EPJ Web of Conferences **63**, 02018 (2013)
DOI: 10.1051/epjconf/20136302018

Dynamics of fragment capture for cluster structures of weakly bound ^{7}Li

A. Shrivastava[1,a], A. Navin[2], A. Diaz-Torres[3], V. Nanal[4], K. Ramachandran[1], M. Rejmund[2], S. Bhattacharyya[5], A. Chatterjee[1], S. Kailas[1], A. Lemasson[2], R. Palit[4], V.V. Parkar[1], R.G. Pillay[4], P.C. Rout[1], and Y. Sawant[4]

[1] *Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India*
[2] *GANIL, CEA/DSM - CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen Cedex 5, France*
[3] *ECT*, Villa Tambosi, I-38123 Villazzano, Trento, Italy*
[4] *DNAP, Tata Institute of Fundamental Research, Mumbai 400005, India*
[5] *Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700064, India*

Abstract.
Role of cluster structures of ^{7}Li on reaction dynamics have been studied by performing exclusive measurements of prompt-γ rays from residues with scattered particles at energy, E/Vb = 1.6, with ^{198}Pt target. Yields of the residues resulting after capture of t and ^{4,5,6}He, corresponding to different excitation energies of the composite system were estimated. The results were compared with three body classical-dynamical model for breakup fusion, constrained by the measured fusion, α and t capture cross-sections. The cross-section of residues from capture of α and t agreed well with the prediction of the model showing dominance of the two step process - breakup fusion, while those from tightly bound ^{6}He showed massive transfer to be the dominant mechanism.

1 Introduction

Correlations among nucleons in case of weakly bound nuclear systems give rise to strong clustering and exotic shapes [1, 2]. Recent studies with weakly bound nuclei have focused on the understanding of the role of these novel structures in the reaction dynamics [3]. Dominant reaction modes in nuclei with low binding energies, involve inelastic excitation to low lying states in the continuum or transfer/capture of one of the cluster fragments from their bound/unbound states to the colliding partner nucleus [3–5]. When the capture occurs from unbound states of the projectile, the process could be looked upon as a two step process - breakup followed by fusion [6–8]. In case of well bound nuclei, nuclear reaction related to capture of heavy fragments by the target has been identified as incomplete fusion or massive transfer [9] and occurs predominately at energies ≥ 10 MeV/A. For weakly bound cluster nuclei such as ^{6,7}Li, the former has been shown to be important both above and at energies much below the Coulomb barrier [10, 11]. Earlier studies have found the process of breakup fusion to be more dominant over one step transfer in case of ^{6}Li(^{7}Li) for deuteron (triton) capture reaction [6–8].

Recently a theoretical description of breakup fusion for weakly bound nuclei has been incorporated in the three-dimensional classical trajectory model [4], considering the peripheral nature of the process for predicting both the spin distribution and sharing of excitation energy. In contrast to most existing models for incomplete fusion, the new approach [4, 5] treats the dynamics of incomplete fusion and provides a number of differential cross sections that are critical for understanding exclusive experimental data. Such a theoretical model now allows for the first time to interpret data from exclusive experiments, which was not possible earlier.

In this presentation, study of the process of fragment capture for the various cluster structures (α + t, ^{6}He+p and ^{5}He+d) of ^{7}Li, exploiting the above model and using exclusive particle-gamma coincidences to uniquely identify reaction channel, is discussed [12]. First section deals with measurements of integrated cross-sections of compound nuclear fusion, t and α-capture using both off- and in-beam gamma decay along with yields of the evaporation residues for different excitation energies of the composite system. These results are compared with those of the recent three-dimensional classical trajectory model [4, 5] in conjunction with the statistical model of compound nucleus evaporation in the second section followed by the summary.

2 Identification and cross-section measurement for fragment capture reaction:

Experiments were performed at the 14UD pelletron-LINAC Facility, Mumbai for measurement of the (a) excitation function for fusion, t-capture and α-capture and (b) measurement of the prompt γ-rays from the heavy residues in coincidence with various light particles α, t, d and p.

