α-particle induced reactions on yttrium and terbium

S. Mukherjee* and B. Bindu Kumar
School of Studies in Physics, Vikram University, Ujjain-456010, India

M. H. Rashid
Variable Energy Cyclotron Center, 1/AF, Bidhan Nagar, Calcutta, India

S. N. Chintalapudi
Inter-University Consortium for DAE Facilities, 3/LB, Bidhan Nagar, Calcutta, India

(Received 29 April 1996)

The stacked foil activation technique has been employed for the investigation of α-particle induced reactions on the target elements yttrium and terbium up to 50 MeV. Six excitation functions for the (α,xn) type of reactions were studied using high-resolution HPGe γ-ray spectroscopy. A comparison with Blann's geometric dependent hybrid model has been made using the initial exciton number $n_0=4(4p0h)$ and $n_0=5(5p0h)$. A broad general agreement is observed between the experimental results and theoretical predictions with an initial exciton number $n_0=4(4p0h)$. [S0556-2813(97)03304-9]

PACS number(s): 22.55.Hp, 27.60.+j

I. INTRODUCTION

During the last decade, there has been increasing experimental evidence pointing out new types of processes that lie in complexity between the direct and many-body compound nuclear reactions. The nuclear reactions are supposed to pass through some intermediate processes in between the direct reaction and equilibrium processes. This third mechanism is known as the pre-equilibrium emission process.

The various pre-equilibrium theories differ appreciably in their flexibility and mathematical rigor. The semiclassical models [1–8] have been applied to a much wider range of reactions than the quantum mechanical models [9–11]. Not only has the validity of these models been extended up to a few hundreds of MeV in excitation but also the important influence of multiparticle emission in the pre-equilibrium mode has been incorporated into the model framework. Further improved computer codes introduced by Blann and Vonach [12], based on the hybrid model and the geometrical-dependent hybrid model, are put forward into the calculation of pre-equilibrium multinucleon emission in an approximate way.

In the recent years, there has been a large number of systematic studies of experimental excitation functions for α-particle induced reactions on light, medium, and heavy target elements [13–17]. These investigations were primarily carried out in order to have a basis for a better understanding of the intricate mechanism of pre-equilibrium emission. The present state of knowledge in this field is still unsatisfactory in many respects.

In the above context, the present work on the α-particle induced reactions on target elements ^{89}Y and ^{159}Tb is intended to supply accurate data on the medium and heavy mass region. Yttrium and terbium, being monoisotopic elements, are useful for the study of (α,xn) reactions. A survey of literature reveals that of the six α-particle induced reactions in yttrium and terbium studied here, only the ^{89}Y(α,n) reaction was earlier studied by Hansen and Stelts [18] up to 14 MeV and by Richter *et al.* [19] with the incident energy of the α particle varying between 10.4 and 10.8 MeV. Bonesso *et al.* [20] have evaluated thick target yields from the (α,xn) $x=2-5$ reactions on terbium. Clearly there is a need for more experimental data on those reactions where the present data are either scanty or not available at all.

In this scenario, the present investigation is undertaken with two main objectives: (1) to make a careful and systematic experimental study of the individual excitation functions of ^{89}Y(α,xn); $x=1,3$ and ^{159}Tb(α,xn); $x=1-4$ reactions and (2) to compare the measured excitation functions of the reactions with Blann's geometric dependent hybrid model (GDH) employing the code ALICE/85/300 which contains both the compound and pre-equilibrium processes and consistently using the same set of parameters [21–24].

II. EXPERIMENTAL PROCEDURE

In the present measurements, the stacked foil activation technique is employed in which a stack of foils with energy degraders is irradiated in a fixed geometry. In this way successive samples of the stack are irradiated at decreasing incident energies.

A. Sample preparation

Spectroscopically pure yttrium and terbium stacks (99.99%) were prepared by the vacuum evaporation technique in the target division of the Variable Energy Cyclotron Centre at Calcutta, India. The samples were prepared from yttrium oxide (Y_2O_3) and terbium oxide (TbO_3), by depositing uniformly on aluminum foils of thickness 6.75 mg/cm^2. Thickness of ^{89}Y and ^{159}Tb deposits were 790 and 800 μg/cm^2, respectively. The samples were cut into pieces

*Author to whom all correspondence should be addressed.

