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IFUSP/P-957

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Dezembro/1991

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Abstract

It is shown 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. Detailed 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.

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 are commonly attributed to nuclear structure effects[3]. 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, as it will be shown, to the opening of important direct channels among which the break up process can be dominant. It is expected that weakly bound nuclei, as i.e. ^{9}Be whose neutron separation energy is 1.67 MeV, might have a low *survival probability* on the *way* to fusion, leading to an 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 letter, 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 break–up 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, forming a given compound nucleus.

In this work, the ^{38}Ar compound nucleus has been formed via different entrance channels. Complete fusion cross section (σ_F) for the ^{9}Be + ^{29}Si [4], ^{11}B + ^{27}Al and ^{19}F + ^{19}F reactions were measured[5] as a function of the bombarding energy. Data for the ^{12}C + ^{26}Mg were obtained from the literature[6] as well as other light systems further presented in the systematics[1,7,8]. Total reaction cross sections (σ_R) were estimated based on optical model fits of the elastic scattering data. Details are presented elsewhere$^{4)}$. The fusion cross section σ_F as well as fusion ratio $\mathbb{P}_F(E) = \sigma_F(E)/\sigma_R(E)$ shown in figure 1 present a well known energy dependence, an increase with energy in the barrier usually called region I up to a saturation value $\mathbb{P}_F$ around the energy regime II. This nomenclature concerning the different energy regimes was introduced in the Glas and Mosel fusion model$^{9)}$. The above behaviour of σ_F and $\mathbb{P}_F$ is illustrated with the data for the ^{9}Be + ^{29}Si reaction.

To account for the break–up effect on the fusion of i.e. ^{9}Be + target, we employ the model recently developed by Hussein et al.$^{10)}$. In this latter reference the one dimensional barrier penetration model based on the Hill–Wheeler expression$^{9)}$ of the transmission coefficient,

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

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

where k is the asymptotic wave number, i.e., $k = \sqrt{\dfrac{2\mu\ E_{c.m.}}{\hbar^2}}$, V_B is the height of the average fusion barrier, R_B its position and $\hbar\omega$ the measure of its curvature, is appropriately modified by multiplying $\mathring{T}^F_\ell$ by the break–up *survival probability* $(1 - T^{bu}_\ell)$. The resulting inhibited fusion cross section is given by$^{10)}$

$$\sigma_F = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1)(1 - T^{bu}_\ell)\, \mathring{T}^F_\ell \tag{2}$$

Thus for all ℓ,s only the fraction of the incident flux that remains intact contribute to complete fusion. In this case, the break–up cross–section is given by

$$\sigma_{bu} = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1)\, T^{bu}_\ell (1 - \mathring{T}^F_\ell)\ , \tag{3}$$

which guarantees that low angular momentum partial waves do not contribute to the break–up. The sum $\sigma_F + \sigma_{bu}$ describes the reaction cross–section (σ_R) of the model. At high bombarding energies, this cross–section is necessarily smaller than the optical model extrated 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 $(1 - T^{bu}_\ell)$ was derived in reference 11 and it reads:

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

where $\mathcal{F}_0^2$ is a strength factor that measures the degree of coupling of the entrance channel to the break–up one$^{12)}$, $\left|S^{(1)}_\ell\right|$ is the modulus of the elastic S–matrix in the break–up channel and is given by $(1 - \mathring{T}^F_\ell\,(E_{c.m.} - Q))^{1/2}$, with Q being the break–up Q–value and $I_\ell(\eta,s,\xi)$ is a Coulomb radial integral

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

with $\xi = (k_1 - k_2)/(k_1 + k_2)$ being the adiabaticity parameter, $\eta = \frac{z_1 z_2 e^2}{\hbar v}$ the Sommerfed parameter, $s = \frac{1}{k\alpha}$, $k_{1(2)}$ the wave number in the elastic (break–up) 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 ^{9}Be, taking b to be a neutron which releases the two α–particles from ^{8}Be, the value of parameter α results in $\alpha \cong 3.75$ fm.

The energy dependence of the fraction $\mathbb{P}_F = \sigma_F/\sigma_R$ vs. $E_{c.m.}$ is shown in figure 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 figure 2 a representative calculation showing $\mathbb{P}_F$ vs. ε_s. One sees a cutoff around $\varepsilon_s \sim 4$ MeV, followed by tendency to saturation. This behaviour reflects the fact that at energies around the fusion barrier break–up 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 break–up have larger ℓ–values than ℓ_c [4]. Figure 2 also indicates that when loosely bound nuclei are involved (low ε_s), the fusion cross section is hindered turning $\mathbb{P}_F$ 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 projectiles with high separation energies are used i.e. $\varepsilon_s \gtrsim 5$ MeV, the break–up influence in σ_F becomes negligible. This fact is responsible for the saturation of $\mathbb{P}_F$ at high ε_s values. Experimentally this is verified if several *strongly bound* targets are used[13–15] with a unique projectile, as seen in figure 3. In this case, the break–up probability of the bound nucleus is small turning $\mathbb{P}_F$ constant. In other words the value of $\mathbb{P}_F$ 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

$$\sigma_F = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) \left[1 - T_\ell^{bu}(\text{target})\right] \left[1 - T_\ell^{bu}(\text{projectile})\right] \overset{o}{T}{}_\ell^F$$

