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FUSION ENHANCEMENT/SUPPRESSION AND IRREVERSIBILITY IN REACTIONS INDUCED BY WEAKLY BOUND NUCLEI

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We show that halo effects enhance fusion cross sections of weakly bound systems, comparing with the situation when there is no-halo. We introduce dimensionless fusion functions and energy variable quantity to investigate systematical trends in the fusion cross sections of weakly bound nuclei at near-barrier energies. We observe very clearly complete fusion suppression at energies above the barrier due to dynamic effects of the breakup on fusion. We explain this suppression in terms of the repulsive polarization potential produced by the breakup.

Fusion reactions between heavy ions have been a subject of great interest in the last four decades. It is well accepted that low lying collective inelastic excitations of the colliding nuclei and transfer channels may produce huge enhancement of fusion cross sections at sub-barrier energy regime (see, for example,[1–4]). The situation is more complicated when weakly bound nuclei, both stable and radioactive, are involved. Such nuclei have low breakup energy threshold and the breakup feeds states in the continuum. Stable nuclei of this type are ^{6}Li, ^{7}Li and ^{9}Be, described as clusters of alpha-deuteron, alpha-tritium and alpha-alpha-neutron, respectively. Radioactive nuclei of great interest are, among others, two-neutron, one-neutron and proton – halo nuclei such as ^{6}He, ^{11}Li, ^{11}Be, ^{8}B, ^{17}F. Following breakup, different processes may occur: non-capture breakup (NCBU), when neither fragment fuses, incomplete fusion (ICF), when part of the fragments fuses and sequential complete fusion (SCF), when all the fragments fuse. Total fusion (TF) is the sum of direct and sequential complete fusion (CF) and ICF.

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The effect of breakup of weakly bound nuclei, especially halo nuclei, on the fusion cross section has been widely investigated[5] but not yet fully understood. One can distinguish effects of two kinds. First, there are the static effects associated with the longer tail of the nuclear density. This tail gives rise to a lower barrier. The second kind is the dynamical effects associated with the strong coupling between the elastic and the breakup channels. These two kinds of effects may lead to opposite consequences on the fusion cross section. In the literature, there are some conflicting results. Maybe the best known are the ones concerned with sub-barrier fusion of the halo ^{6}He nucleus. Kolata et al[6] reported large sub-barrier fusion enhancement for the ^{6}He + ^{209}Bi system. For the ^{6}He + ^{238}U system, Raabe et al.[7] claimed that there was no sub-barrier fusion enhancement. Most of the controversies about the effect of breakup on fusion cross sections actually come from the comparison of data with theoretical predictions from different interaction potentials and to the answer to the following question: Fusion enhancement or suppression in relation to what?

We start the discussion by analyzing static effects due to the diffuse interaction potential related to weakly bound nuclei, particularly of halo nuclei. If one wants to investigate the halo effect on the fusion, one can not use realistic double-folding interaction potentials in the calculation, as it was done by Raabe et al.,[7] because by doing this, the halo effect is already included in the calculations. In figures 1 we show results of three calculations for the "controversial" ^{6}He + ^{238}U and ^{209}Bi systems. The dashed curves are results of non-coupling calculations using the double-folding Sao Paulo potential[8] where the density of ^{6}He used is that of the normal ^{4}He nucleus renormalized for A = 6, that is, supposing that ^{6}He is not a halo nucleus. The dotted curves are those obtained from the same calculations, but using the realistic ^{6}He density of this halo nucleus. One can observe clearly that a large fusion cross section enhancement is obtained due to the halo effect of ^{6}He, contrary to the title of the paper of ref.[7] The full curves are results of coupled channel (CC) calculations when the excited states of the targets are included. The comparison between theoretical and experimental cross sections for both systems shows suppression of fusion cross section at energies above the barrier and some enhancement below the barrier. We point out that the reliable calculations do not include dynamic effects due to breakup and transfer channels (the full curves). The observed suppression and enhancement of fusion cross sections are, therefore, due to effects not included in the CC calculations (in the present example, transfer and dynamic breakup effects). Therefore, there is no contradiction between the two data sets.

To investigate a systematic behavior of dynamic breakup effects on the fusion cross section, it is important to compare fusion data for different systems and to have a benchmark to which the data have to be compared. Recently we have shown[9] that the traditional "reduction methods" to compare fusion cross sections of several systems with different barrier parameters in the same graphic do not fully vanish out the static effects. We have very recently developed a

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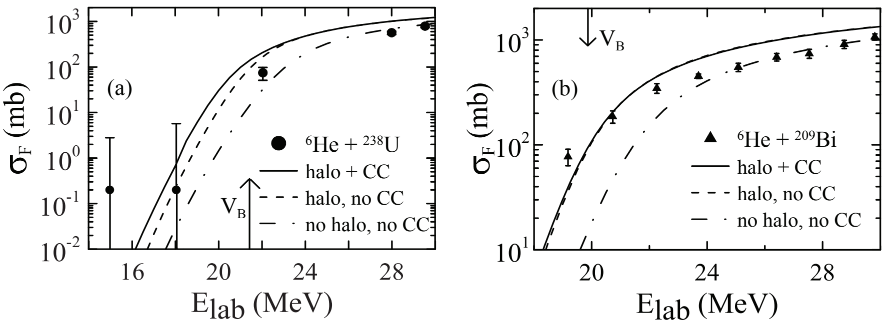

Fig. 1. Static and target dynamics effects on fusion cross sections for the systems ^{6}He + ^{238}U (a) and ^{6}He + ^{209}Bi (b). (see text for details).

