Sub-barrier fusion in $^{12}C + ^{26,24}Mg$: Hindrance and oscillations

A. M. Stefanini,[1] G. Montagnoli,[2] M. Del Fabbro,[2,3] D. Brugnara,[1] G. Colucci,[4] L. Corradi,[1] J. Diklić,[5] E. Fioretto,[1] F. Galtarossa,[2] A. Goasduff,[1] M. Mazzocco,[2] J. Pellumaj,[1,3] E. Pilotto,[1] L. Zago,[1] and I. Zanon[1]

[1] *INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*

[2] *Dipartimento di Fisica e Astronomia Università di Padova and INFN, I-35137 Padova, Italy*

[3] *Dipartimento di Fisica e Scienze della Terra Università di Ferrara, I-44122 Ferrara, Italy*

[4] *Heavy Ion Laboratory, University of Warsaw, 02-093 Warszawa, Poland*

[5] *Ruđer Bošković Institute, HR-10002 Zagreb, Croatia*

(Received 11 May 2023; accepted 23 June 2023; published 5 July 2023)

Background: The existence of fusion hindrance in the light heavy-ion systems of astrophysical interest is not well established, so investigating slightly heavier cases may allow a reliable extrapolation towards the lighter ones. The recent observation of a very high hindrance threshold in $^{12}C + ^{24}Mg$ (with a positive Q value for fusion) at $\sigma_{fus} \simeq 0.75$ mb, misses a valid interpretation within current theoretical models.

Purpose: Our aim has been to search evidence for fusion hindrances in the nearby system $^{12}C + ^{26}Mg$ also having $Q_{fus} > 0$, and to obtain information on the underlying physics from a comparison of the two cases and from coupled-channels calculations.

Methods: The experiment was performed in inverse kinematics using the ^{26}Mg beam from the XTU Tandem accelerator of Laboratori Nazionali di Legnaro (LNL). The targets were thin ^{12}C evaporations 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: The fusion excitation function of $^{12}C + ^{26}Mg$ has been measured down to $\approx 5\,\mu b$. The astrophysical S factor shows a maximum at an energy where the cross section is ≈ 0.03 mb, significantly lower than for $^{12}C + ^{24}Mg$. This difference is confirmed by the comparison of the two S factors. coupled channel calculations give a good account of the data, but they overpredict the cross sections below ≈ 0.03 mb. The logarithmic slopes of the two excitation functions are superimposable to a large extent, with visible oscillations, more noticeable for $^{12}C + ^{24}Mg$.

Conclusions: The hindrance phenomenon is clearly observed in $^{12}C + ^{26}Mg$. The difference between the corresponding threshold energies for $^{12}C + ^{24,26}Mg$ might (only qualitatively) be attributed to the α-like structure of ^{24}Mg. In the Jiang's phenomenological systematics, the different behaviors of $^{12}C + ^{24,26}Mg$ make the situation more complex, and call into question the extrapolation procedure toward the lighter systems of astrophysical interest.

DOI: 10.1103/PhysRevC.108.014602

I. INTRODUCTION

The existence of low-energy hindrance in the fusion of light heavy-ion systems is critical for a variety of stellar environments and the accurate knowledge of sub-barrier fusion cross sections is essential for valid simulations of the nucleosynthesis processes. Moreover, such fusion reactions give fundamental information on quantum tunneling of many-body systems where several intrinsic degrees of freedom are concurring [1–3].

On one side, couplings of the entrance channel with the low-energy collective modes of the colliding nuclei strongly enhance fusion cross sections near the Coulomb barrier. On the other side, the hindrance effect produces a marked decrease of those cross sections at lower energies, as pointed out by Jiang *et al.* for the system $^{60}Ni + ^{89}Y$ [4].

The energy threshold of hindrance is often characterized by a maximum of the astrophysical S factor with decreasing energy [5]. This phenomenon is regarded as an interesting link between heavy-ion fusion and astrophysics. Its existence and the underlying physical motivations are under debate, especially for the light systems relevant for astrophysics. Simenel *et al.* [6] pointed out that the Pauli exclusion principle influences the ion-ion potential. As a consequence, low-energy fusion hindrance is produced, because the Coulomb barrier turns out to be thicker and higher.

