In the present work, we have measured the excitation functions of twenty six reactions of the types $(\alpha, xn)$; $(\alpha, pxn)$ and $(\alpha, axn)$ up to 50 MeV using stacked foil activation technique and high resolution HPGe detector (2.0 keV FWHM for 1332 keV photon of $^{60}$Co). Some of these reactions were measured previously with poor resolution scintillation detector and/or with Ge detector. There are large mutual discrepancies in the cross-section values for the same reactions in some cases.

In this scenario, the present investigation is undertaken with the two fold aim:

(i) to study all those reactions for which divergencies were observed in order to improve the quality of the existing data, and to supplement them with new energy point cross-sections, wherever not available and

(ii) to compare the experimental results with preequilibrium hybrid model of Blann using codes ALICE and also with code COMPLET developed by Ernst for $(\alpha, axn)$ type of reactions, which takes into account the emission of $\alpha$-particle in preequilibrium phase.

In the following paragraphs, the salient features of each reaction are mentioned together with the comparison of the present and previous results, wherever available.

IV.1 Alpha Particle Induced Reactions in the Target Element Nickel

Nickel is a typical multi-isotopic element having isotopes $^{58}$Ni (68.3%), $^{60}$Ni (26.1%), $^{61}$Ni (1.13%) and $^{62}$Ni (3.59%) and obtained in its purest form (99.99%). Some of their reaction residues lie in the region of doubly closed shell at $f_{7/2}$. Therefore, the measurement of alpha particle induced reactions on nickel is
Although in principle the Faraday Cup is a simple device, several sources of error may be present. For example, the region of the Cup in which the beam stops will be a source of secondary electrons which, if they escape, will make the beam intensity overestimated. Therefore, the length of the Cup should be large compared to the diameter of the entrance aperture to ensure a negligible solid angle for the escape of secondary electrons. It may be noted that the places where ever the $\alpha$ - beam strikes (like collimators etc.) are all sources of secondary electrons. The latter has to be prevented from entering the Faraday Cup by proper design. Also, the current collected by the Cup should be measured by a current integrator with a feed-back to hold the Cup potential near ground at all times.

(II) In the second method, the incident flux is determined indirectly by using a standard monitor reaction, whose cross section is accurately measured and is available in literature [7]. An aluminium foil of suitable thickness was placed in front of each stack and irradiated together with the experimental foils. The gamma rays activity of the aluminium foil was measured in the usual way. The reaction $^{27}\text{Al}(\alpha,\alpha2\text{pn})^{24}\text{Na}$ \((t_{1/2} = 15.05\text{ hours})\) was used as monitor reaction for flux calculation.

Using the characteristic photopeak of 1369 keV of $^{24}\text{Na}$ and standard monitor cross section $\sigma'$ for the reaction $^{27}\text{Al} (\alpha, \alpha 2\text{pn})$, the flux $\phi$ of the primary $\alpha$ - particle beam is calculated with the help of equation

$$
\phi = \frac{A_i' A_{\gamma}' \lambda'}{\sigma' \theta_{\gamma} P_{r} W_{i} N_{av} (1-e^{-\lambda t_i'})(e^{-\lambda t_{\gamma'}})(1-e^{-\lambda t_{i'}})} \tag{13}
$$

where all the primed symbols have their usual meaning now with reference to the the monitor aluminium foil, the value of monitor cross section $\sigma'$ corresponding to the energy of incident alpha particle beam is taken from literature [7] and used in the above equation.
The residual nucleus $^{56}\text{Ni}$ formed through $^{58}\text{Ni}(\alpha,\alpha2n)$ reaction was identified by its characteristic 270, 480, 750 and 812 keV gamma rays using HPGe detector having a resolution of 2 keV for 1332 keV photons of $^{60}\text{Co}$. A typical gamma ray spectrum and partial decay scheme are shown in Figs.IV.4 and IV.5(a) respectively.

The residual nucleus has a half life of 6.1d and spin 0+. It decays completely through electron capture (100%). In the present work, the cross-sections were calculated using 812 keV gamma ray. The details of parameters used in cross-section calculations are listed in Table III.9 and the cross-sections are shown in Fig.IV.1 along with the previous results. The error in our measurement was less than 9%. The cross-sections were also calculated using other characteristic gamma rays to get a consistency check on the cross-section measurements.

Fig.IV.1 shows that the present measurement gives systematic shape of the excitation function but there is a large discrepancy between present and previous experimental results. The cross-sections measured by Houck et al and Blann and Merkel are very low compared to the presently measured cross-sections in the overlapping region of incident energies.

**IV.1.2 Excitation function of the $^{58}\text{Ni}(\alpha,\alpha\text{pn})^{60}\text{Co}$ reaction**

This reaction was previously measured by Houck et al [2] in 1961 up to 40 MeV using NaI scintillation counter with an overall error of 15%. Blann and Merkel [3,4] in 1964 and 1965 measured the same reaction covering energy range of 14-68 MeV using proportional and scintillation counters. The error in their measurement was reported to be about 25%.

The residual nucleus $^{56}\text{Co}$ formed in $^{58}\text{Ni}(\alpha,\alpha\text{pn})$ reaction was identified by its characteristic 847, 1038 and 1238 keV gamma rays. A typical gamma ray
spectrum and a partial decay scheme are shown in Figs. IV.4 and IV.5(b) respectively.

The residual nucleus $^{56}\text{Co}$ has a half life 78.8d and a spin 4+. It decays mainly through electron capture (81%) and $\beta^+$-decay (19%). The cross-sections were calculated by using 847 keV gamma ray peak with an overall error less than 9%. The details of parameters used in the cross-section calculations are listed in Table III.10 and the cross-sections are shown in Fig.IV.2 along with the previous results. The cross-sections were also calculated using other characteristic gamma rays to get a consistency check on the cross-section measurements.

It is evident from the Fig.IV.2 that the present results give a better shape of the excitation function and are in general agreement with the previous results.

IV.1.3 Excitation function of the $^{60}\text{Ni}(\alpha,2n)^{62}\text{Zn}$ reaction

The residual nucleus $^{62}\text{Zn}$ formed through $^{60}\text{Ni}(\alpha,2n)$ reaction was identified by its characteristic 507, 548 and 597 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.4 and IV.5(c), respectively.

The residual nucleus $^{62}\text{Zn}$ has a spin and half life of 0$^+$ and 9.2h, respectively and decays mainly through electron capture (93%) and $\beta^+$-decay (7%). The cross-sections were calculated in the present work using 597 keV gamma ray. The details of parameters used in cross-section calculations are listed in Table III.11 and the cross-sections are shown in Fig.IV.3 The cross-sections were also calculated using other characteristic gamma rays to check the consistency of the measurement.