---

[a] e-mail: aradhana@barc.gov.in

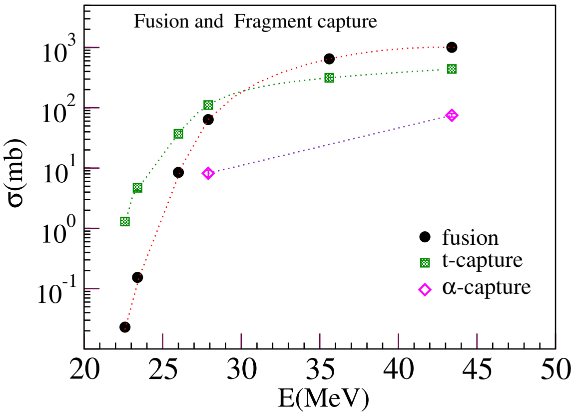

Figure 1. (Color online) Integrated cross-sections for compound-nuclear fusion ($^{199-202}$Tl), *t*-capture ($^{198-200}$Au) and α -capture ($^{199-200}$Hg). The dashed lines are to guide the eye.

The measurement of the cross-section of the residues resulting from the process of fusion and *t*-capture were performed with beams of ^{7}Li in the range of 22 to 45 MeV incident on self supporting foils of ^{198}Pt target followed by an Al catcher foil. Two efficiency calibrated HPGe detectors with Be window were used in a low background counting setup with graded shielding for off-beam gamma ray measurements. The residues in case of fusion ($^{199-202}$Tl) were identified by using KX-γ-ray coincidence of the decay radiations from the irradiated sample with detectors placed face to face. The γ-ray yields for residues formed after *t*-capture ($^{198-200}$Au) were extracted from inclusive γ-ray measurements. The cross-section of the residues, ^{199}Hg and ^{200}Hg from α-capture were deduced by performing in-beam method using four efficiency calibrated clover detectors at beam energies of 29 and 45 MeV. Further details of the setup can be found in Refs. [10, 12]. The excitation function for fusion and fragment capture are plotted in Fig. 1.

The measurements for exclusive in-beam γ decay of the residues were performed using a ^{7}Li beam of energy 45 MeV, incident on ^{198}Pt. Four telescopes (ΔE$\sim$25-30μm and E$\sim$1mm) at 50°, 60°, 120° and 130° (covering the region near and away from the grazing angle) were used to measure the charged particles. Four efficiency calibrated Compton suppressed clover detectors, operated in an addback mode, were placed at 14.3 cm from the target at angles of 35°, -55°, 80°, and 155°. A coincidence between any charged particle recorded in the ΔE and a γ-ray in any clover detector or a two fold γ-ray coincidence between clover detectors was used as the master trigger. The reaction products arising from different channels were identified by their characteristic γ-ray transitions in coincidence with the outgoing particles. In the following we discuss the γ-ray spectra obtained by selecting different ejectiles recorded in the telescopes placed at 50° and 60° that cover region around the grazing angle. At backward angles, the contribution from fragment capture reaction was verified to be negligible.

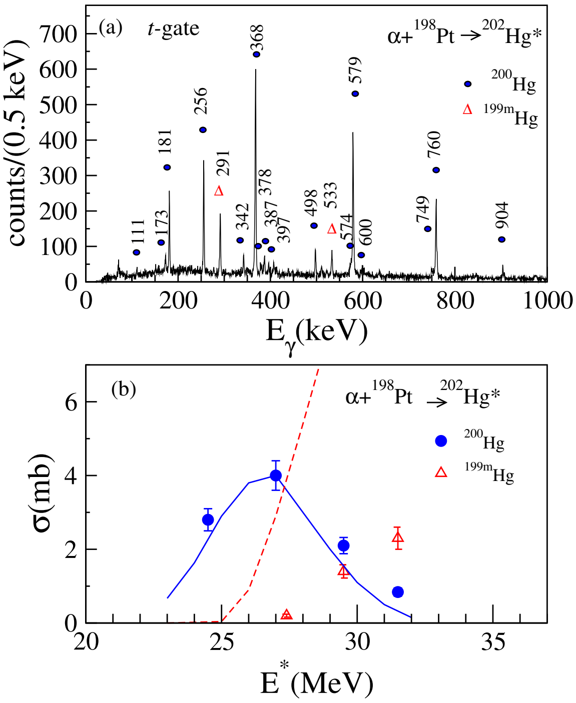

Figure 2. (Color online) (a) Prompt γ-ray spectra obtained in coincidence with outgoing *t* (α-capture) having an energy 10 to 20 MeV (b) Residue cross-sections as a function of excitation energy (E*) of the primary composite system formed after *t*-capture. The E* in ^{202}Hg, corresponding to kinetic energy (E$_\alpha$) of the surviving α- particle is calculated from the classical trajectory model of breakup-fusion - PLATYPUS.

