Fusion of $^{12}$C + $^{24}$Mg at far sub-barrier energies

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Abstract. Recent experiments on $^{12}$C + $^{24}$Mg and preliminary data on $^{12}$C + $^{26}$Mg show that we observe the hindrance phenomenon in these two systems that are close to the lighter ones relevant for astrophysics. The cross section at the hindrance threshold has a remarkably high value for $^{12}$C + $^{24}$Mg, while it is closer to an empirical systematics for $^{12}$C + $^{26}$Mg. The lowest-energy fusion cross sections of $^{12}$C + $^{24}$Mg are consistent with simple one-dimensional barrier penetration calculations, i.e. the coupling strengths seem to be strongly damped far below the barrier. Measurements at slightly lower energies would be essential to discriminate between different models and to allow reliably extrapolating to the lighter systems producing energy and elemental synthesis in stellar environments.

1 The phenomenon of fusion hindrance

Heavy-ion fusion reactions are essential to investigate the fundamental problem of quantum tunnelling of many-body systems in the presence of intrinsic degrees of freedom and allow to extend our knowledge of the nuclear chart. In addition, the fusion of light systems serves as a base for the understanding of the astrophysical reaction networks responsible for the energy production and nucleosynthesis in stellar environments [1–3]. It is well known that the nuclear structure of the colliding nuclei produces large enhancements of the fusion cross section around and below the Coulomb barrier, due to couplings with the low-energy collective modes of the colliding nuclei, producing a splitting of the original barrier into a multitude of barrier, called "barrier distribution". However, at very low energies, below the lowest barrier, the fusion dynamics is made more complex by the appearance of the hindrance phenomenon discovered by Jiang et al. in $^{60}$Ni + $^{89}$Y [4], as a fast decrease of the excitation function below the result of standard CC calculations. Hindrance is experimentally identified by the observation of a maximum of the astrophysical $S$ factor vs energy, and it was soon recognised as a general effect in heavy-ion fusion at deep sub-barrier energies.

Fusion hindrance was first recognized in a number of medium-heavy systems and has created a link between astrophysics and heavy-ion fusion. One of the first, and more clear, examples of hindrance [5] is shown in Fig. 1 for the system $^{64}$Ni + $^{64}$Ni (left panel). The

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difference between the measurements and the black curve (simple tunnelling through the potential barrier) displays the fusion enhancement, while the difference between the red curve (standard CC calculations with a Woods-Saxon potential) and the data shows the fusion hindrance at extreme sub-barrier energies. The $S$ factor develops a maximum at the energy where the logarithmic slope $L(E)$, larger than the CC results, reaches the value $L_{CS} = \pi \eta / E$, as reported in the figure.

![Diagram showing fusion excitation function, logarithmic slope, and S factor for $^{64}$Ni + $^{64}$Ni.](image)

Figure 1. (left) Fusion excitation function, logarithmic slope, and $S$ factor for $^{64}$Ni + $^{64}$Ni. (right) Schematic representation of the $S$ factor trend for $Q < 0$ and $Q > 0$.

The physical mechanism underlying the hindrance effect is still a matter of debate in the nuclear community, however, it has been recently proposed that the Pauli exclusion principle affects fusion of atomic nuclei [6]. When that principle is considered in the ion-ion interaction, the Coulomb barrier turns out to be higher and thicker, thus hindering sub-barrier fusion.

2 Fusion of light nuclei

Fusion of light heavy-ions is characterised by a positive $Q$-value. This brings a substantial difference from the heavier systems where $Q$ is negative and the cross section goes to zero at positive energy. This implies that $S$ must show a maximum at some higher energy, but, conversely, if $Q > 0$ the cross section stays in principle finite down to $E = 0$, so that $S$ may not show any maximum. The situation is schematically shown in Fig. 1 (right panel).

It has been observed that for light systems $L(E)$ and $L_{CS}$ tend to be two nearly parallel curves and the crossing point (if existing) is rather undetermined. The $S$ factor maximum becomes broader and establishing the presence of hindrance requires precise and challenging measurements.

Concerning the very important case of $^{12}$C + $^{12}$C, recent data are shown in Fig. 2 (left) [7–9]. We also recall the results obtained using the Trojan Horse Method by Tumino et al. [10]. The stellar evolution of massive stars, after the phase of helium burning, is determined by the reactions $^{12}$C + $^{12}$C, $^{16}$O, whose measured low-energy $S$ factors suffer from large uncertain-
ties and from the presence of resonances. It is not yet clear whether hindrance is effective in such cases.

