CHAPTER - II

EXPERIMENTAL TECHNIQUE
AND MEASUREMENTS
EXPERIMENTAL TECHNIQUE AND MEASUREMENTS

A nuclear reaction is the process in which a change is brought about either in composition or energy or both, of a target nucleus by bombarding with a nuclear particle or gamma-ray. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles from a particle accelerator, a reactor, a radioactive source or cosmic radiation. Generally, the strength of a particular nuclear reaction is expressed in terms of a parameter called 'cross-section'. The alpha induced reaction cross-section have been measured by stacked foil activation technique. Generally, two techniques are employed for the measurement of alpha induced reaction cross-sections. They are:

1) ON-line studies / IN-beam technique.
2) OFF-line studies / OFF-beam technique.

The present measurements have been done by OFF-beam technique. This is the technique in which a stack of samples along with the suitable energy degraders is irradiated with the alpha particle beam for a desired time. The thicknesses of the foils can be accurately known by cutting to standard sizes and weighing them accurately with the help of an electronic microbalance. The desired projectile energies can
be obtained by using appropriate initial beam energy and thickness of the degrader foils. Activities induced in individual foils are detected and analysed separately, using appropriate detection system. In the present measurement Ge (Li) detector and CANBEERA SERIES-88 Multichannel Analyser have been used for post-irradiation studies. The irradiation of the target and the detection of radiation are done separately. The activity of residual nucleus for a particular reaction has been analysed. The method of inducing artificial radioactivity within a sample through the bombardment of nuclear particles, which leads to the isotopic analysis. High precisions, selectivity and sensitivity are the advantages of this OFF-beam technique. To use this technique the knowledge of decay schemes of residual nuclei and energy levels are required. The details of the technique employed has been given here:

2.1 Target Preparation

Natural metallic Rhodium and hygroscopic compound of Cesium Iodide, Potassium Bromide, Thallium Chloride and Praseodymium Oxide targets were used for the present measurements. These targets were found to be spectroscopically pure (SPECPURE) of purities better than 99.9%. In the case of Rhodium, which is a naturally available metal, foils of thickness 1.24 mg/cm$^2$ were used along with aluminium degraders of thicknesses 6.75 mg/cm$^2$. Pr$_6$O$_{11}$ targets were made by vacuum evaporation technique on
Alumination backing of uniform thickness 6.75 mg/cm$^2$. The other three targets, are hygroscopic compounds and so they were prepared by special vacuum evaporation technique. The thicknesses of CSI, KBr, TlCl were 1.00 mg/cm$^2$, 1.50 mg/cm$^2$ and 3.52 mg/cm$^2$ respectively. These targets were deposited on an Aluminium backing of uniform thickness of 6.75 mg/cm$^2$, placed over the rectangular masking plate. Thin Aluminium layers of thicknesses 200 $\mu$g/cm$^2$ for CSI and 25/$\mu$g/cm$^2$ for KBr and TlCl respectively were further deposited by Vacuum evaporation onto the upper surface of the prepared targets, so that the moisture may not affect the surface of these targets. The weight of these targets was again verified with the help of an electronic microbalance. These target foils were cut into small pieces of standard size 1.5 x 1.5 cm$^2$ for Rhodium and 1.2 x 1.2 cm$^2$ for other targets. The pieces of standard size of targets were fixed using the conducting glue zapon on Aluminium frames of size 40 mm x 40 mm having a circular hole of diameter 10 mm in its centre. Thin foils of Aluminium of thickness 6.75 mg/cm$^2$ have been used as the energy degraders and were suitably placed between two target foils throughout the stack to obtain a required energy variation till the last target foil. In order to check any background activity produced in the Aluminium frames, two blank Aluminium frames were irradiated separately. The stack
foil arrangement of target and the Aluminium degraders is shown in Fig. 2.1. The arrangement of target foils alongwith Aluminium degraders for various target nuclei with different incident α-particle beams, used for irradiation are illustrated in Fig. 2.2.

From the Table 3 of Northcliffe and Schilling(1) the stopping power values of different materials Rh, CsI, KBr, TlCl, Pr$_6$O$_{11}$ and Al have been used for calculating the energy degradation of incident alpha particle beam energy on each foil. The errors mentioned in the incident energy values are due to the energy spread in the thickness of foils and degraders. The energy loss in the target and degraders has been calculated by multiplying the stopping power values with their respective thicknesses viz.,

Energy loss ($\Delta E$) = ( $dE/dX$ ) x ($\Delta X$ )

Where ( $dE/dX$ ) is the stopping power of α-particle and ($\Delta x$) is the thickness of the foil. The stopping power versus alpha particle energy curve for targets Rh, CsI, KBr, TlCl, Pr$_6$O$_{11}$ and Al is shown in Fig. 2.2. The calculated values of alpha-particle energy on each foil alongwith its energy spread is given in Tables 2.1 - 2.5
Fig. 2.1 Stack Foil arrangement of Target and the Aluminium degraders
Fig. 2.2 Arrangement of different target stacks
Fig. 2.2a Stopping Power as a Function of α-particle Energy for various targets and Aluminium degrader
Table 2.1 Rhodium

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_{\alpha}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>13.59 ± 0.62</td>
</tr>
<tr>
<td>5</td>
<td>18.92 ± 0.59</td>
</tr>
<tr>
<td>4</td>
<td>24.66 ± 0.59</td>
</tr>
<tr>
<td>3</td>
<td>29.61 ± 0.57</td>
</tr>
<tr>
<td>2</td>
<td>35.01 ± 0.57</td>
</tr>
<tr>
<td>1</td>
<td>39.88 ± 0.56</td>
</tr>
<tr>
<td>Foil No.</td>
<td>Incident Energy, ( E_\alpha ) (MeV)</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>13</td>
<td>18.06 ± 0.57</td>
</tr>
<tr>
<td>12</td>
<td>19.78 ± 0.56</td>
</tr>
<tr>
<td>11</td>
<td>21.39 ± 0.56</td>
</tr>
<tr>
<td>10</td>
<td>24.26 ± 0.56</td>
</tr>
<tr>
<td>09</td>
<td>26.87 ± 0.55</td>
</tr>
<tr>
<td>08</td>
<td>30.37 ± 0.55</td>
</tr>
<tr>
<td>07</td>
<td>33.63 ± 0.54</td>
</tr>
<tr>
<td>06</td>
<td>36.68 ± 0.54</td>
</tr>
<tr>
<td>05</td>
<td>39.57 ± 0.54</td>
</tr>
<tr>
<td>04</td>
<td>42.36 ± 0.54</td>
</tr>
<tr>
<td>03</td>
<td>44.99 ± 0.53</td>
</tr>
<tr>
<td>02</td>
<td>47.50 ± 0.53</td>
</tr>
<tr>
<td>01</td>
<td>49.93 ± 0.53</td>
</tr>
</tbody>
</table>
Table 2.3(a) - Potassium Bromide (Stack-I)

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_\infty$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>30.28 ± 0.60</td>
</tr>
<tr>
<td>7</td>
<td>32.97 ± 0.59</td>
</tr>
<tr>
<td>6</td>
<td>35.21 ± 0.59</td>
</tr>
<tr>
<td>5</td>
<td>37.34 ± 0.58</td>
</tr>
<tr>
<td>4</td>
<td>40.29 ± 0.58</td>
</tr>
<tr>
<td>3</td>
<td>43.09 ± 0.57</td>
</tr>
<tr>
<td>2</td>
<td>46.56 ± 0.57</td>
</tr>
<tr>
<td>1</td>
<td>49.85 ± 0.57</td>
</tr>
</tbody>
</table>
Table 2.3(b) - Potassium Bromide (Stack-II)

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_\alpha$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>$11.93 \pm 0.68$</td>
</tr>
<tr>
<td>5</td>
<td>$16.11 \pm 0.65$</td>
</tr>
<tr>
<td>4</td>
<td>$19.65 \pm 0.63$</td>
</tr>
<tr>
<td>3</td>
<td>$22.80 \pm 0.62$</td>
</tr>
<tr>
<td>2</td>
<td>$25.65 \pm 0.61$</td>
</tr>
<tr>
<td>1</td>
<td>$28.31 \pm 0.60$</td>
</tr>
</tbody>
</table>
Table 2.4(a)- Thallium Chloride (Stack-I)

