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Fusion hindrance for the positive Q-value system $^{12}C + ^{30}Si$

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Background: The fusion reaction $^{12}C + ^{30}Si$ is a link between heavier cases studied in recent years, and the light heavy-ion systems, e.g., $^{12}C + ^{12}C$, $^{16}O + ^{16}O$ that have a prominent role in the dynamics of stellar evolution. $^{12}C + ^{30}Si$ fusion itself is not a relevant process for astrophysics, but it is important to establish its behavior below the barrier, where couplings to low-lying collective modes and the hindrance phenomenon may determine the cross sections. The excitation function is presently completely unknown below the barrier for the $^{12}C + ^{30}Si$ reaction, thus no reliable extrapolation into the astrophysical regime for the C+C and O+O cases can be performed.
Purpose: Our aim was to carry out a complete measurement of the fusion excitation function of $^{12}C + ^{30}Si$ from well below to above the Coulomb barrier, so as to clear up the consequence of couplings to low-lying states of ^{30}Si, and whether the hindrance effect appears in this relatively light system which has a positive Q value for fusion. This would have consequences for the extrapolated behavior to even lighter systems.
Methods: The inverse kinematics was used by sending ^{30}Si beams delivered from the XTU Tandem accelerator of INFN-Laboratori Nazionali di Legnaro onto thin ^{12}C (50 $\mu g/cm^2$) targets enriched to 99.9% in mass 12. The fusion evaporation residues (ER) were detected at very forward angles, following beam separation by means of an electrostatic deflector. Angular distributions of ER were measured at $E_{beam} = 45$, 59, and 80 MeV, and they were angle integrated to derive total fusion cross sections.
Results: The fusion excitation function of $^{12}C + ^{30}Si$ was measured with high statistical accuracy, covering more than five orders of magnitude down to a lowest cross section $\simeq 3$ μb. The logarithmic slope and the S factor have been extracted and we have convincing phenomenological evidence of the hindrance effect. These results have been compared with the calculations performed within the model that considers a damping of the coupling strength well inside the Coulomb barrier.
Conclusions: The experimental data are consistent with the coupled-channels calculations. A better fit is obtained by using the Yukawa-plus-exponential potential and a damping of the coupling strengths inside the barrier. The degree of hindrance is much smaller than the one in heavier systems. Also a phenomenological estimate reproduces quite closely the hindrance threshold for $^{12}C + ^{30}Si$, so that an extrapolation to the C+C and O+O cases can be reliably performed.

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I. INTRODUCTION

Recent measurements on fusion of medium-heavy systems [1] revealed that going to very low energies the intervening so-called "hindrance" effect shows up, as a noteworthy increase of the slope of the excitation function, not reproduced by standard coupled-channels (CC) calculations.

In the sudden approach, Misicu and Esbensen proposed [2,3] to describe this phenomenon using the M3Y interaction with an additional short-range term from the incompressibility of nuclear matter. The resulting shallow potential was very successful in reproducing the hindrance effect in several cases [4,5]. An adiabatic model was instead proposed by Ichikawa, Hagino, and Iwamoto [6] considering

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neck formation between the colliding nuclei and a damping of the coupling form factors in the nuclear overlap region. They used the Yukawa-plus-exponential (YPE) potential for a number of systems in good agreement with experimental data [7].

It was soon realized that the hindrance phenomenon may have important consequences on the nuclear processes occurring in astrophysical scenarios [8], because, if that phenomenon exists in light systems, the fusion cross sections (viz. the S factors) near the Gamow peak will be substantially smaller than expected previously by simple extrapolations of the high-energy trends, where sets of measurements already exist.

Fusion reactions between light heavy ions have a prominent role in the dynamics of stellar evolution. Indeed, it was pointed out [8] that reactions such as $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^{16}O + ^{16}O$ (all of them have positive Q values for fusion) are important for the evolution of massive stars, beyond the helium burning, and the associated nucleosynthesis [4]. The existence of hindrance in these cases would lead to significant changes of the abundances of many isotopes. In addition, it would increase the ignition temperature of $^{12}C + ^{12}C$ both for quiescent C burning in massive stars and for explosive C burning in accreting white dwarfs, eventually giving rise to thermonuclear supernovae, the standard candles of cosmology. This reaction was also proposed to be a trigger for the superbursts taking place at the surface of accreting neutron stars.

