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Negligible suppression of the complete fusion of ^{6,7}Li on light targets, at energies above the barrier

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Motivated by a recent work performed at Australian National University by S. Kalkal *et al.* [Phys. Rev. C **93**, 044605 (2016)] on breakup and its time scale, where it was shown that the prompt (or near-target) breakup of ^{6,7}Li is almost negligible and consequently the near-barrier complete fusion cross section induced by these weakly bound Li isotopes on light targets should not be suppressed by the breakup, as it is for heavier targets, we estimated the contributions of complete and incomplete fusion in the measured total fusions for several light systems available in the literature. The chosen systems were those for which the fusion cross sections had been measured using the γ-ray spectroscopy method and all evaporation channel cross sections were reported. For the estimation, we used, apart from the data, the predictions of the evaporation code CASCADE. The results show that, indeed, the complete fusion suppression is negligible for such systems at energies slightly above the barrier, in agreement with the above-mentioned recent measurements of breakup time scales.

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I. INTRODUCTION

Reaction mechanisms involving weakly bound nuclei at near-barrier energies have been the subject of intense investigation in recent years. Some comprehensive review papers have been published on this subject [1–6]. In particular, scattering and fusion processes have been extensively investigated, including the effect of the breakup of the weakly bound nuclei on these mechanisms. These nuclei have low energy thresholds for breakup and the breakup may suppress the fusion cross section. Stable weakly bound nuclei, which have qualitatively some similar characteristics to exotic halo nuclei, have attracted considerable interest, since it is possible to obtain beams much more intense with them than with the available radioactive beams. In this way, the data for stable weakly bound nuclei ^{6,7}Li and ^{9}Be are much more precise than those for the exotic radioactive nuclei.

The energy dependence of the optical potential, at near-barrier energies, for these weakly bound nuclei shows a characteristic quite different from the tightly bound ones, known as the breakup threshold anomaly (BTA) [7,8]. For weakly bound systems, for which the breakup cross section remains large even below the Coulomb barrier, the imaginary part of the potential does not decrease as the energy decreases toward the Coulomb barrier energy, as it does for tightly bound nuclei. It may even increase as the bombarding energy decreases. This increase of the imaginary part of the potential is followed by a decrease of its real part, owing to the dispersion relation, which means that the polarization potential is repulsive, as has been demonstrated by Santra *et al.* [9].

The BTA can be more clearly observed for ^{6}Li, than for ^{7}Li, because for the latter, in addition to a relatively larger breakup threshold energy, 2.47 MeV for ^{7}Li and 1.47 MeV for ^{6}Li, there is competition between the repulsive polarization potential associated with breakup and the attractive one arising from couplings with the $1/2^-$ bound inelastic state of ^{7}Li at 0.477 MeV. One finds in the literature contradictory results concerning the presence of BTA for the scattering of ^{7}Li [7,10,11], although not for ^{6}Li with medium and heavy targets, where BTA is always observed. The presence of BTA has a consequence on the fusion cross section of those weakly bound systems, since the predominance of the repulsive breakup polarization potential should lead to the suppression of fusion cross section at energies slightly above the Coulomb barrier, in comparison with what it might happen if there were no breakup. So, one should expect more suppression of fusion of ^{6}Li than of ^{7}Li for similar targets, and more suppression for heavy targets, for which the Coulomb breakup is stronger, than for light targets.

Of course, the imaginary potential must decrease and vanish at low enough energies. So, what actually happens is that the Coulomb barrier is no longer the proper threshold energy for such reactions. This threshold is below the barrier. It is very difficult to find experimentally where the imaginary potential vanishes, since at subbarrier energies the scattering is almost a fully Rutherford type. However, in a few works it was possible to extrapolate the imaginary potential and find that it vanishes at energies around 85% of the height of the Coulomb barrier [12]. Nevertheless, one should not expect that the fusion cross section suppression might be extended to subbarrier energies.

From several papers reported in the last few years, it is already well accepted that the complete fusion (CF) of weakly bound nuclei is suppressed at energies above the barrier, in comparison with calculations using reliable potentials and coupled-channel calculations that do not take into account the breakup and transfer channels. There are several experiments and papers showing this effect for the fusion of ^{6,7}Li and ^{9}Be. When one adds the incomplete fusion (ICF) cross sections, corresponding to the fusion of some fragments of the projectile (and maybe also direct transfer reaction cross sections), the

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so-called total fusion (TF) induced by ^{6,7}Li and ^{9}Be seems to be not suppressed for any target, from very light ones, like ^{12}C, to very heavy ones [13–15].

