^8$ K and $\rho = 10^6$ g cm^{-3} due to these combined reactions. This situation is likely to be realized during the γ-ray burst events on neutron star surface. The amount of material processed in the burst sources is very little compared to the amount of material processed in Novae or Supernovae. Thus it is suggested that rather than contributing to the overall amount of ^{26}Al, γ-ray bursts are likely to contribute more significantly to the inhomogeneity of ^{26}Al distribution in interstellar medium.

1. Introduction

Under usual circumstances hydrogen and helium burning occur in separate mass layers. It was shown originally by Taam and Picklum (1978, 1979) that if hydrogen burns at sufficiently high densities ($\rho = 10^6$ g cm^{-3}) helium must eventually burn within the same mass layer. Extensive analysis of these combined hydrogen and helium-burning reactions at temperatures in excess of 4×10^8 K have been done by Wallace and Woosley (1981). However, at temperatures which are below this but in excess of 10^8 K an important product may be ^{26}Al. This is because the $^{27}\mathrm{Si}(p, \gamma)^{28}\mathrm{P}$ reaction which is the major leak out of the Mg–Al cycle is not of overriding importance at these temperatures. So the production of ^{26}Al as a result of the combined hydrogen and helium-burning reactions has also to be considered; in addition to the normal Mg–Al cycle operating in hydrogen-rich envelopes of Novae (Truran and Cameron, 1978; Woosley and Weaver, 1980; Arnould *et al.*, 1980; Hillebrandt and Thielemann, 1982; Clayton, 1984). We propose that this combined hydrogen and helium-burning reactions, starting with ^{12}C on the neutron star surface can initiate new chains of reaction (A) and (B) leading to the production of ^{26}Al,

$$^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}(\alpha, \gamma)^{20}\mathrm{Ne}(p, \gamma)^{21}\mathrm{Na}(\alpha, \gamma)^{25}\mathrm{Al}(\beta^+)^{25}\mathrm{Mg}(p, \gamma)^{26}\mathrm{Al}(p, \gamma)^{27}\mathrm{Si} \begin{array}{ll} \nearrow (\beta^+)^{27}\mathrm{Al} & (A) \\ \searrow (p, \gamma)^{28}\mathrm{P} & (B) \end{array} .$$

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In Section 2 we have discussed the model of γ-ray burst sources. The reaction rates and the resulting isotopic yields of ^{26}Al and ^{27}Al are calculated in Section 3 and conclusions regarding the contributions of these chains to ^{26}Al are discussed in Section 4.

2. Models of Gamma-Ray Burst Sources

The widely accepted model of γ-ray burst involves accretion of matter on to neutron star surface (Woosley and Taam, 1976). The accreting material is believed to be from Population II objects: namely, $Z = 0.02$, $Y = 0.28$, and $X_p = 0.70$. On reaching the neutron star surface where the densities range from 10^5 to 10^7 g cm^{-3} and temperature from 10^8 to 8×10^8 K, the accreting material ignites explosively and a thermonuclear flash is generated. Such thermonuclear flashes can be sites of synthesis of various chemical elements. The γ-ray line at $E_\gamma = 1.809$ MeV due to decay of ^{26}Al has been detected in the interstellar matter (Mahoney *et al.*, 1984; Shore *et al.*, 1985). This detection of ^{26}Al (half-life $\tau_{26} = 7.4 \times 10^5$ yr) gives a direct evidence of ongoing nucleosynthesis in our Galaxy. Synthesis of ^{26}Al can occur in two distinct modes. The quiet mode in which ^{26}Al is synthesized in a slow stellar nuclear process. This can take place in massive Main-Sequence stars and red giants. The explosive mode can occur when temperature and density reach high values in explosive or short-lived astrophysical situations. Substantial experimental effort was expended recently to understand the ^{25}Mg$(p, \gamma)^{26}$Al as well as ^{26}Al$(p, \gamma)^{27}$Si reactions. Champagne *et al.* (1983a, b) found that S-wave resonance might contribute to the Al-production reaction while Buchmann *et al.* (1984) observed several low-energy resonances in Al-destruction reaction. Thus the chains we are considering contain these reactions as the most likely ones for the synthesis of ^{26}Al in a combined hydrogen and helium-burning process. In the reaction chain (A), the β-decay of ^{27}Si is important at energies less than 2×10^8 K. However, at temperatures in excess of this, the chain (B) is important. It should be mentioned that though the destruction cross-section of ^{27}Si$(p, \gamma)^{28}$P is very large, at temperatures less than 4×10^8 K, the production of ^{26}Al is substantially more than the destruction.

