Role of the breakup process in the hindrance of light-heavy-ion fusion reactions

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It has been found that the fraction of the reaction cross section diverted to complete fusion of light heavy ions is strongly correlated to the nucleon (cluster) separation energy of the participants. The presence of weakly bound nuclei hinder the fusion cross section indicating that they do not survive the collision long enough in order to contribute significantly to the fusion process. Model calculations support this picture. The ^{38}Ar compound nucleus populated by entrance channels with different mass asymmetries, i.e., ^{9}Be+^{29}Si, ^{11}B+^{27}Al, ^{12}C+^{26}Mg, and ^{19}F+^{19}F, has been investigated, supporting the mentioned correlation. Consequence of this effect on the fusion cross section of exotic nuclei is discussed.

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Systematic studies of light heavy-ion reactions indicate that when very light nuclei (s-p nuclei) are involved, the fusion probability is hindered [1,2]. This is reflected in an anomalous increase of the fusion barrier height (V_B) and decrease of its radius (R_B). This change in trend occurs in the case of light nuclei for which the binding energy per nucleon B/A did not reach the saturation value of ~ 8 MeV. In this mass region strong fluctuations observed in R_B as well as maximum fusion cross sections are commonly attributed to nuclear structure effects [3,4]. However, the decrease of the average R_B value, as well as the simultaneous increase of the average value of V_B, can be attributed to the opening of important direct channels among which the breakup process can be very important. It is expected that weakly bound nuclei, as, e.g., ^{9}Be, whose neutron separation energy is $S_n=1.67$ MeV or ^{11}Li ($S_{2n}=0.2$ MeV), might have a low *survival probability* on the *way* to fusion, leading to a hindrance of the fusion cross section. The understanding of this property is fundamental in the context of nuclear astrophysics, where exotic nuclei with very loosely bound structure and with relatively low kinetic energies are involved, leading to fusion cross sections values discrepant from the ones obtained on the basis of simple barrier penetration models.

In this work, we show that a clear correlation exists between the relative cross section diverted to the fusion process and the nucleon (cluster) separation energy of the collision participants up to energies a few times the Coulomb barrier height and that the breakup process can be determinant in this correlation. A quantitative study has been systematically accomplished by investigating several reaction channels, involving bound and loosely bound nuclei.

The ^{38}Ar compound nucleus has been formed via different entrance channels. Complete fusion cross section (σ_F) for the ^{9}Be+^{29}Si [5], ^{11}B+^{27}Al, and ^{19}F+^{19}F reactions were measured [6] as a function of the bombarding energy. Data for the ^{12}C+^{26}Mg were obtained from the literature [7] as well as other light systems further presented in the systematics [1,8,9]. Total reaction cross sections (σ_R) were estimated based on optical model fits of the elastic scattering data. Details are presented elsewhere [5]. The fusion cross section σ_F as well as fusion ratio $P_F(E)=\sigma_F(E)/\sigma_R(E)$ shown in Fig. 1 present a well known energy dependence, an increase with energy in the barrier usually called region I up to a saturation value P_F around the energy regime II. This nomenclature concerning the different energy regimes was introduced in the Glas and Mosel fusion model [10]. The above behavior of σ_F and P_F is illustrated with the data for ^{9}Be+^{29}Si reaction.

To account for the breakup effect on the fusion of, e.g., ^{9}Be+ target, we employ the model recently developed by Hussein *et al* [11]. In this latter reference the one-dimensional barrier penetration model based on the Hill-Wheeler expression [10] of the transmission coefficient,

$$\mathring{\sigma}_F=\frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)\mathring{T}_l^F , \tag{1a}$$

$$\mathring{T}_l^F\equiv\left\{1+\exp\left[\frac{2\pi}{\hbar\omega}\left[V_B+\frac{\hbar^2 l(l+1)}{2\mu R_B^2}-E_{\text{c.m.}}\right]\right]\right\}^{-1} , \tag{1b}$$

where k is the asymptotic wave number, i.e., $k=(2\mu E_{\text{c.m.}}/\hbar^2)^{1/2}$, V_B is the height of the average fusion barrier, R_B its position, and $\hbar\omega$ the measure of its

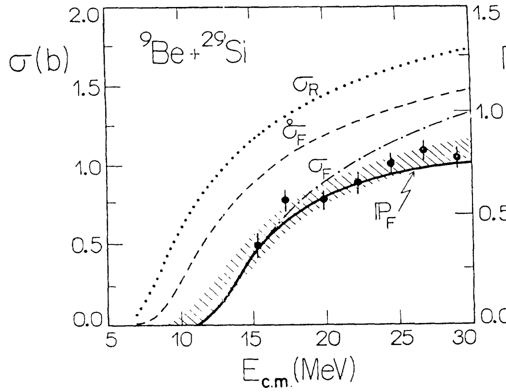

FIG. 1. Energy dependence of the fusion cross section for the $^9Be+^{29}Si$ reaction. Dots describe the experimental values. Hatched area represents a fit of the data by the Glas and Mosel model [10]. The dashed line represents the $\mathring{\sigma}_F$ value [Eq. (1)] expected from the one-dimensional barrier penetration model. The dotted line represents the reaction cross section σ_R estimated from fits to the elastic scattering data. The dash-dot line represents calculations based on Eq. (2) taking into account the coupling to the breakup channel. The calculated energy dependence of the fusion ratio $P_F=\sigma_F/\sigma_R$ is represented by the solid line (right-hand scale).