Some recent works tried to reach a systematic behavior for this suppression, and essentially they showed that the CF suppression is roughly independent of the target for a given projectile [16–21]. Maybe the best examples are the papers by Wang *et al.* [22,23], where it is shown that the suppression depends only on the projectile breakup threshold. The CF suppression is then attributed to the breakup, although it is more correct to say breakup plus transfer channels.

There are some works [24,25] showing that the breakup cross section of ^{6,7}Li increases with the target mass or charge. So it seems that there is an apparent contradiction: the breakup cross section for a given projectile increases with the target mass (charge) but its effect on CF is independent of the target.

Two facts are very important: (i) There are no CF measurements for light targets. For ^{96}Zr, one of the lightest targets measured with the ^{6}Li projectile [26], the CF suppression found was 25%, smaller than the 40% suppression found for heavier targets. This might be just one system out of the systematics or an indication that the CF suppression might be smaller for lighter targets. (ii) Recent very careful works on the measurement of breakup at Australian National University (ANU)-Canberra were able to obtain information concerning the time scale of the breakup for ^{6,7}Li and ^{9}Be. They found that there is a lot of breakup following transfer [27–30] that occurs when the projectile is already leaving the target region. These events are called delayed or asymptotic breakup and can not affect the fusion process. Also, when long lived resonances of the weakly bound projectiles are fed, the time scale is such that the process is a delayed or asymptotic breakup. So, only prompt (or near-target) breakup may affect fusion.

In a very recent paper by the same ANU group [31], it was clearly shown that for light targets such as ^{58}Ni and ^{64}Zn, the direct breakup of ^{6}Li was almost purely of the delayed or asymptotic type (93%), and roughly no direct prompt (or near-target) breakup was detected for ^{7}Li. So, there should be no suppression, or almost no suppression, of CF of lithium isotopes with light targets. On the other hand, for heavy targets there is a considerable percentage of prompt or near-target breakup for both lithium isotopes (74% and 93%), which may affect and suppress fusion. It is important to have in mind that calculations of breakup or previously measured breakup cross sections do not take into account the time scales; that is, what was measured or calculated is the sum of prompt (near-target) and delayed (asymptotic) breakups.

Therefore, the situation is such that it is very important to measure CF cross sections for weakly bound projectiles on light targets. However, this is a very difficult experimental task, since the evaporation of light compound nuclei has the contribution of evaporation of charged particles, in contrast with heavy compound nuclei that evaporate essentially neutrons. A consequence of this characteristic of the evaporation of light compound nuclei is that the residues of the CF and the ICF of the light weakly bound projectiles may coincide, and so it is not possible to disentangle CF and ICF. Owing to this reason, only TF induced by ^{6,7}Li and ^{9}Be are reported for several light systems. Usually, the experimental TF excitation functions for light targets agree with theoretical calculations [15], similar to what happens for heavy targets.

A possible way to overcome this experimental difficulty may occur when the fusion measurements are performed with the γ-ray spectroscopy method. Then, the cross sections of individual evaporation channels may be obtained and the TF cross section is obtained by adding the cross sections of all evaporation channels. Then, with the aid of evaporation codes, one might be able to identify the evaporation channels which have measured cross sections higher than the predicted ones and one may consider that those data are contaminated (have contributions) from ICF. It is interesting to mention that for measurements with heavy targets, when CF can be clearly separated from ICF, the agreement between data and predictions of evaporation codes is usually very good (see, for example, Refs. [32,33]). Then by running the statistical code for ICF of each fragment (α and deuteron for ^{6}Li projectile and α and tritium for ^{7}Li), one might verify whether the corresponding ICF evaporation channels producing the same nuclei as the CF "contaminated" channels are predicted to be important. If this happens, one might estimate the contribution of ICF on the measured TF, and consequently an approximate estimation of the CF cross section and then a comparison between the estimated CF and theoretical predictions could be made. Actually, this procedure was adopted in the measurement of fusion of ^{6,7}Li + ^{64}Ni [34,35], when a small suppression of 13% for ^{6}Li induced fusion [34] and 6.5% for ^{7}Li induced fusion [35] and for ^{9}Be + ^{64}Zn [36], when no more than 5% of the TF could be attributed to ICF.

