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Abstract. The phenomenon of fusion hindrance may have important consequences on the nuclear processes occurring in astrophysical scenarios, if it is a general behaviour of heavy-ion fusion at extreme sub-barrier energies, including reactions involving lighter systems, e.g. reactions in the carbon and oxygen burning stages of heavy stars. The hindrance is generally identified by the observation of a maximum of the S-factor vs. energy. Whether there is an S-factor maximum at very low energies for systems with a positive fusion Q-value is an experimentally challenging question. Our aim has been to search evidence for fusion hindrance in ^{12}C + ^{24}Mg which is a medium-light systems with positive Q-value for fusion, besides the heavier cases where hindrance is recognised to be a general phenomenon. The experiment has been performed at the XTU Tandem accelerator of LNL by directly detecting the fusion evaporation residues at very forward angles. The excitation function has been extended down to $\simeq$10μb, i.e. 4 orders of magnitude lower than previous measurements and we observe that the S-factor develops a clear maximum vs. energy. Coupled-Channels calculations using a Woods-Saxon potential give a good account of the data near and above the barrier but over predict the cross sections at very low energies. Therefore the hindrance phenomenon is clearly recognised in ^{12}C + ^{24}Mg with an energy threshold that nicely fits the systematics in several medium-light systems. The fusion cross sections at the hindrance threshold show that the highest value (σ_s=1.6mb) is indeed found for this system. It may be possible to extend the measurements further down in energy.

1. Introduction

Hindrance of heavy-ion fusion at extreme sub-barrier energies, characterized by a steep fall in the fusion cross section with decreasing energy, was discovered 15 years ago [1]. By plotting the cross section in terms of the S factor, $S(E) = \sigma E \exp(2\pi\eta)$, where η is the Sommerfeld parameter and E is the center-of-mass energy, fusion hindrance is easily recognized by a maximum of $S(E)$ at an energy E_s [2].

This phenomenon was first studied in medium-heavy-mass systems. In this mass region, the fusion Q value is always negative, so that the S factor is 0, when the incident energy approaches $E = -Q$. Thus, under such conditions an S factor maximum is unavoidable [2]. It was soon realised that this behaviour may have important consequences for the nuclear processes occurring in astrophysical scenarios, if the hindrance is a general behaviour of heavy-ion fusion at extreme sub-barrier energies, including reactions involving lighter systems, *e.g.* reactions in the carbon and oxygen burning stages of heavy stars [3]. Whether there is also an S-factor maximum at very low energies for such systems with a positive fusion Q value is an experimentally challenging question.

There are many studies of the fusion reactions ^{12}C + ^{12}C and ^{16}O + ^{16}O (see *e.g.* [4, 5, 6]). However, these measurements often have large uncertainties and there are serious discrepancies between different experiments in the low energy range of astrophysical interest.

It appears that the investigation of slightly heavier systems is of interest since their behaviour at very low energy will give us guidance for the reliable extrapolation of astrophysically interesting cases towards extremely low energies.

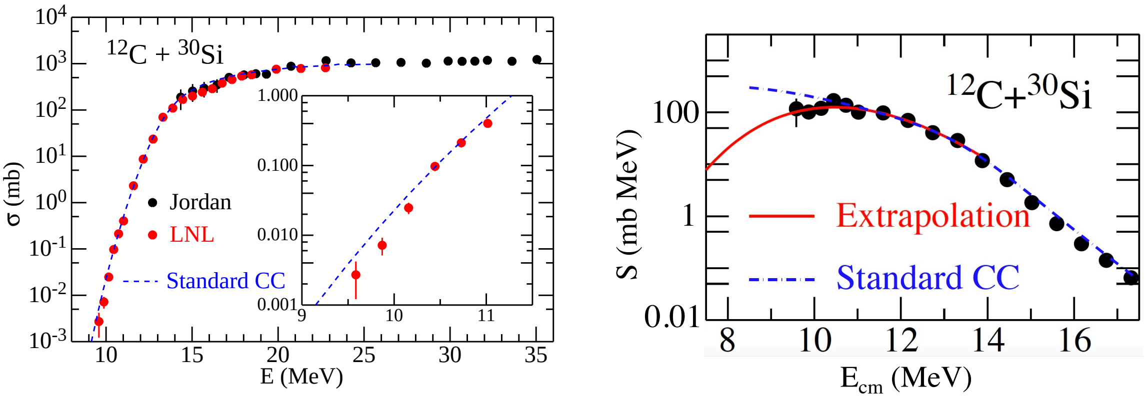

Figure 1. (left panel) Excitation function for the system ^{12}C + ^{30}Si. The black and red circles are from Jordan *et al.* [7] and the recent LNL measurement [8] with the inverse-kinematics technique, respectively. (right panel) The trend of astrophysical S-factor in comparison with a standard CC calculation (blue dashed curve) and the empirical extrapolation of Ref. [3] (red solid line).

