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# Investigation of alpha particle induced reactions on thulium

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**Abstract.** Alpha particle induced reactions on the target element thulium were investigated up to 75 MeV, using foil-stack activation technique and Ge(Li) gamma ray spectroscopy method. Excitation functions for eight reactions of the type $^{169}\text{Tm}(\alpha, xn)$, $x = 1-4$; $^{169}\text{Tm}(\alpha, pxn)$, $x = 3$; and $^{169}\text{Tm}(\alpha, \alpha xn)$, $x = 1, 2, 4$ were investigated. Of these, four reactions $^{169}\text{Tm}(\alpha, p3n)$, $^{169}\text{Tm}(\alpha, \alpha n)$, $^{169}\text{Tm}(\alpha, \alpha 2n)$ $^{169}\text{Tm}(\alpha, \alpha 4n)$, were studied for the first time and in the remaining four reactions, some 19 new energy-point cross-sections were measured for the first time. The experimental cross-sections were compared with the predictions of pre-equilibrium hybrid model, as well as the more recent index model, using the initial exciton number, $n_0 = 4$ ($4p0h$). Both the models show better agreement in respect of $(\alpha, xnyp)$ type of reactions. However they are equally bad for $(\alpha, \alpha xn)$ type of reactions which involve the $\alpha$-particle in the exit channels, and for which some direct reaction contributions are indicated.

**Keywords.** Hybrid model; index model; stacked-foil activation technique; pre-equilibrium decay; ALICE/85/300 code; index code.

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## 1. Introduction

A great deal of recent interest has been focussed on models which treat the equilibration process in nuclear reactions at moderate excitations. While the great success and persuasive usefulness of the traditional compound and direct nuclear reaction mechanisms are well known, it is perhaps less well-known that there is a large body of experimental data that appears to deviate systematically from the predictions of either of these two extreme approximations. It is naive to expect that there is a quantum jump in the reaction mechanism from that of the simple direct reaction on the one extreme to the one describing the complex compound nuclear reaction on the other. At moderate energies, it is reasonable to think that the compound nucleus is not formed just immediately after the entry of the incident particle; it is, however, reached by a fast nuclear cascade where, following the first projectile-target interaction, the few initially excited nucleons called 'excitons' lose their energy exciting more and more nucleons. In this short but finite phase of nuclear relaxation, generally there is a finite probability that an energetic nucleon may be directly emitted without sharing its energy with other nucleons. A particle so emitted will naturally have a higher energy than it would have if it were to be emitted later by a 'relaxed' compound nucleus. Thus, the central theme of pre-compound emission is that the excitation energy is focussed rather on a few degrees of freedom and that the direction of the incident particle is kept in memory to some extent, thereby leading to the emission of the more energetic particles in the forward direction. In order to explain the physics of the nuclear equilibration, several semiclassical and quantum mechanical models were proposed during the past three decades; these models are still in a state of revision and refinement (Blann 1975; Feshbach *et al* 1980; Machner 1985). It was shown that the exciton model (Griffin 1966; Cline and Blann 1971; Gadioli *et al* 1973; Stockhorst *et al* 1982) and hybrid model (Blann 1971) are only closed form approximations of a more general Boltzmann master equation approach (Pauli 1928) applied to nuclear relaxation. Further, there are some conceptual differences between the hybrid and exciton models regarding the emission chances which are discussed and resolved by several authors (Blann 1978; Gadioli *et al* 1978; Ernst and Rama Rao 1977; Bisplinghoff 1986; Akkarmans 1986). Thus in recent years, there have been far reaching improvements in the semi-classical or phenomenological models such as hybrid, exciton, unified and index models (Ernst and Rama Rao 1977; Ernst *et al* 1987). On account of their simplicity and transparency, these models are often used for making comparison with experimental results. Not only has the validity of these models been extended up to a few hundred MeV in excitation but the important influence of multiple chance pre-equilibrium emission in multiparticle reaction has also been incorporated into the model frame work. Further, versatile computer codes have been written incorporating new algorithms. Blann, who is continuously improving his computer codes on hybrid model (Blann 1973, 1976; Blann and Bisplinghoff 1982) in 1984 introduced new algorithms into the last mentioned code to calculate the multiple chance pre-equilibrium emission of nucleons in an approximate way. On the other hand Ernst and Rama Rao (1977) have been continuously improving the exciton and unified models. Recently in 1987, they further improved the unified model by a better treatment of intermediate states and also by including multiple chance pre-equilibrium emission in a rigorous way. These developments have made these models useful and attractive, so that they are used in the present work to compute theoretical excitation functions.

