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Fusion of stable weakly bound nuclei with ^{27}Al and ^{64}Zn

I. Padron,* P. R. S. Gomes,† R. M. Anjos, J. Lubian, C. Muri, and J. J. S. Alves
Instituto de Física, Universidade Federal Fluminense, Avenida Litorânea, s/n, Niterói, R.J., 24210-340, Brazil

G. V. Martí, M. Ramírez, A. J. Pacheco, O. A. Capurro, J. O. Fernández Niello, J. E. Testoni, D. Abriola,
and M. R. Spinella
*Laboratorio TANDAR, Departamento de Física, Comisión Nacional de Energía Atómica, Avenida del Libertador 8250, 1429,
Buenos Aires, Argentina*

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Fusion cross sections were measured for the ^{6,7}Li$+^{27}$Al, ^{64}Zn systems, at energies above the Coulomb barrier, in order to study the influence of the breakup of stable weakly bound nuclei on the fusion process. The analysis was completed by the inclusion of the data of fusion induced by ^{9}Be and the strongly bound ^{16}O and ^{11}B projectiles on the same targets. The fusion excitation functions have similar behavior for all projectiles incident on both targets and they show no indication of fusion hindrance.

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I. INTRODUCTION

The role of the breakup of stable and radioactive weakly bound nuclei on the fusion cross section, at near barrier energies, has become a field of recent interest. Due to the low intensities of the radioactive beams, it is very convenient to produce fusion reactions with the high intensity stable beams that are weakly bound, and consequently should have a significant breakup probability. A full understanding of the fusion and breakup mechanisms involving stable nuclei is very important for the study of reactions induced by radioactive beams. There are three suitable nuclei for such experiments: ^{6}Li, ^{7}Li, and ^{9}Be. Beams of these nuclei are easily produced and they have small separation energies: ^{6}Li breaks up into ^{4}He$+^{2}$H, with separation energy $S_{\alpha}=1.48$ MeV; ^{7}Li into ^{4}He$+^{3}$H, with $S_{\alpha}=2.45$ MeV; and ^{9}Be into $^{8}\mathrm{Be}+n \rightarrow n+{}^{4}\mathrm{He}+{}^{4}\mathrm{He}$, with $S_{n}=1.67$ MeV or into ^{5}He$+^{4}$He, with $S_{\alpha}=2.55$ MeV.

At present, there are some fusion cross section data on this subject, involving radioactive [1–6] and stable [7–15] beams. A major difficulty with many of the fusion experiments is the fact that the complete fusion (CF) and the incomplete fusion (ICF), resulting from the fusion of one of the breakup fragments with the target, may not be separated, depending on the experimental detection method used. In these kinds of experiments the sum of the cross sections of these two mechanisms somehow masks the effect of the breakup on the complete fusion. The measurement of the direct breakup process cross section (not leading to CF nor ICF) has also been reported [16–18]. Most of the mentioned data were obtained for heavy targets, where the Coulomb breakup predominates over the nuclear breakup.

The present theoretical understanding concerning the breakup process and its effect on the fusion cross section is controversial. Some models [19] predict the fusion cross section enhancement, when compared with the fusion induced by strongly bound nuclei, due to the additional breakup channel. This enhancement should be particularly important at sub-barrier energies, where the coupling effects on the fusion may be strong. On the opposite side, some models [20,21] suggest the hindrance of the complete fusion, due to the loss of incident flux in this channel, caused by the breakup, and characterized by a fusion survival probability smaller than one. Hagino *et al.* [22] have predicted fusion cross section enhancement at sub-barrier energies and fusion hindrance at above barrier energies, both effects originating from the breakup process.

Actually, when one studies the breakup process and its influence on the fusion mechanism, at least five different reaction mechanisms should be considered: (i) direct breakup or breakup/ scattering, that occurs at large distances or large angular momenta; (ii) direct breakup or breakup/scattering, that occurs at short distances or small angular momenta; (iii) ICF following the breakup, when one of the fragments fuses with the target; (iv) CF following the breakup, when all projectile fragments fuse with the target; and (v) CF as a single step mechanism, not produced by breakup. The first process (i) should not affect the complete fusion (v), since it is concerned with different partial waves. The other three breakup processes [(ii), (iii), and (iv)] may influence the complete fusion (v) cross section. When one measures the breakup/scattering cross section, actually one is measuring the sum of the (i) and (ii) processes. When one measures the complete fusion cross sections of systems with weakly bound nuclei, actually one is measuring the sum of the cross sections of two processes: (iv) and (v). When one measures the sum of CF and ICF cross sections, three mechanisms [(iii), (iv), and (v)] are mixed together and therefore the possible fusion suppression that could be observed is due to the effect of the direct breakup corresponding to low angular momenta (ii).

