Breakup effects in fusion reactions of stable weakly bound nuclei and light targets

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(Received 26 December 2008; published 25 February 2009)

We use a new method to search systematic trends in total fusion reactions of weakly bound nuclei at near-barrier energies. In a recent work, this method was employed to investigate these reactions in the case of heavy targets. Here, we extend this study to the light targets. Comparing fusion data with a dimensionless fusion excitation function, used as a benchmark, one can identify enhancement or suppression effects in fusion data. Through a proper renormalization of the data, it is possible to disentangle static and dynamic effects arising from the low dissociation energy of the projectile. Applying this method to the available data in the literature, we conclude that there is no appreciable suppression of enhancement in the total fusion data of light weakly bound systems. We point out that some unexpected deviations from this benchmark may possibly indicate problems with the data.

DOI: 10.1103/PhysRevC.79.027606 PACS number(s): 25.60.Pj, 24.10.−i

In recent years, great efforts have been made to investigate the effects of the breakup channel in collisions of weakly bound projectiles [1]. The low binding energy of the projectile affects nuclear reactions in two ways. First, there are the static effects associated with the larger diffusivity of the projectile's density, which leads to a lower potential barrier. Second, there are the channel coupling effects associated with breakup couplings. These effects are particularly important in fusion reactions, because in such cases different fusion processes can take place. The first one is direct complete fusion (DCF), in which fusion occurs without previous excitation of the breakup channel. This is analogous to the case of strongly bound collision partners. However, there may be other fusion processes following breakup. One possibility is that the projectile's fragments produced in the breakup process are only partially absorbed by the target. This reaction mechanism is called incomplete fusion (ICF). There is also the sequential complete fusion (SCF), in which all breakup fragments are absorbed sequentially by the target. From the experimental point of view, DCF and SCF cannot be distinguished. Only the sum of the two, called CF, is measured. Furthermore, most experiments only determine the total fusion cross section (TF), which corresponds to the sum of CF and ICF. However, separate measurements of CF have been achieved in some collisions of light weakly bound projectiles on medium-mass and heavy targets [2–4], because the compound nucleus does not decay through the emission of charged particles. The situation is different in the case of light targets, where the compound nucleus emits also charged particles. In this way, the residues from CF and ICF cannot be distinguished and only the TF cross section can be measured. Several measurements of TF cross sections in collisions of weakly bound projectiles with heavy targets have been performed [5–12]. The fact that these experiments determine TF cross sections rather than CF cross sections is of fundamental importance when one investigates the systematic trends of the data.

When one concludes that the fusion cross section for a particular system is enhanced (hindered), it means that it is larger (smaller) than some standard cross section, to which it has been compared. Therefore, this procedure requires the introduction of some benchmark cross section or excitation function and this is not a trivial task. Different authors have followed different procedures. In some cases, the fusion cross sections are compared to theoretical predictions of optical model or coupled-channel calculations. In other cases one compares the data for the weakly bound projectile with data for a strongly bound isotope in collisions with the same target. A detailed discussion of these procedures can be found in Ref. [13]. Here, we adopt the method we developed in Refs. [13] and [14]. We present below a short summary of this method.

The starting point is the choice of a systematic bare interaction potential. We adopt the double-folding parameter-free São Paulo potential (SPP) [15,16], using reliable nuclear densities of the nuclei involved in the collisions [17,18]. This potential has described successfully several reactions with systems in different mass ranges, including weakly bound nuclei [19,20]. To compare data for several systems in a single plot, it is necessary to eliminate the differences associated with trivial factors, like sizes and charges. This can be achieved through the introduction of the dimensionless energy variable, x, and the fusion function, $F(x)$, defined as [13,14]

$$E \to x = \frac{E - V_B}{\hbar\omega}; \quad \sigma_F \to F(x) = \frac{2E}{\hbar\omega R_B^2}\sigma_F. \qquad (1)$$

Above, V_B, R_B, and $\hbar\omega$ are, respectively, the barrier height, the radius, and the curvature, appearing in the parabolic approximation of the fusion barrier. The above reduction method has a simple meaning. For systems where channel coupling effects can be neglected and the fusion cross section is well approximated by Wong's formula [21], Eq. (1) leads to the Universal Fusion Function (UFF) [14]

$$F_0(x) = \ln[1 + \exp(2\pi x)]. \qquad (2)$$

Our method consists of using the UFF as the benchmark for comparisons with fusion data. First, one evaluates the barrier parameters for the particular system under study using the SPP potential. The experimental fusion function $F_{\exp}(x)$ is then determined from the experimental fusion cross section through Eq. (1). $F_{\exp}(x)$ is then compared with $F_0(x)$.