A complete summary of the results obtained in the present experimental study is given in Table IV.1.
Fig.IV.1 Excitation function of $^{58}\text{Ni}(\alpha,\alpha2n)^{56}\text{Ni}$ reaction

$E_{\text{th}} = 23.9\text{MeV}$

Present results
Previous results
Houck et al (1961)
Blann and Merkel (1964, 1965)
Fig. IV.2 Excitation function of $^{58}\text{Ni}(\alpha,\alpha p n)^{56}\text{Co}$ reaction
Fig. IV.3 Excitation function of $^{60}$Ni($\alpha$,2$n$)$^{62}$Zn reaction

$E_{th}=18.1$MeV

Present results
Fig. IV.4  A typical gamma ray spectrum of activated sample of nickel at 46.6 MeV
Fig. IV.5(a) Partial decay scheme of $^{56}$Ni

Fig. IV.5(b) Partial decay scheme of $^{56}$Co
Fig.IV.5(c) Partial decay scheme of $^{62}\text{Zn}$
Table IV.1 Measured cross-sections for $\alpha$-induced reactions on $^{58,60}$Ni

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$^{58}$Ni ($\alpha,\alpha$2n)</th>
<th>$^{58}$Ni ($\alpha,\alpha$pn)</th>
<th>$^{60}$Ni ($\alpha,2n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Nucleus</td>
<td>$^{56}$Ni</td>
<td>$^{56}$Co</td>
<td>$^{62}$Zn</td>
</tr>
<tr>
<td>Threshold Energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MeV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\alpha}$ (MeV)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
</tr>
<tr>
<td>20.5 ± 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5 ± 0.5</td>
<td></td>
<td></td>
<td>4.0 ± 0.3</td>
</tr>
<tr>
<td>24.7 ± 0.5</td>
<td></td>
<td></td>
<td>27.0 ± 2.0</td>
</tr>
<tr>
<td>27.4 ± 0.4</td>
<td></td>
<td></td>
<td>64.0 ± 4.5</td>
</tr>
<tr>
<td>30.2 ± 0.4</td>
<td></td>
<td></td>
<td>67.6 ± 4.7</td>
</tr>
<tr>
<td>33.0 ± 0.4</td>
<td>4.0 ± 0.3</td>
<td></td>
<td>48.3 ± 3.4</td>
</tr>
<tr>
<td>35.5 ± 0.3</td>
<td>3.0 ± 0.2</td>
<td>15.0 ± 1.0</td>
<td>28.0 ± 2.0</td>
</tr>
<tr>
<td>37.9 ± 0.3</td>
<td>9.7 ± 0.7</td>
<td>42.7 ± 3.0</td>
<td>20.3 ± 1.4</td>
</tr>
<tr>
<td>40.2 ± 0.3</td>
<td>16.4 ± 1.0</td>
<td>72.0 ± 5.0</td>
<td>14.0 ± 1.0</td>
</tr>
<tr>
<td>42.3 ± 0.3</td>
<td>22.0 ± 1.5</td>
<td>118 ± 8</td>
<td>11.0 ± 0.8</td>
</tr>
<tr>
<td>44.6 ± 0.3</td>
<td>30.0 ± 2.0</td>
<td>142 ± 10</td>
<td>8.6 ± 0.7</td>
</tr>
<tr>
<td>46.6 ± 0.3</td>
<td>37.0 ± 2.6</td>
<td>171 ± 12</td>
<td>8.0 ± 0.6</td>
</tr>
<tr>
<td>48.3 ± 0.3</td>
<td>42.3 ± 3.0</td>
<td>195 ± 14</td>
<td>7.5 ± 0.6</td>
</tr>
</tbody>
</table>
IV.2 Alpha Particle Induced Reactions in the Target Element Yttrium

Yttrium is a typical monoisotopic (100%) element and obtained in its purest form (99.99%). It belongs to the shell closure that occurs at N=50 ($g_{9/2}$ shell). Some of the reaction residues are formed near shell closure of the $g_{9/2}$ shell for neutrons. It has been known that yields of nuclides with closed or nearly closed shells are not predicted well with Fermi gas level density. In the above context, the measurement of alpha particle induced reactions on yttrium is interesting in order to study the effect of shell structure on nuclear reaction cross-section. In the present work, we have made a systematic study of the excitation functions for $^{89}\text{Y}[(\alpha,3n); (\alpha,4n); (\alpha,p3n); (\alpha,\alpha\alpha n); (\alpha,\alpha2n)]$ reactions\cite{5,6}.

Previously Smend et al \cite{7} measured the cross-section for $(\alpha,3n)$ reaction and Mukherjee et al \cite{8} measured the $(\alpha,n)$ and $(\alpha,3n)$ reactions on the target element yttrium.

To the best of my knowledge, the excitation functions for $^{89}\text{Y}[(\alpha,4n); (\alpha,p3n); (\alpha,\alpha\alpha n); (\alpha,\alpha2n)]$ reactions were reported for the first time.

IV.2.1 Excitation function of the $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ reaction

This reaction was previously measured by Smend et al \cite{7} in 1967 and Mukherjee et al \cite{8} in 1997

Smend et al studied this reaction in the energy range of 34-54 MeV using scintillation detector some thirty years ago. It is to be mentioned that a large number of closely lying gamma rays are emitted from residual nuclei and the scintillation detector, having a resolution of 8% for 662 keV photon of $^{137}\text{Cs}$, can not isolate any single photopeak clearly from others.

Mukherjee et al studied this reaction up to 50 MeV using HPGe detector with an overall error of 8-12%. It can be seen from the Fig.IV.6 that these two measurements do not agree with each other in the overlapping energy region.
The measurement by Smend et al. is smaller by a factor of two to three than the measurements by Mukherjee et al.

In the present work, the residual nucleus $^{90}$Nb was identified by its characteristic 141 and 1129 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.10 and IV.11(a), respectively. The residual nucleus $^{90}$Nb formed in $^{89}$Y($\alpha$,3n) reaction has two isomers of half lives $T_{1/2} = 18.6$ s($^{90m}$Nb) and $T_{1/2} = 14.6$ h($^{90g}$Nb) having spins 4$^-$ and 8$^+$, respectively. The metastable state ($^{90m}$Nb) decays completely through isomeric transition (100%) to the ground state. The cross-sections were calculated using 1129 keV gamma ray peak after complete decay of metastable state to the ground state. The details of parameters used in cross-section calculations are listed in TableIII.12. The cross-sections were also calculated using 141 keV gamma ray to get a consistency check on the cross-section measurements. The overall error in our measurement was less than 9% thereby showing not only an improved accuracy but also, as evident from Fig.IV.6, a better shape of the excitation function compared to the other two.

**IV.2.2 Excitation function of the $^{89}$Y[(\(\alpha\),4n)+\((\alpha\),p3n)\]$^{89}$Nb +$^{89}$Zr reaction**

The residual nucleus $^{89}$Nb formed in the $^{89}$Y($\alpha$,4n) reaction has two isomers of half lives $T_{1/2} = 2.0$ h and $T_{1/2} = 66$ m having spins (9/2)$^+$ and (1/2)$^-$ respectively. There is no isomeric transition between these two states as they are genetically independent. The peculiarity with (\(\alpha\),4n) and (\(\alpha\),p3n) reactions on yttrium is that they produce isobaric residual nuclei, with one of them, the daughter nucleus, being continuously fed by the parent nucleus. The residual nucleus $^{89}$Zr is produced by (i) $^{89}$Y($\alpha$,p3n)$^{89}$Zr and (ii) $^{89}$Y($\alpha$,4n)$^{89}$Nb ---\(\rightarrow\)$^{89}$Zr. This is because isomers of $^{89}$Nb decay into $^{89}$Zr, which is formed in the two states $^{89m}$Zr and $^{89g}$Zr of spins (1/2) and (9/2)$^+$. Further there is an isomeric transition between $^{89m}$Zr and
\( ^{89}\text{Zr} \). Hence, the cross-section measured is the sum of \((\alpha, 4n)\) and \((\alpha, p3n)\) reactions.