From our knowledge, so far no such complete calculations, involving the five processes separately, have been reported, except for simple calculations based on classical trajectories and restricted to the two-body ^{6,7}Li breakup [12].

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*Permanent address: Center of Applied Studies of Nuclear Development, P.O. Box 6122, Havana, Cuba.

†Corresponding author. FAX: (+55)-21-26203881. Email address: paulogom@if.uff.br

Recent theoretical results [23,24] suggest that the differences in the direct breakup cross sections are not reflected in the values of the fusion cross sections, in agreement with experiments [16–18] that measure the direct breakup cross sections for ^{6,7}Li and ^{6}He on ^{208}Pb and ^{209}Bi. Keeley *et al.* [23] derived the direct breakup, and total (CF+ICF) and reaction cross sections for ^{6,7}Li projectiles on light targets, by continuum discretized coupled channel calculations. The results show that although the breakup process for ^{6}Li has cross sections that are one or two orders of magnitude larger than for ^{7}Li, the total fusion (CF + ICF) cross sections for the two Li isotopes are similar.

Another approach to study the effect of the breakup on the fusion cross section, at near barrier energies, is to analyze the behavior of the energy dependence of the real and imaginary parts of the optical potentials, that gives information on coupling mechanisms at this energy region. What is usually observed is the so-called "threshold anomaly," a localized peak in the real part of the interacting potential, associated with a decrease of the imaginary part of the potential. Experiments on elastic and inelastic scattering of ^{6,7}Li [25,26] and ^{9}Be [13,27] have shown that the usual threshold anomaly is present in the ^{7}Li, but not in the ^{6}Li and ^{9}Be scatterings. This fact was interpreted [25–30] as the effect of the strong coupling of the elastic channel with the first ^{7}Li excited state and the one-neutron transfer channels, giving rise to an attractive polarization potential. For ^{7}Li, since the dissociation energy is much higher than the first low-lying excited state (0.478 MeV), the inelastic scattering is favored in relation to the breakup. Actually, when this inelastic channel is included in the coupled channel calculations [27], the threshold anomaly is destroyed. However, for ^{6}Li and ^{9}Be, the dissociation energy is smaller than the excitation energies of their first excited states and, consequently, the breakup is the dominant direct channel. The role of the breakup channel in the total polarization potential was interpreted [13,25–30] as giving rise to a repulsive potential that might exceed the attractive term arising from the inelastic coupling to bound states, resulting in the vanishing of the threshold anomaly of the optical potential. Therefore, the breakup of ^{6}Li and ^{9}Be inhibits their inelastic excitation and, consequently, does not allow the occurrence of the usual fusion cross section enhancement, relative to the predictions of one dimensional barrier penetration models. From this interpretation, at near barrier energies, the breakup and reaction cross sections for the ^{6}Li induced reactions should be higher than for the ^{7}Li, but the fusion cross section should be smaller.

So, the present situation is far from being theoretically understood, and this is a very rich field to be explored. More data are required for stable and radioactive weakly bound nuclei, spanning the energy region from sub-barrier to twice or three times the barrier, because there is evidence that the role of the breakup on the fusion depends on the energy regime. Efforts should be made to perform experiments that can distinguish among direct breakup, complete fusion, and incomplete fusion.

