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Resonance reaction rate of ^{21}Na(p,γ)^{22}Mg*

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By using the new Coulomb screening model and most recent experimental results, this paper calculates the resonance reaction rates of ^{21}Na(p,γ)^{22}Mg. The derived result shows that the effect of electron screening on resonant reaction is prominent in astrophysical interesting temperature range. In conjunction with the experimental results, the recommended rates of^{21}Na(p,γ)^{22}Mg would increase at least 10%, which undoubtedly affect the nucleosynthesis of some heavier nuclei in a variety of astrophysical sites.

Keywords: electron screening, nucleosynthesis, O–Ne nova, x-ray bursts, supernovae
PACC: 2340, 9760, 9530C

1. Introduction

As is well known, the reaction of ^{21}Na(p,γ)^{22}Mg not only influences the mass abundance of ^{22}Na in the material that is blown off by the stellar explosion events, but also serves as one of the first steps of the rp-process in x-ray bursts. The main importance of the reaction lies within the context of stellar nucleosynthesis in the Ne–Na cycle.[1] Figure 1 shows that the two reaction paths are available for ^{21}Na:[2] the first is so-called 'cold' Ne–Na cycle, the production of ^{21}Na from the seed nuclei ^{20}Ne then leads to ^{21}Na($\beta^+\nu_e$)^{21}Ne(p,γ)^{22}Na; the second is so-called 'hot' Ne–Na cycle, which associated with higher temperatures, proton capture on ^{21}Na dominates over its β^+-decay, followed by the reaction path ^{21}Na(p,γ)^{22}Mg($\beta^+\nu_e$)^{22}Na.

There is little net radioisotope ^{23}Al via ^{22}Mg by proton capture due to the fact that the low Q-value for photodisintegration of ^{23}Al.[3] Thus, ^{22}Mg plays a crucial role on the synthesis of ^{22}Na, which is mainly produced by β^+-decay of ^{22}Mg. Current models of O—Ne nova indicate that the unknown rate of ^{21}Na(p,γ)^{22}Mg is the most important factor responsible for uncertainty associated with calculations of the amount of ^{22}Na in nova event.[4,5] The abundances of ^{22}Na are very sensitive to the rates, and its variation range is up to several orders of magnitude with the reaction rate.[6] The amount of ^{22}Na is a potentially observable quantity, because its β^+-decay (with half-life 2.6 year) leads to emission of a 1.275 MeV gamma-ray, it is expected to serve as an important tracers for new gamma-ray telescopes, and if detected, may help constrain the current nova models.[7,8] Thus far, observational data taken by NASA's COMPTEL onboard CGRO satellite of five O–Ne novae candidates have not found this gamma-ray signature.[9] The recently launched INTEGRAL orbiting gamma-ray telescope may help resolve this situation, it has the potential to detect ^{22}Na with much greater sensitivity than previous telescopes. Moreover, the ^{21}Na(p,γ)^{22}Mg reaction could potentially influence the features of x-ray bursts since the reaction part of the (α,p) process, and following the ^{18}Ne(α,pp)^{21}Na reaction, which initiates one of two most important paths to leak from the hot-CNO cycle.[7] The last but not the least, the reaction of ^{21}Na(p,γ)^{22}Mg is also important in some supernova and other cosmic nucleosynthesis. The rates of ^{21}Na(p,γ)^{22}Mg could potentially influence the amount of ^{26}Al in supernova explosion due to the fact that the anti-correlation of the ^{22}Na and ^{26}Al in stellar evolution in turn influences the gamma-ray characteristics of these unstable radioisotope. Radioactivity is an useful tool in astronomy, measurement of the characteristic of gamma-ray from radioactive isotopes and discussion of the astrophysical origin of radioisotope provide an useful complement to other means to study the cosmic nucleosynthesis, which is particularly interesting to promote and verify the modern stellar evo-

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lution, as well as investigates the theoretical model of novae and supernova.