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_\alpha$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>29.04 ± 0.67</td>
</tr>
<tr>
<td>7</td>
<td>31.94 ± 0.66</td>
</tr>
<tr>
<td>6</td>
<td>34.35 ± 0.65</td>
</tr>
<tr>
<td>5</td>
<td>36.63 ± 0.64</td>
</tr>
<tr>
<td>4</td>
<td>39.72 ± 0.64</td>
</tr>
<tr>
<td>3</td>
<td>42.68 ± 0.63</td>
</tr>
<tr>
<td>2</td>
<td>46.31 ± 0.62</td>
</tr>
<tr>
<td>1</td>
<td>49.76 ± 0.61</td>
</tr>
</tbody>
</table>
Table 2.4(b)- Thallium Chloride (Stack-II)

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_\alpha$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$18.93 \pm 0.72$</td>
</tr>
<tr>
<td>2</td>
<td>$22.29 \pm 0.70$</td>
</tr>
<tr>
<td>1</td>
<td>$25.34 \pm 0.68$</td>
</tr>
</tbody>
</table>
### Table 2.5 - Praseodymium Oxide

<table>
<thead>
<tr>
<th>Foil No.</th>
<th>Incident Energy, $E_\alpha$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>$15.71 \pm 0.94$</td>
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<tr>
<td>5</td>
<td>$18.24 \pm 0.90$</td>
</tr>
<tr>
<td>4</td>
<td>$25.97 \pm 0.82$</td>
</tr>
<tr>
<td>3</td>
<td>$30.14 \pm 0.79$</td>
</tr>
<tr>
<td>2</td>
<td>$35.92 \pm 0.76$</td>
</tr>
<tr>
<td>1</td>
<td>$44.57 \pm 0.72$</td>
</tr>
</tbody>
</table>
2.2 Energy Calibration and Detector Efficiency

The energy calibration of a gamma-ray detector is a pre-requisite of carrying out any spectroscopic work. In the present measurement, Lithium drifted Germanium [Ge(Li)] detector has been calibrated by using the standard gamma-ray source Europium-152 of known strength. The source for calibration was obtained from the Variable Energy Cyclotron, Calcutta (India). The Eu-152 source emits intense gamma-rays in the energy range from 120 KeV to about 1400 KeV. The highly intense peaks can easily be identified, only if the gamma-rays expected to appear in the spectrum are known previously. The gamma-ray spectrum was recorded in the domain of the multichannel analyser CANBERRA-88, by placing the Eu-152 source at a suitable distance, in front of the Ge (Li) detector. Other standard gamma-ray sources such as $^{22}\text{Na}$, $^{54}\text{Mn}$, $^{57}\text{Co}$, $^{60}\text{Co}$, $^{133}\text{Ba}$ and $^{137}\text{Cs}$ have also been used for Energy calibration.

Detector efficiency can be defined as the ratio of the gamma-rays detected by the detector to that incident on it.

\[
\text{Efficiency (E)} = \frac{\text{Events registered by the detector}}{\text{Events impinging on the detector}}
\]

To calculate the detection efficiency, Lithium drifted Germanium Ge(Li) detector has been used with Eu-152 source.
of half life 13.33 years as the standard source. It is found that the variation of efficiency with energy for detectors of roughly the same size and shape is quite similar even though the absolute values may differ. The accuracy of the measurements depends also upon the accuracy with which the detection efficiency is measured. The detection efficiency can be calculated using the relation,

$$\varepsilon = \frac{C}{Co \, e^{-\lambda t} \cdot G \cdot \Theta}$$

Where $C$ is the observed disintegration rate of the gamma-ray source at the time of experiment and $Co$ is absolute disintegration rate of $^{152}$Eu gamma-ray source at the time of manufacturing. $\lambda$ is the decay constant, $t$ is the time gap between the date of manufacturing and observation; $G$ is the geometry factor which takes into account the solid angle subtended by the source at the detector; $\Theta$ is the absolute intensity of the particular gamma-ray. The likely error in the determination of the geometry factor has been avoided by calculating the geometry dependent efficiency using the formula.

$$\varepsilon_G = \frac{C}{Co \, e^{-\lambda t} \cdot \Theta}$$

Now ($\varepsilon_G$) is called the geometry dependent efficiency of the detector.
By using the source detector separation assembly (Figures 2.3), the standard source and the irradiated targets were counted in the same geometry. The prominent gamma-ray energies of the standard source Eu-152 along with the absolute intensities are given in Table 2.6 and the geometry dependent efficiency curves as a function of gamma-ray energy is plotted in Fig. 2.4. Some typical geometry dependent efficiency curves as a function of gamma-ray energies at different source-detector distances are shown in Figure 2.5 & 2.5(a).

2.3 Irradiation Procedure

Keeping in view the thickness and melting point of the targets and the half-lives of the yields, the target stack was irradiated with about 50, 46, 40, 30 and 25 MeV energies of α-particles beam at the variable Energy Cyclotron Centre, Calcutta, India. The experiment set up for the irradiation of the stack is shown in Fig. 2.6. By adjusting the Tantalum Collimator, the diameter of the external alpha-beam was varied according to the dimension of the target. The stack ready for irradiation was screwed at the centre of the flange. The Stack holder was electrically insulated and cooled by specially designed jet assembly for low conductivity water (LCW). The collimated beam falling on the target sample was monitored by a charge integrator, the alpha-particle beam flux was calculated using the charges
Fig. 2.3 A typical arrangement for source - detector separation assembly
Table - 2.6

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Gamma-Ray Energy (MeV)</th>
<th>Absolute Intensity</th>
<th>Area under the photo peak (C)</th>
<th>Geometry dependent Efficiencies $\xi_G \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>121.3</td>
<td>30.70</td>
<td>216630</td>
<td>65.64</td>
</tr>
<tr>
<td>2</td>
<td>245.3</td>
<td>7.70</td>
<td>29148</td>
<td>35.21</td>
</tr>
<tr>
<td>3</td>
<td>345.2</td>
<td>27.20</td>
<td>80083</td>
<td>27.38</td>
</tr>
<tr>
<td>4</td>
<td>445.2</td>
<td>3.16</td>
<td>6136</td>
<td>18.06</td>
</tr>
<tr>
<td>5</td>
<td>780.8</td>
<td>12.70</td>
<td>15588</td>
<td>11.41</td>
</tr>
<tr>
<td>6</td>
<td>869.4</td>
<td>4.10</td>
<td>4203</td>
<td>9.53</td>
</tr>
<tr>
<td>7</td>
<td>966.1</td>
<td>14.30</td>
<td>15055</td>
<td>9.79</td>
</tr>
<tr>
<td>8</td>
<td>1088.2</td>
<td>10.10</td>
<td>12331</td>
<td>11.35</td>
</tr>
<tr>
<td>9</td>
<td>1114.5</td>
<td>13.40</td>
<td>12940</td>
<td>8.98</td>
</tr>
<tr>
<td>10</td>
<td>1410.7</td>
<td>20.70</td>
<td>16753</td>
<td>7.52</td>
</tr>
</tbody>
</table>
Fig. 2.4 Detector Efficiency as a function of Energy (KeV)
Fig. 2.5 Detector Efficiency as a Function of gamma-ray Energy at various Source-Detector distances.
Fig. 2.5a Detector Efficiency as a Function of gamma-ray Energy at various Source-Detector distances
Fig. 2.6 Experimental set up used for Irradiation of the stack

1. Valve gate 2. Tantalum Collimator
3. O-Rings 4. LCW inlet
5. Target 6. To current Integrator (Faraday cup)
7. Insulation Sleeve 8. Screw
9. Perspex Coupling flange 10. LCW outlet
collected in the Faraday cup. After irradiation and cooling, the target foils were brought into the counting room and the spectra of the residual activity were recorded with the help of a pre-calibrated Canberra Series-88 multi-channel analyser, 100 cm$^3$ ORTEC Ge(Li) detector and associated electronics.

