Experimental signatures for distinguishing breakup fusion and transfer in ^{7}Li + ^{165}Ho

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Reactions involving weakly bound nuclei of ^{7}Li show large yields of α particles that have their origin in elastic breakup, breakup followed by fusion, or triton transfer. The latter two processes, breakup fusion and transfer, have similar characteristics and produce the same residual fragments. We report here results of exclusive measurements of charged particles and characteristic γ rays from the heavy residues in the ^{7}Li + ^{165}Ho system at 42 MeV ($E/V_b \simeq 1.6$) to look for experimental signatures to differentiate between transfer and breakup fusion. Such a distinction is essential for a better theoretical understanding of both the fusion process and direct reactions involving weakly bound stable and unstable beams.

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Interactions of weakly bound projectiles have been a focus of recent investigations especially at energies near the Coulomb barrier. This interest is largely fueled by the availability of low-energy beams of radioactive nuclei from recent IS0L facilities [1], which manifest features such as *halos*/*skins* not observed with β-stable nuclei. Pioneering studies in this field were made using ingenious methods to develop beams of unstable nuclei of ^{6}He,^{8}Li,^{8}B, and ^{17}F [2]. Equally interesting are the reactions with stable but weakly bound nuclei such as ^{6,7}Li and ^{9}Be [3–6]. These nuclei with a well-defined cluster structure [7] and small separation energies, have a large breakup probability, similar to that for radioactive ion beams, making them an attractive option for understanding the various aspects of the reactions with weakly bound nuclei. For interactions with weakly bound systems at energies around the Coulomb barrier, breakup of the projectile forms a significant part of the total reaction cross section. This is supported by the experimental observation of large "inclusive" cross sections for the α channel for many nuclei such as ^{6}He, ^{6,7}Li, and ^{9}Be [3,5,8]. Following the breakup of the projectile in the field of the target, one of the fragments can be captured by the target, whereas the other moves away approximately with the beam velocity [9–12]. This is referred to as *incomplete fusion* [10] at higher energies or more appropriately as *breakup fusion* [12] at energies near the barrier.

One of the hurdles in understanding reactions with weakly bound nuclei has been the experimental difficulty in segregating the different components of the total reaction cross section. In many cases, separation between complete fusion (CF) and breakup fusion/transfer may not be possible, as the residues in both cases may be identical or similar. For interaction with beams such as ^{6,7}Li, breaking into charged fragments, with heavy nuclei (where charged particle evaporation from the compound system is negligible) measurement of characteristic γ rays or delayed α activity helps in distinguishing between CF and breakup fusion. Conversely, for interactions with ^{6}He beams with medium mass and fissile targets, exclusive measurements are necessary to identify the various processes [1,13].

Another limitation lies in the experimental difficulty in distinguishing breakup fusion from a transfer channel, both leading to the same final residual nucleus. For example, in the ^{7}Li + ^{165}Ho system [3] the observed large yields of ^{166}Er could arise both from the fusion of the triton with the target, followed by particle evaporation (in this case neutron) from the compound nucleus or the transfer of a triton to the unbound states of the target followed by particle evaporation. The energetics for these two processes are similar, making it difficult to distinguish them in an inclusive measurement. For a deeper understanding it is necessary to identify the status of the complementary heavy fragment. Such studies with ^{6,7}Li beams have been restricted to energies far greater than the Coulomb barrier [11,12].

In this brief report, we present exclusive measurements of particle-γ coincidences for the ^{7}Li + ^{165}Ho system at an incident beam energy of 42 MeV ($E/V_b \simeq 1.6$). The aim is to experimentally delineate between the two-step process, breakup fusion, and the one-step process, transfer, by exclusive studies of the heavy fragments. The differentiation between breakup fusion and transfer has implications on the understanding of the reactions with weakly bound nuclei at energies above the Coulomb barrier.

The experiment was performed using a 42 MeV ^{7}Li beam from the 14UD BARC-TIFR accelerator facility at Mumbai, incident on a 2.68 mg/cm^{2} thick foil of ^{165}Ho. Two telescopes ($40\mu\ \Delta E - 2$ mm E and $30\mu\ \Delta E - 2$ mm E) at 40° and 50° having an opening angle of ±1.4° (covering the region around the grazing angle) were used to measure the charged particles produced. Four efficiency calibrated clover detectors, to record the coincident γ rays, were placed at ≈26 cm from the target position at angles of +55°, −35°, −80°, and −155°. Seven hexagonal BGO detectors (63 mm × 56 mm) in a closed