Moreover, in the inner crust of neutron stars, other exotic fusion reactions take place, e.g., $^{24}O + ^{24}O$, $^{28}Ne + ^{28}Ne$, and $^{34}Ne + ^{34}Ne$ [9], under growing pressure conditions that can also reach the pycnonuclear regime [10,11]. The hindrance phenomenon would affect the composition and thermal evolution of the inner crust. It appears then essential to have estimates of the relevant cross sections. However, it is not conceivable to perform such experiments involving radioactive beams and targets in the laboratory.

Very recently, the fusion cross sections of $^{12}C + ^{16}O$ have been measured [12] at very low energies (down to $\simeq$1 nb), where a decreasing trend of the S factor was evidenced. These new data may be an indication that the hindrance phenomenon is present in such a light system. It is not clear, however, whether that trend of the S factor is because of the hindrance or the existence of quasimolecular resonances. In Ref. [12] it is also pointed out that the $^{12}C + ^{16}O$ reaction plays anyway a minor role in late stellar evolution, compared to, e.g., $^{12}C + ^{12}C$ fusion.

Concerning this case of $^{12}C + ^{12}C$, there are many studies of its cross section at small energies (as well as of $^{16}O + ^{16}O$), but the measurements often have large uncertainties and there are serious discrepancies between the results of different experiments in the very low-energy range relevant for astrophysics.

Hence it appears to be very important to measure the detailed low-energy behavior for medium-light systems slightly heavier than those reactions involving, e.g., fusion of carbon and oxygen nuclei [13,14], because the results will positively guide the extrapolation procedures for those astrophysically significant cases.

Whether there is an S factor maximum at very low energies for systems with a positive fusion Q value was an experimentally challenging question for some years [5]. Some studies of systems with medium to light masses and positive Q values have been recently performed at various laboratories (see, e.g., [15–18]).

Some evidence for an S factor maximum shows up, but its existence was not clearly established, because of the limited energy range covered in those experiments.

In view of all this, we decided to perform measurements of fusion cross sections of $^{12}C + ^{30}Si$, in an energy range near and especially below the Coulomb barrier. This system is actually a link between the heavier cases our group has studied in recent years, and light heavy-ion systems.

In previous experiments on $^{12}C + ^{30}Si$ fusion [19] the excitation function was measured only above the Coulomb barrier, down to $\simeq$200 mb and with large error bars. With those experimental data we are far from being able to deduce the possible appearance of hindrance. Indeed, the S factor in the measured energy range has a monotonically increasing trend with decreasing energy, as expected.

We cannot even determine the effects of couplings to the low-lying excitations of ^{30}Si. It should be kept in mind that the lowest 3^- state of ^{30}Si, as well as the ^{12}C excitations, are weak and lie at high excitation energies. This implies an adiabatic effect on fusion, that can be included in a potential renormalization [20,21]. The 2^+ state of ^{30}Si might have a more important role on sub-barrier fusion enhancement because of its lower excitation energy and larger coupling strength ($E_x = 2.23$ MeV with $\beta_2 = 0.31$). On the other hand, the hindrance may appear at relatively high energies if the effects of the inelastic couplings of ^{30}Si are modest. On the basis of existing data, no reliable extrapolation toward lower energies where the "competition" between enhancement and hindrance takes place, is possible.

This work reports on our recent measurements of sub-barrier fusion of $^{12}C + ^{30}Si$, and of their interpretation within current coupled-channels (CC) models. The obtained data were preliminarily presented at the Fusion17 conference [22]. Section II describes the experimental setup and shows the results that will be compared in Sec. III with CC calculations. A discussion follows in Sec. IV concerning also the astrophysical aspects of the results, and the conclusions of the present work are summarized in Sec. V.

II. EXPERIMENTAL SETUP AND RESULTS

The ^{30}Si beam from the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN was used, at energies ranging from 34 to 80 MeV, with average intensities ~12 pnA. The targets were 50 $\mu g/cm^2$ ^{12}C evaporations, isotopically enriched to 99.9% in mass 12.

