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Uncertainties in the comparison of fusion and reaction cross sections of different systems involving weakly bound nuclei

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We discuss the uncertainties and misinterpretations that may arise from the simultaneous plots of fusion and reaction excitation functions of different systems when weakly bound nuclei are involved, particularly halo nuclei.

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A subject of great interest in the past few years is the role of breakup of weakly bound nuclei on fusion cross sections, particularly when radioactive nuclei are involved. In order to study possible breakup effects, reaction and fusion excitation functions of different systems may be compared in the same graph. Usually one compares the excitation functions of reaction mechanisms induced by weakly and tightly bound nuclei on the same target nucleus or different systems leading to the same compound nucleus. The possible enhancement or suppression of the fusion cross section when weakly bound nuclei are present and when different breakup threshold energies are involved is investigated in this way.

In the 1980s and 1990s, several works on sub-barrier fusion adopted the procedure of eliminating the geometrical factors concerning different systems by "reducing" the cross section and the center of mass energy. See, for example, Refs. [1–3]. The reduction consists of the division of the cross section by the quantity πR_B^2, where the barrier radius R_B is obtained from the fusion data at energies above the barrier and the division of the energy by the height of the Coulomb barrier, V_B. This procedure is very reliable when different systems have similar and known behavior at energies above the barrier and quite different behaviors below the barrier.

In recent years, the same procedure has been widely used in the study of systems with weakly bound nuclei, even when the fusion cross section data involve only energies above the barrier. However, this procedure can lead to important misinterpretation of the processes involving such nuclei, particularly when halo nuclei are present. These nuclei have abnormally large radii and consequently have barrier heights that do not follow the rules of tightly bound nuclei. The usual "reduction" procedure hides this atypical behavior of halo nuclei.

The aim of this paper is to propose an improved procedure for "reduction" of cross sections and energies, in order to compare different systems. The widespread use of different reduction procedures shows that this subject is not yet fully understood. Our comments are intended to clarify the situation.

As an example, we refer to a few recent papers. In order to be quite clear that we do not intend to criticize other authors, the first examples are papers written by ourselves [4–7], where we have compared total fusion excitation functions of different projectiles on the same targets or similar systems by using the usual "reduction." We concluded that there is no breakup effect on the total fusion whenever the reduced fusion excitation functions involving weakly and tightly bound nuclei are similar or coincident. This may be not so critical when there is no halo nucleus involved in the analysis.

Alamanos *et al.* [8] and Signorini [9] tried to systematize the behavior of the fusion excitation functions involving radioactive halo nuclei, when compared with stable beams. In both papers the following systems were analyzed: ^{4,6}He + ^{238}U, ^{4,6}He + ^{209}Bi, ^{9,11}Be + ^{209}Bi. No systematic behavior was found, but it is interesting to note that the conclusions of the two papers are different, because they used different reduction procedures. In Ref. [7] there is the usual "reduction" of the energy but not of the cross section. In Ref. [8] there are different procedures for the comparison, with or without reduction. By reducing the fusion cross section, Signorini [9] observed that at energies above the barrier, the fusion cross sections for the ^{6}He + ^{209}Bi and the ^{4}He + ^{209}Bi systems are equivalent, whereas Alamanos *et al.* [8] concluded that the fusion induced by ^{6}He is larger than that induced by ^{4}He. With the ^{238}U target, Signorini [9] observed a larger fusion cross section for the ^{6}He projectile than for ^{4}He, whereas Alamanos *et al.* [8] concluded that the two are similar. For both pairs of systems, the differing conclusions may be explained by the large value of the ^{6}He radius. For the ^{9,11}Be + ^{209}Bi systems, in both papers there is no reduction of the fusion cross section, and therefore the conclusions are similar; that is, the fusion cross section induced by the ^{11}Be is larger than that induced by ^{9}Be, at energies above the barrier. The conclusion might be different if both fusion cross sections were divided by R_B^2, because the halo ^{11}Be nucleus is larger than the ^{9}Be nucleus.

We believe that the best way to compare different systems is to divide the cross section by $(A_p^{1/3} + A_t^{1/3})^2$ and the center of mass energy by $Z_P Z_T/(A_p^{1/3} + A_t^{1/3})$, where Z_P and Z_T are the charges of the projectile and target, respectively. In this way, the normal geometrical effects are removed, and the eventual "strange" values of the reduced radii, r_o and r_{eff}, which should be related to the physical processes to be investigated, are not washed out. Here, $r_o = R_B/(A_p^{1/3} + A_t^{1/3})$ and $r_{\text{eff}} = Z_P Z_T e^2/(A_p^{1/3} + A_t^{1/3})$.