2.4 Formulation

As a nuclear particle gets into close contact with another nucleus the incident particle and the target nucleus forms a composite system in excited state and after a short while a reaction is produced. Similarly, a beam of alpha-particle is allowed to irradiate the target and nuclear reaction takes place, resulting in the emission of some particles and the residual nucleus. This residual nucleus which is in the excited state, may decay through its characteristic gamma-rays.

If $\sigma_r$ is the reaction cross section, $N_0$ is the number of target nuclei, $\Phi$ is the incident alpha particle flux, $\lambda$ is the decay constant and $t_1$ is the time of irradiation of the target, then the disintegration rate of the activity induced in the target after time $t_1$, may be given by the following expression:

$$\frac{\sigma_r \Phi N_0 [1-\exp(-\lambda t_1)]}{[\exp (\lambda t)]} = \frac{dn}{dt} \quad \ldots \quad (1)$$
The disintegration in the small time interval 'dt' can be written as,

\[ \sigma^r \int N_o \left[ 1 - \exp(-\lambda t_1) \right] / \left[ \exp(\lambda t) \right] dt = dn \quad \ldots (2) \]

If 't_2' seconds is the time lapsed between the stop of irradiation and start of counting and 't_3' seconds is the counting time of 'gamma-rays' emitted from the irradiated target, and if \( D_o \) be the actual number of disintegrations from the radioactive sample recorded in 't_3' seconds, thus,

\[ \int dn = D_o \quad \ldots \quad (3) \]

Therefore,

\[ \sigma^r \int N_o \left[ 1 - \exp(-\lambda t_1) \right] \int_{t_1}^{t_3+t_2} \exp(-\lambda t) dt = D_o \]

So

\[ \sigma^r \int N_o \left[ 1 - \exp(-\lambda t_1) \right] \left[ 1 - \exp(-\lambda t_3) \right] / \lambda \exp(\lambda t_2) = D_o \quad \ldots (4) \]

If \( \lambda \) is the number of counts under the particular photopeak as detected by the detector, \((E \Theta)\) is the geometry dependent efficiency of Ge(Li) detector, \( \Theta \) is the absolute intensity of the characteristic gamma-ray and \( K \) is the self-absorption correction factor, then the actual number of disintegration can be written as,

\[ \frac{\lambda}{(E \Theta) \Theta \cdot K} = D_o \quad \ldots \quad (5) \]
From equations (4) and (5) we get the present experimental reaction cross-section formula:

\[
\sigma_r = \frac{\lambda \exp (\lambda t_2)}{N_0 \int_0^\infty \theta \exp (-\lambda t_1) [1-\exp (-\lambda t_3)]} \quad \ldots (6)
\]

2.5 Errors in the Measurements

Analyses of errors in the experimental measurements is necessary in order to make the experimental data more reliable, because no experiment can be performed with 100% accuracy. The various factors likely to introduce errors are chemical and spectroscopic impurities in the specimen, the detector efficiency due to the statistical errors of counting of standard source, the uncertainty due to the solid angle effect due to non-reproducability of identical geometries for the standard source and the irradiated samples, the variation of beam current which results in the uncertainty of the incident flux. In certain cases, where intensity of activities produced in the irradiated samples were large, the dead time of the detector may also introduce uncertainty in the measured cross-section. The uncertainty in the measured cross-sections are also due to the errors in the estimation of target nuclei in the sample. The additional uncertainties in measured cross-sections are due to recoiling of the nuclei of the sample. The low energy neutrons which are produced when the beam traverses the
stack material may also disturb the yield.

Analyses for the above mentioned factor, expected to introduce errors, have been done. The uncertainty in the detector efficiency due to the statistical errors of counting, is estimated to be $< 1.5 \%$. Since the irradiated targets were not point sources the uncertainty due to solid angle is estimated using the prescription given by Gardner et. al. $^{(3)}$, and is found to be $< 1 \%$. Therefore, the total uncertainty in the efficiency is estimated to be $< 1.5 \%$. In order to incorporate the current fluctuation in the incident beam, at every five minutes interval, the current was noted down and the average current was taken for flux calculation. Moreover, the measurement of flux was also done by charge collection method using Faraday's cup. The uncertainty due to flux variation is $< 4 \%$. In order to minimise the errors due to the dead time, particularly for the cases where the activity in the irradiated samples were large, the sample-detector distance was suitably adjusted to keep the dead time $< 10 \%$. However, the corrections were applied in the counting rates accordingly. In order to estimate the uncertainty in the number of target nuclei and to check the thickness and uniformity of the target, pieces of target foils were weighted on an electronic microbalance and the thickness of each piece was calculated. The errors in the estimation of number of target nuclei were analysed in
this way and are estimated to be $< 1\%$.

To avoid the uncertainty due to recoiling of the nuclei out of the sample, the targets were placed perpendicular to the incident alpha-beam such that sample deposition faced the incident beam. As such, the recoiling nuclei are likely to be trapped in the aluminium backing, hence no correction is applied for that. As the beam traverses the stack material, low energy neutrons may be released which in turn may disturb the yield. However, Ernst et. al\(^{4}\) have indicated that such disturbing yield are also negligible.

The overall error due to all these factors (efficiency, flux variation and number of target nuclei) as mentioned above, is expected to be $< 12\%$. The errors mentioned in the cross-section in Table 2.7(b)-2.27(b) and Tables 5.1.1 - 5.1.9 are the overall errors including the statistical errors of counting and are generally $< 20\%$ except for few points. These errors does not include the uncertainty of the nuclear spectroscopic data such as the branching ratios the decay constants etc., which are taken from the Table of Isotopes and the Nuclear Data Sheets.

There are always some error associated with the uncertainty in the $\alpha$-particle incident energy. There are two factors responsible for the energy spread. (i) the inherent uncertainty in the energy of $\alpha$-particle beam, (ii)
the energy spread due to the thickness of the target. This first factor gives the energy spread of 0.5 MeV at 50 MeV \( \alpha \)-particle energy, however, the contribution of the second factor is very small and found to be lying between 0.1 % and 0.2 % depending upon the \( \alpha \)-particle energy in the present work.