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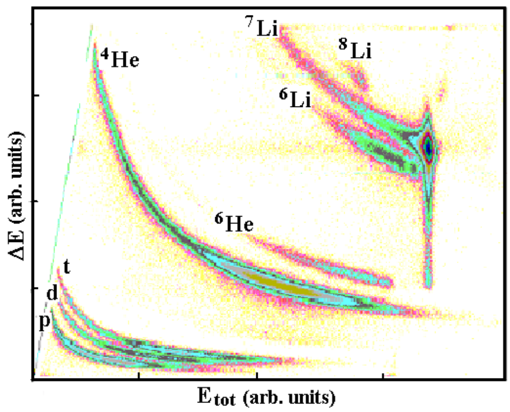

FIG. 1. (Color online) A two dimensional plot of ΔE-E_{total} obtained in the telescope at $\theta_{\mathrm{lab}} = 40^\circ$. The different reaction products were identified and are labeled.

packed geometry were placed below the scattering chamber, with a total efficiency of ~32% at 662 keV to record the multiplicity of the emitted γ rays. A fast coincidence between any charged particle detected in the ΔE and a γ ray in any clover detector was used as an event trigger. Typical counting rates in this configuration were ~500/s.

A typical particle identification spectrum obtained for one ΔE-E telescope is shown in Fig. 1. The focus of the present study is the α and t transfer channels. The ground state Q values (Q_{gg}) for t transfer is very different from the optimum Q value, Q_{opt}, calculated from the semiclassical condition of trajectory matching [14], leading to large excitation energy in the residual nuclei (Table I). It should be pointed out that the yield of α and t observed here does not all arise from direct transfer but has significant contribution from breakup fusion. The lighter fragment *viz*., t should have a higher probability of being captured by the target, because of its lower Coulomb barrier and this is consistent with the observed larger yield of α particles compared to t, as also reported in earlier studies [12].

To understand the large α particle yields, the γ rays in coincidence were analyzed. The large yields could arise from either breakup of ^{7}Li, transfer of triton to the target or fusion of the triton with the target (breakup fusion). The total γ spectra were projected with a two-dimensional gate on the α particles and tritons. The γ spectrum obtained in coincidence with the α particles is shown in Fig. 2(a) and that with tritons in Fig. 2(b). The cascade of γ transitions depopulating the levels in the rotational band of ^{166}Er are marked by full arrows in Fig. 2(a). Also seen are transitions in ^{165}Er. The two processes, transfer and breakup fusion, are consistent with the observance of ^{165,166}Er in coincidence with α particles. The large mismatch between Q_{gg} and Q_{opt} for the triton transfer results in a highly

TABLE I. Q values (in MeV) for the α and t transfer channels observed in the $^{7}\mathrm{Li} + {}^{165}\mathrm{Ho}$ reaction at 42 MeV.

Channel	Q_{gg} (MeV)	Q_{opt} (MeV)	E^* (MeV)
$^{4}\mathrm{He} + {}^{168}\mathrm{Er}$	+10.56	−12.9	23.5
$^{3}\mathrm{H} + {}^{169}\mathrm{Tm}$	−3.67	−26.6	22.9

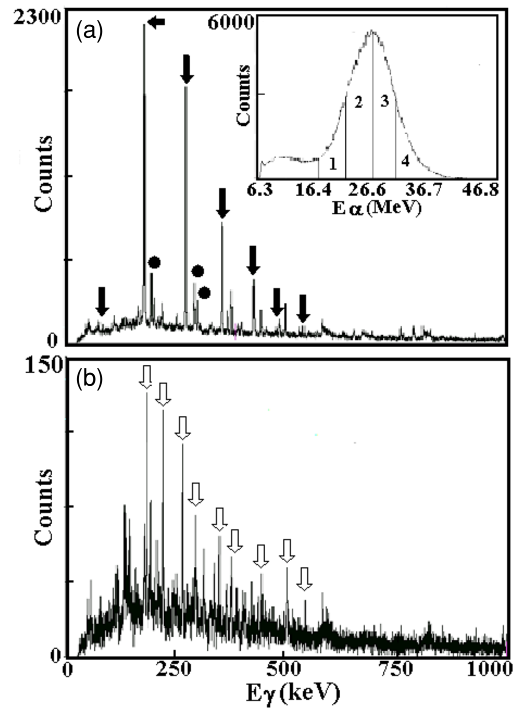

FIG. 2. (a) γ spectra in coincidence with the α particles. The full arrows indicate the transitions in the rotational band of ^{166}Er, whereas the circles indicate γ rays from ^{165}Er. The projection of the α particles from the two-dimensional particle identification spectrum (Fig. 1) is shown in the inset, which peaks at approximately 4/7 of the incident beam energy. (b) γ spectra in coincidence with the tritons, the transitions marked with open arrows are in ^{167}Tm.

