CHAPTER - III

MEASUREMENT OF \((n, \gamma)\) CROSS-SECTIONS IN \(MeV\)
ENERGY REGION

3.1 Introduction:

The knowledge of fast neutron capture cross-sections is important because of several reasons:

(a) From the application point of view, these are useful in the design and development of fast breeder reactors\(^1,2,3\).

(b) These are also useful to understand stellar nucleosynthesis processes\(^4,5\).

(c) The \((n, \gamma)\) cross-section as a function of neutron energy also gives informations about the neutron capture mechanisms.

For energies less than 1 MeV the statistical theory approach gives fairly good agreement with the experimental data, and the reaction takes place through compound nucleus formation, whereas for the neutron energies higher than 4 MeV, the statistical theory fails to account the experimentally measured \((n, \gamma)\) cross-section values and the reaction takes place mainly through direct-semidirect (DSD) process specially in the GDR.
energy region. In the range of energies between 1 and 4 MeV the reaction is supposed to take place through compound nucleus formation and hence statistical theory accounts satisfactorily. It has been suggested by a few workers\textsuperscript{6,7} that non-statistical processes might be started to take part in this energy region. However, this energy range has not been extensively studied either experimentally or theoretically with high degrees of accuracy and hence there is still a demand to investigate this region of energy.

From the inspection of earlier reports\textsuperscript{3,9} and other recent literatures, it was inferred that the information about the \((n,\gamma)\) cross-sections in the energy region above 1 MeV is either inadequate or inconsistent for most of the nuclei. Hence there is still a demand to complete and improve the earlier experimental data in the above energy region with the application of modern high resolution detectors.

We have made an attempt to measure the \((n,\gamma)\) cross-section for six reactions \(^{154}\text{Sm}(n,\gamma)\), \(^{155}\text{Sm}\), \(^{160}\text{Gd}\), \(^{161}\text{Gd}\), \(^{155}\text{In}(n,\gamma)\), \(^{116}\text{In}\), \(^{103}\text{Rh}(n,\gamma)\), \(^{104}\text{Rh}\), \(^{55}\text{Mn}\), \(^{56}\text{Mn}\) and \(^{51}\text{V}(n,\gamma)\) at five different neutron energies of \(1.07 \pm 0.20\) MeV, \(1.48 \pm 0.18\) MeV, \(1.89 \pm 0.17\) MeV, \(2.30 \pm 0.16\) MeV and \(2.35 \pm 0.15\) MeV.
3.2 Sample Preparation:

The enriched isotopes of $^{160}\text{Gd}$ and $^{154}\text{Sm}$ were obtained from Oak Ridge National Laboratory, Oak Ridge, U.S.A., in the form of $\text{Gd}_2\text{O}_3$ and $\text{Sm}_2\text{O}_3$ powder with an isotopic enrichment of 98.1% and 98.69% respectively. Most of samples studied such as $\text{In}_2\text{O}_3$, $\text{V}_2\text{O}_5$, $\text{Mn}$ and $\text{Rh}$ were procured from Johnson Mathey Co. Ltd. London, U.K., as the spectrographically pure (SPECPURX) samples having purity better than 99.99%. The samples were made by uniformly spreading the powder within perspex rings of radius 8 mm and were sandwiched between two thin cellulose tapes. $^{127}\text{I}$ was taken as the standard sample in the form of Potassium Iodide, with reference to which the cross-sections were measured.

In principle the sample should be as thin as possible, to minimize the scattering and self shielding effects during the irradiation and the subsequent radioactivity measurements thereafter. A compromise was made between the area and the thickness of the sample so that self absorption of gamma rays in the sample and the neutron energy spread due to the solid angle subtended by the sample may not be very large. To achieve high neutron flux, the sample cannot be placed very far from the trisium target during irradiation, because the neutron flux varies roughly as inverse of the square
of the distance of the sample from the target. Accuracy of the activation measurements also depend upon the accuracy of the mass of the irradiated samples. Measurement of the masses of the samples were made with a high precision microbalance which can read up to 0.01 milligram. However, the uncertainty in the mass of the samples was estimated to be ± 0.1%. Sample characteristics, used in the present investigations, are tabulated in Table 3.1.

Table 3.1: Sample characteristics

<table>
<thead>
<tr>
<th>Samples (mg/cm²)</th>
<th>Chemical composition</th>
<th>Enrichment purity</th>
<th>Investigated isotope</th>
<th>No. of nuclei of the isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd 48.42</td>
<td>Gd₂O₃</td>
<td>Isotopic enriched 98.1%</td>
<td>160⁹⁶Gd</td>
<td>3.1245 x 10²⁰</td>
</tr>
<tr>
<td>Sm 13.04</td>
<td>Sm₂O₃</td>
<td>Isotopic enriched 98.69%</td>
<td>154⁴⁴Sm</td>
<td>2.17727 x 10²⁰</td>
</tr>
<tr>
<td>In 80.12</td>
<td>In₂O₃</td>
<td>SPECPURE</td>
<td>115⁴⁷In</td>
<td>6.685 e x 10²⁰</td>
</tr>
<tr>
<td>Rh 72.35</td>
<td>Powder</td>
<td>SPECPURE</td>
<td>10³⁴⁷Rh</td>
<td>8.5024 x 10²⁰</td>
</tr>
<tr>
<td>Mn 217.95</td>
<td>Powder</td>
<td>SPECPURE</td>
<td>⁵⁵Mn</td>
<td>46.9027 x 10²⁰</td>
</tr>
<tr>
<td>V(1) 124.95</td>
<td>V₂O₅</td>
<td>SPECPURE</td>
<td>⁵¹V</td>
<td>16.5695 x 10²⁰</td>
</tr>
<tr>
<td>(ni) 95.89</td>
<td>V₂O₅</td>
<td>SPECPURE</td>
<td>⁵¹V</td>
<td>12.7158 x 10²⁰</td>
</tr>
</tbody>
</table>