2.6 Measurements

The excitation functions for the reactions \( ^{103} \text{Rh} (\alpha, n) \), \( ^{106} \text{Ag} \), \( ^{103} \text{Rh} (\alpha, 2n) \), \( ^{105} \text{Ag} \), \( ^{103} \text{Rh} (\alpha, 3n) \), \( ^{104} \text{Ag} \), \( ^{127} \text{I} (\alpha, 2n) \), \( ^{129} \text{Cs} \), \( ^{127} \text{I} (\alpha, 4n) \), \( ^{127} \text{Cs} \), \( ^{133} \text{Cs} (\alpha, 2n) \), \( ^{135} \text{La} \), \( ^{133} \text{Cs} (\alpha, 4n) \), \( ^{133} \text{La} \), \( ^{79} \text{Br} (\alpha, n) \), \( ^{82} \text{Rb} + ^{81} \text{Br} (\alpha, 3n) \), \( ^{82} \text{Rb} \), \( ^{79} \text{Br} (\alpha, 2n) \), \( ^{81} \text{Rb} + ^{81} \text{Br} (\alpha, 4n) \), \( ^{81} \text{Rb} \), \( ^{79} \text{Br} (\alpha, 2n) \), \( ^{81} \text{Rb} \), \( ^{81} \text{Br} (\alpha, 4n) \), \( ^{81} \text{Rb} \), \( ^{203} \text{Tl} (\alpha, n) \), \( ^{206} \text{Bi} + ^{205} \text{Tl} (\alpha, 3n) \), \( ^{206} \text{Bi} \), \( ^{203} \text{Tl} (\alpha, n) \), \( ^{205} \text{Bi} + ^{205} \text{Tl} (\alpha, 4n) \), \( ^{205} \text{Bi} \), \( ^{203} \text{Tl} (\alpha, 2n) \), \( ^{203} \text{Tl} (\alpha, 3n) \), \( ^{204} \text{Bi} \), \( ^{203} \text{Tl} (\alpha, 4n) \), \( ^{203} \text{Bi} \), \( ^{141} \text{Pr} (\alpha, n) \), \( ^{144} \text{Pm} \), \( ^{141} \text{Pr} (\alpha, 2n) \), \( ^{143} \text{Pm} \) have been measured experimentally using stacked foil activation technique. The excitation functions for the individual reactions \( ^{79} \text{Br} (\alpha, 2n) \), \( ^{81} \text{Rb} \), \( ^{81} \text{Br} (\alpha, 4n) \), \( ^{81} \text{Rb} \), \( ^{203} \text{Tl} (\alpha, n) \), \( ^{206} \text{Bi} \), \( ^{205} \text{Tl} (\alpha, 3n) \), \( ^{206} \text{Bi} \), \( ^{203} \text{Tl} (\alpha, 2n) \), \( ^{205} \text{Bi} \) and \( ^{205} \text{Tl} (\alpha, 4n) \) have been deduced using theoretical calculations from the respective composite reactions \( ^{79} \text{Br} (\alpha, 2n) + ^{81} \text{Br} (\alpha, 4n) \), \( ^{81} \text{Rb} \), \( ^{203} \text{Tl} (\alpha, n) \), \( ^{206} \text{Bi} \), \( ^{205} \text{Tl} (\alpha, 3n) \), \( ^{206} \text{Bi} \) and \( ^{203} \text{Tl} (\alpha, 2n) \), \( ^{205} \text{Bi} \), \( ^{205} \text{Tl} (\alpha, 4n) \), \( ^{205} \text{Bi} \), as the product nuclide is same.
But in the case of $^{79}$Br ($\alpha$,n) $^{82}$Rb + $^{81}$Br ($\alpha$,3n) $^{82}$Rb no separate cross-sections could be deduced because of no provision of isomeric state cross-section calculation in the ALICE/LIVERMORE-82 Code. Experiments have been carried out using the alpha-beams of Variable Energy Cyclotron Centre (VEGC) Calcutta, India.

In the present work various reactions induced by alpha particles on $^{103}$Rh, $^{127}$I, $^{133}$Cs, $^{79,81}$Br, $^{203,205}$Tl and $^{141}$Pr were measured by detecting the characteristic gamma-rays obtained from the decay of Ag, Cs, La, Rb, Bi and Pm residual nuclides respectively. The partial decay scheme of the residual nuclides are given in figures 2.7 - 2.21. The typical gamma-ray spectra of targets irradiated by alpha particle beam at particular energy are shown in Figs. 2.22 - 2.26.

2.6.1 Target Nucleus $^{103}$Rh

The excitation functions for the reactions $^{103}$Rh (,$\alpha$,n) $^{106}$Ag, $^{103}$Rh ($\alpha$,2n) $^{105}$Ag and $^{103}$Rh ($\alpha$,3n) $^{104}$Ag have been measured experimentally in the energy range from 13.59$\pm$0.62 MeV to 39.88$\pm$0.56 MeV.

In the case of ($\alpha$,n) reaction, the Q-value is -6.7 MeV. In this reaction, two isomers of $^{106}$Ag are produced having half-lives 8.4 days and 24.1 min. To study this reaction, we followed the gamma-rays of 430 KeV, 451 KeV,
Fig. 2.7 Partial decay schemes of the isomer of $^{106}$Ag produced by the reaction $^{103}$Rh ($\alpha$,n) reaction.
Fig. 2.8 Partial decay schemes of the isomer of $^{105}$Ag produced by the reaction $^{103}\text{Rh} (\alpha, 2n)$ reaction.
Fig. 2.5 Partial decay schemes of the isomer of $^{104}$Ag produced by the reaction $^{103}$Rh ($\alpha$,3$n$) reaction.
Fig. 2.10 Partial decay schemes of the isomer of $^{129}\text{Cs}$ produced by the reaction $^{127}\text{I (}\alpha, 2\text{n)}$ reaction
Fig. 2.11 Partial decay schemes of the isomer of $^{127}$Cs produced by the reaction $^{121}$I ($\alpha$,4n) reaction
Fig. 2.12 Partial decay schemes of the isomer of $^{135}$La produced by the reaction $^{133}$Cs ($\alpha,2n$) reaction
Fig. 2.13 Partial decay schemes of the isomer of $^{133}$La produced by the reaction $^{133}$Cs ($\alpha,4n$) reaction.
Table and text:

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Fig. 2.14 Partial decay schemes of the isomer of $^{82m}$Rb produced by the reaction $^{79}$Br (α,n) reaction.
Fig. 2.15 Partial decay schemes of the isomer of $^{81}$Rb produced by the reaction $^{79}$Br ($\alpha$,2n) reaction.
Fig. 2.16 Partial decay schemes of the isomer of $^{206}$Bi Produced by the reaction $^{203}$Tl (α,n) reaction
Fig. 2.17 Partial decay schemes of the isomer of $^{205}$Bi produced by the reaction $^{203}$Tl ($\alpha$,2n) reaction.
Fig. 2.18 Partial decay schemes of the isomer of $^{204}\text{Bi}$ produced by the reaction $^{203}\text{TI} (\alpha, 3n)$ reaction.
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Fig. 2.19 Partial decay schemes of the isomer of $^{203}\text{Bi}$ produced by the reaction $^{203}\text{Tl} (\alpha,4n)$ reaction
Fig. 2.20 Partial decay schemes of the isomer of $^{144}\text{Pm}$ produced by the reaction $^{141}\text{Pr} (\alpha, n)$ reaction
Fig. 2.21 Partial decay schemes of the isomer of $^{143}\text{Pm}$ produced by the reaction $^{141}\text{Pr (n,2n)}$ reaction
Fig. 2.22 Typical $\gamma$-ray Spectrum obtained by irradiation of $^{103}$Rh target with $\alpha$-particle beam
Fig. 2.23 Typical γ-ray Spectrum obtained by
irradiation of CsI target with
α-particle beam
Fig. 2.24 Typical γ-ray Spectrum obtained by irradiation of KBr target with α-particle beam
Fig. 2.25 Typical $\gamma$-ray Spectrum obtained by irradiation of TlCl target with $\alpha$-particle beam
Fig. 2.26 Typical $\gamma$-ray Spectrum obtained by irradiation of Pr$_6$O$_{11}$ target with $\alpha$-particle beam
616 KeV, 717 KeV, 748 KeV, 804 KeV, 825 KeV, 1046 KeV and 1128 KeV energy corresponding to 8.4 days isomeric state. In this reaction only isomeric state cross-sections have been measured because the 24.1 min. ground state decays only through 512 KeV gamma-rays which always interfere with the annihilation peak of 511 KeV gamma-rays hence excluded. The weighted average cross-section corresponding to various gamma-rays at different energies are given in Table 2.7(b).

In the case of ($\alpha$,2n) reaction, the Q-value is -14.70 MeV. In this reaction, two isomers of $^{105}$Ag are also produced having their half-lives 41.3 days and 7.2 min. To study this reaction we followed the gamma-rays of 281 KeV, 345 KeV, 443 KeV, 645 KeV and 1088 KeV energies corresponding to the decay of 41.3 days ground state of $^{105}$Ag. The gamma-ray of 319 KeV corresponding to the isomeric state of $^{105}$Ag with half-life 7.2 min, was allowed to decay to the ground state of $^{105}$Ag (with 99.7 % of isomeric transition), for enough time about ten half-lives of isomeric state) until all the isomeric transitions are decayed to ground state of $^{105}$Ag so that the total cross-section could have been measured. The weighted average cross-sections are given in Table 2.8(b).

