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No evidence of break-up effects on the fusion of ^{9}Be with medium-light nuclei

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Abstract

Fusion cross sections were measured for the $^{9}\mathrm{Be}+{}^{27}\mathrm{Al}$ and $^{19}\mathrm{F}+{}^{9}\mathrm{Be}$, ^{12}C systems, at energies above the Coulomb barrier, in order to investigate the possible effect of fusion hindrance due to the break-up of the weakly bound nuclei. Comparisons with one-dimensional barrier penetration models and with other similar systems, where no break-up is expected to occur, show no evidence of fusion hindrance.

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Heavy ion fusion reactions, at energies near the barrier, have been extensively studied in the last two decades. In particular, investigations were focused on the coupling effects with inelastic and other reaction channels at sub-barrier energies. The effect of the break-up of weakly bound stable and radioactive nuclei on the fusion cross section has become a field of recent interest [1–5]. It should be reminded at this point that without a full understanding of the fusion mechanism between stable nuclei, it is very difficult to draw conclusions about the behavior

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of the fusion process induced by halo nuclei like ^{11}Li or ^{11}Be. Therefore, the comprehension of the reaction mechanisms induced by intense beams of stable weakly bound nuclei, such as ^{6,7}Li and ^{9}Be, should be very important for the study of reactions induced by the low intensity radioactive beams.

At present there are few experimental data on this subject and the theoretical predictions are controversial. They predict either the enhancement of the fusion, due to the coupling of the break-up channel [1,2] or the hindrance of the fusion, due to the loss of incident flux in the complete fusion channel, caused by the break-up [3–5]. The effect of the break-up on the fusion cross-section can also be predicted to be different at sub-barrier and above barrier regimes [6], with fusion enhancement at low energies and fusion suppression at high energies. The role of the nuclear and Coulomb break-up may be determined by spanning the studies over different target nuclei.

The available data for light systems ($A_t, A_p \leqslant 12$) show controversial results. Takahashi et al. [4] reported a strong suppression for the fusion of ^{6,7}Li and ^{9}Be induced reactions, when compared with highly bound projectiles, based on the small fusion to total reaction cross section ratios. They observed a suppression of fusion up to 75% for the $^{6}\text{Li} + {}^{9}\text{Be}$ system. On the other hand, Mukherjee et al. [7] did not observe any fusion suppression for some of the same systems. A recent work by Mukherjee et al. [8], using the inverse $^{12}\text{C} + {}^{7}\text{Li}$ reaction, confirms the conclusion that there is no fusion suppression for light systems. For medium mass systems, there is only one work, on the $^{9}\text{Be} + {}^{64}\text{Zn}$ system [9], and it shows no fusion suppression. For heavy targets (for instance, ^{208}Pb and ^{209}Bi), important fusion suppressions, of the order of 30%, have been observed at energies above the Coulomb barrier (1.5–2.0V_B) [10–12]. Systems using radioactive beams on heavy targets have been recently studied [13–19], and fusion suppression was also observed at energies near and above the Coulomb barrier, whereas large fusion enhancement is still present at sub-barrier energies [16,17].

Therefore, from the data available in the literature, there are evidences of fusion suppression at energies above the Coulomb barrier due to the break-up, for systems involving heavy targets, both for stable and radioactive beams. However, at sub-barrier energies the fusion is enhanced and it is more intense for radioactive beams. For medium and light systems, however, no systematic behavior was observed so far.