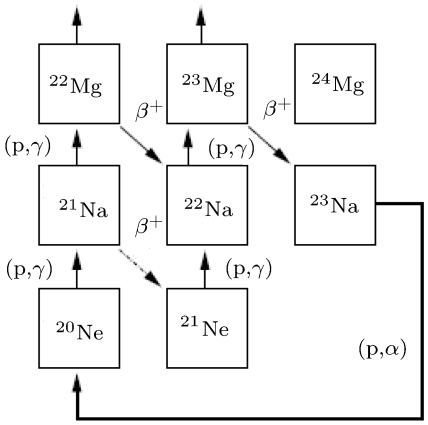


Fig.1. The combined 'cold' and 'hot' Ne–Na reaction cycles. The isotope ^{21}Na will either β^+-decay into ^{21}Ne (the "cold" Ne–Na cycle) or capture a proton leading to ^{22}Mg (the "hot" Ne–Na cycle) depending upon the temperature and the reaction rate.

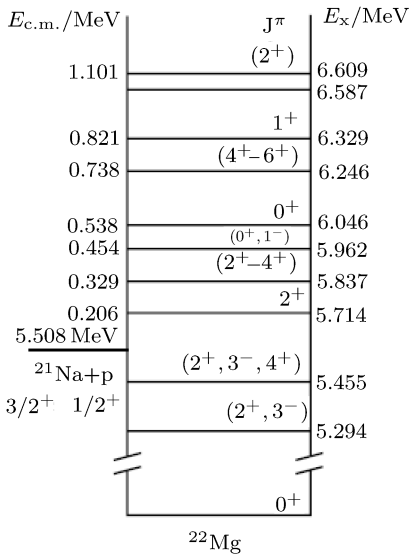


Fig.2. Level scheme of the ^{22}Mg nucleus showing the measured resonant energies $E_{\rm c.m.}$ of ^{21}Na(p,γ)^{22}Mg, the corresponding excitation energies $E_{\rm x}$, and the presumed spin assignments of the states of astrophysical interest.

The reaction of ^{21}Na(p,γ)^{22}Mg has been studied by many experimental and theoretical scholars due to its significance for nucleosynthesis in astrophysical sites. The rate was firstly estimated by Wiescher and Langank,[10] and the recent studies have helped clarify significantly the level structure of ^{22}Mg (see Refs.[2,7,11] and references therein). We present a reanalysis of the ^{21}Na(p,γ)^{22}Mg reaction rate for two reasons. First, a recent experimental study of the ^{21}Na(p,γ)^{22}Mg reaction was published by Chen *et al.*[7] This group has just completed a series of measurements of the resonance strengths at $E_{\rm r}$ = 454, 538, 738, 821 and 1101 keV by using inverse kinematics with DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) facility. The most clarified level scheme of ^{22}Mg was summarized by Trinczek *et al*[11] (see Fig.2), which is based on the gamma-gamma correlation analysis. Compared with previous work, we find that some higher lying energy resonance strengths have large differences. These differences might change the total reaction rates appreciably due to the fact that each resonance contribution to the reaction rates is directly proportional to its corresponding resonance strength. In fact, it is extremely important that the higher lying resonances for astrophysical sites, the change of rates could influence many astrophysical processes. Second, the effect of electron screening on thermonuclear reaction rate in high-density plasma has not been considered in previous work. The effect of electron screening on electron capture and prompt explosion energy for SNII had been discussed, the obtained result shows that consideration the screening effect is extremely important in certain temperature-density conditions.[12−15] It is also important to consider the effect of electron screening on thermonuclear reaction rate, especially for these key reaction. Recently a new screening model is proposed by Liolios[16] and universally used. This paper briefly calculates the resonance reaction rates of ^{21}Na(p,γ)^{22}Mg by using this Coulomb screening model as well as the level parameters and resonance strengths recommended by Refs.[7, 17]. Finally, we use the new rates to discuss its important astrophysical implications.