In the case of ($\alpha$,3n) reaction, the Q-value is -24.50 MeV. In this reaction, two isomers of $^{104}$Ag are produced
having half-lives 33.5 min. and 1.15 hours. To study this reaction we followed the gamma-rays of 444 KeV, 624 KeV, 741 KeV, 768 KeV, 858 keV, and 942 KeV corresponding to the decay of the ground state of $^{104}$Ag with half-life 1.15 hours, while 1238 KeV gamma-ray corresponding to 33.5 min. half-life was followed for the isomeric state cross-section measurement. The total measured cross-sections at different incident alpha-particle energy has also been shown in Table 2.9(b).

2.6.2 Target Nucleus $^{127}$I

The excitation functions for the reactions $^{127}$I ($\alpha$,2n) $^{129}$Cs, $^{127}$I ($\alpha$,4n) $^{127}$Cs have been measured experimentally in the energy range from 18.06 ± 0.57 MeV to 49.93 ± 0.53 MeV.

In the case of ($\alpha$,2n) reaction, the Q-value is -15.3 MeV. To study this reaction we followed the gamma-rays of 177 keV, 279 keV, 318 eV, 372 keV, 412 keV, 549 keV and 589 KeV energy corresponding to 1.34 days half-life. The weighted average cross-section corresponding to different gamma-rays at different energies are given in Table 2.10(b).

In the case of ($\alpha$,4n) reaction, the Q-value is -32.6 MeV. To study this reaction we followed the gamma-rays of 125 keV, 321 keV, 412 keV, 462 keV, 1197 keV and 1307 keV energy corresponding to 6.25 hours half-life. The weighted
average cross-section corresponding to various gamma-rays at different energies are given in Table 2.11(b).

In the present measurement, excitation function for $^{127}_{}I (\alpha,n) ^{130}_{}Cs$, $^{127}_{}I (\alpha,3n) ^{128}_{}Cs$ reactions could not be measured due to short half-lives of the product nuclei. However, the residual nuclei produced in these reactions are also involved in the successive evaporation chain of the other reactions for which excitation functions are measured presently.

2.6.3 Target Nucleus $^{133}_{}Cs$

The excitation functions for the reactions $^{133}_{}Cs(\alpha,2n)$, $^{135}_{}La$ and $^{133}_{}Cs (\alpha,4n) ^{133}_{}La$ have been measured experimentally in the energy range from $18.06 \pm 0.57$ MeV to $47.50 \pm 0.53$ MeV.

In the case of $(\alpha,2n)$ reaction, the Q-value is $-15.0$ MeV. To study this reaction we followed the gamma-ray of $481$ KeV energy corresponding to $19.48$ hours half-life. The weighted average cross-section corresponding to the above gamma-ray at different energies are given in Table 2.12(b).

In the case of $(\alpha,4n)$ reaction the Q-value is $-32.5$ MeV. To study this reaction we followed the gamma-rays of $279$ KeV, $302$ KeV, $565$ KeV, $618$ KeV, $622$ KeV, $846$ KeV energy corresponding to $3.90$ hours half-life. The weighted average
cross-section corresponding to various gamma-rays at different energies are given in Table 2.13(b).

In the present measurement the excitation functions for $^{133}\text{Cs} (\alpha,n) ^{136}\text{La}$ and $^{133}\text{Cs} (\alpha,3n) ^{134}\text{La}$ reaction could not be measured due to short half-lives of the product nuclei. However, the residual nuclei produced in these reactions are also involved in the successive evaporation chain of the other reactions for which excitation functions are measured presently.

2.6.4 Target Nucleus $^{79,81}\text{Br}$

The excitation functions for the reactions $^{79}\text{Br} (\alpha,n) ^{82m}\text{Rb} + ^{81}\text{Br} (\alpha,3n) ^{82m}\text{Rb}$ and $^{79}\text{Br} (\alpha,2n) ^{81}\text{Rb} + ^{81}\text{Br} (\alpha,4n) ^{81}\text{Rb}$ have been measured experimentally in the energy range from $11.93 \pm 0.68$ MeV to $49.85 \pm 0.57$ MeV.

In the case of $^{79}\text{Br} (\alpha,n) ^{82m}\text{Rb} + ^{81}\text{Br} (\alpha,3n) ^{82m}\text{Rb}$ pair, reactions could not be deduced because of non-availability of isomeric state theoretical cross-section calculations. The Q-value of this reaction are $-5.5$ MeV and $-23.6$ MeV. To study this reaction we followed the gamma-rays of 554 keV, 619 keV, 648 keV, 777 keV, 1008 keV, 1044 keV, 1317 keV and 1475 keV energy corresponding to 6.47 hours half-life. The weighted average cross-section corresponding to the above gamma-ray at different energies are given in Table 2.14(b).
In the case of $^{79}\text{Br} (\alpha,2n) ^{81}\text{Rb} + ^{81}\text{Br} (\alpha,4n) ^{81}\text{Rb}$ reaction the Q-value is -14.4 MeV and -32.4 MeV. To study this reaction we followed the gamma-rays of 190 keV and 446 keV energy corresponding to 4.58 hours half-life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.15(b).

In the case of $^{79}\text{Br} (\alpha,2n) ^{81}\text{Rb}$ reaction the Q-value is -14.4 MeV. To study this reaction we followed the gamma-rays of 190 keV, and 446 keV energies corresponding to 4.58 hours half-life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.16(b).

In the case of $^{81}\text{Br} (\alpha,4n) ^{81}\text{Rb}$ reaction the Q-value is -32.4 MeV. To study this reaction we followed the gamma-rays of 190 keV and 446 keV energy corresponding to 4.58 hours half-life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.17(b).

The excitation functions for $^{79}\text{Br} (\alpha,2n) ^{81}\text{Rb}$ and $^{81}\text{Br} (\alpha,4n) ^{81}\text{Rb}$ have been deduced using theoretical calculations from the combined reaction of $^{79}\text{Br} (\alpha,4n) ^{81}\text{Rb} + ^{81}\text{Br} (\alpha,4n) ^{81}\text{Rb}$. 
2.6.5 Target Nucleus $^{203, 205}$\textsubscript{Tl}

The excitation functions for the reactions $^{203}$\textsubscript{Tl} ($\alpha$,n) $^{206}$\textsubscript{Bi} + $^{205}$\textsubscript{Tl} ($\alpha$,3n) $^{206}$\textsubscript{Bi}, $^{203}$\textsubscript{Tl} ($\alpha$,2n) $^{205}$\textsubscript{Bi} + $^{205}$\textsubscript{Tl} ($\alpha$,4n) $^{207}$\textsubscript{Bi}, $^{203}$\textsubscript{Tl} ($\alpha$,3n) $^{204}$\textsubscript{Bi} and $^{203}$\textsubscript{Tl} ($\alpha$,4n) $^{203}$\textsubscript{Bi} have been measured experimentally in the energy range from 22.29 ± 0.70 MeV to 49.76 ± 0.61.

In the case of $^{203}$\textsubscript{Tl} ($\alpha$,n) $^{206}$\textsubscript{Bi} + $^{205}$\textsubscript{Tl} ($\alpha$,3n) $^{206}$\textsubscript{Bi} reaction the Q-values are -11.3 MeV and -25.5 MeV. To study this reaction we followed the gamma-rays of 344 keV, 497 keV, 537 keV, 803 keV, 881 keV, 1019 keV, 1098 keV and 1719 keV energy corresponding to 6.24 days half-life. The weighted average cross-sections corresponding to the above gamma-rays at different energies are given in Table 2.18(b).

In the case of $^{203}$\textsubscript{Tl} ($\alpha$,n) $^{206}$\textsubscript{Bi} reaction the Q-value is -11.3 MeV. To study this reaction we followed the gamma-rays of 344 keV, 497 keV, 537 keV, 803 keV, 881 keV, 1019 keV, 1098 keV and 1719 keV energy corresponding to 6.24 days half-life. The weighted average cross-sections corresponding to the above gamma-rays at different energies are given in Table 2.19(b).