In the present work, the residual nucleus \(^{89}\text{Zr} \) was identified by its characteristic 909 keV gamma ray using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photons of \(^{60}\text{Co} \). A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.10 and IV.11(b) & (c), respectively. The cross-sections were calculated using prominent 909 keV gamma ray peak of \(^{89}\text{Zr} \) residual nucleus after complete decay of metastable state to the ground state. The details of parameters used in cross-section calculations are listed in TableIII.13 and the cross-sections are shown in Fig.IV.7. The error in our measurement was less than 9%.

IV.2.3 Excitation function of the \(^{89}\text{Y}(\alpha, \alpha n)\) \(^{88}\text{Y} \) reaction

The study of \((\alpha, \alpha xn)\) reactions is difficult and interesting at the same time. They have in general low cross-sections so that their characteristic gamma ray photopeaks are marked by the Compton background due to much stronger gamma rays coming from other reactions such as \((\alpha, xn)\) on the same target element. The interest in the study of \((\alpha, \alpha xn)\) reactions is concerned with the mechanism of \(\alpha\)-particle emission.

The residual nucleus \(^{88}\text{Y} \) having a half life of 106.6d and spin 4' was identified by its characteristic 898 keV gamma ray peak using 120cc HPGe detector having resolution of 2 keV for 1332 keV photon of \(^{60}\text{Co} \). A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.10 and IV.11(d), respectively. The cross-sections were calculated using the 898 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.14 and the cross-sections are shown in Fig.IV.8.
IV.2.4 Excitation function of the $^{89}\text{Y}(\alpha,\alpha 2n)^{87}\text{Y}$ reaction

The residual nucleus $^{87}\text{Y}$ formed in $^{89}\text{Y}(\alpha,\alpha 2n)$ reaction was identified by its characteristic 388 and 485 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photons of $^{60}\text{Co}$. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.10 and IV.11(e), respectively. The residual nucleus $^{87}\text{Y}$ has two isomers of half lives $T_{1/2} = 13.0\text{h}(^{87m}\text{Y})$ and $T_{1/2} = 80.3\text{h}(^{87g}\text{Y})$ and having spins $(9/2)^+$ and $(1/2)^-$, respectively. The metastable state $(^{87m}\text{Y})$ decays completely through isomeric transition to the ground state $(^{87g}\text{Y})$. The cross-sections were calculated using the 485 keV gamma ray peak after complete decay of the metastable state to the ground state. The overall error in our measurement was less than 9%. The cross-sections were also calculated using 388 keV gamma ray to get a consistency check on the cross-section measurements.

A complete summary of the results obtained in the present experimental study is given in Table IV.2.
Fig. IV.6 Excitation function of $^{89}\text{Y}(\alpha,3n)^{90}\text{Nb}$ reaction
Fig. IV.7  Excitation function of \( ^{89}Y(\alpha,4n)^{89}Nb + ^{89}Y(\alpha,p3n)^{89}Zr \) reaction
Fig. IV.8: Excitation function of $^{89}\text{Y}(\alpha,\alpha\alpha)^{88}\text{Y}$ reaction.
Fig. IV.9 Excitation function of $^{89}\text{Y}(\alpha,\alpha2n)^{87}\text{Y}$ reaction

$E_a$(MeV) vs $\sigma$(mb)

$E_{th} = 21.7 \text{ MeV}$

Present results
Fig. IV. 10  A typical gamma ray spectrum of activated sample of yttrium at 42.2 MeV
Fig. IV.11(a) Partial decay scheme of $^{90}$Nb

Fig. IV.11(b) Partial decay scheme of $^{89}$Nb
Fig.IV.11(c) Partial decay scheme of $^{89}\text{Zr}$

Fig.IV.11(d) Partial decay scheme of $^{88}\text{Y}$
Fig. IV.11(e) Partial decay scheme of $^{87}$Y
Table IV.2 Measured cross-sections for α-induced reactions on $^{89}Y$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$^{89}Y(\alpha,3n)$</th>
<th>$^{89}Y[(\alpha,4n),+(\alpha,p3n)]$</th>
<th>$^{89}Y(\alpha,\alpha n)$</th>
<th>$^{89}Y(\alpha,\alpha 2n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Nucleus</td>
<td>$^{90}Nb$</td>
<td>$^{89}Nb,^{89}Zr$</td>
<td>$^{88}Y$</td>
<td>$^{87}Y$</td>
</tr>
<tr>
<td>Threshold Energy (MeV)</td>
<td>28.0</td>
<td>38.5333</td>
<td>11.9</td>
<td>21.7</td>
</tr>
<tr>
<td>$E_{\alpha}$ (MeV)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
</tr>
<tr>
<td>28.1 ± 0.5</td>
<td>12.6 ± 1.0</td>
<td>71.0 ± 5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.3 ± 0.5</td>
<td>81.4 ± 6.0</td>
<td>106 ± 8</td>
<td>10 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>32.5 ± 0.5</td>
<td>245 ± 18</td>
<td>125 ± 9</td>
<td>15 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>34.4 ± 0.4</td>
<td>370 ± 27</td>
<td>190 ± 13</td>
<td>140 ± 10</td>
<td>40 ± 0.2</td>
</tr>
<tr>
<td>36.2 ± 0.4</td>
<td>480 ± 34</td>
<td>400 ± 3.0</td>
<td>152 ± 11</td>
<td>77 ± 0.4</td>
</tr>
<tr>
<td>38.0 ± 0.4</td>
<td>580 ± 32</td>
<td>830 ± 6.0</td>
<td>165 ± 12</td>
<td>140 ± 0.7</td>
</tr>
<tr>
<td>39.6 ± 0.4</td>
<td>651 ± 36</td>
<td>148 ± 11</td>
<td>176 ± 1.3</td>
<td>200 ± 1.0</td>
</tr>
<tr>
<td>42.2 ± 0.4</td>
<td>642 ± 46</td>
<td>385 ± 28</td>
<td>190 ± 14</td>
<td>330 ± 2.0</td>
</tr>
<tr>
<td>44.5 ± 0.3</td>
<td>534 ± 29</td>
<td>713 ± 51</td>
<td>202 ± 15</td>
<td>465 ± 2.6</td>
</tr>
<tr>
<td>46.8 ± 0.3</td>
<td>419 ± 23</td>
<td>863 ± 47</td>
<td>212 ± 15</td>
<td>612 ± 4.4</td>
</tr>
</tbody>
</table>
IV.3 Alpha Particle Induced Reactions in the Target Element Rhodium:

Rhodium is a monoisotopic element situated in the middle of the "Periodic Table". Very few experimental studies concerning alpha particle induced reactions on rhodium are reported in the literature.

Previous measurements on rhodium by Hansen et al. [9] and Ansari et al. [10] are confined to (α,xn) type of reactions only. In the present work, excitation functions for the reactions \(^{103}\text{Rh}(\alpha,xn); x=1-4\) and \(^{103}\text{Rh}(\alpha,\alpha xn); x=1-3\) have been studied [11,12].

To the best of my knowledge, the excitation functions for (α,αxn) type of reactions on \(^{103}\text{Rh}\) were measured for the first time. Further, the present measurement add some new energy point cross-sections for some of the reactions studied previously.

IV.3.1 Excitation function of the \(^{103}\text{Rh}(\alpha,n)^{106}\text{Ag}\) reaction

This reaction was previously measured by Hansen et al [9] in 1964 and Ansari et al [10] in 1996. Hansen et al studied this reaction in the energy range of 12-18 MeV using Polyethylene "long counters" with an overall error of 10%. Further, the energy of alpha particle beam incident on various foils was determined using relatively old range-energy data based on the experimental results of Bichsel et al [13]. Ansari et al studied this reaction in the energy range of 10-40 MeV using Ge(Li) detector with an estimated error up to 16%.

