Carbon burning in massive stars

D.G. Jenkins[1],*
[1]School of Physics, Engineering and Technology, University of York, York YO10 5DD, UK
* email: david.jenkins@york.ac.uk

Carbon burning is a key step in the evolution of massive stars, Type 1a supernovae and superbursts in x-ray binary systems. The presence of resonances in this reaction at energies around and below the Coulomb barrier makes it impossible to carry out a simple extrapolation down to the Gamow window—the energy regime relevant to carbon burning in massive stars. The ^{12}C+^{12}C system therefore forms a unique laboratory for challenging the contemporary picture of deep sub-barrier fusion (possible sub-barrier hindrance) and its interplay with nuclear structure (sub-barrier resonances). Here, we report on direct measurements of ^{12}C+^{12}C fusion at energies into the Gamow window using a coincident charged particle/gamma-ray detection technique. We also report on indirect measurements using the $^{24}Mg(\alpha,\alpha')$ reaction which identify potential near-threshold resonances contributing to ^{12}C+^{12}C fusion.

1. Introduction

The number of fusion reactions that are critical for astrophysics is scarce. Among these, the ^{12}C + ^{12}C reaction that is essential for the life cycle of massive stars, may occur at different stages of stellar evolution: explosive scenarios like Type Ia supernovae which can be used as cosmological standard candles, quiescent carbon burning in the contracting core of a massive star at temperatures of the order of 1 GK, and densities above a million g/cm^3 and possibly in superbursts of x-ray binary systems.

The obstacle to reliable extrapolation of the ^{12}C + ^{12}C cross section into the astrophysically relevant Gamow energy window is the presence of resonances in the cross section around the Coulomb barrier that continue down to the lowest collision energies accessible experimentally. This behaviour is strikingly different from the smooth variation in cross section as a function of energy typical of fusion in other heavy-ion systems.

The presence of resonances in the ^{12}C + ^{12}C reaction has been hotly debated for over 60 years. The conventional wisdom is that they correspond to the formation of short-lived molecular states, and this early suggestion has led on to far wider discussion of clustering in alpha-conjugate systems. However, this model remains controversial: an alternate picture is that the resonant behaviour is simply an artifact of the low level density of the ^{12}C + ^{12}C compound system.

2. Direct measurements

Here, we report on measurements of ^{12}C + ^{12}C fusion well into the Gamow window relevant to the most massive stars ($M_\odot \approx 25$) in the energy regime $E_{rel} \approx 2.2$ to 5.4 MeV with the STELLA apparatus for coincident gamma-particle detection [1]. STELLA (see Fig. 1) was mounted on a dedicated beam line at the Andromede accelerator facility at IPN Orsay, France. STELLA comprises an ultrahigh vacuum chamber ($\approx 10^{-8}$ mbar) containing a rotating target mechanism that supports large diameter ($\approx$5 cm) thin ($\approx$200 nm) natural carbon foils which can be rotated at up to 1000 rpm to efficiently dissipate heat from the intense ^{12}C beams and hence, prevent target deterioration. Charged particles are detected in three annular silicon strip detectors covering 30% of the 4π solid angle. For gamma-ray detection, STELLA employs an array of 36 lanthanum bromide [$LaBr_3$:Ce] scintillator detectors which have high energy resolution ($\approx$3% at 662 keV).

The results of the STELLA study (see Fig. 1) identify three distinct regimes in the sub-Coulomb range: (i) The moderate sub-barrier regime above $E_{rel} \approx 4.5$ MeV—where it has been possible to unambiguously validate our experimental concept by accurately measuring the excitation function of the ^{12}C + ^{12}C fusion reaction. (ii) The deep-sub-barrier regime from

$E_{rel} \approx 2.5$ to 4 MeV—where the Fowler standard extrapolation systematically overestimates the results and where hindrance is observed. (iii) The 25 solar masses Gamow window—below $E_{rel} \approx 2.5$ MeV—where the S factor rises up and may indicate a change in the fusion mechanism. The latter may reveal either the presence of a resonance and/or may be interpreted as the consequence of the low level density of states in ^{24}Mg at these excitation energies.

