Fusion hindrance in $^{12}C + {}^{19}F$: insights into astrophysics

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Background: The behaviour of fusion excitation functions at deep sub-barrier energies for light systems relevant for astrophysics (e.g. $^{12}C + {}^{12}C$, $^{12}C + {}^{16}O$, $^{16}O + {}^{16}O$) is far from being clearly established, in particular as far as the existence and features of fusion hindrance is concerned, due to differences between the many data sets, and to the appearance of strong resonance peaks in some cases.

Purpose: To investigate about the existence and the threshold of hindrance in the system $^{12}C + {}^{19}F$, where Q_{fus}= +22.95 MeV, so to clear up the underlying physics by comparing with coupled-channels calculations, and to reliably extrapolate the results to cases of astrophysical relevance such as $^{12}C + {}^{12}C$ and $^{12}C + {}^{16}O$.

Methods: ^{19}F beams from the XTU Tandem accelerator of LNL were sent onto thin ^{12}C targets isotopically enriched to 99.9%. The electrostatic beam deflector PISOLO separated the fusion-evaporation residues ER from beam-like particles. Then a E-ΔE-ToF telescope detected and identified the ER.

Results: The fusion cross sections of $^{12}C + {}^{19}F$ have been measured down to $\sim 70\mu$b. The logarithmic derivative of the energy-weighted excitation function increases at the lowest energies and reaches the L_{CS} value. Coupled-channels calculations predict significantly lower values. We have therefore indication that the hindrance phenomenon shows up in this system. The low-energy cross sections have been fitted using a recently proposed approach.

Conclusions: We compare the low-energy trend of $^{12}C + {}^{19}F$ with near-by and medium-light systems, using the Jiang's phenomenological systematics of the hindrance thresholds, updated with the present data and the behaviour of the recent results for $^{12}C + {}^{24,26}Mg$, $^{28,30}Si$ and $^{16}O + {}^{48}Ca$. Overall, we observe that the fit to the measured data including $^{12}C + {}^{19}F$ and those systems, leads to an extrapolation to the lighter cases, very close to what obtained from the hindrance model. This strengthens the evidence from the combined approach and is especially true for $^{12}C + {}^{12}C$ where the several low-energy resonances cause the direct observation of hindrance to be quite challenging.

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I. INTRODUCTION

The physics underlying the fusion hindrance phenomenon [1] in low-energy heavy-ion collisions and, consequently, its features in the various systems possibly associated to different nuclear structure situations, are under investigation and may yield crucial information on many-body quantum tunnelling, where intrinsic degrees of freedom are present [2, 3]. It has been pointed out by Simenel et al. [4] that the ion-ion potential is influenced by the Pauli exclusion principle, leading to a higher and thicker Coulomb barrier in several cases. As a consequence, low-energy fusion hindrance is produced.

One knows that the existence of fusion hindrance in light heavy-ion systems could have significant consequences in astrophysics [5], i.e., it might influence the stellar evolution and the nucleosynthesis processes. In this sense, hindrance interestingly links heavy-ion fusion dynamics and astrophysics, as the S factor may develop a maximum at deep sub-barrier energies [6], as a counterpart of a marked decrease of the fusion cross sections in that energy range, below the usual exponential fall.

The low-energy behaviour of medium-light systems may allow a reliable extrapolation towards the lighter ones of astrophysical relevance. Indeed, the cases of $^{12}C + {}^{24,26}Mg$ [7, 8], $^{28,30}Si$ [9, 10] have been investigated in recent years, and for all of them, the hindrance phenomenon has been identified. In particular, the fusion excitation function of $^{12}C + {}^{28}Si$ has been measured down to very small cross sections.

