Proton capture reaction of ^{33}S in nova V1065 Centauri*

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The previous studies have shown that ^{33}S(p, γ)^{34}Cl is the most important reaction that affects the abundance of ^{33}S in the product of nova nucleosynthesis. In this paper, a more accurate thermonuclear reaction rate of ^{33}S (p, γ) ^{34}Cl in the nova is calculated based on the newly measured ^{34}Cl nuclear resonance levels. The electron screening correction and the non-resonance and the narrow-resonance contributions are considered. The calculations are also combined with the recent observational data of nova V1065 Centauri and show that the thermonuclear reaction rates of ^{33}S (p, γ) ^{34}Cl are significantly different in the improved method. Because these results can affect the isotopic ratio of sulfur in the nova ejecta significantly, we make an estimate of the values of ^{32}S/^{33}S and ^{33}S/^{33}S$_\odot$, which can be used as a diagnostic tool for the novae.

Keywords: nova, nucleosynthesis, meteorite

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1. Introduction

Primitive meteorites contain grains from the presolar systems. These grains can provide a lot of information about the stellar evolution and nucleosynthesis.[1] An effective way to identify those primitive meteorites is to measure the differences between isotopic ingredients. For example, the isotopic ratios of those meteorite grains may be several orders of magnitude different from those of the grains in the solar system. Recently, José *et al.* measured a large number of isotopic ratios in the primitive meteorites, such as ^{12}C/^{13}C, ^{14}N/^{15}N, and ^{30}Si/^{28}Si. They found that the grains contain a large number of ^{33}S. Since the abnormality of sulfur isotopic ratio (i.e., ^{32}S/^{33}S) is an important feature of the nova explosion product,[2–4] many researchers believe that some primitive meteorites in the solar system come from the nova explosion.

The peak temperature of nova explosion $T_{\rm peak}$ is thought to be (1–4)$\times 10^8$ K.[5] In such a high-temperature and proton-rich environment, protons can overcome the large Coulomb barrier and be captured by some elements above Si.[6] For example, the most important destruction mechanism for ^{33}S in the nova explosion is the reaction ^{33}S(p, γ)^{34}Cl (Q = 5.142.75 keV).[7] The related analyses and researches on the thermonuclear reaction rate of ^{33}S (p, γ)^{34}Cl have been conducted by many scientists. In 2001, José *et al.* calculated the reaction rate of ^{33}S (p, γ)^{34}Cl using the known experimental data of resonant energy levels of that time,[6] in which only the contribution from the narrow resonance was considered. Later, Iliadis *et al.* examined the effects of various ^{33}S(p, γ)^{34}Cl rates on different nova models. They found that the ^{33}S abundance was decreased by a factor of 1000 when the rate was increased by 100 times, and increased by a factor of 3 when the rate was decreased by 100 times.[7] José *et al.* also obtained the ^{33}S mass abundance by using a 1.35$M_\odot$ O–Ne white dwarf model and found ^{33}S/^{33}S$_\odot$ = 150, where $M_\odot$ is the mass of the sun, and ^{33}S$_\odot$ is the mass abundance of ^{33}S in the sun.[6] They concluded that the overproduction of ^{33}S might be a prominent character of the classical nova.[5] Hence, the rate of ^{33}S(p, γ)^{34}Cl is very important for the analysis of prenova and final nucleosynthesis products, and still has a large uncertainty.[4] It is necessary to obtain more precise thermonuclear reaction rates at the peak temperature of the nova. In this paper, we integrate the

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newly obtained experimental data of resonant levels provided recently by Parikh[1] and newly spectrophotometric observations of nova V1065 Centauri[8] to recalculate the rates of ^{33}S(p, γ)^{34}Cl and consider the non-resonance, narrow-resonance, and electron screening contributions. Our results will affect the prediction of the sulphur isotope in the ejecta of novae and may be used as a diagnostic tool for the novae.