The residual nucleus \(^{106}\text{Ag}\) produced through \(^{103}\text{Rh}(\alpha,n)\) reaction has two isomeric states of half lives \(T_{1/2} = 8.5\text{d}(^{106m}\text{Ag})\) and \(T_{1/2} = 24\text{m}(^{106s}\text{Ag})\) having spins \(6^-\) and \(1^-\) respectively. Both the states decay independently through electron capture and \(\beta^-\) decay. The state \(^{106s}\text{Ag}(T_{1/2}=24\text{m})\) has only one prominent gamma ray of energy 512 keV which is very close to annihilation peak of 511 keV. Therefore in the present work, the residual nucleus \(^{106m}\text{Ag}(T_{1/2} = 8.5\text{d})\) was identified by its characteristic 616, 717, 748 and 824 keV gamma rays using 120cc
HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(a), respectively. The cross-sections were calculated in the present work by using 717 keV gamma ray peak of $^{106g}$Ag. The details of parameters used in the cross-section calculations are listed in Table III.16. The uncertainty in our measurement was less than 9%. We have used the range-energy tables of Williamson et al [14] to calculate the energy of alpha particle beam incident on various foils in the present work. Fig.IV.12 shows the present experimental results along with the previous ones. It is evident from Fig.IV.12 that the results of Hansen et al which are in the energy range of 12-18 MeV constitute only the initial rising part of the excitation function and are overestimated by a factor of 10 in the peak region of excitation function. It is also evident from the Fig.IV.12 that the present results are in fair agreement with the results of Ansari et al in the overlapping region of energies. Further, present measurement add three new energy point cross-sections in the region of 40-50 MeV. The cross-sections were also calculated using other gamma rays to get a consistency check on the cross-section measurements.

IV.3.2 Excitation function of the $^{103}$Rh($\alpha,2n$)$^{105}$Ag reaction

Ansari et al [10] in 1996 studied this reaction using alpha particle beam of energy varying between 10-40 MeV with Ge(Li) detector. The maximum uncertainty in the measurement was stated to be 16%.

In the present work, the residual nucleus $^{105}$Ag was identified by its characteristic 280, 344,443 and 644 keV gamma rays using HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(b) respectively.

The residual nucleus $^{105}$Ag formed through $^{103}$Rh($\alpha,2n$) reaction exists in two states of half lives $T_{1/2} = 7.2$ m ($^{105m}$Ag) and $T_{1/2} = 41.3$ d ($^{105g}$Ag)
having spins $7/2^+$ and $1/2'$, respectively. The metastable state ($^{105m}\text{Ag}$) decays completely through isomeric transition (~100%) to the ground state ($^{105g}\text{Ag}$). The cross-sections were calculated in the present work by using 344 keV gamma ray of $^{105g}\text{Ag}$ after complete decay of metastable state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.17. An overall error in our measurement was less than 9%. The cross-sections are shown in Fig.IV.13 along with the previous results. It can be seen from the figure that both the results are in good agreement in the overlapping region of energies. Also, the present measurement add three energy point cross-sections in the energy range of 40-50 MeV.

IV.3.3 Excitation function of the $^{103}\text{Rh}(\alpha,3n)^{104}\text{Ag}$ reaction

This reaction was also studied by Ansari et al [10] in 1996 using Ge(Li) detector with an overall error up to 16%.

The residual nucleus $^{104}\text{Ag}$ produced through $^{103}\text{Ag}(\alpha,3n)$ reaction exists in two states of half lives $T_{1/2} = 33m$ ($^{104m}\text{Ag}$) and $T_{1/2} = 69m$ ($^{104g}\text{Ag}$) and having spins $2^+$ and $5^+$, respectively. The metastable state ($^{104m}\text{Ag}$) decays to the ground state ($^{104g}\text{Ag}$) through isomeric transition (33%) and electron capture along with $\beta^+$-decay (67%). The residual nucleus $^{104}\text{Ag}$ was identified in the present work by its characteristic 556, 767, 857, 925 and 941 keV gamma rays in its ground state using HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}\text{Co}$. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(c) respectively.

The cross-sections were calculated in the present work using 556 keV gamma ray peak of $^{104g}\text{Ag}$ after the complete decay of metastable state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.18 and the cross-sections are shown in Fig.IV.14 along with the results of Ansari et al. The figure shows that both the results are in good
agreement with each other in overlapping region of energies. Also, the present measurement adds three energy point cross-sections in the region of 40-50 MeV.

IV.3.4 Excitation function of the $^{103}$Rh(α,4n)$^{103}$Ag reaction.

To the best of my knowledge, the excitation function for this reaction is reported for the first time.

The residual nucleus $^{103}$Ag was identified in the present work by its characteristic 241, 266 and 531 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(d), respectively.

The residual nucleus $^{103}$Ag formed in $^{103}$Rh(α,4n) reaction exists in two states of half lives $T_{1/2} = 5.7s (^{103m}$Ag) and $T_{1/2} = 1.1h (^{103g}$Ag) having spins $1/2^-$ and $7/2^+$ respectively. The metastable state (103mAg) decays completely through an isomeric transition (100%) to the ground state ($^{103g}$Ag). In the present work, the cross-sections were calculated by using 266 keV gamma ray peaks of $^{103g}$Ag after complete decay of metastable state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.19. The consistency of calculation was checked by doing calculations with other characteristic gamma rays. The cross-sections are shown in Fig.IV.15. Since the threshold energy of the reaction is very high (i.e. 34.3 MeV) and the energy limit in the present work is 50 MeV, there are only few data points in the initial rising part of the excitation function.

IV.3.5 Excitation function of the $^{103}$Rh(α,αn)$^{102}$Rh reaction

The residual nucleus $^{102}$Rh formed in $^{103}$Rh(α,αn) reaction exists in two isomeric states of half lives $T_{1/2} = 206d (^{102m}$Rh) and $T_{1/2} = 2.9Y (^{102g}$Rh) and spins $2^-$ and $6^+$ respectively. The metastable state decays almost independently through electron capture (62%) and $\beta^+$-decay(14%). Therefore, in the present work, the residual nucleus $^{102m}$Rh was identified by its characteristic 475 and 628 keV
gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(e), respectively.

The cross-sections were calculated using 475 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.20 and the cross-sections are shown in Fig.IV.16.

**IV.3.6 Excitation function of the $^{103}\text{Rh}(\alpha,\alpha 2n)^{101}\text{Rh}$ reaction**

The residual nucleus $^{101}\text{Rh}$ produced through $^{103}\text{Rh}(\alpha,\alpha 2n)$ reaction has two isomeric states of half lives $T_{1/2} = 4.34d$ ($^{101m}\text{Rh}$) and $T_{1/2} = 3.3Y$ ($^{101g}\text{Rh}$) and having spins $(9/2)^+$ and $(1/2)^-$, respectively. Since the ground state of the residual nucleus has a very long half life and the metastable state decays almost independently through electron capture (92.8%), the present study is done by identifying the metastable state ($^{101m}\text{Rh}$) of the residual nucleus with its characteristic 307 and 545 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Fig.IV.19 and IV.20(f), respectively.

The cross-sections were calculated using 307 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.21 and the cross-sections are plotted in Fig.IV.17.