In the following, first we show a very simple but illustrative example of the failure of the usual procedure of reducing the cross sections and center of mass energies in the comparison of different systems. Consider the total fusion cross section for the ^{6}Li + ^{64}Zn system [10,11], represented in Fig. 1(a) by

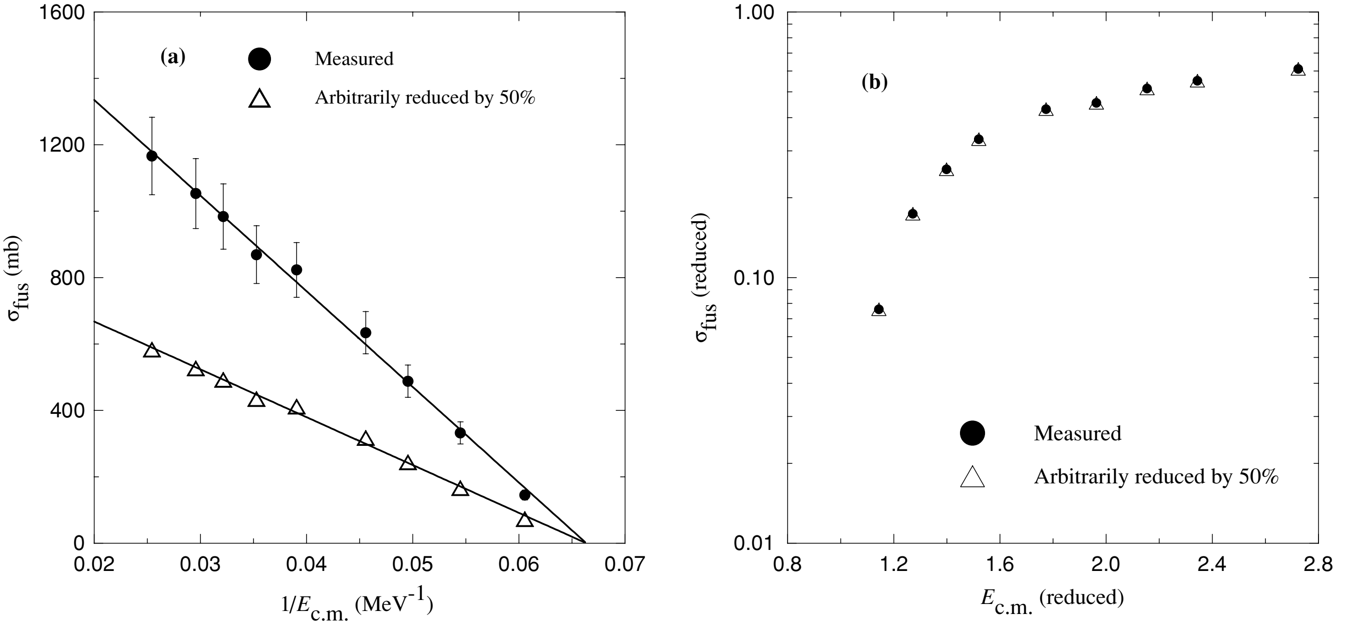

FIG. 1. Measured fusion cross sections (●) and those values divided by an arbitrary factor of two (△), for the ^{6}Li + ^{64}Zn system. (a) Fusion cross sections versus the inverse of the center of mass energy. (b) Reduced fusion excitation functions obtained by dividing the fusion cross sections by R_B^2 and the energy by V_B, obtained from Fig. 1(a).

