2 - 11 Stellar β-decay Rate of ^{59}Fe and Its Impact on the ^{60}Fe Nucleosynthesis

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^{60}Fe is a long-lived nucleus ($T_{1/2}$=2.62×10^6 a) which is mainly synthesized in the Carbon-shell burning of massive stars. It still could be observed nowadays after being ejected to the space after massive star ends its life as supernova. Along with another long-lived nucleus ^{26}Al ($T_{1/2}$=7.17×10^5 a) which is synthesized in the similar stars, the observation of their decay γ could provide the information of stellar evolution. From 2002-2005 the INTEGRAL satellite with γ detector obtained ^{60}Fe/^{26}Al flux ratio in our Galaxy to be 0.148(60)[1]. It's significantly smaller than the theoretical prediction 0.45[2], and indicated that the theory need to be improved to increase the ^{60}Fe yield or decrease ^{26}Al yield. ^{60}Fe is produced by neutron capture reactions: ^{58}Fe(n, γ)^{59}Fe and ^{59}Fe(n, γ)^{60}Fe. The competition between β-decay of ^{59}Fe and its neutron capture plays an important role in ^{60}Fe synthesis path. In the present work, the impact on the ^{60}Fe synthesis of the β-decay process in stellar environment is studied.

Nucleus in stellar environment could be thermally populated to excited states at high temperature with given possibility:

$$P_i(T)=\frac{(2J_i+1)\exp(-\frac{E_i}{kT})}{\sum_k(2J_k+1)\exp(-\frac{E_k}{kT})} ,$$

Here, E_i and J_i are the excitation energy and spin of the i^{th} excited state of a given nucleus. P_i is the possibility of populating the i^{th} excited state for a given temperature T. Thus the β-decay of excited states, which is not likely to be observed in laboratory in most cases, would emerge at stellar environments. The occupation of ^{59}Fe excited states at 1.2 GK (typical temperature of Carbon-shell burning where ^{60}Fe mainly synthesized) are shown in Table 1.

Table 1 The occupation of ^{59}Fe excited states at 1.2 GK.

g.s. $3/2^-$	287 keV $1/2^-$	472 keV $5/2^-$	571 keV $3/2^-$	726 keV $3/2^-$
0.95	0.030	0.015	0.004	1.3×10^{-3}

^{59}Fe decay scheme is presented in Fig. 1 with strong allowed transition to ground state emphasized by dash lines. At temperature less than 3 GK, the low-lying state with allowed transition to the ground state of ^{59}Co would dominate β-decay rate.

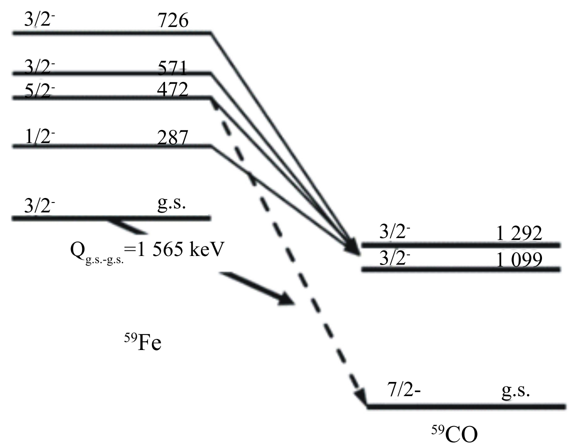

Fig. 1 The stellar β-decay of ^{59}Fe. The dash line represents the allowed transition to the ground state of ^{59}Co while the solid lines represent the allowed transition to the excited states of ^{59}Co.

While it is difficult to observe the β decay of the 472 keV $5/2^-$ state in laboratory, the β-decay rates in stellar environment are mainly determined from theoretical calculation. By now, there are two sets of ^{59}Fe stellar β-decay rates calculations available for Carbon and Neon-Shell burning phase that ^{60}Fe mainly synthesized: Fuller, Fowler, Newman (FFN) data set[3]with empirical logft=5 for the allowed low-lying state transitions, and Langanke,Martínez-Pinedo (LMP) data set[4] based on large-scale shell model calculation.