We point out that in two recent experiments for $^{12}\text{C} + ^{13}\text{C}$ [11, 12], both done with the thick target technique, one does not observe resonances and no $S$ factor maximum shows up. For the case of $^{16}\text{O} + ^{16}\text{O}$, evidence of hindrance is found in most measurements (see right panel of Fig. 2) [13], even if the various sets of data show disagreements in the absolute scale.

### 3 The case of $^{12}\text{C} + ^{24}\text{Mg}$

The existence and features of hindrance in the systems of astrophysical interest are not at all established, so that the study of slightly heavier cases is appealing, with the aim of allowing a reliable extrapolation towards the lighter systems. $^{12}\text{C} + ^{24}\text{Mg}$ is a medium-light system with positive fusion $Q$-value $= +16.3$ MeV, very close to the "astrophysical" cases. We measured its excitation function, by detecting the fusion evaporation residues with the set-up PISOLO [14, 15] at the Tandem XTU of INFN – Laboratori Nazionali di Legnaro (LNL).

In Fig. 3 the data are compared to no-coupling (dashed line) and CC calculations [16] where the ground state rotational band of $^{24}\text{Mg}$ has been taken into account (green line). One sees that the standard CC calculation largely over-predicts the cross section and the $S$-factor at low energies. The blue line is the result of an "empirical" calculation in the spirit of the adiabatic model [17]. The red line is instead obtained using the hindrance parametrisation proposed by Jiang et al. [18].

One notices that fusion hindrance shows up already at $\sim 0.75$ mb, which is a very large value compared to many other systems presenting hindrance. Moreover, the data are well
fitted using both the empirical calculation and the hindrance parametrisation, and it appears that tunnelling a one-dimensional barrier reproduces the lowest energy points. Finally, it is clear that discriminating between the two models requires lower energy measurements and smaller experimental errors.

4 Recent results on $^{12}\text{C} + ^{26}\text{Mg}$

Very recently, the fusion of $^{12}\text{C} + ^{26}\text{Mg}$ has been measured from above to far below the barrier at LNL. The main motivation was to investigate whether the anomalously high threshold energy of hindrance, observed with $^{24}\text{Mg}$, shows up also in this system. Here we show the preliminary results of the experiment. Fig. 4 (left panel) reports the excitation function of $^{12}\text{C} + ^{26}\text{Mg}$ (the lowest data point is an upper limit), compared to CC calculations using a Woods-Saxon potential whose parameters have been only slightly modified with respect to $^{12}\text{C} + ^{24}\text{Mg}$, to reproduce the data near the barrier.

![Figure 4](image)

**Figure 4.** Fusion excitation function measured for $^{12}\text{C} + ^{26}\text{Mg}$ (preliminary data) compared to CC calculations (left) and $S$ factor of the two systems (right panel).

The CC calculation gives a very good account of the data in a large energy range, however, we observe that it starts over-predicting the experimental cross sections at the level of $\approx 0.03$ mb.

This means that the hindrance threshold for this system is significantly lower than for $^{12}\text{C} + ^{24}\text{Mg}$. This difference is confirmed in the comparison of the two $S$ factors, reported in the right panel of Fig. 4, from which we have also an indication that the $S$ factor maximum of $^{12}\text{C} + ^{26}\text{Mg}$ is significantly narrower.

In Fig. 5 we have inserted the threshold energies for hindrance of $^{12}\text{C} + ^{24}\text{Mg}$, $^{26}\text{Mg}$ in the phenomenological systematics of Jiang [18], where each system is characterized by the parameter $\zeta = Z_1Z_2\mu^{1/2}$. Please note that the points for the C+C, C+O

![Figure 5](image)

**Figure 5.** Threshold energies for hindrance in light and medium-light systems.
and O+O systems (open symbols) are only obtained by extrapolating from higher energies. All the plotted systems have positive fusion $Q$ values. The case of $^{12}$C + $^{30}$Si is also reported, which was investigated by our group a few years ago [19]. The line is the phenomenological formula proposed in Ref. [18], as shown in the figure.

The two systems discussed in this contribution have $\zeta$ parameters very close to the lighter cases important for stellar evolution. The difference between these two cases can clearly be seen in this representation, and it is relevant for the wished possibility of extrapolating to the lighter systems on a reliable basis. Indeed, the different behaviour of $^{12}$C + $^{24}$Mg and $^{12}$C + $^{26}$Mg "complicates" the situation, and throws doubt on that procedure should be performed.

The final analysis of the $^{12}$C + $^{26}$Mg data will be ready soon. In any case, we can state that consequences for the dynamics of stellar evolution arising from the phenomenon of fusion hindrance have to be clarified by further experimental and theoretical work.

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