Fusion of $^{12}C + ^{24}Mg$ far below the barrier: Evidence for the hindrance effect

G. Montagnoli,[1] A. M. Stefanini,[2] C. L. Jiang,[3] G. Colucci,[1] S. Bottoni,[4] D. Brugnara,[1,2] P. Čolović,[5] L. Corradi,[2] E. Fioretto,[2] F. Galtarossa,[2] A. Goasduff,[1] O. S. Khwairakpam,[2] M. Heine,[6] G. Jaworski,[7] M. Mazzocco,[1] T. Mijatović,[5] M. Siciliano,[1] F. Scarlassara,[1] S. Szilner,[5] T. Van Patten,[4] and I. Zanon[2,8]

[1]*Dipartimento di Fisica e Astronomia Università di Padova and INFN, I-35131 Padova, Italy*
[2]*INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Dipartimento di Scienze e Tecnologie Fisiche Università di Milano and INFN, I-20133 Milano, Italy*
[5]*Ruđer Bošković Institute, HR-10002 Zagreb, Croatia*
[6]*IPHC, CNRS-IN2P3 Université de Strasbourg, F-67037 Strasbourg, France*
[7]*Institute of Nuclear Physics, Polish Academy of Sciences, PL 31-342 Cracow, Poland*
[8]*Dipartimento di Fisica e Scienze della Terra Università di Ferrara, I-44121 Ferrara, Italy*

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Background: The phenomenon of fusion hindrance may have important consequences on the nuclear processes occurring in astrophysical scenarios, if it is a general behavior of heavy-ion fusion at extreme subbarrier 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.

Purpose: Our aim has been to search for evidence of fusion hindrance in $^{12}C + ^{24}Mg$ which is a medium-light system with positive Q value for fusion, besides the heavier cases where hindrance is recognized to be a general phenomenon. $^{12}C + ^{24}Mg$ is very close to the $^{16}O + ^{16}O$ and $^{12}C + ^{12}C$ systems that are important for the late evolution of heavy stars.

Methods: The experiment has been performed in inverse kinematics using the ^{24}Mg beam from the XTU Tandem accelerator of LNL in the energy range 26–52 MeV with an intensity of 4–8 pnA. The targets were ^{12}C evaporations 50 $\mu g/cm^2$ thick, isotopically enriched to 99.9%. The fusion-evaporation residues were detected at small angles by a E-ΔE-ToF detector telescope following an electrostatic beam deflector.

Results: Previous measurements of fusion cross section for $^{12}C + ^{24}Mg$ were limited to above-barrier energies. In the present experiment the excitation function has been extended down to $\simeq 15$ μb and it appears that the S factor develops a clear maximum vs energy, indicating the presence of hindrance. This is the first convincing evidence of an S factor maximum in a medium-light system with a positive fusion Q value. These results have been fitted following a recently suggested method and a detailed analysis within the coupled-channels model that has been performed using a Woods-Saxon potential and including the ground state rotational band of ^{24}Mg. The coupled-channels calculations give a good account of the data near and above the barrier but overpredict the cross sections at very low energies.

Conclusions: The hindrance phenomenon is clearly observed in $^{12}C + ^{24}Mg$, and its energy threshold is in reasonable agreement with the systematics observed for several medium-light systems. The fusion cross sections at the hindrance threshold show that the highest value ($\sigma_s = 1.6$ mb) is indeed found for this system. Therefore it may even be possible to extend the measurements further down in energy to better establish the position of the S-factor maximum.

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I. INTRODUCTION

Hindrance of heavy-ion fusion at extreme subbarrier energies, characterized by a steep fall off of the fusion cross section with decreasing energy, was discovered 15 years ago [1,2]. 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 [3–5].

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 [3–5]. However, when the fusion reaction is an exothermic process the S factor may not show any maximum. This is the case of the reactions taking place in the carbon and oxygen burning stages of heavy stars [6,7]. Therefore, from the astrophysical point of view, it would be important to investigate whether there is an S-factor maximum at very low energies for such systems. However, these measurements are very challenging.

Indeed, the available results for deep subbarrier fusion reactions of $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ (see, e.g., [8–10]) have large uncertainties and serious discrepancies between different sets of data show up.

