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Measurement and analysis of the excitation functions for alpha particle induced reactions on niobium

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Abstract. Stacked foil activation technique and Ge(Li) gamma ray spectroscopy have been used for determining the excitation functions up to 45 MeV, of six reactions ^{93}Nb[(α, n), $(\alpha, 2n)^m$, $(\alpha, 2n)^g$, $(\alpha, 3n)$, $(\alpha, p3n)$ and $(\alpha, \alpha n)$]. Excitation functions were also calculated theoretically by means of the hybrid model with and without the inclusion of pre-equilibrium emission of particles. A general agreement was found in (α, xn) type of reactions.

Keywords. Excitation functions; stacked-foil activation technique; pre-equilibrium decay hybrid model.

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1. Introduction

Nuclear reactions induced by medium energy projectiles (10–200 MeV), were studied to understand the equilibrium and pre-equilibrium processes. A priori knowledge of the excitation functions is essential to explain the equilibrium and pre-equilibrium emission of particles in $(\alpha, xnypz\alpha)$ reactions, and to test the adequacies of the various pre-equilibrium models, developed during the last few decades [1–9], in order to explain the underlying physics.

Niobium is a typical monoisotopic element situated in the middle of the periodic table and ideally suitable for such studies. Extensive measurements of alpha particle induced reactions are available over a wide region of energy using scintillation and germanium detectors [10–16]. However, a close scrutiny reveals that not only there are divergences beyond the experimental errors among the various reported values, but also a wide gap exists between 30 and 60 MeV [15].

Gadioli *et al* [16] studied these reactions in steps of 20MeV alpha particle energy, and there is only one energy point cross-section at 40 MeV available in each of these reactions, with no measurements in the low energy regions, where the transition from equilibrium to pre-equilibrium reaction mechanism takes place. Thus, the available Ge(Li) measurements for the above reactions at the low energy region (10 to 50 MeV) is still far from adequate.

In this context, the present investigations are undertaken with two aims: (i) to improve the quality of existing data, measured about a decade back and to add new energy point cross-sections wherever not available, and (ii) to compare the experimental results so obtained with one of the latest available theoretical codes

[17], for the first time, for these reactions, in the energy range between 10–45 MeV. Although, Ernst *et al* [15] have studied these reactions up to 170 MeV their data are not supported by any suitable theoretical calculations.

Thus, there is a strong motivation in the present work to measure the excitation functions of six reactions in the above mentioned energy range.

2. Experimental procedure

Six excitation functions for the reaction residues ^{96}Tc, ^{95m}Tc, ^{95g}Tc, ^{94}Tc ^{93}Mo and ^{92}Nb, in the alpha particle induced reaction on ^{93}Nb were measured using stacked-foil activation technique and Ge(Li) gamma ray spectroscopy.

Stacks of self-supporting niobium foils of thickness 11 mg/cm^2 each and purity greater than 99·99%, were interspersed with suitable aluminium degraders, to degrade the alpha particle energies from 45 MeV. At the front of the stack, an aluminium foil of thickness 20 mg/cm^2 was used as a flux monitor. The energy of alpha particles after they had traversed half of the thickness to each foil was determined from the range-energy tables of Williamson *et al* [18].

The alpha irradiation was performed at the Variable Energy Cyclotron Centre, Calcutta, India. Keeping in view the half lives and the yields, beam currents of the order of 200 nA was maintained throughout the irradiation. 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 [19]. The reaction residues were identified by their characteristic gamma rays as mentioned in table 1 [20], and using Ge (Li) detector ($\sim$ 2·0 KeV FWHM for 1332 KeV photons of ^{60}Co) in conjunction with a 4 K multichannel analyser. The energy and efficiency calibration of the Ge(Li) detector was done by a ^{152}Eu standard source. The formula used in the cross-section measurement alongwith other details is given in literature [21].

3. Experimental results

The main sources of error in the present measurement of cross-section essentially include, uncertainties in the photopeak area, monitor cross-section, uniformity of the

Table 1. Reactions studied in the present work and the relevant decay characteristics of residual nuclei.

