Breakup Processes in the Systems ^{9}Be+^{208}Pb,^{209}Bi and ^{6}Li+^{208}Pb around the Coulomb Barrier

C. Signorini,[1,*)] T. Glodariu,[1,2,**)] Z. H. Liu,[3] M. Mazzocco,[1] M. Ruan[3] and F. Soramel[4]

[1] *Physics Department and INFN, via Marzolo 8, I-35131 Padova, Italy*
[2] *INFN, Laboratori Nazionali di Legnaro, viale dell'Università 2, I-35020 Legnaro (Padova), Italy*
[3] *China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, People's Republic of China*
[4] *Physics Department and INFN, via delle Scienze 208, I-33100 Udine, Italy*

From recent experimental data for the systems ^{9}Be+^{208}Pb,^{209}Bi and ^{6}Li+^{208}Pb it results that the complete fusion process is hindered with respect to realistic theoretical predictions (CCFUSS). However the ^{9}Be+^{208}Pb,^{209}Bi complete fusion cross sections are different from each other contrary to expectations. The ^{6}Li data show breakup of the projectile into two outgoing fragments, well reproduced by CDCC approach, as well as α or deuteron capture from the target; this is relevant for the theories on the reaction dynamics around the Coulomb barrier.

In this contribution we want to discuss the interaction at Coulomb barrier energies of the two most loosely bound stable projectiles (^{9}Be and ^{6}Li) at the light of recent experimental data and related theories. These nuclei play an important role as link to the light radioactive ion beams like ^{11}Be, ^{6}He, ^{8}B and the future ones even more loosely bound with additional halo or skin structure. The nuclei ^{9}Be and ^{6}Li, loosely bound by 1.57 and 1.47 MeV respectively, but still stable, allow to perform experiments with statistical accuracy much higher than what can be presently achieved with radioactive ion beams; this can give good hints about how the above mentioned radioactive ion beams might behave concerning the reaction dynamics. On this point many theoretical considerations have already been going on for many years. As a brief summary we can say that the "complete fusion cross section", i.e. the fusion of the whole projectile, is expected to be somehow enhanced below the barrier, mainly due to the halo structure with the consequent lowering of the Coulomb barrier, while it should be somehow reduced above the barrier because of the competing breakup process. Indeed this seems to happen in the ^{6}He+^{238}U, although recent experimental results at the Louvain la Neuve laboratory, still under analysis, indicate a much smaller enhancement. The ^{6}He+^{209}Bi system shows a limited enhancement, while the ^{11}Be+^{209}Bi system does not show for the moment any hindrance. These results are extensively discussed in Ref. 1).

The key point is the interplay between the halo/skin structure and the small binding energy. For many of the mentioned nuclei a strong "inclusive" α-channel has been observed at colliding energies around the Coulomb barrier: "inclusive" means

*) E-mail: signorini@pd.infn.it
**) On leave from: NIPNE, 76900 Magurele, Romania.

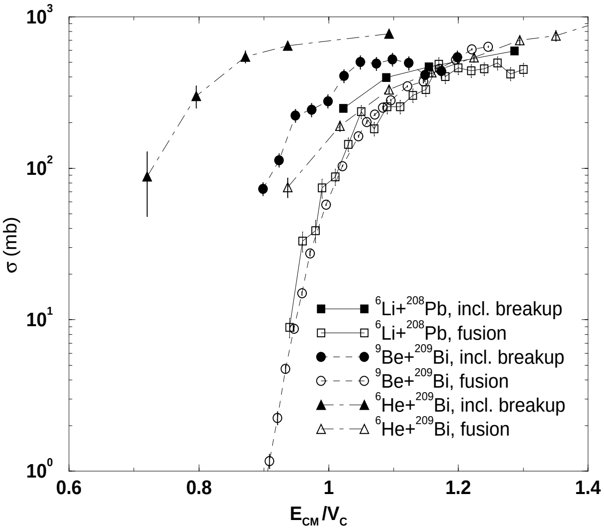

Fig. 1. Cross sections for the "inclusive" production of α particles ("inclusive breakup") compared to the "complete" fusion cross section for the systems ^{6}Li+^{208}Pb, ^{9}Be+^{208}Pb and ^{6}He+^{208}Pb.

that the α-particles were detected regardless the coincidences with other fragment(s) of the incoming projectile.