In order to contribute to this field, we have measured the fusion cross sections for the ^{6,7}Li+^{27}Al, ^{64}Zn systems, at energies above the Coulomb barrier. We have already reported the measurements of the fusion of ^{9}Be with ^{27}Al [15] and ^{64}Zn [13,14]. At present, there are very few data on the fusion of weakly bound nuclei on medium-light targets. It is important to span the mass region from light to heavy targets, in order to study the competition between the Coulomb and nuclear breakups, and the relation between the distance where the breakup occurs, the partial waves that are involved, and their influence on the fusion cross section. For these three stable weakly bound nuclei, the separation energies, the coupling characteristics, the breakup probabilities, and the energy dependence of the elastic scattering are very different. Therefore, the comparison of the fusion cross sections induced by them and by strongly bound nuclei on the same targets is an important contribution to the understanding of the effect of the breakup on the fusion process.

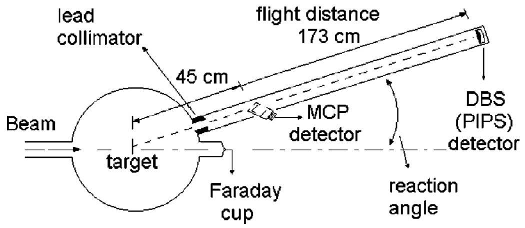

FIG. 1. Schematic picture of the experimental set-up of the time of flight device used in the present work.

II. THE EXPERIMENTAL SETUP AND MEASUREMENTS

The experiments were performed at the 20-UD tandem accelerator of the TANDAR Laboratory, at Buenos Aires. Beams of ^{6,7}Li were produced by a SNICS type ion source, from cathodes consisting of a mixture of 70% lithium isotopes, with 30% silver powder. The beam energies at the laboratory system ranged from 24.0 to 43.0 MeV, well above the nominal Coulomb barriers ($V_{B,Lab} \approx 15$ MeV and ≈ 10 MeV for ^{64}Zn and ^{27}Al targets, respectively). Therefore, this work is not concerned with sub-barrier fusion. The incident beam was collimated, at the entrance of the scattering chamber, by a 2 mm lead collimator. The ^{27}Al target was self-supported, with thickness of 46 μg/cm^2. The metallic ^{64}Zn target, with a thickness of 50 μg/cm^2, was deposited on a 10 μg/cm^2 carbon backing. The detector system was a time of flight (TOF) heavy ion system, specially designed and built for these experiments. The reaction product detection angles could be varied by the use of a sliding flange between the scattering chamber and the TOF tube, allowing the measurement of angular distributions at a reasonably wide angular range, and with angle uncertainty of 0.1°. The data were taken from $\theta_{Lab} = 10°$ to 30°. Figure 1 shows, schematically, the experimental setup. Another lead collimator was placed at the entrance of the time of flight tube, in order to shield the start detector from the x rays produced when the beam impinges on the target. The flight distance between the start and stop detectors was 173 cm.

The detection assembly consisted of one microchannel plate (MCP) from Barle S1396-5025 used as the start detector, and one passivated implanted planar silicon (PIPS) detector—Canberra TMPD900-27-300—used as the stop de-