In recent years we studied the medium-light system $^{12}C + ^{24}Mg$ [7,8] by measuring its excitation function near and below the barrier. This system has a positive fusion Q value $Q_{fus} = +16.3$ MeV, and it is close to the lighter cases of astrophysical interest. It shows interesting features, i.e., 1) the lowest cross sections, below the enhancement region, are well reproduced by simple tunneling through a one-dimensional potential barrier and 2) the hindrance effect already shows up at $\sigma \simeq 0.75\,\mu b$, well above the threshold observed in most other cases with $Q_{fus} > 0$.

We decided to extend the measurements to the nearby case ^{12}C + ^{26}Mg (where $Q_{\rm fus} = +18.5$ MeV) to shed light on those features by comparing the low-energy trend of the two systems, and by an overall theoretical analysis using the coupled channels (CC) model. The same two systems ^{12}C + ^{24,26}Mg were measured by Daneshvar *et al.* [9] in direct kinematics above the energy range investigated in the present work.

This article reports on the results of the experiment on the ^{12}C + ^{26}Mg fusion. In Sec. II the experimental setup is described and the results are presented. Section III introduces the CC calculations we performed, in comparison with the experimental data. Section IV highlights the analogies and differences with respect to ^{12}C + ^{24}Mg, and a final discussion on systematic behaviors is given in Sec. V. The most relevant results of the present work are summarized in Sec. VI, as well as an outlook for future measurements.

II. EXPERIMENTAL

^{26}Mg beams in the energy range 25–50 MeV, with intensities $\simeq$ 2–6 pnA, were provided by the XTU Tandem accelerator of the INFN-Laboratori Nazionali di Legnaro (LNL). The targets were 50 µg/cm^2 ^{12}C evaporations, isotopically enriched to 99.9% in mass 12. The setup based on an electrostatic beam deflector, recently used for the experiment on ^{12}C + ^{24}Mg fusion [8], was employed for fusion-evaporation residue (ER) detection. A ΔE-E-ToF detector telescope is installed downstream of the beam separator, with two microchannel plates (MCP) detectors, and a ionization chamber (IC) for energy loss measurements. A silicon detector is placed in the same IC gas volume to measure the residual ER energy.

Four silicon detectors were installed at $\theta_{\rm lab} = 16^o$ for beam control and normalization between the different runs. More details can be found in Ref. [10].

Two ER angular distributions were measured at $E_{\rm beam} =$ 43.5, 36.5 MeV in the angular range -8° to $+9^\circ$ in the laboratory system (see Fig. 1). The small width difference between the two distributions allowed us to interpolate and extrapolate their shape to all other energies where the fusion cross section was measured only at $\theta_{\rm lab} = 2^\circ$ (3° at the lower energies). This way we obtained the full excitation function (see Table I).

The statistical uncertainties determine the relative errors on the cross sections (2–3 % near and above the barrier, larger at lower energies). As in previous measurements, we estimate the error on the absolute cross section scale ±7–8% [10]. The lowest measured cross section is (5.7 ± 2.2)µb. An upper limit $\sigma \leqslant 1.5$ µb can be put for the lowest energy $E_{\rm beam} = 25$ MeV.

Figure 2 reports the excitation function of ^{12}C + ^{26}Mg (the lowest data point is an upper limit), compared to the CC calculations we are going to present in the next section.