SPECPURE (99.99% spectrographically pure)
3.3 Detection Efficiency Determination

The knowledge of detection efficiency of the detector is an essential requirement for determining the absolute emission rate of the gamma rays emitted by the activated sample under investigation and the standard sample. The intrinsic detection efficiency for a point source at different gamma energies can be calculated by using standard \( \gamma \)-ray sources with the help of following relation,

\[
\varepsilon = \frac{C \cdot \exp(\lambda t)}{S_0 \cdot G}
\]

where \( \varepsilon \) is the intrinsic photopeak efficiency of the detector, \( C \) is the number of events recorded in one second under full energy peak (photopeak), \( S_0 \) is the actual number of radiation quanta emitted by the standard source per second, at the time of its fabrication. \( G \) is the geometry factor \( (\Omega/4\pi) \), \( \Theta \) is the intensity of particular gamma-ray per disintegration, \( \lambda \) is the decay constant of the radioactive nuclei, \( t \) is the time lapsed between start of counting and the date of fabrication of standard \( \gamma \)-ray source.

Although efficiency of Ge(Li) detector can be estimated from published data or calculation for detectors of similar size, the accuracy of the results based on these values will not be very reliable as it is generally observed that
the detection efficiency of the Ge(Li) detector varies with time\(^{10}\)). Hence the detection efficiency was determined using seven standard gamma ray source whose decay data are given in Table 3.2. The source-detector distance is a very critical factor which should be measured accurately to minimize the errors in the reproducibility of the geometry.

The detection efficiency curve of 50 cc Ge(Li) detector which was used in our experiment has been plotted in Fig. 3.1. This curve was used to determine the absolute emission rate of the gamma rays emitted by the activated samples, whose cross-sections are to be measured.

Table 3.2: Decay data for Radionuclides used for photopeak detection efficiency of Ge(Li) detector.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-life</th>
<th>Gamma ray Energy ( E_\gamma ) (keV)</th>
<th>Percentage intensity of the ( \gamma )-ray per disintegration of radioactive nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{109})Cd</td>
<td>453 days</td>
<td>88.0</td>
<td>3.38%</td>
</tr>
<tr>
<td>(^{57})Co</td>
<td>272 days</td>
<td>122.0</td>
<td>85.6%</td>
</tr>
<tr>
<td>(^{138})Ba</td>
<td>10.7 years</td>
<td>356</td>
<td>62%</td>
</tr>
<tr>
<td>(^{22})Na (Annihilation) 1274.5</td>
<td>2.60 years</td>
<td>511</td>
<td>181.14%</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>30.0 years</td>
<td>661.6</td>
<td>85.3%</td>
</tr>
<tr>
<td>(^{54})Mn</td>
<td>312.5 days</td>
<td>834.8</td>
<td>7.5%</td>
</tr>
<tr>
<td>(^{60})Co</td>
<td>5.27 years</td>
<td>1173.2</td>
<td>99.88%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1332.5</td>
<td>99.98%</td>
</tr>
</tbody>
</table>
FIG. 3.1: PHOTODETECTION EFFICIENCY CURVE OF 50cc ORTEC GE(Li) DETECTOR
3.4 **Experimental Details:**

The measurement of neutron activation cross-section using activation technique consists of two major steps:

3.4.1 **Neutron production and irradiation of the samples.**

3.4.2 **Counting of the induced gamma activities.**

3.4.1 **Neutron production and irradiation of the samples:**

Monoenergetic neutrons were produced from $^3\text{He}(p,n)^4\text{He}$ reaction in the present measurements. The reaction equation may be written as,

\[ ^1\text{p} + ^3\text{He} \rightarrow ^2\text{He} + ^1\text{n} - 0.764 \text{ MeV}. \]

The protons of the desired energies were obtained from Variable Energy Cyclotron at Panjab University, Chandigarh (India). The proton beam was allowed to fall on a 16 Curie tritium target procured from Bhabha Atomic Research Centre, Trombay (India), which consists of a thin titanium layer impregnated with tritium on the copper circular disc of diameter 25 mm. The target was attached to the lateral surface of a brass cylindrical shell which we call the target holding assembly. The hollow copper spiral tube with an inner diameter of 5 mm was wound to this target holder, through which chilled water was allowed to circulate continuously during irradiation. This arrangement
was made to cool the trisium target by heat conduction process. The irradiation of the samples with neutrons were carried out in free space at a distance of 25 mm from the target at zero degree to the proton beam as shown in Fig. 3.2. Precautions were taken to remove the possible scattering materials from the surroundings of the irradiation so that the neutrons of degraded energies may not incident on the sample. There are three factors that have been considered in order to determine the uncertainty associated with a given neutron energy. One of them is the finite spread in the proton beam energy ($E_p$) before it strikes the trisium target. In the present case this spread is $\sim 20$ keV. The second main factor for the uncertainty in the neutron energy is the degradation of the incident proton beam energy in the trisium target, which varies from $210$ keV to $140$ keV for the proton beam energy between 1 MeV and 3 MeV. The corresponding neutron energy spread lies between $190$ keV to $130$ keV. The third factor for the energy spread of the neutron is the angle subtended by the samples studied, at the point neutron source. The spread in the neutron energy due to this factor lies between $25$ keV to $55$ keV.