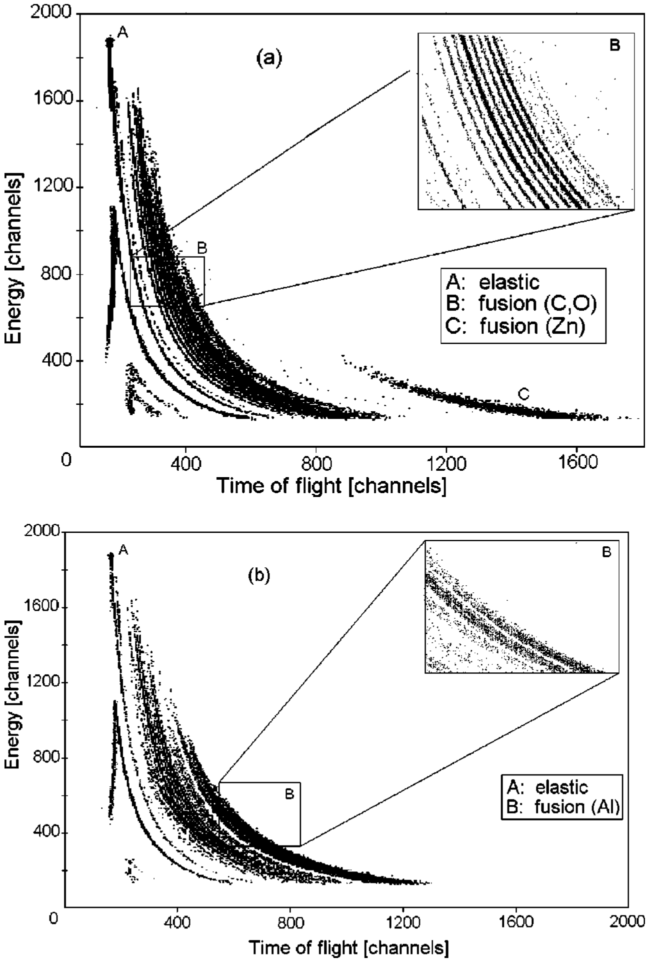

FIG. 2. Typical time of flight spectra, for the (a) $^{6}\mathrm{Li}+^{64}\mathrm{Zn}$ and (b) $^{6}\mathrm{Li}+^{27}\mathrm{Al}$ systems.

tector. A time resolution of 700 ps was achieved for a typical time of flight of 400 ns ($<0.2\%$). Figures 2(a) and 2(b) show typical energy vs TOF spectra, taken for $E_{Lab}=43$ MeV and $\theta_{Lab}=10°$, for $^{6}\mathrm{Li}+^{64}\mathrm{Zn}$ and $^{27}\mathrm{Al}$ systems, respectively. The enlargement shows that the system was able to separate events differing by one unit of atomic mass and that the fusion reaction products are well separated from the fusion products with $^{12}\mathrm{C}$ backing and $^{16}\mathrm{O}$ contaminants. The electronic cutoff threshold was set close to the minimum values but, even so, the spectra were corrected by the use of the statistical model code PACE [31], in order to take into account the events with energies below that threshold.

The masses of the residual nuclei originating from the complete fusion (CF) and those from the incomplete fusion (ICF) are mostly the same, and we were not able to separate CF from ICF. Therefore, the measured fusion cross sections correspond to the sum of these two processes.

III. THE FUSION CROSS SECTIONS

Differential fusion cross sections were measured for $\theta_{Lab}=10°$, 12°, 15°, and 20°, for the $^{6,7}\mathrm{Li}+^{27}\mathrm{Al}$, and for $\theta_{Lab}=10°$, 12°, 15°, 20° and 30° for the $^{6,7}\mathrm{Li}+^{64}\mathrm{Zn}$ reactions. The maxima of the angular distributions are located at $\theta_{Lab}\approx 10°-15°$, and the measured angular ranges cover around 60% of the complete angular distributions, according to the shape of the theoretical predictions obtained by the statistical code PACE. The extrapolation to the most forward and backward parts of the angular distributions was performed using the code PACE. Figure 3 shows the measured differential fusion cross section for one bombarding energy, for the $^{7}\mathrm{Li}+^{64}\mathrm{Zn}$ system, and the prediction of the PACE code, represented by the full line. The precision of this method allows the evaluation of the complete angular distributions with an accuracy of the order of 5%.

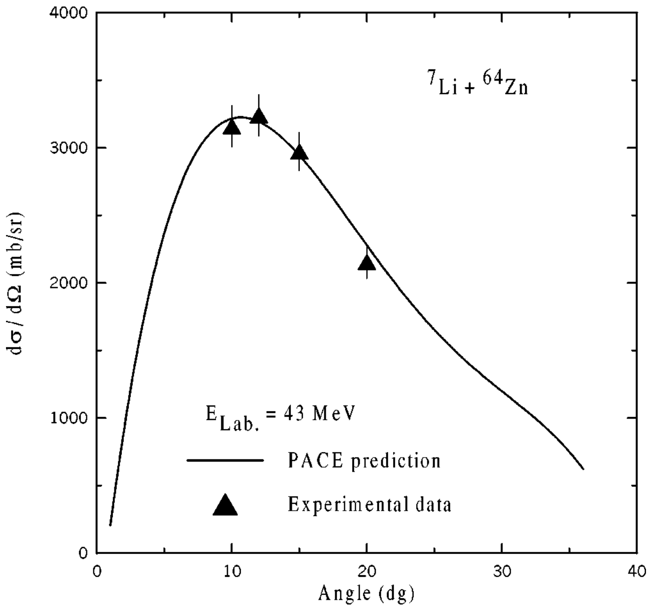

FIG. 3. Measured differential fusion cross section for the energy of 43 MeV, for the $^{7}\mathrm{Li}+^{64}\mathrm{Zn}$ system, and the prediction of the PACE code, represented by the full line.