Reactions	Residual nucleus	Q value (MeV)	Half-life of residual nucleus $T_{1/2}$	Characteristic γ-ray energy E_γ(keV)	% abundance θ_γ(%)
^{93}Nb(α, n)	^{96}Tc	−7·03	4·35 d	778	99·1
^{93}Nb($\alpha, 2n$)	^{95m}Tc	−14·92	61·0 d	204·1	66·2
^{93}Nb($\alpha, 2n$)	^{95g}Tc	−14·92	20·0 h	766	92·0
^{93}Nb($\alpha, 3n$)	^{94}Tc	−24·84	4·88 h	871	100
^{93}Nb($\alpha, p3n$)	^{93}Mo	−31·9	6·95 h	1477	99·1
^{93}Nb($\alpha, \alpha n$)	^{92m}Nb	−8·96	10·14 d	934·5	99·2
Monitor reactions					
^{27}Al($\alpha, \alpha 2pn$)	^{24}Na	−31·4	15·05 h	1369	100
^{27}Al($\alpha, 2\alpha n$)	^{22}Na	−22·5	2·60 a	1275	100

Table 2. Experimental cross-section for the α-induced reaction on ^{93}Nb.

Reaction product nucleus / E_α (MeV) — Cross section (mb)	Nb(α, *n*) $^{96m+g}Tc$ Present	Previous	Nb(α, 2*n*) ^{95g}Tc Present	Previous	^{95m}Tc Present	Previous
16·0	—	433 ± 33*	—	38 ± 3*	—	—
16·9	309 ± 24	—	—	—	—	—
21·2	276 ± 30	—	232 ± 28	—	93·4 ± 13·1	—
23·0	—	92 ± 7*	—	849 ± 66*	—	—
24·4	106 ± 15	—	489 ± 54	—	169 ± 22	—
29·0	—	22 ± 2·4*	—	913 ± 70*	—	—
29·5	22·6 ± 3·4	—	665 ± 67	—	203 ± 24	—
32·6	—	—	—	666*	—	—
34·1	—	—	—	387 ± 30*	—	—
34·3	20·5 ± 3·1	—	812 ± 81	—	223 ± 27	—
38·0	12·8 ± 1·9	—	349 ± 38	—	91·8 ± 12·8	—
38·8	—	—	—	184 ± 15	—	—
40·0	—	11·5 ± 0·1**	—	227 ± 3	—	—
42·0	9·98 ± 1·5	—	156 ± 22	—	—	—
43·2	—	—	—	104 ± 9*	—	—
	Nb(α, 3*n*) ^{94g}Tc		Nb(α, *p*3*n*) ^{93}Mo		Nb(α, α*n*) ^{92m}Nb	
16·0	—	—	—	—	—	—
16·9	—	—	—	—	—	—
21·2	—	—	—	—	3·14 ± 0·47	—
23·0	—	—	—	—	—	—
24·4	—	—	—	—	14·6 ± 2·8	—
29·0	—	83 ± 6*	—	—	—	—
29·5	8·21 ± 1·20	—	—	—	26·4 ± 3·9	—
32·6	—	397*	—	—	—	—
34·1	—	518 ± 40	—	—	—	—
34·3	119 ± 15	—	2·24 ± 0·49	—	32·3 ± 3·9	—
38·0	485 ± 49	—	21·3 ± 3·2	—	39·6 ± 4·7	—
38·8	—	684 ± 53*	—	—	—	—
40·0	—	—	—	2·01 ± 0·05**	—	18·3 ± 0·5**
42·0	650 ± 65	—	32·1 ± 4·7	25 ± 2*	43·4 ± 4·8	—
43·2	—	609 ± 47*	—	—	—	—

*Ernst *et al* [15]; **Gadioli *et al* [16] foil thickness, detection efficiency and spectroscopic data. The overall projected error in the present work ranges between 9 and 14%.

The calculated values of cross-sections for the reactions measured in the present work alongwith the previous results wherever available are given in table 2.