Four collimated silicon detectors were placed symmetrically around the beam direction at $\theta_{lab} = 16^\circ$, so as to check the beam position and focusing, and to allow normalization 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

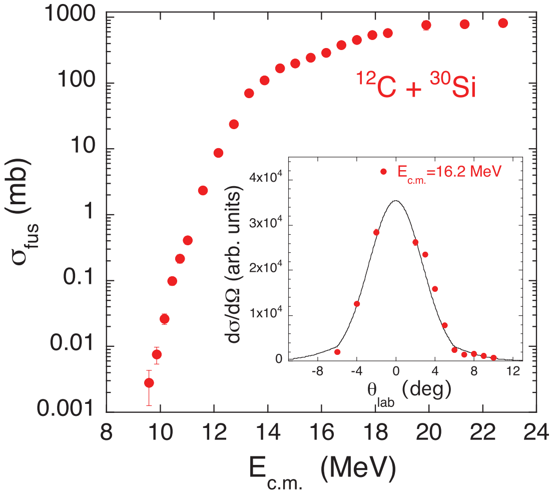

FIG. 1. Measured fusion excitation function for $^{12}C + ^{30}Si$ covering more than five orders of magnitude. The reported uncertainties are purely statistical, and do not exceed the symbol size except for the lowest energies. The inset shows the ER angular distribution obtained at $E_{\mathrm{lab}} = 59$ MeV, compared with a PACE4 calculation [26,27] (line).

at small angles. The experimental setup and the procedures are described in some detail in recent papers [23,24].

ER angular distributions were measured at $E_{\mathrm{beam}} = 45$, 59, and 80 MeV (the nominal Coulomb barrier is $V_b \simeq 46$ MeV [25]) in the angular range -6° to $+10^\circ$. This allowed us to determine the ratio between the differential ER cross sections and the total, angle-integrated one. We did not observe any significant variation with energy of the width of the angular distribution.

The accuracy of the absolute cross section scale ($\sim \pm 7\%$ overall) relies on such angular distribution measurements, on the beam quality and focusing precision, and, additionally, on the knowledge of the relevant solid angles and of the transmission efficiency T of the electrostatic deflector ($T = 0.80 \pm 0.03$). 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 thissection.

Our purpose was to extend the fusion excitation function down in energy as much as possible. The Coulomb barrier V_C is around 13.1 MeV [25], so that the ER would have only a few MeV of energy with normal kinematics. We have used the inverse kinematics, so that the ER had higher energies and therefore they were reliably and efficiently detected. We show in Fig. 1 the fusion excitation function obtained in the present experiment. The lowest measured cross section is around 3 μb well below the Coulomb barrier. The angular distribution obtained at the intermediate energy 59 MeV is reported in the insert of the figure. We have also performed a PACE4 calculation [26,27] using standard parameters, and we observe (see the full line) that the agreement with the experimental data is very good. Analogous situations are found for the other two energies where the angular distributions have been measured.

In Fig. 2 the excitation function is compared with the theoretical calculations described in Sec. III, and from that we have derived the astrophysical S factor and the logarithmic slope, which are shown in Figs. 3 and 4.

Figure 3 shows the logarithmic slope of the excitation function compared to the value expected for a constant S factor L_{CS} [28]. Even if the experimental uncertainties are somewhat