2. The resonance reaction rate

The total reaction rates of proton capture is the sum of the resonant and non-resonant reaction (also called direct capture) contributions to the nuclear reaction mechanism. The direct capture contributions of ^{21}Na(p,γ)^{22}Mg reaction was calculated by Davids *et al*[18] with relative accuracy by using the low-energy S-factor given in Ref.[19] value of 7.9 keV·b at zero energy. The derived result shows that the direct capture only contributes significantly to the reaction rate at the stellar temperatures below T_9 = 0.07 (T_9 the temperature in units of 10^9 K). This work will therefore not repeat here and only consider the resonant contributions. And the contribution of resonance to

the total reaction rate is given by

$$N_{\rm A}\langle\sigma v\rangle_{\rm r} = 1.54\times10^{11}(\mu T_9)^{-2/3} \times\sum_i \omega\gamma_i \exp(-11.605E_{r_i}/T_9) \quad {\rm cm^3\cdot mol^{-1}\cdot s^{-1}}, (1)$$

where $N_{\rm A}$ is the Avogadro's constant, μ is the reduced mass of the two collision partners in amu, $\langle\sigma v\rangle$ is the thermally averaged nuclear cross section, E_{r_i} are the resonance energies and $\omega\gamma_i$ are the strengths of the resonance in MeV. The resonance strength $\omega\gamma$ for a (p, γ) reaction is given by

$$\omega\gamma = \frac{2J_{\rm R}+1}{(2J_{\rm P}+1)(2J_{\rm T}+1)}\frac{\Gamma_{\rm p}\Gamma_\gamma}{\Gamma}, \qquad (2)$$

where $J_{\rm P}$, $J_{\rm T}$ and $J_{\rm R}$ are the spins of projection, target and resonance respectively, and the total width Γ is the sum of the proton partial width $\Gamma_{\rm p}$ and the gamma-ray partial width Γ_γ. The level parameters and resonance strengths through experimental measurements are listed in Table 1 recording by Refs.[7,17]. In order to obtain more accurate resonance strengths, we choice the experimental results as follows. For the first two and sixth resonances, the strengths are very similar and the values given in Ref.[7] were adopted. For the middle three resonances, the strengths are taken from Ref.[16] due to the fact that the resonance strengths are fixed values and in the range of uncertainties of the results given in Ref.[7]. For the last resonance, we adopt directly the result given by Ref.[7] because they were first detected.

The recommended resonance reaction rates of the ^{21}Na(p,γ)^{22}Mg can be parametrized by

$$N_{\rm A}\langle\sigma v\rangle_{\rm r} = \sum_i A_i T_9^{-2/3}\exp(B_i/T_9)\ {\rm cm^3\cdot mol^{-1}\cdot s^{-1}}. (3)$$

The parameters A_i, B_i ($i = 1, 2, 3, \cdots 7$) are listed in Table 2.

Table 1. Level parameters and resonance strengths for the reaction ^{21}Na(p,γ)^{22}Mg.

$E_{\rm x}$/MeV	$E_{\rm r}$/MeV	$\omega\gamma$/meV[7]	$\omega\gamma$/meV[17]	adopted
5.714	0.206	1.03±0.21	$1.03\pm0.16_{\rm stat}\pm0.14_{\rm sys}$	1.03
5.837	0.329	≤ 0.29	< 0.4	0.29
5.962	0.454	0.86±0.29	≈ 1	1
6.046	0.538	11.5±1.36	10	10
6.246	0.738	219±25	250	250
6.329	0.821	556±77	556±77	556
6.609	1.101	368±62		368

Table 2. Recommended parameters for the ^{21}Na(p,γ)^{22}Mg reaction rate.