This paper is presented as the following. In Sec. II we describe the aim of the present work and the adopted methodology. In Sec. III we present the results. In Sec. IV we draw some conclusions.

II. AIM OF THIS WORK AND ADOPTED METHODOLOGY

To contribute to the investigation of the effect of breakup on the CF of light systems induced by ^{6,7}Li, we identified, within several works available in the literature, those using the γ-ray method to derive TF cross sections and reporting the cross sections of all evaporation channels. We found seven suitable systems: ^{6,7}Li + ^{12}C, ^{13}C, ^{16}O [37–39] and ^{7}Li + ^{24}Mg [40]. All those papers also reported the comparison of each evaporation channel with the predictions of the statistical code CASCADE [41]. However, the authors only used the CASCADE code to analyze the contributions of different evaporation channels to the TF cross section, they did not disentangle the contribution of the ICF channels. Moreover, all the conclusions were only related to TF data, but not to CF cross sections. We used those results in our present work. The CASCADE code was employed to separate the ICF from the TF, and consequently to estimate CF cross sections. By comparing the CF data with coupled-channel (CC) calculations, which do not take into account the breakup channel, the suppression of CF cross sections above the barrier can be explored [14]. In this paper, we only focus on the CF suppression on light targets. We emphasize that the suppression can be explored from the CF data only, but not from TF data. It is well known that the TF is not affected by the breakup reaction, even for reactions with heavy targets [5,14]. In the present work we derive a conclusion stronger than the ones given in the original papers (Refs. [37–39]) where the main conclusions were devoted to the study of the effect of the breakup channel on TF cross sections and the comparison with the works that claimed that the TF was hindered due to breakup for the light systems [42–45].

To verify whether the evaporation channels with cross sections larger than the predicted ones might correspond to ICF of any of the two fragments, we ran the evaporation code CASCADE for the ICF for each system. By considering the sharing of energy between the fragments, we adopted the corresponding energy $(E_{\rm lab} - E_{\rm th})m_f/m_p$, as the energy of the fragments, where $E_{\rm lab}$ is the incident energy of the projectile, $E_{\rm th}$ is the threshold breakup energy of the projectile, m_f is the mass of the fusing fragment, and m_p is the mass of the projectile.

The next step is the discussion of the estimation of the CF cross sections of the eight investigated systems. For all of them we perform the same procedure: From the published data and their comparison with the CASCADE predictions we identify possible residual nuclei formed by both CF and ICF. Then, using the CASCADE predictions for the ICF, we verify whether some of them might have contributions from ICF. When this happens, we estimate the ICF contribution by the difference between the experimental cross section and the theoretical prediction for CF. Then, we estimate the CF and ICF cross sections.

After that, we compare the estimated CF cross section (TF − ICF) with theoretical predictions obtained by CC calculations. Depending on the suppression factor of CF data, we can explore if the CF suppression exists for ^{6}Li on light target nuclei. In the theoretical calculations we take the Sao Paulo potential [46,47] as the bare potential. For the energy range investigated, this is a double-folding potential using a systematic of realistic densities [48,49], which has been widely and successfully used in the last years. In the coupling scheme we consider the first 2^+ inelastic excitations of the targets ^{12}C and ^{24}Mg, the first $3/2^-$ state for ^{13}C, the 3^- state for ^{16}O, and the bound excited $1/2^-$state of ^{7}Li. Although inelastic coupling effects are not expected to influence significantly fusion above the Coulomb barrier, we performed the CC calculations. All CC calculations were performed using the code FRESCO [50]. The quadrupole deformation parameters β_2 were obtained from the systematics of Raman *et al.* [51] and the octupole β_3 from the systematics of Kibedi *et al.* [52].

We plot the results for each channel in linear scale to better observe possible effects of the breakup plus transfer (that are left out of the coupling scheme) at energies above the barrier, since this is the aim of the present work.