On the experimental side, all the previous measurements of alpha-induced reactions on thulium were carried out using poor resolution detectors and there were no improved measurements during the last two decades. Further, in some reactions, the cumulative yield due to the decay of all isobars of the reaction product was measured and no attempt was made to separate them analytically or otherwise. In this scenario, it is felt that there is certainly a need for systematic reinvestigation of alpha particle induced reactions in thulium, using high resolution germanium detectors, with extension to higher energies. In recent years a lot of technological input has gone into designing particle accelerators and as a result, it has become possible to get high-energy good-quality beams up to a few hundred MeV with continuous energy variation for nuclear reaction studies. Concurrently, during the past twenty years, semi-conductor radiation detector has become one of the principal tools in studies requiring high resolution measurements of gamm rays. The use of high resolution germanium detector has resulted in a quantum jump in the quality of spectroscopic data, and thereby to an increasing degree of accuracy in spectral analysis, leading to nuclear reaction data of high quality especially in the activation measurements of excitation functions, With the motivation of improving the quality as well as the quantity of data and to test the recent pre-equilibrium models with it, the present investigation is undertaken to study the excitation functions of eight reactions in the energy range 35–75 MeV, where pre-equilibrium decay is the dominant mode, and to compare the results with pre-equilibrium model predictions.

## 2. Experimental procedure

The excitation functions of $^{169}$Tm[$(\alpha, n)$, $(\alpha, 2n)$, $(\alpha, 3n)$, $(\alpha, 4n)$, $(\alpha, p3n)$, $(\alpha, \alpha n)$, $(\alpha, \alpha 2n)$, $(\alpha, \alpha 4n)$] reactions were measured up to 75 MeV using foil-stack activation technique and gamma ray spectroscopy method.

Spectroscopically pure (99·99%) thulium foils of thickness 30 mg/cm$^2$ were used as targets while aluminium foils of varying thicknesses served as energy degraders to reduce the beam energy to the desired levels. As the beam passes through the successive foils of the stacks, the alpha beam loses its energy but not the intensity. Hence, each experimental foil sees effectively a beam of different energy falling on it. Using the standard range-energy tables of Williamson *et al* (1966) the energy of the alpha particle incident on each foil was determined. The total thickness of the stack was so chosen to be definitely less than the range of the alpha particle beam in the material of the stack. Also, care was taken to ensure that the total thickness of the stack was not too large to avoid errors in the particle straggling as well as loss of beam intensity due to nuclear interaction in which the alpha particles are either absorbed or removed from the beam. The irradiation with 75 MeV alpha particles were performed at the Variable Energy Cyclotron Centre (VECC), Calcutta, India (Mohan Rao 1989). Beam current of the order of 200 nA was maintained in the stack. The duration of irradiation was decided keeping in view the half-lives of the activities of interest. Although the half-lives of residual nuclei of interest ranged from few hours to several days, a few hours of irradiation was found to produce enough intense activities to give good statistics of counting. The flux monitor reactions used were $^{27}$Al$(\alpha, \alpha 2pn)^{24}$Na and $^{27}$Al$(\alpha, 2\alpha n)^{22}$Na for which well measured cross-sections are available in literature (Probst *et al* 1976). Gamma activities produced in each foil were measured in conjunction with a 4 K multi channel analyser at VECC, Calcutta and Physics Department, Banaras Hindu University, Varanasi, using 95 cc Ge(Li) and 50 cc HPGe detectors having resolution of 2 keV for 1332 keV photons. The energy and efficiency calibrations were done using a standard $^{152}$Eu point source. The formula used in the cross-section calculation was reported in our earlier papers (Rama Rao *et al* 1987; Mohan Rao *et al* 1991)

$$\sigma = \frac{A_\gamma A_{gm} \lambda}{\phi w p_i \vartheta_\gamma P_\gamma (1 - \exp(-\lambda t_i)) \exp(-\lambda t_w)(1 - \exp(-\lambda \Delta))} \qquad (1)$$

where, $\sigma$ is the cross section for the reaction; $A_\gamma$ is the photopeak area of the characteristic gamma ray of the residual nucleus; $A_{gm}$ is the gram atomic weight of the target element; $\lambda$ is the disintegration constant of the residual nucleus; $\phi$ is the flux of the incident particle; $w$ weight per unit area of the target foil; $p_i$ is the fractional abundance by weight of the target isotope of interest; $\vartheta_\gamma$ is the fractional abundance of characteristic gamma rays emitted per decay of the residual nucleus; $P_\gamma$ is the photopeak efficiency of the gamma ray $t_i$, $t_w$ and $\Delta$ are the periods of irradiation, waiting and counting respectively.