The above mentioned reactions were earlier studied employing Ge(Li) detector spectroscopy by two groups of investigators about a decade back [15, 16]. The mutual disagreement between the two measurements are beyond the limits of error. Gadioli *et al* [16] measured the cross-sections for these reactions in steps of 20 MeV alpha particle energy, and there is only one energy point cross-section at 40 MeV in each reaction, with no measurements in the low energy region, where the transition from equilibrium to pre-equilibrium mechanism takes place, while Ernst *et al* [15] have reported their results with errors as high as 23% in some measurements. To the best of our knowledge, none of the above two authors have measured the ^{93}Nb$(\alpha, 2n)$ ^{95m}Tc reaction in the present energy range.

4. Comparison with the hybrid model

The observed excitation functions are characterized by a equilibrium peak followed by a high energy tail. Therefore the experimental cross-sections may be compared with the theoretical predictions based on Weisskopf–Ewing estimates giving the compound nucleus contribution as well as with the hybrid model in its latest form [9]. Basically, the hybrid model is semi-classical, hence invloves a large number of physical parameters alongwith a few adjustable parameters. A short description of the options chosen is given below. The nuclear masses were calculated from the Myers–Swiatecki mass formula [22] with the liquid drop having shell correction term without pairing, i.e. the level density pairing absorbed in binding energies. The inverse cross-sections were calculated by optical model subroutine included in the code. A level density parameter of A/8 MeV^{-1} was used. For the equilibrium part, the so called S-wave approximation is used which takes into account the full gamma, competition with particle emission. The initial exciton number $n_0(P_0 h_0)$ plays an important role because it governs the entire cascading process of binary collisions and thereby influence the shape of hard component in the particle spectra.

We have made the theoretical calculations using the initial excitation configurations 4(4*p*0*h*), 5(5*p*0*h*) and 6(5*p*1*h*). It was observed that the theoretical predictions of the hybrid model with 4(4*p*0*h*) gives better results, as compared to the predictions of the 5(*p*0*h*) and 6(5*p*1*h*) configurations. Therefore we have shown 4(4*p*0*h*) configuration in the comparison.

Figures 1 to 4 show the measured excitation functions for the reactions ^{93}Nb$[(\alpha, n)$, $(\alpha, 2n)$, $(\alpha, 3n)$, $(\alpha, p3n)$ and $(\alpha, \alpha n)]$, alongwith the theoretical predictions of Weisskopf–Ewing estimates giving compound nucleus contributions alongwith the hybrid model calculations [17]. The (α, n) reaction proceeds through evaporation mode, roughly up to 30 MeV. The energy region 33 to 45 MeV for this reaction is almost completely dominated by the pre-equilibrium neutron emission. Thus, the hybrid model more or less gives a satisfactory agreement with the initial exciton configuration 4(4*p*0*h*). As suggested by the bell shaped curve of the Weisskopf–Ewing estimate, the $(\alpha, 2n)$ reaction, in the energy region 15–45 MeV, mainly proceeds through the well known compound nucleus mode. The onset of pre-equilibrium neutron emission starts only beyond 45 MeV. However, the excitation function underestimates the theoretical curves almost by a factor of 1·5. This is due to the fact that the angular