Plotted in Fig. 2a is the γ-ray spectrum gated by the outgoing tritons with kinetic energy between 10 to 20 MeV, showing peaks from the residues of the composite system, ^{202}Hg, corresponding to capture of α-particles by the ^{198}Pt target. In case of ^{199}Hg, the γ-ray transitions feeding the long lived isomeric state (13/2$^+$, T$_{1/2}$ $\sim$ 42.8 min), known from an earlier study in α +^{198}Pt system are labeled. The triton spectrum from the two telescopes was further divided in to smaller energy bins (2.5 MeV) to study the variation in population of the residues as function of triton energy and is shown in Fig. 2b. The relative population of ^{200}Hg corresponding to each bin of the triton spectrum were estimated from the efficiency corrected yields of γ-ray transition to the ground state. A similar procedure was followed for ^{199}Hg for transitions above the isomeric state, 13/2$^+$ at 532 keV.

In Fig. 3a, the γ-ray spectrum obtained in coincidence with α-particles shows contribution arising from different reaction channels. The main γ-ray transitions in the spectrum arise from ^{198,199}Au (residues due to *t*-capture). Shown in Figs. 4a,b are the γ-ray spectrum in coincidence with the deuterons and protons respectively. Comparing these spectra with Fig. 2a, it can be noticed that more neutron rich residues (due to capture of the heavier complementary particle), are populated in going from spectra in coincidence with *t* to *p*. In the γ-ray spectrum gated by the deuterons, the peaks arise mainly from the residues that

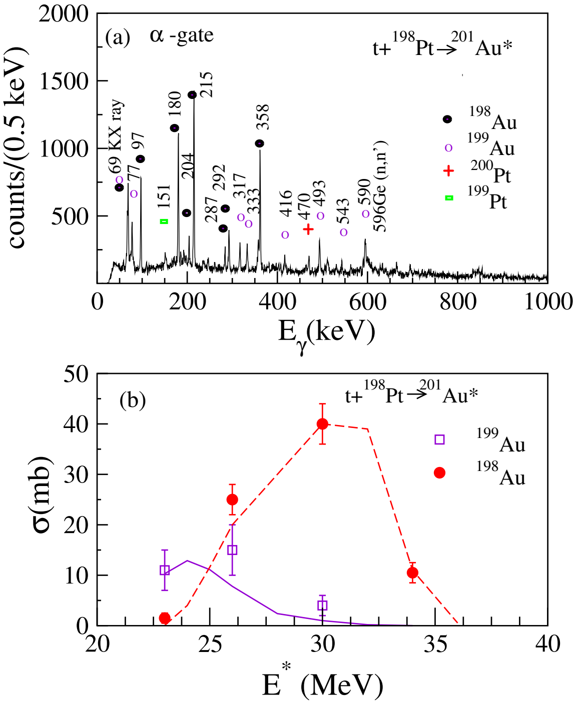

Figure 3. (Color online) Same as Fig.2 but for *t*-capture

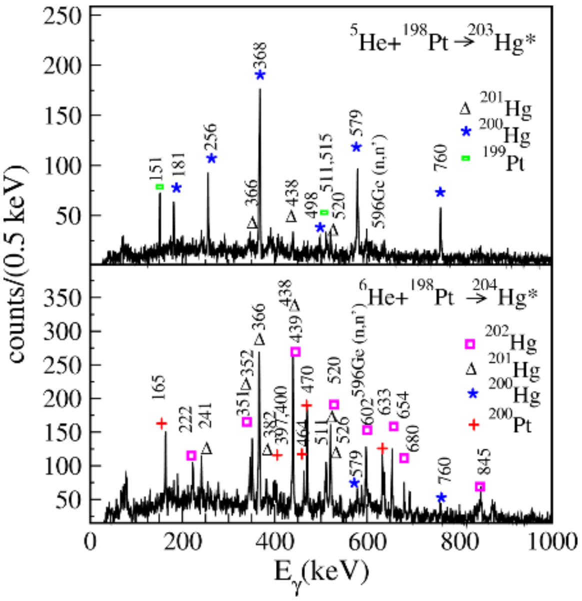

Figure 4. (Color online) In beam γ-ray spectra in coincidence with outgoing fragments (a) d and (b) p. The gamma transitions from the residues populated from capture of ^{5}He and ^{6}He are indicated in (a) and (b) respectively. The γ-rays arising from 1n and 2n-transfer (^{199,200}Pt) are also labeled.

can be attributed to decay of ^{203}Hg arising from the capture of ^{5}He (Fig 4a). The known γ-ray transitions from ^{200,201}Hg could be identified. The dominant peaks observed in Fig. 4b are from the ^{201,202}Hg residues, of the composite system ^{204}Hg formed after capture of ^{6}He. The γ-ray transitions from ^{199,200}Pt, corresponding to one and two neutron transfer reactions are observed in the α, d and p gated spectra resulting from neutron transfer followed by breakup reactions [13].