More often than not, nuclear reactions in which two genetically related product nuclei (e.g. isobars or isomers) are formed with comparable half-lives and one of them, the daughter nucleus being continuously fed by the mother nucleus by radioactive decay. In such cases the expression given above cannot be employed to determine the cross-section of the daughter nucleus, since it does not take into account the contribution from feeding precursor nucleus. Therefore, the cross-section $\sigma_1$ of the mother nucleus is first determined using (1). The the cross-section $\sigma_2$ for the daughter nucleus is determined using the expression

$$\frac{A_\gamma}{P_\gamma \vartheta_\gamma} = N_T \phi \left[ \frac{\sigma_1 \lambda_2}{\lambda_2 - \lambda_1}(1 - \exp(-\lambda_1 t_i)) \left\{ \frac{\exp(-\lambda_1 t_w) - \exp(-\lambda_1 (t_w + \Delta))}{\lambda_1} - \frac{\exp(-\lambda_2 t_w) - \exp(-\lambda_2 (t_w + \Delta))}{\lambda_2} \right\} + \frac{\sigma_1 + \sigma_2}{\lambda_2}(1 - \exp(-\lambda_2 t_i)) \left\{ \exp(-\lambda_2 t_w) - \exp(-\lambda_2 (t_w + \Delta)) \right\} + \frac{\sigma_1}{\lambda_2 - \lambda_1} \{ (\exp(-\lambda_1 t_i) - \exp(-\lambda_2 t_i))(\exp(-\lambda_2 t_w) - \exp(-\lambda_2 (t_w + \Delta)) \} \right], \quad (2)$$

where suffix 1 stands for mother nucleus and 2 for daughter nucleus.

Table 1 taken from table of isotopes (Lederer and Shirley 1978), shows the decay characteristics of the residual nuclei formed in various reactions.

## 3. Results and discussion

### 3.1 $^{169}Tm(\alpha, xn)$ reactions; $x = 1 - 4$

Figure 1 shows the $^{169}$Tm$(\alpha, xn)$ reactions; $x = 1 - 4$ together with the previous measurements up to 54 MeV by Sau *et al* (1968). They employed a 7·6 cm × 7·6 cm NaI(T1) detector having a resolution of 8% for 662 keV photons of $^{137}$Cs and there is no further work reported during the last twenty years. Because of the inadequate resolution of the detector, the closely-lying gamma rays of some of the reaction residues could not be separated and they took the combined photopeak in such cases and the cross-section assignments were ambiguous because of the incorrect efficiencies for different gamma rays in the combined photopeak.

In the present work we have made a systematic reinvestigations of these reactions employing a high resolution Ge(Li) and HPGe detectors having resolution 2 keV for 1332 keV photons and using the spectroscopic data given in table 1. As can be seen from figure 1, there is a definite improvement in the quality of the data as compared to that of Sau *et al* (1968). Nineteen new energy-point cross-sections up to 70 MeV were measured in the present work.

### 3.2 $^{169}Tm(\alpha, p3n)$ and $^{169}Tm(\alpha, \alpha xn)$ reactions; $x = 1, 2, 4$

Figures 2–5 show the excitation functions for $^{169}$Tm$(\alpha, p3n)$, $^{169}$Tm$(\alpha, \alpha n)$, $^{169}$Tm$(\alpha, \alpha 2n)$ and $^{169}$Tm$(\alpha, \alpha 4n)$ reactions which are investigated for the first time. The salient features of the experimental observations of each reaction is given below.