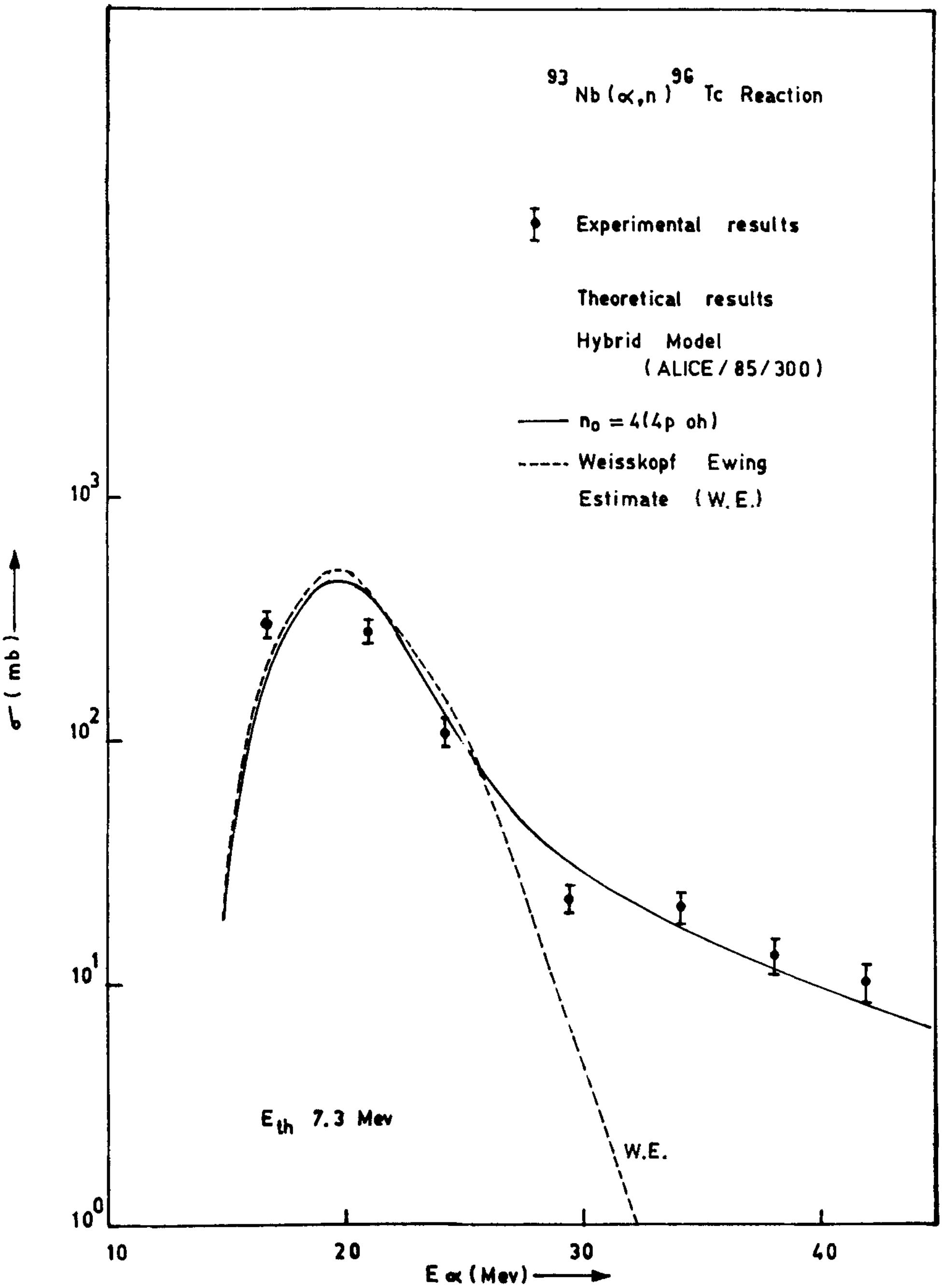

Figure 1. Comparison of theoretical and experimental excitation function of ^{93}Nb(α, n) ^{96}Tc reaction.

momentum effects are not properly accounted for in the code. More elaborate computing using the Hauser–Feshbach theory may bring about a better agreement.

The threshold energy for (α, 3n) reaction is rather large(25·9 MeV), as such we have only the rising part of the excitation function. However, the shape of the theoretical curve is reproduced within a factor of 2. There are only three points in the initial