3. Calculation of the Abundances

The rates of change of the fractional abundances of nuclides are given by the set of equations given below. For reaction chain (A), the following relations hold:

$$\frac{dX_{12}}{dt}\,(^{12}\mathrm{C}) = -0.25\rho X_{12} X_\alpha [N_A \langle \sigma v \rangle_{\alpha,\gamma} (^{12}C)]\,, \tag{1}$$

$$\frac{dX_{16}}{dt}\,(^{16}\mathrm{O}) = \frac{1}{3}\rho X_{12} X_\alpha [N_A \langle \sigma v \rangle_{\alpha,\gamma} (^{12}\mathrm{C})] - - \rho X_{16} X_\alpha [N_A \langle \sigma v \rangle_{\alpha,\gamma} (^{16}\mathrm{O})]\,, \tag{2}$$

$$\frac{\mathrm{d}X_{20}}{\mathrm{d}t}\,(^{20}\mathrm{Ne}) = \frac{5}{16}\,\rho X_{16}X_{\alpha}[N_A\,\langle\sigma v\rangle_{\alpha,\gamma}(^{16}\mathrm{O})] - \rho X_{20}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{20}\mathrm{Ne})]\,, \tag{3}$$

$$\frac{\mathrm{d}X_{21}}{\mathrm{d}t}\,(^{21}\mathrm{Na}) = \frac{21}{20}\,\rho X_{20}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{20}\mathrm{Ne})] - \frac{1}{4}\,\rho X_{21}X_{\alpha}[N_A\,\langle\sigma v\rangle_{\alpha,\gamma}(^{21}\mathrm{Na})]\,, \tag{4}$$

$$\frac{\mathrm{d}X_{25}}{\mathrm{d}t}\,(^{25}\mathrm{Al}) = \frac{25}{84}\,\rho X_{21}X_{\alpha}[N_A\,\langle\sigma v\rangle_{\alpha,\gamma}(^{21}\mathrm{Na})] - \frac{0.693}{7.17}\,X_{25}(^{25}\mathrm{Al})\,, \tag{5}$$

$$\frac{\mathrm{d}X_{25}}{\mathrm{d}t}\,(^{25}\mathrm{Mg}) = \frac{0.693}{7.17}\,X_{25}(^{25}\mathrm{Al}) - \rho X_{25}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{25}\mathrm{Mg})]\,, \tag{6}$$

$$\frac{\mathrm{d}X_{26}}{\mathrm{d}t}\,(^{26}\mathrm{Al}) = \frac{25}{26}\,\rho X_{25}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{25}\mathrm{Mg})] - \rho X_{26}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{26}\mathrm{Al})]\,, \tag{7}$$

$$\frac{\mathrm{d}X_{27}}{\mathrm{d}t}\,(^{27}\mathrm{Si}) = \frac{27}{26}\,\rho X_{26}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{26}\mathrm{Al})] - \frac{0.693}{4.14}\,X_{27}(^{27}\mathrm{Si})]\,, \tag{8}$$

$$\frac{\mathrm{d}X_{27}}{\mathrm{d}t}\,(^{27}\mathrm{Al}) = \frac{0.693}{4.14}\,X_{27}(^{27}\mathrm{Si})\,. \tag{9}$$

For reaction chain (B), the first seven relations remain same as that of chain (A). The last two relations are

$$\frac{\mathrm{d}X_{27}}{\mathrm{d}t}\,(^{27}\mathrm{Si}) = \frac{27}{26}\,\rho X_{26}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{26}\mathrm{Al})] - \rho X_{27}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{27}\mathrm{Si})]\,, \tag{10}$$

$$\frac{\mathrm{d}X_{28}}{\mathrm{d}t}\,(^{28}\mathrm{P}) = \frac{28}{27}\,\rho X_{27}X_P[N_A\,\langle\sigma v\rangle_{P,\gamma}(^{27}\mathrm{Si})]\,. \tag{11}$$

The reaction rates of the elements occurring in the chains are obtained from Woosley *et al.* (1975), Harris *et al.* (1983), Caughlan *et al.* (1985), and Wiescher *et al.* (1986). These rates are then modified by taking into account the screening effect at high densities $\rho = 5 \times 10^5$–10^7 g cm^{-3}. The strong screening multiplicative correction factor is calculated using the formulae due to Itoh *et al.* (1979). The screening effect which enhances the nuclear reaction rates has greater influence at high-density situations. In

