Enhancement of sub-barrier fusion of two-neutron halo nuclei

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The tunneling of composite systems, where breakup may occur during the barrier penetration process is considered in connection with the fusion of halo-like radioactive, neutron- and proton-rich nuclei on heavy targets. The large amount of recent and new data clearly indicates that breakup hinders the fusion at near and below the Coulomb barrier energies. However, clear evidence for the halo enhancements, seems to over ride the breakup hindrance at lower energies, owing, to a large extent, to the extended matter density distribution. In particular we report here that at sub-barrier energies the fusion cross section of the Borromean two-neutron halo nucleus ^{6}He with the actinide nucleus ^{238}U is significantly enhanced compared to the fusion of a no-halo ^{6}He. This conclusion differs from that of the original work, where it was claimed that no such enhancement ensues. This sub-barrier fusion enhancement was also observed in the ^{6}He + ^{209}Bi system. The role of the corresponding easily excitable low lying dipole pygmy resonance in these systems is therefore significant. The consequence of this overall enhanced fusion of halo nuclei at sub-barrier energies, on stellar evolution and nucleosynthesis is evident.

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Fusion processes between heavy ions have been a subject of major interest in the last four decades. Two major motivations are the potential production of super heavy elements which do not exist in nature, and the understanding of stellar evolution and nucleosynthesis. At energies below the Coulomb barrier, tunneling becomes the only means for fusion to occur. This purely quantum mechanical effect predicted more than 70 years ago by Gamow, remains a subject of great interest for theorists. What happens when the tunneling systems are composite? How the internal structure of system modifies Gamow's theory? These are important questions for which nuclear physics can supply clear answers. In recent years the fusion of extended nuclear systems such as neutron and proton rich halo isotopes has attracted great interest [1–6]. Two competing effects seem to operate in such cases. The dynamic effects related to the very low threshold for breakup of the halo nucleons, and the static effects of the extended matter distribution of these same nucleons. The major question is how to clearly identify these effects and check how they individually influence the tunneling/fusion at low energies. One guiding principle used to answer this question is that the dynamic breakup coupling effect is strongly energy dependent and dispersive while the static effects are mostly accounted for through the use of the proper matter density distribution in the construction of the overall double folding interaction potential, an energy-independent entity.

Here we present clear evidence of the enhancement of the fusion probability of the Borromean nucleus ^{6}He with the heavy targets ^{209}Bi and ^{238}U at sub-barrier energies. This is in contrast to the conclusions reached by Raabe et al. [7], where it was claimed that no such enhancement ensues in the ^{6}He + ^{238}U system. As we show below, a proper account of the static effects of the halo as manifested in the use of the correct matter density of ^{6}He used in the double folding model and used to calculated the tunneling probability with the coupled channels model containing the dynamic breakup coupling effects would lead to a fusion cross section which contains the above mentioned enhancement. What Raabe et al. did was to compare their data with such theory, which would only show concurrence and would lead to the conclusion they reached. One would need to make a comparison with a theory which does not contain the halo static effects in order to assess the matter. In the following we do exactly this.

A large body of fusion data is available which can be used to define unambiguously what we call the "background" with which a sensible comparison can be made in order to decide whether the halo fusion system exhibits enhancement at sub-barrier energies or not. How to present this background tunneling/fusion data of the many complex many-body

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systems alluded to above is a subtle question which has recently been addressed and with success [8, 9]. The idea is to define a universal fusion function (UFF), which accounts for most of the, properly scaled, fusion data. This UFF is defined by first transforming the collision energy and the fusion cross section into dimensionless quantities, according to the prescription

$$F_{exp}(x) = \frac{2E}{\hbar\omega R_B^2}\ \sigma_F \tag{1}$$

where, $x = \frac{E-V_B}{\hbar\omega}$, with, R_B, V_B and $\hbar\omega$, being the barrier radius, height, and curvature parameters of the fusion (Coulomb) barrier, respectively. One can determine the optical fusion function, $F_{opt}(x)$, using the cross section $\sigma_{F,opt}$ predicted by the optical model calculation with a potential which leads to those barrier parameters. This fusion function is system-independent when $\sigma_{F,opt}$ is accurately described by Wong's formula [10]. In this case

$$F_{opt}(x) \rightarrow F_0(x) = \ln\left[1 + \exp\left(2\pi x\right)\right] \tag{2}$$