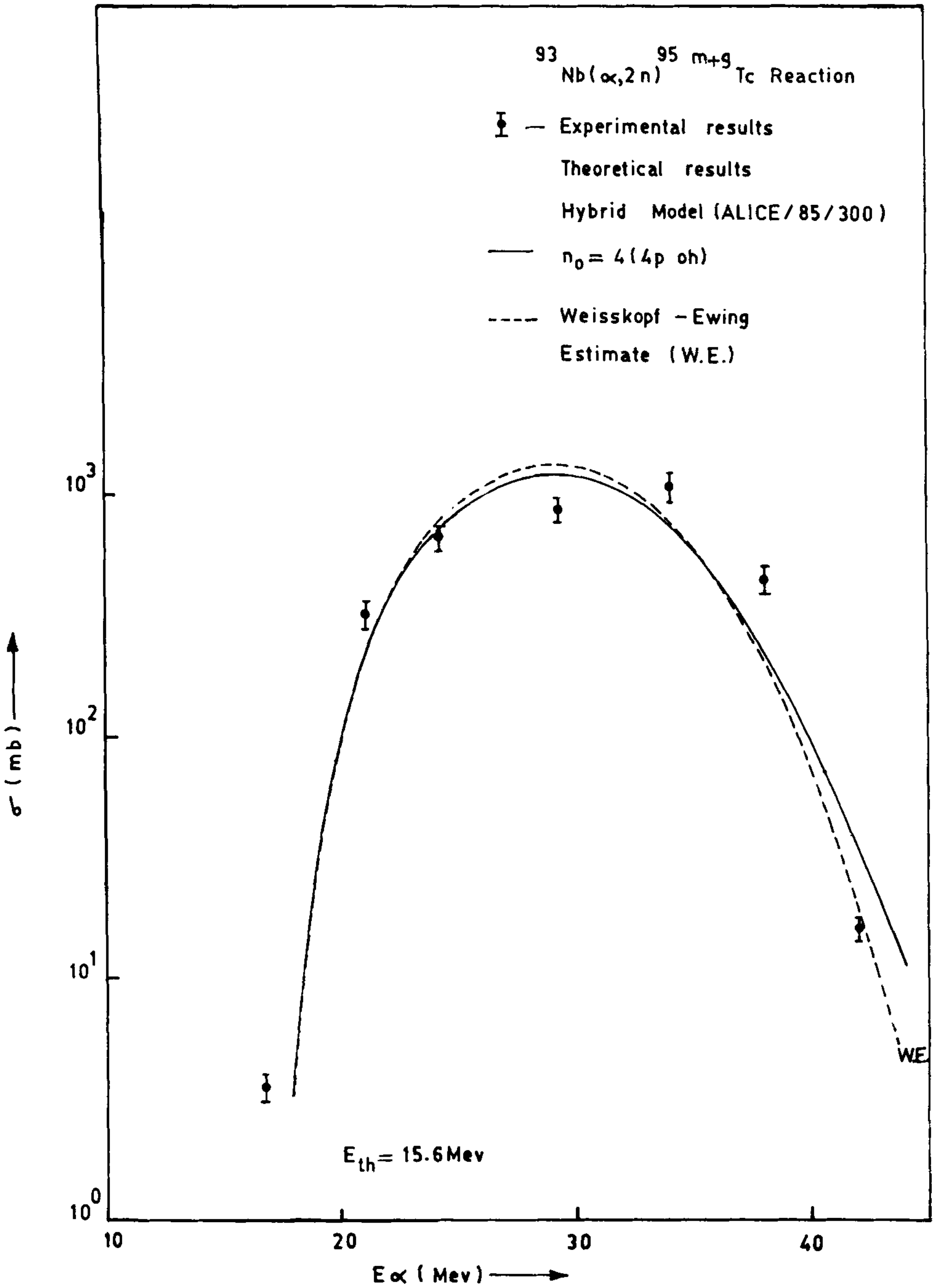

Figure 2. Comparison of theoretical and experimental excitation function of $^{93}Nb(\alpha, 2n)\,^{95m+g}Tc$ reaction.

rising part of the experimental excitation function of $(\alpha, p3n)$ reaction. In this region there are no pre-equilibrium contributions.

In figure 4, the excitation function of $^{93}Nb(\alpha, \alpha n)$ is shown. The theoretical curves fail to reproduce even the shape of the excitation function. This is not surprising because the hybrid model is not designed to deal with the alpha emission in