excited ^{168}Er nucleus (see Table I) leading to the residues ^{165,166}Er by neutron emission. In a very simplistic picture for the breakup fusion, the projectile energy is first used to break up ^{7}Li into α and t and the rest of the kinetic energy is shared by α particles and tritons in proportion to their mass numbers. The Q value for the fusion of the triton with the target, ^{165}Ho, is +13 MeV, leading to the compound nucleus ^{168}Er with an excitation energy similar to that produced in a one-step transfer process. The γ rays in coincidence with tritons shown in Fig. 2(b) are predominantly transitions in ^{167}Tm, formed after $2n$ evaporation from ^{169}Tm (compound nucleus from the fusion of α and ^{165}Ho). A nearly identical spectra was obtained using an α beam of 25 MeV from the accelerator, an energy corresponding to the peak of the alpha spectrum.

The coincident γ-ray spectra do not seem to easily differentiate between the transfer and breakup fusion process. Thus a further attempt was made to differentiate between the direct one step process, transfer, and the two step process breakup fusion. The α spectrum was divided into small energy bins (inset of Fig. 2) and each bin was associated with a triton energy calculated assuming two body kinematics [12]. The higher energy α particles (lower triton energies) produce more of ^{166}Er, which is a $2n$ evaporation channel from the compound system ^{168}Er, whereas for the lower energy α particles (higher triton energies) ^{165}Er (further evaporation of another neutron) is also observed. Plotted in Fig. 3 are the intensities of the

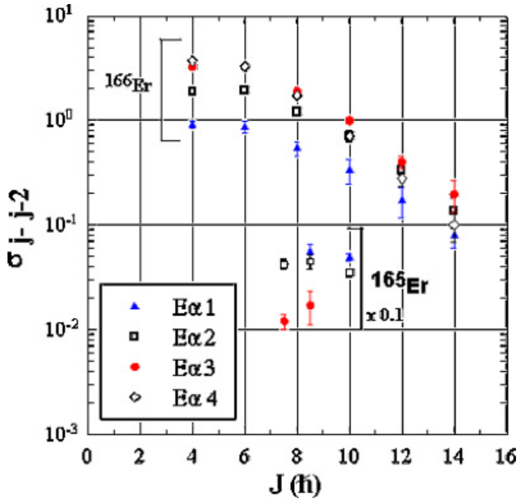

FIG. 3. (Color online) The side-feeding pattern for the various energy bins of the α particles shown in Fig. 2 for ^{165,166}Er. The yields have been normalized for the number of α particles in each bin.

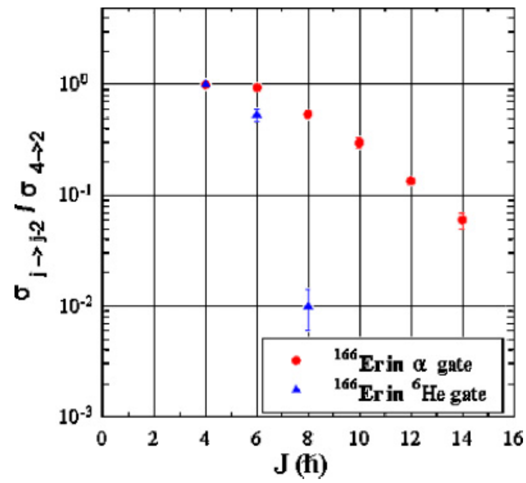

FIG. 5. (Color online) Comparison of the side-feeding pattern for ^{166}Er produced via triton transfer/fusion and p transfer. The data have been normalized for the $4 \rightarrow 2$ transition.

various low lying levels in ^{165,166}Er as a function of their spin. The counts are normalized to the number of α particles in their corresponding bin. These intensities were extrapolated to 0 spin to obtain the relative cross sections for the production of ^{166}Er nuclei at different energies of the outgoing α particles. A similar procedure could not be followed for ^{165}Er, as fewer transitions were observed.

The cross sections for the production of ^{166}Er corresponding to different triton energies are compared with statistical model calculation for the decay of the compound system ^{168}Er formed in the fusion of t with ^{165}Ho. The calculations were performed using the code CASCADE [15] with the same parameters as used in Ref. [3] and are shown in Fig. 4. The data has been normalized with the calculation at 12.3 MeV. As can be seen from the figure the cross sections are satisfactorily reproduced, considering the simple model assumed for obtaining the triton

