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The β-decay rates of ^{59}Fe isotopes in shell burning environments and their influences on the production of ^{60}Fe in massive star

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Abstract. The experimental B(GT) strengths of the ^{59}Fe excited states were employed to determine the transition strengths which greatly contribute ^{59}Fe stellar $\beta-$decay at typical carbon shell burning temperature. The result has been compared with the theoretical rates FFN (Fuller-Fowler-Newman) and LMP (Langanke&Martinez-Pinedo). Impact of the newly determined rate on the synthesis of cosmic γ emitter ^{60}Fe has also been studied using one-zone model calculation. Our results show ^{59}Fe stellar $\beta-$decay rate plays an important role in the ^{60}Fe nucleosynthesis. However the uncertainty of the decay rate is rather large due to the error of B(GT) strength that requires further studies.

1 Introduction

The radioactive isotope ^{60}Fe ($T_{1/2}$ = 2.62 Myr) is believed to be synthesized through ^{58}Fe(n,γ)^{59}Fe(n,γ)^{60}Fe during the hydrostatic burning in massive stars and explosive shell burning when stars end their life as a core collapsed supernova. In the similar stellar environments, the other long-lived isotope, ^{26}Al ($T_{1/2}$ = 0.717 Myr), is thought to be co-produced. Due to their long life times, both isotopes can survive toward the end of stellar life and are dispersed into interstellar medium after explosion, further enriched by next generation of stellar evolution. Their decay γ-ray fluxes reflect the averaged contributions of their production over the entire stellar evolution and over stellar groups with many individual sources, allowing for interpretation in terms of stellar and supernova burning sites, structure, and dynamics. [1]

Observations by RHESSI and INTEGRAL report a ratio of the fluxes from the decays of ^{60}Fe to that of ^{26}Al of 0.17±0.13 and 0.148±0.060, respectively [2, 3]. Both measurements are quite consistent with the early predicted value by Timmes *et al* [4]. However, later calculations using improved stellar and nuclear physics yield larger ^{60}Fe/^{26}Al flux ratios. E.g., Woosley and Heger [5] predicted a flux ratio of ^{60}Fe/^{26}Al=0.45, which is about a factor of 3 higher than the observation. Due to the uncertainties arising from both nuclear physics and stellar model, it is challenging to identify where the problems come from and a rather large ambiguity exists in the current prediction. To resolve this puzzle, it is essential to examine the crucial nuclear physics inputs and reduce their incurred uncertainties.

^{60}Fe is produced in massive stars during the He shell burning ($T \sim 0.4$ GK), C shell burning($T \sim$ 1.2 GK), together with explosive Ne burning (peak temperature $T \sim 2.2$ GK) [1]. The main reaction

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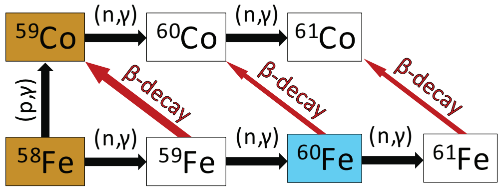

Figure 1. The net reaction flow of ^{60}Fe synthesis

flow is ^{58}Fe(n,γ)^{59}Fe(n,γ)^{60}Fe, as illustrated in Fig. 1. Since ^{59}Fe is unstable ($T_{1/2}$ = 44.5 days), the ^{59}Fe(n,γ)^{60}Fe must compete with the ^{59}Fe β-decay to produce an appreciable amount of ^{60}Fe. The surviving possibility of ^{60}Fe also depends on its neutron capture and β-decay rate. As discussed in reference [1], more than half of ^{60}Fe was synthesized at carbon shell burning and explosive Ne burning, where the temperature is higher than 1GK. At such high temperatures, the low-lying excited states of ^{59,60}Fe can be thermally populated with fractions sensitive to the environmental temperature. Even though most of these states decay by gamma transition in laboratory, the high temperature in stellar environments hinders this possibility and weak interaction process becomes dominant. Owing to the favorable selection rule and higher decay energy, stellar β-decay rate including the excited state contributions becomes much faster than its terrestrial rate.

