Dominance of Sequential Transfer in Large $\alpha$-Production for $^6\text{Li}+^{51}\text{V}$ System

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Abstract

Inclusive $\alpha$-production cross-section has been measured for $^6\text{Li}+^{51}\text{V}$ system near coulomb barrier. Theoretical calculations for contributing reaction channels were performed using limited range coupled reaction method from FRESCO code to understand the reaction mechanisms. Cross-section from breakup($\alpha+d$) and 1-n, 1-p, 1-d and sequential ($n+p$ or $p+n$) transfer and statistical decay channel leading to $\alpha$-production were estimated to get the cumulative production cross-section. It is observed that these channels could reproduce the integral $\alpha$-production and their angular distributions quite well. The sequential transfer shows a dominant contribution compared to direct transfer channels.

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I. INTRODUCTION

In heavy ion reactions induced by weakly bound projectiles, cluster breakup/transfer becomes one of the important reaction channel, mainly around the barrier. The breakup of weakly bound light nuclei such as $^6\text{Li}$ with cluster structure ($\alpha+d$) is a well established phenomenon while moving in the field of target nucleus [1–5]. Numerous observations assist for larger yield of $\alpha$-particles in comparison to its complementary constituent and the mechanism lying behind is still the current interest of investigation for projectiles with cluster structures like $^6,^8\text{He}$, $^6,^7\text{Li}$, $^7,^9\text{Be}$ [6,9]. In a representative example $\text{P+T} \rightarrow (\alpha+x)+\text{T}$, when any one or more than one of the outgoing fragments is unrecognized then reaction is inclusive with respect to unobserved particle(s). Identified larger yield of inclusive $\alpha$-particles implies existence of several more processes apart from breakup. For the systematic understanding of inclusive data, the different reaction channels not yet clearly identified in inclusive/exclusive/theoretical estimations of individual reaction channels.

Large number of studies are performed with weakly bounded projectile $^6\text{Li}$ to have better understanding of breakup influences. The $^6\text{Li}$ has 1.474 MeV separation energy and is supposed to have $\alpha$ and deuterons as major transfer reaction channels, but, yield of $\alpha$ is typically substantial than that of deuterons which indicates deuterons transfer is favored over $\alpha$-transfer. In the vision of better understanding of reaction mechanism from loosely bound projectiles, inclusive/exclusive cross sections are determined through measurement of total $\alpha$-yield. Inclusive $\alpha$-production incorporates distinct reaction mechanisms, right from breakup to compound nuclear evaporation along with nucleon transfer trailed by breakup; incomplete fusion or transfer of a cluster. Out of the possible reaction channels for production of $\alpha$, the system can undergo the reactions like (a) $^6\text{Li} + ^{51}\text{V} \rightarrow ^6\text{Li}^*+^{51}\text{V} \rightarrow \alpha+d+^{51}\text{V}$ (b)$^6\text{Li} + ^{51}\text{V} \rightarrow \alpha+^{53}\text{Cr}$ (c)$^6\text{Li} + ^{51}\text{V} \rightarrow \alpha+^{55}\text{Mn}$ (d)$^6\text{Li} + ^{51}\text{V} \rightarrow ^6\text{Li}^*+^{52}\text{V}$ (e)$^6\text{Li} + ^{51}\text{V} \rightarrow ^{5}\text{He}^*+^{52}\text{Cr}$ (f)$^6\text{Li} + ^{51}\text{V} \rightarrow ^{57}\text{Fe}^*$ and subsequent decay of the excited residues.

Presently, none of the coupled channel code is competent enough to include breakup and transfer in single calculation. The Coupled Reaction Channel(CRC) calculations handle transfer but not along with breakup, whereas Continuum Discritized Coupled channel calculations take care of breakup but not along with transfer. Several reports [6,10,12] manifest this aspect to define breakup cross section and have done exclusive and inclusive measurements to find the solution of this open question of various contributions to inclusive $\alpha$ production.

Hereby, we are reporting the energy and angular distributions of inclusive-$\alpha$ for the system $^6\text{Li}+^{51}\text{V}$ and integral cross section for the same. Theoretical calculations for breakup and various transfer channels are performed to interpret the experimental data. The results manifest contribution from breakup/transfer channels. The article contains following outline. Sec.II dedicated to experimental details. Sec.III belongs to data reduction procedure and brief discussion. Theoretical analysis using statistical model, coupled reaction calculation of 1-n, 1-p, 1-d and sequential ($p+n$ or $n+p$) transfer using FRESCO are described in Sec. IV. Discussion and conclusion are reported in sec. V.

II. EXPERIMENTAL DETAILS

Details of the experimental setup are given in an earlier publication [13] and a short summary is given here.
for completeness. The experiment was performed at 14-UD BARC-TIFR Pelletron-Linac accelerator facility, in Mumbai, India with $^6$Li$^3^+$ beam at energies 14, 20, 23 and 26 MeV energies. The beam current was ranging between 5-28 nA. The beam was incident overself-supported $^{51}$V target of thickness 1.17 $\mu$g/cm$^2$. The detection system was consisting a set of four solid state silicon surface barrier telescope detectors in $\Delta E+E$ arrangement and two monitors at $\pm 10^\circ$ for absolute normalization. The angles covered by telescope detectors were 14$^\circ$ to 170$^\circ$ in lab frame. A $\Delta E$-E particle spectrum is given in Fig. 1. The statistical errors were in the range of less than 1% percent to 9%. The data were recorded using the Linux based data acquisition system [14].