The efficiency of the MCP start detector was calculated for each spectrum as the ratio between the number of coincidence events with the MCP recorded by the PIPS detector, and number of counts in the single spectrum recorded by this stop detector. Its value is within the range 0.13–0.20 obtained for the $^{7}\mathrm{Li}+^{64}\mathrm{Zn}$ reactions, and 0.28–0.38 obtained for the $^{7}\mathrm{Li}+^{27}\mathrm{Al}$ reactions. The associated uncertainties in these values are in the range 2%–4%.

The normalization of the fusion cross sections was obtained by counting the elastic scattering events in the spectra, when the experimental conditions were such that the scattering was purely Rutherford. Otherwise, it was obtained using the integrated beam current in the Faraday cup. From the comparison of the normalization factors obtained when both methods could be applied simultaneously, it was proved that the normalization method using the Faraday cup was quite reliable. When the first method was used, the associated uncertainty was around 2%, otherwise it was the sum of three contributions: around 2% from the beam intensity, 5% from the target thickness, and 1% from the solid angle determination.

Table I shows the derived fusion cross sections for the measurements reported in this paper. The overall error bar for the total fusion cross sections was found to be of the

TABLE I. Total fusion cross sections measured in this work (in mb).

E_{Lab} (MeV)	^{6}Li + ^{27}Al	^{7}Li + ^{27}Al	^{6}Li + ^{64}Zn	^{7}Li+ ^{64}Zn
24	1090 ± 93	1050 ± 94	597 ± 45	656 ± 56
28	1014 ± 93	1050 ± 94	823 ± 59	883 ± 66
31	1173 ± 100	1238 ± 99	869 ± 60	922 ± 64
34	1152 ± 90	1210 ± 95	984 ± 68	1002 ± 69
37	1162 ± 86	1237 ± 91	1053 ± 71	1134 ± 77
40	1148 ± 78	1238 ± 84	1022 ± 65	1105 ± 75
43	1170 ± 77	1252 ± 83	1166 ± 71	1254 ± 81

order of 6–8 % for the ^{6,7}Li+^{64}Zn systems, and 7–10 % for the ^{6,7}Li+^{27}Al systems.

IV. DISCUSSION OF THE RESULTS

In order to investigate the influence of the breakup on the fusion cross section, in the following we analyze and compare the fusion excitation functions of nine medium-light systems, at above barrier energies: the weakly bound ^{6,7}Li and ^{9}Be, the strongly bound ^{16}O ($S_{\alpha}=7.16$ MeV) and ^{11}B ($S_{\alpha}=8.66$ MeV) nuclei as projectiles, and the ^{27}Al and ^{64}Zn nuclei as targets. Four of these systems (^{6,7}Li+^{27}Al, ^{64}Zn) are related with the measurements reported in this paper, while the data for the other five systems have already been published: ^{9}Be+^{27}Al [15], ^{9}Be+^{64}Zn [13,14], ^{11}B+^{27}Al [32], ^{16}O+^{64}Zn [33], and ^{16}O+^{27}Al [34].

Each fusion excitation function was fitted using the Wong model [35]. The use of this simple one dimensional barrier penetration model is justified in the energy region above the Coulomb barrier, where inelastic and transfer channel couplings do not affect the fusion cross section significantly. If the direct breakup/scattering process had an important influence on the fusion cross section, the derived barrier parameters should have anomalous values. Reasonable fits (not shown here) were obtained for all the systems, and the barrier parameters, shown in Table II, agree with the values from the systematic range [36], within the usual fluctuations around the average values. In the systematic range proposed by Vaz [36], the values of the barrier parameters are $r_{ef}=2.2951-0.2966\log_{10}(Z_1Z_2)$ fm and $r_{of}=2.0513-0.245\,56\log_{10}(Z_1Z_2)$ fm, where $V_B=Z_1Z_2e^2/[r_{ef}(A_1^{1/3}+A_2^{1/3})]$ and $R_B=r_{of}(A_1^{1/3}+A_2^{1/3})$.