2. Thermonuclear reaction rates of ^{33}S(p, γ)^{34}Cl in nova V1065 Centauri

The classical nova V1065 Centauri (or named as nova Cen 2007) is a bright nova with a magnitude of $m_{\rm V} \approx 8.2$, and it is 8.7 kpc away from the earth.[9,10] Recently, Helton *et al.* investigated the composition and the evolution of its ejecta based on the new observations.[8] They obtained the abundances of some important nuclides by photoionization modeling, e.g., He/H=1.6±0.3, N/H=144±34, O/H=58±18, Ne/H=316±58, S/H=54±31 (comparing with the solar abundances). We can find from the above data that the uncertainty of the sulfur abundance is large. As for the isotopic ratio of sulfur, more theoretical and observational works are needed. In the following, we will give an estimate of the abundance of ^{33}S according to the observations of nova V1065 Centauri and the improved reaction rates. The method used to calculate the thermonuclear reaction rate has been described in detail in many references, for example, see Refs. [11]–[13]. Here we only give a brief introduction.

The total cross section is $\langle\sigma\rangle = \langle\sigma\rangle_{\rm nr} + \langle\sigma\rangle_{\rm r}$, where $\sigma_{\rm nr}$ and $\sigma_{\rm r}$ are the non-resonance and the resonance cross sections, respectively. The averaged reaction probability of non-resonant can be approximated by[11]

$$\begin{aligned}\langle\sigma v\rangle_{\rm nr} &= 6.998\times10^{-16}\tau^2\frac{1}{\mu Z}\,{\rm e}^{-\tau}S(0)\\ &\times\left[1+\frac{5}{12\tau}+\frac{S'(0)}{S(0)}\left(E_0+\frac{35}{36}kT\right)\right.\\ &\left.+\frac{1}{2}\frac{S''(0)}{S(0)}\left(E_0^2+\frac{89}{36}E_0kT\right)\right],\end{aligned}\tag{1}$$

where v is the velocity of the colliding particle, $\tau = 4.248(Z^2\mu/T_9)^{1/3}$, Z is the number of protons in the target nucleus, μ is the reduced mass, T_9 is the temperature in units of 10^9 K, and k is the Boltzmann constant. The astrophysical S factor is a smooth function of bombarding proton energy E and usually obtained by experiments, and $E_0 = 0.122(Z^2\mu T_9^2)^{1/3}$ denotes the central location of the Gamow peak.

The averaged reaction probability of the narrow-resonance is given by

$$\begin{aligned}\langle\sigma v\rangle_{\rm r} &= 2.557\times10^{-13}\mu^{-3/2}T_9^{-3/2}\sum_i(\omega\gamma)_i\\ &\times\exp(-11.605E_{{\rm r}i}/T_9),\end{aligned}\tag{2}$$

where $E_{{\rm r}i}$ are the resonant energies, and $(\omega\gamma)_i$ are the strengths of the resonances in units of MeV.

Thermonuclear reaction rates in the stars are generally higher than those obtained in the laboratories because of the presence of the dense electron gas. The negative charge surrounding each nucleus reduces the Coulomb repulsion to a value smaller than $Z_1Z_2e^2/r$, where Z_1, Z_2 are the atomic numbers of the two colliding particles, e is the charge of an electron, and r is the distance between the two colliding particles. This reduction makes the penetration of the Coulomb barrier easier, which in turn enhances the cross section in comparison with that of the bare nucleus having the same relative velocity at infinity. So the influence of electron screening on the reaction ^{33}S(p, γ)^{34}Cl should not be ignored. The electron screening effects on the thermonuclear reaction have been analyzed theoretically by many scientists.[14–17] Based on the previous theories, Hartmann *et al.* developed a program to calculate the electron screening correction in the thermonuclear reaction, which includes weak, medium, and strong screenings. In this paper, we use the program provided by JINA school. The screening correction to the cross section is denoted by $f_{\rm sc}$ in Eq. (3). The electron screening is dependent on both densities and temperatures. In our calculations, the stellar density is assumed to be an adjustable parameter. The range of density considered is from 1×10^3 g·cm^{-3} to 1×10^5 g·cm^{-3}. We find that the screening correction to ^{33}S(p, γ)^{34}Cl is very small if the density is lower than the minimal density chosen. Therefore, the thermonuclear reaction rate of ^{33}S(p, γ)^{34}Cl in nova V1065 Centauri can be written as

$$\begin{aligned}\lambda &= \lambda_{\rm nr}+\lambda_{\rm r}\\ &= n_{^{33}{\rm S}}n_{\rm p}f_{\rm sc}(\langle\sigma v\rangle_{\rm nr}+\langle\sigma v\rangle_{\rm r})\ ({\rm cm}^{-3}\cdot{\rm s}^{-1}),\end{aligned}\tag{3}$$