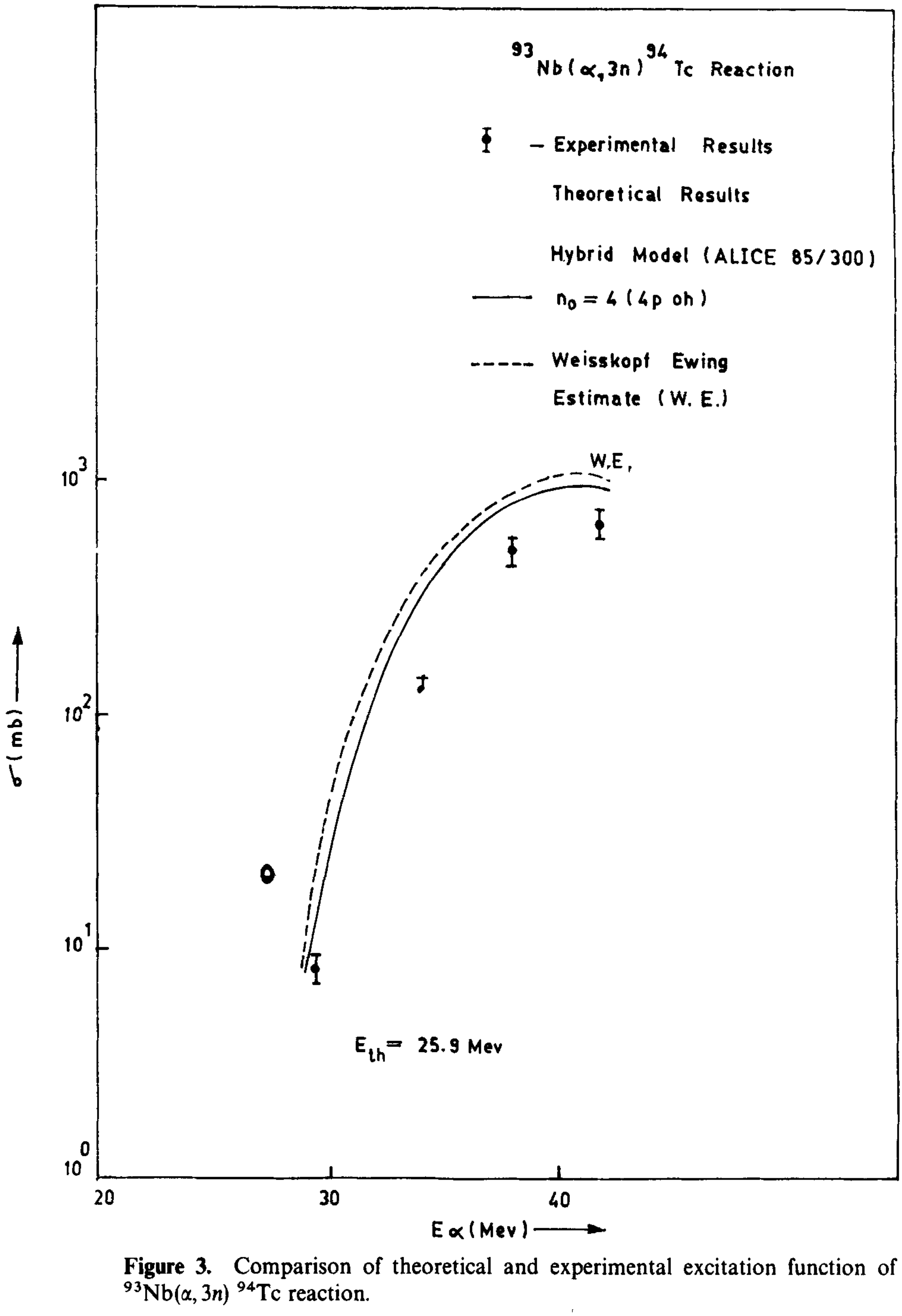

Figure 3. Comparison of theoretical and experimental excitation function of $^{93}Nb(\alpha, 3n)$ ^{94}Tc reaction.