**Table 1.** Decay characteristics of the nuclides investigated.

| Reaction | Residual nucleus | $Q$-value (MeV) | Half-life | $E_\gamma$ (keV) | $I_\gamma$ (%) |
|---|---|---|---|---|---|
| $^{169}$Tm$(\alpha, n)$ | $^{172}_{71}$Lu | −10·18 | 6·70 d | 810 | 15·7 |
| | | | | 900 | 28·5 |
| | | | | 912 | 14·6 |
| | | | | 1094 | 63·2 |
| $^{169}$Tm$(\alpha, 2n)$ | $^{171}_{71}$Lu | −17·6 | 8·22 d | 667 | 11·8 |
| | | | | 740 | 51·0 |
| | | | | 780 | 4·7 |
| | | | | 840 | 3·2 |
| $^{169}$Tm$(\alpha, 3n)$ | $^{171}_{71}$Lu | −25·74 | 2·02 d | 985 | 5·4 |
| | | | | 1138 | 3·5 |
| | | | | 1280 | 7·9 |
| | | | | 1365 | 4·4 |
| $^{169}$Tm$(\alpha, 4n)$ | $^{171}_{71}$Lu | −33·2 | 34·06 h | 960 | 20·3 |
| | | | | 1450 | 8·6 |
| $^{169}$Tm$(\alpha, p3n)$ | $^{169}_{70}$Yb | −30·0 | 32·02 d | 110 | 18·0 |
| | | | | 130 | 11·4 |
| | | | | 177 | 21·7 |
| $^{169}$Tm$(\alpha, \alpha n)$ | $^{168}_{69}$Tm | −8·0 | 93·1 d | 447 | 22·0 |
| | | | | 720 | 11·0 |
| | | | | 730 | 4·5 |
| | | | | 741 | 11·3 |
| | | | | 816 | 46·3 |
| $^{169}$Tm$(\alpha, \alpha 2n)$ | $^{169}_{69}$Tm | −14·87 | 9·25 d | 208 | 41·0 |
| | | | | 532 | 1·6 |
| $^{169}$Tm$(\alpha, \alpha 4n)$ | $^{165}_{69}$Tm | −30·63 | 30·06 h | 243 | 35·0 |
| | | | | 297 | 24·7 |
| | | | | 460 | 4·0 |
| | | | | 1397 | 9·3 |

*$^{169}Tm(\alpha, p3n)$ reaction*: Of all the nuclear particles, neutrons are the easiest to come out of an excited nucleus because they do not feel the Coulomb barrier. Protons and other charged particles have to surmount the Coulomb barrier before they can be emitted. Consequently their probability of emission is small compared to that of the neutrons. Naively, as a thumb rule, one can say that the cross-sections of the reaction involving neutrons, protons and $\alpha$-particles generally decreases by an order of magnitude down the ladder For example, the cross-section of $^{169}$Tm$(\alpha, p3n)$ reaction is 10 times smaller than that of $^{169}$Tm$(\alpha, 4n)$ reaction at comparative energies.

The peculiarity with $(\alpha, p3n)$ and $(\alpha, 4n)$ reactions on the same target is that they produce isobaric residual nuclei, the one with higher $Z$ being produced in the $(\alpha, 4n)$ reaction. A case in point is the pair of reactions: $^{169}$Tm$(\alpha, 4n)$ $^{169}$Lu and $^{169}$Tm$(\alpha, p3n)$ $^{169}$Yb. Both products being neutron-deficient isotopes, naturally the isobar with higher $Z$ decays to that with the lower $Z$ by $\beta^+$ emission and/or electron capture. Thus, since both these reactions are energetically possible (their thresholds differ by a couple of MeV) in activation measurements, the cross-sections determined for the lower $Z$ isobar, always include the contributions from higher $Z$ isobar. The interfering contribution to the $(\alpha, p3n)$ cross-section from that of $(\alpha, 4n)$ reaction is really a major problem specifically in view of the fact that the latter cross-section is generally ten