The function $F_0(x)$ is universal as it is independent on the fusing system. At very small values of x, $F_0(x) \rightarrow e^{2\pi x}$, while at large x, it acquires the simple linear form, $F_0(x) \rightarrow 2\pi x$. It has the conspicuous limiting value of $\ln 2$ at $x = 0$, namely at a center of mass energy equal the Coulomb barrier height. These characteristics makes $F_0(x)$ a quite convenient benchmark to which reduced data are compared.

The first step to use this method in the analysis of the fusion data is to build the experimental fusion function, $F_{exp}(x)$. This is done using the experimental fusion cross section defined before. However, as in most cases the fusion cross section is strongly affected by channel couplings and Wong's model is not exact for light systems and at sub-barrier energies, one introduces [8, 9] a renormalized experimental fusion function,

$$\bar{F}_{exp}(x) = \frac{F_{exp}(x)}{\left[\frac{\sigma^A_{F,cc}}{\sigma_{F,opt}}\right]}. \tag{3}$$

Here, $\sigma_{F,opt}$ is the theoretical fusion cross section with all couplings switched off, and $\sigma^A_{F,cc}$ is the cross section obtained from a coupled channel (CC) calculation including a set of channels A. If all relevant channels are included in A and the correct coupling strengths are used, the renormalized experimental fusion function, Eq.(3), should match the benchmark, Eq.(2), namely,

$$\bar{F}_{exp}(x) \rightarrow F_0(x) \tag{4}$$

If on the other hand some relevant set of channels B is left out of the CC calculation then $\bar{F}_{exp}/F_0 = \sigma^{A+B}_{F,cc}/\sigma^A_{F,cc}$. Clearly, the ratio $\bar{F}_{exp}/F_0$, would give a precise measure of the importance of the left out channels not included in the CC calculation A. Through this procedure, one is able to isolate the effect of the breakup channel coupling on the fusion cross section of weakly bound systems using as a theoretical model a CC calculation involving bound channels only (A). However, the inclusion of transfer channels in calculations of $\sigma_{F,cc}$ may be a difficult task, specially in collisions with large positive transfer Q-values, such as neutron transfer in collisions with ^{6}He. When transfer channels are important and they are not included in the CC calculation, the differences between $\bar{F}_{exp}(x)$ and the $F_0(x)$ should be assigned to the combined effects of couplings to breakup and transfer channels.

We now use this method of analysis to take a new look at "old" data.

In order to make a sensible description of the fusion of weakly bound nuclei, it has been customary to distinguish between the complete fusion (CF) where the whole projectile is captured by the target, and the incomplete fusion (ICF), where a fragment of the broken projectile is captured. The total fusion (TF) is then defined as the sum of these two cross sections [1]. In many instances it has been rather difficult to separate experimentally these two components. The same can be said about the theoretical view point. The widely used Continuum Discretized Coupled Channels (CDCC) model can calculate the total fusion cross section, the total absorption cross section form the continuum channels, but it fails to supply an unambiguous way to calculate the ICF of a given fragment [11].

In Fig. 1, we show the renormalized experimental fusion function $\bar{F}_{exp}(x)$, of Eq.(3), vs. x, for several tightly and weakly bound systems. The results are shown in a logarithmic scale. We see clearly that the "data" for the tightly bound systems follow quite closely the Universal Fusion Function (UFF), F_0, indicating that the chosen A channels are adequate to describe the fusion of these systems, as has been emphasized in [12, 13]. The results for the weakly bound systems indicate strong deviations from the UFF at above-barrier energies. This deviation becomes quite visible if the data are presented on a linear scale. This is shown in Fig. 2. For the TF for one stable weakly bound system (^{9}Be +^{208}Pb) [14, 15] and for another, unstable, bound system (^{17}F + ^{208}Pb) [16], there is good agreement above the barrier ($x > 0$) and a slight enhancement at sub-barrier energies ($x < 0$). The CF for the same ^{9}Be + ^{208}Pb system and for the ^{6,7}Li + ^{209}Bi systems [15] is suppressed by about 30% at energies above the barrier. Thus, this suppression is attributed to the loss of flux going to ICF, following breakup. The fusion enhancement at sub-barrier energies is attributed to prompt and resonance breakups and transfer channels. For fusion induced by ^{6}He [7, 17], there is also a significant suppression above the barrier and some slight enhancement at sub-barrier energies. However, for this latter very weakly bound halo nucleus induced fusion system, only TF was measured. As sharing energy considerations [8] show that the ICF of ^{4}He with the targets is unlikely, the fusion suppression for the neutron halo systems is attributed to transfer and/or non-capture breakup channels, rather than to ICF.