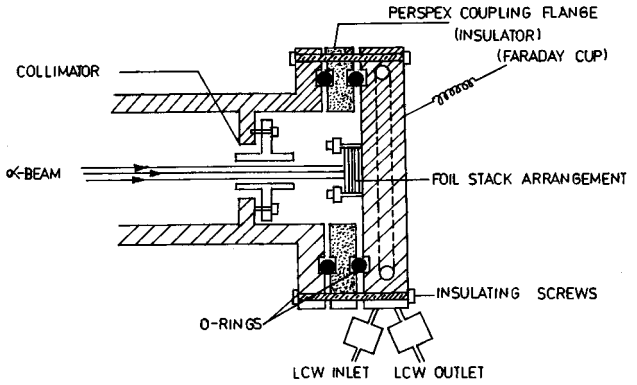

FIG. 1. Experimental setup for stacked foil irradiation with an α-particle beam.

of size 1.2×1.2 cm^2 each and were fixed on identical holders having concentric holes of 8-mm diameter at their centers. The aluminum degraders of different thickness were also inserted in the target stack so that the α-particle beam of 50 MeV energy can be degraded considerably.

B. Irradiation and counting

The irradiations were carried out at the Variable Energy Cyclotron Centre, Calcutta, India. The experimental setup for the irradiation of the stacked foils is shown in Fig. 1. The exact beam energy was determined by the auxiliary experiment on α scattering. The incident energy of α particles on each foil in the stack was calculated using the stopping power tables of Northcliffe and Schilling [25]. No consideration of straggling is made in these calculations on account of its negligible effects [26] for α particles. The stacks of ^{89}Y and ^{159}Tb were irradiated by a 50-MeV α-particle beam. During the irradiation a low conductivity water (LCW) jet directly cooled both the flange as well as the stack. The incident α-particle flux was calculated by measuring the activities of $^{27}\mathrm{Al}(\alpha,\alpha 2pn)^{24}\mathrm{Na}$, for which well-measured cross sections are available in the literature [27]. The charge collected in the Faraday cup was also used to calculate the average incident α-beam flux. In general, the two values agreed within 5%. The average incident beam flux for the different runs was of the order of 10^{14} α particles/hr cm^2. The diameter of the α beam was more than 10 mm, however, a tantalum collimator was used to keep the beam diameter 8 mm and thus a uniform spatial distribution of α-particles in the beam was assumed. Irradiation periods were about 30 min to 1.75 h keeping in view of the half lives of the activities of interest. An α-beam current of about 100 nA was maintained in each stack.

C. Formulation

The activation cross section is computed using the following formula:

$$\sigma=\frac{A_\gamma A_{\mathrm{gm}}\lambda}{\phi W P\theta_\gamma P_\gamma N_{\mathrm{AV}}[1-e^{-i\lambda t_i}]e^{-\lambda t_w}[1-e^{-\lambda\Delta}]},$$

where σ is the cross section for the reaction, A_γ is the photopeak area of the characteristic γ ray of the residual nucleus, A_{gm} is the gram atomic weight of the target element, λ is the disintegration constant of the residual nucleus, ϕ is the flux of the incident particle, W is the weight per unit area of the target foil, P is the fractional abundance by weight of the target isotope of interest, θ_γ is the fraction of characteristic γ rays emitted, P_γ is the photopeak efficiency of the γ rays, N_{AV} is the Avogadro number, t_i is the time of irradiation, t_w is the waiting time, and Δ is the counting time.

D. Measurements

The irradiated samples were taken for counting at the end of irradiation. The activities produced in each foil were measured using a 100 cc p-type HPGe (EG&G,USA) detector having a resolution of 2 keV for 1.33 MeV γ rays of ^{60}Co, coupled to a CANBERRA-88 multichannel analyzer. The residual nuclei were identified using their characteristic γ rays as listed in Table I [28]. The residual nucleus of a particular reaction may, in general, emit γ rays of more than one energy. Out of these γ rays a few may have good statistics. In order to check the experimental setup, the relative intensities of identified γ rays were also measured and found to agree well with the literature values. The cross sections for the same reaction were determined from the observed intensities of the various γ rays originating from the same residual nucleus and finally their weighted average was taken. Reported cross-section values are the weighted average along with their internal or external errors, whichever is larger.

E. Experimental errors

The overall projected error in the present experimentally measured cross section may be subdivided into the following categories.

(1) In order to estimate the number of nuclei in the sample and to check the uniformity of the sample, pieces of sample foils of different dimensions were weighted on an electronic microbalance and the thickness of each foil was calculated. This nonuniformity in the foil thickness may introduce a 1 to 2 % error (δ_1).