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

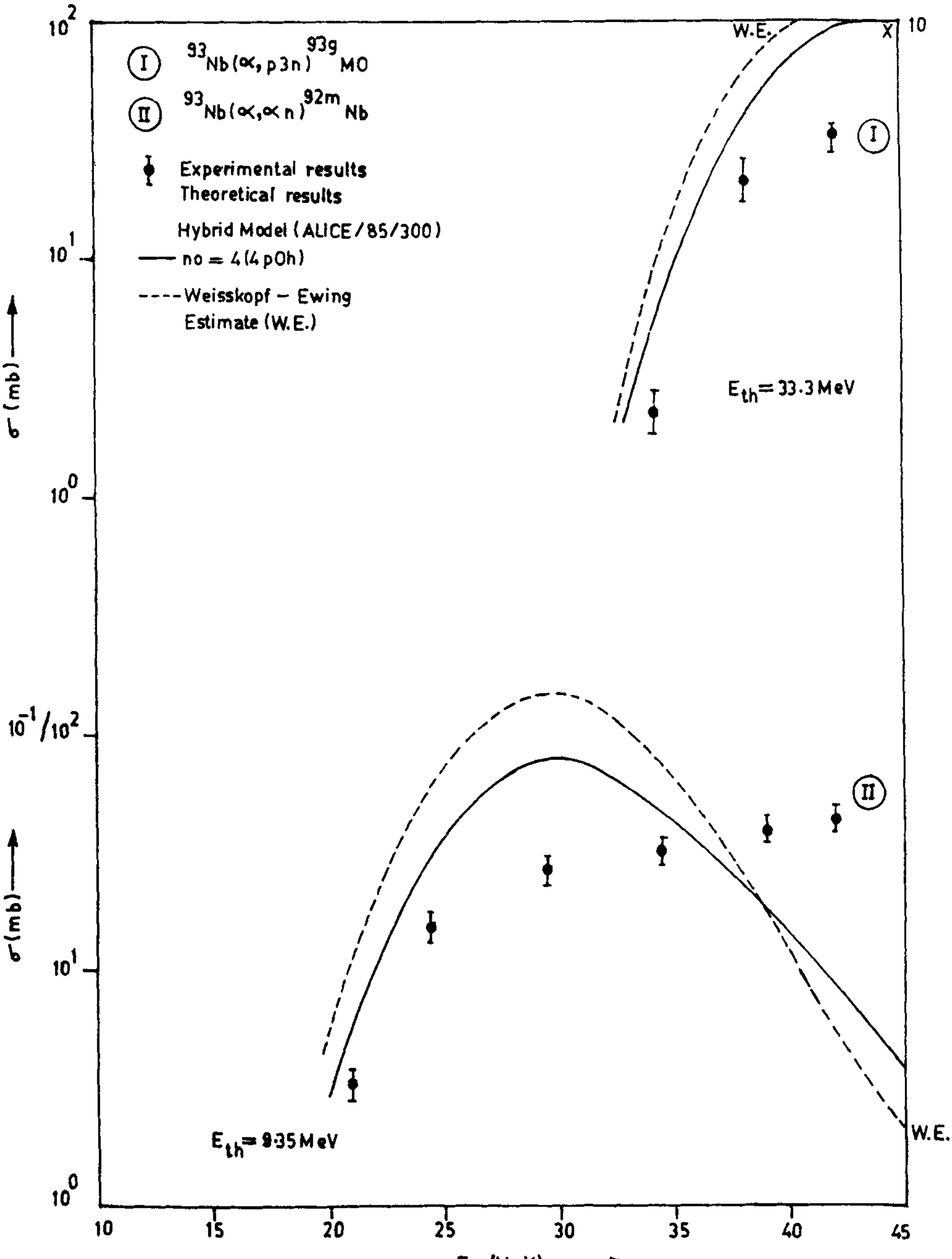

Figure 4. Comparison of theoretical and experimental excitation functions of ^{93}Nb[(α, p3n) and (α, αn)] reactions.

evaporation. Similar observations were made by Lanzafame and Blann [23], while studying alpha particle induced reactions on gold. They studied the recoil ranges of the residual nuclei in (α, αxn) type of reactions and found that there is a very little momentum transfer to the recoiling nucleus, as expected for a direct interaction.

5. Conclusions

Excitation functions for six reactions of the type ($\alpha, xnypz\alpha$) were studied in the present work. The present experimental results are systematic and more accurate over many of the previous measurements, adding several useful energy point cross-sections not measured earlier.