Figure 1 shows these results for the systems ^{9}Be+^{209}Bi, ^{6}Li+^{208}Pb, ^{6}He+^{209}Bi compared with the relative fusion cross sections. These α channels have cross sections larger than the fusion ones especially below the barrier. Similar effects are reported for ^{9}Be+^{208}Pb[2] as well as in lighter systems like ^{6}Li+^{28}Si.[3] We are dealing with a very strong channel not observed with well bound projectiles, which is definitely originating from the expected breakup process of the loosely bound projectile. This channel together with the "complete" fusion one exhausts the total reaction cross section deduced from elastic scattering data; this is shown in Fig. 2 for the same systems of Fig. 1.

How does this strong channel influence the global fusion process? In the following we will review the systems ^{9}Be+^{208}Pb (mostly studied at ANU, Canberra), ^{9}Be+^{209}Bi and ^{6}Li+^{208}Pb (studied at Padova in collaboration with CIAE, Beijing).

In the system ^{9}Be+^{208}Pb[4] the complete fusion cross section resulted to be $\sim$ 30% smaller than the predictions based onto the CCFULL calculations and this was attributed to the breakup of the projectile. In addition this work reports the incomplete fusion of He-fragments, originating from the ^{9}Be breakup, that accounts for this 30% reduction. In ^{9}Be+^{209}Bi,[5] similarly to the previous system, a complete fusion reduction of $\sim$ 30% is also reported. This evidence of the incomplete fusion contribution was also confirmed from an additional analysis of our experimental data: Fig. 3 shows the results of the cross section for the production of ^{212}At, mainly coming from the partial fusion of He-fragments originated from ^{9}Be breakup.

In conclusion these two systems behave in a very similar way. However there is still a discrepancy since the two complete fusion cross sections, contrary to simple expectations, differ systematically above the barrier from each other as shown in the

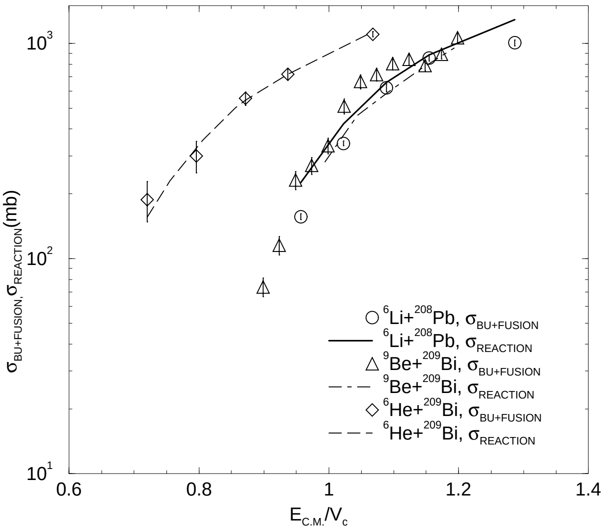

Fig. 2. Total reaction cross sections compared with the sum of the "complete" fusion and the "inclusive" α channels for the systems ^{6}Li+^{208}Pb, ^{9}Be+^{208}Pb and ^{6}He+^{208}Pb.

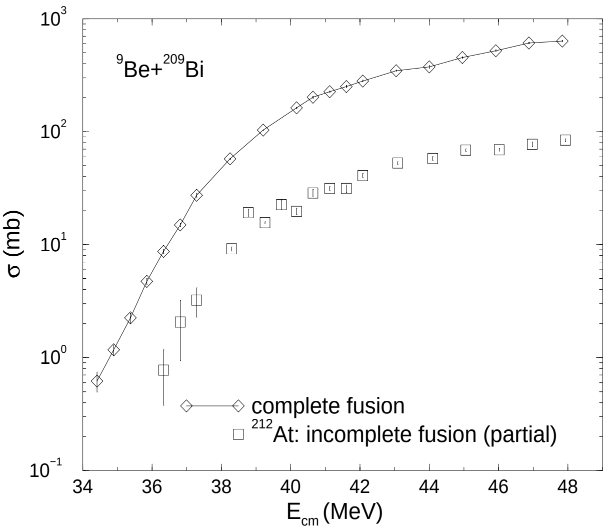

Fig. 3. Cross sections for the production of ^{212}At in the system ^{9}Be+^{208}Pb. This nucleus is produced most likely by the partial fusion with the target of Helium fragments originating from ^{9}Be breakup.