III. COUPLED-CHANNELS CALCULATIONS

Coupled-channels calculations have been performed for ^{12}C + ^{26}Mg using the code CCFULL [11]. A Woods-Saxon (WS) potential was employed, with parameters close to those

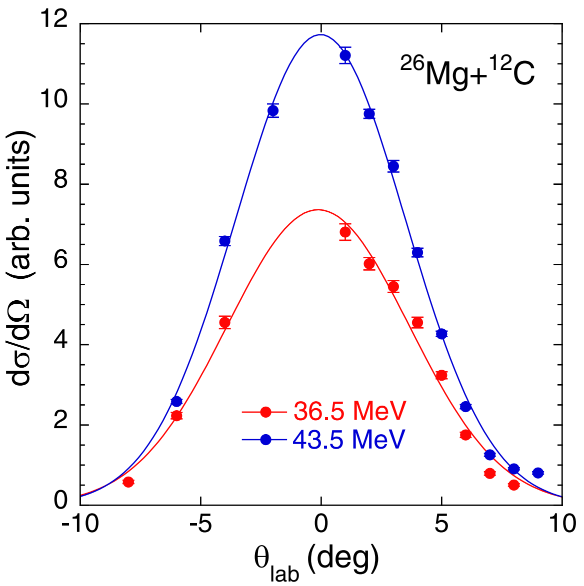

FIG. 1. ER angular distributions measured in this work, together with Gaussian fits. Only statistical (relative) errors are plotted.

of the Akyüz-Winther systematics [12], i.e., radius parameter $r_o = 1.10$ fm, and diffuseness $a = 0.60$ MeV, as already used in the analysis of ^{12}C + ^{24}Mg [7]. The depth was taken $V_o =$ 43.52 MeV to fit the cross sections in the barrier region. This choice allows for a more meaningful comparison between the two systems, even if the fit above the barrier for the present system is not perfect.

^{12}C was considered as an inert nucleus. ^{26}Mg has a stable prolate deformation ($\beta_2 = 0.48$), with the lowest 2^+ state at $E_x = 1.809$ MeV. Besides this, also the 4^+ state of the ground state rotational band was included in the coupling scheme. The weak octupole vibration of ^{26}Mg lies at $E_x = 6.876$ MeV,

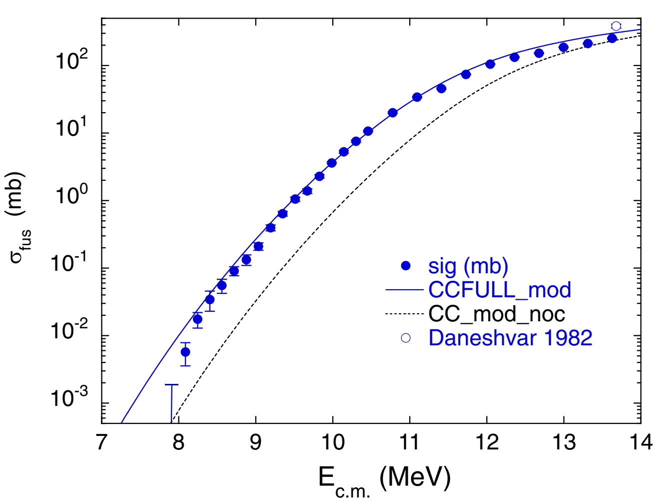

FIG. 2. Fusion excitation function measured for ^{12}C + ^{26}Mg compared to CC calculations. The quoted errors are statistical uncertainties. The open symbol is the lowest energy point of Ref. [9] (Daneshvar 1982). It is ≈30% higher than our results at comparable energies.

TABLE I. Fusion cross sections of $^{12}C + ^{26}Mg$ measured in this work. The quoted uncertainties are only statistical.

$E_{c.m.}$ (MeV)	σ (mb)
8.09	0.0057 ± 0.0022
8.25	0.017 ± 0.005
8.40	0.034 ± 0.011
8.56	0.055 ± 0.013
8.72	0.091 ± 0.014
8.88	0.133 ± 0.023
9.03	0.210 ± 0.026
9.19	0.396 ± 0.040
9.35	0.639 ± 0.50
9.51	1.050 ± 0.075
9.67	1.39 ± 0.11
9.83	2.29 ± 0.13
9.99	3.62 ± 0.11
10.14	5.27 ± 0.23
10.30	7.57 ± 0.27
10.46	10.65 ± 0.29
10.78	20.03 ± 0.57
11.09	34.03 ± 0.75
11.41	45.64 ± 1.18
11.73	73.9 ± 1.0
12.04	104.6 ± 1.4
12.36	132.5 ± 2.3
12.68	152.0 ± 2.3
13.00	186.5 ± 2.6
13.31	211.9 ± 2.7
13.63	252.8 ± 3.5
15.68	536.0 ± 4.4

and its effect is contained in the adjustment of the ion-ion potential.