From an overall comparison between experimental results and theoretical predictions based on the compound nucleus Weisskopf–Ewing estimates as well as pre-equilibrium hybrid model one can infer that the model gives a fairly good account of nucleon emission in (α, xn) type of reactions in the medium mass region with an initial exciton configuration $n_0 = 4$ ($4p0h$). The above initial configuration justifiably implies 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 only a few degrees of freedom are initially excited in a reaction at moderate energies.

However, the hybrid model fails to reproduce even the shapes of the excitation function of ($\alpha, \alpha xn$) type of reactions. This is because, basically this model is not designed to handle complex (alpha) particle emission. It can treat only nucleon emission (either proton or neutron) in the pre-equilibrium phase. The alpha particle emission in the hybrid model is far from the level of the nucleon emission. The problem here is that the alpha particle in a nucleus does not exist on a semi-permanent basis as nucleons do. Recently, certain refinements have been reported [24, 25] in order to explain the emission of alpha particles in an approximate way. Further work in this direction is under progress, using more elaborate theoretical codes [26].

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References

[1] J J Griffin, *Phys. Rev. Lett.* **17**, 478 (1966)
[2] C K Cline and M Blann, *Phys. Rev.* **A172**, 225 (1971)
[3] M Blann, *Phys. Rev. Lett.* **27**, 337, 700E, 1550E (1971)
[4] E Gadioli, E Gadioli-Erba and P G Sona, *Nucl. Phys.* **A217**, 589 (1973)
[5] M Blann, *Ann. Rev. Nucl. Sci.* **25**, 123 (1975)
[6] G Mantzouranis, D Agassi and H A Weidenmuller, *Z. Phys.* **A27**, 145 (1976)
[7] J Ernst and J Rama Rao, *Z. Phys.* **A281**, 129 (1977)
[8] H Machner, *Phys. Lett.* **B86** 129 (1979)
[9] M Blann and H K Vonach, *Phys. Rev.* **C28**, 1475 (1983)
[10] P H Stelson and F K McGowan, *Phys. Rev.* **B133**, 911 (1964)
[11] L F Hanson and M L Stelta, *Phys. Rev.* **B136**, 1000 (1964)
[12] I Matsuo, J M Matuszek, N D Dubey and T T Sugihara, *Phys. Rev.* **B139**, 886 (1965)
[13] P Bond and S Jha, *Phys. Rev.* **C2**, 1887 (1970)
[14] C L Branouinho, S M A Hoffmann, G W A Newton, V J Robinson, H Y Wang, J S Grant and J A B Goodalo, *J. Inorg. Nucl. Chem.* **41**, 617, 791 (1979)

[15] J Ernst, R Ibowaki, H Klampfl, H Machner, T Mayer Kuckuk and R Schanz, *Z. Phys.* **A308**, 301 (1982)
[16] E Gadioli, E Gadioli-Erba, J J Hogan and B V Jacak, *Phys. Rev.* **C29**, 76 (1984)
[17] M Blann, Code ALICE/85/300 UCID-20169 (1984)
[18] C F Williamson, J P Boujot and J Picard, *CENS Report*, CEAR 3042 (1966)
[19] H J Probst, S M Qaim and R Weinreich, *Int. J. Appl. Radiat. Isotopes* **27**, 431 (1976)
[20] C M Lederer and V S Shirley, *Table of isotopes* (John Wiley, New York, 1978)
[21] S Mukherjee, A V Mohan Rao and J Rama Rao, *Il. Nuovo Cimento* **A104**, 863 (1991)
[22] R D Myers, *Droplet model of atomic nuclei* (Plenum, New York, 1977)
[23] F M Lanzafame and M Blann, *Nucl. Phys.* **A142**, 542 (1972)
[24] H Machner, *Phys. Rep.* **127**, 309 (1985)
[25] C Kalbach, *Phys. Rev.* **C23**, 124 (1984)
C Kalbach, *Phys. Rev.* **24**, 819 (1981)
[26] C Kalbach, PRECO-D2. *Program for calculating pre-equilibrium and direct reaction double-differential cross sections*, LOS Alamos National Laboratory Report LA-10248-MS, 1985