In order to contribute to this subject, we have measured the fusion and elastic scattering cross sections for the $^{9}\text{Be} + {}^{19}\text{F}$, ^{27}Al systems, at energies above the Coulomb barrier. In addition, a different interpretation to the data previously reported in Ref. [20] for the $^{9}\text{Be} + {}^{29}\text{Si}$ system is given. The ^{9}Be nucleus breaks up as $n + 2\alpha$, $S_n = 1.57$ MeV or $\alpha + {}^{5}\text{He}$, $S_\alpha = 2.47$ MeV. The effect of the ^{9}Be break-up on the fusion was studied by comparing the fusion excitation functions for the ^{9}Be induced reactions with the ones for similar systems available in the literature, where no break-up is expected to occur or to be important. The separation energies for the ^{6,7}Li and ^{9}Be nuclei are $S = 1.48, 2.45$ and 1.57 MeV, respectively, and it has been shown [21] that the break-up effects on the fusion for the ^{7}Li induced reactions are much less important than for ^{6}Li and ^{9}Be. Among the nuclei involved in the other systems analyzed in this Letter, the ^{17}O is the one with the smallest separation energy, $S_n = 4.14$ MeV, that is much larger than the separation energy for the ^{7}Li. Therefore, the $^{19}\text{F} + {}^{9}\text{Be}$ system was compared with the $^{18}\text{O} + {}^{10}\text{B}$ and $^{17}\text{O} + {}^{11}\text{B}$ systems [22], all of them leading to the same compound nucleus, and with the $^{19}\text{F} + {}^{12}\text{C}$ system [23], which keeps the same projectile. The fusion of the $^{19}\text{F} + {}^{12}\text{C}$ system was also measured and the results are presented and discussed in this report. The results obtained for the $^{9}\text{Be} + {}^{27}\text{Al}$ system were compared with those of the neighboring systems $^{11}\text{B} + {}^{27}\text{Al}$ [24] and also with $^{9}\text{Be} + {}^{29}\text{Si}$ [20], which leads to the same compound nucleus. The energy range for all the systems discussed here lies in the so-called "region I", which spans the energy range from slightly above the Coulomb barrier to around three times this value. In some cases the data extend to higher energies, the "region II", where the fusion cross section reaches a saturation value. The following data analysis was restricted only to the region I and, therefore, this work is not concerned with sub-barrier fusion. Total reaction cross sections were derived from the optical model analysis of the elastic scattering data, to obtain the fusion to reaction cross section ratios for the systems reported here.

For the fusion cross section measurements of the $^{9}\text{Be} + {}^{27}\text{Al}$ system, the experiments were carried out at the 20UD TANDAR Laboratory at Buenos Aires. The $^{19}\text{F} + {}^{9}\text{Be}$, ^{12}C reactions were studied using the 8UD

Pelletron Laboratory of the University of São Paulo. Elastic scattering for the ^{9}Be + ^{27}Al system were also obtained at São Paulo.

For the fusion of ^{9}Be + ^{27}Al, the ^{9}Be beams were produced starting with BeO-ions at the ion source. The beams were accelerated at ten energies in the range 33 MeV $\leqslant E_{\mathrm{Lab}} \leqslant$ 55 MeV, well above the Coulomb barrier. The target thickness was approximately 80 μg/cm^2, a thin Au layer of 10 μg/cm^2 was evaporated on it for normalization purposes. For the fusion of the ^{19}F + ^{9}Be and ^{12}C systems, fluorine beams were accelerated at eight energies within the range 48 MeV $\leqslant E_{\mathrm{Lab}} \leqslant$ 72 MeV. The ^{9}Be target thickness was approximately 80 μg/cm^2, deposited onto a carbon backing of $\sim$ 10 μg/cm^2, which in addition allowed the study of the ^{19}F + ^{12}C reaction. A thin Au layer of 10 μg/cm^2 was also deposited over the ^{9}Be target.

The used detection systems were $E - \Delta E$ telescopes consisting of a large ionization chamber, followed by a surface barrier detector for the ^{9}Be + ^{27}Al experiment, and a large anode-splitted ionization chamber and a position sensitive silicon detector for the ^{19}F + ^{9}Be, ^{12}C experiments. The entrance windows of the detectors were 250 μg/cm^2 and 80 μg/cm^2 mylar foils, respectively. The ionizing-gas pressures were 25 Torr and 20 Torr of P10, respectively. The ΔE resolution in both experiments was good enough to separate events differing by one unity of atomic number (Z).

For the ^{9}Be + ^{27}Al experiment, angular distributions were obtained in the range $10^\circ \leqslant \theta_{\mathrm{Lab}} \leqslant 20^\circ$, at four different angles (10°, 12°, 15° and 20°). For the ^{19}F + ^{9}Be, ^{12}C experiments, angular distributions were obtained in the range $7^\circ \leqslant \theta_{\mathrm{Lab}} \leqslant 37^\circ$, and the anode plate of the ionization chamber had five segments that allowed to measure simultaneously at five angles (in steps of 1°) of the angular distribution. The maxima of the angular distributions were located near 12°, and therefore the experimental angular distributions covered around 80% of the complete angular distribution. The extrapolations to the most forward part of the distributions were performed with the use of the shape of the theoretical predictions obtained by the statistical code PACE [25]. Deviations from these calculations are second order corrections. The precision of this method allows the evaluation of the complete angular distributions with an accuracy better than 5%, and consequently reliable results of the total fusion cross sections are obtained.

