Contribution ID: **13**

Type: **Poster**

The triple-alpha reaction at low temperatures by an exact three-body model

Tuesday, January 28, 2025 4:40 PM (1h 20m)

The triple-alpha reaction plays a significant role in nucleosynthesis heavier than 12C and concomitant stellar evolution [1]. The reaction rates of this reaction at the helium-burning temperatures, T_9 > 0.1, are dominated by the sequential process via two narrow resonances: alpha+alpha -> 8Be(0+_1: g.s.), 8Be+alpha -> 12C(0+_2: E=0.379 MeV) [2,3], and they have been understood relatively well through the studies of the Hoyle state. T_9 is temperature in unit of 10^9 K; E is the center-of-mass energy to the 3 alpha threshold in 12C. In contrast, the direct triple-alpha process from ternary continuum states, alpha+alpha+alpha -> 12C, for T_9 < 0.1 still seems to remain in an open question. The direct process corresponds to the non-resonant component in [4], and it is thought to be important in the astrophysical sites of novae, X-ray bursts, and Type-Ia SNe, leading to the nucleosynthesis of the hot CNO cycle and rp-process [5].

In NACRE [2], 8Be is assumed to be bound as a particle, and the reaction rates have been estimated by an improved model based on the pioneering works of [4]. To determine the rates more dynamically, the methods with hyper-spherical coordinates are used in [6-9], and the Coulomb modified Faddeev method is adopted in [10]. Whereas 8Be continuum states are treated adiabatically in [8-10], the direct process is calculated non-adiabatically in [6,7].

In this presentation, I discuss the direct triple-alpha process by using a non-adiabatic Faddeev hyper-spherical harmonics and R-matrix (HHR*) expansion method [6]. I illustrate that the calculated photo-disintegration cross sections of 12C(2+_1(E=-2.835 MeV) -> 0+) of HHR* are much smaller than those of the recent adiabatic models [9,10] for 0.15 < E < 0.35 MeV. The resultant rates have the strong temperature dependence at T_9 = 0.1, as well as NACRE, and their numerical values are expressed in a simple analytic form. From the comparison between the calculations, I find that the current standard rates [2,3] can be reduced by about 10^-4 at T_9 ~ 0.05, because of the accurate description of 8Be break-up. As an example of new rates, I also examine the ignition critical density [4] of helium burning in accreting white dwarfs. The present model with [11] leads to the ignition density of about (3 x 10^8) g cm^-3 at T_9= 0.01, which seems to be consistent with [4]. Due to the reduction of the rate at T_9= 0.05, the derived ignition density appears to be insensitive to the temperatures in 0.01 < T_9 < 0.05.

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Session Classification: Poster Presentation