A_i	1.701×10^2	4.789×10^1	1.420×10^2	1.65×10^3	4.129×10^4	9.182×10^4	6.077×10^4
B_i	−2.391	−3.818	−5.269	−6.244	−8.565	−9.528	−12.777

3. The effect of electron screening

The resonant energies declined relatively due to the effect of electron screening, namely $E'_{r_i} < E_{r_i}$, where E'_{r_i} are the corrected resonance energies. Thus Eq.(1) can be rewritten as

$$N_{\rm A}\langle\sigma v\rangle_{\rm r'} = 1.54\times10^{11}(\mu T_9)^{-2/3} \times\sum_i \omega\gamma_i \exp(-11.605E'_{r_i}/T_9) \quad {\rm cm^3\cdot mol^{-1}\cdot s^{-1}}. (4)$$

Generally speaking, the values of E'_{r_i} should be measured by experiment, but it is too hard to provide sufficient data. In general and approximate analyses, take $E'_{r_i} = E_{r_i} - U_0$.[20] In the recent Liolios's Coulomb screening model,[16] $U_0 = 15Z_1Z_2{\rm e}^2/8a$ and $a = \left(15/8Z_1^2\pi\right)^{1/3}a_0$, where a_0 is the Bohr radius. We introduce a screening enhancement factor (SEF) for considering the screening effect. The SEF for the resonant reaction can be expressed as

$$f_{\rm r} = \exp(11.605U_0/T_9). \qquad (5)$$

Obviously, the resonant SEF is determined by stellar temperature as well as screening potentials altogether. By the above discussion, the resonance reaction rates of ^{21}Na(p,γ)^{22}Mg, due to the screening effect, should be corrected as

$$N_{\rm A}\langle\sigma v\rangle = f_{\rm r}N_{\rm A}\langle\sigma v\rangle_{\rm r}. \qquad (6)$$

4. Numerical analysis and discussion

The resonant SEF as a function of the stellar temperature for the reaction ^{21}Na(p,γ)^{22}Mg is presented in Fig.3. The resonant SEF declines exponentially with the increase of temperature, which made the resonance reaction rate increase at least 6% at the stellar temperatures below $T_9 = 1.0$. One can see that, at the stellar temperatures $T_9 = 0.1 - 1.0$ range, the effect of screening on resonant contribution is prominent. Therefore, it is extremely important to consider the influences of electron screening for meticulous analysis of the reaction rate in certain temperature–density conditions, which is consistent with previous results.[12−15]

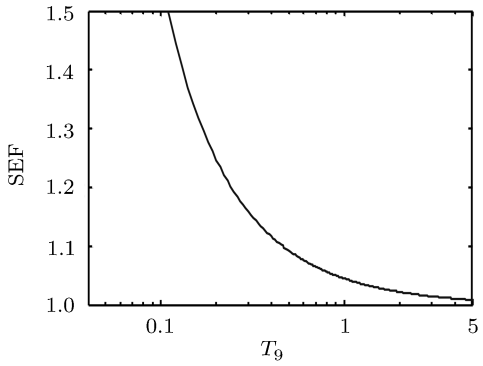


Fig.3. The resonant SEF as a function of temperature (T_9).

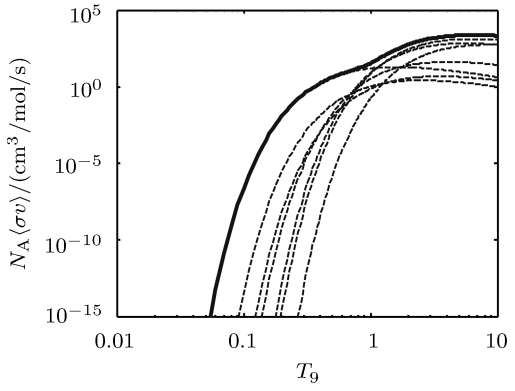


Fig.4. The total rates (solid line) and individual contributions (dashed line) to the reaction ^{21}Na(p,γ)^{22}Mg. (The dashed line from left to right refers to the individual resonance contributions from low to high energy in turn).