Some studies of systems with medium to light masses and positive Q values have been performed at LNL and other laboratories (see *e.g.* [9, 10, 11, 12, 13, 14, 15]), but the existence of an S-factor maximum is far from being firmly established.

Recently an experiment using the inverse kinematics technique for ^{12}C + ^{30}Si has been performed [8] at LNL. The excitation function was measured down to 3 μb and is displayed in Fig. 1 (left panel). The inset shows the signature of a small hindrance effect, because the low-energy cross sections are over-predicted by standard CC calculations. In Fig. 1 (right panel) we show a plot of the S-factor vs. energy, that seems to indicate a maximum around 10.5 MeV. The evidence, however, is not conclusive.

A measurement for ^{12}C + ^{24}Mg has been recently performed. The compound nucleus is lower by six mass units, and, thus, is nearby the systems of astrophysical interest. In particular, the empirical analysis of Ref. [3] shows that the behaviour of a system, as far as hindrance threshold and trend are concerned, is governed by "system parameter" $\zeta = Z_1 Z_2 \mu^{1/2}$.

ζ is 88.2, 181.0, 203.6, 245.9 for ^{12}C + ^{12}C, ^{16}O + ^{16}O, ^{12}C + ^{24}Mg and ^{12}C + ^{30}Si, respectively. The close similarity expected between ^{12}C + ^{24}Mg and the lighter systems is then obvious. ^{12}C + ^{30}Si is not far away, but a bit more distant.

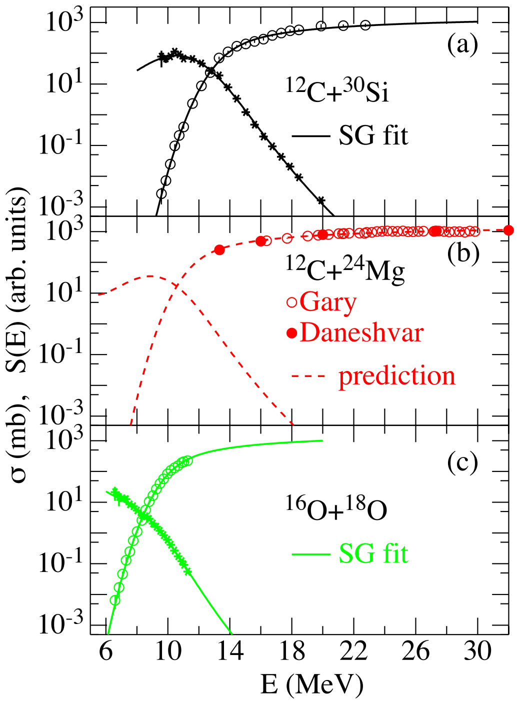

Figure 2. Comparison for cross sections and S-factors for the three fusion reactions ^{16}O + ^{18}O (green), ^{12}C + ^{24}Mg (red), and ^{12}C + ^{30}Si (black). The curves for ^{16}O + ^{18}O and ^{12}C + ^{30}Si (S.G.) are the results of three-parameter fits that have been interpolated to obtain the predictions for ^{12}C + ^{24}Mg [18].

For ^{12}C + ^{24}Mg only measurements of fusion cross sections above the barrier have been reported [16, 17] (see Fig. 2).

Recently, a new formula (with only three parameters) has been obtained, which can accurately reproduce many fusion excitation functions in a wide energy range [18]. Results of least-square fitting to excitation functions of ^{16}O + ^{18}O and ^{12}C + ^{30}Si are shown in Fig. 2. On one side the maximum of the S-factor of ^{12}C + ^{30}Si is well reproduced, while on the other side ^{16}O + ^{18}O does not show any maximum in the measured energy range.

From the parameters of these two systems, interpolated parameters for ^{12}C + ^{24}Mg can be obtained. The resulting excitation function and S factor of ^{12}C + ^{24}Mg are also shown in Fig. 2. We observe that at high energies previous measurements are well fitted, and at low energies an S-factor maximum is predicted slightly below 10 MeV.

The experiment may confirm this, or even determine a higher threshold for hindrance. In this case, we will be able to measure more data points below the threshold, and consequently the S-factor maximum (if existing) for this system will be well defined.