curvature, is appropriately modified by multiplying $\mathring{T}_l^F$ by the breakup *survival probability* $(1-T_l^{bu})$. The resulting inhibited fusion cross section is given by [11]

$$\sigma_F=\frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)(1-T_l^{bu})\mathring{T}_l^F . \tag{2}$$

Thus for all l,s only the fraction of the incident flux that remains intact contributes to complete fusion. In this model, the competing processes are considered to be fusion and breakup. Thus, the breakup cross section is given by

$$\sigma_{bu}=\frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T_l^{bu}(1-\mathring{T}_l^F) , \tag{3}$$

which guarantees that low angular momentum partial waves do not contribute to the breakup. Few data on breakup, fusion, and total reaction cross sections are available in the literature for light heavy-ion reactions; however, the existing ones [12–15] suggest that, at low bombarding energies, the two considered processes dominate the reaction cross section. The sum $(\sigma_F+\sigma_{bu})$ describes the reaction cross section (σ_R) of the model. At high bombarding energies $\sigma_F+\sigma_{bu}$ is necessarily smaller than the optical model extracted one owing to the existence of other processes that do not affect σ_F in the near barrier region and contribute appreciably to σ_R at higher energies.

A closed expression for $(1-T_l^{bu})$ was derived in Ref. [16] and it reads

$$1-T_l^{bu}=\exp\left[-4\frac{\mathcal{F}_0^2}{E_{c.m.}(E_{c.m.}-Q)}\left|S_l^{(1)}\right|I_l^2(\eta,s,\xi)\right] , \tag{4}$$

where $\mathcal{F}_0^2$ is a strength factor that measures the degree of coupling of the entrance channel to the breakup one [17], $|S_l^{(1)}|$ is the modulus of the elastic S matrix in the breakup channel and is given by $[1-T_l^{0F}(E_{c.m.}-Q)]^{1/2}$, with Q being the breakup Q value, and $I_l(\eta,s,\xi)$ is a Coulomb radial integral

$$I_l(\eta,s,\xi)=\int_0^{\infty}F_l(\eta_1,k_1,r)F_l(\eta_2,k_2,r)e^{-r/\alpha} , \tag{5}$$

with $\xi=(k_1-k_2)/(k_1+k_2)$ being the adiabaticity parameter, $\eta=z_1z_2e^2/\hbar v$ the Sommerfed parameter, $s=1/k\alpha$, $k_{1(2)}$ the wave number in the elastic (breakup) channel, and $\alpha^{-1}\equiv\sqrt{2\mu_{bx}\varepsilon_s/\hbar^2}$ with b and x being the two clusters forming the projectile and ε_s is the $b-x$ separation energy. Small separation energies make I_l vary slowly with l. For ^9Be, taking b to be a neutron which releases the two α particles from ^8Be, the value of parameter α results in $\alpha\cong 3.75$ fm.

This model considers the inclusive breakup cross section which includes the three-body final-state process, in which the projectile breaks in two components and the target acts as a spectator, as well as the two-body final-state process, in which one of the two projectile components is captured by the target. This latter process is also denominated incomplete fusion [15]. The two processes can be treated separately as done by, e.g., Tabor *et al.*, [12,13] based on a modified Serber model [18], totally decoupled from the fusion process.

Since the effect of the breakup mechanism on fusion is clearly inclusive, the approach of the present model appears to be convenient for the determination of fusion cross sections.

The energy dependence of the fraction $P_F=\sigma_F/\sigma_R$ vs $E_{c.m.}$ is shown in Fig. 1 indicating that a satisfactory overall agreement is achieved. To give an idea of the dependence of σ_F [Eq.(2)] on the separation energy of the projectile ε_s we plot in Fig. 2 a representative calculation showing P_F vs ε_s. One sees a cutoff around $\varepsilon_s\sim 4$ MeV, followed by tendency to saturation. This behavior reflects the fact that at energies around the fusion barrier