The proton beam current during irradiation of different samples (at different energies) varied between 2 to 12 $\mu$A, but for a particular irradiation the beam
current was kept nearly constant. For an individual irradiation the variation in the beam current was not more than 6%. A rotating shutter, coated with zinc sulphide was brought in front of the target to view the alignment of the beam spot so that the beam could be properly focused before allowing it to fall on the target. Instead of a pin point focus the size of the beam spot was kept about 3 mm x 9 mm in order to achieve a homogeneous illumination of the target and to obtain more neutron flux.

The sample under investigation was sandwiched between two standard samples of Potassium iodide. The size of the sample under investigation was the same as that of the standard samples. The sample along with the two standard samples was placed in a perspex frame vertically, facing the neutron beam. The sample was irradiated in the zero degree forward direction with respect to the proton beam for a reasonable time to achieve sufficient activity. The irradiation time varied from sample to sample. It was three to four half-lives in the case of short lived activities and about 45 minutes in those whose half-life is a few hours. The neutron flux at the place of irradiation was generally $\sim 10^7$ neutrons/cm$^2$-sec.

3.4.2 Counting of induced gamma activities: The last and the major step of the experiment is the determi-
nation of the induced activity in the investigated sample and the standard samples. The most accurate way for this measurement is the use of high resolution gamma ray spectroscopy, with a calibrated Ge(Li) detector. This method guarantees clean background corrections and allows us to sort out the characteristic gamma ray lines of the radioactive nucleus.

A 50 c.c. cylindrical shape Ortec Ge(Li) detector (FWHM of 2 keV at 1.33 MeV) with a heavy lead shielding was used to detect the characteristic gamma lines.

As soon as the proton beam is switched off, the sample under investigation along with the standard samples were removed from the place of irradiation and thereafter were placed at the flat surface of the Ge(Li) detector in the same geometry. The gamma ray spectra from the decay of the samples were recorded by a pre-calibrated 4096 channels ND-100 analyser for time intervals which varied from case to case, so as to get good statistics. The gamma ray spectra was also recorded at subsequent time intervals so as to confirm the half-life of the activity produced. The reaction product nuclei were identified by characteristic $\gamma$-transitions following their decay. The counts under the characteristic gamma peaks were recorded and the activities were determined
by using the values of the detection efficiency at the corresponding energies.

3.5 Errors analysis in the Measurements:

The reliability and utility of experimental data in a certain measurement depends upon the various errors involved. The errors involved here in the cross-section measurements contain statistical and systematic errors. The possible sources of errors in our measurements and the corrections applied for minimizing the same are described in the following paragraphs:

1. The erratic behaviour of the electronic equipments may introduce some error in the measurement. We could get rid of this by stabilizing the electronic equipments for a few hours before its use.

2. Fluctuation in the proton beam current as well as the size of the proton beam spot causes an error in the neutron flux during irradiation. Hence care was taken to keep the beam current constant specially in the irradiation of those specimen samples whose half-lives were much different from that of the standard sample. The error due to fluctuation in the proton beam was estimated between ± 1/ to ± 6/ from one case to another. The runs with large beam current fluctuations were discarded.
3. Errors may also be present in the estimation of the total number of nuclei present in the sample. This may be due to the impurities present in the sample and due to errors in weighing the sample. The former was minimized up to less than 0.2\% by taking specpure samples having purity better than 99.99\% and the latter was minimized by weighing the sample with a microbalance which could weigh correctly up to 0.01 mg. The maximum error introduced in weighing the sample was estimated to be 0.03\%. Hence the total error in the estimation of the number of nuclei present in the sample was at the most ± 0.3\%.

4. Gamma rays self absorption in the sample is also a significant factor, especially in the samples which have high Z values and are comparatively thick. This correction was applied to each case.

5. Detection efficiencies of the Ge(Li) detector were determined using absolutely calibrated standard γ-sources supplied by IAEA, Vienna, whose strengths were known up to an accuracy of ± 1\%. The efficiency curve was obtained by a smooth joining of the efficiency points at various gamma ray energies. The overall uncertainty in the detection efficiencies was estimated to be between ± 2\% to ± 6\%. 
6. The inaccurate measurement of irradiation time, the time lapse between the stopping of irradiation and the starting of counting as well as the counting time may introduce some errors. An error up to $+2\%$ was estimated in our measurement.

7. Some errors may also be introduced due to non-reproducibility of the geometries of the irradiation and the counting systems. However, this type of error was minimized by fixing the position of the sample holder during irradiation and counting. An estimate of about $+2\%$ was made for the non reproducibility of the geometries.

8. Decay properties of the nuclei studied here such as, half-life gamma ray energies, branching ratios and natural abundance may also introduce some errors. To minimize this error recent nuclear data were consulted. However the errors in the decay parameters have not been incorporated because any revision in these decay parameters would permit an easy recalculation of the cross-section in future.

9. Some errors are also associated with the integration of the pulse height spectrum specially in the $\gamma$-spectrum of poor statistics. An error of about $+1\%$ to $+5\%$ was estimated in different cases.
10. Errors due to pulse summing effect was negligibly small in our measurements. The spectra were recorded with less than 3% dead time in the multichannel analyser, and hence the error due to this effect was always less than ± 0.2%.