In the present work, experimental GT strength obtained from charge exchange experiment was used to determine the strength of the strong allowed transition ^{59}Fe (472 keV 5/2-) →^{59}Co (g.s. 7/2-) which contributes ^{59}Fe stellar β-decay mostly at Carbon and Neon-shell burning scenario. The other allowed transitions of higher lying states were estimated with GXPF1a shell model. The comparisons of the new ^{59}Fe stellar decay rates with the previous two theoretical calculations are list in Table 2. At 1.2 GK,^{59}Fe β-decay rate from the present work is about 2 orders of magnitude higher than the ground state decay rate observed in laboratory. The new rate is about a factor of 1/2 of the FFN rate and about a factor of 5 times higher than the LMP rate.

One zone Carbon-Neon shell burning calculation has been performed with NucNet[6] to investigate the impact of the new rate to the ^{60}Fe nucleosynthesis. Table 2 lists the ^{60}Fe abundance after Carbon and Neon shell burning. The strong dependence of the ^{60}Fe abundance on the ^{59}Fe stellar β-decay rate indicates that the β-decay plays an important role in the ^{60}Fe nucleosynthesis. However, the inaccuracy of the experimental GT strength leads large uncertainty in the ^{60}Fe abundance which couldn't provide tight constrain for the study of nuclear astrophysics. Therefore more precise experiment is called for to improve the stellar β-decay rate of ^{59}Fe.

Table 2 ^{59}Fe stellar β-decay rates at 1.2 GK and their impact on ^{60}Fe synthesis.

	^{59}Fe decay rate / s^{-1}	^{60}Fe abundance	relative ratio
g.s.	1.80×10^{-7}	2.47×10^{-6}	1
present work	$\mathbf{1.23\times10^{-5}}$	$\mathbf{4.63\times10^{-7}}$	**18.7%**
FFN	2.64×10^{-5}	7.92×10^{-8}	3.2%
LMP	2.56×10^{-6}	1.37×10^{-6}	55.2%

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2 - 12 Fusion Cross Section of ^{13}C + ^{12}C at Sub-barrier Energies

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Heavy-ion fusion reactions between light nuclei such as carbon and oxygen isotopes have been studied because of their importance in a wide variety of stellar burning scenarios. However, due to extremely low cross sections and signal/background ratio, all the measurements could only be carried out at energies well above the region of astrophysical interest. The reaction rates in stellar environment could be estimated only by extrapolating the existed cross sections or the astrophysical S-factors at higher energies. The situation is even more complicated by the strong, relatively narrow resonances in some reactions, such as ^{12}C+^{12}C, ^{12}C+^{16}O. Traditionally, optical model or equivalent square-well optical model (ESW) were used to fit the average cross section and predict the reaction cross sections at the energies of astrophysical interest[1]. Recently, a new model, the hindrance model, was proposed to provide systematic fits to fusion reaction data at extreme sub-barrier energies[2]. Lacking of experimental data within this energy range, large discrepancies exist among different nuclear reaction models.

In this work, ^{12}C+^{13}C reaction is chosen to test the predictive power of different reaction models. The ^{12}C (^{13}C, p) ^{24}Na reaction cross section was studied with a ^{13}C beam, delivered by the 3 MeV tandem accelerator of IFIN-HH. The ^{13}C beam energy range of 5.2 ∼ 6.8 MeV, in steps of 0.2 MeV and the beam intensity in the range of 2 ∼ 8 pμA were used in different runs. The residual activity of the ^{24}Na ($T_{1/2}$=15 h) was measured by detecting the gamma rays emitted by the beta-decay daughter at two different sites, *i.e.* IFIN-HH Low Background γ-Ray Spectrometry Laboratory (GAMASPEC)[3] and Unirea (Slanic-Prahova) salt mine ultra-low background radiation laboratory (microBq)[4]. Because the background rate in the microBq lab is only 0.016 count/h/kg/keV in the vicinity of E_γ= 1.4 MeV, which is about 59 times lower than that in the GAMASPEC lab, the measurements for the energies below 5.8 MeV ($E_{\rm cm}$=2.78 MeV) were only performed in the microBq lab. The preliminary results are