III. DATA REDUCTION AND DISCUSSION

A. $\alpha$-Particle Energy Spectra

The $\alpha$-particle produced after $^6$Li breakup will be maximally around 2/3rd of the incident $^6$Li energy where kinetic energy per nucleon of the $\alpha$-particle is approximately equal to that of the incoming particle. The energy spectra at various angles are shown in Fig. 2 and Fig. 3 for 26 MeV and 20 MeV, respectively. The experimental energy spectra include $\alpha$-particles originating through direct and compound nucleus reaction. As it can be easily concluded that at backward angles, compound nuclear contribution and experimentally deduced energy spectra matching well to offer almost the only contribution from evaporation/complete fusion/compound, while the front angles show the contribution from different direct channels. Also, the non-compound reaction contribution reduces significantly at lower energies compared to higher incident energies.

B. Differential Cross Section

The energy integrated $\alpha$-particles yields were obtained at different angles. The energy integrated measured differential angular cross section was obtained using the equation [5] as follows:

$$\frac{d\sigma}{d\omega} = \frac{Y_\alpha}{Y_{el}} \times \frac{d\sigma_{el}}{d\Omega}$$

Here, $Y_\alpha$, $Y_{el}$ are $\alpha$-particle and elastic scattering counts, $d\sigma_{el}/d\Omega$ is elastic scattering cross section, obtained from Ref. [13]. Angular distribution of $\alpha$-particle production cross section is shown in Fig. 4. It is clear that large angle cross-section is dominated by evaporation through compound nuclear or complete fusion reaction whereas...
breakup and transfer following $\alpha$-particles are peaking near grazing angles.

C. Angle integrated cross section

The angle integrated direct-$\alpha$ cross sections at each energy were obtained by fitting the Gaussian shape to $d\sigma/d\Omega \times 2\pi \sin \theta$ distribution and an integral $\alpha$-cross section was deduced using equation-

$$\sigma_\alpha = \int_0^{2\pi} d\phi \int_0^\pi \frac{d\sigma_\alpha(\theta)}{d\Omega} \sin \theta d\theta$$  \hspace{1cm} (2)

The error caused by fitting procedure was weighted error with goodness of fits. The error shown in the experimental $\alpha$-cross section are due to errors in the fitting parameters. Table 2 illustrates the derived experimental total $\alpha$ cross section along with errors.

FIG. 3: Energy spectra of $\alpha'$s at 20 MeV and at different angles for $^6$Li+$^51$V reaction. Notations are same as given in Fig. 2.

FIG. 4: Energy integrated angular distribution of $\alpha$-spectra at different energies for $^6$Li+$^51$V system. The solid circles represent total $\alpha$- cross section, solid line is contribution from compound system and direct/non-compound (Total - Compound) are depicted by empty triangles.

IV. THEORETICAL ANALYSIS

A. Theoretical Analysis: Statistical Model Calculations

The contribution from compound nuclear reaction for $\alpha$-production cross section was calculated using statistical model PACE[15]. The angular distribution and energy spectra show resemblance at backward angles with experimental data. The Ignatyuk [16] prescription of level density with parameter ($\tilde{a}=A/10$ MeV$^{-1}$, A=mass number), was used. The diffusion parameter was equal to 4 and other model parameters, like optical potentials were used as default ones. The angular distribution of $\alpha$-production due to compound nucleus evaporation reaction is given in Fig. 4.

B. Coupled Reaction Channel Calculations

It is a well accepted fact that, to explore the internal properties of nuclei, the arrangement of nucleons somewhere inside the nucleus with the help of transfer/inelastic reactions are an appreciable exercise. Therefore, for this purpose, transfer reactions have kept an standard exercise to calculate single particle structure of nuclei and extraction of spectroscopic factors. In this section, we demonstrate the influence of $1n$, $1p$, $1d$ direct and ($1p + 1n$ or $1n + 1p$) sequential transfer cross-section for the reactions $^{51}$V($^6$Li, $^5$Li)$^{52}$V, $^{51}$V($^6$Li, $^5$He)$^{52}$Cr and
The 1n-transfer followed by breakup of $^6$Li $\Rightarrow$ $^{51}$V($p^+ + ^4$He)+n can contribute to $\alpha$-production. The CRC calculations of 1n-transfer resulted in considerable contribution to inclusive $\alpha$-cross-section by the reaction $^{51}$V($^6$Li,$^5$Li)$^{52}$V. The optical potentials for the incoming channel, were obtained from elastic scattering data [13]. The Woods–Saxon form factors were used with reduced radii $r_0=1.25$fm and diffuseness $a_0=0.65$fm, for projectile as well as target bound state potentials. The spin-orbit interaction was included with standard depth of 6MeV. The depth of the real potential was allowed to vary to reproduce experimental neutron binding energies. The finite range transfer approximation in FRESCO [17] was used for the calculations in post form. Full complex remnant term were used with two way coupling scheme. The other important parameter, spectroscopic factor for the projectile was taken from [18]. The calculations were performed for single n-transfer to the $2p_{1/2}$, $1f_{5/2}$, $2p_{1/2}$ and $1g_{9/2}$ orbits of available model space of $^{52}$V with the assumption of closure of $1f_{7/2}$ subshell in the ground state. The continuum coupling, above neutron bound state, was considered with angular momentum of L=0→5h and using equal linear momentum bins up to $\sim$15MeV of energies. The schematic picture of target overlaps and discrete states for coupling are shown in Fig. 5 which were part of the calculations. The contribution of 1-n transfer is mentioned in Table 1. The total angular distribution for 1-n transfer having sum of all participating states included.
D. 1-p transfer

