# Origin of large $\alpha$-production in $^{7}$Li+$^{93}$Nb reaction

S. K. Pandit[1,2],* A. Shrivastava[1,2], K. Mahata[1,2], V. V. Parkar[1], R. Palit[3], N. Keeley[4], P. C. Rout[1], A. Kumar[1], K. Ramachandran[1], S. Bhattacharyya[5], V. Nanal[3], C. S. Palshetkar[3], T. N. Nag[6], Shilpi Gupta[1,2], S. Biswas[3], S. Saha[3], J. Sethi[3], P. Singh[3], P. Patale[1], A. Chatterjee[1], and S. Kailas[1]

[1]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, India*
[2]*Homi Bhabha National Institute, Anushaktinagar, Mumbai - 400094, India*
[3]*Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai 400005, India*
[4]*National Centre for Nuclear Research, ul. Andrzeja Sołtana 7, 05-400 Otwock, Poland*
[5]*Variable Energy Cyclotron Centre, Kolkata - 700064, India and*
[6]*Radiochemistry Division, Bhabha Atomic Research Centre, Mumbai - 400085, India*

The $\alpha$-particle production cross section has been reported to be large compared to that of the complementary fragment in the reaction involving weakly bound nuclei with $\alpha+x$ cluster structure, e.g. $^{6,8}$He, $^{6,7}$Li, and $^{7,9}$Be [1]. Different reaction mechanisms, e.g. breakup (direct and sequential), nucleon transfer followed by breakup, cluster transfer, incomplete fusion (only part of the projectile fuses), and compound nuclear (CN) evaporation, contribute to the $\alpha$ yield. It is difficult to separate the contributions of these individual reaction mechanisms from an inclusive $\alpha$-particle spectrum. Exclusive measurements are therefore needed to investigate the origins of the large $\alpha$ production and to study the role of the weakly-bound cluster structure in the reaction dynamics. The present work aims to study the sources of the large $\alpha$-yield for reactions induced by $^{7}$Li nuclei by extensive measurements of different reaction channels.

Two independent experiments were carried out for in-beam and off-beam $\gamma$-ray counting, using the $^{7}$Li beam from the BARC-TIFR Pelletron-Linac facility, Mumbai. Both measurements were performed at beam energies of 24, 26, 28 and 30 MeV. Self-supporting $^{93}$Nb foils of thickness $\sim$ 1.6 mg/cm$^{2}$ were used as targets. Particle-$\gamma$ coincidence measurements were performed using three Si surface barrier telescopes for non captured charged fragments and the Indian National Gamma Array (INGA) for prompt $\gamma$-ray transitions [2]. One Si surface barrier detector of a thickness $\sim$ 300 $\mu$m was fixed at 20° to monitor Rutherford scattering for absolute normalization purposes. The details of the experimental setup are same as given in Ref [3]. The off-beam $\gamma$-ray counting was carried out using an efficiency calibrated high-purity germanium (HPGe) detector to measure the cross-sections of the $\beta$-unstable nuclei having an isomeric state in the yrast band.

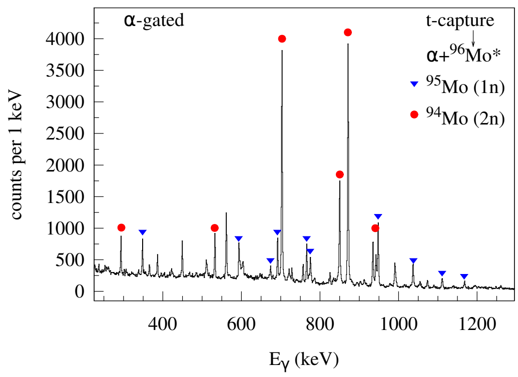


FIG. 1: A typical in-beam $\gamma$-ray spectrum in coincidence with $\alpha$ particles selected as the outgoing fragment for the $^{7}$Li+$^{93}$Nb reaction at $E_{\rm beam}$ = 28 MeV.

