Study of breakup reactions of weakly bound stable and radioactive nuclei

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Study of projectile breakup involving weakly bound nuclei in the field of target nuclei is topic of spreading interest, particularly due to the recent advent of the availability of the weakly bound exotic beams. Limited measurements of the direct and sequential breakup of weakly bound nuclei with α+x cluster states are available in the literature [1–3]. The detailed information of the cluster structure of those nuclei are essential for predicting possible breakup modes. ^{6}Li(^{7}Li) nucleus has well known α+d(t) cluster with a binding energy of 1.47 MeV (2.47 MeV) only. For the ^{6}Li case, one can expect its breakup through all three resonance states corresponding to L=2, i.e., (3^{+}, 2.18 MeV), (2^{+}, 4.31 MeV), and (1^{+}, 5.65 MeV) [4]. Similarly for ^{7}Li, the breakup into α + t can take place through all possible resonance states corresponding to L=3 i.e., ($7/2^{-}$,4.63 MeV) and ($5/2^{-}$, 6.67 MeV) [4]. Direct breakup of ^{6}Li(^{7}Li) into α + d(α + t) and sequential breakup via the first two resonance states (first resonance state of ^{7}Li) of the cluster were measured for several systems [2, 3]. But there was no measurement available on the sequential breakup corresponding to the 1^{+} resonance state for ^{6}Li and similarly for $5/2^{-}$ resonance state of ^{7}Li. Hence detection and quantification of these new breakup channels were the prime motivations of the present work.

In addition to the well-known α + x cluster, ^{6}Li and ^{7}Li also reveal some additional cluster structures, such as ^{6}Li exhibits ^{3}He+t with breakup threshold $\sim$ 16 MeV and ^{7}Li shows ^{6}Li+n and ^{6}He+p structures with breakup threshold of 7.25 and 9.97 MeV respectively. Examination of the separation modes ^{7}Li $\rightarrow$ ^{6}He + p will reveal insight into the possibility of the another cluster structure of ^{7}Li.

Other than α + d(t) breakup, the α particles can be produced through transfer triggered breakup. For example, the transfer reactions of (^{7}Li,^{6}Li), (^{7}Li,^{5}Li), (^{7}Li,^{8}Be), (^{7}Li,^{6}He), and (^{7}Li,^{5}He) followed by breakup into α + d, α + p, α + α, α + 2n, and α + n, respectively, can contribute individually to the inclusive α production. Transfer reaction can also produce weakly bound exotic nuclei which in turn disintegrates into its cluster fragments if sufficient excitation energy are available due to the field exerted by the target nuclei. For example, radioactive ^{7}Be nuclei can be produced through the transfer reaction ^{112}Sn(^{6} Li, ^{7}Be $\rightarrow$ α + ^{3}He) ^{111}In. Though the direct breakup of ^{7}Be have been studied by several authors but there was no measurement available for the resonant breakup states of ^{7}Be due to its limited availability. Several studies on heavy and light targets pointed out different conclusions regarding the dominance of particular breakup mode over other [2, 3]. Motivated by the above mentioned objectives, the breakup phenomena was probed in-details involving ^{6,7}Li as projectiles with a medium mass target (^{112}Sn) at an above barrier energy. The breakup phenomenon of ^{6}Li by ^{112}Sn have also been carried out at two different energies to see the energy dependence of the breakup probabilities. The α+d breakup cross-sections were also measured with ^{209}Bi target which was used to derive astrophysical S-factor for α+d $\rightarrow$ ^{6}Li+γ reaction.

Several measurements were carried out involving weakly bound projectiles ^{6}Li and ^{7}Li with ^{112}Sn target using BARC-TIFR Pelletron-Linac facility with an array of max-

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imum five-strip telescopes [6–9].

Using the energies and laboratory detection positions of two breakup fragments (α and x) of each coincident event, the 'Q-Value' and 'α-x relative energy E_{rel}' were reconstructed and corresponding efficiency of the detector array has been obtained by a Monte-Carlo simulation [7–9]. Different breakup processes, like breakup of ^{6}Li (^{6}Li $\rightarrow \alpha$ + d) together with 1d-pickup followed by breakup (^{6}Li $\rightarrow$ ^{8}Be $\rightarrow$ α + α) and 1n stripping followed by breakup (^{6}Li $\rightarrow$ ^{5}Li $\rightarrow \alpha$ + p) were disentangled by using the 3-body kinematics method [6]. Although 3^+ and 2^+ resonance states were identified earlier, the observation of 1^+ state was observed for the first time [6]. Similarly, for ^{7}Li, the direct breakup into α+t and ^{6}He+p, resonant breakup into α+t via the resonance states $7/2^-$ and $5/2^-$ together with the 1p-pickup followed by breakup (^{7}Li $\rightarrow$ ^{8}Be $\rightarrow \alpha$ + α) and 1n-stripping followed breakup (^{7}Li $\rightarrow$ ^{6}Li $\rightarrow \alpha$ + d) were identified through relative energy reconstruction [7, 8]. The breakup of ^{7}Li into α+t via the second resonance state i.e. via $5/2^-$ state was identified for the first time [7]. The observation of breakup into ^{6}He+p was also for the first time indicating the possibility of additional cluster state of ^{7}Li [7]. The angular distribution of each of the breakup channels were estimated and compared with the coupled channel calculations via FRESCO [5]. From the present work, it has been observed that the breakup of ^{6}Li into α + d is much larger as compared to ^{6}Li $\rightarrow$ ^{5}Li $\rightarrow \alpha$ + p breakup at above barrier energy and they are comparable at around barrier energy. In addition to exclusive breakup measurements for the above channels, cross sections for direct and resonant breakup of radioactive ^{7}Be nuclei produced in a transfer reaction ^{112}Sn(^{6} Li, ^{7}Be $\rightarrow \alpha$ + ^{3}He) ^{111}In have been measured [9]. Breakup of ^{7}Be into α and ^{3}He cluster fragments via its resonant states of $7/2^-$(4.57 MeV) and $5/2^-$(6.73 MeV) in the continuum have been identified for the first time using the measured distribution of α- ^{3}He relative energy and the reaction Q value obtained from the α-^{3}He coincident events [9]. The breakup cross sections compares well with the results of the coupled-channels calculations. Significant cross sections for breakup of ^{7}Be into its cluster fragments directly or through resonant states highlight the importance of the ground-state structure of ^{7}Be as a cluster of α and ^{3}He. The cross sections for inclusive breakup α are found to be much larger than all the known noncapture breakup channels combined together that make up only $\approx 15\%$. It indicates the existence of other possible sources of α production, such as incomplete fusion (where one of the breakup fragments which is complementary to α is captured by the target) and new noncapture breakup modes that need further investigations.

The results on direct, resonant, and transfer breakup of ^{6,7}Li by ^{112}Sn presented here provide a good foundation toward the comprehensive understanding of the reaction mechanisms of the projectile breakup as well as the production of large inclusive α in a reaction involving a weakly bound stable or unstable light projectile.

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