In this paper, we review the past theoretical calculations of the stellar β-decay rates of ^{59}Fe. Using the Gamow-Teller transition probability B(GT) values obtained from charge exchange reaction and the empirical logft value of β-decay process, we provide a new stellar β-decay rate for ^{59}Fe. The impact of the new rate on the production of ^{60}Fe is investigated with one-zone carbon shell burning model.

2 Past works on the ^{59}Fe decay in stellar environment

Fuller, Fowler and Newman (FFN) estimated the weak interaction rates systematically for nuclei in the mass range $21 \leq A \leq 60$ at temperature range $0.01 \leq T$[GK]≤ 100 and density range $10 \leq \rho Y_e$[g/cm^3]$\leq 10^{11}$ [6]. Four different weak interaction processes, including electron capture, positron capture, β^+ decay and β^- decay, were considered in their calculation. Excitation energies and spins were taken from the 1978 compilations [7]. To estimate the transition strength, experimentally determined transition matrix elements were employed, whenever available. Unmeasured allowed GT transition has normally been assigned an empirical values (logft = 5) unless experiments gives an indication of logft >> 5 despite satisfaction of the selection rule for allowed transition. Single particle model was employed to calculate GT resonances. Until now the FFN weak interaction rates have been popularly used in supernova simulations.

Langanke and Martinez-Pinedo (LMP) used large-scale shell-model calculation to obtain electron capture and β-decay rates in stellar environment. The LMP data used KB3G effective shell-model hamiltonian based on realistic nucleon-nucleon interaction with optimization in the monopole interaction channel [8, 9]. With modern computational resources and more recent experimental data, the B(GT) resonances in the mass range $45 \leq A \leq 65$ are better described globally for its application in the range of $10 \leq \rho Y_e$[g/cm^3]$\leq 10^{11}$ and $0.01 \leq T$[GK]≤ 100.

The density of hydrostatic and explosive burning relevant to ^{60}Fe nucleosynthesis is below 10^5g/cm^3 at which β decay is the most dominant decay channel for ^{59,60}Fe. In such stellar environments, the differences of the ^{59,60}Fe β-decay rates between FFN and LMP are rather large. For example, at T=1.2 GK (a typical carbon burning temperature), the FFN rate is about ten times the LMP rate. Comparing with the FFN rate, the LMP rate focused on more reliable contribution from GT resonances. However, its predictive power on the B(GT) values of low-lying discrete states, which is crucial to stellar decay in high temperature and low density environment, might be overlooked [10].

3 Calculation of the β decay rate for ^{59}Fe in stellar environment

In stellar environment, nucleus is thermally populated to its excited states. The possibility of its population on a particular state with excitation energy of E_i and spin of J_i is given by the following equation,

$$P_i = \frac{(2J_i + 1)e^{-\frac{E_i}{kT}}}{\sum_k (2J_k + 1)e^{-\frac{E_k}{kT}}} \tag{1}$$

In the present work we include the ground state (g.s.) and seven lowest excited states of ^{59}Fe with excitation energy up to 1.02 MeV, which are listed in Fig. 2. As it will be shown in this section later, the states with higher excitation energy do not contribute significantly at $T < 2$ GK. In NNDC database the state 0.571 MeV was tentatively assigned as $5/2^-$ which could undergo allowed transition to the ground state of ^{59}Co. Although the fusion-evaporation measurement [13] assigned this state as $5/2^-$, the analysis of gamma transition alone could not exclude the assignment of $3/2^-$. With the analysis of angular distribution of differential cross section in the experiment ^{58}Fe(d,p) and ^{57}Fe(t,p) [12], the J^π of the state 0.571 MeV is identified as $3/2^-$. Thus the β-decay of this state should not be important because it cannot undergo allowed transition to ^{59}Co ground state. The 0.613 MeV and 0.643 MeV states are only weakly populated in two measurements, ^{58}Fe(n,γ) [14] and ^{58}Fe(d,p) [15]. Other important information such as J^π is missing. Thus these two states are excluded in the present work.