(2) Variations in the incident α-particle flux may introduce some uncertainty in the final calculation of the cross section. In the present experiment the standard monitor cross sections were taken from literature [27] in the flux determination. This may introduce an overall error of 6% (δ_2). (3) The calculated detection efficiency may be inaccurate due to the uncertainty in the spectroscopic data of the standard source and the statistical errors in the counts. No corrections were applied for the uncertainty in the spectroscopic data, however, the statistical error in the counting of the standard ^{152}Eu γ source used for the efficiency calculation was estimated to be around 3% (δ_3).

(4) The dead time in the pulse processing electronics may lead to a loss of counts. The sample-detector distance was suitably adjusted to keep the dead time low ($<5\%$) and corrections for it were applied accordingly in the counting rates. However, the error introduced in the determination of photopeak areas of the characteristic γ rays were within the limits of 1 to 4 % in the best and the worst cases (δ_4).

(5) The errors in the absolute abundances of the characteristic γ rays vary between 1 to 8 % (δ_5).

TABLE I. Reactions, Q values, half-lives of residual nuclei, γ-ray energies, and branching ratios of γ decay.

Reaction	Residue	Q-value (MeV)	$T_{1/2}$ of residual nucleus	Identified γ-ray energy (keV)	I_γ (%)
^{89}Y(α,n)	^{92m}Nb	−6.8	10.15 d	934	99.2
^{89}Y(α,3n)	^{90}Nb	−26.8	14.6 h	144	66.7
				1129	92.7
^{157}Tb(α,n)	^{162m}Ho	−10.2	1.133 h	185	29.3
				282	11.5
^{157}Tb(α,n)	^{162g}Ho	−9.14	15 min	52.1	13.9
				80.5	7.7
^{157}Tb(α,2n)	^{161}Ho	−16.1	2.48 h	77.4	2.2
				103	3.6
^{157}Tb(α,3n)	^{160m}Ho	−24.9	5.02 h	879	20.2
				1271	2.5
^{157}Tb(α,3n)	^{160g}Ho	−24.99	25.6 min	645	16.2
				728	30.8
				962	18.1
^{157}Tb(α,4n)	^{159}Ho	−32.0	35 min	121	33
				132	21.7
				310	13.8
		Monitor reactions			
^{27}Al(α,α2pn)	^{24}Na	−31.4	15.05 h	1369	100
^{27}Al(α,2αn)	^{22}Na	−22.5	2.6 d	1275	100

Therefore the total absolute error in the measured cross section is

$$\sqrt{\sum_{i=1}^{5} (\delta_i)^2}$$

and found to vary between 8 to 12 % for the best and the worst cases. Other factors which may influence the cross section measurements, are as follows.

(1) In the irradiation experiment the initial beam energy was degraded down to around half of its original value. As the α beam traverses the stack material, the initial beam intensity may become disturbed. This decrease in beam intensity may introduce certain errors. The maximum beam loss at the end of the niobium stack is calculated to be $<2\%$, hence it is neglected.

(2)Straggling effects may introduce some errors but are neglected because for α particles the energy straggling at the end of the stack is always much smaller than the energy of the beam in the target foil itself. It was pointed out by Ernst *et al.* [26] that a large number of low-energy neutrons may be released as the beam traverses through the stack of foils and this in turn may disturb the yield. However, this disturbed yield is also negligible. The above-mentioned errors in the measurement of experimental cross sections, do not include the uncertainty of the nuclear data (e.g., half lives of residual nuclei, branching ratio, etc.) that were taken from the table of isotopes [28].

III. RESULTS AND DISCUSSION

A. Experimental results

The measured excitation functions for the reactions ^{89}Y(α,xn); $x=1,3$ and ^{159}Tb(α,xn); $x=1-4$ are shown, respectively, in Figs. 2 and 3, along with the absolute errors as discussed in the last section. The experimentally measured results are shown by the solid circles and the cross-section errors are shown by the vertical bars.

1. Excitation functions for the reactions ^{89}Y(α,xn); $x=1,3$

In the reaction ^{89}Y(α,n)^{97}Nb, the ground state ^{92}Nb is having a very long half life of 3.2×10^7 years and is not measurable using the activation technique. While ^{92m}Nb ($T_{1/2}=10.15$ days) measured in the present work, decays independent through electron capture (99.4%) and β decay (0.6%). The ^{89}Y(α,3n)^{90}Nb reaction has two isomers ^{90m}Nb and ^{90g}Nb. The metastable state ^{90m}Nb ($T_{1/2}=18.6$ sec) decays completely through isomeric transition (100%) to the ground state ($T_{1/2}=14.4$ h). The total cross section was measured by allowing for complete decay of the isomeric state to the ground state.