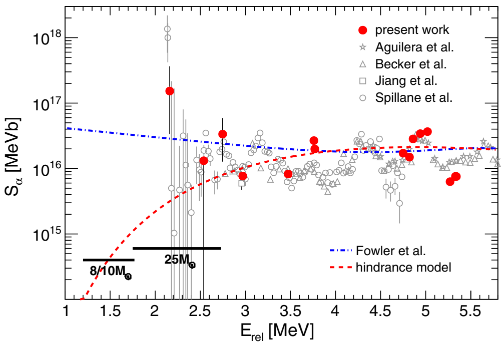

Fig. 1: Astrophysical S-factor measurements for the ^{12}C + ^{12}C fusion reaction as a function of E_{rel} for the final system ^{20}Ne + α. Direct measurements with STELLA are shown as red data points. The blue dash-dotted line is a standard extrapolation of the data, while the red dashed line corresponds to a sub-barrier hindrance model [1].

3. Indirect measurements

As shown in Fig. 1, the region corresponding to the Gamow window for massive stars of 8-10 solar masses is inaccessible to direct measurement. To learn about potential resonances in this region, we are forced to turn to indirect techniques. ^{12}C+^{12}C fusion is mediated through even-spin, natural-parity isoscalar states since it involves the fusion of two identical isoscalar bosons. The ^{24}Mg(α, α')^{24}Mg reaction is an attractive probe for studying the mediating states since it favours the population of isoscalar, natural-parity states. Antisymmetrized molecular dynamics calculations predict that 0^+ states associated with cluster structures in ^{24}Mg should be strongly populated by the ^{24}Mg(α,α')^{24}Mg reaction.

A study of the ^{24}Mg(α,α')^{24}Mg reaction using the K600 spectrometer at iThemba Laboratory [2] identified several new 0^+ levels including those with E_x = 13.78(3) and 13.88(3) MeV which lie close to the ^{12}C + ^{12}C, ^{16}O + 2α, and ^{16}O + ^{8}Be breakup thresholds, as well as two other strongly populated 0^+ states at 15.31(4) and 15.75(4) MeV which have energies within the Gamow window for superbursts and massive stars. The existence of the latter states has the potential to accelerate carbon burning around 0.5 GK by a factor of ten. There is an interesting analogy with the Hoyle state paradigm where the existence of the Hoyle state in ^{12}C just above the threshold for break-up into three alpha particles greatly accelerates helium fusion in stars (see Fig. 2).

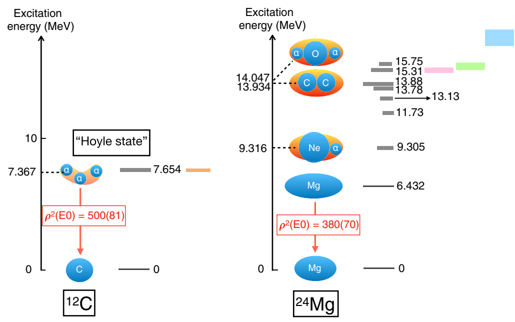

Fig. 2 Analogy between the Hoyle state in ^{12}C as the driver of 3a fusion and candidate cluster states in ^{24}Mg as drivers of ^{12}C+^{12}C fusion. Left: The Hoyle state in ^{12}C shown as a bent arm of three α particles close to the 3α threshold. To the right, the Gamow window is shown (in orange) for helium burning around $T_9 \approx 0.1$. Right: A subset of the excited ^{24}Mg 0^+ states that are strongly populated by ^{24}Mg(α,α')^{24}Mg. The size of the grey bars is proportional to the fraction of the energy-weighted sum rule (EWSR) [2].

References

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