III. RESULTS AND DISCUSSION

For ^{6}Li +^{12}C and ^{6}Li + ^{13}C systems, the cross sections of all evaporation channels and the predictions from the CASCADE code were obtained in Ref. [38]. Figures 7 and 8 of that paper show that there is no residual nucleus formed with cross sections larger than those predicted by the CASCADE code. For the ^{6}Li + ^{12}C system, the main residual nuclei (channels)

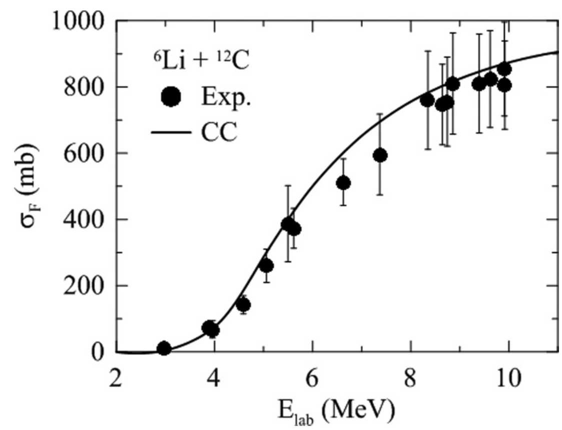

FIG. 1. Estimated complete fusion excitation function for the ^{6}Li + ^{12}C system and theoretical CC calculations. For this system, the measured total fusion was considered as equivalent to the complete fusion.

predicted for the ICF of the α fragment are ^{15}N(1p) and ^{15}O(1n) and for the deuteron fragment they are ^{12}C(2p) and some ^{13}C(1p) and ^{13}N(1n). Among all those nuclei, only ^{13}C was detected or used to derive the TF cross section, but its cross section agrees with the predictions of CASCADE for CF. For ^{6}Li + ^{13}C system, the main residual nucleus (channel) predicted for the ICF of the α fragment is ^{16}O(1n) and for the deuteron fragment the main one is ^{13}C(pn) with some ^{14}N(1n) and ^{14}C(1p). Among all those nuclei, ^{16}O, ^{14}N, and ^{14}C were detected or used to derive the TF cross section, but their cross sections agree with the predictions of CASCADE for CF. So we consider that there is no ICF for these two systems. Figures 1 and 2 show the comparison of the estimated CF excitation function with theoretical CC calculations for ^{6}Li + ^{12}C and ^{6}Li + ^{13}C systems, respectively. One can observe that the data for the TF or CF excitation function agree with the results of the CC calculations and therefore, from the present analysis, we say that there is no suppression of CF for these two systems.

For the ^{7}Li + ^{12}C and ^{7}Li + ^{13}C systems, the cross sections of all evaporation channels and the predictions from the CASCADE code were obtained in Ref. [37].

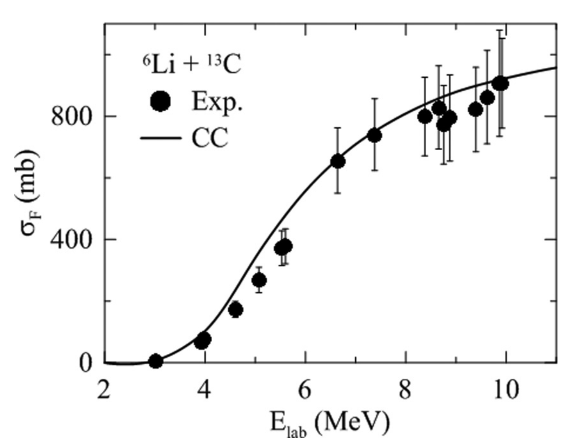

FIG. 2. Same as Fig. 1, but for the ^{6}Li + ^{13}C system, for which the measured total fusion was also considered as equivalent to the complete fusion.

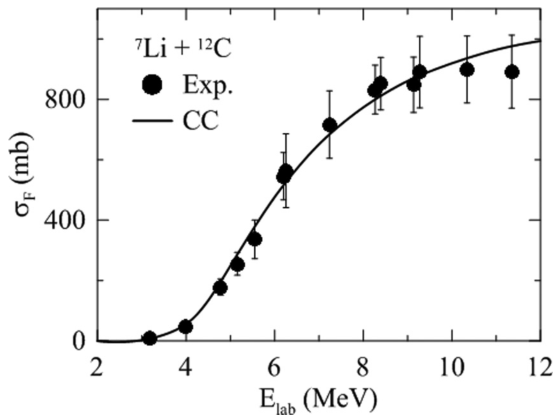

FIG. 3. Estimated complete fusion excitation function for the ^{7}Li + ^{12}C system and theoretical CC calculations. For this system, the measured total fusion was considered as equivalent to the complete fusion.