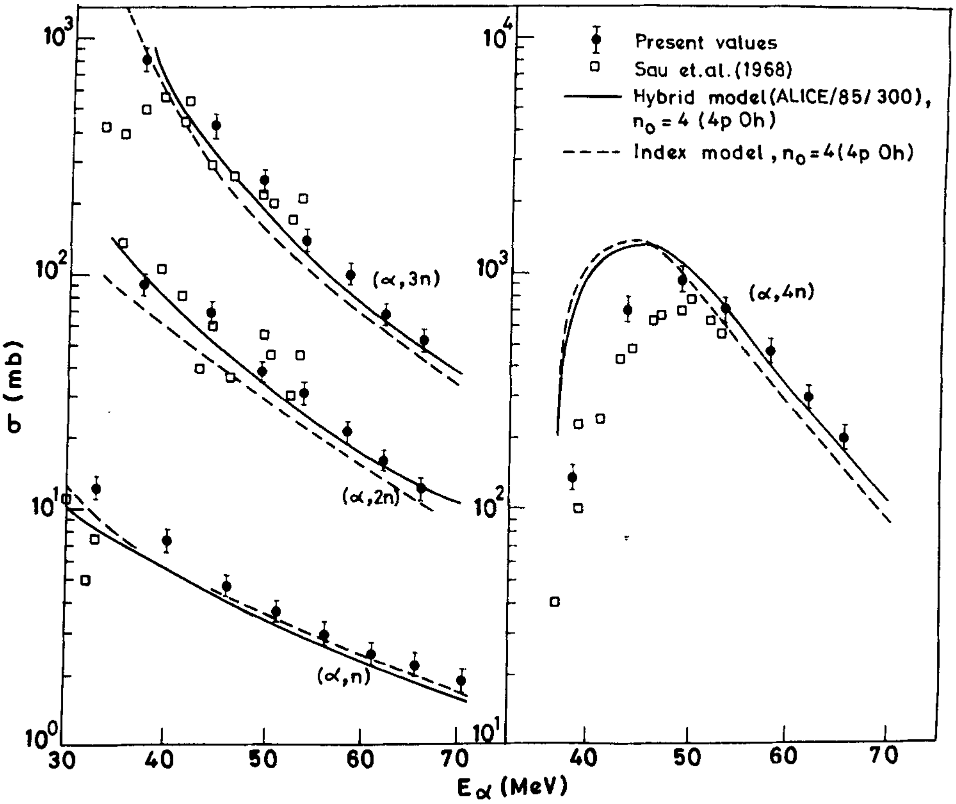


**Figure 1.** Excitation function for $^{169}Tm(\alpha, xn)$ $^{171-X}Lu$ reactions.

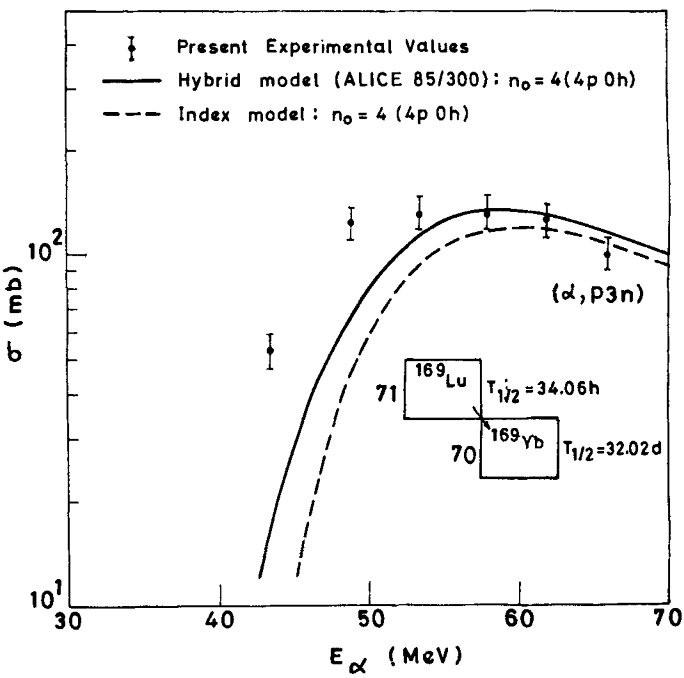


**Figure 2.** Excitation function for $^{169}Tm(\alpha, p3n)$ $^{169}Yb$ reaction.

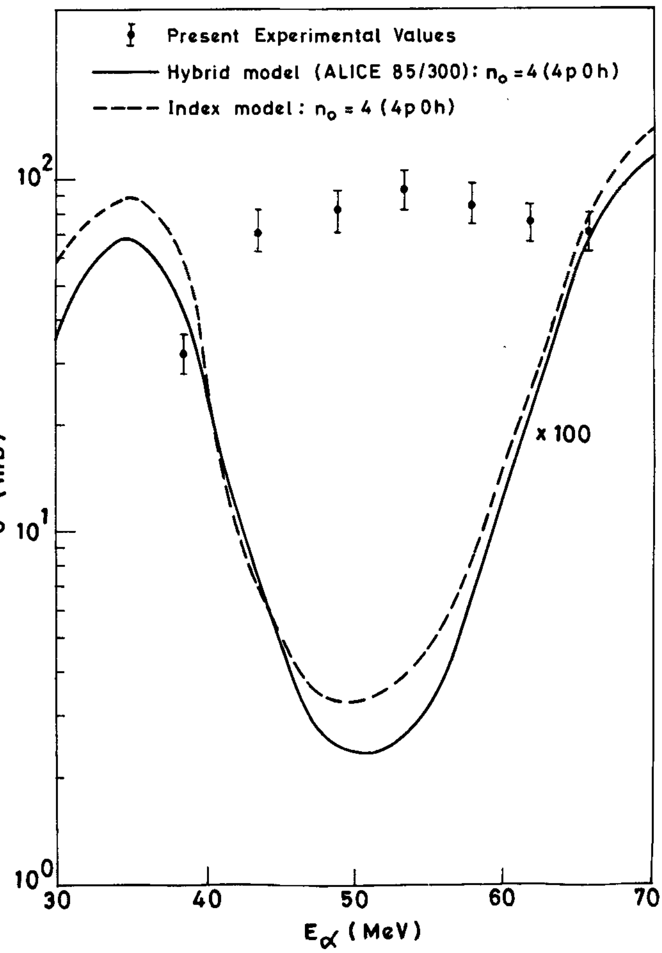


**Figure 3.** Excitation function for $^{169}$Tm($\alpha, \alpha n$) $^{168}$Tm reaction.

times larger than the former. It is precisely for this reason that Sau *et al* (1968) could not succeed in studying the excitation functions of $^{169}$Tm($\alpha, p3n$) although they made an unsuccessful attempt by measuring the activity of the residual nucleus $^{169}$Yb($T_{1/2} = 32{\cdot}02$ d). In the present investigation, the excitation function for this reaction is exclusively and carefully measured for the first time employing the complex cross-section formula, eq. (2), by which the individual cross-section $\sigma_2$ for $^{169}$Tm($\alpha, p3n$) reaction is extracted by employing our measured values of $^{169}$Tm($\alpha$, 4$n$) reaction subtracting out the contribution from the $^{169}$Tm($\alpha$, 4$n$) reaction. The results are shown in figure 2.

*$^{169}$Tm($\alpha, \alpha n$) $^{168}$Tm reaction*: As indicated previously the study of excitation function is generally complicated by the possibility of two isobaric precursors one coming from ($\alpha, px'n$) and the other from ($\alpha, x''n$) reaction. In this specific case, such isobaric contributions are absent simply because the immediate precursor $^{168}$Yb happens to be a stable nucleus.