Figure 2 shows that the CC calculation gives a very good account of the data in a large energy range, however, we observe that it starts overpredicting the experimental cross sections at the level of ≈0.03 mb. This means that the hindrance threshold for this system is significantly lower than for $^{12}C + ^{24}Mg$ where it was observed at ≈0.75 mb. This point deserves a more detailed discussion that is presented in the next section

The upper cross section limit determined at the lowest measured energy for the present system gives a convincing indication that the no-coupling limit (pure tunneling a one-dimensional barrier) would reproduce the cross sections at still lower energies, as already observed for $^{12}C + ^{24}Mg$.

IV. COMPARISON OF $^{12}C + ^{26,24}Mg$

This difference between the two systems is confirmed from the comparison of the two S factors, reported in Fig. 3. The S factor maximum for $^{12}C + ^{26}Mg$ appears much lower in energy than for $^{12}C + ^{24}Mg$. It is also clear that the S factor maximum of $^{12}C + ^{26}Mg$ is significantly narrower.

The different positions of the hindrance threshold for the two systems are indicated also by the results of the CC calculations described above, which well reproduce the experimental S factors down to ≈8.4 MeV and ≈9.9 MeV for $^{12}C + ^{26}Mg$ and $^{12}C + ^{24}Mg$, respectively.

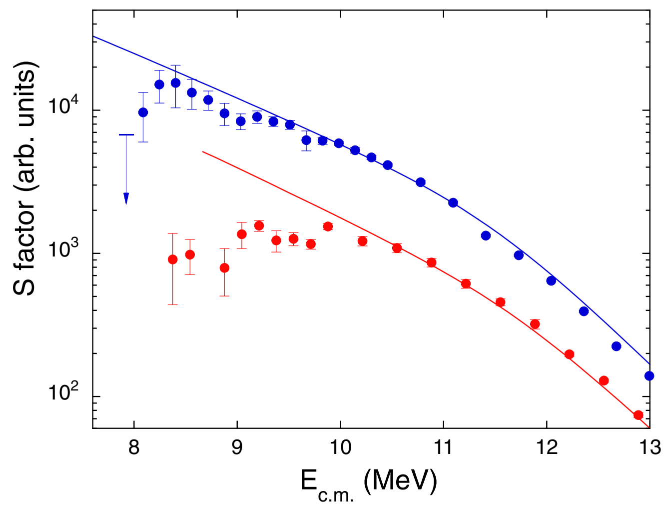

FIG. 3. S factor of $^{12}C + ^{26,24}Mg$. The Y scale is arbitrarily multiplied by a factor different for the two systems. The lines are the results of the CC calculations discussed in the previous section.

The upper panel of Fig. 4 shows the excitation functions of the two systems. The energy scale is not normalized to the Coulomb barrier which differs (in the c.m. system) by only ≈ 100 keV in the two ^{12}C + Mg systems. As a matter of fact, the two excitation functions essentially coincide above the barrier. However, we note that the cross sections of $^{12}C + ^{26}Mg$ start to be larger than for $^{12}C + ^{24}Mg$ from the barrier down, until they are a factor 4–5 greater at the lowest energies.

The reason for this relative enhancement can be hardly ascribed to nuclear structure differences. The target ^{12}C is common to the two systems. ^{24}Mg has a larger prolate deformation with respect to ^{26}Mg ($\beta_2 = 0.60$ vs 0.48), and the lowest 2^+ states are found at $E_x = 1.369$ MeV in ^{24}Mg and at $E_x = 1.809$ MeV in ^{26}Mg. The octupole excitation is weak and very high in energy in both cases, anyway at higher excitation in ^{24}Mg. For both systems, all one- and two-nucleon transfer channels have negative (and comparable) Q values. Only the α-transfer channels leading to ^{28}Si or ^{30}Si have positive Q values (+2.618 MeV and +3.277 MeV, respectively).