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 $\mathbb{P}_F$ as a function of ε_s, for $\varepsilon_s < 5$ MeV as seen in figure 2.

In summary, we have shown in this work that the hindrance of fusion observed in light heavy ion reaction is correlated to the low nucleon (cluster) separation energy of s–p nuclei and also the enhancement of break–up cross sections. This correlation is supported quantitatively by a model calculation which couples the break–up channel to the fusion channel. 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).

This work was supported in part by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brasil.

The authors acknowledge Drs. N. Added, N. Carlin, R.M. Anjos and L. Fante Jr. for the fruitful discussions.

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12. *The strength factor* $\mathcal{F}_0$ *has been adjusted to fit the* $^9Be+^{29}Si$ *data (figure 1). The value obtained from this fit is* $\mathcal{F}_0^2 = 15\ MeV$. *Since* $\mathcal{F}_0$ *is related to the normalization of the relative cluster wavefunction, we expect* $\mathcal{F}_0^2$ *to scale as* $1/\varepsilon_s$ – *(ref. 11). This scaling has been used to obtain the fusion cross section for the other systems mentioned in this work.*
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FIGURE CAPTIONS

Figure 1. Energy dependence of the fusion cross section for the $^{9}Be+^{29}Si$ reaction. Dots describe the experimental values. Hatched area represents a fit of the data by the Glas and Mosel model 9). The dashed line represents the $\overset{o}{\sigma}_F$ 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 equation 2 taking into account the coupling to the break–up channel. The calculated energy dependence of the fusion ratio $\mathbb{P}_F = \sigma_F/\sigma_R$ is represented by the solid line (right hand scale).

Figure 2. Dependence of the fusion ratio $\mathbb{P}_F \equiv \sigma_F/\sigma_R$ on the cluster separation energy. Circles describe the experimental values determined around the saturation energy (at $E_{c.m.} = 2\,V_B$) for $A \equiv {}^{9}Be + {}^{29}Si$, $B \equiv {}^{19}F + {}^{19}F$ 5), $C \equiv {}^{12}C + {}^{26}Mg$ 6), and $D \equiv {}^{11}B + {}^{27}Al$ 5). The solid line describes the calculations of $\mathbb{P}_F$ as a function of the separation energy ε_s for $^{9}Be + ^{29}Si$ reaction at several bombarding energies ($E_{c.m.} = 25$; 20; 15 and 10 MeV). The open squares represent the calculated values of the $\mathbb{P}_F$ for the systems presented and calculated according to eq. (2) at the same energies of the experimental points.

Figure 3. Fusion ratio $\mathbb{P}_F$ for ^{9}Be projectile on several targets. Data for the $^{9}Be+^{10,11}B$ were extracted from ref. 14); $^{9}Be+^{27}C$ from ref. 15) and $^{9}Be+^{28}Si$ from ref. 13).