The separation of the residues from the fusion with ^{9}Be and ^{12}C target nuclei was performed as follows: residues with atomic numbers $Z > 13$ are originated just from the fusion with ^{12}C. From the predictions of the evaporation code PACE we learned that the residues corresponding to $11 \leqslant Z \leqslant 13$ originate from the fusion with both ^{9}Be and ^{12}C (the $Z = 13$ channels are important for the ^{12}C while the channels for $Z = 11$, 12 are important for the fusion with ^{9}Be) and for $Z < 11$ they come just from the fusion with ^{9}Be. Therefore, for $Z = 11$, 12 and 13 we made experimental corrections, using the kinematics for the energy spectra predicted by the code PACE and taking into account the target thicknesses. This procedure allowed the separation of the contributions from each system to those evaporation channels. The error associated with this procedure was estimated as of the order of 4%. This correction method was checked by the comparison of our results for the fusion cross section of the ^{19}F + ^{12}C system with the ones available in the literature [23]. Also, the derived relative intensities for the different evaporation channels, for both systems, were in agreement with the predictions of the code PACE.

The overall fusion cross section error is of the order of 10–15% in both experiments.

The elastic scattering data for the ^{19}F + ^{9}Be, ^{12}C systems were simultaneously obtained with the fusion data. The elastic scattering for the ^{9}Be + ^{27}Al system was measured with a set of nine collimated surface barrier detectors, with 5° angular separation between two adjacent detectors and a resolution of the order of 350 keV. The Be-beams had energies within the range 12 MeV $\leqslant \mathrm{E}_{\mathrm{Lab}} \leqslant$ 35 MeV and the angular distributions were taken in the range $10^\circ \leqslant \theta_{\mathrm{Lab}} \leqslant 170^\circ$.

Fig. 1 shows the fusion excitation functions for three systems: ^{19}F + ^{9}Be and two other systems leading to the same compound nucleus where no breakup is expected to occur, ^{18}O + ^{10}B and ^{17}O + ^{11}B (the experimental data were obtained from Ref. [22]). The separation energies for the nuclei of these systems are $S_{2n} = 12.19$ MeV for ^{18}O, $S_n = 4.14$ MeV for ^{17}O, $S_\alpha = 4.46$ MeV for ^{10}B and $S_\alpha = 8.66$ MeV for ^{11}B; these are much larger than the separation energies of ^{9}Be and ^{6,7}Li. As the detection system used in

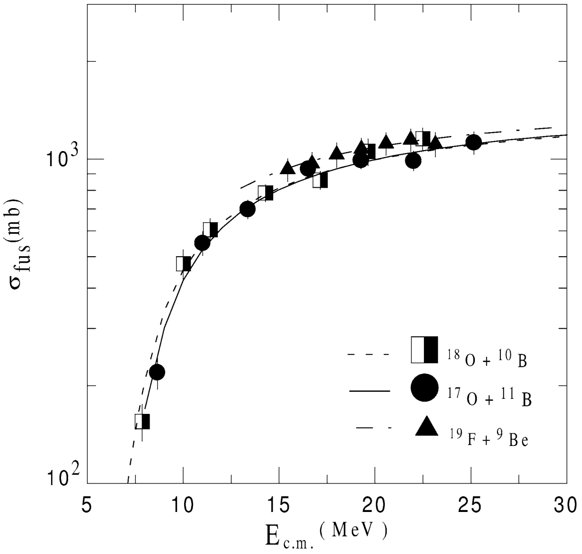

Fig. 1. Fusion excitation functions for the $^{19}F + {}^{9}Be$ (this work), $^{18}O + {}^{10}B$ [22] and $^{17}O + {}^{11}B$ [22] systems, all of them leading to the same compound nucleus. The fitting curves were obtained using the Wong model [26].