11. The presence of scattered neutrons at the place of irradiation of the sample may introduce a serious error in the cross-section because at low energies the \((n,\gamma)\) cross-sections are generally very high. In our measurements the sample targets were held in the perspex frame of very small thickness during irradiation. Moreover, the irradiation was performed in the open space of a big hall where minimum scattering materials were present nearby. The flux of scattered neutrons with respect to the primary neutrons was estimated to be less than ± 3%.

12. Errors may also be present due to uncertainty in the experimental cross-section values of the standard reaction. The various measurements of the standard reaction cross-section gave an error of about ± 7% in the neutron energies of our interest.

13. In addition to all the above systematic errors there is statistical error in the counts under the photo-
peaks. This error vary from one case to another, depending upon the activities produced in the samples. This statistical error in counts under the peak was estimated to be lying between $\pm 1\%$ to $\pm 10\%$ from one case to another.

The uncertainty associated with neutron energy reflects the uncertainty in the measured cross-section values. There are three factors responsible for the uncertainty associated with neutron energy. First, it is due to the finite spread in the proton beam energy before it strikes the trisium target. In the present case this spread is \(\sim 20\) keV. The second main factor for the uncertainty in the neutron energy is degradation of the incident proton beam energy in the trisium target, which varies from 210 keV to 140 keV for \(1\) MeV \(\leq E_p \leq 3\) MeV. This proton energy spread resulted in the neutron energy spread correspondingly from 190 keV to 130 keV. The third factor responsible for the neutron energy spread is the angle subtended by the samples studied at the point neutron source and lying between 25 keV to 55 keV. The total neutron energy spread \(\Delta E_n\) due to all the three factors was found to be lying between 200 keV to 150 keV.

3.6 Standard Reaction:

All the \((n,\gamma)\) cross-sections in the neutron energy region of 1 to 3 MeV have been measured relative to $^{127}$I,
which is considered as the standard sample, because of the following reasons:

(i) The cross-section for the reaction $^{127}\text{I} (n,\gamma) ^{128}\text{I}$ is precisely known as a function of neutron energy up to 5 MeV, hence below this energy it can easily be used as a standard sample.

(ii) $^{128}\text{I}$ has a moderate half-life (24.99 min) which is comparable to the half-lives of most of the $(n,\gamma)$ reaction products of the isotopes studied in the present work. Of course, $^{196}\text{Au} (n,\gamma) ^{197}\text{Au}$ reaction may also be treated as one of the standard reactions, but the half-life of $^{197}\text{Au}$ is about 2.69 days, which is comparatively quite long with respect to the isotopes studied here. Therefore, the choice of $^{127}\text{I}$ as a standard sample enabled us to correct for any fluctuations which otherwise could have affected the sample activity with respect to the standard if the respective half-lives were much different.

(iii) $^{127}\text{I}$ is monoisotopic and its decay scheme is well established.

(iv) It is easily available with a high purity.
Here $^{127}$I was taken in the form of Potassium iodide which when irradiated by neutrons gives an admixture of two activities $^{128}$I (24.99 min) and $^{42}$K (12.5 hrs). Activity of $^{42}$K is obtained as a result of $^{41}$K (n,γ) $^{42}$K reaction. Since the two activities have half-lives which differ by a factor of 30, they can be easily separated without causing any sizable statistical counting error. The (n,γ) cross-section of $^{41}$K is very low in the 1 MeV to 3 MeV energy region and its natural abundance in KI is only 6.88%. Moreover, since the maximum duration of irradiation of the samples in the present measurement is 45 minutes, the 12.5 hr $^{42}$K activity produced was not appreciable. This was also confirmed by singles spectrum of irradiated KI at each neutron energy.

The (n,γ) cross-sections for the reaction $^{127}$I(n,γ) $^{128}$I at neutron energies, $E_n = 1.07 \pm 0.20$ MeV, $1.48 \pm 0.18$ MeV, $1.89 \pm 0.17$ MeV, $2.30 \pm 0.16$ MeV and $2.85 \pm 0.15$ MeV were taken as 78 ± 6 mb, 69 ± 5 mb, 62 ± 4 mb, 49 ± 4 mb and 34 ± 3 mb respectively as given in the BNL report (1976).

3.7 Experimental Results:

Among the six isotopes studied here, $^{160}$Gd and $^{154}$Sm were isotopically enriched samples. Rest of the samples were spectrographically pure (SPECPURE) elements.
or compounds having purity better than 99.99%. The details about the chemical composition, purity and thickness of the samples are given in Table 3.1.

The details of measurements at different neutron energies of all the six target samples are described separately. To obtain more reliable and consistent results each measurement was repeated in most of the cases. Moreover, for cases (wherever the half-life of the product nucleus is reasonably large, and activity is good enough), the activity was recorded in many "Sets" of observations during its decay. Each activated nucleus was also identified by following the half-life of the product nucleus. The singles spectrum of each irradiated sample was recorded to check any unwanted contamination. The one or more intense photopeaks were selected and counts under the peaks were recorded for a particular time interval $t_3$, depending upon the half-lives and counting rates. The counts under the individual peaks were determined after subtracting the background counts. The recent decay schemes of the reaction products formed by (n,γ) reactions were taken from the latest 'Table of Isotopes' (1978) by Lederer and Shirley\(^{11}\).
A typical example of the mode of calculation of cross-section for the reaction $^{154}\text{Sm} (n, \gamma) ^{155}\text{Sm}$ at neutron energy $(E_n) 1.07 \pm 0.20$ MeV has been given in more details here. All the $(n, \gamma)$ cross-section measurements were made by counting the gamma activities induced in the samples.