We now turn to the important question of how does the coupling to the breakup channel competes with the extended matter distribution, which is expected to play a major role, as emphasized by several authors? Even with extensive experimental and theoretical efforts during the last two decades [1–6], a full understanding of the competing effect of the breakup coupling and the halo is still not fully reached though great progress towards this goal have been made. The reason behind this is the lack of a full exact theory of three- and four-body nature of the reactions of one- and two- nucleon halo nuclei, and how tunneling of a structured system is described.

We first dwell on the dynamic effects of the halo, exemplified by the coupling to the breakup channel. This is conveniently described through the dynamic polarization potential (DPP) which represents the Feshbach reduction of a CC description into an one effective channel description. The breakup, dispersive, energy-dependent DDP for weakly bound systems, $V_{bu,pol}(E)$, has been extensively studied within the CDCC, and the conclusion reached, [18–20], is that its imaginary part was found to suffer a slight increase as the energy is lowered below the barrier, followed by a drop to zero as the break up channel closes. The real part of the $V_{bu,pol}$ was found to be repulsive (positive) in the barrier region. The over all effect of the breakup DPP, $V_{bu,pol}$, is to induce a reduction in the fusion at energies above the barrier due to a large extent to the rather long range nature of "dynamic absorption" described by $ImV_{bu,pol}$, and to the repulsive $ReV_{bu,pol}$. The effect of $V_{bu,pol}$ below the barrier is rather small. In contrast, the static effect of the halo, present in the bare optical potential described by an appropriate double-folding model, is always present at all energies. In figure 3 we show the barrier calculated with and without the halo, for the ^{6}He + ^{238}U system. Clearly the halo makes the barrier lower. The overall effect is a larger penetrability when compared to the no halo barrier.

The connection between the imaginary and real parts of the DDP is dictated by the dispersion relation. The results discussed above concerning the breakup DPP, $V_{bu,pol}(E)$, has been referred to as the Breakup Threshold Anomaly (BTA), [21], quite useful in the analysis of elastic scattering of weakly bound systems. In contrast, the DDP for bound channels, which also obeys a dispersion relation, presents a real and imaginary parts in the barrier region, with characteristics which are opposite to those of the breakup DDP, namely, the real part is attractive while the imaginary part drops as the energy is lowered below the barrier. This behavior has come to be known as the Threshold Anomaly (TA).

Guided by the above considerations we proceed now with a detailed discussion of the fusion of ^{6}He. In figure 4 we show results of two coupled channels calculations for the ^{6}He + ^{238}U system, toghether with the data. We use as the bare potential the double –folding Sao Paulo potential (SPP) [22, 23]. Data are from ref [7]. The full curve is the result of the calculation which does not include the effect of the two neutron halo of ^{6}He. The folding potential here was obtained by using the typical nuclear density of the strongly bound projectile ^{4}He, scaled to the size of ^{6}He. In this case, the differences with respect to the data originate from the absence, in the calculation, of the static effect of the halo and couplings to the breakup channel. When the static halo effects are included, by using the realistic ^{6}He density in the construction of the SPP, the calculated fusion cross section is increased, as seen in the dashed curve in Fig. 4. This result agree with Raabe et al [7] and also show suppression of fusion cross section above the barrier. As already emphasized, the dynamic effects associated with the breakup channel, not included in either calculations, result in a reduction of the fusion at above barrier energies, and are insignificant at sub-barrier energies. Thus the static effect of the halo is very important and enhances the fusion cross section in the whole energy range, especially at sub-barrier energies. The above behaviour of the fusion of Borromean nuclei such as ^{6}He is independent on the target, as it is shown in figure 5 for the ^{6}He + ^{209}Bi system [17]. While we find similar static halo enhancement in the fusion of the two above mentioned systems, the authors of the original papers reach opposing conclusions. We believe that we have resolved this issue and put the problem of the fusion enhancement of halo nuclei to rest.