However, the above-described procedure has two shortcomings. The first is that Wong's approximation is not valid for light systems at subbarrier energies. The second is that a comparison of $F_{\exp}(x)$ with the UFF indicates the global effect of channel coupling on the fusion cross section. In this way, breakup couplings are entangled with couplings with other bound channels. To single out the effects of breakup coupling and eliminate deviations arising from the inaccuracy of Wong's formula at subbarrier energies, it is necessary to renormalize the experimental fusion function as [14]

$$F_{\exp}(x) \to \bar{F}_{\exp}(x) = F_{\exp}(x)\frac{F_0(x)}{F_{\rm CC}(x)}, \tag{3}$$

where $F_{\rm CC}(x)$ is the fusion function of Eq. (1) with σ_F obtained from a coupled-channel calculation including couplings to all relevant bound channels.

In Refs. [13] and [14] we have applied our method in collisions of the weakly bound projectiles ^{6,7}Li, ^{9}Be, and ^{6}He with the heavy nuclei of ^{208}Pb, ^{209}Bi, and ^{238}U. The results are summarized below. At above-barrier energies, we found a systematic suppression of CF cross sections of about 30%. Below the barrier, the CF cross section was shown to be slightly enhanced. On the other hand, the analysis of TF cross sections for stable weakly bound nuclei showed no appreciable deviations from the UFF at above-barrier energies, whereas a significant enhancement was found at subbarrier energies. The suppression of the CF cross section above the barrier was then attributed to the ICF process.

Effects of breakup coupling on fusion cross sections in collisions of lighter systems have been performed employing standard methods. Gomes *et al.* [4] found that the experimental CF cross section for the ^{9}Be + ^{144}Sm system was slightly suppressed, as compared to results of CC calculations. In their calculations, they used the SP potential as the bare interaction and included couplings to all relevant bound channels. The suppression factor was about 10%. They also investigated the effects of the breakup channel on the TF cross section. They found that these effects were negligible. This suggests that the suppression of CF arises from the ICF process, which for the ^{9}Be + ^{144}Sm system is weaker than in the cases of heavier targets, studied in Refs. [13] and [14].

TABLE I. Barrier parameters for the systems considered in the present work and channels included in our CC calculations.

System	R_B (fm)	V_B (MeV)	$\hbar\omega$ (MeV)	Channels
^{6}Li + ^{12}C	7.9	3.0	2.2	2_1^+(T)
^{7}Li + ^{12}C	7.7	4.1	2.5	2_1^+(T); $\frac{1}{2}^-$(P)
^{6}Li + ^{13}C	7.9	3.0	2.3	2_1^+(T)
^{7}Li + ^{13}C	8.1	3.0	2.1	2_1^+(T); $\frac{1}{2}^-$(P)
^{6}Li + ^{27}Al	8.3	6.2	2.8	2_1^+(T)
^{7}Li + ^{27}Al	8.5	6.1	2.6	2_1^+(T); $\frac{1}{2}^-$(P)
^{7}Be + ^{27}Al	8.2	8.4	3.1	2_1^+(T)
^{9}Be + ^{27}Al	8.5	8.1	2.8	2_1^+(T)
^{7}Li + ^{28}Si	8.5	6.6	2.7	2_1^+(T); $\frac{1}{2}^-$(P)
^{6}Li + ^{59}Co	9.0	12.8	3.7	2_1^+(T)
^{7}Li + ^{59}Co	9.2	12.6	3.4	2_1^+(T); $\frac{1}{2}^-$(P)
^{6}Li + ^{64}Zn	9.2	13.1	3.7	2_1^+(T)
^{7}Li + ^{64}Zn	9.4	12.8	3.4	2_1^+(T); $\frac{1}{2}^-$(P)
^{9}Be + ^{64}Zn	9.4	17.0	3.5	2_1^+(T)

In this article we extend the study of Refs. [13] and [14] to lighter systems. We consider collisions of ^{6,7}Li and ^{9}Be with light- and medium-mass targets. In these cases, there are only TF experimental data available in the literature and the data are usually taken at above-barrier energies. The only exceptions are for the ^{7}Li + ^{12}C and ^{6,7}Li + ^{59}Co, for which there are a few data points just below the barrier. The barrier parameters of the bare potential (the SP potential) and the channels included in CC calculations for the systems investigated in the present work are listed in Table I. The notations (P) and (T) in the last column indicate channels corresponding to excitations of the projectile and target, respectively. In all cases of odd-even target nuclei the multiplet of identified excited levels was approximated by a single level 2_1^+. The deformation parameters were taken from Ref. [22].