We decided to investigate the low-energy fusion of $^{12}C + {}^{19}F$, and the possible existence of the hindrance phenomenon with its threshold and features. That system has a large positive fusion Q-value Q_{fus}= +22.95 MeV, and is very near to the cases important for astrophysics. Our aim has been to clear up the underlying physics by comparing the excitation function with the results of coupled-channels calculations, down to very small cross sections. Furthermore, the knowledge of the low-energy fusion of $^{12}C + {}^{19}F$ would make very reliable extrapolating to cases such as $^{12}C + {}^{12}C$ or $^{16}O + {}^{16}O$, whose predicted hindrance thresholds only rely, sofar, on their higher energy data and on the hindrance model. Previ-

ous experimental results on ^{12}C + ^{19}F fusion are limited to energies above the barrier [11–13].

In Sect. II we describe the experimental set-up and show the measured excitation function. In Sect. III the experimental data are compared with the results of coupled-channels (CC) calculations. Sect. IV presents a fit of the low-energy data, as recently suggested in Ref. [14]. A discussion on systematic behaviors of medium-light systems is given in Sect. V, and Sect. VI summarises the present work.

II. EXPERIMENTAL

The fusion of ^{12}C + ^{19}F has been studied in inverse kinematics, using the ^{19}F beams produced by the XTU Tandem accelerator of the INFN-Laboratori Nazionali di Legnaro, in the energy range 15.5–30.0 MeV. The beam intensity was 5-10 pnA and the carbon targets were 50 μg/cm^2 in thickness, isotopically enriched to 99.9% in mass 12. The beam energy loss across half of the target was $\simeq$250 keV, slowly depending on the energy, and it was taken into account in the data reduction.

The fusion-evaporation residues (ER) were detected at 2^o (3^o for sub-barrier energies) with respect to the beam direction, downstream of the electrostatic beam deflector of LNL [15]. The detector telescope consisted of two micro-channel plates detectors (MCP1 and MCP2) 30×50 mm^2 in area, yielding fast time signals, a transverse-field ionization chamber (IC) for energy loss measurements and a 600 mm^2 silicon detector placed in the same gas (CH_4) volume, measuring the residual ER energy. The silicon detector also provided the fast start signals for the two Time-of-Flights with MCP1 and MCP2, as well as the trigger for the data acquisition.

Four 50 mm^2 silicon detectors collimated to $\varnothing$=1.5 mm, were used for beam control and normalisation between the different runs. They were installed on a ring frame at θ_{lab}=16^o symmetrically around the beam direction. The beam itself, beam-like particles, and ER travelled inside that frame, and then entered the electrostatic field region through an entrance collimator that stopped the direct beam. After separation, the ER entered the detector telescope through an exit collimator, where most beam-like particles were stopped a few cm aside.

The geometrical solid angle of the set-up was $\Delta\Omega$= 49.9±0.3 μsr (determined by the final silicon detector). The overall rejection factor for beam and beam-like particles was $\approx 10^7$ for the present reaction ^{12}C + ^{19}F in inverse kinematics. See Ref. [15] for further details. Fig. 1 shows the E-ToF and ΔE-ToF matrices taken at E$_{lab}$=23 MeV (close to the Coulomb barrier). The inverted kinematics leads to a relatively small separation between ER and beam-like ions, nevertheless the identification of the ER group is quite clear.

The ER angular distribution was measured at E$_{beam}$= 23.0 MeV in the angular range −6° to +9°. Then the