Example:

3.7.1 $^{154}\text{Sm}(n, \gamma) ^{155}\text{Sm}$ - reaction:

**Neutron Energy, $E_n$:** $1.07 \pm 0.20$ MeV

1. **Calculation of average neutron flux**: The neutron flux at neutron energy $1.07 \pm 0.20$ MeV has been measured in three sets $A(1), A(2)$ and $A(3)$ for the same irradiation in different time intervals during its decay, by placing one experimental sample in between the two standard samples together in the same geometry. The average of results of these three sets gives the average neutron flux at the place of irradiation. The method of calculation of neutron flux for the set $A(1)$ is as follows:

(a) **Cross-section for the reaction** $^{127}\text{I}(n, \gamma) ^{128}\text{I}$

at $E_n = 1.07 \pm 0.20$ MeV, $\sigma = 78 \pm 6$ mb$^9$,

(b) **Number of** $^{127}\text{I}$ **nuclei present in both the KI standard samples, in between which the** $^{154}\text{Sm}$ **sample was sandwiched,**

$N_0 = N_{01} + N_{02} = (7.7646 + 7.5396) \times 10^{20} = 15.3042 \times 10^{20}$
(c) Detection efficiency of Ge(Li) detector for the 443 keV gamma ray, $\varepsilon = 0.0285$

(d) Absolute intensity of the 443 keV $\gamma$-ray per decay of $^{128}$I, $I = 0.16$.

(e) Self absorption correction factor for the gamma ray in the standard samples, $K = 0.0238$.

(f) Time of irradiation, $t_1 = 1860$ sec.

(g) Time lapsed between stopping of irradiation and starting of countings, $t_2 = 60$ sec.

(h) Time of the recording the events under 443 keV photopeak, $t_3 = 160$ sec.

(i) Number of counts under the photopeak registered during time $t_3$, $A = 1578$.

Hence the flux $(\phi G)_1$ in the set A(1) using the relation (2.32)

$$\frac{A \cdot \lambda \cdot \exp(\lambda t_2)}{c \cdot \text{No.e.g.} \cdot K[1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}$$

is obtained as $3.9270 \times 10^7$ neutrons/cm$^2$-sec.

Similarly, the neutron flux $(\phi G)_2$ and $(\phi G)_3$ in the other two consecutive sets A(2) and A(3) were determined to be $3.8840 \times 10^7$ neutrons/cm$^2$-sec and $3.9388 \times 10^7$ neutrons/cm$^2$-sec respectively. In these sets, $t_2$, $t_3$ and $A$ are different from set A(1). Therefore, the average neutron
flux passing through the sample $^{154}\text{Sm}$, $(\phi G)_{av}$ is obtained as

$$(\phi G)_{av} = \frac{[(\phi G)_1 + (\phi G)_2 + (\phi G)_3]}{3}$$

or,

$$(\phi G)_{av} = \phi_{av} \cdot G = 3.9166 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec}.$$

(ii) **Calculation of the $^{154}\text{Sm}(n,\gamma)^{155}\text{Sm}$ reaction cross-section:**

Jet A(l): The isotopically enriched (93.69%) sample of $^{154}\text{Sm}$ in the form of $\text{Sm}_2\text{O}_3$ powder was used as a target whose mass and area was 0.0652 g and 2.011 cm$^2$ respectively. The $^{154}\text{Sm}$ sample was sandwiched between two standard samples of Potassium iodide and was irradiated in zero-degree forward direction with respect to the proton beam for a period of 1860 sec. Induced $\gamma$-activity was recorded after 60 sec, from the stop of irradiation, for a time of 166 seconds. The counts under the $\gamma$-ray peak of 104 keV in the decay of $^{155}\text{Sm}$, registered during this counting period was determined by subtraction of background counts in the respective channels in which 104 keV peak was recorded. 104 keV $\gamma$-ray due to the decay of $^{155}\text{Sm}$ and 443 keV $\gamma$-ray due to the decay of $^{128}\text{I}$ at each neutron energy are shown in Figs. 3.5 to 3.9 for a single set. A singles spectrum of $^{155}\text{Sm}$ along with $^{128}\text{I}$ produced by neutron irradiation is shown in Fig. 3.3. The decay scheme of $^{155}\text{Sm}$ is also shown in the Fig. 3.3. A typical
Fig 3.3 (a) Singles spectrum of $^{155}\text{Sm}$ + $^{128}$I decay produced by neutron irradiation.
(b) Decay scheme of $^{155}\text{Sm}$. 
decay curve of 104 keV γ-ray in $^{155}$Sm is shown in Fig. 3.4.