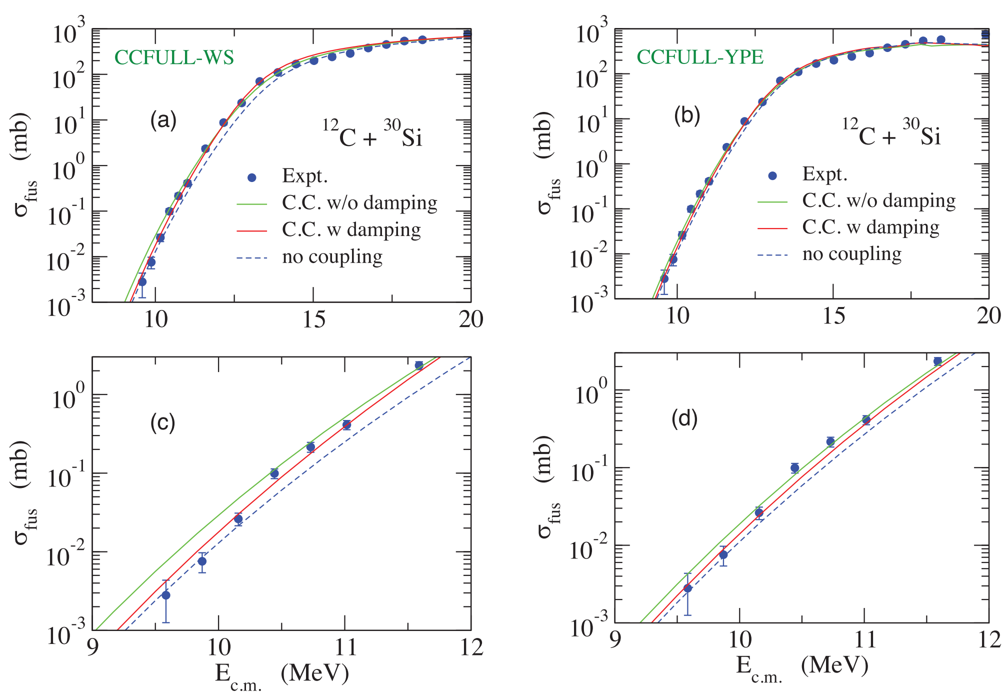

FIG. 2. The excitation function measured in this work was compared to the results of various CC calculations employing the WS (a) and (c), and the YPE (b) and (d) potentials, with and without damping of the coupling strengths. The no-coupling limit is also reported in both cases. (c) and (d) Expanded views of the low-energy range. See text for details.

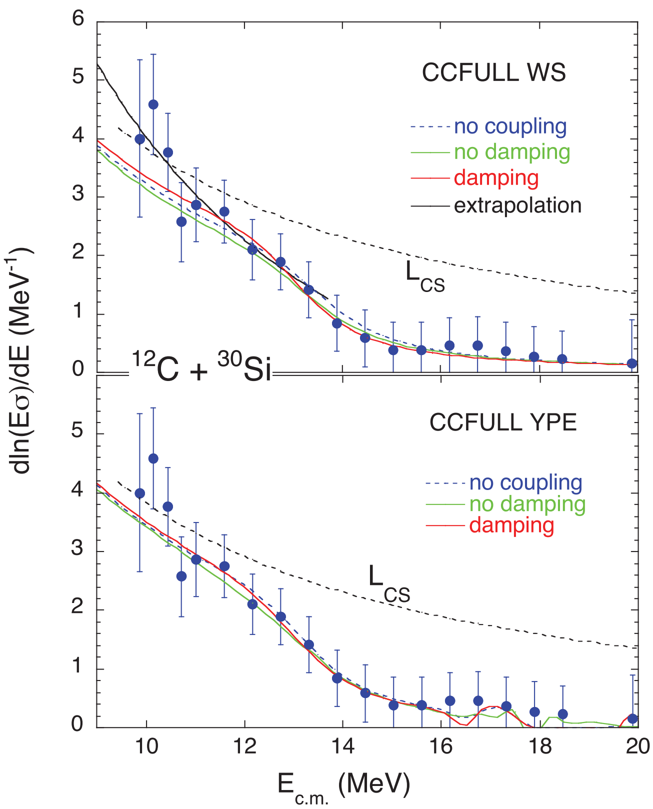

FIG. 3. Logarithmic slope of the excitation function. It appears that the slope overcomes the L_{CS} value at the lowest energies. The results of theoretical calculations are also shown and within the experimental uncertainties all of them give a reasonable fit of the data. The full black line in the upper panel is a phenomenological extrapolation of the slope based on Ref. [14], that allows a clear identification of the crossing point with the value L_{CS}.

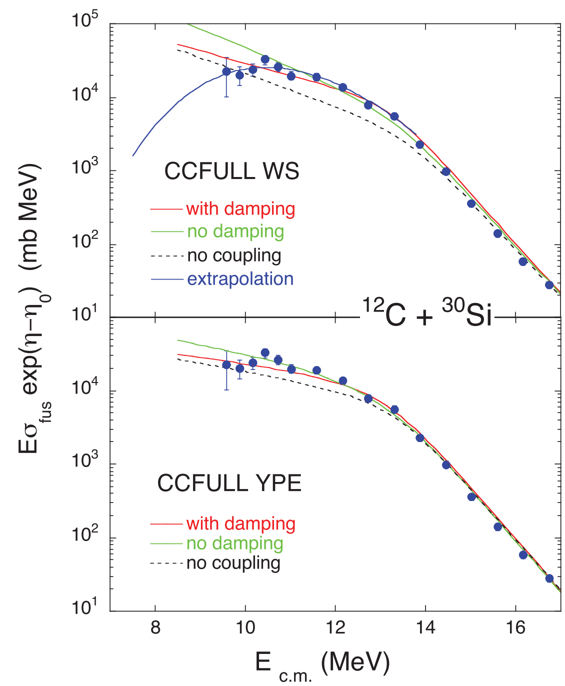

FIG. 4. Astrophysical S factor for $^{12}C + ^{30}Si$ in comparison with the CC calculations. The experimental evidence is that a maximum of S factor vs energy tends to develop around 10.5 MeV. The presence of this maximum is not reproduced by the present calculations which, however, fit the overall trend of the data. In particular, it appears that the low-energy damping of the coupling strengths is needed. The blue curve in the upper panel is a phenomenological extrapolation of S based on Ref. [14].

large at low energies, one notices that the slope reaches and overcomes L_{CS}. Correspondingly the S factor tends to develop a maximum with decreasing energy (see Fig. 4). This was usually taken as the phenomenological evidence for the hindrance effect.