2. Excitation functions for ^{159}Tb(α,xn); $x=1-4$ reaction

In the reaction ^{159}Tb(α,n)^{162}Ho the residual nucleus has one metastable state ($T_{1/2}=68$ min) 61% of which decays through isomeric transition to the ground state ^{162}Ho ($T_{1/2}=15$ min) and the remaining 39 % through electron capture and β-ray emission. In the present work, cross sections

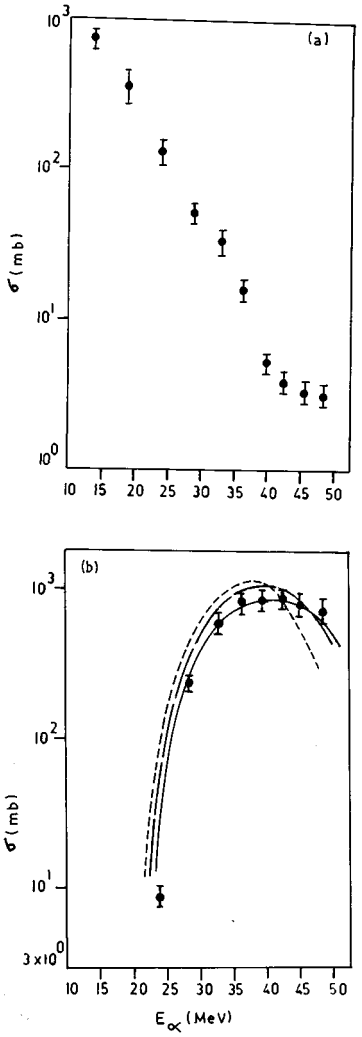

FIG. 2. Excitation function for $^{89}Y(\alpha,xn)x=1,3$ reactions: (a) $^{89}Y(\alpha,n)^{92m}Nb$ and (b) $^{89}Y(\alpha,3n)^{90}Nb$. ●, present work; (- - -), pure EQ (equilibrium), ((WE) Weisskopf-Ewing); EQ with the PE (pre-equilibrium) using GDH model, (—), $n_0=4(4p0h)$ and (– –), $n_0=5(5p0h)$.

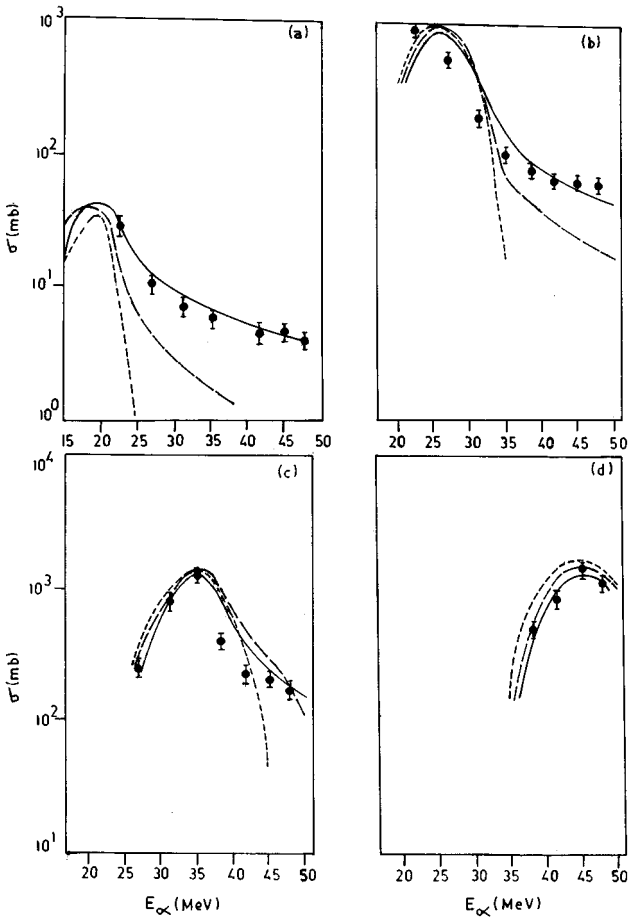

FIG. 3. Excitation function for $^{159}Tb(\alpha,xn)$ $x=1-4$ reactions: (a) $^{159}Tb(\alpha,n)^{162}Ho$; (b) $^{159}Tb(\alpha,2n)^{161}Ho$; (c) ^{159}Tb $(\alpha,3n)^{160}Ho$; and (d) $^{159}Tb(\alpha,4n)^{159}Ho$. ●, present work; (- - -), pure EQ (WE); EQ with the PE using GDH model, (—), $[n_0=4(4p0h)]$ and (– –), $[n_0=5(5p0h)]$.