The method of calculation of cross-section is as follows:

(a) Number of $^{154}$Sm nuclei present in the sample

$$N_0 = 2.1772 \times 10^{20},$$

(b) The average neutron flux obtained from the induced γ-ray activity in $^{127}$I of KI sample, placed on the two sides of $\text{Sm}_2\text{O}_3$ sample was obtained as,

$$(\phi\gamma)_{av} = 3.9166 \times 10^7 \text{ neutrons/cm}^2\text{-sec},$$

(c) Detection efficiency of Ge(Li) detector for the 104 keV gamma ray, $\varepsilon = 0.116,$

(d) The absolute intensity of the 104 keV γ-ray in the decay of $^{155}$Sm, $\theta = 0.697,$

(e) Self absorption correction factor for gamma ray in $\text{Sm}_2\text{O}_3$ sample, $\kappa = 0.988,$

(f) The time of irradiation of the sample, $t_1 = 1860$ sec,

(g) Time lapsed between stopping of irradiation and starting of counting, $t_2 = 60$ sec,

(h) Time of recording the particular event (104 keV γ-ray), $t_3 = 166$ sec,

(i) The number of events registered during the time $t_3$, $A = 3329 \pm 66$ counts
Fig. 3.4: A typical decay of $^{155}$Sm by 104 KeV gamma ray.
Fig. 35: Characteristic gamma ray of 104 KeV in the decay of $^{155}$Sm and 443 KeV in the decay of $^{128}$I.

Energy $E_n = 1.07 \pm 0.20$ MeV

Set: A(1)
Hence the cross-section for the reaction $^{154}_{\text{Sm}}(n,\gamma)^{155}_{\text{Sm}}$, using the expression (2.32) may be calculated as,

$$
\sigma = \frac{A \cdot \lambda \cdot \exp (\lambda t_2)}{(\phi G)_{av} \cdot \varepsilon \cdot \theta \cdot [1 - \exp (-\lambda t_1)][1 - \exp (-\lambda t_3)]}
$$

$$
= \frac{(3329) \times (5.1562 \times 10^{-4})}{[(3.9166 \times 10^7) \times (2.17727 \times 10^{20}) \times (0.697)}
$$

$$
= \frac{(0.116) \times (0.938) \times [1 - e^{-5.1562 \times 10^{-4} \times 166}]}{[1 - e^{-5.1562 \times 10^{-4} \times 166}]} \times 51.3712 \times 10^{-27} \text{ cm}^2 = 51.37 \text{ mb}
$$

Total error associated with $\sigma$ is 13.86%. Hence cross-section will be,

$$
\sigma = 51.37 \pm 7.12 \text{ mb}
$$

Similarly, the cross-section for this reaction was obtained by using the 104 keV $\gamma$-ray spectra recorded at different time intervals during the decay of $^{155}_{\text{Sm}}$. These are given by sets $A(2), A(3)$ and $A(4)$. 
Set A(2):

\[
A = 1360 \pm 140 \, \text{counts} \quad \lambda = 5.1562 \times 10^{-4} \, \text{sec}^{-1}
\]
\[
t_1 = 1360 \, \text{sec} \quad t_2 = 300 \, \text{sec}
\]
\[
t_3 = 1000 \, \text{sec} \quad \theta = 0.697
\]
\[
\epsilon = 0.116 \quad \phi_0 = 2.17727 \times 10^{20}
\]
\[
K = 0.988 \quad \phi_{av} = 3.9166 \times 10^7 \, \text{neutrons/cm}^2\cdot\text{sec}
\]
\[
\sigma = 43.36 \pm 6.99 \, \text{mb}
\]

Set A(3):

\[
A = 6791 \pm 100 \, \text{counts} \quad \lambda = 5.1562 \times 10^{-4} \, \text{sec}^{-1}
\]
\[
t_1 = 1360 \, \text{sec} \quad t_2 = 1300 \, \text{sec}
\]
\[
t_3 = 1025 \, \text{sec} \quad \theta = 0.697
\]
\[
\epsilon = 0.116 \quad \phi_0 = 2.17727 \times 10^{20}
\]
\[
K = 0.988 \quad \phi_{av} = 3.9166 \times 10^7 \, \text{neutrons/cm}^2\cdot\text{sec}
\]
\[
\sigma = 48.33 \pm 7.29 \, \text{mb}
\]

Set A(4):

\[
A = 915 \pm 50 \, \text{counts} \quad \lambda = 5.1562 \times 10^{-4} \, \text{sec}^{-1}
\]
\[
t_1 = 1360 \, \text{sec} \quad t_2 = 4680 \, \text{sec}
\]
\[
t_3 = 500 \, \text{sec} \quad \theta = 0.697
\]
\[
\epsilon = 0.116 \quad \phi_0 = 2.17727 \times 10^{20}
\]
\[
K = 0.988 \quad \phi_{av} = 3.9166 \times 10^7 \, \text{neutrons/cm}^2\cdot\text{sec}
\]
\[
\sigma = 55.18 \pm 8.33 \, \text{mb}
\]
The average cross section measured at $E_n = 1.07 \pm 0.20$ MeV is given by

$$\sigma = 50.49 \pm 6.16 \text{ mb}$$

**Neutron Energy, $E_n = 1.48 \pm 0.18$ MeV**

**Set A(1):**

\[ A = 5636 \pm 85 \text{ counts} \quad \lambda = 5.1562 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 35 \text{ sec} \]
\[ t_3 = 400 \text{ sec} \quad \theta = 0.697 \]
\[ \varepsilon = 0.116 \]
\[ \kappa = 0.988 \]

\[ \Phi_{av} G = 4.0240 \times 10^7 \text{ neutron/cm}^2\text{-sec} \]

$$\sigma = 49.17 \pm 5.64 \text{ mb}$$

**Set A(2):**

\[ A = 4505 \pm 78 \text{ counts} \quad \lambda = 5.1562 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 450 \text{ sec} \]
\[ t_3 = 400 \text{ sec} \quad \theta = 0.697 \]
\[ \varepsilon = 0.116 \]
\[ \kappa = 0.988 \]