Figure 1 shows experimental TF cross sections for very light systems, in comparison to the UFF. The data are for collisions of ^{6,7}Li projectiles with ^{12,13}C [5]. Figure 2 is similar to Fig. 1, except that the data are for the slightly heavier systems [7,8,23, 24]. It shows TF cross sections for several light stable weakly bound projectiles in collisions with ^{27}Al and ^{28}Si targets. The

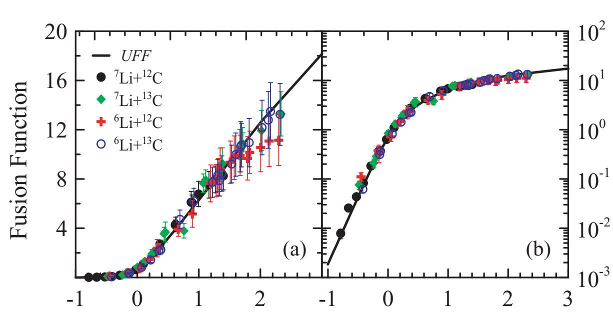

FIG. 1. (Color online) Experimental TF cross section for the ^{6,7}Li + ^{12,13}C systems. The solid line represents the UFF. For details, see the text.

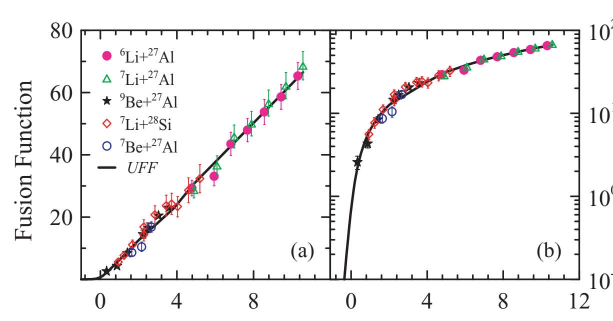

FIG. 2. (Color online) Same as Fig. 1, but here the data are for slightly heavier systems. For details, see the text.

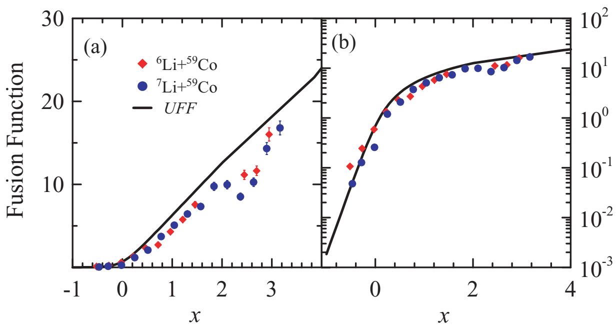

FIG. 3. (Color online) Experimental TF cross section in collisions of light weakly bound projectiles with medium-mass targets. The solid line represents the UFF. For details, see the text.

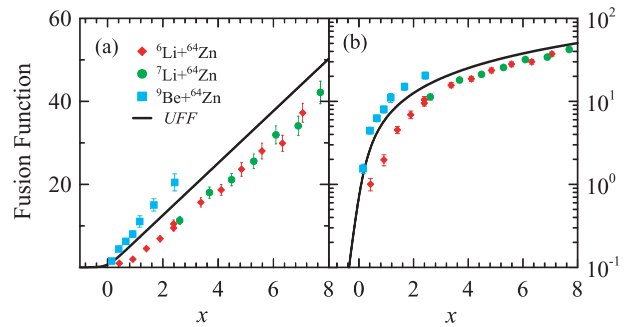

FIG. 4. (Color online) Experimental TF cross section for other medium-mass systems. For details, see the text.

agreement between the data and the universal curve is very impressive, for all systems in Figs. 1 and 2. The only exceptions are the data points for ^{6}Li + ^{12}C at energies well above the barrier, which fall below the UFF. We conclude that there is neither enhancement nor hindrance of the experimental TF cross section, as compared with the UFF. This indicates that the effects of breakup coupling on the TF cross section in this mass range are negligible. In the case of the systems in Fig. 2 this conclusion only applies for above-barrier energies, because there are no subbarrier data available. However, for the light systems of Fig. 1, this conclusion is also valid at subbarrier energies. This is not surprising. The Coulomb field for very light systems is not strong enough to produce appreciable breakup along the trajectory.

We now consider TF data in collisions of ^{6,7}Li and of ^{9}Be projectiles with medium-mass targets. Figure 3 shows TF data for the ^{6,7}Li + ^{59}Co systems [12], in comparison to the UFF. The data points are mainly at above-barrier energies. Figure 3(b) shows that at $x \simeq -0.2$, which is just below the barrier, the experimental cross section for ^{7}Li is very close to the UFF while that for ^{6}Li is slightly larger. Inspecting the linear plot [Fig. 3(a)], one notices that the data for both projectiles are slightly suppressed as compared with the UFF. This result is not expected. Even in the case of very heavy targets, where Coulomb field in much stronger, Coulomb breakup does not lead to suppression [13,14]. We believe that this system should be the object of further investigations.