*$^{169}$Tm($\alpha, \alpha 2n$) $^{167}$Tm reaction*: This excitation function is also studied for the first time and is shown in figure 4. In this case, the residual nucleus $^{167}$Tm($T_{1/2} = 9{\cdot}2$ d)

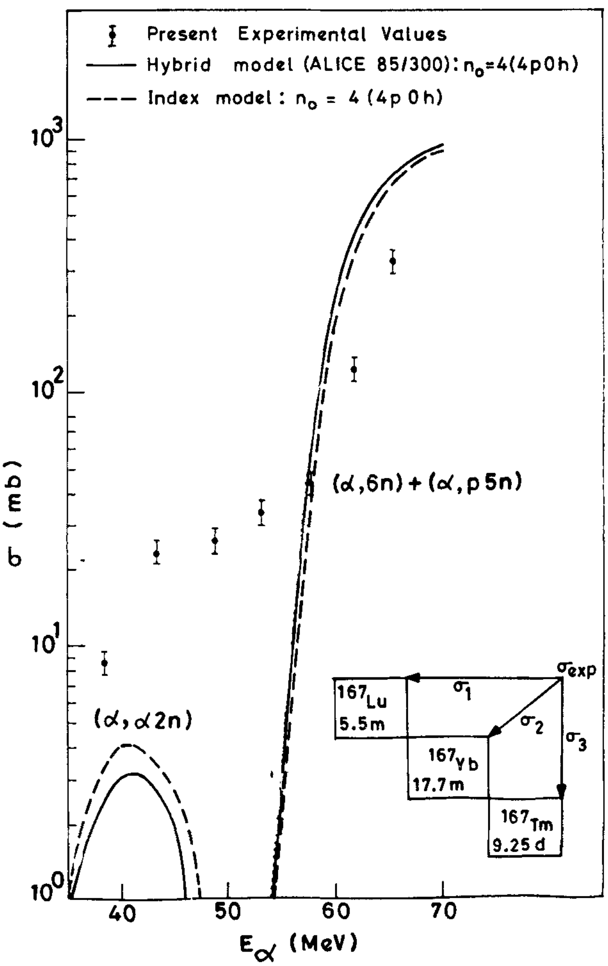


**Figure 4.** Excitation function for $^{169}$Tm($\alpha$, $\alpha 2n$) $^{167}$Tm reaction.

has major contributions from its isobaric precursors $^{167}$Yb($T_{1/2}$ = 17·7 m) and $^{167}$Lu($T_{1/2}$ = 51·5 m) formed in $^{169}$Tm($\alpha$, $p5n$) and $^{169}$Tm($\alpha$, $6n$) reaction respectively. Effectively, as the activity measurement of $^{167}$Tm was commenced after allowing both $^{167}$Lu and $^{167}$Yb to decay completely to $^{167}$Tm, the sum of the cross-sections producing the three isobars is measured in present work. The experimental excitation function obtained in the present work has a strange shape with a sudden increase in the experimental cross-section starting around 55 MeV; this gives concrete evidence for isobaric precursor contribution. It is interesting to note that the effective thresholds for the two reactions $^{169}$Tm($\alpha$, $p5n$) and $^{169}$Tm($\alpha$, $6n$) lie just around 55 MeV.