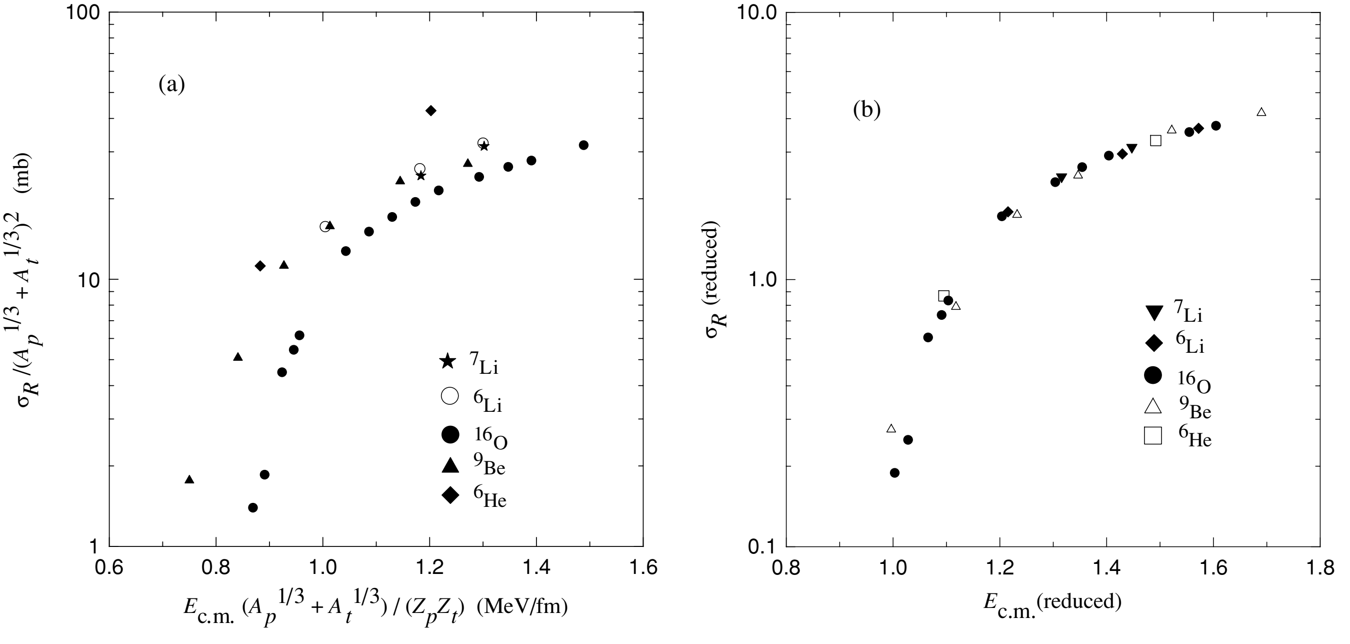

FIG. 2. "Reduced" reaction cross sections for systems consisting of different projectiles on the same ^{64}Zn target. (a) Using the "reduction" recommended by us. (b) Using the usual reduction procedure. See text for details.

the solid circles. Let us now artificially reduce fusion cross sections to 50% of their measured values and represent them in the same figure by the open triangles. The barrier radii and heights can be obtained, for the two situations, by the usual procedure of extrapolating straight lines until they reach both axes. The value of the barrier height is the same in both situations, whereas the value of R_B^2 is reduced by 50% of its original value. Therefore, when one "reduces" the fusion cross section corresponding to the second situation, one divides the cross section by half of the value of the cross section from the