In view of this, the smaller fusion cross sections of $^{12}C + ^{24}Mg$ are possibly due to the very high hindrance threshold observed in this system. We consider now the lower panel of Fig. 4 where we report the logarithmic derivatives (slopes) of the two excitation functions, which have been obtained as the incremental ratio between every second cross section point. They are very similar to each other and are characterized by oscillations in the sub-barrier energy region, with peaks appearing at essentially the same energies for the two systems. L_{CS} is the value of the slope for which the S factor develops a maximum vs energy.

The highest-energy peak for $^{12}C + ^{24}Mg$ overcomes the L_{CS} value, and corresponds to the adopted threshold hindrance energy of that system. On the other hand, a further peak appears at the lower energy ≈ 9 MeV and we have some indication that a third peak might display slightly below the

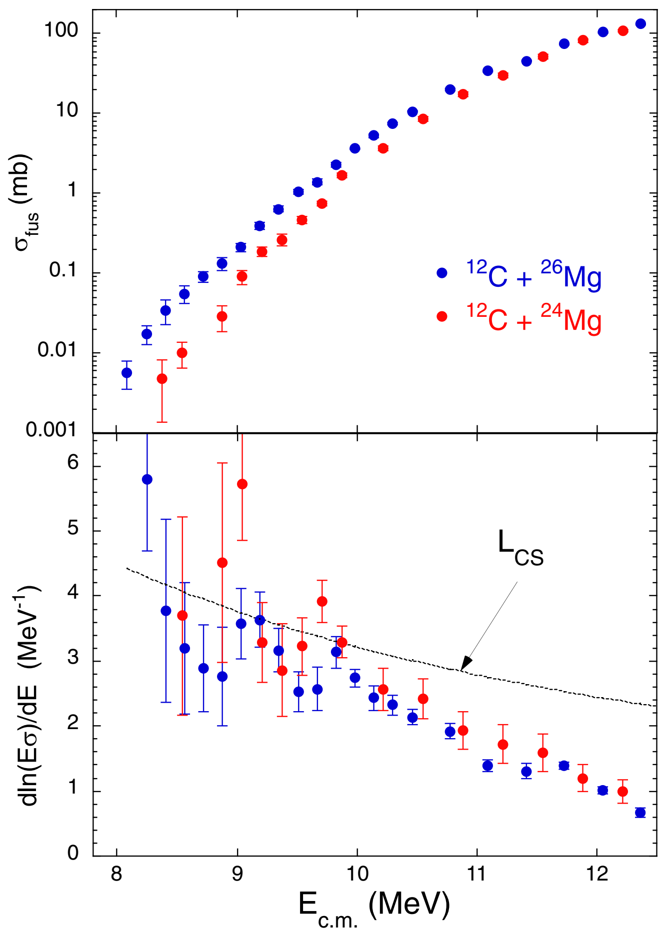

FIG. 4. Fusion excitation functions (top) and corresponding logarithmic derivatives (bottom) for $^{12}C + ^{26,24}Mg$. The L_{CS} values for the two systems are essentially overlapping.

lowest measured energy. Concerning $^{12}C + ^{26}Mg$, the two corresponding higher energy peaks (see Fig. 4) appear to be "damped", just reaching L_{CS}, while the lowest-energy slope increase is much more pronounced, clearly crossing the L_{CS} line. That is where the hindrance threshold has been identified for this system.