**IV.3.7 Excitation function of the $^{103}\text{Rh}(\alpha,\alpha 3n)^{100}\text{Rh}$ reaction**

The residual nucleus $^{100}\text{Rh}$ formed in $^{103}\text{Rh}(\alpha,\alpha 3n)$ reaction was identified in the present work by its characteristic 446, 540, 588 and 822 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.19 and IV.20(g), respectively.

The residual nucleus $^{100}\text{Rh}$ exists in two isomeric states of half lives $T_{1/2} = 4.7m$ ($^{100m}\text{Rh}$) and $T_{1/2} = 20.8h$ ($^{100g}\text{Rh}$) and spins $5^+$ and $1^-$ respectively. The decay of metastable state ($^{100m}\text{Rh}$) to the ground state ($^{100g}\text{Rh}$) is mostly through isomeric transition (93%). The cross-sections were calculated using 540 keV...
gamma ray peak after the complete decay of metastable state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.22 and the cross-sections are shown in Fig.IV.18.

The cross-sections are in general low due to the emission of alpha particles. Since the effective threshold energy of this reaction is large, there are only few data points in the initial rising part of the excitation function.

A complete summary of the results obtained in the present experimental study is given in Table IV.3.

IV.4 Alpha Particle Induced Reactions in the Target Element Terbium:

Terbium is a typical monoisotopic element belonging to the rare earth group and obtained in its purest form (99.99%). Therefore, the study of excitation functions for alpha particle induced reactions on terbium is important from the viewpoint of preequilibrium reaction mechanism. In the present work, excitation functions for the reactions $^{159}$Tb[$(\alpha,n)$, $(\alpha,3n)$, $(\alpha,4n)$ and $(\alpha,\alpha3n)$] have been studied up to 50 MeV [15,16].

Mukherjee et al [8] measured the excitation functions for $(\alpha,xn)$; $x=1-4$ reactions on $^{159}$Tb. Since there is only a single measurement available on alpha particle induced reactions on terbium, the present investigation is interesting to check the consistency and reliability of the cross-section measurements.

IV.4.1 Excitation function of the $^{159}$Tb$(\alpha,n)^{162}$Ho reaction

In general, the single neutron emitting reactions of the type $(\alpha,n)$ are interesting because in such reactions, the preequilibrium mechanism is expected to play a major role at energies exceeding few tens of MeV.

This reaction was measured by Mukherjee et al [8] in 1997 up to 50 MeV using HPGe detector with an overall error of 8-12%.
Fig. IV.12 Excitation function of $^{103}$Rh($\alpha$,n)$^{106}$Ag reaction

Present results
Previous results
Ansari et al (1996)
Hansen et al (1964)

$E_{th} = 7.0$ MeV
Fig. IV.13 Excitation function of $^{103}\text{Rh}(\alpha,2n)^{105}\text{Ag}$ reaction

$E_{th} = 15.2$ MeV

Present results
Previous results
Ansari et al (1996)
Fig. IV.14 Excitation function of $^{103}$Rh($\alpha,3n$)$^{104}$Ag reaction

Present results
Previous results
Ansari et al (1996)
Present results

$E_\text{th} = 34.3 \text{ MeV}$

Fig.IV. 15 Excitation function of $^{103}\text{Rh}(\alpha,4n)^{103}\text{Ag}$ reaction
Fig. IV. 16 Excitation function of $^{103}\text{Rh}(\alpha,\alpha n)^{102}\text{Rh}$ reaction

$E_\alpha$ (MeV)

$\sigma$ (mb)

- Present results
Fig.IV.17 Excitation function of $^{103}\text{Rh}(\alpha,\alpha2n)^{101}\text{Rh}$ reaction
Fig.IV.18 Excitation function of $^{103}$Rh($\alpha$,3$n$)$^{100}$Rh reaction
Fig. IV.19 A typical gamma ray spectrum of activated sample of rhodium at 38.0 MeV
Fig.IV.20(a) Partial decay scheme of $^{106}$Ag

Fig.IV.20(b) Partial decay scheme of $^{105}$Ag
Fig. IV.20(c) Partial decay scheme of $^{104}$Ag

Fig. IV.20(d) Partial decay scheme of $^{103}$Ag
Fig. IV.20(e) Partial decay scheme of $^{102}$Rh

Fig. IV.20(f) Partial decay scheme of $^{101}$Rh
Fig.IV.20(g) Partial decay scheme of $^{100}$Rh
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Product Nucleus</th>
<th>Threshold Energy (MeV)</th>
<th>E_a (MeV)</th>
<th>σ (mb)</th>
<th>σ (mb)</th>
<th>σ (mb)</th>
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<tr>
<td></td>
<td>106Ag</td>
<td>17.6 ± 1.2</td>
<td>126 ± 10</td>
<td>17.6 ± 1.2</td>
<td>126 ± 10</td>
<td>17.6 ± 1.2</td>
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<tr>
<td></td>
<td>108Rh</td>
<td>21.5 ± 1.1</td>
<td>28.0 ± 0.4</td>
<td>21.5 ± 1.1</td>
<td>28.0 ± 0.4</td>
<td>21.5 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>109Ag</td>
<td>25.0 ± 0.5</td>
<td>33.1 ± 0.5</td>
<td>25.0 ± 0.5</td>
<td>33.1 ± 0.5</td>
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<tr>
<td></td>
<td>110Rh</td>
<td>31.4 ± 0.8</td>
<td>46.0 ± 0.8</td>
<td>31.4 ± 0.8</td>
<td>46.0 ± 0.8</td>
<td>31.4 ± 0.8</td>
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<tr>
<td></td>
<td>111Rh</td>
<td>34.4 ± 0.8</td>
<td>49.0 ± 0.8</td>
<td>34.4 ± 0.8</td>
<td>49.0 ± 0.8</td>
<td>34.4 ± 0.8</td>
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<tr>
<td></td>
<td>112Rh</td>
<td>38.0 ± 1.0</td>
<td>53.0 ± 1.0</td>
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<td>53.0 ± 1.0</td>
<td>38.0 ± 1.0</td>
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<tr>
<td></td>
<td>113Rh</td>
<td>41.5 ± 1.0</td>
<td>58.0 ± 1.0</td>
<td>41.5 ± 1.0</td>
<td>58.0 ± 1.0</td>
<td>41.5 ± 1.0</td>
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<tr>
<td></td>
<td>114Rh</td>
<td>44.9 ± 1.0</td>
<td>63.0 ± 1.0</td>
<td>44.9 ± 1.0</td>
<td>63.0 ± 1.0</td>
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</table>

Table IV.3. Measured cross-sections for α-induced reactions on $^{103}$Rh.
In the present work, the residual nucleus $^{162}$Ho was identified by its characteristic 185, 283 and 937 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.25 and IV.26(a), respectively.

The residual nucleus $^{162}$Ho formed in the $^{159}$Tb(α,n) reaction exists in two states of half lives $T_{1/2} = 68\text{m} (^{162m}\text{Ho})$ and $T_{1/2} = 15\text{m} (^{162g}\text{Ho})$ having spins $6^-$ and $1^+$, respectively. The metastable state ($^{162m}\text{Ho}$) decays through isomeric transition (61%) to the ground state ($^{162g}\text{Ho}$) and remaining 39% through electron capture and $\beta^-$ emission. In the present work, the cross-sections were calculated using 185 keV gamma ray peak for $^{162m}\text{Ho}$ residual nucleus. The details of parameters used in the cross-section calculations are listed in Table III.23. The calculation was also done with the other characteristic gamma rays in order to get a consistency check on the cross-section measurements. The present results along with the results of Mukherjee et al are shown in Fig.IV.21. It can be seen from the figure that the present results generally agree with the previous ones to enable a meaningful comparison with theoretical predictions to be made in the next chapter.