This contribution reports on our recent measurements of sub-barrier fusion of ^{12}C + ^{24}Mg, and of their interpretation within current coupled-channels (CC) models.

2. Experimental set-up and results

The ^{24}Mg beam from the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN was delivered, at energies ranging from 26 MeV to 52 MeV, with average intensities of 4-8 pnA. The targets were 50μg/cm^2 ^{12}C evaporations, isotopically enriched to 99.9% in mass 12. Four collimated silicon detectors were placed symmetrically around the beam direction at θ_{lab}= 16°, so as to check the beam position and focusing, and to allow normalisation between the different runs. The fusion-evaporation residues (ER) were detected by a double Time-of-Flight ΔE-Energy telescope following an electrostatic beam deflector, at 0° and at small angles. The experimental set-up and the procedures are described in some detail in recent papers [19, 20].

The ER angular distribution was measured at E$_{beam}$= 42 MeV in the angular range $-7°$ to +8°. This allowed us to determine the ratio between the differential ER cross sections and the total, angle-integrated one. For all other energies, we exploited the results of PACE4 [21] calculations to take into account the shape variation of the angular distribution with energy.

The accuracy of the absolute cross section scale has been estimated $\sim \pm 7\%$ overall. Statistical uncertainties are generally very small, apart from the very low-energy points. These statistical (relative) errors determine the accuracy of the slope extracted from the excitation function, see below in this Section.

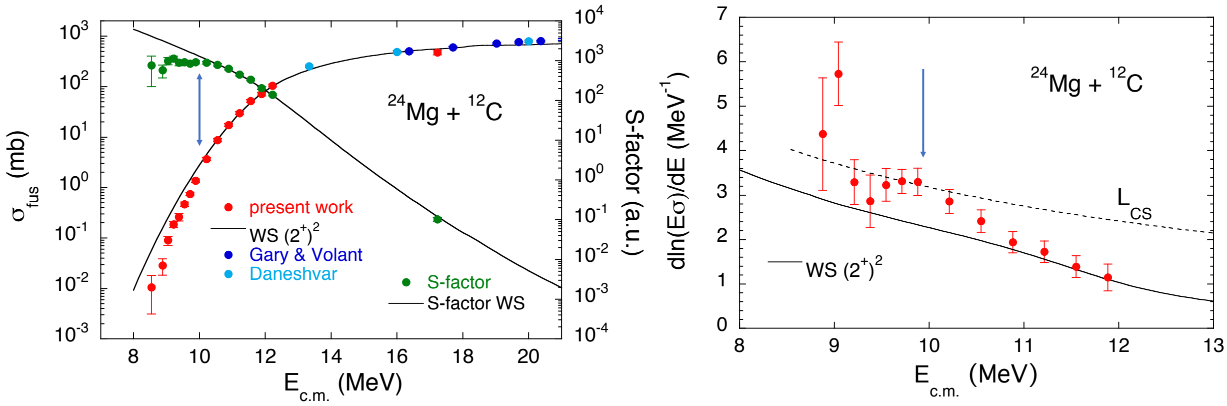

Figure 3. (left panel) Excitation function and S-factor for the system ^{12}C + ^{24}Mg, compared with standard CC calculations (see text). (right panel) Logarithmic derivative of the excitation function compared with the L_{CS} value and with the CC calculations. The two blue arrows mark the threshold energy of the hindrance.

The measured cross sections are shown in the left panel of Fig. 3 together with the astrophysical S-factor. The lowest measured cross section is about 10μb. Fig. 3 (right panel) shows the logarithmic slope of the excitation function compared to the value expected for a constant S factor L_{CS} [22]. Even if the experimental uncertainties are rather large at low energies, one notices that the slope reaches and overcomes L_{CS}. Correspondingly the S factor develops a maximum with decreasing energy (see left panel). This has been usually taken as the phenomenological evidence for the hindrance effect. The prediction of Ref. [18] (see Fig. 2) that the S factor shows a maximum slightly below 10 MeV, appears to be confirmed by experiment.

3. Comparison with model calculations

The data obtained in the present work has been analysed on the basis of coupled-channels calculations. We have used the computer code CCFULL [23]. To this end, a Woods Saxon (WS) internuclear potential was employed, with the depth of V_0= 40.47 MeV, the radius parameter of r_0 = 1.10 fm, and the diffuseness of a=0.60 MeV. We included the lowest 2^+ state of ^{24}Mg in the vibrational approximation and the ^{12}C was considered as an inert nucleus.