*$^{169}$Tm($\alpha$, $\alpha 4n$) $^{165}$Tm reaction*: The excitation function for this reaction is shown in figure 5, and is studied for the first time. Since, both the isobaric precursors have much shorter half-lives, $^{165}$Yb(9·9 m) and $^{165}$Lu(11·8 m), compared to $^{165}$Tm(30·0 h), the sum of the three cross-sections is experimentally measured through the activity of $^{165}$Tm. From the shape of the excitation function it can be said that the isobaric contributions, though present, are very small. On this basis, the shape of the excitation

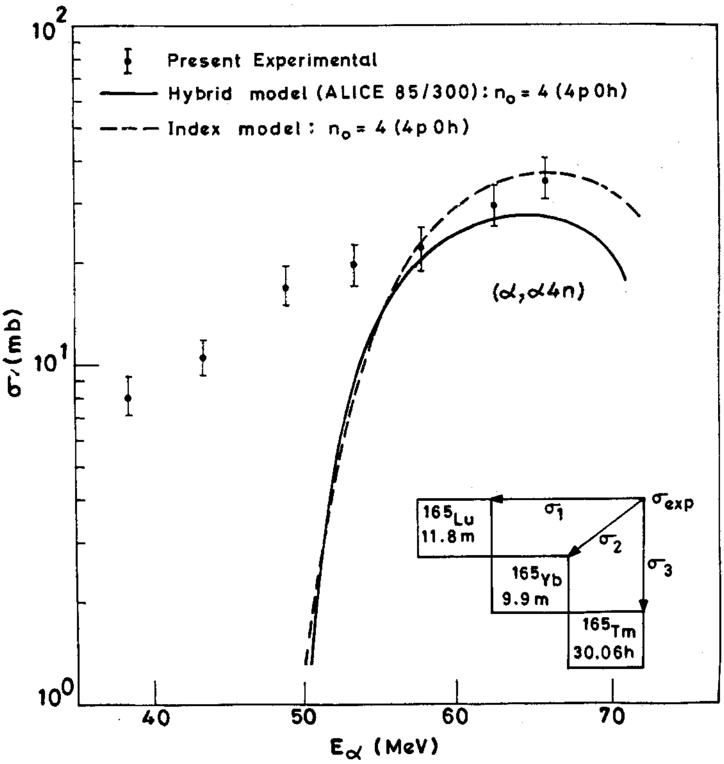


**Figure 5.** Excitation function for $^{169}$Tm($\alpha, \alpha 4n$) $^{165}$Tm reaction.

function of this ($\alpha, \alpha 4n$) reaction appears to be consistent with the shape of the other two ($\alpha, \alpha xn$) type of reactions studied in this work.

## 4. Comparison with hybrid and index model predictions

The experimental results are compared with two versions of pre-equilibrium models, namely the updated hybrid model (Blann and Vonach 1983), and the index model (Ernst *et al* 1987). The forerunner for all these models is the idea of Griffin (1966), called as the "statistical model of intermediate structure", to qualitatively explain the observed non-Maxwellian structure of continuous particle spectra. This model has been later quantified by deriving the unknown value of the matrix element for binary collision through various means. There are versions called exciton models in which the matrix element obtained semi-empirically (Cline and Blann 1971) or through a picture of particle-hole interactions in a Fermi sea (Gadioli *et al* 1973) or by simply treating it as a fit parameter (Stockhorst *et al* 1982). An attempt to derive it from free nucleon–nucleon scattering cross-sections or from the imaginary part of the optical potential (Blann and Vonach 1983) resulted in what are popularly known as the hybrid model versions. The newly proposed index (independently interacting excitons) model (Ernst *et al* 1987) has a similar but slightly different philosophy.

All these models start with a given number of initial excitons, $n_0$ (being the excited particles above and holes below the Fermi sea) and then pool up the available chances for particle emission at each step in the equilibration process. Since, in the index model, the excitons interact independently of one another, the second stage is reached only when all the excitons, which are not emitted, have created a particle hole pair each, through a binary collision. Hence, omitting the particle emission, the number of excitons in consecutive stages grown by a factor of three. On the other hand, in hybrid model, the next stage is reached when any one of the excitons creates a particle-hole pair, increasing the number of excitons only by two. Computationally, the process of equilibration is completed in two or three stages at most in the index model, whereas it extends over more stages in the hybrid model.