In conclusion, we have presented convincing arguments to support our thesis that the fusion of halo nuclei at sub-barrier energies is enhanced when compared to the fusion of non-halo nuclei. This, together with the existence of threshold dipole strength (the so-called pygmy resonances) would inflict important changes in the scenario of the r-process in nucleosynthesis as theoretically predicted by Goriely [24].

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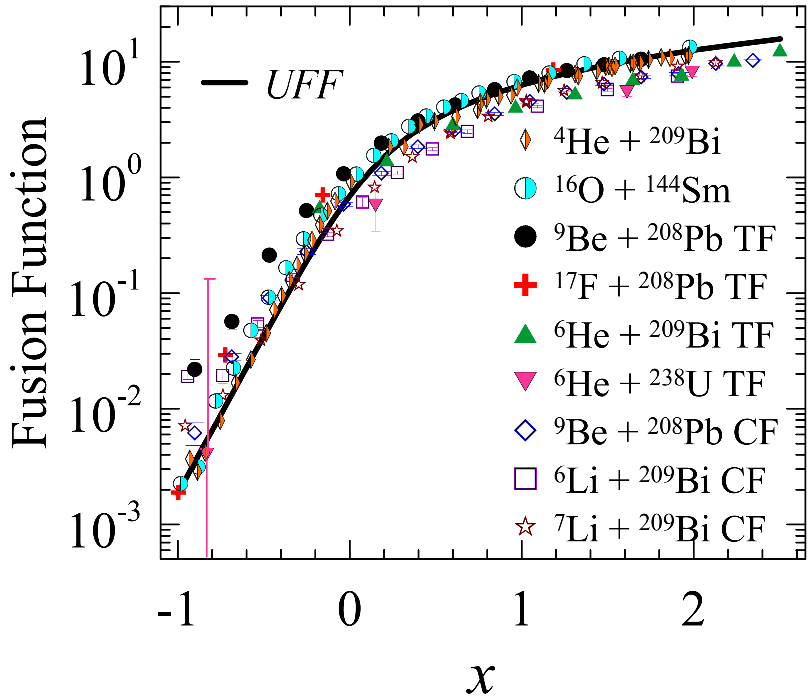

FIG. 1: The renormalized experimental fusion function $\bar{F}_{exp}(x)$, of Eq.(3), vs. the variable x, for a sample of tightly bound systems, ^{16}O + ^{144,154}Sm, and ^{4}He + ^{209}Bi, the data points are, respectively from [12, 13], and for a sample of weakly bound systems, ^{9}Be + ^{208}Pb, ^{17}F + ^{208}Pb, ^{6,7}Li + ^{209}Bi, ^{6}He + ^{209}Bi, and ^{6}He + ^{238}U. The full curve is the UFF, $F_0(x)$ of Eq. (2). The data points are respectively from [12] (^{16}O), [13] (^{4}He), [14, 15] (^{9}Be), [16] (^{17}F), [15] (^{6,7}Li), [7, 17] (^{6}He)

