Interaction of loosely bound ^{6}Li with ^{208}Pb at Coulomb barrier energies.

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Abstract

The breakup interaction of ^{6}Li with ^{208}Pb target at Coulomb barrier turns out to be rather complex from the experimental data. In fact we observe the breakup into $\alpha + d$ and, in addition, incomplete fusion/stripping breakup of either fragment namely the alpha and the deuteron. This makes the scenario of the breakup interaction of a loosely bound nucleus like ^{6}Li quite complex and needs more effort to be fully understood both theoretically and experimentally.

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In the present contribution we want to discuss the dynamics of the interaction between a heavy target ^{208}Pb and a light projectile like ^{6}Li the most loosely bound ($S_d = 1.474\,MeV$) stable nucleus with a r.m.s. radius nearly equal to the one of ^{6}He n-skin nucleus. These two features make ^{6}Li the closest stable nucleus to halo light Ion Beams like ^{11}Be, ^{11}Li, ^{8}B. We could therefore considered ^{6}Li a "doorway" nucleus for the study of the reaction dynamics induced by loosely bound/halo nuclei.

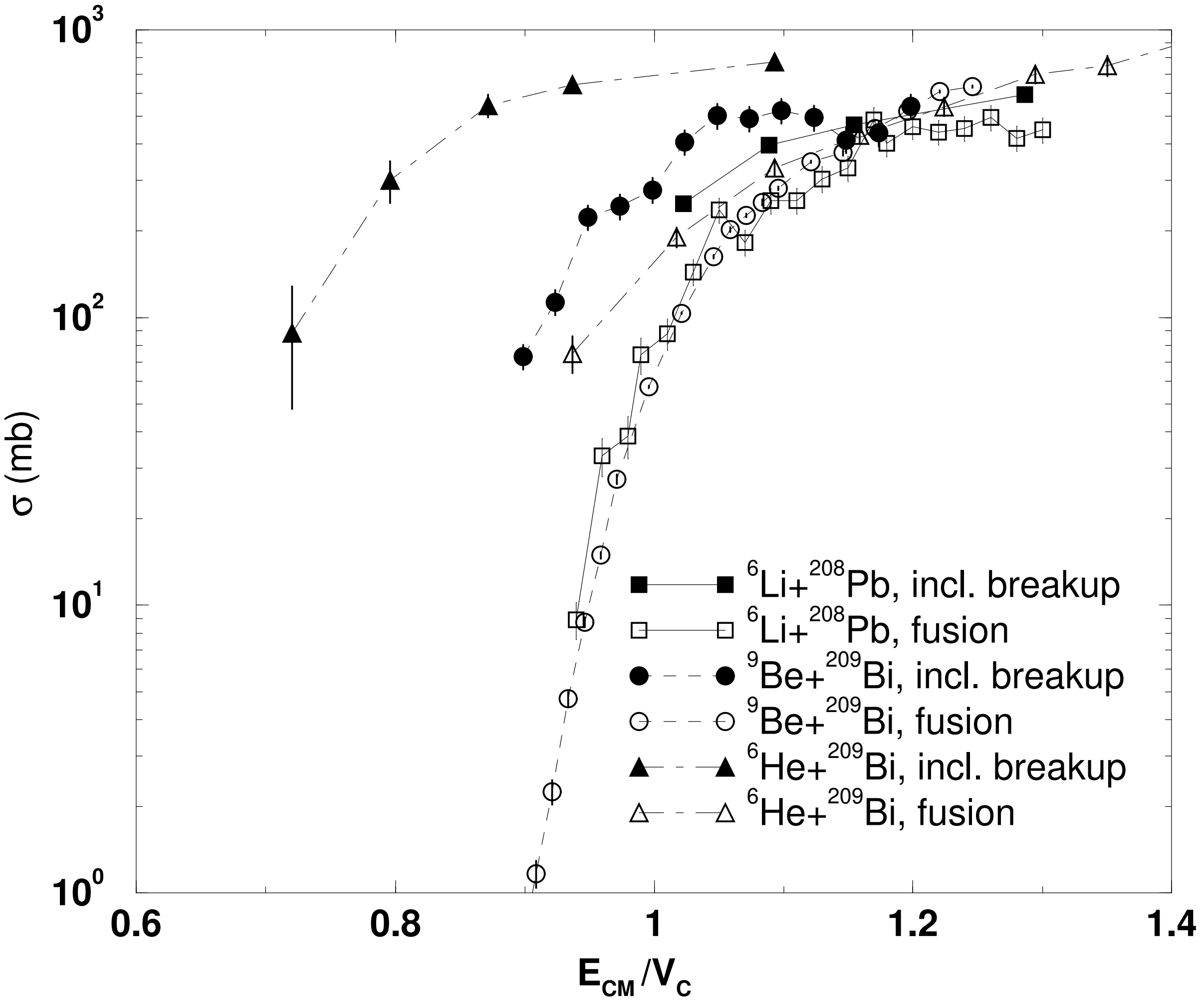

FIG. 1: Inclusive breakup and fusion cross section around the Coulomb barrier for three systems with weakly bound/radioactive projectiles.