comparative plots of Figs. 4 and 5. It is evident from these figures that above the barrier the ^{209}Bi cross sections are 50 to 100 mb larger than for ^{208}Pb ones beyond the experimental (statistical) errors.

We have undertaken a critical analysis of our data in order to look for possible errors as origin of this discrepancy. Possible candidates are:

- fission cross sections. They were measured only in Ref. 6), where no coincidences among fission fragments were done. These cross sections are a factor ~10 larger

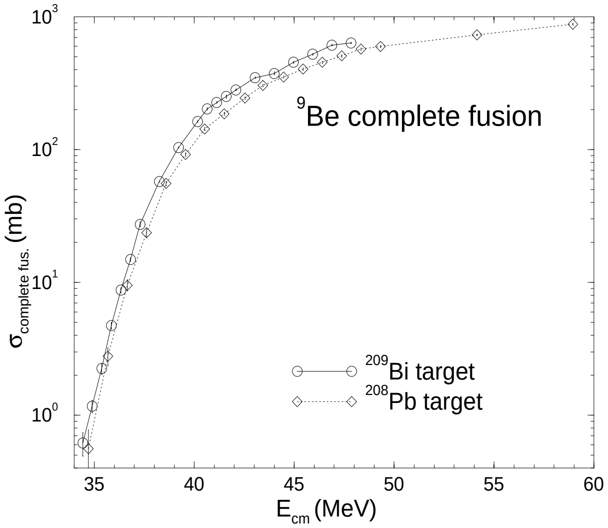

Fig. 4. Comparison between ^{208}Pb and ^{209}Bi complete fusion cross section with ^{9}Be projectile. The E_{cm} for the ^{208}Pb target has been normalized to the ^{209}Bi one via the ratio of the two Coulomb barriers with respect to ^{9}Be.

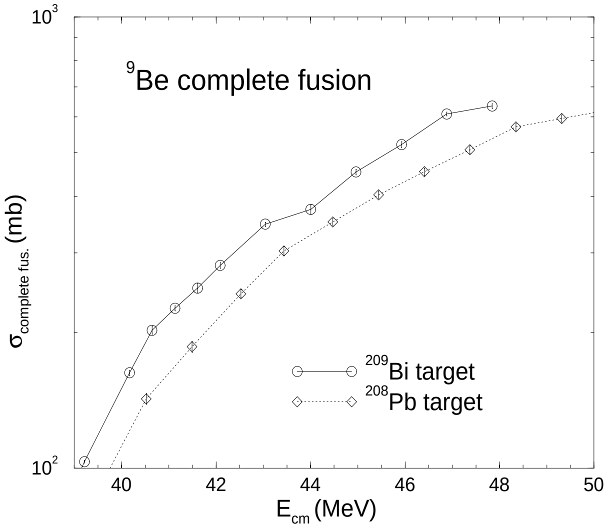

Fig. 5. Expanded portion of Fig. 4.

than the ^{208}Pb ones.[4)] This result is however not unrealistic since it is known that, in region where the fission of the compound nucleus just starts being relevant, a difference of one unit in the charge number (as in the case of ^{208}Pb and ^{209}Bi) can make a considerable increase in fission cross section. These fission cross sections are moreover similar to the ^{6,7}Li+^{209}Bi ones,[7)] which are again a factor ∼10 bigger than the ^{9}Be+^{208}Pb ones;

- evaporation residues cross sections. They were measured three times by our group[5),6),8)] in two different laboratories: Munich (Germany) and Tsukuba

(Japan) with similar results. So both the absolute energy scale as well as the absolute cross section normalizations are quite reliable.