The observed oscillations remind us of the S factor behavior in $^{12}C + ^{16}O$ [13] and $^{12}C + ^{12}C$ (see [14] and references therein). We point out that in those systems the oscillations are clearly observable in the S factor (cross section) trend, while in the present cases, they show up in the first derivatives of the excitation functions vs energy (see again Fig. 4, lower panel), while they are less evident in the corresponding S factors. Fusion oscillations in $^{12}C + ^{16}O$ were associated to the elastic α-transfer channel, and they were recently suggested to arise from quasimolecular resonances [13]. In $^{12}C + ^{12}C$, the more pronounced oscillatory behavior was initially attributed to quasimolecular resonances [15,16]. This gave rise to a vast debate about their origin linked to the α-like nature of the two nuclei (see [17–19] and references therein). More recently, it has been proposed that the oscillations are of resonant origin, caused by the low level density of the compound nucleus ^{24}Mg in the relevant excitation energy range [20].

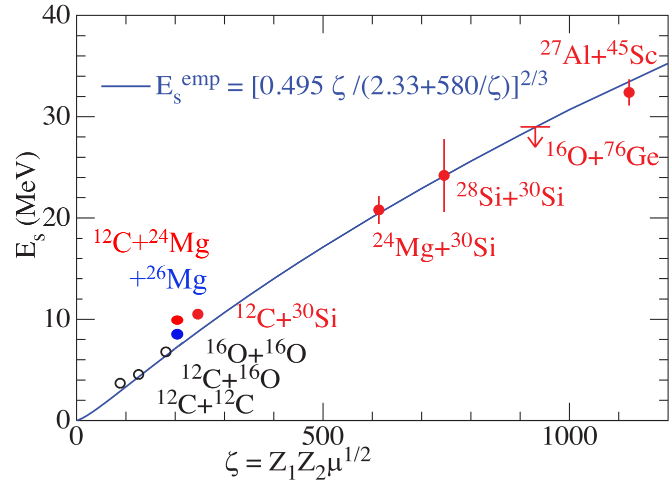

FIG. 5. Systematics of threshold energies for hindrance in light systems [21]. The open symbols for C + C, C + O, and O + O are obtained by extrapolating from higher energies, using the empirical hindrance model (see Ref. [3]). The uncertainties on the points for $^{12}C + ^{24}Mg$, ^{26}Mg are smaller than the symbol size.

We point out that the previous experiments at energies above the barrier on $^{12}C + ^{26,24}Mg$ [9] evidenced the presence of oscillations in the excitation function of $^{12}C + ^{24}Mg$, while the data on $^{12}C + ^{26}Mg$ are relatively smoother. In that work, Daneshvar *et al.* pointed out that comparing with direct channel behavior would perhaps provide some insight into the nature of those phenomena.

The oscillations we observe in the same two systems below the barrier may be related to what was observed at higher energies. In any case, an unambiguous theoretical interpretation is still needed, which should as well account for the strong similarity between the two cases below the barrier.

V. SYSTEMATICS

In this section, beyond the issues we have just discussed concerning the oscillatory behavior of the excitation function slopes, we try to obtain information from the trend of the hindrance phenomenon in several medium-light systems.

In Fig. 5 we have placed the adopted threshold energies of $^{12}C + ^{24}Mg$, ^{26}Mg in the phenomenological systematics of Ref. [21]. The ordinate E_s is the adopted hindrance threshold energy for each system which is characterized by the parameter $\zeta = Z_1 Z_2 \mu^{1/2}$, where μ is the reduced mass. All the plotted systems have positive fusion Q values. The case of $^{12}C + ^{30}Si$ is also reported [22]. The phenomenological formula of Ref. [21] is represented by the blue line in the figure.

The ζ parameters of the two systems discussed in this work are near the lighter cases relevant for stellar evolution. The threshold difference between them can clearly be seen, and makes quite uncertain the extrapolation to the lighter systems.

VI. SUMMARY AND OUTLOOK

The fusion of $^{12}C + ^{26}Mg$ has been measured from above to far below the barrier at LNL. The basic motivations were to investigate whether the anomalously high threshold energy of hindrance at $\sigma_{fus} \simeq 0.75$ mb, observed in $^{12}C + ^{24}Mg$, shows up also in this system, and, on the other side, whether fusion cross sections at very low energies are reproduced by simple tunneling through a one-dimensional potential barrier, as observed in the nearby system.