**IV.4.2 Excitation function of the $^{159}$Tb(α,3n)$^{160}$Ho reaction**

This reaction was measured by Mukherjee et al [8] in 1997 up to 50 MeV using HPGe detector with an overall error of 8-12%.

In the present work, the residual nucleus $^{160}$Ho was identified by its characteristic 728, 962 and 966 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.25 and IV.26(b), respectively.

The residual nucleus $^{160}$Ho formed through the $^{159}$Tb(α,3n) reaction exists in two isomeric states of half lives $T_{1/2} = 5.02\text{h} (^{160m}\text{Ho})$ and $T_{1/2} = 25.6\text{m} (^{160g}\text{Ho})$

having spins $2^\circ$ and $5^+$ respectively. The cross-sections were calculated using 728 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.24. and the cross-sections are shown in Fig.IV.22. The calculation was also done for other characteristic gamma rays to get a consistency check on the cross-section measurements. It is evident from the figure that the present results generally agree with the results of Mukherjee et al. The uncertainties in our measurement are less than 9%.

IV.4.3 Excitation function of the $^{159}$Tb($\alpha$,4n)$^{159}$Ho reaction

This reaction was also measured by Mukherjee et al [8] in 1997, up to 50 MeV using HPGe detector with an error of 8-12%.

In the present work, the residual nucleus $^{159}$Ho was identified by its characteristic 121, 132, 253 and 310 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and partial decay scheme are shown in Figs.IV.25 and IV.26(c), respectively.

The residual nucleus $^{159}$Ho formed in the $^{159}$Tb($\alpha$,4n) reaction has two isomers of half lives $T_{1/2} = 8.3$ s ($^{159m}$Ho) and $T_{1/2} = 33m$ ($^{159g}$Ho) having spins $(1/2)^+$ and $(7/2)^-$ respectively. The metastable state ($^{159m}$Ho) decays completely through isomeric transition (100%) to the ground state ($^{159g}$Ho). The cross-sections were calculated using the 310 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.25. The error in our measurement was less than 9%. The calculation was also done for other characteristic gamma rays to get a consistency check on the cross-section measurements. Fig.IV.23 shows the present experimental results along with the previous one. It is evident from the figure that the present measurements give systematic data and better shape of the excitation function.
IV.4.4 Excitation function of the $^{159}\text{Tb}(\alpha,\alpha 3\text{n})^{156}\text{Tb}$ reaction

To the best of my knowledge, the excitation function for $^{149}\text{Tb}(\alpha,\alpha 3\text{n})^{156}\text{Tb}$ is reported for the first time.

The residual nucleus $^{156}\text{Tb}$ was identified by its characteristic 199, 534 and 1222 keV gamma rays using 120cc HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}\text{Co}$. A typical gamma ray spectrum and partial decay scheme are shown in Figs.IV.25 and IV.26(d), respectively.

The residual nucleus $^{156}\text{Tb}$ formed in $^{159}\text{Tb}(\alpha,\alpha 3\text{n})$ reaction has two isomers of half lives $T_{1/2} = 5.0\text{h} \ (^{156\text{m} }\text{Tb})$ and $T_{1/2} = 5.3\text{d} \ (^{156\text{g} }\text{Tb})$ having spins $0^+$ and $3'$, respectively. The metastable state ($^{156\text{m} }\text{Tb}$) decays completely through isomeric transition (100%) to the ground state ($^{156\text{g} }\text{Tb}$). The cross-sections were calculated in the present work by using 534 keV gamma ray peak after the complete decay of metastable state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.26. The cross-sections were also calculated using other characteristic gamma rays to check consistency of cross-section measurements. The overall error in our measurement was less than 9%. The results are shown in Fig.IV.24.

A complete summary of the results obtained in the present experimental study is given in Table IV.4.

IV.5 Alpha Particle Induced Reactions in the Target Element Rhenium:

Rhenium has two odd mass stable isotopes of abundances 37.4%($^{185}\text{Re}$) and 62.6%($^{187}\text{Re}$). When natural rhenium is used as target in the reaction studies, more than one isotope may contribute to the production of a given product nucleus through different reaction channels, for example, $^{185}\text{Re}(\alpha,\text{n})$ and $^{187}\text{Re}(\alpha,3\text{n})$ reactions lead to the same residual nucleus $^{188}\text{Ir}$. In such cases, the measured cross-
Fig. IV.21 Excitation function of $^{159}$Tb($\alpha$,n)$^{162}$Ho reaction

- Present results
- Previous results
- Mukherjee et al (1997)

$E_{th} = 9.4$ MeV

$E_\alpha$ (MeV) vs $\sigma$ (mb)
Fig. IV.22 Excitation function of $^{159}\text{Tb}(\alpha,3n)^{160}\text{Ho}$ reaction

- Present results
- Previous results

E$_{\alpha}$ (MeV) vs. $\sigma$ (mb)
Present Results

Previous results

Mukherjee et al (1997)

$E = 32.8 \text{MeV}$

Fig. IV.23 Excitation function of $^{159}\text{Tb}(\alpha, 4n)^{155}\text{Ho}$ reaction
Excitation function of $^{159}\text{Tb}(\alpha,\alpha'3n)^{156}\text{Tb}$ reaction

Present Results

$E_a (\text{MeV})$

$q_\omega \rho$

$E_{th} = 24.1 \text{ MeV}$

Fig. IV.24
Fig. IV.25 A typical gamma ray spectrum of activated sample of terbium at 39.4 MeV
Fig. IV.26(a) Partial decay scheme of $^{162}$Ho

Fig. IV.26(b) Partial decay scheme of $^{160}$Ho
Fig.IV.26(c) Partial decay scheme of $^{159}$Ho

Fig.IV.26(d) Partial decay scheme of $^{156}$Tb
Table IV.4. Measured cross-sections for α-induced reactions on $^{159}$Tb

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$^{159}$Tb(α,n)</th>
<th>$^{159}$Tb(α,3n)</th>
<th>$^{159}$Tb(α,4n)</th>
<th>$^{159}$Tb(α,α3n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Nucleus</td>
<td>$^{162m}$Ho</td>
<td>$^{160m}$Ho</td>
<td>$^{159}$Ho</td>
<td>$^{156}$Tb</td>
</tr>
<tr>
<td>Threshold Energy (MeV)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
<td>$\sigma$ (mb)</td>
</tr>
<tr>
<td>15.5 ± 1.5</td>
<td>170 ± 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5 ± 1.7</td>
<td>385 ± 30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.1 ± 1.1</td>
<td>166 ± 12</td>
<td>120 ± 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.5 ± 0.9</td>
<td>103 ± 08</td>
<td>1045 ± 71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.5 ± 0.9</td>
<td>73 ± 05</td>
<td>1285 ± 87</td>
<td>270 ± 20</td>
<td></td>
</tr>
<tr>
<td>39.4 ± 0.9</td>
<td>53 ± 03</td>
<td>633 ± 43</td>
<td>486 ± 34</td>
<td>11 ± 00</td>
</tr>
<tr>
<td>43.0 ± 0.8</td>
<td>45 ± 03</td>
<td>310 ± 21</td>
<td>1050 ± 71</td>
<td>24 ± 01</td>
</tr>
<tr>
<td>46.4 ± 0.5</td>
<td>39 ± 03</td>
<td>203 ± 14</td>
<td>1195 ± 81</td>
<td>44 ± 03</td>
</tr>
</tbody>
</table>
The section is the weighted average over the two reaction channels and can easily be interpreted taking into account the differences in the threshold energies and their relative predominance in a given energy range as explained in the chapter III.3.5. The two contributions can therefore be separated out pretty accurately using either the known theoretical ratio of cross-sections [17] or by subtracting the contribution of one of the reactions measured with an enriched isotope[18]. Efforts were made to separate the individual contributions of the reactions \([^{185}\text{Re}(\alpha,n)+^{187}\text{Re}(\alpha,3n)]^{188}\text{Ir}\) and \([^{185}\text{Re}(\alpha,2n)+^{187}\text{Re}(\alpha,4n)]^{187}\text{Ir}\) using theoretical excitation functions in the Eqns.(11) and (12) of chapter III.3.5.

