The Joint Institute for Nuclear Astrophysics

Reaction Rates in Dense Stellar Matter

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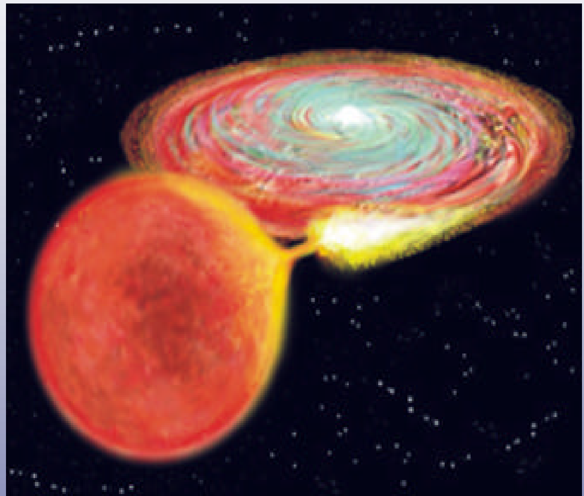
Introduction

It is well known that nuclear physics plays a vital role in stellar evolution, determining the life spans and isotopic composition of the stars. Nuclear mechanisms also govern the final stages of development, such as explosive stellar events.

What is less know however is the fate of matter when exposed to the high density, low temperature conditions presented by a white dwarf and neutron stars. Matter at these extreme conditions can be probed by studying compact objects in binary star systems.

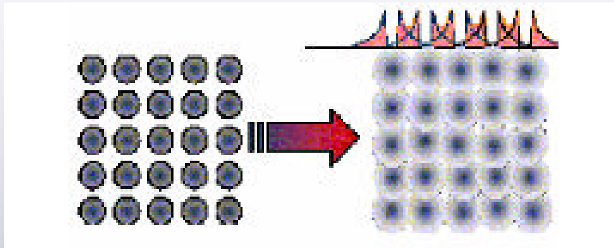


X-ray bursts have been identified as thermonuclear explosions on the surface of accreting neutron stars.

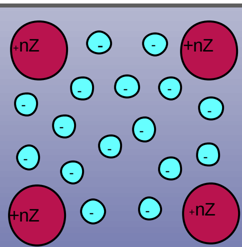
During the thermonuclear runaway the initially hydrogen and helium rich accreted material is rapidly converted by the rp-process toward heavy elements in the mass A=100 range. The evolution and time-scale, as well as the final abundance distribution for the thermonuclear runaway ashes, depends critically on nuclear decay and reaction rates along the rp-path. Of interest to the development of later stellar evolution is the fate of these ashes, particularly the subsequent electron capture and pycnonuclear reaction processes in the deep layers of neutron star crust. Presented here are the necessary conditions for pycnonuclear reactions to occur.

Dense matter burning

Pycnonuclear reactions occur in the cold, high density cores of white dwarf and neutron star crusts. Unlike the more familiar thermonuclear regime, pycnonuclear burning has a high density dependence, and a near temperature independence. These density dependent reactions set in when the nuclei are arranged into a dense lattice structure. Though frozen into place, the nuclei still experience quantum fluctuations around there lattice sites. This allows the nuclear wave functions to overlap, promoting reactions even at low energies.



As well as being arranged in a dense lattice structure, the nuclei are also surrounded by a degenerate electron gas. This effectively shields the nuclei from each other, reducing the deflective Coulomb barrier between nuclei. This phenomena has a vital effect on the reaction rate, increasing it by several orders of magnitude.



Pycnonuclear Formalism

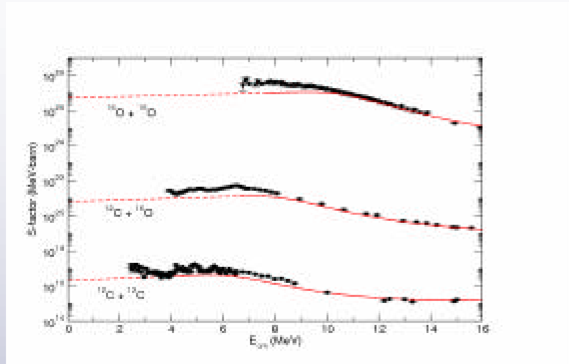
The pycnonuclear reaction rate for a multi component plasma can be written as,

$$R = 10^{46} C_{pyc} \frac{8 r X_N c_i c_j A_i A_j \langle A \rangle Z_i^2 Z_j^2}{(1+d_{ij}) A_c^2} S(E_{ij}^{pk}) l_{ij}^{3-C_{pl}} \exp\left(-\frac{C_{\exp}}{(l_{ij})^{1/2}} \right) cm^{-3} s^{-1}$$

$$l_{ij} = \frac{A_i + A_j}{A_i A_j Z_i Z_j (Z_i^{1/3} + Z_j^{1/3})} \left(\frac{r X_N \langle Z \rangle}{\langle A \rangle 1.3574\ x10^{11}\ g/cm^3} \right)^{1/3}$$

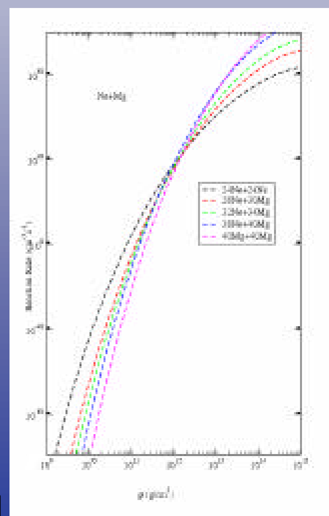
Calculating Reaction Rates

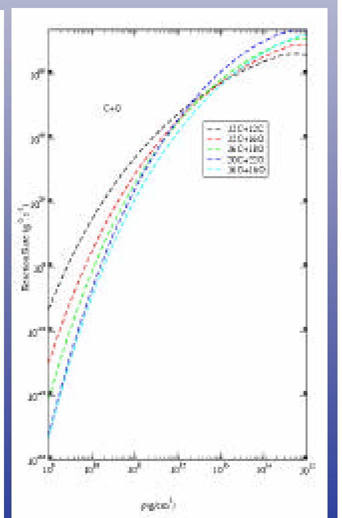
One of the most important parameters for calculating the reaction rate is S, the astrophysical S-factor. The S-factor for a reaction can be calculated with knowledge of the cross section.
The required cross sections were calculated in the framework of a potential model.



Reaction Rates

Using the reaction rate expression, pycnonuclear reaction rates can be estimated.





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