^{24}Mg + ^{12}C fusion reaching the no coupling limit far below the barrier

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Abstract. In the present work the fusion cross section of the ^{12}C+^{24}Mg system has been measured down to energies far below the coulomb barrier around 4μb. This system is slightly heavier than those of astrophysical interest, like ^{12}C+^{12}C and ^{16}O+^{16}O. The data points highlight the presence of hindrance in ^{12}C+^{24}Mg because the excitation function is over-estimated by standard Coupled-Channels calculations, and a clear maximum of the S factor has been observed. The cross section at hindrance threshold is found to be remarkably large (σ ≈0.75mb). The S-factor maximum is nicely fitted using both an empirical interpolation in the spirit of the adiabatic model, and the hindrance parametrisation. The data far below the barrier may suggest that the coupling strengths gradually decrease and vanish, so that the excitation function seems to be well reproduced by a simple one-dimensional tunnelling through the potential barrier in that energy range. On the other hand, the equally good fit obtained with the hindrance model, indicates that discriminating between the two approaches would require further precise measurements at slightly lower energies.

1. Introduction
Studying the excitation function of light systems at very low energies requires challenging measurements, hence the hindrance effect in these systems of astrophysical interest is not yet clearly established. The study of slightly heavier systems is useful to validate the extrapolation to the lighter systems important in stellar environments. This contribution presents the results of an experiment on ^{12}C+^{24}Mg that confirms the presence of hindrance clarify the behaviour of this system at the hindrance threshold, comparing it with preliminary results on ^{12}C+^{26}Mg.

2. Experimental set-up and results
Fusion cross sections were experimentally determined by direct detection of evaporation residues (ER) using a ^{24}Mg beam provided by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro (LNL) of INFN in the energy range 25.5-48 MeV. The beam intensity was 4-8 pnA.

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The apparatus consists of an electrostatic deflector, that allows the separation at forward angles of the ER from the residual beam exploiting their different electrical rigidity [1]. The deflector is followed by an energy (E), energy loss (ΔE) and time of flight (TOF) telescope.

Four silicon detectors are placed at an angle of $\theta_{lab} = 16.05°$ with respect to the beam line. These detectors are used to normalize the fusion yields to the Rutherford cross section and to monitor the beam position on the target.

By correlating the measured quantities, TOF, DeltaE and E, it is possible to identify the ER and obtain the total fusion cross sections.

The ER angular distribution has also been measured at two energies, just above the Coulomb barrier at $E_{lab} = 42$ MeV and just below at $E_{lab} = 35$ MeV. The two distributions have a Gaussian shape whose widths are very similar, and in good agreement with PACE4 [6] calculations.

The fusion cross sections obtained for ^{24}Mg+^{12}C is shown in Fig. 1 and the astrophysical S factor is reported in Fig. 2. From the data we can notice the large value of the cross section at the hindrance threshold $\sigma \approx 0.75$ mb compared to other similar systems (for ^{30}Si+^{12}C is about ten times smaller [3]). Moreover, at vary low energies the experimental data are well reproduced by a simple one-dimensional barrier penetration calculation.

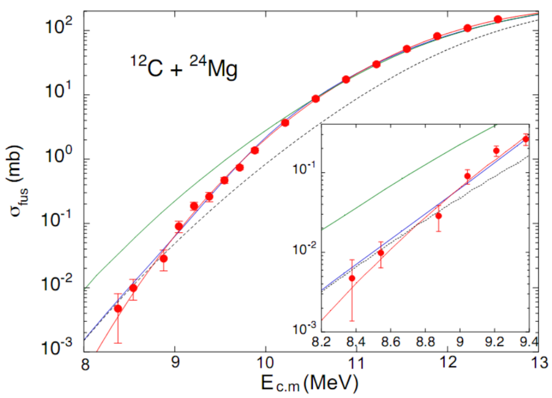

Figure 1. Fusion excitation function for the ^{24}Mg+^{12}C system.

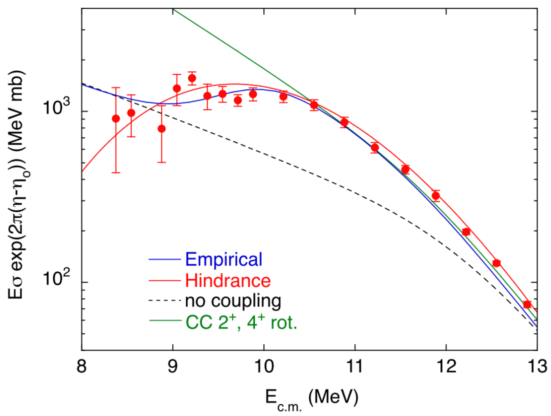

Figure 2. Astrophysical S factor for the ^{24}Mg+^{12}C system.

3. Comparison with ^{26}Mg+^{12}C

The reason behind the behavior of ^{24}Mg+^{12}C at the hindrance threshold is not clear but qualitatively speaking might be attributed to the large prolate deformation or to the α-like structure of the ^{24}Mg. To better understand the fusion dynamics the system ^{26}Mg+^{12}C has been studied, since the nucleus ^{26}Mg has a prolate deformation as ^{24}Mg but it doesn't present the α-like structure (being similar to ^{30}Si). Therefore a behaviour of the ^{26}Mg+^{12}C similar to that of the ^{24}Mg+^{12}C (or ^{30}Si+^{12}C) would address subsequent further investigations on nuclear deformation (or α-like structure) effects. The cross section and the astrophysical S factor for the system ^{26}Mg+^{12}C (preliminary results) are shown in Fig. 3 and Fig. 4 and one can notice that a maximum for the S factor shows up also for this system. Compared to ^{24}Mg+^{12}C the maximum is found at lower energies.