The new feature with such nuclei is the presence of a strong reaction channel most likely originating from the breakup of the loosely bound projectile. As an example, strong reaction channels of alpha production were observed in the following systems: $^{6}He + {}^{209}Bi$ [1], $^{9}Be + {}^{209}Bi$ [2], $^{6}Li + {}^{208}Pb$ [3–5]. Fig.1 shows the cross sections for the inclusive

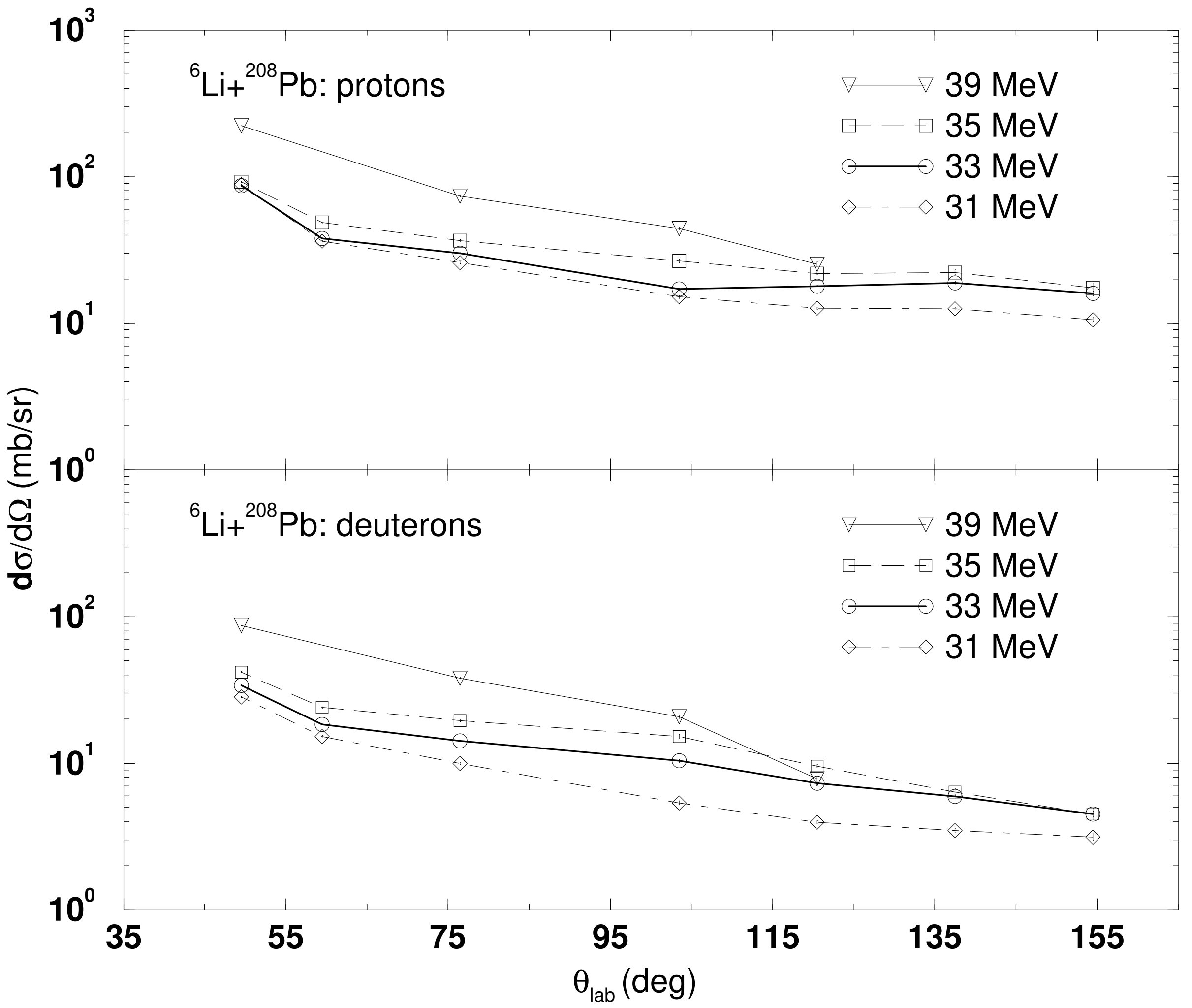

FIG. 2: Inclusive protons and deuterons angular distributions in the system $^{6}Li + {}^{208}Pb$ at four different beam energies around the Coulomb barrier.