The peaks at 366 keV and 241 keV in Fig. 4b could not be identified among the known transitions of ^{200,201,202}Hg and ^{200}Pt. A probable candidate could be from the decay of states above the $13/2^+$ isomer in ^{201}Hg. No spectroscopy information of the prompt gamma transition above this state is presently available in literature. Change in γ-ray intensity of these transitions as compared to transitions from ^{202}Hg was studied with different energy bins of the scattered proton, further confirming this assignment to ^{201}Hg. This observation shows advantage of the breakup fusion reaction for studying nuclear states at higher spin, not accessible by the compound nuclear fusion, earlier demonstrated in Ref. [14].

2.1 Analysis with Classical Trajectory model

The PLATYPUS calculations were carried out considering ^{7}Li as α + t cluster, having a binding energy of 2.47 MeV. In this calculation breakup fusion occurs when any of the breakup fragment (α or t) penetrates the Coulomb barrier between the fragment and the target. Complete fusion occurs when the entire projectile, ^{7}Li or both α and t get captured inside the interaction barriers. Parametrization of the Coulomb and nuclear potential was same as in Ref. [4]. Parameters necessary for the breakup-probability function [$A\exp(-\beta R)$], where R denotes the internuclear distance] were obtained by reproducing the measured integrated cross-section of t-capture and α- capture and the complete fusion for ^{7}Li + ^{198}Pt (Fig.1). The calculations were found to be in agreement with the shape of the measured energy spectrum of surviving α-particles and t.

To get further insight into the mechanism of fragment-capture, the measured yields of the evaporation residues obtained from the particle-gamma coincidence data were compared with the predictions from PLATYPUS + PACE2 for different excitation energies (E*) of the primary composite system as discussed below. The spectrum of the surviving α-particles, after capture of the complementary fragment (t), represents the cross-section for breakup-fusion as a function of the kinetic energy of the α-particles (E$_\alpha$). This can be expressed as a function of E* of the composite system ^{201}Au, by obtaining the E* for each value of E$_\alpha$, using the dynamical variables at the instant of breakup of ^{7}Li into α+t on an event by event basis. The calculated E* and the corresponding breakup fusion cross-section as a function of spin (σ_J vs J) were given as input to the statistical model code PACE2 [15] for calculating the evaporation residue cross-sections from decay of ^{201}Au formed after triton-fusion. The calculated values of absolute cross-sections for the residues, ^{198,199}Au, are plotted as solid and dashed curves in Fig. 3b. The measured yields of ^{198}Au from the second bin of α-particle spectrum, were normalized to the calculated cross-section obtained using PACE2 for the E* = 30 MeV that corresponds to the E$_\alpha$ = 24 MeV (center of the bin used). The cross-section for ^{198,199}Au deduced after applying the same normalization to their respective yields in each bin and are plotted in Fig. 3b. The errors on cross-sections are only statistical in nature. A reasonably good agreement is observed with the calculation. These results suggest that the main mechanism responsible for t- capture is fusion of t after breakup of ^{7}Li, as modeled in the PLATYPUS code. Following the same procedure, cross-sections for residues arising from the capture of α-particles for a given energy (corresponding to outgoing triton energy) were calculated from PACE2, using spin distribution and excitation energy of ^{202}Hg obtained from PLATYPUS and are shown in Fig. 2b. The calculated cross-section of ^{200}Hg at E*=27 MeV was used to normalize the measured yield of ^{200}Hg and ^{199}Hg. In case of ^{199}Hg the γ -ray transitions only above the (13/2$^+$) isomeric state were considered hence the measured cross-sections only provide a lower limit for this channel. The energy dependence of formation of both the residues agrees well with the statistical model calculations, showing a similar dominance of the breakup fusion process. The PLATYPUS calculations indicate that the breakup fusion process is dominated by breakup events with $E_{rel} \leq 4$ MeV, which only includes prompt breakup. This type of breakup is critical, as the resonant states have life time larger than the interaction time [16].