In the present work, we have made a systematic study of the excitation functions of \(^{185}\text{Re}\) \([((\alpha,n); (\alpha,2n); (\alpha,3n)]\) and \(^{187}\text{Re}\) \([((\alpha,n), (\alpha,2n); (\alpha,3n); (\alpha,4n)]\) reactions [19,20].

Previously, Ismail [21] measured the excitation functions for alpha particle induced reactions on \(^{185,187}\text{Re}\) by conventional thick target thick recoil catcher technique for bombarding energies up to 65 MeV. He has reported the excitation functions for \(^{185}\text{Re}[(\alpha,4n); (\alpha,2pn); (\alpha,\alpha n), (\alpha,\alpha 2n)]\) and \(^{187}\text{Re}[(\alpha,n); (\alpha,2n)]\) reactions.

To the best of my knowledge, the excitation functions for \(^{185}\text{Re}\) \([((\alpha,n); (\alpha,2n); (\alpha,3n)]\) and \(^{187}\text{Re}\) \([(\alpha,3n); (\alpha,4n)]\) reactions were measured for the first time.

### IV.5.1 Excitation function of the \([^{185}\text{Re}(\alpha,n)+^{187}\text{Re}(\alpha,3n)]^{188}\text{Ir}\) reactions

Consequent on the use of natural rhenium as a target, the isotopic contributions arise in the production of a given final nucleus. The residual nucleus \(^{188}\text{Ir}\) is formed via \(^{185}\text{Re}(\alpha,n)\) and \(^{187}\text{Re}(\alpha,3n)\) reactions jointly. Therefore, the experimental cross-section in this case gives the weighted average cross-section for the two reactions \(^{185}\text{Re}(\alpha,n)\) and \(^{187}\text{Re}(\alpha,3n)\)
Below the threshold energy of $^{187}\text{Re}(\alpha, 3\text{n})$ reaction (i.e. 25.1 MeV), the measured cross-section is due to $^{185}\text{Re}(\alpha, \text{n})$ reaction only. The relative contribution of the two reactions above 25.1 MeV was separated at each energy point using theoretical excitation function based on preequilibrium model, which predicts the shape and absolute value of the experimentally measured excitation functions.

The residual nucleus $^{188}\text{Ir}$ has a half-life of 41.5h and spin $2^+$. It decays mainly through electron capture (99.6%). The residual nucleus was identified by its characteristic 155, 478 and 633 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.32 and IV.33(a), respectively.

The weighted average cross-sections were calculated using the following expression with 633 keV gamma ray. The details of parameters used in the cross-section calculations are listed in Table III.27 and the cross-sections are shown in Fig.IV.27.

$$\langle \sigma \rangle = \frac{P_1 \sigma_1}{A_1} + \frac{P_2 \sigma_2}{A_2}$$

Beyond the threshold energy of $^{187}\text{Re}(\alpha, 3\text{n})$ reaction, namely 25.1 MeV, the contribution due to $^{185}\text{Re}(\alpha, \text{n})$ reaction is separated out using the theoretical ratio of the cross-sections for $(\alpha, \text{n})$ and $(\alpha, 3\text{n})$ reactions on $^{185}\text{Re}$ and $^{187}\text{Re}$ respectively in the Eqns.(11) and (12) of chapter III.3.5. The cross-sections were also calculated using other characteristic gamma rays to check consistency of cross-section measurements. It is clear from the shape of the excitation function that, below 25.1 MeV, the $^{185}\text{Re}(\alpha, \text{n})$ reaction is dominant whereas, beyond 25.1 MeV, $^{187}\text{Re}(\alpha, 3\text{n})$ reaction predominates.
IV.5.2 Excitation function of the \([^{185}\text{Re}(\alpha,2n)+^{187}\text{Re}(\alpha,4n)]^{187}\text{Ir}\) reactions

The residual nucleus \(^{187}\text{Ir}\) is formed through \(^{185}\text{Re}(\alpha,2n)\) and \(^{187}\text{Re}(\alpha,4n)\) reactions with threshold energies 18.1 MeV and 31.9 MeV respectively. The residual nucleus \(^{187}\text{Ir}\) having a half life of 10.5h and spin \((3/2)^+\) was identified in the present work by its characteristic 401, 427, 611, 913 and 977 keV gamma rays. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.32 and IV.33(b), respectively.

The weighted average cross-sections were calculated with 913 keV gamma ray peak using the expression given in the previous case. The details of parameters used in the cross-section calculations are listed in Table III.28 and the cross-sections are shown in Fig.IV.28. The cross-sections were also calculated using other characteristic gamma rays to check the consistency of cross-section measurements. The contribution of \(^{185}\text{Re}(\alpha,2n)\) reaction is separated from that of \(^{187}\text{Re}(\alpha,4n)\) reaction beyond 31.9 MeV, using the theoretical cross-sections of \(^{185}\text{Re}(\alpha,2n)\) and \(^{187}\text{Re}(\alpha,4n)\) reactions. Fig.IV.28 clearly shows that the \(^{185}\text{Re}(\alpha,2n)\) reaction is dominant below 31.9 MeV whereas the \(^{187}\text{Re}(\alpha,4n)\) reaction predominates beyond this energy.

IV.5.3 Excitation function of the \(^{185}\text{Re}(\alpha,3n)^{186}\text{Ir}\) reaction

The residual nucleus \(^{186}\text{Ir}\) formed through the \(^{185}\text{Re}(\alpha,3n)\) reaction exists in two genetically independent isomeric states having half lives of 1.7h and 16h and spins \(2^+\) and \(5^+\), respectively. Both these states decay independently through electron capture and \(\beta^+\)-decay.

In the present work, the residual nucleus \(^{186}\text{Ir}\) \((T_{1/2} =16h)\) was identified by its characteristic 137, 297 and 435 keV gamma rays. A typical gamma ray spectrum and partial decay scheme are shown in Figs.IV.32 and IV.33(c), respectively. The partial cross-sections were calculated using 297 keV gamma ray.
peak. The details of parameters used in the cross-section calculations are listed in Table III.29 and the cross-sections are shown in Fig.IV.29. The consistency of measurement was checked by doing calculations with other characteristic gamma rays.

IV.5.4 Excitation function of the $^{187}\text{Re}(\alpha,n)^{190}\text{Ir}$ reaction

The study of single neutron emitting reactions of the type $(\alpha,n)$ is important from the view point of preequilibrium particle emission which is expected to play a major role beyond energies of few tens of MeV.