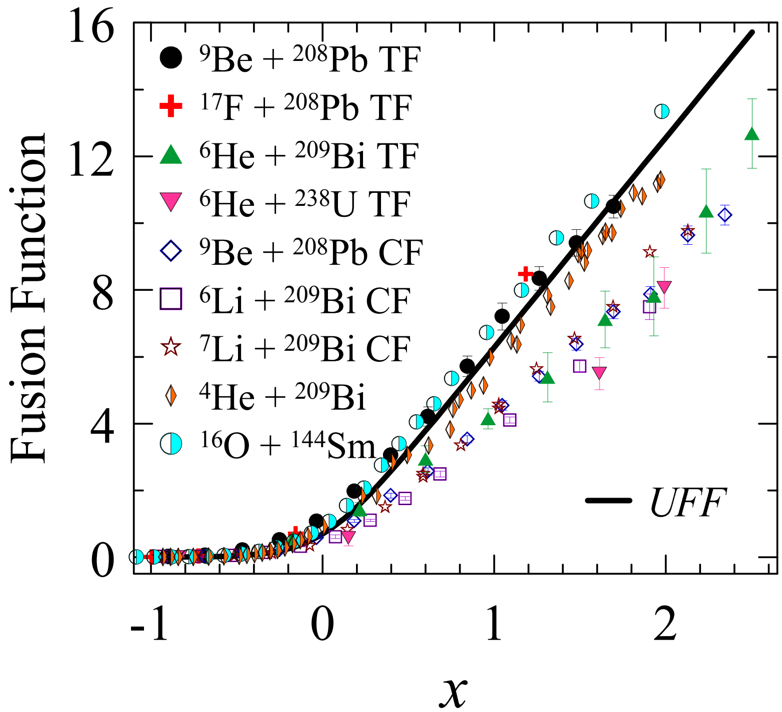

FIG. 2: Same as Fig. 1 on a linear scale

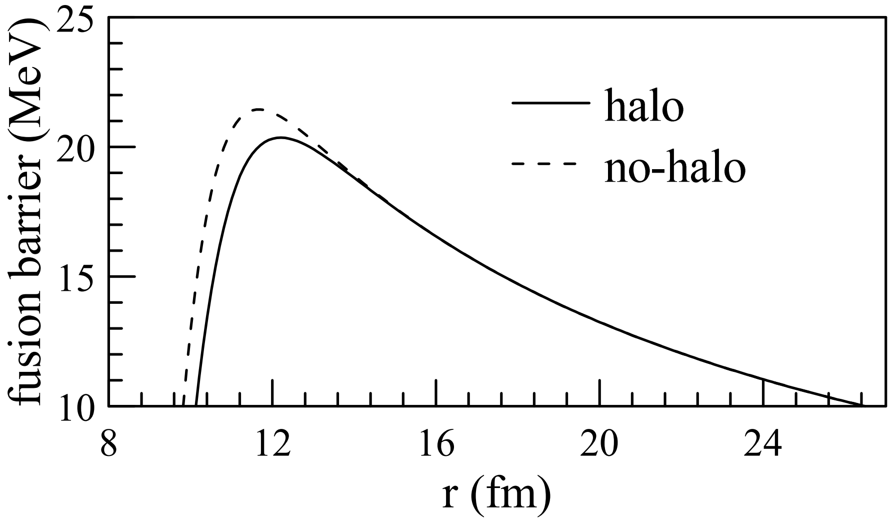

FIG. 3: The Coulomb barrier of the system ^{6}He + ^{238}U calculated using the double folding-based São Paulo potential [22, 23]. The dashed curve is obtained with the actual realistic matter density of ^{6}He containing the two-neutron halo effect, while the full curve shows the result obtained with a normal, non-halo, density of a ^{6}He nucleus treated as an α particle with six nucleons