new method[9] to investigate systematical trends in the fusion of weakly bound nuclei, through the dimensionless energy variable and fusion function quantities $E \to x = \frac{E-V_B}{\hbar\omega}$, $\sigma_F \to F(x) = \frac{2E}{\hbar\omega R_B^2}$, where $\hbar\omega$ is the barrier curvature parameter. This fusion function becomes system independent when the fusion cross section can be described by the Wong formula.[10] This benchmark curve was called[9] Universal Fusion Function (UFF) and it is written as $F_0(x) = \ln[1 + \exp(2\pi x)]$. Experimental fusion functions renormalized to take into account the failure of the Wong model for some light systems at the sub-barrier energy regime and the effects of inelastic couplings[9] are then compared with UFF. The differences are due to the channels left out of the CC calculations, such as breakup and transfer reactions. We have compared fusion data for tens of systems, both tightly and weakly bound, with UFF and then we were able to disentangle static from dynamic effects of the breakup on fusion and to observe a general trend of this effect.[9,11,12] In figure 2 we show, as example, the comparison of the renormalized fusion function for some representative systems. The CC calculations used to renormalize the experimental data were performed using using the Sao Paulo potential. In the left panel we observe several renormalized experimental fusion functions coincident with the UFF curve. They correspond to fusion of tightly bound systems and total fusion of weakly bound projectiles with targets with masses ranging from light to heavy. The same results are obtained for several other systems.[9,11,12] The right panel show complete fusion of weakly bound systems and total fusion induced by the two-neutron halo ^{6}He. The renormalized experimental fusion functions are around 30% smaller than UFF, showing significant fusion suppression at above barrier energies for these systems. Similar results are obtained for other weakly bound systems. One may wonder whether all systems investigated obey the systematic behavior mentioned above. The answer is no. Among the tens fusion functions investigated by us from the available data in literature, only very few of them do not follow the systematic. We believe that possible explanations for these anomalous behaviors might be either something very special with those systems or something wrong with the data or our

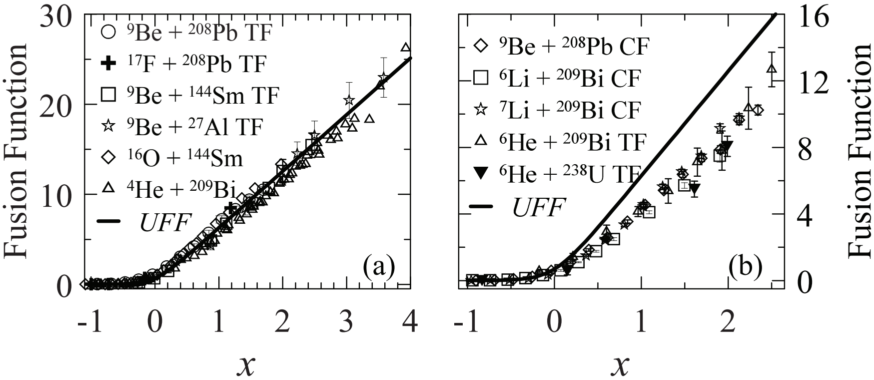

Fig. 2. Comparison of reduced cross section for several systems with the UFF. (see text for details).

CC calculations. The breakup feeds continuum states and so continuum-continuum couplings (CCC) have to be included in any realistic theoretical calculation. Continuum discretized coupled channel (CDCC) calculations for fusion of halo nuclei show[13] huge sub-barrier fusion suppression at energies below and above the barrier, when compared to calculations not including CCC. So, in a first thought one might conclude that the inclusion of CCC strengthens the absorptive imaginary potential and consequently the quasi-elastic cross section should become larger, due to the increase of breakup. The suppression of complete fusion would then arise from some kind of irreversibility of the transition to the continuum.[14] However, CDCC calculations for breakup cross sections for halo nuclei[?]nclusion of CCC in the calculations leads to a substantial suppression of the breakup cross section. This result rules out the irreversibility hypothesis. An alternative explanation[14] is that the inclusion of CCC makes the real part of the polarization potential more repulsive, so that the incident current has to cross a higher barrier to produce fusion. If this were true, complete fusion should be reduced and the elastic cross section should be enhanced when CCC are taken into account. In fact, calculations and comparison with data show[?]ection as compared with results without CCC. These results confirm the alternative explanation.

The above explanation for the suppression of complete fusion cross section due to dynamic breakup effects is compatible with calculations[14,17,18] of approximate breakup polarization potentials, where it is found that the real polarization potential becomes repulsive with the inclusion of CCC. The repulsive polarization potential is, in fact, responsible for the so-called Breakup Threshold Anomaly[19,20] present in the elastic scattering of halo and some weakly bound nuclei such as ^{6}Li.[19,21–23] On the other hand, for the weakly bound nucleus ^{7}Li with excited bound state, the usual attractive polarization potential due to inelastic excitations compensates the repulsive breakup potential.[24]

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We would like to finish this paper by pointing out some of the challenges and open questions on this subject. From the experimental part, one needs more data and with much better precision on fusion, breakup, transfer and scattering of weakly bound radioactive nuclei, specially halo nuclei. It is particularly interesting to further investigate the sub-barrier energy regime, not yet fully understood and very important for the nucleosynthesis and production of superheavy nuclei. It is important to obtain separated data for complete and incomplete fusion, so far not available for light systems, for which the residual nuclei of both processes coincide. One also needs more exclusive data on non-capture breakup (resonant and non-resonant) and to disentangle incomplete fusion from direct transfer reactions. From the theoretical side, one needs models which take into account and disentangle all reaction processes following breakup (NCBU, ICF and SCF) and direct transfer reactions. Also, one needs CDCC calculations which take into account transfer channels to the continuum and predict their influence on the complete fusion.

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