The results of these CC calculations are shown by the full curves in Fig. 3. We observe that the CC calculations start to over-predict the data at around the same energy where the S-factor develops a maximum (see the blue arrow in the left panel). The calculated slope (see the right panel) is quite flat and under-predicts the experimental trend, remaining well below the L_{CS} value. This comparison with CC results clearly confirms the existence of hindrance in ^{12}C + ^{24}Mg.

4. Astrophysical aspects of the results

For very light systems as for instance ^{12}C+^{12}C the hindrance effect may have important consequences in the astrophysical scenarios. To establish in these cases the behaviour of the S-factor at very low energy is very challenging and still much debated [4, 24, 25]. However the investigation of the phenomenon of hindrance in slightly heavier systems such as ^{12}C+^{24}Mg (Q_{fus}=+16.3 MeV) allows us to extrapolate towards the lighter cases interesting for astrophysics. Indeed its ζ parameter (see Fig.4) is very near to the lighter systems important for stellar evolution.

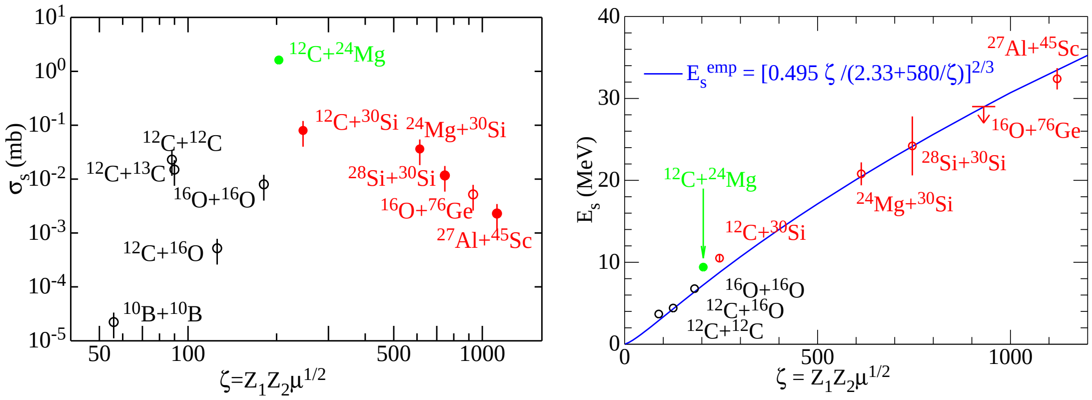

Figure 4. (left panel) Cross sections at hindrance threshold for ^{12}C + ^{24}Mg and for several other light- and medium-light mass systems. (right panel) Systematic of energy threshold of hindrance E_S vs. the ζ parameter that characterises the system.

It is interesting to note that the cross section corresponding to the hindrance threshold is very high ($\sigma_s \simeq 1.6$mb), probably the highest measured so far. This is reported in Fig. 4 (left panel) together with several other medium-light systems.

The energy threshold for hindrance (E_s) for ^{12}C + ^{24}Mg nicely fits in the phenomenological systematics that was developed by Jiang et al. a few years ago [3], and that is shown in Fig. 4 (right panel). This gives us confidence that the extrapolation towards lighter systems as ^{12}C + ^{12}C and ^{16}O + ^{16}O using that systematics, is reliable.

5. Summary

The phenomenon of hindrance in sub-barrier heavy-ion fusion is a general effect recognised by the trend of the logarithmic slope and of the S-factor at low energies, and by the comparison with standard CC calculations. Hindrance has been recently observed even in light systems, independent of the sign of the fusion Q-value, with different features, as observed in ^{12}C + ^{30}Si. In this contribution I have presented the results of measurements concerning ^{12}C + ^{24}Mg, very close to the cases of astrophysical interest.

The S-factor shows a rather clear evidence of a maximum so that even if the hindrance effect is not so strong, it is well recognised. Standard CC calculations using a Woods-Saxon potential, start to overpredict the measured fusion cross sections at $E_{cm} \simeq 9.7$ MeV in agreement with the observed position of the S-factor maximum.

The experimental value of the hindrance threshold is rather well reproduced by the phenomenological systematic of Jiang et al. [3]. The cross section at threshold is very high ($\sigma_s \simeq 1.6$mb) and allowed one to identify rather clearly the onset of hindrance. It may also be possible to extend the measurements further down in energy. The consequences for the dynamics of stellar evolution have to be clarified by further experimental and theoretical work.

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