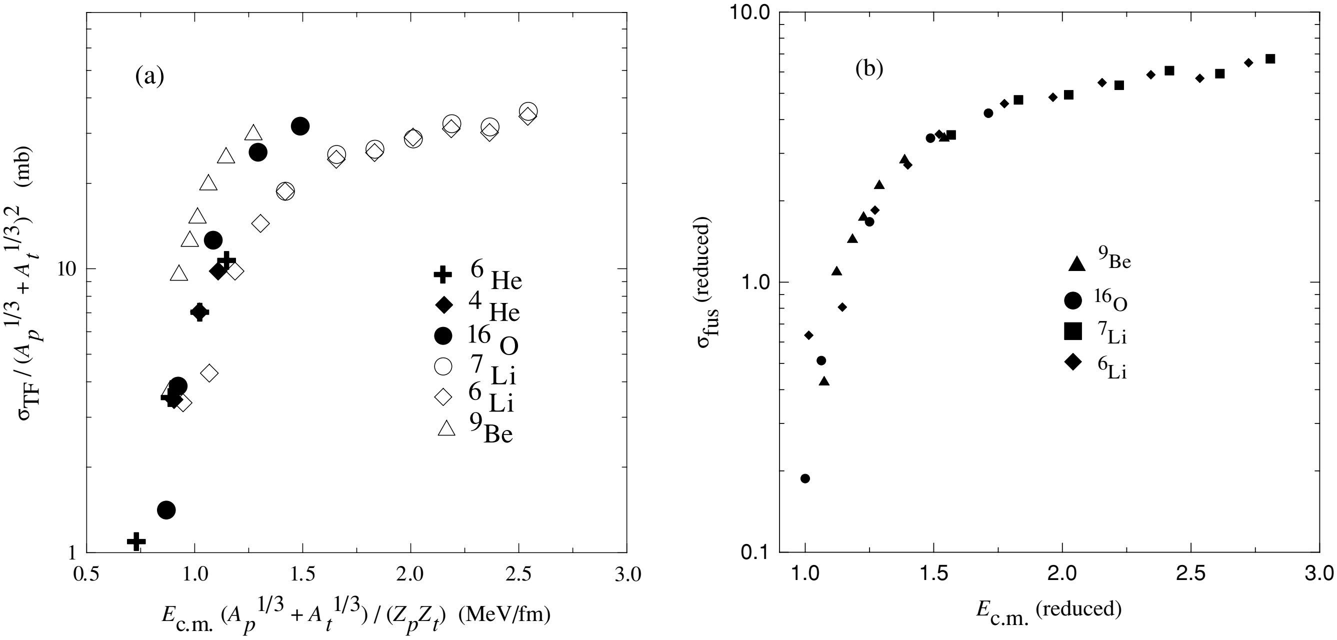

FIG. 3. "Reduced" total fusion cross sections for systems consisting of different projectiles on the same ^{64}Zn target. (a) Using the "reduction" recommended by us. (b) Using the usual reduction procedure. See text for details.

first situation. Obviously, the two situations lead to identical reduced fusion excitation functions, as can be observed in Fig. 1(b), but this does not mean that the fusion excitation functions are similar. For sure, in this drastic example the situation corresponding to the open triangles leads to an unreasonable value for R_B. However, when we compare different systems for which barrier parameters are unknown, as is the case when halo nuclei are involved, it is very difficult to draw any conclusion on possible enhancement or suppression of the fusion cross section.

Figure 2(a) shows the reduced reaction cross sections for the ^{6}He,^{6}Li,^{9}Be, and ^{16}O + ^{64}Zn systems [12], obtained by the procedure that we recommend. One can notice that the reaction cross section is largest for the system with the ^{6}He projectile, which is a halo nucleus with very small threshold breakup energy. Then there are three similar reaction cross sections for the three stable weakly bound projectiles (^{6}Li,^{7}Li, and ^{9}Be), and finally the smallest cross section is found for the tightly bound ^{16}O induced reaction. This result is compatible with the concept that the smaller the threshold breakup energy, the larger the reaction cross section. However, if we reduce the cross sections and energies in the usual way, all systems show the same reduced reaction cross sections, as can be observed in Fig. 2(b). The large $r_o = 2.0$ fm value derived for the system with the ^{6}He projectile, when compared with the normal r_o values around 1.2–1.5 fm derived for the other projectiles, is washed out by this procedure. The same effect happens with the relatively smaller barrier height for the reaction with this halo nucleus projectile. Similarly, Figs. 3(a) and 3(b) show total fusion excitation functions for the same systems [12], reduced by the two procedures. From Fig. 3(a), one observes different behaviors for the different systems, whereas from Fig. 3(b) one would conclude that the excitation functions are similar.

In summary, we stress the existence of uncertainties associated with the "reduction" of fusion and reaction excitation functions of different systems. We propose that, if one has to use any of the possible "reduction" procedures, the most reliable one is to divide the cross section by $(A_p^{1/3} + A_t^{1/3})^2$ and the center of mass energy by $Z_P\ Z_T/(A_p^{1/3} + A_t^{1/3})$. Even so, it is desirable that conclusions are drawn from the analysis of the data for each system, separately.

Furthermore, one has to be careful before drawing conclusions about possible effects on the fusion cross section due to the breakup process based only on the analysis of fusion excitation functions. The breakup cross sections were measured directly by the coincidence technique for systems involving weakly bound nuclei such as ^{6}Li + ^{208}Pb [13] and ^{9}Be + ^{208}Pb [14], and their values are smaller than fusion cross sections at energies above the barrier. For these systems, transfer channels were found to be mechanisms as important as the breakup. A recent paper by Raabe *et al.* [15] has shown that the supposed large sub-barrier cross-section enhancement observed for the ^{6}He + ^{238}U reaction [16] is, in fact, due to transfer cross section rather than fusion.

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