III. COMPARISON WITH MODEL CALCULATIONS

The data obtained in the present work was analyzed on the basis of coupled-channels calculations. We first performed the calculations using the computer code CCFULL [29]. To this end, we have used a Woods Saxon (WS) internuclear potential with the depth parameter of $V_0 = 48.24$ MeV, the radius parameter of $r_0 = 1.1$ fm, and the diffuseness parameter of $a = 0.61$ MeV. For collective excitations, we have included couplings to the first 3^- state at 5.488 MeV and the first 2^+ state at 2.235 MeV in ^{30}Si within the vibrational coupling scheme, with the deformation parameter of $\beta_3 = 0.27$ and $\beta_2 = 0.31$, respectively (with the radius parameter for the coupling being 1.2 fm). For simplicity, we ignore excitations in the target nucleus ^{12}C, whose contribution is expected to be smaller than the effect of the projectile excitations. The results of this calculation are shown in Figs. 2(a) and 2(c), together with the result without the coupling effects. The corresponding logarithmic slope as well as the astrophysical S factor are shown in the upper panels of Figs. 3 and 4, respectively.

The coupled-channels calculations lead to an overall agreement with the experimental data, except for the lowest three points, which is more evident in the expanded scale shown in Figs. 2(c) and 2(d) as well as in the astrophysical S factor shown in Fig. 4. The fusion cross sections appear to be somewhat hindered as compared to the result of the coupled-channels calculations, that is a signature of the deep subbarrier hindrance phenomenon [1,4].

We have then used the adiabatic model [6,7,30,31] to account for the hindrance of fusion cross sections. In this model, one considers a quenching of the coupling strengths (for each eigenchannel) in the region inside the touching point of the two colliding nuclei (see also Refs. [32,33]). To this end, one introduces a Gaussian function,

$$\Phi_\alpha(r) = e^{-(r-R_d-\lambda_\alpha)^2/2a_d^2} \quad (r < R_d + \lambda_d), \tag{1}$$

where λ_α is the eigenvalue of the coupling operator $\hat{O}$ for the eigenchannel α, and $R_d = r_d(A_P^{1/3} + A_T^{1/3})$ and a_d are adjustable parameters, A_P and A_T being the mass number of the projectile and the target nuclei, respectively. To adjust those parameters, we have used the computer code CCFULL-YPE [34], with a small modification for $C_0(r)$ in Eq. (8) of Ref. [7], that is, we did not subtract this function from the coupling matrix elements so that they are consistent with those in CCFULL [29]. The red curve in Figs. 2(a) and 2(c), 3, and 4 show

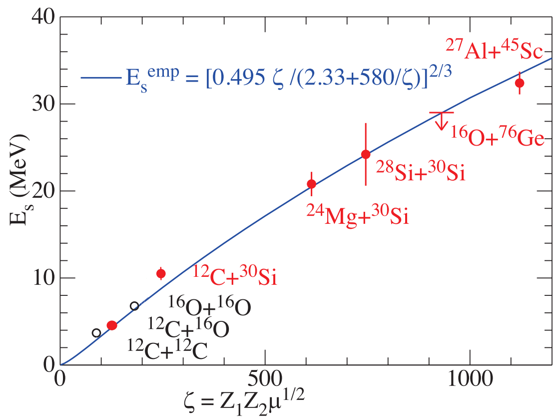

FIG. 5. Systematics of E_s in several light- and medium-light mass systems [14]. The location for $^{12}C + ^{30}Si$ is very close to the astrophysically relevant $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ cases. For these systems several data sets exist, but they are sometimes contradictory to each other and the errors are large. This results in large uncertainties in the expected values for their hindrance threshold. The corresponding points (open symbols) have therefore been obtained only from extrapolations.

the result so obtained with $r_d = 1.32$ fm and $a_d = 0.38$ fm. The low-energy cross sections are reasonably well accounted for with this calculation, employing the WS potential with a damping function.