In all the pre-equilibrium models it is customary to use $n_0$, the initial exciton number as a fit parameter to match the theoretical predictions with experimentally observed shapes of spectra and excitation function. A good guess would be the number of nucleons in the projectile or an additional particle-hole if need be (Ernst *et al* 1989). This view is quite consistent with the basic physics of the pre-equilibrium decay that only a small number of degrees of freedom is initially excited in nuclear reactions at moderate energies. So, we have made the theoretical calculations using $n_0 = 4$ ($4p0h$), $n_0 = 5$ ($5p0h$), $n_0 = 6$ ($5p1h$) as the initial configurations. It was generally found that both index and hybrid models give by far the best results with $n_0 = 4$. From figure 1 it can be seen that both index and hybrid models show fair agreement in all the four reactions of $(\alpha, xn)$ type. Similarly in figure 2 the model predictions are satisfactory in the case of $\mathrm{Tm}(\alpha, p3n)$ reaction.

In figures 3–5 the excitation functions for $^{169}\mathrm{Tm}(\alpha, \alpha n)$, $^{169}\mathrm{Tm}(\alpha, \alpha 2n)$ and $^{169}\mathrm{Tm}(\alpha, \alpha 4n)$ respectively are shown. It can be seen that both hybrid and index model predictions fail very badly in predicting the excitation function of $^{169}\mathrm{Tm}(\alpha, \alpha xn)$ type of reactions. This is of course not surprising because none of the models, hybrid or index is designed to deal with the alpha emission in pre-equilibrium phase. Moreover, the radical difference between the predicted and observed shape of the excitation function strongly suggests the influence of direct interaction effect in the emission of alpha particles. The observed slowly rising monotonic shape, which is common to all the $(\alpha, \alpha xn)$ type of reactions, points out to a possible inelastic scattering of the incident alpha particle, followed by neutron evaporation. Similar observations were made by Lanzafame and Blann (1972) while studying alpha particle induced reactions on gold. They studied the recoil ranges of the residual nuclei in $(\alpha, \alpha xn)$ type of reactions and found that there is a very little momentum transfer to the recoiling nucleus, as expected for a direct interaction.

However the peculiar shape of the experimental excitation function of $^{169}\mathrm{Tm}(\alpha, \alpha 2n)$ reaction needs some explanation. As discussed earlier, due to isobaric contributions, the measured cross-section is in general the sum of the three cross-sections for $(\alpha, 6n)$, $(\alpha, p5n)$, $(\alpha, \alpha 2n)$ reactions. It can be seen that up to 55 MeV theoretical predictions of both the models are down by an order of magnitude or more, but show better agreement beyond 55 MeV, where $\mathrm{Tm}(\alpha, 6n)$ and $\mathrm{Tm}(\alpha, p5n)$ reactions (with an effective threshold of 55 MeV) dominate. Obviously the deviation by an order of magnitude between theory and experiment below 55 MeV, may in part be due to the inadequacy of both the models to account for the pre-equilibrium alpha emission involved in $\mathrm{Tm}(\alpha, \alpha 2n)$ reaction with threshold energy being about 15 MeV.

## 5. Conclusions

Excitation functions for eight reactions of the type ($xnypz\alpha$) were studied in the present work; out of them four excitation functions were studied for the first time and in the remaining four, nineteen new energy-point cross-sections were measured for the first time using high resolution detectors.

From an overall comparison between experimental results and theoretical predictions based on hybrid and index models one can infer that using an initial exciton configuration $n_0 = 4$ ($4p0h$) both hybrid and index models describe successfully the pre-equilibrium emission of nucleons in ($\alpha, xnyp$) type of reactions. The above initial configuration justifiably implies (a) that, following the first projectile-target interaction, only four excitons share the excitation energy and they being the four nucleons of the alpha particle of pre-equilibrium mechanism and (b) that only a few degrees of freedom are initially excited in a nuclear reaction at moderate energies.

Both the pre-equilibrium models are designed to take into account the pre-equilibrium emission of nucleons only and not the alpha particles. Hence in the reactions of type ($\alpha, \alpha xn$), the model predictions underestimate by more than an order of magnitude. Another possible reason for the large experimental cross-section is the likely contribution of a direct reaction mechanism, namely, the direct inelastic scattering of the alpha particle followed by neutron evaporation in ($\alpha, \alpha xn$) type of reactions.

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