TABLE II. Barrier parameters obtained by the fitting of the fusion excitation functions, using the Wong model (Ref. [35]), and the barrier parameters obtained from the systematic (syst) range (Ref. [36]).

System	$V_{B,\text{c.m.}}$ (MeV)	r_{ef}-exp (fm)/ [r_{ef}-syst (fm)]	R_B (fm)	r_{of}-exp (fm)/ [r_{of}-syst (fm)]
^{6}Li+^{27}Al	7.55	1.55 / [1.82]	7.21	1.50 / [1.66]
^{7}Li+^{27}Al	7.38	1.55 / [1.82]	7.36	1.50 / [1.66]
^{9}Be+^{27}Al	8.81	1.67 / [1.79]	7.29	1.44 / [1.63]
^{11}B+^{27}Al	11.2	1.60 / [1.76]	7.69	1.47 / [1.61]
^{16}O+^{27}Al	16.1	1.69 / [1.70]	7.95	1.44 / [1.56]
^{6}Li+^{64}Zn	14.0	1.61 / [1.72]	7.46	1.28 / [1.57]
^{7}Li+^{64}Zn	13.8	1.59 / [1.72]	7.71	1.30 / [1.57]
^{9}Be+^{64}Zn	16.2	1.76 / [1.68]	10.0	1.65 / [1.54]
^{16}O+^{64}Zn	32.5	1.63 / [1.59]	10.0	1.53 / [1.47]

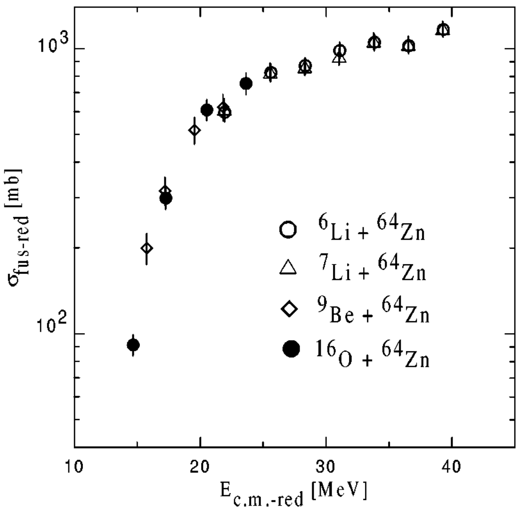

FIG. 4. Fusion excitation functions for the ^{6}Li, ^{7}Li, ^{9}Be, and ^{16}O+^{64}Zn systems.

The usual fluctuations of the values of r_{ef} and r_{of} are typically of the order of 0.15–0.20 fm. From Table II one can notice that just for the ^{6,7}Li+^{64}Zn systems the derived values of r_{of} are slightly smaller than the systematic range. Therefore, the overall results are a indication that there is no effect of the direct breakup on the fusion cross section, at least for these systems and energy regime.

Figure 4 shows the fusion excitation functions for the ^{64}Zn target bombarded by ^{6}Li, ^{7}Li, ^{9}Be, and ^{16}O, as a function of $E_{\text{c.m.}}-V_B$. One can see that the behavior of the fusion cross sections for the four systems are very similar. Figure 5 shows the fusion excitation functions for the ^{27}Al target bombarded by ^{6}Li, ^{7}Li, ^{9}Be, ^{16}O, and ^{11}B. Again, the behavior of the fusion cross sections for all the systems is

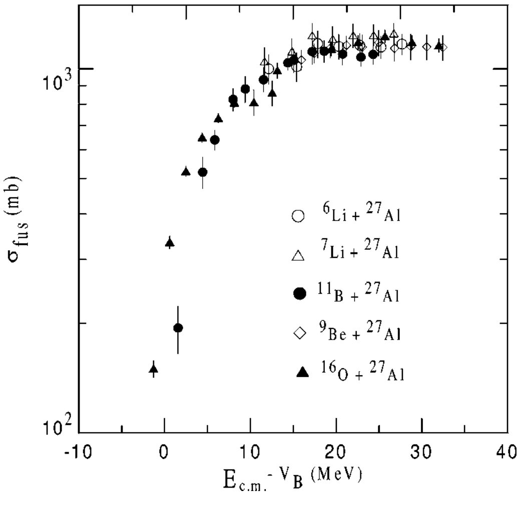

FIG. 5. Fusion excitation functions for the ^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, and ^{16}O+^{27}Al systems.