production of alpha particles and the pertinent fusion cross sections at energies around the Coulomb barrier (30.35 MeV). The inclusive breakup cross sections are larger than the fusion ones; extreme case is the $^{6}He + {}^{209}Bi$ in the sub-barrier region. We deal with a relevant new process in the interaction of two nuclei around the barrier. It is rather obvious that such a process influences (renormalizes) the fusion one; but the interplay of these two phenomena is yet not so clear both theoretically and experimentally.

From our recent work [5] it results clearly that the strong alpha inclusive channel does not originate uniquely from the breakup of ^{6}Li into $\alpha + d$ and $\alpha + p + n$ but also from other processes that have to be identified. This channel partly originates from a process where the deuteron is captured by the target (stripping breakup) and the alpha particle

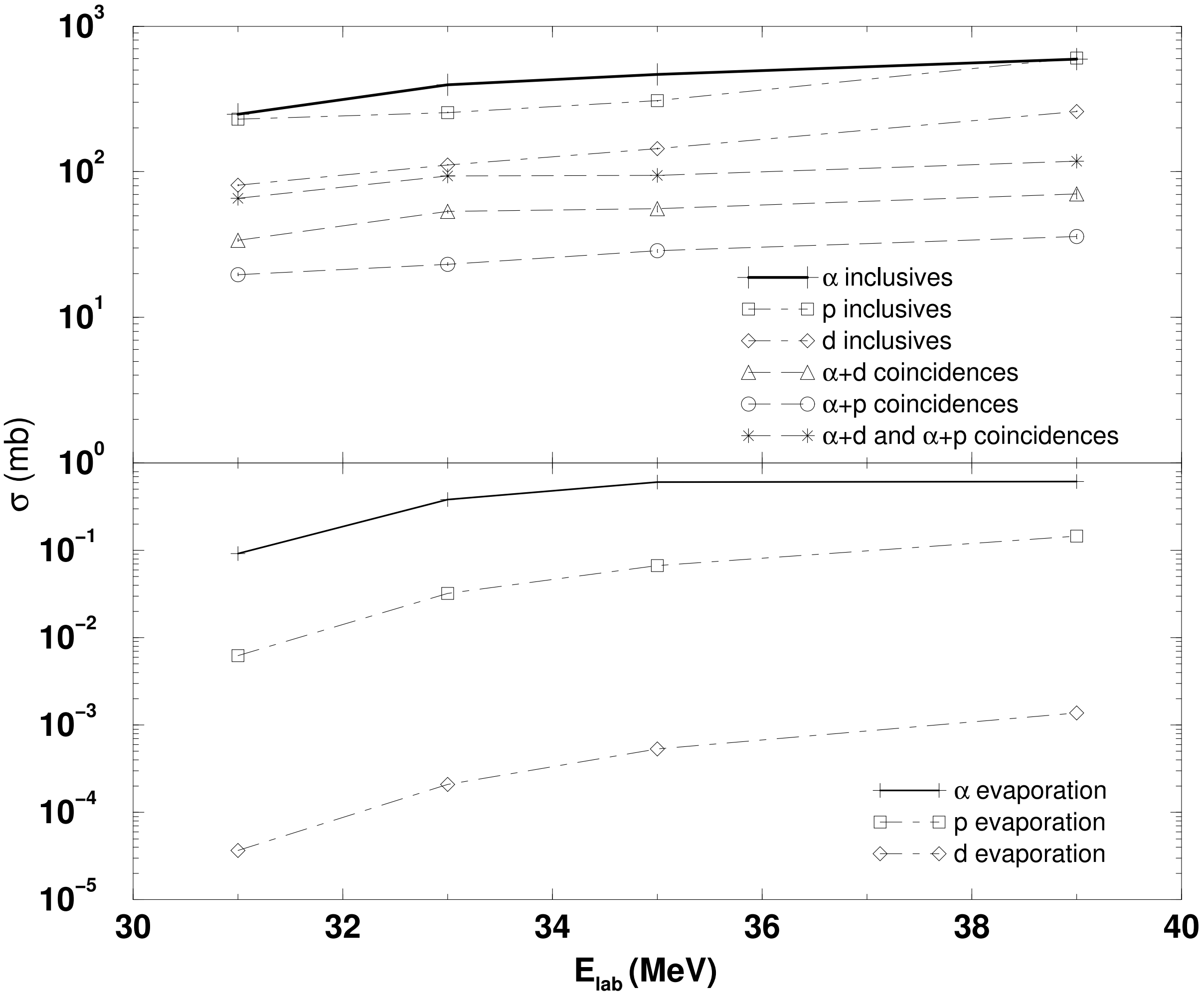

FIG. 3: Alphas, protons, deuterons inclusive, and $\alpha+d$ and $\alpha+p$ coincidence total cross sections for the reaction ${}^6Li+{}^{208}Pb$ at Coulomb barrier energies (upper part); alphas, protons, and deuterons evaporation residues estimated with the EMPIRE-II code for the same reaction (lower part).

flies away. Evidences of such incomplete fusion/stripping breakup mechanism are indicated and discussed in our work [5]. Fig.2 top panel shows that the alpha inclusive cross section is larger than the sum of the $(\alpha-d)$+$(\alpha-p)$ coincidences. According to these results we considered that, in addition to the partial fusion of d, produced by the ${}^6Li$ breakup process, also α partial fusion might occur. We have therefore analyzed in detail the d and p channel clearly visible in our previous experiments [3, 5]. Fig.3 shows the angular distributions at 31, 33, 35, 39 MeV ${}^6Li$ beam energy of p and d identified via the $8\pi LP$ apparatus telescopes (ΔE 300 $micron\ Si,\ E$ 3 $mm\ CsI$). The total inclusive cross sections were obtained from the integration of these angular distributions after a quadratic extrapolation to forward and backward non detected angles. We did not include the reduced efficiency of the telescopes due to low energy p and d stopped in the (rather thick) ΔE detector and consequently not observed in the telescopes. A rough estimate indicates that the cross sections are underestimated most likely between 10% and 