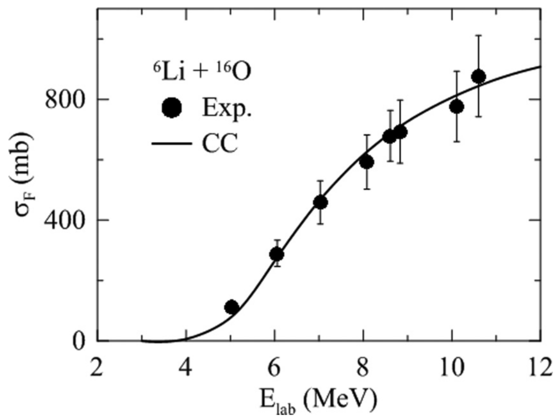

FIG. 5. Estimated complete fusion excitation function for the ^{6}Li + ^{16}O system and theoretical CC calculations. For this system, the measured total fusion was considered as equivalent to the complete fusion.

Figures 7 and 8 of that paper show that the only residual nucleus formed with cross sections larger than those predicted by the CASCADE code is ^{17}O for ^{7}Li + ^{12}C, and the only residual nuclei are ^{17}O and ^{12}B for ^{7}Li + ^{13}C system, which cannot be formed by ICF. For ^{7}Li + ^{12}C, the main residual nuclei (channels) predicted for the ICF of the α fragment are ^{15}N($1p$) and ^{15}O($1n$) and for the tritium fragment they are ^{14}N($1n$) and ^{14}C($1p$). For ^{7}Li + ^{13}C, the main residual nucleus (channel) predicted for the ICF of the α fragment is ^{16}O ($1n$) and for the tritium fragment they are ^{15}N($1n$) and ^{14}C(pn). Among all those nuclei, only ^{15}O and ^{14}N were detected for ^{7}Li + ^{12}C and only ^{15}N was detected for ^{7}Li + ^{13}C, or used to derive the TF cross sections of these two systems, but their cross sections agree with the predictions of CASCADE for CF. So, we consider that there is no ICF for these two systems. Figures 3 and 4 show the comparison of the estimated CF excitation function with theoretical CC calculations for these two systems, respectively. One can observe that the data for the TF or CF excitation function agree with the results of the CC calculations and therefore, from the present analysis, we say that there is no suppression of CF for these two systems. For ^{7}Li + ^{12}C system, the total fusion was also measured by particle detection [13], and the cross section obtained was coincident with the one obtained by the γ-ray method.

For ^{6}Li + ^{16}O and ^{7}Li + ^{16}O systems, the cross sections of all evaporation channels and the predictions from the CASCADE code were obtained in Ref. [39]. Figure 5 of that paper shows that the only residual nucleus formed with cross sections larger than the predicted by the CASCADE code is ^{21}Na, which cannot be formed by ICF. Figure 6 of that paper shows that the only residual nuclei formed with cross sections larger than the predicted by the CASCADE code are ^{18}O and ^{19}F. For ^{6}Li + ^{16}O system, the main residual nuclei (channels) predicted for the ICF of the α fragment are ^{16}O(α) and some ^{19}F($1p$), and for the deuteron fragment it is ^{16}O(pn). None of these nuclei were detected or used to derive the TF cross section. So we consider that there is no ICF for this system. Figure 5 shows the comparison of the estimated CF excitation function with theoretical CC calculations. One can observe that the data for the TF or CF excitation function agree with the results of the CC calculations and therefore, from the present analysis, we say that there is no suppression of CF for this system.

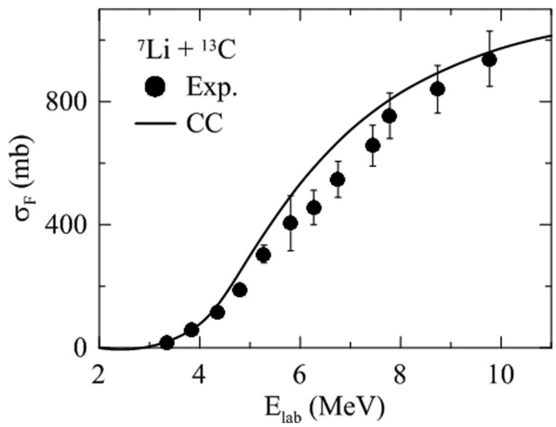

FIG. 4. Same as Fig. 3, but for the ^{7}Li + ^{13}C system, for which the measured total fusion was also considered as equivalent to the complete fusion.