The residual nucleus $^{190}\text{Ir}$ formed in the $^{187}(\alpha,n)$ reaction exists in three isomeric states having half lives 3.2h, 1.2h and 11.8d and spins $1^+$, $7^+$ and $4^+$ respectively. The isomeric state having half life of 3.2h decays mostly through electron capture (95%) whereas the isomeric state having half life of 1.2h decays completely through the isomeric transition to the ground state.

The residual nucleus $^{190}\text{Ir}$ ($T_{1/2}=11.8\text{d}$) was identified in the present work by its characteristic 187, 518, 558 and 605 keV gamma rays using HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}\text{Co}$. A typical gamma ray spectrum and partial decay scheme are shown in Figs.IV.32 and IV.33(d) respectively. The cross-sections were calculated using 558 keV gamma ray peak after allowing for complete decay of isomeric state to the ground state. The details of parameters used in the cross-section calculations are listed in Table III.30 and the cross-sections are shown in Fig.IV.30. The uncertainty in our measurement was less than 9%.

This reaction was previously measured by Ismail[21] in 1993 using Ge(Li) detector up to 65MeV with an overall error of about 8%. From Fig.IV.30, it is observed that the cross-sections measured by Ismail are higher and also there is a shift in peak position toward high energy side. This discrepancy may be due to measurement of flux, efficiency of the detector, etc. Further, it is important to note
that Ismail used the commercially available self supporting rhenium foils as target whereas we have used spectroscopically pure (99.99%) rhenium foils as target.

**IV.5.5 Excitation function of the $^{187}$Re($\alpha,2n$)$^{189}$Ir reaction**

This reaction was also previously measured by Ismail [21] in 1993 using Ge(Li) detector up to 65 MeV with an overall error of about 8%.

The residual nucleus $^{189}$Ir was identified in the present work by its characteristic 245 keV gamma ray using HPGe detector having a resolution of 2 keV for 1332 keV photon of $^{60}$Co. A typical gamma ray spectrum and a partial decay scheme are shown in Figs.IV.32 and IV.33(e), respectively.

The residual nucleus $^{189}$Ir formed through the $^{187}$Re($\alpha,2n$) reaction has a half life of 13.1d and spin (3/2)$^+$ and it decays through electron capture to the ground state. The cross-sections were calculated using 245 keV gamma ray peak. The details of parameters used in the cross-section calculations are listed in Table III.31 and the cross-sections are shown in Fig.IV.31 along with the previous results. The overall error in our measurement was less than 9%. It is evident from the figure that the cross-sections measured by Ismail are higher and there is a shift in the peak position toward high energy side similar to the case of previous reaction.

A complete summary of the results obtained in the present experimental study is given in Table IV.5.
Fig. IV.27 Excitation function of the \(^{185}\text{Re}(\alpha, n) + ^{187}\text{Re}(\alpha, 3n) \rightarrow ^{188}\text{Ir} \) reactions.

Present results

\[^{186}\text{Re}(\alpha, n) \rightarrow ^{188}\text{Ir} \]
\[^{187}\text{Re}(\alpha, 3n) \rightarrow ^{188}\text{Ir} \]

$E_{\alpha}(\alpha, 3n)=25.1\text{MeV}$

$E_{\alpha}(\alpha, n)=11.2\text{MeV}$
Present results
Separated with theory
$^{185}\text{Re}(\alpha,2n)\rightarrow^{187}\text{Ir}$
$^{187}\text{Re}(\alpha,4n)\rightarrow^{183}\text{Ir}$

Excitation function of the $[^{185}\text{Re}(\alpha,2n)+^{187}\text{Re}(\alpha,4n)]^{187}\text{Ir}$ reactions

Fig. IV.28
Fig.IV.29  Excitation function of $^{185}$Re($\alpha$,3n)$^{186}$Ir reaction
Fig. IV.30 Excitation function of $^{187}\text{Re}(\alpha,n)^{190}\text{Ir}$ reaction

$E_\alpha = 10.3\ \text{MeV}$

Present results
Previous results
Ismail (1993)
Fig. IV.31 Excitation function of $^{187}\text{Re}(\alpha,2n)^{189}\text{Ir}$ reaction

- Present results
- Previous results

$E_\alpha (\text{MeV})$

$E_{\text{th}} = 16.8 \text{ MeV}$

(qω)ø
Fig. IV.32 A typical gamma ray spectrum of activated sample of rhenium at 42.1 MeV
Fig. IV.33(a) Partial decay scheme of $^{188}\text{Ir}$

Fig. IV.33(b) Partial decay scheme of $^{187}\text{Ir}$
Fig. IV.33(c) Partial decay scheme of $^{186}\text{Ir}$

Fig. IV.33(d) Partial decay scheme of $^{190}\text{Ir}$
Fig. IV.33(e) Partial decay scheme of $^{189}\text{Ir}$
Table IV.5 Measured cross-sections for α-induced reactions on $^{185,187}$Re

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$^{185}$Re(α,n) + $^{187}$Re(α,3n)</th>
<th>$^{185}$Re(α,2n) + $^{187}$Re(α,4n)</th>
<th>$^{185}$Re(α,3n)</th>
<th>$^{187}$Re(α,n)</th>
<th>$^{187}$Re(α,2n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Nucleus</td>
<td>$^{188}$Ir</td>
<td>$^{187}$Ir</td>
<td>$^{186}$Ir</td>
<td>$^{190}$Ir</td>
<td>$^{189}$Ir</td>
</tr>
<tr>
<td>Threshold Energy (MeV)</td>
<td>11.2, 25.1</td>
<td>18.1, 31.9</td>
<td>27.0</td>
<td>10.3</td>
<td>16.8</td>
</tr>
<tr>
<td>$E_a$ (MeV)</td>
<td>$\sigma$(mb)</td>
<td>$\sigma$(mb)</td>
<td>$\sigma$(mb)</td>
<td>$\sigma$(mb)</td>
<td>$\sigma$(mb)</td>
</tr>
<tr>
<td>8.3 ± 6.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18.4 ± 4.0</td>
<td>49.2 ± 4.0</td>
<td>155 ± 12</td>
<td>-</td>
<td>23.0 ± 2.0</td>
<td>217 ± 16</td>
</tr>
<tr>
<td>25.7 ± 3.3</td>
<td>150 ± 12</td>
<td>679 ± 51</td>
<td>-</td>
<td>10.4 ± 0.8</td>
<td>572 ± 43</td>
</tr>
<tr>
<td>31.9 ± 2.9</td>
<td>1198 ± 90</td>
<td>295 ± 22</td>
<td>1088 ± 82</td>
<td>6.5 ± 0.5</td>
<td>175 ± 13</td>
</tr>
<tr>
<td>37.2 ± 2.6</td>
<td>681 ± 51</td>
<td>639 ± 48</td>
<td>1018 ± 76</td>
<td>5.4 ± 0.4</td>
<td>72.0 ± 5.6</td>
</tr>
<tr>
<td>42.1 ± 2.3</td>
<td>271 ± 20</td>
<td>1240 ± 93</td>
<td>382 ± 29</td>
<td>5.0 ± 0.4</td>
<td>49.0 ± 3.7</td>
</tr>
<tr>
<td>46.4 ± 2.0</td>
<td>183 ± 14</td>
<td>1026 ± 77</td>
<td>175 ± 13</td>
<td>4.7 ± 0.3</td>
<td>40.0 ± 3.0</td>
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</table>
References