In the case of $^{205}$\textsubscript{Tl} ($\alpha$,3n) $^{206}$\textsubscript{Bi} reaction the Q-value is -25.5 MeV. To study this reaction we followed...
the gamma-rays of 344 keV, 497 keV, 537 keV, 803 keV, 881 keV, 1019 keV, 1098 keV and 1719 keV energy corresponding to 6.24 days half-life. The weighted average cross-sections corresponding to the above gamma-rays at different energies are given in Table 2.20(b).

The excitation functions for $^{203}$Tl $(\alpha,n)\;^{206}$Bi and $^{205}$Tl $(\alpha,3n)\;^{206}$Bi have been deduced using theoretical calculations from the combined reaction of $^{203}$Tl $(\alpha,n)\;^{206}$Bi + $^{205}$Tl $(\alpha,3n)\;^{206}$Bi.

In the case of $^{203}$Tl $(\alpha,2n)\;^{205}$Bi + $^{205}$Tl $(\alpha,4n)\;^{205}$Bi reaction the Q-values are $-18.4$ MeV and $-32.6$ MeV. To study this reaction we followed the gamma-ray of 704 keV energy corresponding to 51.31 days half-life. The weighted average cross-section corresponding to the above gamma-ray at different energies is given in Table 2.21(b).

In the case of $^{203}$Tl $(\alpha,2n)\;^{205}$Bi reaction the Q-value is $-18.4$ MeV. To study this reaction we followed the gamma-ray of 704 keV energy corresponding to 15.31 days half life. The weighted average cross-section corresponding to the above gamma-ray at different energies is given in Table 2.22(b).

In the case of $^{205}$Tl $(\alpha,4n)\;^{205}$Bi reaction the Q-value is $-32.6$ MeV. To study this reaction we followed
the gamma-ray of 704 keV energy corresponding to 15.31 days half-life. The weighted average cross-section corresponding to the above gamma-ray at different energies are given in Table 2.23(b).

The excitation functions for $^{203}$Tl ($\alpha, 2n$) $^{205}$Bi and $^{205}$Tl ($\alpha, 4n$) $^{205}$Bi have been deduced using theoretical calculations from the combined reaction of $^{203}$Tl ($\alpha, 2n$) $^{205}$Bi + $^{205}$Tl ($\alpha, 4n$) $^{205}$Bi.

In the case of $^{203}$Tl ($\alpha, 3n$) $^{204}$Bi reaction the Q-value is -27.4 MeV. To study this reaction we followed the gamma-rays of 375 keV, 671 keV and 948 keV energy corresponding to 11.20 hours half-life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.24(b).

In the case of $^{203}$Tl ($\alpha, 4n$) $^{203}$Bi reaction the Q-value is -34.0 MeV. To study this reaction we followed the gamma-ray of 820 keV energy corresponding to 11.76 hours half-life. The weighted average cross-section corresponding to the above gamma-ray at different energies are given in Table 2.25(b).

2.6.6 Target Nucleus $^{141}$Pr

The excitation functions for the reactions $^{141}$Pr ($\alpha, n$) $^{144}$Pm and $^{141}$Pr ($\alpha, 2n$) $^{143}$Pm have been measured
experimentally in the energy range from $18.71 \pm 0.94$ MeV to $44.57 \pm 0.72$ MeV.

In the case of $^{141}\text{Pr} (\alpha, n) ^{144}\text{Pm}$ reaction the Q-value is $-10.3$ MeV. To study this reaction we followed the gamma-rays of 477 keV, 618 keV and 697 keV energy corresponding to 363 days half-life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.26 (b).

In the case of $^{141}\text{Pr} (\alpha, 2n) ^{143}\text{Pm}$ reaction, the Q-value is $-16.8$ MeV. To study this reaction we followed the gamma ray of 742 keV energy corresponding to 265 days half life. The weighted average cross-section corresponding to the above gamma-rays at different energies are given in Table 2.27(b).

In the present measurement alpha induced reaction cross-sections have been calculated by using the following expression

$$\sigma = \frac{A \lambda \exp (\lambda t_2)}{N_0 \phi(E) \Theta K [1-\exp(-\lambda t_1)][1-\exp(-\lambda t_3)]}$$

Where $A$ is the total number of counts under the photopeak of characteristic $\gamma$-rays, recorded in time $t_3$, is the decay constants of the product nucleus, $N_0$ is the number
of nuclei of the isotope under investigation, present in the sample, \( \phi \) is the average flux of the incident, \( \alpha \)-particle beam, \((G)\) is the geometry dependent efficiency of the detector, \( \mathcal{I} \) is the absolute intensity of the characteristic \( \gamma \)-ray, \( K \) is the correction for the self-absorption of gamma ray in the sample, \( t_1 \) is the time of irradiation, \( t_2 \) is the time elapsed between stop of irradiation and start of counting and \( t_3 \) is the counting time.

In the following Tables 2.7 - 2.27 the numerical values of the parameters used for the present activation cross-sections measurements are listed. The weighted average measured cross-sections have been listed in the last column of each Table.
Table 2.7(a)

**Activation crosssection for $^{103}$Rh($\alpha$,n) $^{106m}$Ag**

$\lambda = 9.5486 \times 10^7 \text{ sec}^{-1}$

$\tau_1 = 4932 \text{ Sec}$

$N_0 = 4.01678 \times 10^{18}$

$\phi = 6.7562 \times 10^{11} \alpha$-particles/cm$^2$-Sec

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Table 2.8 (a)

Activation crosssection for $^{103}$Rh(\(\alpha\),2n) $^{105}$Ag

\[ \lambda = 1.9426 \times 10^{-7}\text{ Sec}^{-1} \]

\[ t_1 = 4932\text{ Sec} \]

\[ N_0 = 4.01678 \times 10^{18} \]

\[ \Phi = 6.7562 \times 10^{11} \alpha\text{-particles/cm}^2\text{ Sec} \]

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Table 2.9(a)

Activation crosssection for $^{103}\text{Rh}(\alpha,3n)^{104}\text{Ag}$

$$
\lambda = 1.6696 \times 10^4\, \text{(iso)} & 3.4478 \times 10^4\, \text{(ground)} \, \text{Sec}^{-1}
$$

$$
t_1 = 4932 \, \text{Sec}
$$

$$
N_0 = 4.01678 \times 10^{18}
$$

$$
\Phi = 6.7562 \times 10^{11} \, \alpha\text{-particles/\text{cm}^2\text{-Sec}}
$$

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Table 2.10(a)

Activation crosssection for $^{127}\text{I}(\alpha,2n)^{129}\text{Cs}$

$\lambda = 5.9857 \times 10^6 \text{ Sec}^{-1}$

$t_1 = 7308 \text{ Sec}$

$N_0 = 1.28332 \times 10^{18}$

$\phi = 8.04035 \times 10^{11} \alpha\text{-particles/cm}^2\cdot\text{Sec}$

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Table 2.11(a)

Activation crosssection for $^{122}$I($\alpha$,4n) $^{127}$Cs

$\lambda = 3.08 \times 10^{-5}$ Sec$^{-1}$

$t_1 = 7308$ Sec

$N_0 = 1.28332 \times 10^{18}$

$\phi = 8.04035 \times 10^{11} \alpha$-particles/cm$^2$-Sec

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Table 2.12(a)

Activation crosssection for $^{133}\text{Cs}(\alpha,2n)^{135}\text{La}$

$\lambda = 9.7222 \times 10^{-6} \text{ Sec}^{-1}$

$t_1 = 7308 \text{ Sec}$

$N_0 = 1.28337 \times 10^{18}$

$\phi = 8.04035 \times 10^{11} \alpha - \text{particles/cm}^2\cdot\text{Sec}$

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**Table 2.13(a)**

Activation crosssection for $^{133}\text{Cs}(\alpha,4n)^{135}\text{La}$

\[
\lambda = 4.9208 \times 10^{-5} \text{Sec}^{-1}
\]

\[t_1 = 7308 \text{ Sec}\]

\[N_0 = 1.28337 \times 10^{18}\]

\[\Omega = 8.04035 \times 10^{11} \alpha-\text{particles/cm}^2-\text{Sec}\]