The most probable decay channel is controlled by the transition mode and the β-decay energy. The stellar β-decay scheme of ^{59}Fe is shown in Fig. 2. Only allowed transitions are listed.

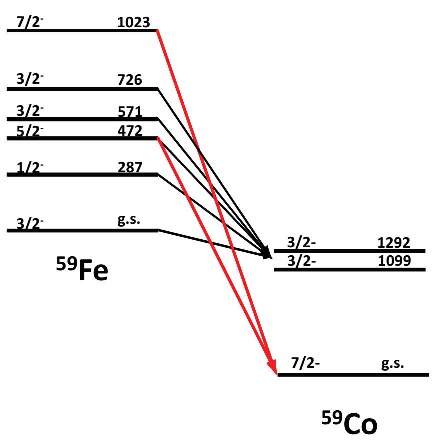

Figure 2. The stellar β-decay of ^{59}Fe. The red lines represent the allowed transitions to the ground state of ^{59}Co while the black lines represent the allowed transition to the excited states of ^{59}Co.

The allowed transitions to the ground state of ^{59}Co are highlighted with red lines, which could contribute the decay rate greatly due to their large decay energy. While the terrestrial β-decay rate of ^{59}Fe has been well studied in laboratory with a half-life of 44.495 days, the measurement of β-decay of excited states is not feasible in laboratory due to the γ-transition is much faster than the β-decay process. Although the shell model calculation could provide the GT strength, their prediction often can not reach the desired precision. To achieve a reliable estimation of the decay rate, indirect methods are developed to evaluate their β-decay rate.

Charge exchange reaction, such as ^{59}Co(n,p)^{59}Fe and ^{59}Co(t,^{3}He)^{59}Fe, offers an indirect approach to determine the allowed transition strength from the excitation states of ^{59}Fe to the ^{59}Co ground state. By now, only the ^{59}Co(n,p)^{59}Fe has been studied and the B(GT) strengths for the allowed transitions from the ^{59}Fe excited states to the ^{59}Co ground state were derived [16]. The B(GT) value of these transition is listed in Table 1 which are derived from ^{59}Co(n,p) measurement, along with ground state β-decay. Due to the limit of energy resolution, the extracted B(GT) value has a large uncertainty of $\sim 40\%$.

Table 1. Summary of the B(GT) and $\log ft$ values for the transitions from ^{59}Fe to ^{59}Co

Transitions	B(GT)	$\log ft$
472keV → g.s.	$3.49(138) \times 10^{-2}$	$5.04^{-0.14}_{+0.22}$
1023keV → g.s.	$3.90(149) \times 10^{-3}$	$6.00^{-0.14}_{+0.21}$
g.s → 1099keV	7.78×10^{-4}	6.70
g.s → 1292keV	4.05×10^{-3}	5.98
Other allowed transition	4.87×10^{-3}	5.9

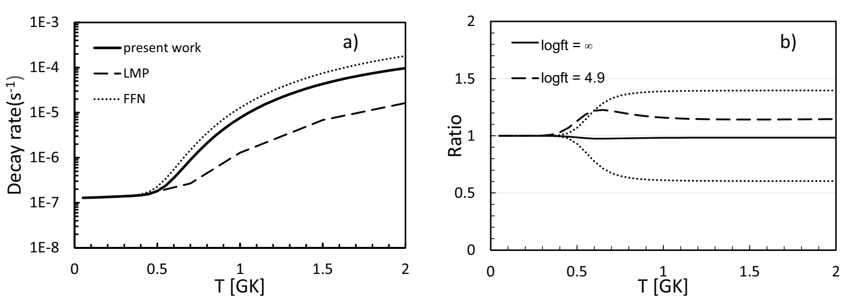

Figure 3. (a) The stellar β-decay rate of ^{59}Fe versus temperature. FFN and LMP rates are also plotted with dotted and dashed lines, respectively. (b) The impact on ^{59}Fe stellar β-decay rate with various uncertainties, with the relative decay rate to the present work. Dotted lines present the uncertainty due to the experiment data error of B(GT). The rates with empirical $\log ft$=4.9 and infinity are presented with dash and solid lines.

