Charged Particle Emission in Carbon-Carbon Burning at Astrophysical Energies

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Introduction

Massive stars (>10 Msun) acquire temperatures that can lead to heavy ion burning. In standard stellar models, the $^{12}C+^{12}C$ fusion reaction is one of the key factors differentiating between the evolutionary paths leading to either white dwarfs or further heavy element burning stages. The uncertainty in the rate of Carbon-Carbon fusion reaction is responsible for the present uncertainty in the cut-off mass (~8 M_{sun}) separating these two paths. In type Ia supernovae, Carbon-Carbon fusion initiates a thermonuclear runaway on the white dwarf once the Chandrasekhar mass has been exceeded. Therefore changes in the reaction rate will have a significant effect on further nucleosynthesis process.

The experimental determination of the rate of these reactions is very difficult in the laboratory as relative energies at which the reactions occur are far below the Coulomb barrier. The theoretical calculations are therefore a very useful tool to study such reactions. Whereas the R-matrix formalism is useful to calculate the fusion excitation functions at the Gamow energy for light charged particle reactions, they are not so suitable for heavy ion burning reactions. One reason is because higher level densities are involved in these reactions where the statistical model is more appropriate. More interestingly unlike for the light charged particle burning reactions heavy ion burning has particle decay branches even at astrophysical energies due to the Q values of these channels being positive. The branching ratios of these channels can play important role in the elemental abundance of the reaction products that can also lead to light ion burning reactions.

Most of the measurements for the heavy ion burning reactions have concentrated on the fusion excitation functions and their analysis by various fusion models. The particle channels are mostly obtained from the gamma spectroscopy of their residues [1-5]. Clearly in such studies the population to the ground state of the residual is missed. This missing cross-section can only be obtained from statistical model calculations of the particle cross-sections.

Statistical Model Calculations and Discussions

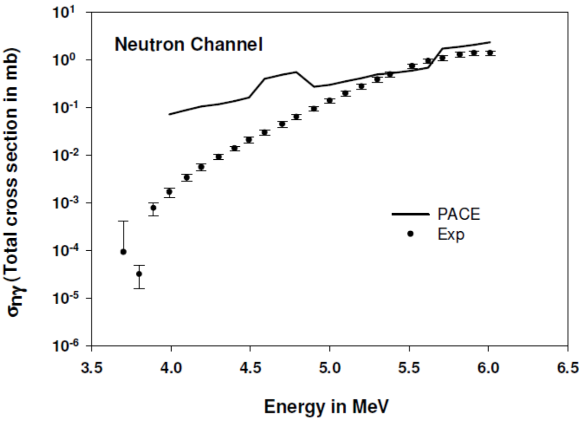

Fig. 1 The neutron excitation function from $^{12}C+^{12}C$ reaction measured by Barron-Palos et al [4] and PACE4 calculations performed by us.

In order to make statistical model calculations we need the entrance and exit channel optical potentials to calculate the transmission coefficients for the entrance and exit channels. The optical potential for $^{12}C+^{12}C$ fusion is studied in [6] and in [7]. At sub-Coulomb energies the elastic scattering data may have strong channel coupling effects. The common procedure of calculating the exit channel transmission coefficients is by using some global optical potentials. There are some well known global optical potentials for n [8], p [9] and α [10] particles.

There are a number of statistical model codes like PACE [11], CASCADE [12] that can be used for on shelf calculation. We show in the figures 1-3 statistical model calculations with PACE4 for the Carbon burning reactions $^{12}C(^{12}C, n)$, $^{12}C(^{12}C, p)$ and $^{12}C(^{12}C, \alpha)$. The optical potentials are the default optical potential parameters used by the code and the level density is taken as $\frac{A}{8}$ where A is the mass number of the nucleus. However PACE do not use the exact Hauser Feshbach formalism, instead it uses Monte-Carlo sampling to calculate the probability of formation of each residue after particle emission. This avoids the calculation of transmission coefficients for emissions from cascading residues in excited states. Moreover, it gives an average cross-section of emission of a particle average over the different residues formed. It does not give particle emission populating a particular state of the residual nucleus. For example let us look at the following reactions