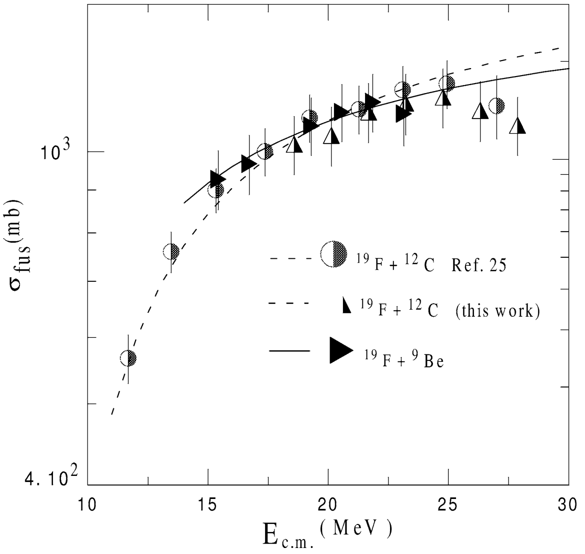

Fig. 2. Fusion excitation functions for $^{19}F + {}^{9}Be$ (this work) and $^{19}F + {}^{12}C$ (this work and Ref. [23]). Only for the ^{9}Be target system the break-up process should occur.

these experiments is sensitive just to the atomic number of the residues, contributions from incomplete fusion could not be separated experimentally from complete fusion in these data.

One can see that the experimental data for the three systems are quite similar. The fitting curves are the results of the calculations using the Wong model [26], and it can be seen that the fits are reasonably good. Fits were also performed using the Krappe–Nix–Sierk (KNS) [27] model (not shown), leading to similar results. The present results provide evidence that there is no fusion suppression for the $^{19}F + {}^{9}Be$ system, for energies above the Coulomb barrier.

Fig. 2 shows the fusion excitation functions for two systems: $^{19}F + {}^{9}Be$ and $^{19}F + {}^{12}C$. No break-up is expected to occur in the last system. The data for the $^{19}F + {}^{12}C$ system were also obtained from the literature [23] and they agree with the ones obtained in the present work. The experimental data are fairly well reproduced by the calculations, except for the highest energies, corresponding to the region of saturation of the fusion cross section ("region II"), where the Wong and KNS models are no longer valid.

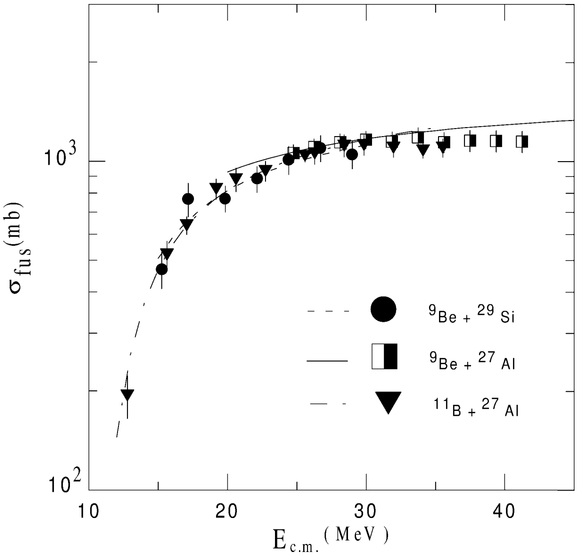

Fig. 3. Fusion excitation functions for the $^{9}Be + {}^{27}Al$ (this work), $^{9}Be + {}^{29}Si$ [20] and $^{11}B + {}^{27}Al$ [24] systems. These are similar systems, but with a higher probability of the projectile break-up for the first two of them.

Fig. 3 shows the fusion excitation functions for the three systems: $^{9}Be + {}^{27}Al$ (this work), $^{9}Be + {}^{29}Si$ [20] and $^{11}B + {}^{27}Al$ [24]. The two latter systems lead to the same compound nucleus. Fits were performed using the Wong and KNS models. Their agreement with the data obtained for the "region I" is reasonably good,