20%. The total inclusive p and d cross sections are shown in the upper panel of Fig.2. It is rather striking that the p inclusive cross sections are as large as the α inclusive ones. Before drawing conclusions for the α, p, d channel, especially the p one, it is important to evaluate the contribution from the evaporation following the complete fusion of $^{6}Li +\ ^{208}Pb$. This contribution was evaluated using the statistical model code EMPIRE-II [7] with the simplified Coupled-Channels approach [8] for the calculation of the fusion cross section. The results are shown in Fig.3 lower panel. All three charged particles channels are at least two orders of magnitude smaller than the inclusive ones; the d-evaporation channels are 4 order of magnitude smaller than the experimental ones. The most realistic conclusion is that the charged particle channels do NOT originate mainly from evaporation but rather from ^{208}Pb capture of part of the the ^{6}Li projectile (α, d or p). These considerations are a clear indication that not only d-stripping breakup is an important channel, as evidenced in Ref.5, but also α-stripping breakup gives an important contribution to the breakup process. This means that in the interaction of ^{6}Li with ^{208}Pb we have in addition to the normal fusion: i) breakup into $\alpha + d$ and possibly $\alpha + p + n$, ii) stripping breakup/partial fusion of either ^{6}Li fragments namely alpha and deuteron. All these processes have comparable strength and are stronger than the fusion below the barrier. This makes the scenario of the breakup interaction at the barrier fairly complex and makes the theoretical handling of the breakup interaction much complicated than up to now considered.

In order to have a deeper understanding of this point we have compared the data for a heavy and a light compound system formed by the $^{6,7}Li$ projectile (also ^{7}Li is rather loosely bound with $S_t = 2.467\,MeV$) with the predictions of the statistical model:

A) $^{7}Li +\ ^{160}Gd$, Fig.4 [6]. For this system the estimation was realized with the code PACE2. The $xn(pxn)$ evaporation channels are shown in the lower(upper) panel. The pxn experimental cross sections are $\sim$ 1 order of magnitude larger than the calculated ones; see i.e. the strongest $p4n$ channel with an excitation function much wider than the calculated one. On the contrary the xn experimental channels are