A similar analysis was attempted by modeling ^{7}Li as a cluster of ^{6}He+p (breakup threshold 9.975 MeV). The average E* of the composite system ^{204}Hg computed using PLATYPUS is high (42 MeV) due to large positive Q-value (+12.4 MeV) for ^{6}He fusing with ^{198}Pt. The major residue channels predicted at this E* and over the measured range of proton energies are ^{199,200}Hg. The γ-transitions for ^{199}Hg are not observed while those from ^{200}Hg are found to be populated weakly (with the proton gate). Multi-nucleon transfer reactions are known to take place preferentially at an optimum Q-value (Q$_{opt}$) obtained from the semi-classical trajectory matching condition [17]. The available E* (Q$_{gg}$-Q$_{opt}$ = 31 MeV) from transfer of ^{6}He is favorable for populating the residue channels ^{201,202}Hg, which is consistent with the present measurement (Fig. 4b). The same is found to be applicable for the ^{5}He + d cluster structure of ^{7}Li (breakup threshold = 9.522 MeV, fusion Q value = +6.75 MeV). The average E* calculated from PLATYPUS for this combination favors residue channels ^{198,199}Hg for which the γ transitions are not visible in the d gated spectrum. While the lower E* estimated from transfer Q-values is more suited for populating ^{200}Hg, in concurrence with the data (Fig 4a). Based on these observations it can be inferred that, for the capture of ^{5,6}He from the well-bound cluster configurations of ^{7}Li, the large value of the breakup threshold does not favor the process of breakup fusion, unlike that for the t and α particles that are weakly bound in ^{7}Li, and massive transfer from bound states could be the main process.

2.2 Summary

The cross-section of evaporation residues for different excitation energies of the composite system, formed after fusion of t and α particles were successfully explained, by the classical dynamical model of breakup fusion. This information can be useful for studying nuclear structure of the nuclei formed as ^{5,6}He +target or t + target, using a ^{7}Li beam [18]. A good agreement between the calculations and the measured quantities suggests, the dominant mechanism of capture of the fragments with low binding energy in ^{7}Li (t and α) after the inelastic excitation of ^{7}Li above the breakup threshold is breakup followed by fusion. In case of capture of ^{5}He+d and ^{6}He+p clusters with relatively high binding energy in ^{7}Li, the evaporation residues are more neutron rich than predicted from the model for fusion of ^{5}He and ^{6}He after the breakup, suggesting that the mechanism is not breakup fusion but could be massive transfer.

References

[1] H. Horiuchi, K. Ikeda and K. Kato, Prog. Theor. Phys. Suppl.**192**, 1 (2012).

[2] M. Freer Rep. Prog. Phys. **70**, 2149 (2007); W. von Oertzen, M. Freer and Y. Kanada-En'yo, Phys. Rep. **432**, 43 (2006).

[3] N. Keeley, R. Raabe, N. Alamanos, and J. L. Sida, Prog. in Part. and Nucl. Phys. **59**, 579 (2007); N. Keeley, N. Alamanos, K.W. Kemper, and K. Rusek, Prog. Part. Nucl. Phys. **63**, 396 (2009).

[4] A. Diaz-Torres *et al.*, Phys. Rev. Lett. **98**, 152701 (2007).

[5] A. Diaz-Torres, J. Phys. G. Nucl. Part. Phys. **37**, 075109 (2010).

[6] C.M. Castaneda *et al.*, Phys. Lett. B **77**, 371 (1978).

[7] H. Utsunomiya *et al.*, Phys. Rev. C **28**, 1975 (1983).

[8] V. Tripathi *et al.*, Phys. Rev. C **72**, 017601 (2005).

[9] J. Wilczynski *et al.*, Phys. Rev. Lett. **45**, 606 (1980); J. H. Barker *et al.*, Phys. Rev. Lett. **424**, 45 (1980) 45.

[10] A. Shrivastava *et al.*, Phys. Rev. Lett. **103**, 232702 (2009).

[11] Yu. E. Penionzhkevich *et al.*, J. Phys. G. Nucl. Part. Phys. **36**, 025104 (2009).

[12] A. Shrivastava *et al.*, Phys.Lett. B **718**, 931 (2013).

[13] A. Shrivastava *et al.*, Phys. Lett. B **633**, 463 (2006).

[14] G.D. Dracoulis *et al.* J. Phys. G. Nucl. Part. Phys. **23**, 1191 (1997).

[15] A. Gavron, Phys. Rev. C **21**, 230 (1980).

[16] D.H. Luong *et al.*, Phys. Lett. B **695**, 105 (2011).

[17] R. Broglia, A. Winther, Heavy Ion Reactions, volume 84, Addison Wesley, Redwood City, CA, 1991.

[18] A. Jungclaus *et al.*, Phys. Rev. C **66**, 014312 (2002); R.M. Clark *et al.*, Phys. Rev. C **72**, 054605 (2005).