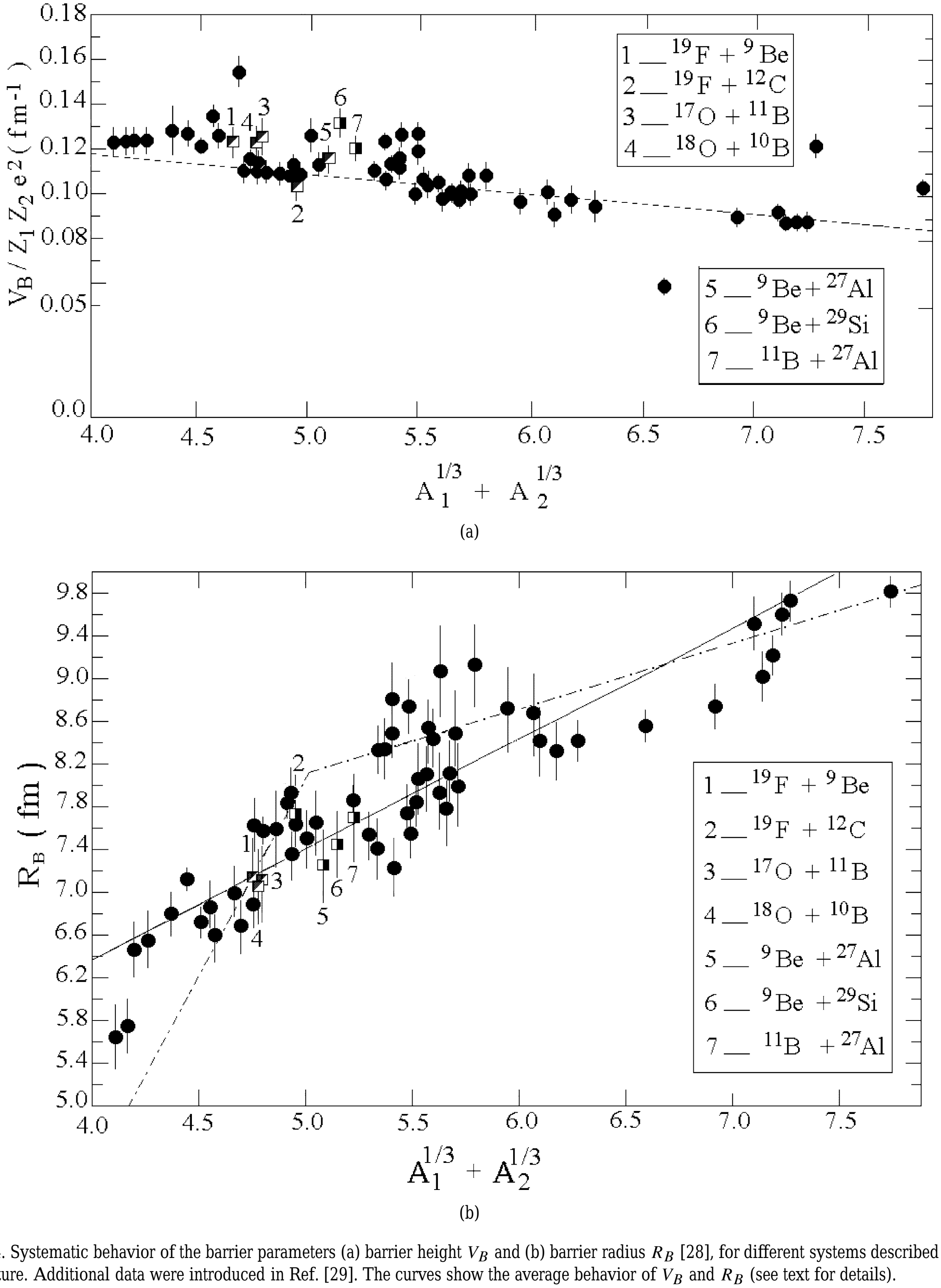

Fig. 4. Systematic behavior of the barrier parameters (a) barrier height V_B and (b) barrier radius R_B [28], for different systems described in the literature. Additional data were introduced in Ref. [29]. The curves show the average behavior of V_B and R_B (see text for details).

and there is no evidence of break-up effects for the ^{9}Be induced reactions, when compared with the $^{11}\mathrm{B}+{}^{27}\mathrm{Al}$ system.