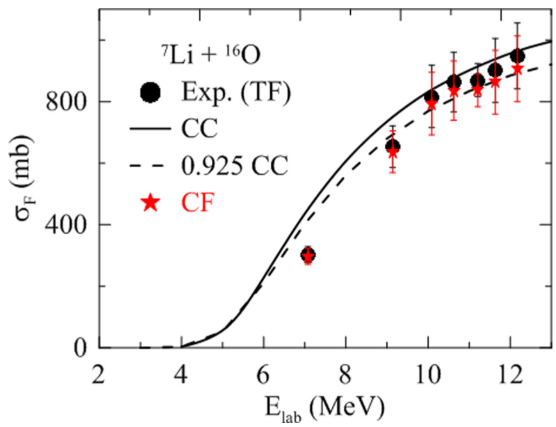

FIG. 6. Measured total fusion and estimated complete fusion excitation functions for the ^{7}Li + ^{16}O system and theoretical CC calculations.

For $^{7}Li + ^{16}O$ system, the main residual nucleus (channel) predicted for the ICF of the α fragment is $^{16}O(\alpha)$ and for the tritium fragment they are $^{18}O(1p)$ and $^{18}F(1n)$. Among those nuclei, ^{18}O and ^{18}F were detected or used to derive the TF cross section. The ^{18}F cross section agrees with the predictions of CASCADE for CF. However, the measured ^{18}O cross section is larger than that predicted by CASCADE, what means that these data may have contributions from CF and ICF. Then we computed the difference between the experimental and theoretical cross sections, predicted by the CASCADE code, for these nuclei. Figure 6 shows the TF experimental data (full circles), the estimated CF data (full stars), and the coupled-channel results (solid line). The dashed line corresponds to the multiplication of the results of CC calculation by 0.925 (0.9 CC in the legend), that is the value needed to fit the experimental value of the CF. So, the average value of the estimation of the possible ICF was found to be 7.5% of the TF cross section, which might correspond to the estimation of the upper limit of the CF suppression, since, as shown in Fig. 6, the TF cross section data agree with the CC calculations. However, from Fig. 6 one can notice that the error bars of the measured TF cross sections are larger than 10%. So, we consider that the estimated suppression of the CF cross section for this system, also shown in Fig. 6 by dashed curve and full stars, is within the range of 0–7.5%.

For the $^{7}Li + ^{24}Mg$ system, the cross sections of all evaporation channels and the predictions from the CASCADE code were obtained in Ref. [40]. Figure 6 of that paper shows that the only residual nucleus formed with cross sections larger than those predicted by the CASCADE code is ^{26}Al. The main residual nuclei (channels) predicted for the ICF of the α fragment are $^{27}Al(1p)$ and $^{27}Si(1n)$, and for the tritium fragment they are $^{26}Mg(1p)$, $^{25}Mg(pn)$, and $^{26}Al(1n)$. Among those nuclei, ^{26}Mg, ^{25}Mg, and ^{26}Al were detected, or used to derive the TF cross section, but only ^{26}Al has cross sections larger than those predicted by CASCADE, what means that these data may have contributions from CF and ICF. Then we computed the difference between the experimental and theoretical cross sections predicted by the CASCADE code for these nuclei. Figure 7 shows the TF experimental data (full circles), the estimated CF data (full stars) and the coupled-channel results (solid line). The factor of 0.9 on the CC results leads to the fit of the CF data (represented by the dashed curve in Fig. 7). The average value of the estimation of the possible ICF was found to be in the range of 15–18% of the TF cross section, which might correspond to the estimation of the upper limit of the CF suppression, since, as shown in Fig. 7, the TF cross section data agree with the CC calculations. However, from Fig. 7 one can notice that the error bars of the measured TF cross sections are of the same order as the 15–18%. So, we consider that the estimated suppression of the CF cross section for this system, also shown in Fig. 7 by dashed curve and full stars, is within the range of around 5–20%.