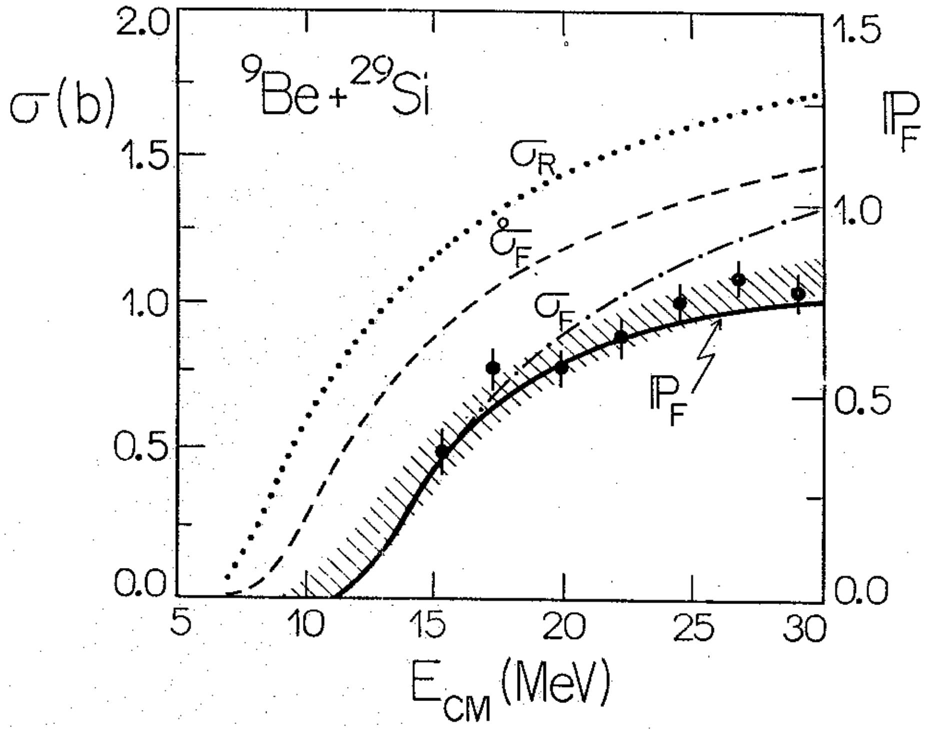
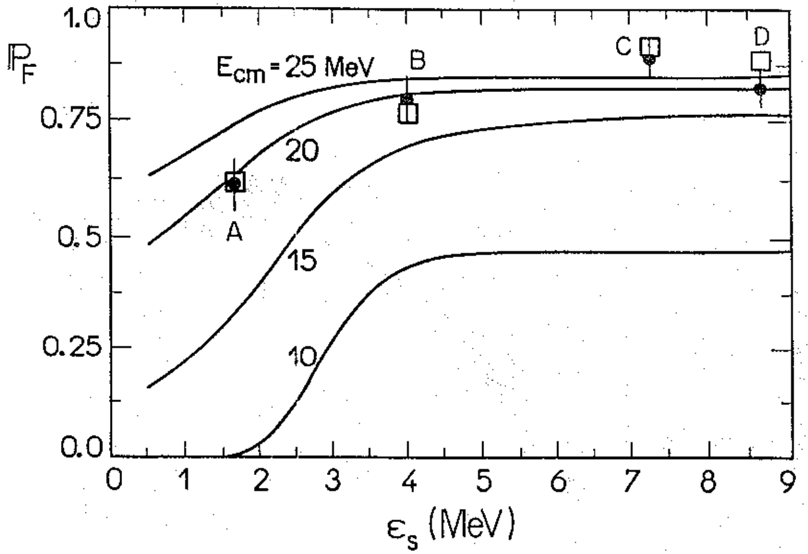
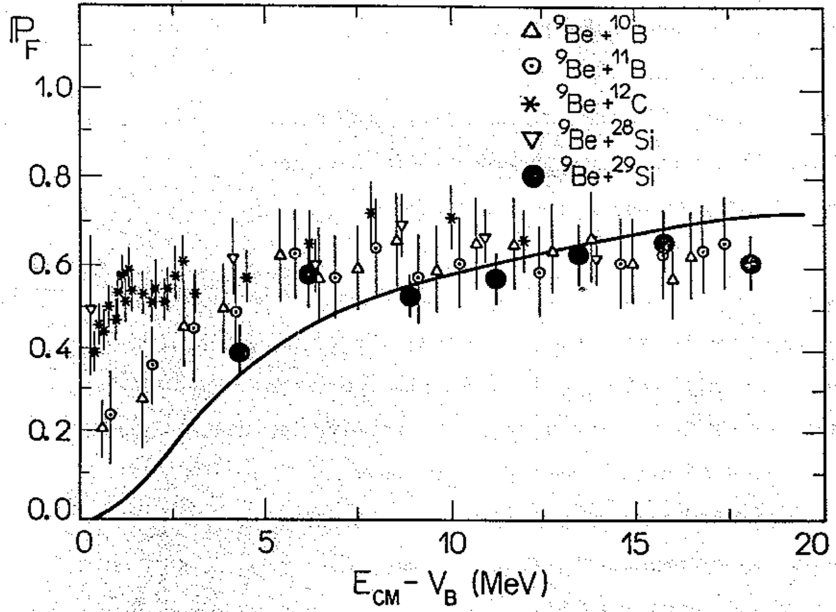


Fig. 1



$\mathbb{P}_F$
1.0
0.75
0.5
0.25
0.0
E_{cm} = 25 MeV
20
15
10
A
B
C
D
0
1
2
3
4
5
6
7
8
9
ε_s (MeV)

Fig. 2



$\mathbb{P}_F$
1.0
0.8
0.6
0.4
0.2
0.0
^{9}Be + ^{10}B
^{9}Be + ^{11}B
^{9}Be + ^{12}C
^{9}Be + ^{28}Si
^{9}Be + ^{29}Si
0
5
10
15
20
$E_{CM} - V_B$ (MeV)

Fig. 3