In order to study the 1-p stripping/transfer contribution and thus to carry out the reaction $^{51}$V($^6$Li,$^5$He)$^{52}$Cr, CRC calculations have been performed. The calculations were performed for single p-transfer to the 1f$_{7/2}$, 2p$_{3/2}$ orbits in the model space of $^{52}$Cr. The schematic picture of target overlaps and states for coupling is shown in Fig. 6. The spectroscopic factors for target were taken from Ref. [20]. The spectroscopic factors were assumed as one to get the contribution of higher states up to 9.5 MeV. The Continuum couplings up to 20 MeV above bound state was included which gives rise to small contribution. The 1-p transfer cross-section is mentioned in Table I. The total angular distribution for 1-p stripping having sum of all participating states in calculation is presented in Fig. 7.

E. d-cluster transfer

The 1-d transfer contribution which leads to direct $\alpha$-production through $^{51}$V($^6$Li, $^4$He)$^{54}$Cr reaction, CRC calculations were performed. The spectroscopic factors for the projectile and target were taken as one. As the Q-value for this channel is quite high (14.745 MeV), the transfer to low lying discrete states was insignificant. Thus, The transfer to continuum coupling of $^{53}$Cr states up to $\sim$27 MeV energies above deuteron binding energy with equal momentum bins of bin width $\Delta k = 0.1 \text{fm}^{-1}$ and angular momentum of L=0 to 7 $\hbar$ were considered. The cross-section contribution of d-transfer is reported in Table I. The angular distribution for 1-d transfer with sum of all continuum states in calculation is presented in Fig. 7.

F. n-p(p-n) sequential transfer

In case of one cluster outside the core, the interfering transfer reaction is simultaneous or one-step transfer but if transfer takes place in two step by transfer of n/p and p/n one after other it is termed as sequential transfer. The individual contribution of sequential transfer can be comparable or even more than the single step direct transfer/emission [21–25] which also depends on kinematic parameters. The sequential transfer calculations were included to emphasis the understanding of the relative importance of the processes governed by transfer mechanism. The incoming, outgoing channel and binding potential parameters are same as taken in n-, p-transfer reactions. Successive paths for the transition $^6$Li(g.s.) $\rightarrow$ $^4$He(g.s.) involve one intermediate channels that populate the 3/2$^-$ (g.s.) in $^5$Li ($^3$He) nucleus. In this model of two-step transfer of single-nucleons, the interaction potential acts twice and the form factors are calculated by incorporating the appropriate single nucleon separation energies. The reaction calculations are done in the prior-post combination to avoid the non-orthogonality terms. The contribution of n-p/p-n transfers is mentioned in Table I. The total angular distribution for n-p/p-n transfer having sum of all participating states in calculation is presented in Fig. 7.

FIG. 6: Schematic diagram of coupling of different levels used in calculation for 1-p transfer.

FIG. 7: Total angular distribution for n-p/p-n transfer having sum of all participating states in calculation is presented.
V. CONCLUDING REMARKS

Direct (inclusive) $\alpha$-production cross-section has been measured for $^6$Li-$^{51}$V system around coulomb barrier and large $\alpha$-particle yields were observed. Contribution of evaporation channel is extracted using statistical model code PACE. Break-up calculation using CDCC method, CRC calculations for n-, p-, d- and sequential n-p/p-n transfer are performed with FRESCO code to disentangle the contribution from these channels to $\alpha$ production. Addition of all these Channel cross-sections leading to $\alpha$-production reproduce experimental data well. Deutron cluster transfer gives negligible contribution to discrete states due to high Q-value. Cluster transfer to continuum gives significant contribution but does not reproduce inclusive $\alpha$-production cross-sections. Transfer to continuum enhances n- and p-transfer along with discrete state contributions. Sequential n-p/p-n transfer is dominant over direct n-, p-, d-transfer channel. In sequential transfer, n-p transfer is more compared to p-n sequential transfer. The large angle distribution is dominated by n-p transfer. Triple coincidence measurement (particle, neutron and gamma) may disentangle these processes more clearly.

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