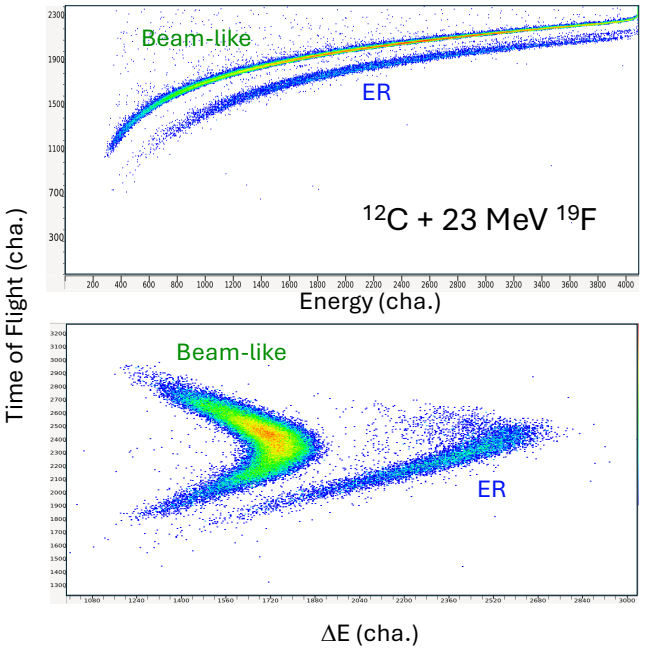


FIG. 1. *Two-dimensional spectra of ToF vs energy (top panel) and of ToF vs energy loss ΔE (bottom panel), at E_{lab}=23 MeV.*

ratio between the differential ER cross section and the total, angle-integrated one was determined. Standard PACE4 calculations [16] anticipate that the angular distribution shape does not significantly vary with the beam energy in the measured range. Several previous measurements with the same set-up confirm this [10, 17]. Therefore, we used the obtained fit parameters for all energies where the differential cross section was determined at one angle only. Finally, the absolute cross section scale was normalised to the lowest energy point of Kovar et al. [11].

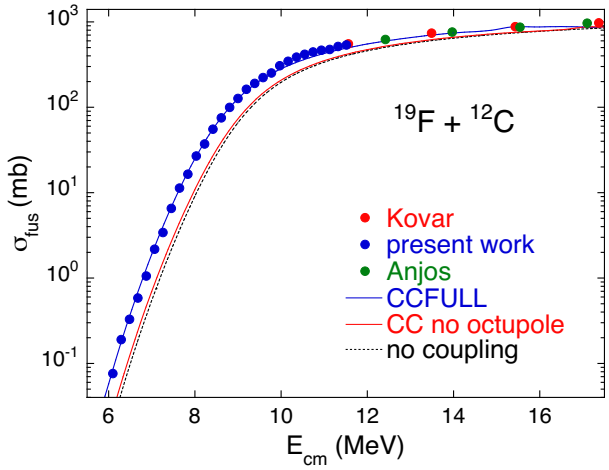


FIG. 2. *Fusion excitation function measured for ^{12}C + ^{19}F compared to CC calculations, and to previous experiments [11, 12]. The plotted errors are statistical uncertainties.*

The statistical uncertainties on the detectors' counts

determine the relative errors on the cross sections ($\sim$ 1.5% near and above the barrier, up to $\sim$ 15% for the lowest energies). The lowest measured cross section has been (76±18)μb. An upper limit $\sigma \leq 69\mu$b could be put for the lowest energy E_{beam}=15.5 MeV. Fig. 2 shows the measured excitation function of ^{12}C + ^{19}F. The CC calculations will be discussed in the next Section.

III. COUPLED-CHANNEL CALCULATIONS

The present data on ^{12}C + ^{19}F fusion have been analysed on the basis of the coupled-channels model, using the code CCFULL [18]. A nuclear potential of Woods Saxon (WS) was employed, with depth V_0= 46.38 MeV, radius parameter r_0 = 1.10 fm, and diffuseness a=0.60 MeV. These parameters are close to those of the Akyüz-Winther systematics [19]. They were chosen so to fit the cross sections in the barrier region ($\sim$ 40-60 mb). ^{12}C was considered inert in the CC calculations. The parameters of low-energy quadrupole and octupole modes of ^{19}F have been taken as the average between the values adopted for the two isotones ^{18}O and ^{20}Ne. This is justified by the fact that most of the enhancement originates by the octupole mode (having similar excitation energy and strength in those two near-by even-even nuclei), as can be seen from Fig. 2 showing the calculated excitation function compared with data.