for the reaction residues were measured separately and added together to get the total cross section.

Two isomers ^{161m}Ho and ^{161g}Ho are formed in the reaction $^{159}Tb(\alpha,2n)^{161}Ho$. The residue ^{161m}Ho having a half life of 6.7 sec decays completely to the ground state ($T_{1/2}=2.48$ h) through an isomeric transition (100%). The total cross section was measured by allowing for the complete decay of the isometric state to the ground state. In the $^{159}Tb(\alpha,3n)^{160}Ho$ reaction, the product nucleus has an isomeric state with a half life of 5.02 h, decays to the ground state have a shorter half life of 25.6 min. Decay of the metastable state is through isometric transition (65%) and electron capture along with β decay (35%). Decay of the ground state is mostly through electron capture (99.6%). The cross sections for both the metastable and ground states were measured separately and added together to get the total cross section.

The metastable state ^{159m}Ho ($T_{1/2}=8.3$ sec) formed in the reaction $^{159}Tb(\alpha,4n)^{159}Ho$ decays completely through isomeric transition (100%) to ^{159g}Ho ($T_{1/2}=33$ min). The measurements were done after the complete decay of the metastable state to the ground state.

As mentioned in the Introduction, only one reaction, namely, $^{89}Y(\alpha,n)$ was earlier studied by Hansen and Stelts [18] in the energy region, 10 to 14 MeV. Richter *et al.* [19] have also studied the same reaction for energies of the incident beam between 10.4 and 1.8 MeV. This energy region is considerably below the Coulomb barrier (V_c) for the $\alpha+^{89}Y$ system ($V_c=12.9$ MeV). Moreover, Richter *et al.* have not measured the absolute cross sections for this reaction. Bonesso *et al.* [20] have studied the $(\alpha,xn)x=2-5$ reactions on terbium up to 55 MeV. However, their study is based on the evaluation of thick target yields, from the measured cross sections.

In the present work, a systematic study of the excitation functions for the (α,xn) reactions on yttrium and terbium was carried out up to 50 MeV of α-particle energy. To the best of our knowledge, some of the reactions, namely, ^{89}Y (α,xn) $x=1,3$ and $^{159}Tb(\alpha,n)$ are reported for the first time for the α-particle energy varying between 20 and 50 MeV.

B. Theoretical predictions

The theoretical excitation function calculations were done using the geometric-dependent hybrid model with and with-

out the inclusion of pre-equilibrium emission of particles. For analyzing the equilibrium part, the compound nucleus model of Weisskopf and Ewing [21] was adopted. The contribution from the pre-equilibrium process has been included only at the first step of evaporation. The geometric-dependent hybrid model was used for analyzing the pre-equilibrium part [22,23]. For performing these calculations, the computer code ALICE/85/300 [24] was used. Due to its semiclassical nature, the geometric-dependent hybrid model involves a large number of physical parameters as well as a few adjustable parameters. There are three main points for discussion when using the geometric-dependent hybrid model options of ALICE/85/300. (1) The initial exciton configuration, (2) the intranuclear transition rate, and (3) the mean-free path multiplier parameter.

It is customary to use the initial exciton number n_0 separated into proton and neutron excitons (n_p and n_n, respectively) above and a hole n_h below the Fermi level as a fit parameter to match the theoretical prediction with the experimentally observed shape of the spectra and excitation functions. It governs the entire cascading process of binary collisions and thereby influences the shape of the hard component in the particle spectra. A good guess would be the number of the nucleons in the projectile, an additional particle/hole, or both. On this basis we have made theoretical calculations using $n_0=4(4p0h)$ and $n_0=5(5p0h)$.

