Investigation of the waiting point ^{22}Mg in the rp-process

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Nucleosynthesis in stars occurs via several reaction chains, including a combination of the (α,p)-process, (p,γ)-process, and β^+-decay. A nucleus is a waiting point if the (α,p) or (p,γ) reaction rate is so low that the nuclear processing has to wait for β^+-decay. Since the nucleosynthesis grows to the ^{22}Mg nucleus via the following reaction chains, $^{14}O(\alpha,p)(p,\gamma)^{18}Ne(\alpha,p)(p,\gamma)^{22}Mg$-$(\alpha,p)(p,\gamma)^{26}Si(\alpha,p)(p,\gamma)^{30}S(\alpha,p)(p,\gamma)^{34}Ar(\alpha,p)(p,\gamma)^{38}K$, there are three possible ways by which the reactions can proceed through ^{22}Mg: $^{22}Mg(\beta^+)^{22}Na$, $^{22}Mg(\alpha,p)^{25}Al$, and $^{22}Mg(p,\gamma)^{23}Al$. Because of the small Q-value (Q = 0.125 MeV) of the *(p,γ)*-reaction, it is thought that the photodisintergration of ^{23}Al prevents a significant part of the flow through this reaction. In addition, at high-temperature condition, i.e., T_9 = 1 – 10 GK, the $^{22}Mg(\alpha,p)^{25}Al$ reaction was thought to be dominant. If the reaction rate of $^{22}Mg(\alpha,p)^{25}Al$ is lower than the rate of beta decay, the nucleosynthesis must await the decay from ^{22}Mg, and subsequently, the ^{22}Mg nucleus becomes a waiting point. To investigate the potential waiting of ^{22}Mg, we measured the ^{22}Mg+α reaction and determined the resonance states[1)] of ^{26}Si that are used to calculate the reaction rate of $^{22}Mg(\alpha,p)^{25}Al$ under such stellar conditions. According to the results of a previous work,[2)] we could estimate the rate of the (α,p)-process, (p,γ)-process, and β^+-decay in ^{22}Mg.

The reaction rate of $^{22}Mg(\alpha,p)^{25}Al$ was determined by using the resonance states of ^{26}Si obtained from alpha scattering in the ^{22}Mg+α experiment. The calculation was performed by using following expression:

$$N_A \langle \sigma v \rangle_{tot} = 8.08\times10^{-9} \left(\mu T_6\right)^{-3/2} \sum_i \left(\omega\gamma\right)_i \exp\left(-\frac{11605 E_i}{T_6}\right) \quad (1)$$

where μ, (ωγ), E_i, and T_6 are reduced mass, resonance strength, resonance states, and temperature in million Kelvin, respectively. The resonance strength was calculated by assuming that of the proton occupied 10% of the total width. As shown in Fig. 1, the rates of the (α,p) reaction corresponding to the first resonance is the highest. The reaction rate is low under concerned stellar conditions, with a value in the range of 10^{-30} – 10^{-7}. The speed of the (α,p) reaction, which depends on the abundance of isotopes in the stellar environment, and that of beta decay were obtained from the following equations:

$$R_{\alpha p} = \left({\rho X_\alpha}/{m_\alpha} \right) N_A \langle \sigma v \rangle_{\alpha p} \quad (2)$$

$$R_{\beta+} = \ln 2 / T_{1/2}, \quad (3)$$

where ρ, X_a, $N_A<\sigma v>$, m_a, and $T_{1/2}$ are the density of the materials in the stellar environment, abundance of ^{4}He, rate of the (α,p) reaction, mass of ^{4}He, and half-life of ^{22}Mg. According to the rates obtained in the previous work,[2)] we could determine the speed of the (p,γ) reaction. The results show that in the temperature range of T_9 = 1 – 10 GK, the (p,γ) reaction is the dominant. Table 1 compares the three processes.

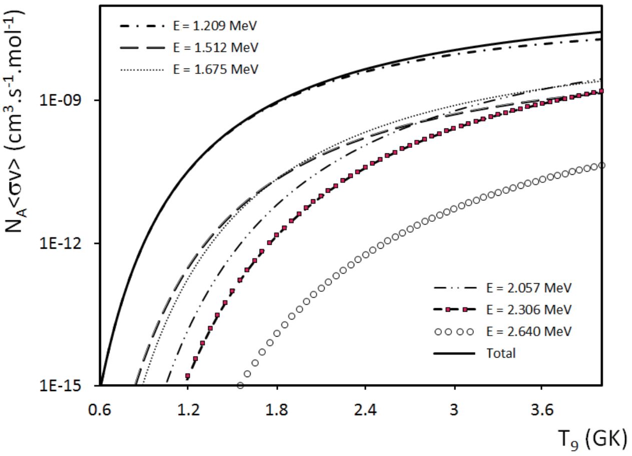

Fig. 1. Rates of the reaction $^{22}Mg(\alpha,p)^{25}Al$ calculated by using the resonance states of ^{26}Si via alpha scattering of ^{22}Mg.

Table 1. Speed of the reactions and beta decay

T_9 (GK)	$R_{\alpha p}$ (reaction/s)	$R_{p\gamma}$ (reaction/s)	$R_{\beta+}$ (decay/s)
1.0	2.99E-06	7.80E+03	0.1789
1.5	1.79E-04	2.47E+04	0.1789
2.0	1.26E-03	4.92E+04	0.1789
2.5	3.90E-03	7.80E+04	0.1789
10	7.50E-02	----	0.1789

Since the speed of the (p,γ) reaction is much higher than that of the others, it does not wait for beta decay. Therefore, under the conditions of X-ray burst and Type-II supernovae, the ^{22}Mg nucleus does not act as a waiting point. Subsequently, beta decay does not occur. Once the beta decay is skipped, the ^{22}Na unstable isotope which decays beta-plus (β+) to the excited state of ^{22}Ne, which de-excites to ground state by emitting gamma rays with energy of 1.275 MeV, cannot be formed. Therefore, such gamma rays have not been observed by satellites up to date. In addition, the ^{22}Ne/^{20}Ne ratio changes, which is one of the causes of the Ne-E problem.

References

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