The cross section enhancement near and below the barrier with respect to the no-coupling limit is not large, as one expects for this light system. It appears that the data fit is good over the whole energy range, however, the logarithmic derivative of the excitation function (slope) and the S factor can show better evidence of the trend of the data and of the calculations at the lowest energies.

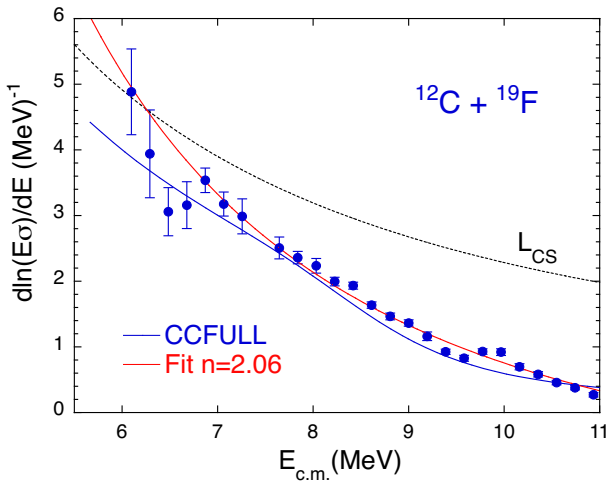


FIG. 3. *Logarithmic derivative of the energy-weighted excitation function for ^{12}C + ^{19}F compared to CC calculations (blue line) and to the fit (red line) described in the text.*

The slope is reported in Fig. 3. The experimental points have been obtained from the measured cross sections as incremental ratios with energy steps of 0.4 MeV, and the same procedure has been applied to the results of CC calculations. We observe that the two lowest energy points show an increasing slope above the calculated one, and in particular the lowest one reaches the L_{CS} value. This is evidence of hindrance, even if the errors are rather large.

The following Fig. 4 shows the astrophysical S factor. As expected from the behaviour of the slope, the experimental points tend to flatten out around $E_{c.m.}$=6.2 MeV, possibly indicating hindrance, while the calculated S factor keeps increasing with decreasing energy. The red lines are the results of the fitting procedure presented in the next Section.

IV. FITTING THE LOW-ENERGY EXCITATION FUNCTION

As originally discussed by Jiang et al. [5], a low-energy maximum of the S factor (i.e. the hindrance effect) is not algebraically necessary for systems with positive fusion Q-value, as is the case of ^{12}C + ^{19}F and of several other light and medium-light systems, where one can apply a phenomenological approach to extrapolate cross sections and S factors to very low energies, as an alternative to a full quantitative treatment of the hindrance phenomenon, that has not been achieved sofar. We are going to use the expression

$$L(E) = A_o + B_o/E^n \qquad (1)$$

for the logarithmic derivative of the low-energy excitation function [5], where A_o, B_o and n are fit parameters. To be noted that n=1.5 is the value for collisions between point-charge nuclei.

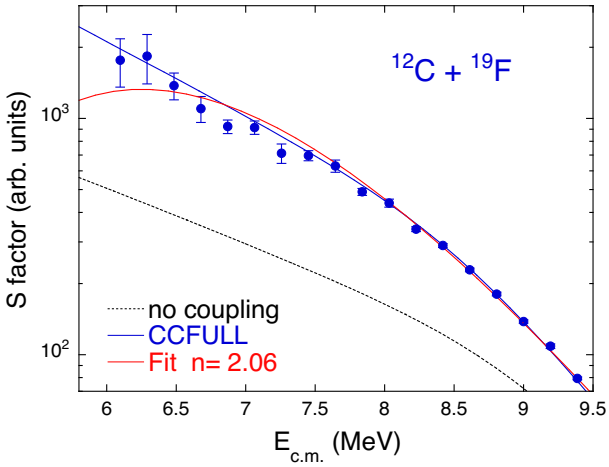


FIG. 4. *Astrophysical S-factor of ^{12}C + ^{19}F compared to CC calculations (blue line) and to the result of the fit described in Sect. IV (red line).*

The recent work of Uzawa and Hagino [14] has explored the consequences of releasing this condition in the analysis of the two systems ^{12}C + ^{12}C and ^{12}C + ^{13}C. For the

first case they show that, due also to the many resonances observed, the energy behaviour of the S factor depends on the selected data sets and on the fitting method. Instead, no hindrance is found in the fusion cross sections of ^{12}C + ^{13}C, where the fitted value of n is smaller than 1.5 in any case.