\[ \Phi_{av} G = 4.0240 \times 10^7 \text{ neutron/cm}^2\text{-sec} \]

$$\sigma = 48.68 \pm 5.93 \text{ mb}$$
$E_n = 1.48 \pm 0.18 \text{ MeV}$

**Set: A(1)**

Fig. 36: Characteristic gamma ray of 104 KeV in the decay of $^{155}\text{Sm}$ and 443 KeV in the decay of $^{128}\text{I}$. 
Set A(3):

\begin{align*}
A &= 3085 \pm 70 \text{ counts} \\
\tau_1 &= 1200 \text{ sec} \\
\tau_2 &= 400 \text{ sec} \\
\varepsilon &= 0.116 \\
\chi &= 0.938 \\
\lambda &= 5.1562 \times 10^{-4} \text{ sec}^{-1} \\
\phi_{av} G &= 4.0240 \times 10^7 \text{ neutrons/ cm}^2 \text{-sec}
\end{align*}

\[ \sigma = 44.97 \pm 5.82 \text{ mb} \]

Set A(4):

\begin{align*}
A &= 2600 \pm 63 \text{ counts} \\
\tau_1 &= 1200 \text{ sec} \\
\tau_2 &= 400 \text{ sec} \\
\varepsilon &= 0.116 \\
\chi &= 0.938 \\
\lambda &= 5.1562 \times 10^{-4} \text{ sec}^{-1} \\
\phi_{av} G &= 4.0240 \times 10^7 \text{ neutrons/ cm}^2 \text{-sec}
\end{align*}

\[ \sigma = 49.79 \pm 6.44 \text{ mb} \]

Hence, the average \((n,\gamma)\) cross-section measured at

\[ E_n = 1.48 \pm 0.18 \text{ MeV} \]

is given by

\[ \sigma = 48.16 \pm 4.52 \text{ mb} \]

Neutron Energy, \( E_n \): 1.89 \( \pm \) 0.17 MeV

Set A(1):

\begin{align*}
A &= 7427 \pm 102 \text{ counts} \\
\lambda &= 5.1562 \times 10^{-4} \text{ sec}^{-1}
\end{align*}
$E_n = 1.89 \pm 0.17 \text{ MeV}$

Set, A(1)

**Fig. 3.7**: Characteristic gamma ray of 104 keV in the decay of $^{155}\text{Sm}$ and 443 keV in the decay of $^{128}\text{I}$. 
Henoe th0(n,γ) orosa-aection for $^{154}$Sm at $E_n = 1.89 \pm 0.17$ MeV is given by

$$\sigma = 45.88 \pm 5.69 \text{ mb}$$

Hence the(n,γ) cross-section for $^{154}$Sm at $E_n = 1.89 \pm 0.17$ MeV is given by

$$\sigma = 45.88 \pm 5.69 \text{ mb}$$

**Neutron Energy $E_n$: 2.30 ± 0.16 MeV**

**Set A(1):**

- $A = 5600 \pm 86$ counts
- $\lambda = 5.1562 \times 10^{-4}$ sec$^{-1}$
- $t_1 = 1800$ sec
- $t_2 = 180$ sec
- $t_3 = 1000$ sec
- $\theta = 0.697$
- $N_0 = 2.17727 \times 10^{20}$
- $K = 0.988$
- $\varphi_{av \cdot G} = 2.0213 \times 10^7$ neutrons/cm$^2$-sec

$$\sigma = 27.44 \pm 3.65 \text{ mb}$$

**Set A(2):**

- $A = 390 \pm 40$ counts
- $\lambda = 5.1562 \times 10^{-4}$ sec$^{-1}$
- $t_1 = 1800$ sec
- $t_2 = 5400$ sec
- $t_3 = 1000$ sec
- $\theta = 0.697$
- $N_0 = 2.17727 \times 10^{20}$
- $K = 0.988$
- $\varphi_{av \cdot G} = 2.7257 \times 10^7$ neutrons/cm$^2$-sec

$$\sigma = 27.44 \pm 3.65 \text{ mb}$$

ACC No

124-74

KASAM MUSLIM UNIVERSITY, ALG.
Fig. 3.8: Characteristic gamma ray of 104 KeV in the decay of $^{155}$Sm and 443 KeV in the decay of $^{128}$I.
\[ t_3 = 1000 \text{ sec} \quad \Theta = 0.697 \]
\[ t_1 = 3300 \text{ sec} \quad t_2 = 30 \text{ sec} \]
\[ t_3 = 1000 \text{ sec} \quad \Theta = 0.697 \]
\[ \varepsilon = 0.116 \quad \text{No} = 2.17727 \times 10^{20} \]
\[ K = 0.988 \quad \varphi_{av.} \Theta = 2.7257 \times 10^7 \text{ neutrons/} \text{cm}^2\cdot\text{sec} \]
\[ \sigma = 29.53 \pm 4.11 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section for \(^{154}\text{Sm}\) at
\[ E_n = 2.30 \pm 0.16 \text{ MeV} \]

is measured as:
\[ \sigma = 28.28 \pm 3.45 \text{ mb} \]