The individual resonance contributions to the total reaction rate are displayed in Fig.4. In conjunction with the results about the direct capture contributions given by Ref.[18], the resonance $E_r = 206$ keV dominates the reaction rates in the stellar temperature $T_9 = 0.07 - 0.8$ range, of which the upper limit lower than the values given in Ref.[7]. For the stellar temperature $T_9 > 0.8$, the resonances $E_r = 738$ keV as well as $E_r = 821$ keV dominate the reaction rates together, while the resonances $E_r = 538$ keV and 1101 keV have a little contributions. Compared with the mentioned resonances, others are negligible over the whole temperature range. In novae, the typical temperature range are around $T_9 = 0.1 - 0.4$, this work shows that the resonant reaction rates would increase around $12 - 60\%$ in comparison with the previous results in the case without the screening effect. In one word, considering the screening effect for analyses we find that the thermonuclear reaction rate of ^{21}Na(p,γ)^{22}Mg in novae is extremely important. The resonance E_r=206 keV is the only one of most importance in calculations of the production of ^{22}Na in O–Ne nova explosions, which are consistent with the results given by Ref.[17]. In x-ray bursts, the thermonuclear runaway is triggered by the ignition of the triple-alpha reaction and the break-out reactions from the hot CNO cycle, the typical peak temperatures are about $T_9 = 1-2$, the new rates would increase around $3\% - 6\%$ due to the effect of electron screening. The effect of electron screening on resonant reaction is obvious in x-ray bursts. We should note that the latter two resonance contributions, $E_r = 738$ keV and $E_r = 821$ keV, are more significant to the stellar reaction rates in this temperature range. Compared with previous work, at stellar temperatures above $T_9 = 0.8$, the new reaction rates are larger than the recent results given in Ref.[7] by about 10% due to the increase of resonance strengths. Without question, the increase rates could influence the features of x-ray bursts due to the fact that the hydrogen burning via the rp-process is the main energy source for x-ray bursts and determines the x-ray light curve. Moreover, the faster rates also influence the ^{18}Ne(α,p)^{21}Na reaction, and then in turn influence the features of x-ray burst because the x-ray burst critically depends on the rates of the alpha capture reactions on ^{18}Ne.

The reaction rates of ^{21}Na(p,γ)^{22}Mg are very important in supernova due to the fact that the explosive stellar event also takes place in these astrophysics sites. In supernova, the typical temperatures are about $T_9 = 0.2 - 5$, the effect of screening on resonant reaction is prominent in the lower temperature range. The faster the reaction rates of ^{21}Na(p,γ)^{22}Mg are, the lower the amount of ^{22}Na that survives in the explosion is. This is because the ^{22}Na

yields results from the fact that the increasing proton capture rate on ^{21}Na reduces the role of the reaction path ^{21}Na($\beta^+\nu_e$)^{21}Ne(p,γ)^{22}Na, but favours the synthesis path through ^{21}Na(p,γ)^{22}Mg($\beta^+\nu_e$)^{22}Na.[10] Moreover, the nucleosynthesis of ^{22}Na via ^{21}Na(p,γ)^{22}Mg($\beta^+\nu_e$)^{22}Na path in the presupernova would be destroyed more readily by proton capture in high temperature and density conditions. The comparatively fast rates of ^{23}Mg(p,γ)^{24}Al and the subsequent β^+-decay of ^{24}Al with very short half-life (only 2.1 s) accelerate the reaction leakage from the Ne–Na cycle into Mg–Al cycle.[15] At the stellar temperature above $T_9 = 1$, the reaction via the sequence ^{21}Na(p,γ)^{22}Mg(p,γ)^{23}Al(p,γ)^{24}Si($\beta^+\nu_e$)^{24}Al escapes from the network, and the subsequent reaction ^{24}Al($\beta^+\nu_e$) converts ^{24}Al into Mg–Al cycle.[15,21] In a word, the increase rates reduce the production of ^{22}Na final content in the supernova explosion. However, the results may partly solve the questions why not the 1.275 MeV gamma-ray emissions from ^{22}Na decay have been detected, while ^{26}Al is overabundant in the interstellar medium. Quantitative predictions have to await the results of large scale stellar nuclear network calculations.