Besides of the decays to the ground state of ^{59}Co, all states can also decay to the excited state of ^{59}Co, e.g., 1.099 MeV ($3/2^-$) and 1.292 MeV ($3/2^-$) with allowed transition. Since the transitions of ^{59}Fe to ^{59}Co excitation states are not accessible for charge exchange reaction, we choose to use empirical $\log ft = 5.9$ based on β-decay statistics with selection-rule [18] for the allowed transitions to ^{59}Co excitation states, which are also listed in Table 1.

The obtained stellar decay rate is shown in Fig. 3(a). At low temperature ($T < 0.5$ GK) the g.s. β-decay dominates the rate. With raising temperature, the decay rate increases rapidly. At $T = 1.2$ GK, which is a typical carbon shell burning temperature, our stellar rate is about two orders of magnitude higher than the ground state decay rate ($1.80 \times 10^{-7} s^{-1}$).

The stellar decay rate of ^{59}Fe is dominated by the transitions from the ^{59}Fe ground state decay, and the two allowed transitions to ^{59}Co ground state (472 keV→g.s. and 1023 keV→g.s.). To illustrate their importance, we have calculated the decay rate which only takes these three transitions into account. The result is shown in Fig. 3(b) as the solid line. One can see it is almost the same as the decay rate including other transitions. This indicates these three transitions play an important role in the stellar β-decay. The large error bars associated with the two allowed transitions (472 keV→g.s. and 1023 keV→g.s.) incur about 40% uncertainty in the decay rate at the typical carbon shell burning temperature $T = 1.2$ GK.

The uncertainty incurred by the usage of empirical logft for the unmeasured transitions has been investigated by varying the logft values within a range obtained from observation. According to the statistical, the logft for allowed transition distributed in the range of 4.9 to 6.9 (1 σ) [18]. The decay rate with logft=4.9 is shown in Fig. 3(b) with dash line. At temperature $T = 1.2$ GK, the decay rate increases about 15% with log$ft = 4.9$, which is less than the 40% uncertainty incurred by the experimental B(GT) values for the two transitions, 472 keV→g.s. and 1023 keV→g.s.. The calculation of 3 states in the previous paragraph is equivalent to setting the logft of these excited state transitions to infinity. Therefore, this calculation can serve as the lower limit for the contributions to the total decay rate by the transitions to the excited states of ^{59}Co.

For investigating contribution of the higher states, we re-calculate the decay rate by including ^{59}Fe excited states up to 2 MeV. In the calculation, both allowed and first forbidden transitions are included. Empirical logft values from Ref. [18] are used for unmeasured transitions up to 2 MeV states. The result has less than 1% difference at $T = 1.2$ GK. Thus, the ^{59}Fe state higher than 1 MeV can be ignored for the nucleosynthesis of carbon shell burning.

It is clear that the uncertainties of the B(GT) values of ^{59}Fe(472 keV)→^{59}Co(g.s.) and ^{59}Fe(1023 keV)→^{59}Co(g.s.) are the dominant sources in the error budget. Therefore, the determination of the transition strength of those allowed transitions to the ^{59}Co ground state will be essential for the ^{59}Fe stellar β-decay rate at carbon burning temperature. This can be done with ^{59}Co(t,^{3}He)^{59}Fe with better resolution. In our calculation, the $E_x = 0.613$ MeV and 0.643 MeV states are excluded due to lacking of enough information. Their ambiguities in the stellar decay rate can also been fixed with the ^{59}Co(t,^{3}He)^{59}Fe reaction.