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

Some studies of systems with medium to light masses and positive Q values have been performed at LNL and other laboratories (see, e.g., [11–17]), 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 [18] at LNL. The excitation function was measured down to 3 μb and the signature of a weak hindrance effect was observed, because the low-energy cross sections are overpredicted by standard coupled-channels (CC) calculations. The evidence, however, is not at all conclusive.

For the case of $^{12}C + ^{24}Mg$ the compound nucleus is lower by six mass units and, thus, is closer to the systems of astrophysical interest. In particular, the empirical analysis of Refs. [6,7] shows that the behavior of a system, as far as hindrance threshold and trend are concerned, is governed by the "system parameter" $\zeta = Z_1 Z_2 \mu^{1/2}$. This parameter 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. In Fig. 1(a) a plot of the S factor vs energy for this system is reported, that seems to indicate a maximum around 10.5 MeV.

For $^{12}C + ^{24}Mg$, only measurements of fusion cross sections above the barrier have been reported [20,21] [see Fig. 1(b)]. Recently, a new formula (with only three parameters) has been obtained, which can accurately reproduce many fusion excitation functions in a wide energy range [19]. Results of least-square fitting to excitation functions of $^{16}O + ^{18}O$ and $^{12}C + ^{30}Si$ are shown in Fig. 1.

On one side, the maximum of the S factor of $^{12}C + ^{30}Si$ is well reproduced, while on the other side, $^{16}O + ^{18}O$ [see Fig. 1(c)] 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 shown in Fig. 1(b) (SG prediction). It can be seen that at high energies previous measurements are well fitted, and at low energies an S-factor maximum is predicted slightly below 10 MeV.

This work reports on our recent measurements of fusion cross sections for $^{12}C + ^{24}Mg$ far below the barrier, and of their interpretation within current coupled-channels (CC) models. The obtained data were preliminarily presented at the INPC 2019 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.

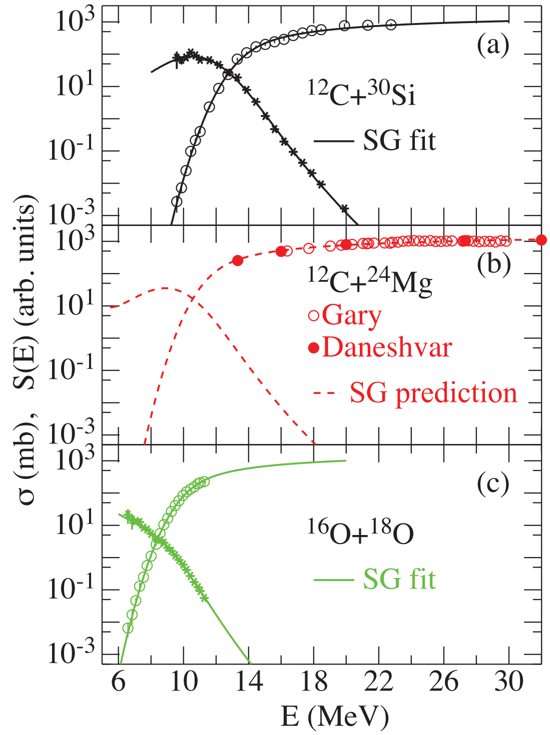

FIG. 1. Comparison for cross sections and S factors for the three fusion reactions $^{16}O + ^{18}O$ (c), $^{12}C + ^{24}Mg$ (b), and $^{12}C + ^{30}Si$ (a). The curves for $^{16}O + ^{18}O$ and $^{12}C + ^{30}Si$ (SG fit) are the results of three-parameter fits that have been interpolated to obtain the single-Gaussian predictions for $^{12}C + ^{24}Mg$ (see Ref. [19] for more details).

II. EXPERIMENTAL SETUP AND RESULTS

The measurements were made using ^{24}Mg beams in the energy range 26–52 MeV, with intensities $\simeq$ 4–8 pnA, provided by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN. The ^{12}C targets were installed in a sliding seal scattering chamber and consisted of 50 $\mu g/cm^2$ ^{12}C evaporations isotopically enriched to 99.9% in mass 12. The beam energy loss in the target was taken into account in the data analysis. The evaporation residues (ERs) were detected by using the setup based on an electrostatic beam deflector, that is described in more detail in Refs. [23,24]. Following the separation from the beam, the ERs entered a telescope consisting of two microchannel plate detectors (MCPs), an ionization chamber (IC) with tilted electrodes [25], giving an energy loss (ΔE) signal. The ERs were finally stopped in a circular 600 mm^2 silicon detector placed in the same gas (CH_4) volume. The silicon detector provided the residual energy E_R, as well as the start signal used for the times of flight (TOFs) from each MCP, and triggered the data acquisition. The geometrical solid angle of the whole setup was $\Delta\Omega = 49.9 \pm 0.3$ μsr (determined by the silicon detector size).