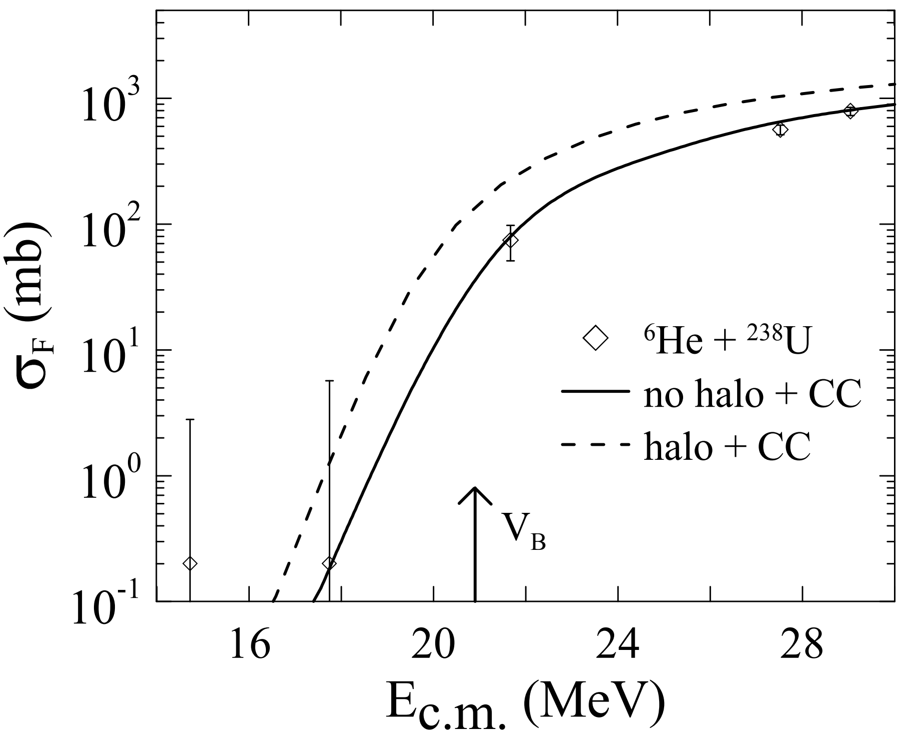

FIG. 4: shows results of two calculations of the fusion cross section for the ^{6}He + ^{238}U system, together with the data of ref [7]. The *SPP* interaction of [22, 23] is employed as a background optical potential. The full curve is the result of the coupled channels calculation which does not include the static effect of the two neutron halo of ^{6}He. The dashed curve is the corresponding coupled channels result obtained with a background potential which contains the static halo effect. The coupled channels included in both calculations correspond to couplings to the main excitations of the target, ^{238}U.

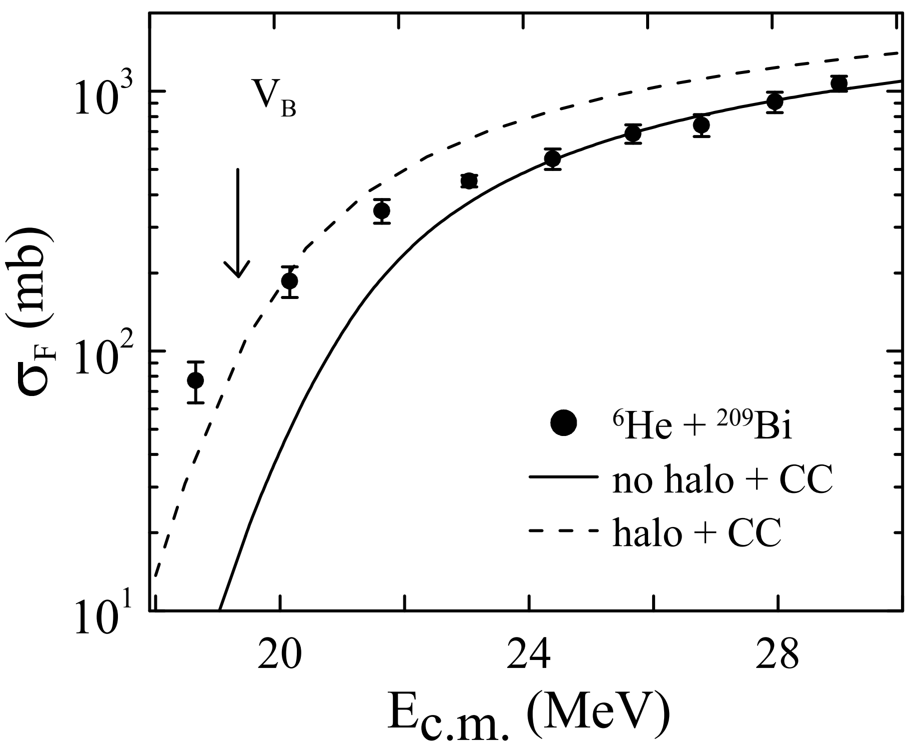

FIG. 5: Same as Fig. 4 for the system ^{6}He +^{209}Bi. The data points are from ref. [17]. The theoretical curves corresponds to the ones of Fig. 4 as well.