Indeed, $n < 1.5$ implies a double intersection of L(E) with L_{CS}, that is, the S factor shows a decreasing trend below the maximum, reaching a minimum with decreasing energy, with a further increase at even lower energies.

We show in Fig. 3 (red line) the result of the fit of the logarithmic derivative using Eq. (1) for ^{12}C + ^{19}F with the weighted least squares (WLS) method [14]. The resulting parameters are A_o = -1.61±0.29, B_o = 273.3±104.0 and n = 2.06± 0.22. Since n is larger than 1.5 we have a single crossing of L(E) with L_{CS}, taking place at $E_{c.m.} \simeq$ 6.2 MeV. So this is probably the hindrance threshold E_s, in agreement with what indicated by the experimental points even though the errors are rather large.

The corresponding red line in Fig. 4 is the S factor obtained using the same parameters, with E_s=6.2 MeV and σ_s=0.1 mb. The S maximum vs energy indicates the position of the hindrance threshold.

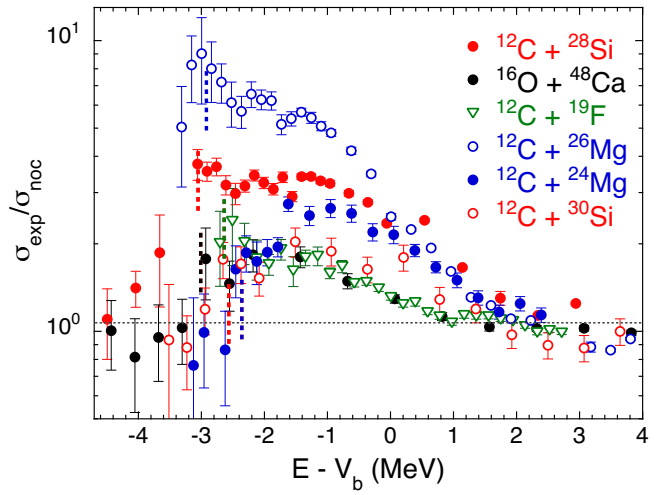


FIG. 5. *Ratio of the experimental fusion cross sections to no-coupling calculations vs the energy difference from the Coulomb barrier, for several systems [8–10, 20], and for ^{12}C + ^{19}F. The Akyüz-Winther potential has been used. The dashed lines mark the hindrance threshold for the different cases (see also Ref. [2]).*

V. BEHAVIOUR OF OTHER MEDIUM-LIGHT SYSTEMS

Fig. 5 displays the near- and sub-barrier trends of medium-light systems investigated in recent years. The plot includes several cases already shown in Ref. [20], and the present system ^{12}C + ^{19}F has been added. The lowest measured cross section for this case is larger than