4. Coupled Channel Calculation

The coupled-channels (CC) calculations [2], shown in Fig. 3 and Fig. 4 based on a Woods–Saxon potential (green solid line) give a good account of the excitation function near and above the barrier. The ^{12}C has been considered inert, since its contribution is already included in the

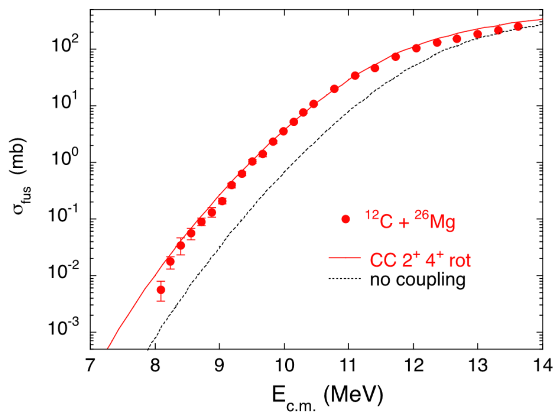

Figure 3. Fusion excitation function for the ^{26}Mg+^{12}C system.

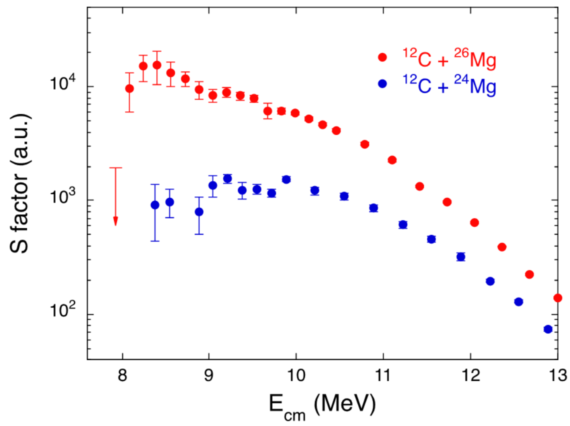

Figure 4. Astrophysical S factor for the ^{26}Mg+^{12}C system.

renormalization of the ion–ion potential, needed to reproduce the barrier position. The three lowest states of the ground state rotational band of ^{24}Mg were included. Still, the calculations overestimate the cross sections at very low energies, clearly indicating the presence of the hindrance The enhancement for the ^{24}Mg+^{12}C is small compared to heavier systems and the result of the no-coupling calculation is similar to the one based on the adiabatic model assuming a complete damping of the coupling strengths.

4.1. Empirical analysis in the spirit of the adiabatic model
In order to reproduce the behaviour of the data at low energies an empirical formula (equation (1)) has been introduced based on the idea that at very low energies the coupling strength is completely damped [4].

$$ln(\sigma_{exp}) = \beta(E) ln(\sigma_{CC}) + (1 - \beta(E)) ln(\sigma_{noc}) \tag{1}$$

$\beta(E)$ can be obtained at each measured energies from the data points and its energy dependence can be fitted with a Fermi function.

$$\beta(E) = \frac{1}{1 + e^{\alpha_0 (E - E_0)}} \tag{2}$$

The parameters obtained from the fit are α_0= -2.728 MeV^{-1} and E$_0$= 9.594 MeV. According to the equation (1) the fitted $\beta(E)$ function allows to calculate the cross section σ_{fit} and the S factor (blue line in Fig. 1 and Fig. 2). This empirical formula fits well the experimental data, reproducing the maximum for the S factor, and at the lowest energies increases again following the no-coupling calculation.

4.2. Hindrance model
In the hindrance model one fit the logarithmic derivative L(E) with the following formula that successfully reproduce the behaviour of many systems with positive fusion Q-value at low energies [5]

$$L(E) = A_0 + \frac{B_0}{E^{3/2}} \tag{3}$$

where A_0 and B_0 are fit parameters. From this equation one can derive the excitation function at low energies:

$$\sigma(E) = \frac{\sigma_s E_s}{E} exp\left(A_0(E - E_s) - \frac{2B_0}{\sqrt{E_s}}\left[\sqrt{\frac{E_s}{E}} - 1\right]\right) \tag{4}$$

where E_s is the hindrance threshold and σ_s is the cross section at $E = E_s$. The low energy cross sections for ^{24}Mg+^{12}C have been fitted using equation (4) obtaining $A_0 = -4.62$ MeV^{-1}, $B_0 = 239.6$ MeV$^{1/2}$, $E_s = 9.67$ MeV and $\sigma_s = 0.75$ mb. The results of the fit are shown in Fig. 1 and Fig. 2 (red line) and one notices that according to this approach there is a clear maximum for the S factor that doesn't follow the no-coupling limit but keep decreasing at lower energies.

Since both the empirical formula and the hindrance parametrization well reproduce the data, discriminating between these two approaches would require further precise cross section measurements at lower energies.

5. Summary and Conclusion

The measurements have been performed on near- and sub-barrier fusion of ^{24}Mg+^{12}C, using the inverted kinematics allowed to calculate the fusion cross section of ^{24}Mg+^{12}C down to few μb and to confirm the manifestation of the hindrance phenomenon in this light system that is near to the cases relevant for astrophysics. The value of the cross section at the hindrance threshold is quite large compared with similar systems and the comparison with ^{26}Mg+^{12}C qualitatively suggests that the reason for this may be the α-like structure of ^{24}Mg but theoretical analyses are obviously needed. The cross section at the lowest energies seems to be consistent with the no-coupling calculation suggesting that the coupling strengths are strongly damped at very low energies as predicted by the adiabatic model. However, the data are also well fitted by an hindrance parametrization predicting a different behaviour. In order to distinguish between these two models further measurements of lower cross sections will be required.

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