The experiment was performed in inverse kinematics using the ^{26}Mg beam from the XTU Tandem accelerator of LNL. The ER were detected at small angles using a E-ΔE-ToF detector telescope downstream of an electrostatic beam separator. The fusion excitation function was measured down to a few μb.

CC calculations have been performed using a WS potential only slightly modified with respect to the previous case of $^{12}C + ^{24}Mg$. This gives a very good account of the data, however, the CC results start overpredicting the measured cross sections at $\sigma_{fus} \approx 0.03$ mb which is then adopted as the hindrance threshold. This is much lower than what was observed with ^{24}Mg, and this difference is confirmed in the comparison of the two astrophysical S factors.

As a consequence, the cross sections of $^{12}C + ^{26}Mg$ are larger than for $^{12}C + ^{24}Mg$ in the whole sub-barrier energy range (by a factor 4–5 at the lowest energies). The logarithmic derivatives of the two excitation functions are quite similar to each other, both showing an oscillatory structure below the barrier. When comparing their energy trend vs the L_{CS} value, one notices that the peaks in the slope of $^{12}C + ^{24}Mg$ are higher and better structured than the corresponding ones in $^{12}C + ^{26}Mg$. This situation brings a certain degree of uncertainty in the identification of the energy threshold for hindrance in the two systems, even if the phenomenon is clearly present in both cases.

This uncertainty is reflected in the reliability of an extrapolation of the threshold to the lighter systems important for astrophysics, when a systematic of several medium-light systems is examined. A necessary step forward is to correctly explain the (almost identical) oscillations observed in the logarithmic slope of the excitation functions of both $^{12}C + ^{26}Mg$ and $^{12}C + ^{24}Mg$.

Interesting further data might come from the study of $^{12}C + ^{28}Si$, given the α-like structure and the oblate deformation of this silicon isotope. A full comparison with the behavior of $^{12}C + ^{30}Si$ (spherical) [22] would complete the information on low-energy fusion dynamics in this mass region linking fusion of heavier nuclei to lighter systems relevant for astrophysics.

ACKNOWLEDGMENTS

We acknowledge the very professional work of the XTU Tandem staff, and of M. Loriggiola for preparing targets of excellent quality. The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 654002. J.D. acknowledges the support of the Croatian Science Foundation under Project No. IP-2018-01-1257.

[1] B. B. Back, H. Esbensen, C. L. Jiang, and K. E. Rehm, Rev. Mod. Phys. **86**, 317 (2014).

[2] G. Montagnoli and A. M. Stefanini, Eur. Phys. J. A **53**, 169 (2017).

[3] C. L. Jiang, B. B. Back, K. E. Rehm, K. Hagino, G. Montagnoli, and A. M. Stefanini, Eur. Phys. J. A **57**, 235 (2021).

[4] C. L. Jiang, H. Esbensen, K. E. Rehm, B. B. Back, R. V. F. Janssens, J. A. Caggiano, P. Collon, J. Greene, A. M. Heinz, D. J. Henderson, I. Nishinaka, T. O. Pennington, and D. Seweryniak, Phys. Rev. Lett. **89**, 052701 (2002).

[5] C. L. Jiang, K. E. Rehm, R. V. F. Janssens, H. Esbensen, I. Ahmad, B. B. Back, P. Collon, C. N. Davids, J. P. Greene, D. J. Henderson, G. Mukherjee, R. C. Pardo, M. Paul, T. O. Pennington, D. Seweryniak, S. Sinha, and Z. Zhou, Phys. Rev. Lett. **93**, 012701 (2004).

[6] C. Simenel, A. S. Umar, K. Godbey, M. Dasgupta, and D. J. Hinde, Phys. Rev. C **95**, 031601(R) (2017).

[7] G. Montagnoli, A. M. Stefanini, C. L. Jiang, G. Colucci, S. Bottoni, D. Brugnara, P. Colovic, L. Corradi, E. Fioretto, F. Galtarossa, A. Goasduff, O. S. Khwairakpam, M. Heine, G. Jaworski, M. Mazzocco, T. Mijatovic, M. Siciliano, F. Scarlassara, S. Szilner, T. Van Patten *et al.*, Phys. Rev. C **101**, 044608 (2020).