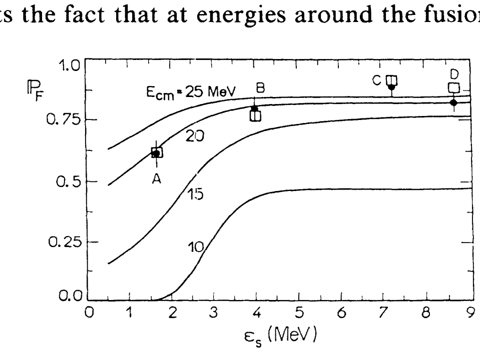

FIG. 2. Dependence of the fusion ratio $P_F\equiv\sigma_F/\sigma_R$ on the cluster separation energy. Circles describe the experimental values determined around the saturation energy (at $E_{c.m.}=2V_B$) for $A\equiv{}^9Be+^{29}Si$, $B\equiv{}^{19}F+^{19}F$ [6], $C\equiv{}^{12}C+^{26}Mg$ [7], and $D\equiv{}^{11}B+^{27}Al$ [6]. The solid line describes the calculations of P_F as a function of the separation energy ε_s for $^9Be+^{29}Si$ reaction at several bombarding energies ($E_{c.m.}=25$, 20, 15, and 10 MeV). The open squares represent the calculated values of the P_F for the systems presented and calculated according to Eq. (2) at the same energies of the experimental points.

breakup process competes with fusion for partial waves slightly lower than the fusion critical angular momentum l_c. With increasing bombarding energy this competition subsides as most of the partial waves that contribute to breakup have larger l values than l_c [5]. Figure 2 also indicates that when loosely bound nuclei are involved ($\varepsilon_s \lesssim 3$ MeV), the fusion cross section is considerably hindered turning P_F smaller for lower separation energies ε_s. Just to point out the projectiles which have low separation energies and consequently could present inhibited fusion cross sections we mention that for ^{9}Be($\varepsilon_n = 1.67$ MeV); ($\varepsilon_\alpha = 2.47$ MeV); ^{6}Li($\varepsilon_\alpha = 1.47$ MeV); ^{7}Li($\varepsilon_\alpha = 2.47$ MeV); ^{10}B($\varepsilon_\alpha = 4.46$ MeV); ^{11}B($\varepsilon_\alpha = 8.66$ MeV); ^{12}C($\varepsilon_\alpha = 7.37$ MeV), and ^{16}O($\varepsilon_\alpha = 7.16$ MeV).

If the projectiles with high separation energies are used, i.e., $\varepsilon_s \gtrsim 5$ MeV, the breakup influence in σ_F becomes negligible. This fact is responsible for the saturation of P_F at high ε_s values. Experimentally this is verified if several *strongly bound* targets are used [19–21] with a unique projectile, as seen in Fig. 3. In this case, the breakup probability of the bound nucleus is small turning P_F constant. In other words the value of P_F is determined by the least bound participant of the collision. If two weakly bound nuclei are involved in the collision, the projectile and target *survival probability* can be taken into account by the expression

$$\sigma_F = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1)[1 - T_l^{\mathrm{bu}}(\text{target})] \times [1 - T_l^{\mathrm{bu}}(\text{projectile})] \mathring{T}_l^F ;$$

however, unless the target and projectile separation energy are comparable, the fusion hindrance is dominated by the least bound participant of the collision. This fact is due to the rapid variation of P_F as a function of ε_s, for $\varepsilon_s < 5$ MeV as seen in Fig. 2.

In summary, we have shown that the hindrance of fusion observed in the light heavy-ion reaction can be correlated to the low nucleon (cluster) separation energy of s-p nuclei and also the enhancement of breakup cross sections. This correlation is justified by a model calculation which couples the breakup channel to the fusion channel and considers these two reaction channels as being dominant. In the case of nuclear reactions of astrophysical interest, involving weakly bound exotic nuclei as ^{11}Li ($\varepsilon_{2n} \sim 0.2$ MeV), ^{14}Be, etc., it is expected that a significant reduction of the fusion cross section in the barrier region results owing to the low survival probability of the participant(s). Furthermore, sub-barrier fusion reactions of neutron rich unstable nuclei are considered in order to enhance the probability of formation of very heavy compound nuclei. Some of these nuclei may have low binding energies and consequently a low "survival probability," thus reducing the fusion cross section.

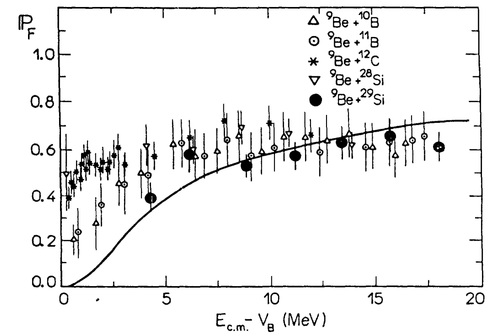

FIG. 3. Fusion ratio P_F for ^{9}Be projectile on several targets. Data for the ^{9}Be + ^{10,11}B were extracted from Ref. [20], ^{9}Be + ^{12}C from Ref. [21], and ^{9}Be + ^{28}Si from Ref. [19].

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