In *a priori* formulation of the geometric-dependent hybrid model, the intranuclear transition rates are calculated either from the imaginary part of the optical model or from the free nucleon-nucleon scattering cross section. However, for particle energies exceeding 55 MeV the optical model parameters of Becchetti and Greenlees [29] are no longer applicable and thus at higher energies the mean-free path for intranuclear transitions must be calculated from the nucleon-nucleon scattering cross section. The mean-free path multiplier K_{MFP} which is a free parameter originally introduced by Blann to account for an apparently longer mean-free path of nucleons in the nuclear surface, was kept at unity. This is also in agreement with the findings of Djalaeis *et al.* [30], Michel and Brinkman [31], and Singh *et al.* [32]. The statistical and pre-equilibrium calculations depend on entrance channel transmission coefficients. These were calculated using the real parabolic potential barrier penetration of Huizenga and Igo [33].

C. Comparison with the theory

The excitation functions of six (α,xn)-type reactions have been measured for ^{89}Y and ^{159}Tb. In Figs. 2 and 3, the measured excitation functions are compared with geometric-dependent hybrid (GDH) model results for different initial exciton configurations ($n_0=4$ and 5). Evidently, an initial exciton configuration $n_0=4(4p0h)$ which is equivalent to a breakup of the α particle in the field of the nucleus and the nucleus occupying excited states above the Fermi energy gives a better description of the excitation function compared to other configurations for the α-particle bombarding energies up to 50 MeV. With respect to initial configuration Blann and Migneray [34] used $n_0=4(4p0h)$ to calculate ^{59}Co(α,p) spectra. Gadioli *et al.* [35] have also discussed this point in detail and recommended the general application of $n_0=4$. In the present study the excitation function for the (α,xn) reactions are most appropriate to examine the initial exciton number for the α-induced reaction on yttrium and terbium.

The excitation functions of (α,xn) reactions are characterized by a broad maxima, which is the hallmark of the compound nucleus mechanism, as shown in the theoretical Weisskopf-Ewing estimates presented in Figs. 2 and 3. Any departure from this traditional shape is the indication of the onset of a new reaction mechanism, that is how the high-energy tails observed in the experimental excitation function are taken to be the signatures of a nonequilibrium reaction mechanism against the conventional compound nucleus mode.

In an attempt to understand the reaction mechanism, a comparison is made between the theoretical predictions of the pre-equilibrium geometric-dependent hybrid (GDH) model and the experimentally observed excitation functions. The details of the comparison is presented below, for each reaction.

1. ^{89}Y(α,xn); x=1 and 3 reactions

Figures 2(a) and 2(b) show the excitation functions for (α,n) and $(\alpha,3n)$ reaction on ^{89}Y. As discussed earlier, the reaction $^{89}\mathrm{Y}(\alpha,n)^{92}\mathrm{Nb}$ has only a metastable state cross section. Since the code theoretically calculates the total cross section, the comparison between theoretical and experimental values of the excitation functions, for the $^{89}\mathrm{Y}(\alpha,n)$ reaction is not possible. It can be observed that there is a little structure in the experimental excitation function in the energy region 35 to 50 MeV, which is not completely understood by the present authors. The excitation function for the $(\alpha,3n)$ reaction is dominated by the compound nucleus mechanism almost over the entire region, as such a reaction is not very suitable to test the pre-equilibrium content of the GDH model. However, it may be observed that the theoretical curve corresponding to $n_0=(4p0h)$ is close to the experimental points, indicating the onset of pre-equilibrium effects in this multinucleon emission reaction.

2. ^{159}Tb(α,xn); x=1−4 reactions

The excitation functions for the α-induced reactions on terbium $^{159}\mathrm{Tb}(\alpha,xn)$; $x=1-4$, are shown in Figs. 3(a), 3(b), and 3(c), respectively. For the (α,n) reaction the compound nucleus contributions are important only below 25 MeV or so. Therefore, a thorough comparison can be made between theory and experiment over an extensive energy region, 25 to 50 MeV, for this reaction. It can be seen in Fig. 3(a) that the predictions of the GDH model, using $n_0=4(4p0h)$ configuration are fairly good for this reaction especially at the high-energy region of the excitation function, where the pre-equilibrium neutron emission is predominant.