[8] G. Montagnoli, A. M. Stefanini, C. L. Jiang, K. Hagino, F. Niola, D. Brugnara, P. Colovic, G. Colucci, L. Corradi, R. Depalo, E. Fioretto, A. Goasduff, G. Pasqualato, F. Scarlassara, S. Szilner, and I. Zanon, J. Phys. G: Nucl. Part. Phys. **49**, 095101 (2022).

[9] K. Daneshvar, D. G. Kovar, S. J. Krieger, and K. T. R. Davies, Phys. Rev. C **25**, 1342 (1982).

[10] A. M. Stefanini, G. Montagnoli, L. Corradi, S. Courtin, E. Fioretto, A. Goasduff, F. Haas, P. Mason, R. Silvestri, Pushpendra P. Singh, F. Scarlassara, and S. Szilner, Phys. Rev. C **82**, 014614 (2010).

[11] K. Hagino, N. Rowley, and A. T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999).

[12] Ö. Akyüz and Å. Winther, Nuclear structure and heavy-ion physics, in *Proceedings of the International School of Physics "Enrico Fermi", Course LXXVII, Varenna*, edited by R. A. Broglia and R. A. Ricci (North Holland, Amsterdam, 1981).

[13] X. Fang, W. P. Tan, M. Beard, R. J. deBoer, G. Gilardy, H. Jung, Q. Liu, S. Lyons, D. Robertson, K. Setoodehnia, C. Seymour, E. Stech, B. Vande Kolk, M. Wiescher, R. T. deSouza, S. Hudan, V. Singh, X. D. Tang, and E. Uberseder, Phys. Rev. C **96**, 045804 (2017).

[14] W. P. Tan, A. Boeltzig, C. Dulal, R. J. deBoer, B. Frentz, S. Henderson, K. B. Howard, R. Kelmar, J. J. Kolata, J. Long, K. T. Macon, S. Moylan, G. F. Peaslee, M. Renaud, C. Seymour, G. Seymour, B. Vande Kolk, and M. Wiescher, E. F. Aguilera, P. Amador-Valenzuela, D. Lizcano, and E. Martinez-Quiroz, Phys. Rev. Lett. **124**, 192702 (2020).

[15] D. A. Bromley, J. A. Kühner, and E. Almqvist, Phys. Rev. Lett. **4**, 365 (1960).

[16] K. A. Erb, R. R. Betts, S. K. Korotky, M. M. Hindi, P. P. Tung, M. W. Sachs, S. J. Willett, and D. A. Bromley, Phys. Rev. C **22**, 507 (1980).

[17] M. Freer, H. Horiuchi, Y. Kanada-En'yo, D. Lee, and Ulf-G. Meißner, Rev. Mod. Phys. **90**, 035004 (2018).

[18] A. Diaz-Torres and M. Wiescher, Phys. Rev. C **97**, 055802 (2018).

[19] Y. Taniguchi and M. Kimura, Phys. Lett. B **823**, 136790 (2021).

[20] C. L. Jiang, B. B. Back, H. Esbensen, R. V. F. Janssens, K. E. Rehm, and R. J. Charity, Phys. Rev. Lett. **110**, 072701 (2013).

[21] C. L. Jiang, K. E. Rehm, B. B. Back, and R. V. F. Janssens, Phys. Rev. C **79**, 044601 (2009).

[22] G. Montagnoli, A. M. Stefanini, C. L. Jiang, K. Hagino, F. Galtarossa, G. Colucci, S. Bottoni, C. Broggini, A. Caciolli, P. Colovic, L. Corradi, S. Courtin, R. Depalo, E. Fioretto, G. Fruet, A. Gal, A. Goasduff, M. Heine, S. P. Hu, M. Kaur *et al.*, Phys. Rev. C **97**, 024610 (2018).