Equation (1) through (11) we have used the modified reaction rates due to screening. For solving the equations the initial values chosen for the fractional abundances of carbon, hydrogen, and helium are, respectively, as $X_{12} = 0.02$, $X_p = 0.70$, and $X_\alpha = 0.28$ in conformity with the Population II objects. With these values and modified reaction rates the equations are solved at $T = 1 \times 10^8$ K–3×10^8 K and $\rho = 5 \times 10^5$–1×10^7 g cm^{-3}. The set of equations may be written symbolically in a general form as

$$X_n = \alpha_{n,\,n-1} X_{n-1} - \alpha_{n,\,n} X_n \,, \tag{12}$$

where $n = 1, 2, 3 \ldots 9$ and $\alpha_{10} = 0$, $\alpha_{99} = 0$.

The solution of these equations may also be written in a general form as

$$x_j = \left\{ \int \alpha_{j,\,j-1} \alpha_{j-1}\, e^{\alpha_{jj} t}\, \mathrm{d}t \right\} e^{-\alpha_{jj} t} + \text{constant} \,. \tag{13}$$

The initial conditions at time $t = 0$ implies constant = 0.

The solution of the first equation is

$$X_1 = x_0\, e^{-\alpha_{10} t} \,, \quad x_0 = 0.02 \,.$$

The fractional abundances are thus calculated and then expressed in terms of number densities by the use of the equation

$$n(A) = \frac{\rho X_H}{AH} \,,$$

where H, A are the mass of hydrogen atom and mass number, respectively. These number densities are then normalized to the abundance of ^{25}Mg as given by Cameron (1982) which in turn were normalized to $^{28}\mathrm{Si} = 10^6$.

The abundance ratios of ^{26}Al/^{27}Al at $T = 2 \times 10^8$ K and $\rho = 5 \times 10^5$–1×10^7 g cm^{-3} are calculated and are shown in Table I. Few observed values of ^{26}Al/^{27}Al ratio in supernovae are: 1×10^{-2} (Arnould *et al.*, 1980), 1×10^{-3} (Woosley and Weaver, 1980), 5×10^{-3} (Mahoney *et al.*, 1982). The abundance ratio of ^{26}Al/^{27}Al at hydrodynamic time (τ_{HD}) and at temperature $T = 2 \times 10^8$ K is calculated to be about 1.358×10^{-5} at $\rho = 5 \times 10^5$ g cm^{-3} and 7.7611×10^{-8} at $\rho = 1 \times 10^6$ g cm^{-3}. Considering that there are about 2300 γ-ray burst sources yr^{-1} in our Galaxy (Meegan *et al.*, 1985), the amount of ^{26}Al being fed into the interstellar medium looks quite substantial compared to yields from Supernovae (Woosley and Weaver, 1980; Clayton, 1984) whose frequency is only once in 30 years. However, it should be remembered that the amount of material processed in a γ-ray burst source is only about $10^{-14}\,M_\odot$ (Epstein, 1985) whereas supernovae process and disperse about 1 $M_\odot$ per event. Hence, the yield from the γ-ray burst is inconsequential if one considers the whole of the galactic volume.

TABLE I

Abundance ratio of ^{26}Al/^{27}Al

Density (ρ) (g cm^{-3})	$\tau_{HD} = \frac{446}{(\rho)^{1/2}}$ (s)	$t = 4.99 \times 10^{-3}$ (s)	$t = 2.5 \times 10^{-2}$ (s)	$t = 7.0 \times 10^{-2}$ (s)	$t = 0.15$ (s)	$t = 0.275$ (s)	$t = 0.455$ (s)	$t = 0.70$ (s)	$t = 1.02$ (s)	$t = \tau_{HD}$
5.0×10^5	0.631	1.995×10^4	4.845×10^2	2.586×10^1	1.554	5.489×10^{-2}	7.379×10^{-4}	2.842×10^{-6}	2.461×10^{-9}	1.358×10^{-5}
1.0×10^6	0.446	8.740×10^3	1.442×10^2	4.174	5.839×10^{-2}	1.631×10^{-4}	5.272×10^{-8}			7.761×10^{-8}
2.0×10^6	0.315	3.401×10^3	3.095×10^2	1.908×10^{-1}	1.035×10^{-4}	1.614×10^{-9}				4.887×10^{-11}
3.0×10^6	0.257	1.802×10^3	9.244	9.746×10^{-3}	1.924×10^{-7}					
4.0×10^6	0.223	1.094×10^3	3.014	5.109×10^{-4}	3.616×10^{-10}					
5.0×10^6	0.199	7.202×10^2	1.015	2.705×10^{-5}						
6.0×10^6	0.182	5.000×10^2	3.471	1.439×10^{-6}						
7.0×10^6	0.169	3.605×10^2	1.197×10^{-1}	7.678×10^{-8}						
8.0×10^6	0.158	2.669×10^2	4.150×10^{-2}	4.103×10^{-9}						
9.0×10^6	0.149	2.016×10^2	1.444×10^{-2}	2.195						
1.0×10^6	0.141	1.546×10^2	5.035×10^{-3}							