In Ref. [6], it was pointed out that a YPE internuclear potential partly accounts for the deep sub-barrier fusion hindrance observed with a coupled-channels calculation with a WS potential, because the YPE potential phenomenologically takes into account the saturation property of nuclear matter. We have therefore repeated the calculations with the YPE potential. The results are shown in Figs. 2(b) and 2(d) and the lower panels of Figs. 3 and 4. For the parameters in the damping function, we have used $r_d = 1.36$ fm and $a_d = 0.85$ fm, which are closer to those used for analyses for other systems [7], as compared to the values obtained with the WS potential. One can see that the calculations with YPE potential reproduce the data better than that with the WS potential, as would have been expected from the previous analysis of Ref. [6]. Yet, one can observe that the experimental data are described slightly better by the calculation with damping, especially the energy dependence of the S factor shown in the lower panel of Fig. 4. However, the calculations are not able to reproduce the tendency shown by the data to develop a maximum around 10.5 MeV. In such a case the energy threshold for the onset of hindrance is better identified by the comparison with the extrapolation curves (upper panel of Figs. 3 and 4). Indeed, the point for the present system in Fig. 5 was placed on the basis of that phenomenological extrapolation.

One may argue that fusion cross sections at even lower energies would be fit by CC calculations with coupling strengths completely damped, that is, by single-barrier penetration calculations (no couplings).

In the upper panels of Figs. 3 and 4 we have also reported the extrapolation curves for the slope and the S factor obtained by fitting the excitation function according to the empirical recipe reported in Eqs. (5) and (8) of Ref. [14]. Obviously, the extrapolation curve reproduces the data very well while the CC calculations only give an average fit and do not predict a clear S factor maximum.

IV. DISCUSSION

The CC analysis presented in the previous section confirms that the hindrance effect, although being not so strong, is observed in $^{12}C + ^{30}Si$ as suggested (see Sec. II) by the low-energy behavior of the logarithmic slope and of the S factor. This is consistent with the average trend observed for medium-light and light systems as reported in Fig. 5. Here the threshold energy E_s for hindrance is shown as a function of the system parameter $\zeta = Z_1 Z_2 \mu^{1/2}$, following the empirical analysis of Ref. [14]. E_s is taken as the energy where the S factor shows a maximum. The blue line is the result of the phenomenological formula (also explicitly written in the figure), that was originally proposed [14] for heavier stiff systems. We observe that it also reproduces the experimental observations for a number of medium-light systems quite well.

The threshold for the present case $^{12}C + ^{30}Si$ can be estimated from Figs. 3 and 4 $E_s \simeq 10.5$ MeV which is not far from the empirical value. An uncertainty of ± 0.6 MeV was associated with this value and is reported in Fig. 5. Very recently a threshold for hindrance was experimentally established for the case $^{12}C + ^{16}O$ [12] and it is in excellent agreement with the empirical prediction. This result and the present data for $^{12}C + ^{30}Si$ validate the phenomenological formula for light systems, in particular for the cases of most relevant astrophysical interest like $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$, so that the formula may probably be used to a certain confidence level to estimate the reaction rates for such systems at stellar energies.

We would like to mention also the recent work on the very asymmetric systems ^{12}C, $^{7}Li + ^{198}Pt$, and $^{11}B + ^{197}Au$ [35,36], where the fusion hindrance was found to become progressively significant when going to the heavier projectiles, although remaining relatively small.

V. SUMMARY

In this work we have presented the results of fusion cross-section measurements for the system $^{12}C + ^{30}Si$ in a wide energy range down to $\sigma_{fus} \simeq 3\ \mu b$. The previous existing excitation function was extended downwards by about five orders of magnitude. The logarithmic slope and the astrophysical S factor have been extracted from the data. An empirical evidence of the hindrance effect shows up, because the slope reaches and overcomes the L_{CS} value and the S factor appears to develop a maximum with decreasing energy.

This is supported by CC calculations that have been performed within the adiabatic model, using both the WS and the YPE potentials. A damping of the coupling strengths was found to improve the data fit at low energies and, overall, the YPE potential gives better results. The hindrance effect is somewhat weak but clearly observable from the comparison with the calculations.

The threshold for the onset of hindrance was found to be in good agreement with the phenomenological estimate of Ref. [14], that well describes the experimental S factor trend. The empirical recipe and the present CC model are then probably reliable tools for the extrapolation to even lighter systems of astrophysical relevance.

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