The fusion cross section can be parametrized in terms of the barrier height V_B and barrier radius R_B by $\sigma_{\mathrm{fus}} = \pi R_B^2(1 - V_B/E)$, that is the limit of the expression [26] $\sigma_{\mathrm{fus}} = (R_B^2\hbar\omega/2E)\ln\{1 + \exp[2\pi(E - V_B)/\hbar\omega]\}$ for relatively large values of E. Fig. 4 shows the systematic behavior [28,29] for the parameters V_B and R_B, obtained by the analysis of many previously studied systems, including the systems studied and discussed in the present work. They are represented by the expressions:

$$\frac{V_B}{Z_1 Z_2 e^2} = 0.153 - 0.00875\left(A_1^{1/3} + A_2^{1/3}\right)\ (\mathrm{fm}^{-1}),$$

$$R_B = \begin{cases} -10.5 + 3.71\left(A_1^{1/3} + A_2^{1/3}\right)\ \mathrm{fm}, \\ \quad \text{for } \left(A_1^{1/3} + A_2^{1/3}\right) < 5, \\ 5.06 + 0.61\left(A_1^{1/3} + A_2^{1/3}\right)\ \mathrm{fm}, \\ \quad \text{for } \left(A_1^{1/3} + A_2^{1/3}\right) \geqslant 5, \end{cases}$$

shown as dashed lines in Fig. 4. The full curve is a trial of obtaining just one systematic curve for the whole mass region [29]:

$$R_B = 2.25 + 0.035\left(A_1^{1/3} + A_2^{1/3}\right)\ \mathrm{fm}.$$

One can see that the barrier parameters derived from the fits of the fusion excitation functions agree well with their systematic behavior.

It is interesting to mention that the data of the $^9\mathrm{Be}+{}^{29}\mathrm{Si}$ system were used by the authors of Ref. [20] as an evidence that there is some fusion hindrance caused by the break-up, due to the fact that the fusion to reaction cross section ratios were much smaller than the one for this system. The same argument was used in Ref. [4] for other light systems with weakly bound nuclei. In Table 1 the values of this ratio for the seven systems studied in this work are quoted. These ratios were derived at the high energy part of the “region I”. One can see that the ratio is less than one for all the systems, and that there is no evidence that it is smaller for the ^{9}Be induced reactions. The conclusion is that the reaction cross section is larger than the fusion cross section for these medium-light systems in this energy regime, but this does not mean that there is evidence of fusion hindrance.

Table 1
Fusion to total reaction cross section ratios for the different systems (* values were obtained from the experimental data reported in the present work), and values of the corresponding maximum experimental fusion cross sections extracted from the data and from the systematic (all the values have uncertainties of the order of 10%)

System	$\sigma_{\mathrm{fusion}}/\sigma_{\mathrm{reaction}}$	$\sigma^{\mathrm{exp}}_{\mathrm{fus(max)}}$ (mb)	$\sigma^{\mathrm{theor}}_{\mathrm{fus(max)}}$ (mb)
$^{19}\mathrm{F}+{}^9\mathrm{Be}$*	0.71	1150	1000
$^9\mathrm{Be}+{}^{27}\mathrm{Al}$*	0.71	1180	1060
$^9\mathrm{Be}+{}^{29}\mathrm{Si}$ [20]	0.65	1100	1050
$^{19}\mathrm{F}+{}^{12}\mathrm{C}$* [23]	0.85	1200	1100
$^{17}\mathrm{O}+{}^{11}\mathrm{B}$ [22]	0.45	1120	1060
$^{18}\mathrm{O}+{}^{10}\mathrm{B}$ [22]	0.53	1150	1060
$^{11}\mathrm{B}+{}^{27}\mathrm{Al}$ [24]	0.80	1120	1050

In Table 1 also the maximum values obtained for the experimental fusion cross sections for all the systems discussed in this report are included and the corresponding expected values obtained from the systematic [30]. The experimental and expected values are comparable. This is another signature that there is no fusion cross section suppression due to the ^{9}Be break-up.

In summary, we have measured and analyzed different medium-light systems, at energies above the Coulomb barrier. Experimental data for three of these systems are presented in this work. Some of the systems have the weakly bound ^{9}Be as one of the colliding nuclei. The similar behavior of the fusion excitation functions for all the systems show that the break-up of ^{9}Be does not inhibit the fusion cross sections in this energy regime. The maximum values of the experimental cross sections are similar to the expected values, with no significant break-up influence. For all these systems the fusion cross sections are found to be smaller than reaction cross sections, but there is no signature that this fact comes from the effect of the break-up. From these results we may conclude that, for these medium-light systems of stable nuclei, the short range nuclear break-up dominates the break-up process and does not inhibit the fusion cross sections. For halo nuclei beams the conclusions could be different, since the nuclear break-up has a long range polarization potential [6]. From the literature we notice that for heavy systems of stable nuclei, the long range Coulomb break-up predominates and leads to the fusion suppression at high energies.

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