However, in the case of $(\alpha,2n)$ reaction as shown in Fig. 3(b), a similar comparison reveals a different picture, showing no agreement in the compound nucleus part, up to 35 MeV. In the pre-equilibrium region also the shape of the measured experimental excitation function is not reproduced by the GDH model predictions, for both the initial exciton numbers and $n_0=4$ and 5. It can be remarked that while the theoretical excitation function for $n_0=4(4p0h)$ predict a

smooth monotonic variation of the cross section in the pre-equilibrium region, that is between 35 to 50 MeV, the experimental points of the excitation function show some structure, similar to the one observed in the $^{89}Y(\alpha,n)$ reaction. It is not easy, however, to prove in the cause of such structures, in an investigation of the present type, where only the integral cross sections (summed over the energies and angles of all emitted particles) are experimentally studied and compared with essentially nuclear calculations, which do not take into account, the structure of the nucleus. Within this limitations, it may be inferred from the comparison presented in Fig. 3(b) that the theoretical predictions of the GDH model for an initial configuration of $n_0=4(4p0h)$, lie close (within a factor of 1.5) to the experimental values.

For the $(\alpha,3n)$ reaction, the experimental and theoretical excitation functions based on the GDH model predictions are shown in Fig. 3(c). It can be seen from the figure that the theoretical excitation function corresponding to $n_0=4(4p0h)$ gives a better account for the shape of the experimental excitation function. However, there is a systematic overestimation within a factor of 2 of the experimental cross sections in the energy region 35 to 45 MeV for this reaction. The shape of the excitation function for the $(\alpha,4n)$ reaction as shown in Fig. 3(d) is similar to that observed in $^{89}Y(\alpha,3n)$ reaction, showing only a part of the compound nucleus peak. It can be seen from the figure that the theoretical curves for $n_0=4(4p0h)$ definitely give a better agreement, compared to the other curve for $n_0=5(5p0h)$.

IV. CONCLUSIONS

α-particle induced reactions on the target elements yttrium and terbium were investigated up to 50 MeV in the present work. The present analysis indicates that the measured excitation functions of α-induced reactions cannot be accounted for by a pure compound nuclear mechanism and they have contributions from pre-equilibrium emission. Proper admixture of equilibrium and pre-equilibrium processes is needed in theoretical calculations for the reproduction of experimentally measured excitation functions. In the observed high-energy tails of the excitation functions of the (α,xn) reaction, there are the veritable signatures of pre-equilibrium decay, irrespective of any model or theory. For α-induced reactions, the choice of a four exciton state $(n_0=4)$ for the initial configurations of the compound system gives satisfactory results and supports the findings of many earlier investigators [36–40]. An initial exciton configuration $n_0=4(4p0h)$ signifies that only four excitons share the initial excitation energy at the instant of first projectile-target interaction. The four nucleons of the projectile are the most likely candidates to be endowed with the excitation energy and their picture is consistent with the α particle as the projectile.

In general, the geometric-dependent hybrid model fits the excitation functions reasonably well, taking into account its limitations that the Weisskopf-Ewing model was used for the calculation of the statistical contribution and this is usually less accurate than a Hauser-Feshbach calculation. In view of the above facts and the multitudes of uncertainties in pre-equilibrium calculations such as (1) range of equilibrium and pre-equilibrium reaction cross sections involved and (2) in parameters such as inverse reaction cross section and level densities, etc., Blann [41] considered that a result which is within a factor of 2 (as in the present investigation) of the experimental results in absolute cross section and which, generally, has the correct spectral shape and variation of yield with excitation energy is an encouraging result. However, further investigation of this point could include the use of a more accurate Hauser-Feshbach calculation for the statistical contribution. This can be added to the pre-equilibrium calculation to match the experimental data.

ACKNOWLEDGMENTS

The authors are thankful to the operating staff of VECC, Calcutta, India, for their effective cooperation in the experiment. The authors acknowledge thankfully the suggestions and help given by Dr. B. S. Tomar, Radiochemistry Division, BARC, Bombay. Thanks are also due to Professor S. K. Ghosh and Professor P. M. Agrawal, Vikram University, Ujjain, for their cooperation. One of the authors (S.M.) thanks the MPCST Bhopal, India, for funding this work through a minor project.