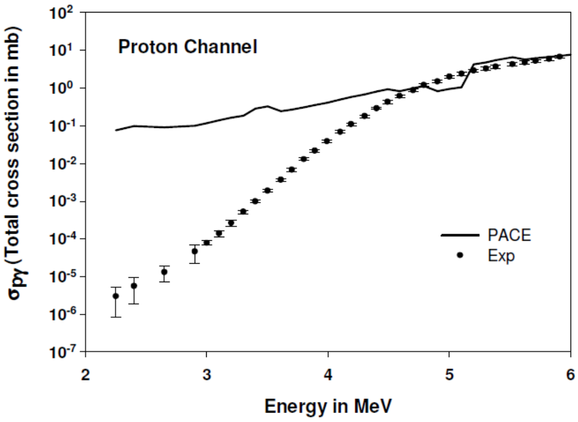

Fig. 2 Same as fig.1 except for protons.

$$
\begin{array}{lll}
^{12}C+^{12}C \longrightarrow & ^{24}Mg \longrightarrow & ^{23}Na + p1 \\
 & ^{23}Na \longrightarrow & ^{22}Ne + p2 \\
 & ^{22}Ne \longrightarrow & ^{21}F + p3
\end{array}
$$

So PACE calculates the sum of proton cross-sections (p1, p2, p3 ....) from all possible residues provided it is energetically possible. The probability of formation of cascading residues like ^{23}Na and ^{22}Ne or ^{21}F are obtained by Monte-Carlo method. But it does not provide the cross-section of proton emission populating ^{23}Na at specific energy states. So the mismatch between experimental and PACE calculations cannot be attributed entirely to transitions to the ground state alone. Therefore instead of calculating the particle emission cross section we have calculated the probability of formation of the residual nuclei i.e. ^{23}Mg in case of neutron, ^{23}Na in case of proton and ^{20}Ne in case of alpha emission. Now the difference between the experimental data and the PACE calculation is mainly due the population of the residues in their ground states. From the figure we can argue that at higher energy the neutron and proton are emitting from the excited states of the residues whereas for alpha the decay populating the ground state is prominent at all energies. The choice of level density parameter needs to be investigated as well. Results of other popular statistical model codes like CASCADE will be studied. However in CASCADE there is no scope for calculation of particle angular distribution and one has to incorporate an isotropic distribution. So a Hauser-Feshbach calculation is required.

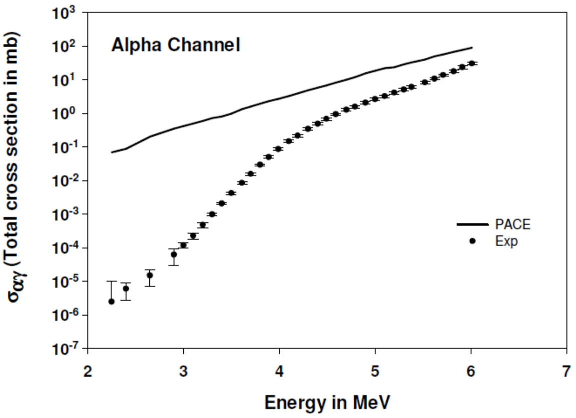

Fig. 3 Same as fig.1 except for alphas.

Summary and Conclusions

The particle channels of the ^{12}C+^{12}C reaction is investigated using the statistical model program PACE4. Results show that a substantial part of the cross-section at lower energies come from population of the residues in their ground state. The particle channels are difficult to be measured due to target contamination effects. Thus the statistical model as in the present case can be used with suitable care to estimate the total cross-section to determine the branching ratios of different channels.

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