4. Discussion and Conclusions

The explosive hydrogen and helium-burning reactions on the surface of neutron stars are studied in detail. It is assumed that these reactions starting with ^{12}C on the neutron star surface, can initiate new chains of reactions leading to the production of ^{26}Al. The cross-sections have been obtained from published literature and is seen to be significant. The occurrence of these chains at the temperature density conditions relevant to the γ-ray burst sources is certainly possible. The rise time of γ-ray burst events in neutron star surface are found to be quite short, of the order of a few milliseconds (Mazets *et al.*, 1981). Once the reaction chain (A) is initiated it leads to the production of ^{26}Al in a time t which is of the order of or less than the hydrodynamic time-scale for free fall or free expansion. This is evident from Table I. The density range considered here gives the hydrodynamic time-scale which ranges from 0.14 s to 0.63 s. The persistence of the temperature conditions for time-scales longer than the peak burst period, is very likely, as the burst is the result of the dominant reactions and the slower reactions do take place more or less under the same conditions on a longer time-scale within Novae (Hildebrandt and Thielemann, 1982). In all these calculations two types of reaction chains have never been taken into account, probably due to the small reaction cross-sections for the same. In view of the importance of even the small yields from sources which may be numerous, like the γ-ray burst sources, these two chains are investigated here. For temperatures exceeding about $4–5 \times 10^8$ K alpha captures on to the most abundant nuclei in the CNO group via $^{14}O(\alpha, p)^{17}F$ and $^{15}O(\alpha, \gamma)^{19}Ne$ occur (Taam, 1985; Wiescher *et al.*, 1986) which change the character of the nuclear processing. These two reaction leaks are neglected here as they are not dominant reactions in our adopted temperature density conditions.

Keeping in view of the astrophysical settings we have also not taken into account the reaction leak $^{27}Si(p, \gamma)^{28}P$ which has certain influences on the ^{26}Al abundance and leads to very small values for temperatures above 2×10^8 K (Arnould *et al.*, 1980; Wiescher *et al.*, 1986). In the reaction chain (A) we have considered $^{27}Si(\beta^+)^{27}Al$ reaction. It is likely that at the adopted density conditions proton capture lifetime in ^{27}Si becomes small and thus can compete effectively with the β-decay rates. It has been observed in the case of certain nuclei that β-decay lifetimes drastically change at certain temperature density condition (Fuller and Fowler, 1979). In the event that β-decay lifetime of ^{27}Si also changes under appropriate physical conditions, we can surmise that β-decay may take precedence over proton capture. A number of protons also gradually get depleted as lighter elements capture them at a faster rate and only a small fraction will be left for ^{27}Si to capture them. Therefore, our consideration that ^{27}Si will β-decay rather than capture a proton can be justified. However, detailed calculation of proton capture and β-decay rates at appropriate temperature conditions in stellar situations may be necessary before making a definitive conclusion.

The amount of material processed in the burst sources is very little compared to the amount of material processed in Novae or Supernovae. Hence, for the enrichment of the general interstellar medium throughout the Galaxy the contribution from γ-ray burst sources seems negligible. But in the neighbourhood of burst sources the average abundance of ^{26}Al will be substantially higher than in the interstellar medium. Thus rather than contributing to the overall amount of ^{26}Al, γ-ray bursts are likely to contribute more significantly to the inhomogeneity of ^{26}Al distribution in the interstellar medium. It is expected that a relatively precise determination of reaction rates will finally give a definitive picture of the whole situation in regard to ^{26}Al production in neutron star surface and its distribution in the intergalactic space.

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