We believe however that a new measurement of both total fusion cross sections for the two systems should be undertaken. If this difference is confirmed we should conclude that the two targets do not surprisingly behave in the same way as expected in the weak coupling approximation.

We move now to a detailed analysis of the α particles inclusive production, strongly related to the breakup process. In the system ^{9}Be+^{208}Pb, in addition to the "complete" and "incomplete" fusion, the following processes are reported: a strong "inclusive" α-channel, a 1n-transfer to ^{209}Pb (see also a previous work[9)]) as well as a breakup channel.[2),10)] This makes quite complex the whole scenario of the interaction at the Coulomb barrier.

In the system ^{6}Li+^{208}Pb several processes may occur following the projectile breakup and most of them contributing to the inclusive α production:

1. $\alpha + d$+^{208}Pb with the possible subsequent deuteron breakup into $p + n$;
2. $\alpha + p + n$+^{208}Pb;
3. $d + (\alpha$+^{208}Pb): α-capture;
4. $\alpha + (d$+^{208}Pb): d-capture;
5. $\alpha + p + (n$+^{208}Pb): 1n-transfer;
6. $\alpha + n + (p$+^{208}Pb): 1p-transfer.

In addition, the complete fusion of the colliding nuclei produces the evaporation of protons, deuterons, α particles and obviously neutrons.

Using the 4π charged particle detecting system 8πLP[11)] at LNL, we have measured the total cross sections of the following channels for the system ^{6}Li+^{208}Pb: *i*) α-inclusive production (σ_α); *ii*) $\alpha - d$ ($\sigma_{\alpha-d}$) and $\alpha - p$ ($\sigma_{\alpha-p}$) coincidences; *iii*) deuteron inclusive production (σ_d), *iv*) proton inclusive production (σ_p). Figure 6 upper panel shows the cross sections of these processes at four different ^{6}Li bombarding energies.

The lower panel of this figure shows the predictions of the statistical code EMPIRE-II,[12)] that evaluates the evaporation cross sections two orders of magnitude smaller than the experimental values. From this analysis we came to the conclusion that deuteron, proton and α channels do not significantly originate from the evaporation process, but from breakup. From the cross sections shown in Fig. 6 we deduced the component originating from the deuterons (α particles) emitted after the capture of the α (deuteron) fragment into the target (incomplete fusion + transfer). These cross sections, under the assumptions that the evaporation processes and the 1p-transfer are negligible, were obtained in this way:

- $\sigma_{d-capture} = \sigma_\alpha - \sigma_{\alpha-d} - \sigma_{\alpha-p}$;
- $\sigma_{\alpha-capture} = \sigma_d - \sigma_{\alpha-d} - \sigma_{\alpha-p}$.

In these formulas we have also assumed that all the protons in coincidence with the α particles mainly originate from the deuteron breakup. These cross sections (preliminary results) are shown in Fig. 7. It is clear that the two incomplete fusion + transfer channels have considerable cross sections. They cannot therefore be neglected in any theoretical description of the reaction dynamics at the barrier. In addition it results that the lighter fragment (deuteron) is captured with higher probability than the