Four collimated silicon detectors were used for beam control and normalization between the different runs by measuring the Rutherford scattering from the target. They were

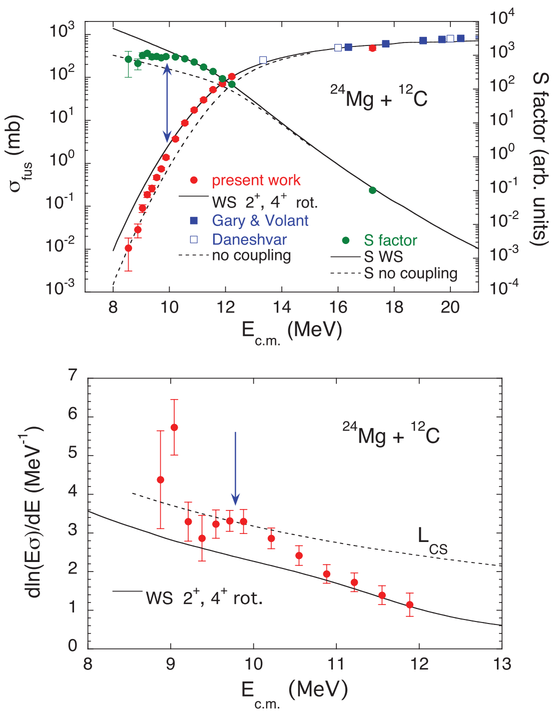

FIG. 2. Top panel: Excitation function and S factor for the system $^{12}C + ^{24}Mg$, compared with standard CC calculations (see text). Bottom panel: Logarithmic derivative of the excitation function compared with the L_{CS} value and with the CC calculations. The two blue arrows mark the threshold energy of the hindrance. Only statistical errors are reported in both panels.

placed above and below, and to the left and right of the beam at the same scattering angle $\theta_{lab} = 16^{\circ}$.

The ER angular distribution was measured at $E_{beam} = 42$ MeV in the angular range -7°–$+8^{\circ}$. 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 [26] calculations to take into account the shape variation of the angular distribution with energy.

Relative errors of the cross sections are essentially determined by statistical uncertainties which do not exceed 2–3% near and above the barrier, but become much larger at low energies where fewer fusion events were detected. Systematic errors on the absolute cross section scale are estimated ±7–8% (see Ref. [23]).

The measured cross sections are shown in the top panel of Fig. 2 together with the astrophysical S factor. The lowest measured cross section is about 10 μb. Figure 2 (bottom panel) shows the logarithmic slope of the excitation function compared to the value expected for a constant S factor L_{CS} [3]. Even if the experimental uncertainties are comparably large at low energies, one notices that the slope reaches L_{CS}. Correspondingly the S factor develops a maximum with decreasing energy (see top panel, at $E_{cm} \simeq 9.7$ MeV where $\sigma_{fus} \simeq 1.6$ mb). This has been usually taken as the phenomenological evidence for the hindrance effect. The prediction of Ref. [19] [see Fig. 1(b)] that the S factor shows a maximum slightly below 10 MeV appears to be confirmed experimentally.

III. COMPARISON WITH MODEL CALCULATIONS

The data obtained in the present work have been analyzed on the basis of coupled-channels calculations. We have used the computer code CCFULL [27]. 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.

These parameters are close to those of the Akyüz-Winther systematics [28], and were chosen in order to fit the cross sections in the barrier region, when the 2^+ quadrupole excitation of ^{24}Mg ($E_x = 1.369$ MeV with $\beta_2 = 0.60$) was already taken into account. In all calculations ^{12}C was considered as an inert nucleus. It is well known that the nucleus ^{24}Mg has a prolate deformation, with the ratio $E(4^+)/E(2^+)$ being close to the rotational limit. Therefore the ground state rotational band of ^{24}Mg was included in the coupling scheme up to the 4^+ state. The possible effect of the high energy ($E_x = 5.235$ MeV) octupole vibration of ^{24}Mg was already taken into account by the renormalization of ion-ion potential.