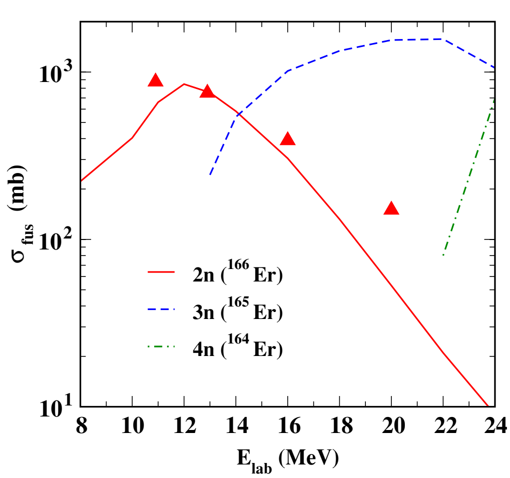

FIG. 4. (Color online) The comparison of the relative cross sections for ^{166}Er (solid red triangles) as a function of the "fusing" triton energy and statistical model calculations using CASCADE (see text).

energy. The agreement of the energy dependence of the cross section with statistical model calculations suggests that the residues observed in coincidence with the α particles arise from the decay of an excited compound system. The most obvious conclusion is that they are produced by breakup fusion. However, it could be argued that the residues formed in triton transfer are also fully equilibrated, but for such a process to occur one needs a large spectroscopic factor for states in the continuum in the rare-earth region. It is more likely that there exist large spectroscopic factors for α-like states in the continuum given its larger binding in these nuclei. However, as mentioned earlier triton yields are seen to be relatively smaller. This inconsistency is resolved if we assume the breakup fusion picture, where an α particle is less likely to fuse because of its higher Coulomb barrier [12]. For high Z targets as used in the present study, it is likely that Coulomb breakup dominates over nuclear breakup. Thus breakup occurs at larger distances and one can talk about a Coulomb barrier as seen by the fusing fragment (triton in this case). However, if the breakup were to occur at smaller distances inside the barrier radius, then the magnitude of the Coulomb barrier seen by the fusing nuclei would not play a role. The energy dependence of the observed cross section points to breakup occurring at large distances in the present case. The fact that ^{7}Li has a well-defined cluster structure that easily separates into its constituents seems to corroborate the two-step process of breakup fusion. The possibility of a direct mechanism of the production of α particles cannot be ruled out completely on the basis of the present results.

The present data also presents an additional experimental signature for further distinguishing between the two processes. The residual nucleus in the one proton stripping channel (^{6}He) is also ^{166}Er. The low S_{2n} of ^{6}He implies that all the excitation energy resides in ^{166}Er. Figure 5 shows the side-feeding patterns for ^{166}Er produced in a $-1p$ transfer process (^{6}He gate) and triton fusion (α gate). As can be seen from the figure much higher spin states are populated in the latter as excepted.

Also the slopes of the two curves are very different, being much steeper for a $-1p$ process, implying a small angular momentum. Thus the analysis of the coincident γ-rays provides evidence to suggest that the large α particle yields have their origin in the two-step breakup fusion process. A similar conclusion was reached by Udagawa and Tamura [16], when analyzing the energy and angular distribution of emitted fast particles in ^{159}Tb(^{14}N, αxn) at much higher energies.

The distinction between transfer and breakup fusion is crucial to the understanding of the influence of weak binding on the fusion process at energies around the Coulomb barrier. Experiments [3,4] and theoretical calculations [17,18] indicate that complete fusion cross sections are reduced at energies above the barrier. Experimentally the suppression is found to be about $\sim$30% when compared to the reaction with tightly bound nuclei, almost equal to the cross section observed in breakup fusion. This appears to support the fact that the loss of complete fusion at above barrier energies because of breakup of the projectile manifests as breakup fusion. However, such a supposition *assumes* that these residues did not have their origin in a transfer process. Also, the sum of complete fusion and breakup fusion cross section, referred to "total" cross section, are compared with theoretical predictions of fusion cross sections. This would be incorrect in the presence of a large transfer component, as such a total cross section would then represent a reaction cross section. The present work illustrates for the case of ^{7}Li induced reactions the dominance of breakup fusion over transfer making the above assumptions valid. However, the relative importance of these two seemingly different processes could also depend on the relative importance of the nuclear and Coulomb field on the breakup mechanism. Exclusive investigation of Li induced reactions near and above barrier energies on medium mass targets may yield a more detailed understanding [19].

In summary we have presented exclusive measurements of charged particles and γ rays to look for *experimental signatures* to differentiate between breakup fusion and transfer to the continuum. The various evidences presented seem to favor a breakup fusion picture in the case of ^{7}Li interacting with a high Z target at energies above the barrier. Recent calculations have been trying to model, using classical trajectories, various aspects of the reaction mechanism of loosely bound systems and it would be interesting to compare with these exclusive measurements [20]. We hope that such measurements will complement newer calculations being planned in this direction [21].

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