where λ, $\lambda_{\rm nr}$, $\lambda_{\rm r}$ denote the total, the non-resonance, and the resonance reaction rates, respectively. The $n_{\rm p}$ is the number density of proton, $n_{\rm p} = \rho N_{\rm A}Y_{\rm p}$, where ρ is the mass density at the burning location, $N_{\rm A}$ is the Avogadro's constant, and $Y_{\rm p}$ is the proton

fraction. According to the observation of nova V1065 Centauri,[8] $Y_{\rm p} \approx 0.65$. The $n_{^{33}{\rm S}} = n_{\rm p}\chi_{^{33}{\rm S}}/\chi_{\rm H}|_{\rm nova}$, $n_{^{33}{\rm S}}$ and $\chi_{^{33}{\rm S}}$ are the number density and the fraction of ^{33}S, respectively. The initial ^{33}S abundance in the sulfur isotope is the same to that in Ref. [6]. Hydrogen fraction $\chi_{\rm H}$ is obtained from the observational data of nova V1065 Centauri. Note that the standard solar element fractions are needed in the calculations, and we choose the data from Refs. [18] and [19].

3. Numerical analysis and discussion

The thermonuclear reaction rates of ^{33}S(p,γ)^{34}Cl with screening correction in nova V1065 Centauri are shown in Tables 1 and 2 (the density is assumed to be 1×10^4 g·cm^{-3} and 1×10^5 g·cm^{-3} respectively). Because the resonance rates are generally more than two orders of magnitude larger than the non-resonance rates, the non-resonance contribution is not important here. Comparing the rates, we find that the improved energy levels change the reaction rates significantly and the screening can play an important role in the nova, especially at low temperatures and high densities. Because different rates can bring huge differences to the final nucleosynthesis product, we make a prediction of the nucleosynthesis product combining the methods in Refs. [1], [11], and [20]. For example, assume the prenova is an O–Ne white dwarf with mass $1.35M_{\odot}$, its $T_{\rm peak}$ is 3.3×10^8 K. When José's rates are adopted, the product has $^{33}{\rm S}/^{33}{\rm S}_{\odot} \approx 150$, $^{32}{\rm S}/^{33}{\rm S}\approx 97$. When Parikh's rates are adopted (the rates for ^{33}S are seven times larger than José's), the product has $^{33}{\rm S}/^{33}{\rm S}_{\odot} \approx 12.5$, $^{32}{\rm S}/^{33}{\rm S}\approx 1164$. Similarly, we can obtain the values of $^{32}{\rm S}/^{33}{\rm S}$ and $^{33}{\rm S}/^{33}{\rm S}_{\odot}$ for different temperatures. Compared with the solar result ($^{32}{\rm S}/^{33}{\rm S}= 127$ in the sun[19]), the ratio for ^{33}S in the sulfur isotope changes obviously in the nova explosion product. If $T_{\rm peak} > 2\times10^8$ K, $^{32}{\rm S}/^{33}{\rm S}$ increases; the case is reversed if $T_{\rm peak} < 2\times10^8$ K, and this is caused by the reaction rates. At high temperatures, the reaction rates are comparatively large. The increase of the rate of ^{33}S(p, γ)^{34}Cl means the destruction of ^{33}S, causing the ratio $^{32}{\rm S}/^{33}{\rm S}$ to increase. But it can be seen from Tables 1 and 2 that the abundance of ^{33}S is always at least one order of magnitude larger than $^{33}{\rm S}_{\odot}$.

Table 1. Thermonuclear reaction rates and nucleosynthesis products of ^{33}S(p, γ)^{34}Cl in nova V1065 Centauri ($\rho = 1\times10^4$ g·cm^{-3}). Subscripts 1 and 2 denote the resonant energy levels obtained from Refs. [20] and [1], respectively.