The results of the CC calculations are shown by the full curves in Fig. 2. They are in good agreement with the data around and above the barrier. Also the previous data of Refs. [20,21] are correctly reproduced. However we observe that the calculations start to overpredict the data at around the same energy where the S factor develops a maximum (see the blue arrow in both panels). The calculated slope (bottom 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 $^{12}C + ^{24}Mg$.

We also notice that the two lowest measured energy points agree quite well with the no-coupling limit (dashed line, upper panel). The same situation was observed for $^{12}C + ^{30}Si$ (please see Fig. 2 of Ref. [18]). It appears as if the no-coupling situation is recovered at very low energy. Alternatively we might expect that the cross sections become lower than the no-coupling prediction at still lower energies as indicated by the phenomenological extrapolation of Ref. [7].

IV. ASTROPHYSICAL ASPECTS OF THE RESULTS

As already pointed out in the Introduction, 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 behavior of the S factor at very low energy is very challenging and still much debated [8,29,30]. 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. 3) is very near to the lighter systems important for stellar evolution.

Figure 2 (top panel) shows that the maximum of the S factor (threshold of hindrance marked by the blue arrow) appears at an energy where the fusion cross section is $\sigma_s \simeq 1.6$ mb. This value is the highest measured so far for near-by systems and even for heavier ones [1] at least for the cases where a maximum of the S factor has been observed. In other

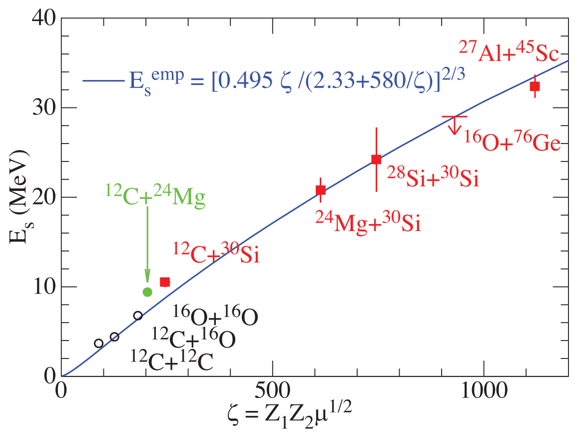

FIG. 3. Systematic of energy threshold of hindrance E_S vs the ζ parameter, for several medium-light systems. The points for the astrophysically relevant system (open symbols) have only been obtained from extrapolations. The threshold for $^{12}C + ^{24}Mg$ is marked by a green full dot and its uncertainty is within the symbol size, as for $^{12}C + ^{30}Si$.

systems the presence of hindrance was recognized by the low energy cross sections being overpredicted by standard CC calculations, but no S factor maximum develops. This is the case of $^{36}S + ^{48}Ca$ [12] where hindrance appears at a high energy where the cross section is as large as $\simeq 3$ mb, that is, twice as large as in $^{12}C + ^{24}Mg$. In the systems where no S-factor maximum shows up [2], however, the location of the hindrance threshold (and of the corresponding cross section) may be more questionable, because it depends on the way the "standard" CC calculations were performed.

Anyway, the very high value of the cross section at hindrance we observe for $^{12}C + ^{24}Mg$ makes, on one side, this observation very convincing because several data points have been measured at energies lower than the hindrance threshold. On the other side, it indicates that further studies at still lower energies are very attractive for the present and nearby systems.

The energy threshold for hindrance ($E_s \simeq 9.7$ MeV) for $^{12}C + ^{24}Mg$ is rather close to the value expected from the phenomenological systematics that was developed in Refs. [6,7] a few years ago, and that is shown in Fig. 3. 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.

V. SUMMARY

The phenomenon of hindrance in subbarrier heavy-ion fusion is a general effect recognized 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 paper we have presented the results of measurements concerning $^{12}C + ^{24}Mg$, very close to the cases of astrophysical interest.

The S factor shows a clear evidence of a maximum as predicted by the single-Gaussian fit method of Ref. [19]. The hindrance effect is not so strong but it is well recognized. Standard CC calculations using a Woods-Saxon potential start overpredicting the measured fusion cross sections a little lower than 10 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.* [6,7]. The cross section at threshold is very high ($\sigma_s \simeq$ 1.6 mb) and has allowed us to identify rather clearly the onset of hindrance. The physical reason why that cross section is so high in this particular system is presently unknown. 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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