A typical in-beam $\gamma$-ray add-back spectrum in coincidence with the $\alpha$-particle in the outgoing channel is shown in Fig. 1. The dominant $\gamma$-ray transitions are found to be corresponding to the residues of $t$-capture ($^{94,95}$Mo) reaction. This observation implies that $t$-capture

*Electronic address: `sanat@barc.gov.in`

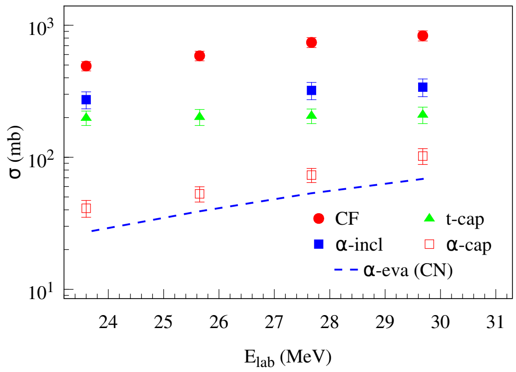


FIG. 2: The measured cross sections for $t$-capture, $\alpha$-capture, CF, $\alpha$-incl (from Ref. [4]) are denoted by filled triangles, open squares, filled circles, and filled squares, respectively. The dashed line is the estimated $\alpha$-evaporation cross section from the statistical model calculations.

is the main source of $\alpha$-production.

The absolute cross-sections of residues arising from capture of various fragments and complete fusion reaction have been extracted from the inclusive $\gamma$-ray measurements. The cross-sections of the residue that are stable and have even-even nucleons were obtained from the yrast $\gamma$-ray transitions built on the ground state. In case of odd-even nuclei, the cross-sections were extracted by adding the $\gamma$-ray transitions feeding directly to the ground state. The $\beta$-unstable residues with reasonable half lives for decay were identified by measuring the off-beam $\gamma$-ray activity. The cross-sections were extracted following the half lives and intensities of each transition. The uncertainty in the measurement was estimated from statistical fluctuation, $\gamma$-ray detection efficiency, and available spectroscopic information of the residues. For off-beam measurements uncertainty in the target thickness was also included.

Statistical model calculations were performed to estimate the compound nuclear contribution to the cross sections of residues populated in $t$-capture and $\alpha$-capture reactions. The statistical model parameters were fixed by reproducing the individual cross-sections of the residues arising from complete fusion. The measured cross-sections of CF, $t$-capture, $\alpha$-capture along with the inclusive-$\alpha$ from Ref. [4] are shown in Fig.2. The estimated $\alpha$-particle evaporation is also presented in Fig.2. The measured $t$-capture cross sections are found to be greater than the $\alpha$-capture cross sections at all energies.

The present study shows that the $t$-capture mechanism is the dominant reaction channel for the production of $\alpha$-particles and accounts for 62-73% of the measured inclusive-$\alpha$ cross sections. The $2n$ stripping ($^5$Li $\rightarrow \alpha + p$) cross sections together with earlier data on the $1p$ pickup ($^8$Be $\rightarrow \alpha+\alpha$), inelastic excitation ($^7$Li$^*$ $\rightarrow \alpha + t$) and $1n$ stripping ($^6$Li$^*$ $\rightarrow \alpha + d$) from Ref. [4] explain $\sim$15% of the inclusive $\alpha$ cross sections. The statistical model predictions of the compound nuclear contributions from $\alpha$-evaporation account for 10-20% of the inclusive $\alpha$ cross sections. The present work explains almost all the inclusive $\alpha$-particle yield. Although at present it is still not possible to say about the exact reaction mechanism responsible for $t$-capture. An analysis of the present data set on $\alpha$-production using stochastic breakup model calculations [5] could shed light on whether the observed $t$-capture is a direct and/or two-step process [6, 7].

We thank the Mumbai Pelletron-Linac accelerator staff for providing steady and uninterrupted beam.

## References

[1] L. F. Canto *et al.*, Phys. Rep. **596**, 1 (2015); L. F. Canto *et al.*, Phys. Rep. **424**, 1 (2006).
[2] R. Palit *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **680**, 90 (2012).
[3] S. K. Pandit *et al.*, Proc. of DAE Symp. on Nucl. Phys. **16**, 340 (2014).
[4] S. K. Pandit *et al.*, Phys. Rev. C **93**, 061602 (2016).
[5] A. Diaz-Torres *et al.*, Phys. Rev. Lett. **98**, 152701 (2007).
[6] A. Shrivastava *et al.*, Phys. Lett. B **718**, 931 (2013).
[7] S. K. Pandit *et al.*, Phys. Rev. C. (under review)