References

[1] Hernanz M, José J, Coc A, Gómez-Gomar J and Isern J 1999 *ApJ* **526** 97

[2] Bishop S, Azuma R E, Buchmann L, Chen A A, Chatterjee M L, D'Auria J M, Engle S, Gigliotti D, Greife U, Hernanz M, Hunter D, Hussein A, Hutcheon D, Jewett C C, José J, King S, Kubono S, Laird A M, Lamey M, Lewis R, Liu W, Michimasa S, Olin A, Ottewell D, Parker P, Rogers J, Strider and Wrede C 2003 *Phys. Rev. Lett.* **90** 162501

[3] Wiescher M, Schatz H and Champage A E 1998 *Philos. Trans. Roy. Soc. London* **356** 2105

[4] José J, Coc A and Hernanz M 1999 *ApJ* **520** 347

[5] Smirnova N A and Coc A 2000 *Phys. Rev.* C **62** 045803

[6] Iliadis C, Champage A E, José J, Starrfield S and Tupper P 2002 *ApJ* S **142** 105

[7] Chen A A, Azuma R E, Bishop S, Buchmann L, Chatterjee M L, D'Auria J M, Engle S, Gigliotti D, Greife U, Hunter D, Hussein A, Hutcheon D, Jewett C C, José J, King S, Kubono S, Laird A M, Lamey M, Lewis R, Liu W, Olin A, Ottewell D, Parker P, Rogers J, Ruiz C, Strider and Wrede C 2005 *Nuc. Phys.* A **752** 510

[8] Peng Q H 1995 *Progress in Astronomy* **13**(4) 315 (in Chinese)

[9] Iyudin A F, Bennett K, Bloemen H, Diehl R, Hermsen W, Lichti G G, Morris D, Ryan J, Schoenfelder V and Steinle H 1995 *Astron. & Astrophys.* **300** 422

[10] Wiescher M and Langank K 1986 *Z. Phys.* A **325** 309

[11] Trinczek M, Jewett C C, D'Auria J M, Bishop S, Buchmann L, Chen A A, Engle S, Gigliotti D, Greife U, Hunter D, Hussein A, Hutcheon D, José J, Laird A M, Lamey M, Lewis R, Olin A, Ottewell D, Parker P, Pavan P, Pearson J E, Rogers J, Ruiz C and Wrede C 2005 *Nuc. Phys.* A **758** 729

[12] Luo Z Q, Liu M Q, Lin L B and Peng Q H 2005 *Chin. Phys.* **14** 1272

[13] Luo Z Q, Liu M Q, Lin L B and Peng Q H 2006 *ChA & A* **30** 19

[14] Liu M Q, Zhang J and Luo Z Q 2006 *Acta Phys. Sin.* **55** 3197 (in Chinese)

[15] Liu H L, Liu M Q, Lai X J and Luo Z Q 2007 *Chin. Phys.* **16** 1637

[16] Liolios T E 2000 *EPJA* **9** 287

[17] Hutcheon D A and the DRAGON Collaboration 2004 *Nuc. Phys.* A **746** 359

[18] Davids B, Beijiers J P M, van den Berg A M, Dendooven P, Harmsma S, Hunyadi M, de Huu M A, Siemssen R H, Wilschut H W and Wortch H J 2004 *Phys. Rev.* C **68** 065805

[19] Bateman N, Abe K, Ball G, Buchmann L, Chow J, D'auria J M, Fuchi Y, Iliadis C, Ishiyama H and Jackson K P 2001 *Phys. Rev.* C **63** 035803

[20] Itoh N, Tomizawa N, Wanajo S and Nozawa S 2003 *ApJ* **586** 1436

[21] Peng Q H 1994 *Chin. Phys. Lett.* **11**(8) 480