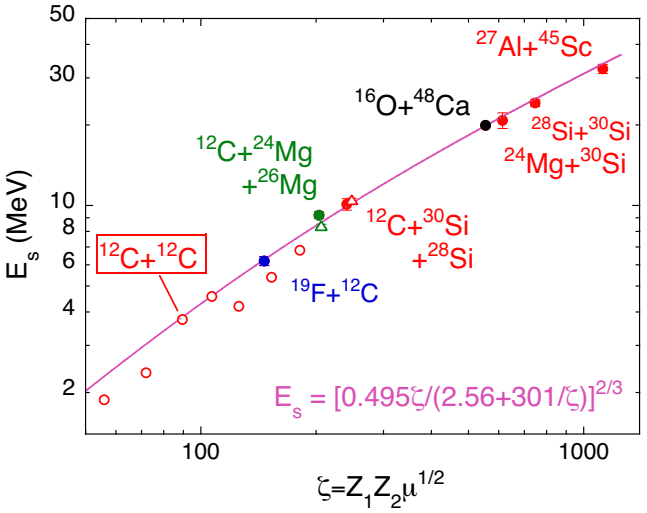


FIG. 6. *Threshold energies for hindrance in light systems (updated from Ref. [21]). The uncertainties on some of the reported points are smaller than the symbol size. The system studied in the present work is represented by a blue dot. The open symbols at low ζ values are obtained by extrapolating from higher energies, using the hindrance model (see Ref. [2]). They represent, with increasing ζ, ^{10}B+ ^{10}B, ^{11}B + ^{12}C, ^{12}C + ^{12}C, ^{12}C + ^{14}N, ^{12}C + ^{16}O, ^{14}C + ^{16}O, and ^{16}O + ^{16}O.*

for most of the other systems, so we cannot observe the decrease of the ratio $\sigma_{exp}/\sigma_{noc}$ down to one, which is a common feature of the other cases, apart from ^{12}C + ^{26}Mg where the cross section enhancement is largest, see Ref. [8]. We notice that the enhancement sharply starts decreasing just below the hindrance threshold, in all cases. The trends at far sub-barrier energies are still uncertain, based on the available data, however, there is a reasonable evidence that the ^{16}O + ^{48}Ca cross sections follow the no-coupling limit since the four lowest energy points are compatible with one.

The systematics of hindrance threshold energies for medium-light systems with Q_{fus} >0 has been updated with the present data of ^{12}C + ^{19}F. We show it in Fig. 6 where the new expression best fitting the data is also displayed in magenta (please note the logarithmic scale on both axes). The parameters are somewhat different from the one recently obtained [9] due to presence of the ^{12}C + ^{19}F data point which brings the extrapolation to ^{12}C + ^{12}C almost coincident with the (plotted) value obtained by applying the hindrance model to the higher-energy data of this system. This close agreement makes the prediction of $E_s \simeq$3.75 MeV for ^{12}C + ^{12}C quite reliable, in spite of the "confusing" resonance peaks showing up in the S factor, and of the large discrepancies observed between the many data sets existing for this system [14].

VI. SUMMARY AND CONCLUSIONS

We have measured the fusion cross sections of ^{12}C + ^{19}F from above the barrier down to $\sim$70μb. CC calculations are able to reasonably fit the data in the whole range, however, the logarithmic derivative of the energy-weighted excitation function significantly increases at the 2-3 lowest energies and reaches the L_{CS} value, above the CC results. The S factor, accordingly, displays a plateau at the same energies. The hindrance phenomenon therefore appears to show up in this system.

The fitting procedure recently proposed in Ref. [14] has been applied in the low-energy part of the excitation function, supporting the indication that hindrance shows up around $E_{c.m.}$=6.2 MeV.

We analyze the low-energy behavior of ^{12}C + ^{19}F in comparison with nearby and medium-light systems, applying Jiang's phenomenological systematics for hindrance thresholds. This framework is updated to incorporate the present data as well as recent results for ^{12}C + ^{24,26}Mg, ^{28,30}Si and ^{16}O + ^{48}Ca. Overall, fitting the experimental data for ^{12}C + ^{19}F together with these systems yields an extrapolation toward lighter systems that closely matches the predictions of the hindrance model. This consistency reinforces the validity of the combined approach. The agreement is particularly notable for ^{12}C + ^{12}C, where numerous low-energy resonances make the direct identification of hindrance especially difficult.

DATA AVAILABILITY

The data supporting this study's findings are available from the authors following a reasonable request.

ACKNOWLEDGMENTS

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