Impact of the molecular resonances on the ^{12}C $+^{12}$ C fusion reaction rate[†]

Y. Taniguchi[*1,*2] and M. Kimura[*2]

The ^{12}C $+^{12}$ C fusion reaction plays a vital role in explosive phenomena in the universe, such as X-ray superbursts, type Ia supernovae, and the evolution of massive stars. However, the reaction rate at low temperatures remains inconclusive due to the uncertainties in the measurements. The standard estimation by Caughlan and Fowler (CF88)[1)] assumes a constant astrophysical spectroscopic factor, whereas the hindrance model[5)] asserts its suppression at low temperatures. On the contrary, Cooper *et al.*[2)] discussed an increased reaction rate. Hence, imposing a constraint by the nuclear model calculations is crucial. For the first time, we imposed a constraint on the reaction rate based on the microscopic nuclear model in this work.

We employ the generator coordinate method (GCM) to obtain energies and wave functions of low-energy resonances using the Hamiltonian with the Gogny and Skyrme density functionals. We prepare the basis wave functions of ^{12}C$+^{12}$C, $\alpha+^{20}$Ne, $p+^{23}$Na (Fig. 1), and $n+^{23}$Mg channels and compound nucleus ^{24}Mg using the antisymmetrized molecular dynamics. With the R-matrix theory, we calculate the partial decay widths of the obtained resonances and estimate the ^{12}C$+^{12}$C fusion reaction rate.

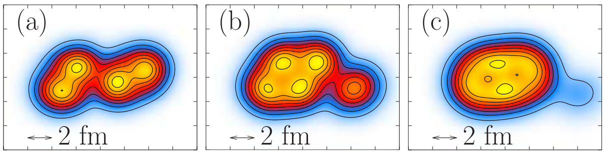

Fig. 1. Density distribution of the GCM basis of (a) ^{12}C$+^{12}$C, (b) $\alpha+^{20}$Ne, and (c) $p+^{23}$Na channels. Panels (a) and (b) are modified figures from Ref. 3).

Figure 2 shows the estimated ^{12}C $+^{12}$ C fusion reaction rate at stellar temperatures calculated with the Gogny (D1M* and D1S) and Skyrme (SLy4, SkM*, and SIII) density functionals. The Gogny functionals yield reaction rates close to the CF88 estimation. In contrast, Skyrme functionals predict lower reaction rates, similar to the hindrance model. We interpret the Gogny and Skyrme functionals as giving the upper and lower limits of the reaction rate, respectively, originating in the uncertainty in the density functionals.

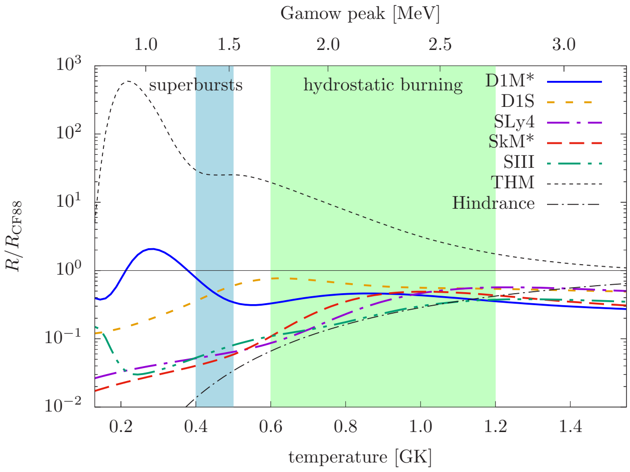

Fig. 2. The ^{12}C $+^{12}$ C fusion reaction rates relative to CF88[1)] obtained by using the Gogny and Skyrme functionals. The upper scale shows the Gamow peak energies in MeV. The reaction rates obtained from the THM experiment[4)] and the hindrance model[5)] are also shown. This figure is taken from Ref. 6).

The difference between the Gogny and Skyrme functionals is due to the 0+ and 2+ resonances at deep sub-barrier energies, where the resonance energies are below 2 MeV that is more than approximately 8 MeV lower than the Coulomb barrier. This energy region is significant for reaction rates below temperatures $T \lesssim 0.8$ GK. In the case of the Gogny functionals, ^{12}C $+^{12}$ C molecular resonances appear at approximately 1 MeV due to its coupling with other channels, leading to a substantial enhancement of the reaction rate. On the other hand, the Skyrme functionals do not yield such low-energy resonances.

Hence, exploring the 0^+ and 2^+ resonances at deep sub-barrier energy is a crucial step toward reducing the uncertainties in the reaction rate. For this purpose, we propose the measurements of the isoscalar transitions associated with these resonances.

References

1) G. R. Caughlan, W. A. Fowler, At. Data Nucl. Data Tables **40**, 283–334 (1988).
2) R. L. Cooper, A. W. Steiner, E. F. Brown, Astrophys. J. **702**, 660–671 (2009).
3) Y. Taniguchi, M. Kimura, Phys. Lett. B **823**, 136790 (2021).
4) A. Tumino *et al.*, Nature **557**, 687–690 (2018).
5) C. L. Jiang, K. E. Rehm, B. B. Back, R. V. F. Janssens, Phys. Rev. C **75**, 015803 (2007).
6) Y. Taniguchi, M. Kimura, Phys. Lett. B **849**, 138434 (2024).

[†] Condensed from the article in Phys. Lett. B **849**, 138434 (2024)
[*1] Department of Computer Science, Fukuyama University
[*2] RIKEN Nishina Center

DOI:10.34448/RIKEN.APR.58-043