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Table 2.14(a)

Activation cross-section for

\[ ^{79}\text{Br} (\alpha,n) ^{82}\text{m}_{\text{Rb}} + ^{81}\text{Br} (\alpha,3n) ^{82}\text{m}_{\text{Rb}} \]

\[ \lambda = 2.8378 \times 10^{-5} \text{ Sec}^{-1} \]

\[ t_1 = 7500 \text{ Sec} \]

\[ N_0 = 1.49764 \times 10^{18} \]

\[ \phi = 35.6253 \times 10^{11} \text{ \alpha-particles/cm}^2 \text{-Sec} \]

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Table 2.15(a)

Activation cross section for $^{79}$Br($\alpha$,2n) $^{81}$Rb + $^{81}$Br ($\alpha$,4n) $^{81}$Rb

$\lambda = 3.8758 \times 10^{-5}$ Sec$^{-1}$

$t_1 = 7500$ Sec

$N_0 = 1.49764 \times 10^{18}$

$\Phi = 35.6253 \times 10^{11}$ $\alpha$-particles/cm$^2$-Sec

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\[ t_1 = 12900 \text{ sec} \]
\[ N_0 = 1.49764 \times 10^{18} \]
\[ \phi = 16.5296 \times 10^{11} \text{ } \alpha\text{-particles/cm}^2 \text{ } \text{sec} \]

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Table 2.16(a)

Activation crosssection for $^7\text{Br}$(α,2n) $^8\text{Rb}$

\[ \lambda = 3.8758 \times 10^{-5} \text{ Sec}^{-1} \]
\[ t_1 = 7500 \text{ Sec} \]
\[ N_0 = 1.49764 \times 10^{18} \]
\[ \phi = 16.5296 \times 10^{11} \alpha \text{-particles/cm}^2\text{-Sec} \]

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Table 2.17(a)

Activation crosssection for $^{81}$Br($\alpha$,4n) $^{81}$Rb $^{81}$Rb

\[ \lambda = 3.8758 \times 10^{-5} \text{ Sec}^{-1} \]

\[ t_1 = 7500 \text{ Sec} \]

\[ N_0 = 1.42089 \times 10^{18} \]

\[ \phi = 16.5296 \times 10^{11} \alpha\text{-particles/cm}^2\text{-Sec} \]

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Table 2.18(a)

Activation crosssection for

\[ ^{203}_{\text{Tl}}(\alpha, n) \rightarrow ^{206}_{\text{Bi}} + ^{205}_{\text{Tl}}(\alpha, 3n) \rightarrow ^{206}_{\text{Bi}} \]

\[ \lambda = 1.2801 \times 10^{-6} \text{ Sec}^{-1} \]

\[ t_1 = 11700 \text{ Sec} \]

\[ N_0 = 1.4894 \times 10^{18} \]

\[ \Phi = 10.8921 \times 10^{11} \alpha\text{-particles/cm}^2\text{-Sec} \]

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Table 2.19(a)

Activation crosssection for 
\( ^{203} \text{Tl}(\alpha, n) ^{206} \text{Bi} \)

\[ \lambda = 1.2801 \times 10^{-6} \text{ Sec}^{-1} \]
\[ t_1 = 11700 \text{ Sec} \]
\[ N_0 = 1.4894 \times 10^{18} \]
\[ \phi = 10.8921 \times 10^{11} \text{ \( \alpha \)-particles/cm}^2\text{-Sec} \]

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\[ t_1 = 10860 \text{ Sec} \]

\[ N_0 = 1.4894 \times 10^{18} \]

\[ \Phi = 9.7632 \times 10^{11} \text{ } \alpha \text{-particles/cm}^2 \text{ - Sec} \]

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|                | 803          | 0.989 | 0.0034  | 1262| 19.00       |              |
|                | 881          | 0.662 | 0.0031  | 771 | 19.00       |              |
|                | 1019         | 0.076 | 0.0027  | 77  | 19.00       |              |
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Table 2.20(a)

Activation crosssection for

\( {^{205}}\text{Tl}(\alpha, 3n) {^{206}}\text{Bi} \)

\[ \lambda = 1.2801 \times 10^{6} \text{ Sec}^{-1} \]

\[ t_1 = 10860 \text{ Sec} \]

\[ N_0 = 3.5247 \times 10^{18} \]

\[ \phi = 9.7632 \times 10^{11} \text{ } \alpha-\text{particles/cm}^2\text{-Sec} \]

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Table 2.20(b)

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### Table 2.21(a)

Activation crosssection for $^{203}\text{Tl}(\alpha,2n)^{205}\text{Bi}$

\[ \lambda = 5.2348 \times 10^{-7} \text{ Sec}^{-1} \]

\[ t_1 = 11700 \text{ Sec} \]

\[ N_0 = 1.4894 \times 10^{18} \]

\[ \Phi = 10.8921 \times 10^{11} \alpha\text{-particles/cm}^2\text{-Sec} \]

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\[ \lambda = 5.2348 \times 10^{-7} \text{ Sec}^{-1} \]

\[ t_1 = 10860 \text{ Sec} \]

\[ N_0 = 1.4894 \times 10^{18} \]

\[ \Phi = 9.7632 \times 10^{11} \alpha\text{-particles/cm}^2\text{-Sec} \]

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Table 2.22(a)

Activation crosssection for $^{203}$Tl($\alpha,2n$) $^{205}$Bi

$\lambda = 5.2348 \times 10^{-7}$ Sec$^{-1}$

$t_1 = 11700$ Sec

$N_0 = 1.4894 \times 10^{18}$

$\phi = 10.8921 \times 10^{11}$ $\alpha$-particles/cm$^2$-Sec

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\[ \lambda = 5.2348 \times 10^{-7}\text{ Sec}^{-1} \]
\[ t_1 = 10860\text{ Sec} \]
\[ N_0 = 1.4894 \times 10^{18} \]
\[ \phi = 9.7632 \times 10^{11} \text{ } \alpha\text{-particles/cm}^2\text{-Sec} \]

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<th>(\bar{\sigma}_T) (mb)</th>
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<tr>
<td>29.04 ± 0.67</td>
<td>704</td>
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<td>0.0038</td>
<td>6415</td>
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<td>614.18</td>
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<tr>
<td>31.94 ± 0.66</td>
<td>704</td>
<td>0.311</td>
<td>0.0021</td>
<td>1947</td>
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<td>186.18</td>
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<tr>
<td>34.35 ± 0.65</td>
<td>704</td>
<td>0.311</td>
<td>0.0021</td>
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<td>0.0021</td>
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<td>0.0021</td>
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<td>65.00</td>
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Table 2.22(b)

<table>
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<tr>
<th>E_{\alpha} (MeV)</th>
<th>^{203}\text{Tl}(\alpha,2n)^{205}\text{Bi} Cross-section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.34 ± 0.68</td>
<td>475.1 ± 60.3</td>
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<td>614.2 ± 88.4</td>
</tr>
<tr>
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<td>186.2 ± 38.9</td>
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<td>94.4 ± 36.1</td>
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<td>120.0 ± 16.6</td>
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<tr>
<td>39.72 ± 0.64</td>
<td>88.0 ± 20.7</td>
</tr>
<tr>
<td>42.68 ± 0.63</td>
<td>65.0 ± 8.2</td>
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</tr>
<tr>
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<td>41.0 ± 5.0</td>
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</table>
Table 2.23(a)

Activation crosssection for $^{205}_{\text{Tl}}(\alpha,4n)\ ^{205}_{\text{Bi}}$

$\lambda = 5.2348 \times 10^{-7} \text{ Sec}^{-1}$

$t_1 = 10860 \text{ Sec}$

$N_0 = 3.5247 \times 10^{18}$

$\phi = 9.7632 \times 10^{11} \alpha$-particles/cm$^2$.Sec

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$E_\gamma$ (keV)</th>
<th>$\theta$</th>
<th>$\epsilon_G$</th>
<th>$\lambda$ (mb)</th>
<th>$\sigma_T$ (mb)</th>
<th>$\bar{\sigma_T}$ (mb)</th>
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Table 2.23(b)