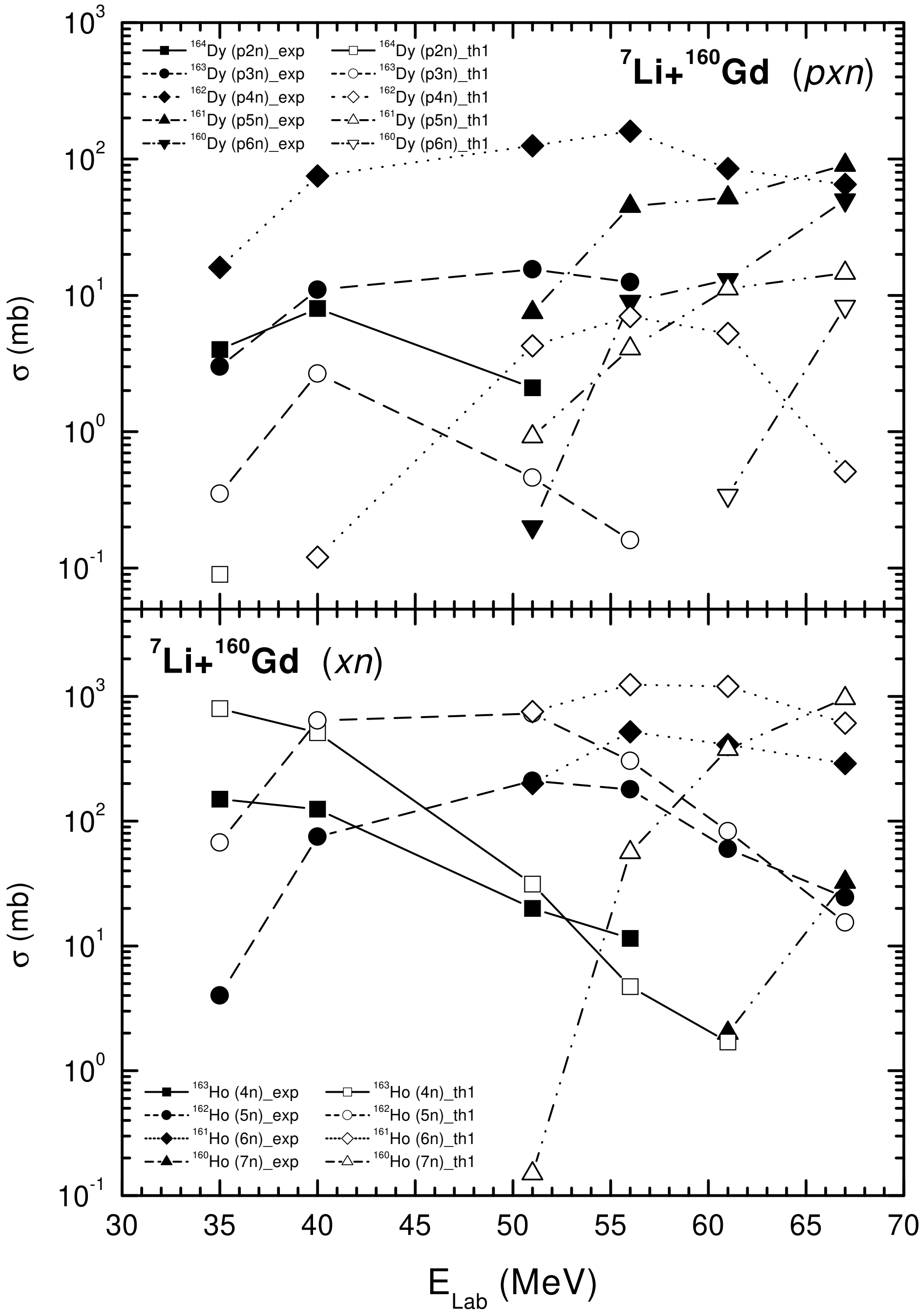

FIG. 4: Comparison between experimental data (full symbols) [6] and theoretical predictions (open symbols) of the evaporation channels, for the system $^{7}Li + {}^{160}Gd$.