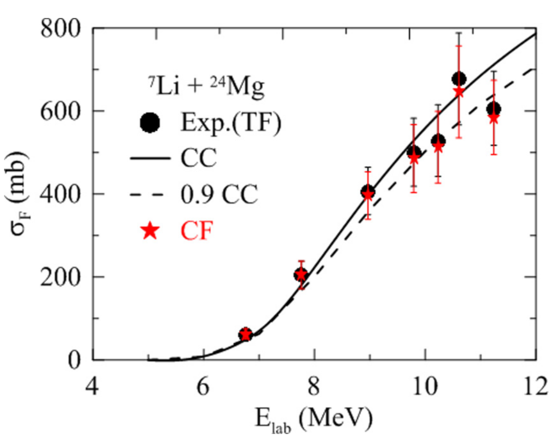

FIG. 7. Same as Fig. 6, but for the $^{7}Li + ^{24}Mg$ system.

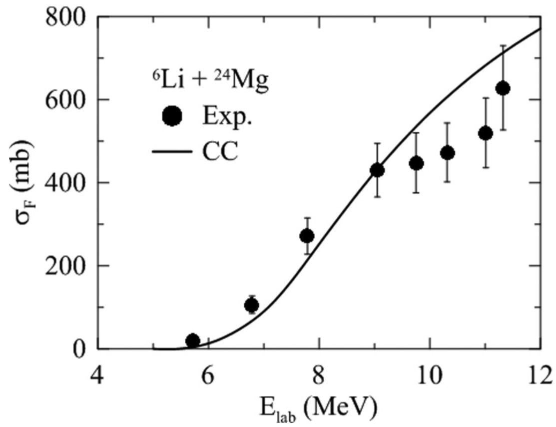

FIG. 8. Same as Fig. 6, but for the $^{6}Li + ^{24}Mg$ system.

We note that in Ref. [40] for the $^{6}Li + ^{24}Mg$ system, the measured TF cross section has also been reported, in addition to the $^{7}Li + ^{24}Mg$ system investigated in the previous work. We did not consider this system in our present analysis because in our region of interest, energies not too much above the Coulomb barrier energy, contrary to what happens with all other seven systems already investigated by us, the measured TF excitation function does not agree with the CC calculations. This can be observed in Fig. 8 and even in the original paper [40], where the excitation function is plotted in logarithmic scale in a much wider energy range. Therefore, we considered that those data were not suitable for the present investigation of the suppression of the estimated CF at near-barrier energies.

IV. SUMMARY AND CONCLUSIONS

We have estimated the values of complete fusion induced by $^{6,7}Li$ of several light weakly bound systems, at energies slightly above the Coulomb barrier energy, from published total fusion cross section data and from predictions of the statistical evaporation code CASCADE. The direct measurements of complete fusion cross sections for such kind of systems have not yet been reported because some of the evaporation residues of CF and ICF are coincident. The systems chosen by us for the present investigations were those for which the cross sections of individual evaporation channels were reported.

Our aim was to investigate whether the value of the suppression of CF in this energy range, found in systematic studies for heavier systems to be independent of the target, stems the same for light targets. Our main motivation was to verify whether the results of a very recent paper by Kalkal *et al.* [31] on breakup and its time scale, predicting a very small CF suppression for light targets, were compatible with such kind of estimation. In Ref. [31] it was shown that the prompt (or near-target) breakup of ^{6,7}Li in the field of light targets is almost negligible, and consequently the breakup process should have no significant role of the CF of such systems.

Our results show that, indeed, the CF suppression is negligible for such systems at this energy regime for the very light targets ^{12,13}C and ^{16}O. For the relatively heavier target, ^{24}Mg, a CF suppression much smaller than the ones found for heavier targets was found. Our results are in agreement with the ones predicted in Ref. [31].

It is important to finish this paper by saying that the estimation that we have done is powerful enough to reach the above-mentioned conclusions but not to give a quantitative value of the CF suppression, owing to the limitations and uncertainties of the method used. We do believe that the present results bring an important contribution to this field, since until very recently it was widely accepted that the CF induced by ^{6,7}Li and ^{9}Be stable weakly bound nuclei was suppressed, owing to the breakup process, by a percentage dependent on the breakup threshold energy of the projectiles, but not on the characteristics of the target nuclei.

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