$T_{\rm peak}/10^8$ K	λ_1/cm$^{-3}\cdot$ s^{-1}	λ_2/cm$^{-3}\cdot$s^{-1}	λ/cm$^{-3}\cdot$s^{-1}	$f_{\rm sc}$	$^{32}{\rm S}/^{33}{\rm S}$	$^{33}{\rm S}/^{33}{\rm S}_{\odot}$
2.0	5.724×10^{19}	9.722×10^{19}	1.050×10^{20}	1.080	278.455	52.252
2.5	9.062×10^{20}	4.270×10^{21}	4.512×10^{21}	1.056	772.593	18.832
3.0	8.847×10^{21}	5.700×10^{22}	5.944×10^{22}	1.042	1056.4	13.773
3.5	6.225×10^{22}	4.150×10^{23}	4.290×10^{23}	1.033	1093.0	13.311
4.0	3.039×10^{23}	1.905×10^{24}	1.957×10^{24}	1.027	1027.6	14.159

Table 2. Thermonuclear reaction rates and nucleosynthesis products of ^{33}S(p, γ)^{34}Cl in nova V1065 Centauri ($\rho = 1\times10^5$ g·cm^{-3}).

$T_{\rm peak}/10^8$ K	λ_1/cm$^{-3}\cdot$s^{-1}	λ_2/cm$^{-3}\cdot$s^{-1}	λ/cm$^{-3}\cdot$s^{-1}	$f_{\rm sc}$	$^{32}{\rm S}/^{33}{\rm S}$	$^{33}{\rm S}/^{33}{\rm S}_{\odot}$
1.0	1.083×10^{16}	8.646×10^{14}	1.735×10^{15}	2.006	16.256	895.014
1.5	7.530×10^{19}	2.247×10^{19}	3.283×10^{19}	1.461	55.088	264.120
2.0	5.724×10^{21}	9.722×10^{21}	1.240×10^{22}	1.275	300.742	48.380
2.5	9.062×10^{22}	4.270×10^{23}	5.140×10^{23}	1.203	816.317	17.824
3.0	8.847×10^{23}	5.700×10^{24}	6.509×10^{24}	1.141	1101.6	13.207
3.5	6.225×10^{24}	4.150×10^{25}	4.641×10^{25}	1.118	1129.9	12.876
4.0	3.039×10^{25}	1.905×10^{26}	2.076×10^{26}	1.089	1055.9	13.779

Figure 1 shows the variations of the fraction of ^{33}S with temperatures and densities. It is shown that besides the temperature, the density is also an important factor influencing $^{33}{\rm S}/^{33}{\rm S}_{\odot}$ and $^{32}{\rm S}/^{33}{\rm S}$. The $^{33}{\rm S}/^{33}{\rm S}_{\odot}$ decreases while $^{32}{\rm S}/^{33}{\rm S}$ increases with the increase of the density. If more detailed observations of nova V1065 Centauri (e.g., $^{32}{\rm S}/^{33}{\rm S}$) were made, the environment of ^{33}S(p, γ)^{34}Cl in that nova can be de-

rived by using our method.

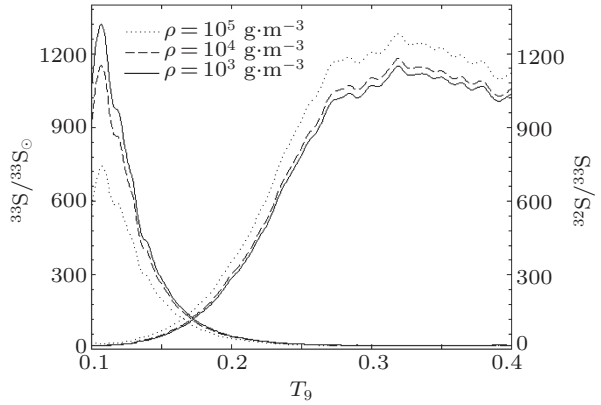


Fig. 1. The $^{33}S/^{33}S_\odot$ and $^{32}S/^{33}S$ in nova V1065 Centauri each as a function of temperature.

4. Conclusion

In this paper, we recalculate the rates and the nucleosynthesis products of $^{33}S(p, \gamma)^{34}Cl$ by considering the newly obtained experimental resonant levels of ^{34}Cl, the realistic observations of nova V1065 Centauri, and the electron screening. A small correction of proton capture reaction rate of ^{33}S may result in an obvious change of the fraction of ^{33}S. Our results improve the accuracy and can be used in the other similar environment.[21] The predicted ^{33}S fraction may provide a remarkable signature for the classical nova events.

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