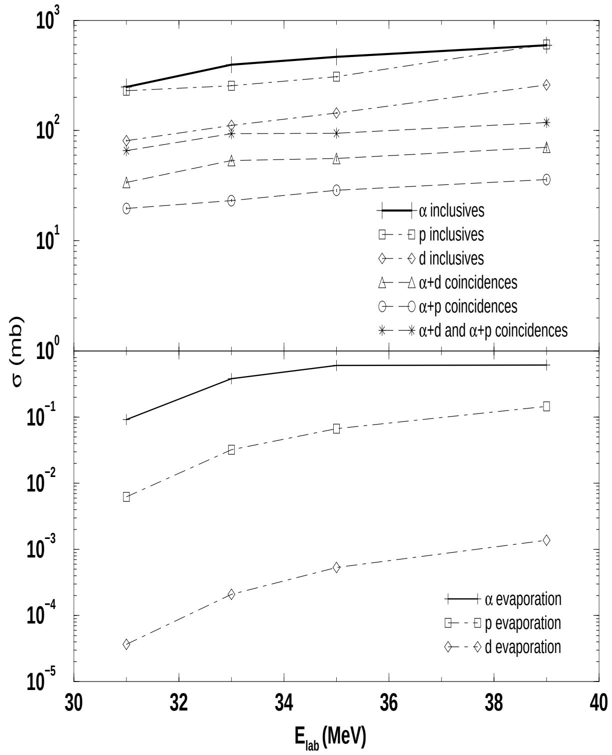

Fig. 6. Upper part: experimental cross sections for the various ^{6}Li breakup channels. Lower part: statistical evaporation channels following the fusion of ^{6}Li with the ^{208}Pb target.

heavier one (α particle).

It is believed that this process is strongly influenced by the breakup of ^{6}Li which obviously proceeds via continuum unbound states. Extensive coupled channel calculations are going on with the code FRESCO[13)] in the framework of the Continuum Discretized approach (CDCC), as partly described in Refs. 14),15). The breakup channel of ^{6}Li into $\alpha + d$ is very well reproduced (see Fig. 7). The same calculations also reproduce very well the ^{6}Li continuum excitation energy distribution, as discussed in detail in Ref. 15). Figure 8 shows the experimental and theoretical ^{6}Li complete fusion (usual CCFULL approach)[16)] and the total fusion (= complete fusion + d-capture + α-capture). The CCFUSS theory overestimates the complete fusion cross section; this suggests that the complete fusion is hindered, as in the previously discussed case, due to the breakup channel. Figure 8 also shows the predictions of extensive CDCC calculations;[17)] these calculations performed for a ^{209}Bi target were scaled for our ^{208}Pb case. They coincide with CCFUSS theory except in the subbarrier region, where they foresee a cross section much larger than experimentally observed. Both CCFULL and CDCC approach underestimate the total fusion and this is somehow puzzling.

In conclusion we can say that the breakup interaction around the barrier with such loosely bound nuclei has a large cross section and splits most likely in several

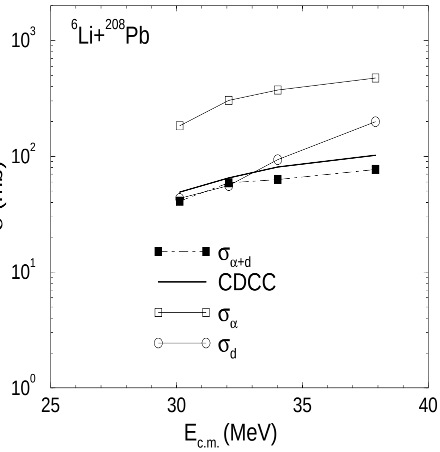

Fig. 7. Cross sections for the various breakup channels in the system ^{6}Li+^{208}Pb.

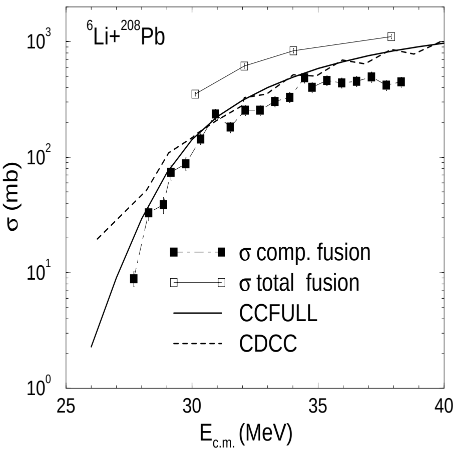

Fig. 8. Fusion cross sections for the system ^{6}Li+^{208}Pb.

components in all the analyzed cases:

1. two (or more than two) fragments in the exit channel, whose masses add up to the total mass of the projectile;
2. the capture (incomplete fusion or transfer) of one of the fragments originating from the projectile breakup with a larger probability for the lighter one.

All these processes, with fairly large cross section, have to be included in the theoretical description of the reaction dynamics at the Coulomb barrier which unfortunately becomes quite complex!

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