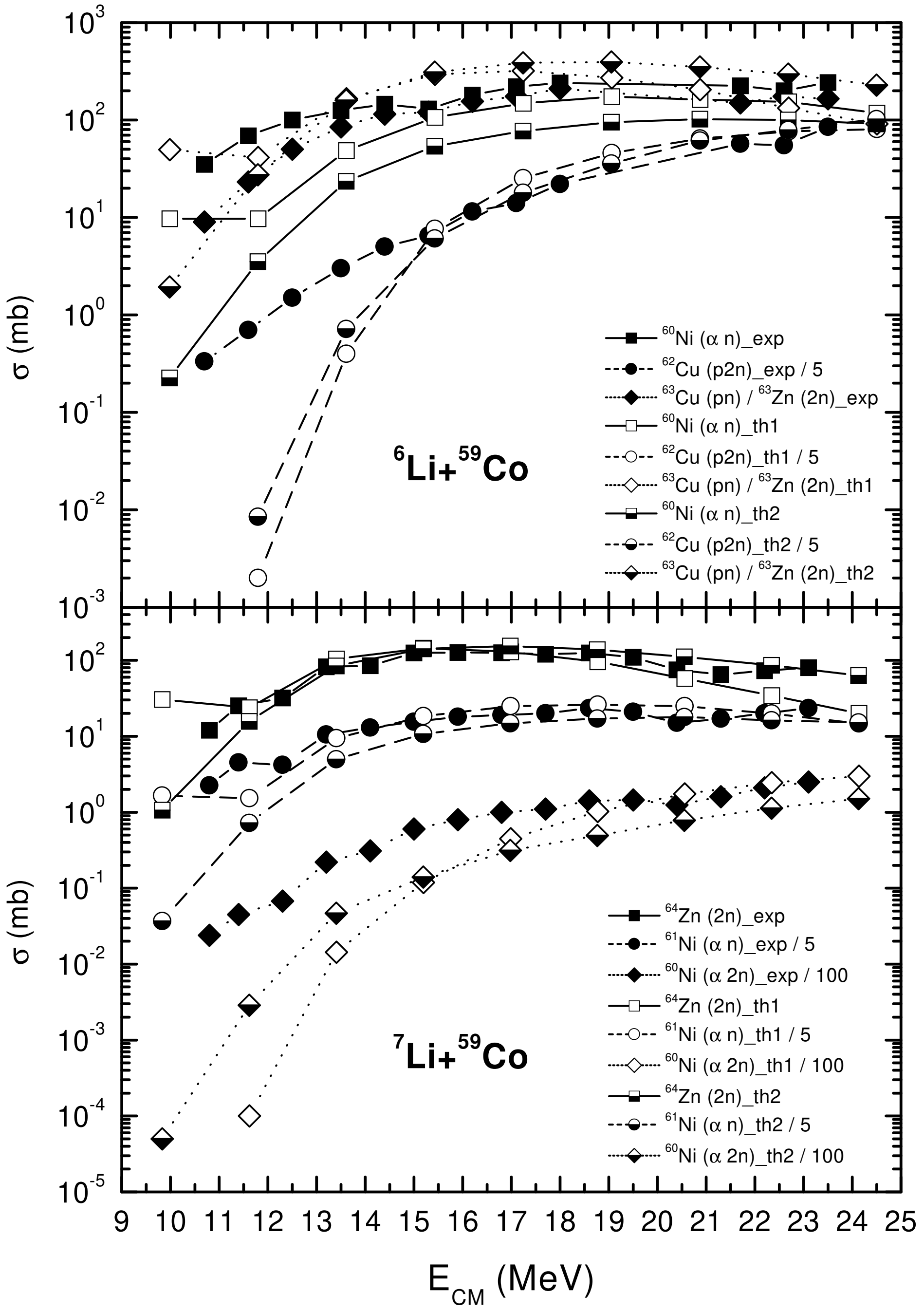

FIG. 5: Comparison between experimental data (full symbols) [9] and the theoretical calculations using two different codes: open symbols(PACE2), and half-open symbols(EMPIRE-II).

smaller than calculated. Moreover, if we renormalize the theoretical cross sections with the xn experimental data the pxn experimental data differ even more from the theoretical ones. This strongly suggest that the pxn channels originate mainly from alpha incomplete fusion/stripping breakup as in our $^{6}Li+\ ^{208}Pb$ case.

$B)$ $^{6,7}Li+\,^{59}Co$, Fig.5 [9]. In this case the incomplete fusion process is apparently less relevant. The theoretical calculation were made with both codes: PACE2 and EMPIRE-II that give more or less the same result. With $^{6(7)}Li$ the $p2n(\alpha 2n)$ channel is underpredicted but only in the lower energy portion; this would imply alpha(tritium) incomplete fusion.

In conclusion these experimental results, once compared with the evaporation codes predictions, suggest that the breakup process of a loosely bound projectile like ^{6}Li by a heavy target is rather complex. This must be more extensively investigated using halo light beams in many cases less bound than ^{6}Li.

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