quite similar, regardless of the projectile separation energy. Therefore, the present results for the fusion cross sections induced by the stable weakly bound ^{6,7}Li and ^{9}Be projectiles, at energies above the barrier, show no signature of fusion hindrance, when compared with the fusion cross sections of the strongly bound nuclei ^{16}O and ^{11}B. One can make a conjecture that the direct breakup cross sections for the three weakly bound nuclei may be large and quite different for each of these projectiles, and they may increase the reaction cross sections, but they do not affect the total fusion cross section (CF+ICF), at least within the experimental uncertainties. This effect has been recently suggested by Keeley *et al.* [23] for light systems, and verified by Kolata [37] for heavy systems. It is also in agreement with the conclusions drawn from low energy elastic scattering of ^{6,7}Li on heavy targets [25,26].

V. SUMMARY

We have designed and built a time of flight heavy ion detector system that is able to measure angular distributions of the evaporation residues of fusion of light projectiles on a wide variety of targets, simultaneously with elastically scattered nuclei. We have measured and analyzed the fusion cross sections, at above barrier energies, for the ^{6,7}Li $+ ^{27}$Al, ^{64}Zn systems. These data, complemented by the previously reported data for ^{9}Be on the same targets, make an interesting set of available results that allows the comparison of the effect of the breakup of stable weakly bound nuclei on the fusion of medium-light systems. The results show almost identical fusion excitation functions not just for these three projectiles, but also for the fusion of strongly bound nuclei reacting with the same targets. Furthermore, within experimental error limits, no evidence of suppression of the total fusion cross section due to the breakup was observed. Although the breakup threshold energy is quite different for each of the studied projectiles, and the cross sections for direct breakup may differ by one or two orders of magnitude among these nuclei [16–18], these facts are not reflected in the fusion cross section, as already pointed out in theoretical work [23] and experiments with heavy targets [12,37]. Also, although the behavior of ^{6}Li and ^{9}Be scattering is qualitatively different from ^{7}Li scattering [25–30], this is not reflected in the total fusion cross sections.

We conclude that direct breakup that does not lead to complete fusion or incomplete fusion is the Coulomb breakup that takes place at large distances or for trajectories corresponding to large angular momenta [process (i)], and it does not affect the fusion mechanism, although it affects the elastic scattering and reaction cross section [25–30]. The breakup process that might inhibit or enhance the complete fusion occurs at small distances or central trajectories, where both Coulomb and nuclear breakups are important. For heavy targets it has been observed [10–12] that although the ICF cross sections were found to be significant, when compared to CF cross sections (of the order of 30% of CF above the barrier), at high energies the sum of the measured CF + ICF cross sections agrees with the predictions of one dimensional barrier penetration models that do not consider the breakup effect. So, for heavy targets it is found that the effect of the direct breakup, corresponding to low partial waves [process (ii)], on the total fusion is negligible. For the ^{9}Be $+ ^{64}$Zn system, where the CF and ICF cross sections could be measured separately [13], the ICF cross section was found to be negligible. Therefore, we expect that the ICF is not as important for light systems, at energies above the barrier, as it is for the heavy ones. Furthermore, if the ICF is not important, the CF following breakup [process (iv)] is not expected to be relevant. Therefore, the present results for the ^{6,7}Li, ^{9}Be$+ ^{27}$Al, ^{64}Zn systems show that the total fusion cross section (CF+ICF) is also not inhibited for medium-light systems, due to breakup effects. These results show that for the medium-light systems, the effect on the total fusion cross section of the direct breakup that occurs at low angular momenta is also negligible.

For a complete understanding of the influence of the breakup process on the fusion cross section, complete fusion, incomplete fusion, direct breakup, and elastic scattering have to be measured with enough degree of precision to evaluate the influence of each process separately. While such complex experiments are lacking, the relevant information has to be extracted from the available data. In addition, further theoretical models and calculations deserve to be developed.

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