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Table 2.24(a)

Activation crosssection for $^{203}$Tl($\alpha,3n$) $^{204}$Bi

$\lambda = 1.69351 \times 10^5$ Sec$^{-1}$

$t_1 = 10860$ Sec

$N_0 = 1.4894 \times 10^{18}$

$\Phi = 9.7632 \times 10^{11} \alpha$-particles/cm$^2$-Sec

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<th>$E_\gamma$ (keV)</th>
<th>$\Theta$</th>
<th>$E_G$</th>
<th>$\lambda$ (mb)</th>
<th>$\sigma^\alpha$ (mb)</th>
<th>$\bar{\sigma}^\alpha$ (mb)</th>
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<tbody>
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<th>$\Lambda$</th>
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<th>$\sigma_T$ (mb)</th>
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Table 2.24(b)

<table>
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<th>$E_\alpha$ (MeV)</th>
<th>$^{204}<em>{\text{Tl}}(\alpha,3n)^{204}</em>{\text{Bi}}$ Cross-section (mb)</th>
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<td>34.35 ± 0.65</td>
<td>560.8 ± 82.1</td>
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<td>36.63 ± 0.64</td>
<td>790.4 ± 110.9</td>
</tr>
<tr>
<td>39.72 ± 0.64</td>
<td>550.8 ± 79.2</td>
</tr>
<tr>
<td>42.63 ± 0.63</td>
<td>538.8 ± 78.3</td>
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<td>46.31 ± 0.62</td>
<td>402.3 ± 61.8</td>
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<tr>
<td>49.76 ± 0.61</td>
<td>967.8 ± 131.8</td>
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</tbody>
</table>
Table 2.25(a)

Activation crosssection for $^{203}\text{Tl}(\alpha,4n)\ ^{203}\text{Bi}$

\[
\lambda = 1.5693 \times 10^{-5} \text{ Sec}^{-1} \\
t = 10860 \text{ Sec} \\
N_0 = 1.4894 \times 10^{18} \\
\Phi = 9.7632 \times 10^{11} \alpha\text{-particles/cm}^2\text{-Sec}
\]

<table>
<thead>
<tr>
<th>$E_\alpha$</th>
<th>$E_\gamma$</th>
<th>$\Theta$</th>
<th>$\epsilon_G$</th>
<th>$\lambda$</th>
<th>$\sigma_\gamma$</th>
<th>$\overline{\sigma_\gamma}$</th>
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<td>(keV)</td>
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<td></td>
<td>(mb)</td>
<td>(mb)</td>
<td>(mb)</td>
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<tr>
<td>36.63 ± 0.64</td>
<td>820</td>
<td>0.296</td>
<td>0.00185</td>
<td>327</td>
<td>18.61</td>
<td>18.61</td>
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<tr>
<td>39.72 ± 0.64</td>
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<td>0.00185</td>
<td>1569</td>
<td>79.97</td>
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<td>0.296</td>
<td>0.00185</td>
<td>6782</td>
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<td>333.54</td>
</tr>
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<td>46.31 ± 0.62</td>
<td>820</td>
<td>0.296</td>
<td>0.00185</td>
<td>11249</td>
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<td>820</td>
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<td>0.00185</td>
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Table 2.25(b)

<table>
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<th>(^{203}\text{Tl}(\alpha,4n)^{203}\text{Bi}) Cross-section (mb)</th>
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</thead>
<tbody>
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<td>36.63 ± 0.64</td>
<td>18.6 ± 10.4</td>
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<tr>
<td>39.72 ± 0.64</td>
<td>80.0 ± 17.7</td>
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<tr>
<td>42.68 ± 0.63</td>
<td>333.5 ± 51.4</td>
</tr>
<tr>
<td>46.31 ± 0.62</td>
<td>536.3 ± 77.8</td>
</tr>
<tr>
<td>49.76 ± 0.61</td>
<td>467.2 ± 70.0</td>
</tr>
</tbody>
</table>
Table 2.26(a)

Activation cross section for $^{141}$Pr($\alpha$,n) $^{144}$Pm

\[ \lambda = 2.2096 \times 10^{-8} \text{ sec}^{-1} \]
\[ t_1 = 33480 \text{ sec} \]
\[ N_0 = 6.8019 \times 10^{18} \]
\[ \phi = 10.7893 \times 10^{11} \text{ } \alpha \text{-particles/cm}^2 \text{ } \text{sec} \]

| $E_\alpha$ (MeV) | $E_\gamma$ (keV) | $\Theta$ | $\varepsilon_G$ | $\lambda$ (mb) | $\sigma_\tau$ (mb) | $\overline{\sigma_\tau}$ (mb) |
|-----------------|-----------------|----------|---------------|----------------|----------------|----------------|----------------|
| 15.71 ± 0.94    | 477             | 0.422    | 0.019         | 3457           | 13.66          |                  |
|                 | 618             | 0.991    | 0.015         | 7133           | 20.77          | 19.88           |
|                 | 697             | 1.000    | 0.014         | 6538           | 20.21          |                  |
| 18.24 ± 0.90    | 477             | 0.422    | 0.019         | 24711          | 133.37         |                  |
|                 | 618             | 0.991    | 0.015         | 49942          | 145.39         | 139.75          |
|                 | 697             | 1.000    | 0.014         | 45451          | 140.49         |                  |
| 25.97 ± 0.82    | 477             | 0.422    | 0.019         | 3157           | 17.04          |                  |
|                 | 618             | 0.991    | 0.015         | 7846           | 22.84          | 21.26           |
|                 | 697             | 1.000    | 0.014         | 7737           | 23.91          |                  |
| 30.14 ± 0.79    | 477             | 0.422    | 0.019         | 2041           | 11.01          |                  |
|                 | 618             | 0.991    | 0.015         | 5477           | 15.94          | 11.89           |
|                 | 697             | 1.000    | 0.014         | 2825           | 8.73           |                  |
| 35.92 ± 0.76    | 477             | 0.422    | 0.019         | 10797          | 9.69           |                  |
|                 | 618             | 0.991    | 0.015         | 4572           | 13.30          | 9.97            |
|                 | 697             | 1.000    | 0.014         | 2244           | 6.93           |                  |
| 44.57 ± 0.72    | 697             | 1.000    | 0.014         | 1600           | 5.19           | 5.19            |
### Table 2.26(b)

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$^{141}\text{Pr}(\alpha, n); ^{144}\text{Pm}$ Cross-section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.71 ± 0.94</td>
<td>19.9 ± 3.2</td>
</tr>
<tr>
<td>18.24 ± 0.90</td>
<td>139.8 ± 17.8</td>
</tr>
<tr>
<td>25.97 ± 0.82</td>
<td>21.3 ± 3.8</td>
</tr>
<tr>
<td>30.14 ± 0.79</td>
<td>11.9 ± 2.4</td>
</tr>
<tr>
<td>35.92 ± 0.76</td>
<td>10.0 ± 2.1</td>
</tr>
<tr>
<td>44.57 ± 0.72</td>
<td>5.2 ± 1.7</td>
</tr>
</tbody>
</table>
### Table 2.27(a)

Activation crosssection for $^{141}\text{Pr}(\alpha, 2n)\; ^{143}\text{Pm}$

\[ \lambda = 3.0267 \times 10^8 \text{ Sec}^{-1} \]

\[ t_1 = 33480 \text{ Sec} \]

\[ N_0 = 6.8019 \times 10^{18} \]

\[ \Phi = 10.7893 \times 10^{11} \alpha \text{-particles/cm}^2 \cdot \text{Sec} \]

<table>
<thead>
<tr>
<th>$E\alpha$ (MeV)</th>
<th>$E'\gamma$ (keV)</th>
<th>$\Theta$</th>
<th>$\epsilon G$</th>
<th>$A$</th>
<th>$\sigma T$ (mb)</th>
<th>$\bar{\sigma_T}$ (mb)</th>
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REFERENCES