Other medium-mass systems are studied in Fig. 4. It shows experimental results for collisions of ^{6,7}Li and ^{9}Be projectiles with a ^{64}Zn target [7,9–11]. One observes that the TF data for the Li isotopes are hindered with respect to the UFF, while those for ^{9}Be are enhanced. In both cases no relevant effect of breakup coupling was expected, because the Coulomb field is not very strong. We believe that these deviations of the experimental fusion functions with respect to the UFF do not arise from breakup coupling. They probably result from problems with the data analysis. In the case of ^{6,7}Li data [7], there may have been a problem with the efficiency of the time-of-flight setup. This problem was probably responsible for the deviations of the data with respect to the UFF. Presently, this point is being investigated. The discrepancies between the ^{9}Be data and the UFF are also likely to arise from problems with data analysis. One should point out that at some energies above the barrier the TF cross section of Ref. [9] was larger than the total reaction cross section, although they were similar within the error bars. This suggests that there may have been problems with the normalization of the data.

We conclude that couplings with the breakup channel do not affect total fusion in collisions of light weakly bound projectiles with light targets at above-barrier energies. On the other hand, the situation for collisions of the same projectiles with medium-mass targets is unclear. In these cases, we found deviations between experimental fusion functions and the universal fusion function. These deviations did not show any systematic trend and in some cases they could be traced back to problems with the analysis of the experimental data. This suggests that our method can be a useful tool to detect problems in experiments or in the coupled-channel calculations used to renormalize the experimental fusion function. Further investigations are under way. At subbarrier energies there is not enough experimental information available for a reliable study. There are only two points in the literature, one for each system. In both cases, the energies are just below the barrier. More data at subbarrier energies is needed.

This work was supported in part by the CNPq, the FAPERJ, and the FAPERJ/CNPq through the PRONEX program.

[1] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein. Phys. Rep. **424**, 1 (2006).
[2] M. Dasgupta *et al.*, Phys. Rev. Lett. **82**, 1395 (1999); Phys. Rev. C **66**, 041602(R) (2002); **70**, 024606 (2004).
[3] C. Signorini *et al.*, Eur. Phys. J. A **5**, 7 (1999).
[4] P. R. S. Gomes *et al.*, Phys. Lett. **B634**, 356 (2006); Phys. Rev. C **73**, 064606 (2006).
[5] A. Mukherjee *et al.*, Nucl. Phys. **A596**, 299 (1996); **A635**, 305 (1998); **A645**, 13 (1999); Phys. Lett. **B526**, 295 (2002).
[6] R. M. Anjos *et al.*, Phys. Lett. **B534**, 45 (2002).
[7] I. Padrón *et al.*, Phys. Rev. C **66**, 044608 (2002).
[8] G. V. Martí *et al.*, Phys. Rev. C **71**, 027602 (2005).
[9] S. B. Moraes *et al.*, Phys. Rev. C **61**, 064608 (2000).
[10] P. R. S. Gomes *et al.*, J. Phys. G: Nucl. Part. Phys. **31**, S1669 (2005).
[11] P. R. S. Gomes *et al.*, Phys. Lett. **B601**, 20 (2004).
[12] C. Beck *et al.*, Phys. Rev. C **67**, 054602 (2003).

[13] L. F. Canto *et al.*, Nucl. Phys. A (2009) (submitted for publication).
[14] L. F. Canto *et al.*, J. Phys. G: Nucl. Part. Phys. **36**, 015109 (2009).
[15] L. C. Chamon, D. Pereira, M. S. Hussein, M. A. Candido Ribeiro, and D. Galetti, Phys. Rev. Lett. **79**, 5218 (1997).
[16] L. C. Chamon *et al.*, Phys. Rev. C **66**, 014610 (2002).
[17] C. P. Silva *et al.*, Nucl. Phys. **A679**, 287 (2001).
[18] M. A. G. Alvarez *et al.*, Nucl. Phys. **A723**, 93 (2003).
[19] E. Crema, L. C. Chamon, and P. R. S. Gomes, Phys. Rev. C **72**, 034610 (2005).
[20] E. Crema, P. R. S. Gomes, and L. C. Chamon, Phys. Rev. C **75**, 037601 (2007).
[21] C. Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).
[22] S. Raman, C. W. Nestor Jr., and P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).
[23] K. Kalita *et al.*, Phys. Rev. C **73**, 024609 (2006).
[24] M. Sinha *et al.*, Phys. Rev. C **78**, 027601 (2008); **76**, 027603 (2007).