[1] J. J. Griffin, Phys. Rev. Lett. **17**, 478 (1966).
[2] M. L. Goldberger, Phys. Rev. **74**, 1268 (1948).
[3] J. J. Griffin, Phys. Lett. **24B**, 5 (1967).
[4] M. Blann, Phys. Rev. Lett. **27**, 337 (1971); **27**, 700(E) (1971); **27**, 1550(E) (1971).
[5] C. K. Cline and M. Blann, Nucl. Phys. **A172**, 225 (1971).
[6] E. Gadioli, E. Gadioli-Ebra, and P. G. Sona, Nucl. Phys. **A217**, 589 (1973).
[7] C. K. Cline, Nucl. Phys. **A210**, 590 (1976).
[8] E. Betak and J. Dobes, Z. Phys. A **279**, 319 (1976).
[9] D. Agassi, H. A. Weidenmuller, and G. Mantzouranis, Phys. Rep. **22**, 145 (1975).
[10] H. Feshbach, A. Kerman, and S. Koonin, Ann. Phys. (N.Y.) **125**, 429 (1980).
[11] T. Tamura, T. Udagawa, and H. Lenske, Phys. Rev. C **26**, 379 (1982).
[12] M. Blann and H. K. Vonach, Phys. Rev. C **28**, 1475 (1983).
[13] N. L. Singh, S. Mukherjee, A. V. Mohan Rao, L. Chaturvedi, and P. P. Singh, J. Phys. G **21**, 399 (1995).
[14] S. Sudar and S. M. Qaim, Phys. Rev. C **50**, 2402 (1994).
[15] M. K. Bhardwaj, I. A. Rizvi, and A. K. Chauby, Int. J. Mod. Phys. E **1**, 389 (1992).
[16] B. P. Singh, M. G. V. Sankaracharyulu, M. A. Ansari, H. D. Bhardwaj, and R. Prasad, Phys. Rev. C **47**, 2055 (1993).
[17] N. L. Singh, S. Mukherjee, and D. R. S. Somayajulu, Nuovo Cimento A **107**, 1635 (1994).
[18] L. F. Hansen M. I. Stelts, Phys. Rev. **136**, B1000 (1964).
[19] A. Richter, E. Gross, J. Hufner, H. A. Weidenmuller, and J. W.

Tepel, Phys. Lett. **38B**, 349 (1972).
[20] O. Bonesso, H. O. Mosca, and S. J. Nassiff, J. Radioanal. Nucl. Chem. Letts. **137**, 29 (1989).
[21] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[22] M. Blann, Phys. Rev. Lett. **28**, 757 (1972).
[23] M. Blann, Annu. Rev. Nucl. Sci. **25**, 123 (1975).
[24] M. Blann, ALICE/85/300, Report No. UCID-20169, 1984 (unpublished).
[25] L. C. Northcliffe and R. F. Schilling, Nucl. Data, Sec. A **7**, 256 (1970).
[26] J. Ernst, R. Iowski, H. Klampfl, H. Machner, T. Mayer-Boricke, and R. Sehans, Z. Phys. A **30E**, 301 (1982).
[27] H. J. Probst, S. M. Qaim, and R. Weinreich, Int. J. Appl. Radiat. Isot. **27**, 431 (1976).
[28] E. Browne and R. B. Firestone, *Table of Radioactive Isotopes* (Wiley, New York, 1986).
[29] F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182**, 1910 (1969).
[30] A. Djalaeis, P. John, H. J. Probst, and C. Mayer Boricke, Nucl. Phys. **A250**, 149 (1975).
[31] R. Michel and G. Brinkmann, Nucl. Phys. **A333**, 167 (1980).
[32] N. L. Singh, S. Agarwal, and J. Rama Rao, J. Phys. G **18**, 927 (1992).
[33] J. R. Huizenga and G. Igo, Nucl. Phys. **29**, 462 (1961).
[34] M. Blann and A. Migneray, Nucl. Phys. **196**, 245 (1972).
[35] E. Gadioli, E. Gadioli-Ebra, L. Sajo-Bohus, and G. Tagliaferri, Riv. Nuovo Cimento **6**, 1 (1976).
[36] R. Michel, F. Peiffer, and R. Stuck, Nucl. Phys. **A441**, 617 (1985).
[37] I. A. Rizvi, M. Afzal Anzari, R. P. Gautum, R. K. Y. Singh, and A. K. Choubey, J. Phys. Soc. Jpn. **56**, 3135 (1985).
[38] M. K. Bhardwaj, I. A. Rizvi, and A. K. Chaubey, Phys. Rev. C **15**, 2338 (1992).
[39] P. Masaelides and M. Munzel, J. Inorg. Nucl. Chem. **42**, 937 (1980).
[40] G. W. A. Newton, V. J. Robinson, and E. M. Shaw, J. Inorg. Nucl. Chem. **43**, 2227 (1981).
[41] M. Blann, Nucl. Phys. **A213**, 570 (1973).