4 Impact on the nucleonsynthesis of ^{60}Fe in the carbon shell burning processes

We employ the network calculation code, NUCTNET [19], to investigate the influences of the new ^{59}Fe stellar β-decay rate on the nucleonsynthesis of ^{60}Fe in the carbon shell burning processes. The trajectory of temperature and density for the shell burning processes and initial abundances are taken from Ref. [20]. In the original NUCTNET code the terrestrial β-decay rates were used for calculation.

The ^{60}Fe abundance produced by carbon shell burning has been calculated with 4 different ^{59}Fe decay rates: terrestrial rate, FFN rate, LMP rate and our rate. The results are shown in Fig. 4. With our rate, the abundance of ^{60}Fe drops to 30% compared with the one obtained from the ground state rate. It shows the importance of the ^{59}Fe stellar β-decay rate to the ^{60}Fe synthesis. The abundance obtained from LMP is 3 times larger than the one obtained from FFN rates. The abundance of present work is between the abundances calculated with LMP and FFN rates.

Besides β-decay, ^{59}Fe(n,γ) rate also plays an important role in ^{60}Fe synthesis. In the present work the (n,γ) rate is taken from REACLIB [21] based on theoretical calculation. Recently experimental data is available based on ^{60}Fe(γ,n) measurement [22] . New rate is ~20% higher than the original one. To investigate the ^{60}Fe abundance uncertainty incurred by ^{59}Fe(n,γ)^{60}Fe rate, we update the ^{59}Fe(n,γ)^{60}Fe reaction rate and repeat the carbon shell burning calculation. Results are shown in Fig. 4.

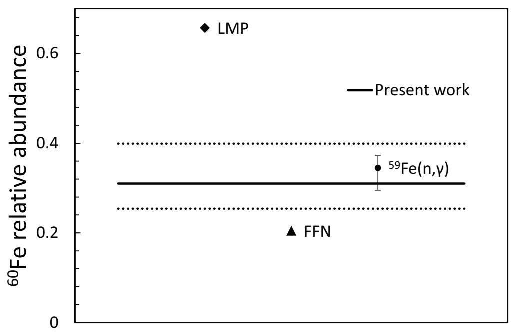

Figure 4. Relative ^{60}Fe abundances calculated with terrestrial rate, FFN rate and our rate. The results have been normalized by the ^{60}Fe abundances obtained with terrestrial ^{59}Fe rate. The ^{60}Fe abundance obtained with our rate is shown as the solid lines while the associated upper and lower limits are shown as the dotted lines. The ^{60}Fe abundance uncertainty incurred by ^{59}Fe(n,γ) is also shown.

5 Summary

The stellar β-decay of ^{59}Fe and its impact on ^{60}Fe are studied in this work. The charge exchange experiment data is employed to determine the transition strength from ^{59}Fe low-lying states to ^{59}Co ground state. Our analysis indicates that at carbon shell burning temperature the B(GT) strengths of two excited states (E_x = 472 keV and E_x = 1023 keV) are essential for the ^{59}Fe stellar β-decay rate. Our ^{59}Fe decay rate in present work is between FFN and LMP rates. However, due to the limitations of (n,p) measurement, the insufficient experiment resolution leads a large uncertainty in ^{59}Fe stellar β-decay rate. The impact on ^{60}Fe synthesis with stellar β-decay rate is studied with one-zone model calculation. It shows that ^{59}Fe stellar β-decay would significantly affect the ^{60}Fe synthesis. However at present the uncertainty is still very large due to the experiment data limit. One may expect that the further investigation like (t,^{3}He) would not only help to confirm the spin-parity assignment low-lying states of ^{59}Fe, but also to obtain more precise transition strength to reduce the uncertainty in ^{60}Fe synthesis.

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