**Neutron Energy** \(E_n = 2.85 \pm 0.15 \text{ MeV}\)

*Set A(1):*

\[ A = 3408 \pm 82 \text{ counts} \quad \lambda = 5.1562 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 3300 \text{ sec} \quad t_2 = 30 \text{ sec} \]
\[ t_3 = 1000 \text{ sec} \quad \Theta = 0.697 \]
\[ \varepsilon = 0.116 \quad \text{No} = 2.17727 \times 10^{20} \]
\[ K = 0.988 \quad \varphi_{av.} \Theta = 1.2936 \times 10^7 \text{ neutrons/} \text{cm}^2\cdot\text{sec} \]
\[ \sigma = 24.08 \pm 3.32 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section measured at
\[ E_n = 2.85 \pm 0.15 \text{ MeV} \]

for \(^{154}\text{Sm}\) is given by,
\[ \sigma = 24.08 \pm 3.32 \text{ mb} \]
$E_n = 2.85 \pm 0.15$ MeV

Set: A(1)

Fig. 39: Characteristic gamma ray of 104 KeV in the decay $^{155}$Sm and 443 KeV in the decay of $^{128}$I.
Table 3.3: Activation cross-sections for the reaction

\[ ^{154}\text{Sm} (n,\gamma) ^{155}\text{Sm}. \]

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy, ( E_n [\text{MeV}] )</th>
<th>Cross-section ( \sigma(n,\gamma) [\text{mb}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07 ± 0.20</td>
<td>50.49 ± 6.16</td>
</tr>
<tr>
<td>2</td>
<td>1.48 ± 0.18</td>
<td>48.16 ± 4.52</td>
</tr>
<tr>
<td>3</td>
<td>1.89 ± 0.17</td>
<td>45.88 ± 5.69</td>
</tr>
<tr>
<td>4</td>
<td>2.30 ± 0.16</td>
<td>28.28 ± 3.45</td>
</tr>
<tr>
<td>5</td>
<td>2.85 ± 0.15</td>
<td>24.08 ± 3.32</td>
</tr>
</tbody>
</table>

3.7.2 \( ^{160}\text{Gd}(n,\gamma) ^{161}\text{Gd} \)-reaction:

Gadolinium Oxide (\( \text{Gd}_2\text{O}_3 \)) enriched in \( ^{160}\text{Gd} \) with isotopic enrichment of 98.1% was used for the preparation of the sample target. The sample of mass and area 0.0973 gm and 2.011 cm² respectively, was irradiated along with two standard samples in zero-degree forward direction with the proton beam at five different neutron energies of 1.07 ± 0.20 MeV, 1.48 ± 0.18 MeV, 1.89 ± 0.17 MeV, 2.30 ± 0.16 MeV and 2.85 ± 0.15 MeV. After capturing neutrons, \( ^{160}\text{Gd} \) transforms into \( ^{161}\text{Gd} \) which is an unstable nuclide with half life 3.7 min. \( ^{161}\text{Gd} \) decays through \( \gamma \)-emission to the excited states of \( ^{161}\text{Tb} \). Gamma rays of different energies are emitted in the de-excitation of
Fig. 3.10 (a): Singles spectrum of $^{161}$Gd $^{128}$I decay produced by neutron irradiation.
(b) Decay scheme of $^{161}$Gd.
the levels in $^{161}$Tb. We had recorded two of the most intense gamma rays of energies 315 keV and 361 keV and their intensities were measured in each set of irradiation, for a particular time $t_3$ for the present cross-section measurements. The decay scheme of $^{161}$Gd and singles spectrum of $^{161}$Gd along with that of $^{128}$I is shown in Fig. 3.10. The characteristic $\gamma$-rays of 315 keV and 361 keV in the decay of $^{161}$Gd and 443 keV in the decay of $^{128}$I at each irradiation energy for a single set has been shown in Figs. 3.11 to 3.15. A typical decay curve of $^{161}$Gd is shown in Figure 3.11. Calculations at different neutron energies in different sets of irradiations are given as

*Neutron Energy $E_n$: $1.07 \pm 0.20$ MeV*

**Set A(1)/$\gamma$; 315 keV:**

\[
\begin{align*}
A & = 618 \pm 25 \text{ counts} & \lambda & = 3.1216 \times 10^{-3} \text{ sec}^{-1} \\
t_1 & = 1220 \text{ sec} & t_2 & = 35 \text{ sec} \\
t_3 & = 500 \text{ sec} & \theta & = 0.229 \\
\varepsilon & = 0.0425 & \text{No} & = 3.1245 \times 10^{20} \\
K & = 0.998 & \varphi_{\text{av.}} & = 3.4031 \times 10^{7} \text{ neutron/cm}^2\text{sec} \\
\sigma & = 26.97 \pm 3.74 \text{ mb}
\end{align*}
\]

**Set A(1)/$\gamma$; 361 keV:**

\[
\begin{align*}
A & = 1317 \pm 41 \text{ counts} & \lambda & = 3.1216 \times 10^{-3} \text{ sec}^{-1} \\
t_1 & = 1220 \text{ sec} & t_2 & = 35 \text{ sec}
\end{align*}
\]
Fig. 3.11 (a) Characteristics gamma rays of 315 KeV and 361 KeV in the decay of $^{161}$Gd and 443 KeV in the decay of $^{128}$I. (b) Typical decay curve of $^{161}$Gd.
\[ t_3 = 500 \text{ sec} \quad \theta = 0.606 \]
\[ \epsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av.} G = 3.4031 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 24.93 \pm 3.46 \text{ mb} \]

**Set A(2)/\gamma=361 \text{ keV}:**

\[ A = 243 \pm 22 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1220 \text{ sec} \quad t_2 = 580 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.606 \]
\[ \epsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av.} G = 3.4031 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 25.21 \pm 4.35 \text{ mb} \]

**Set B(1)/\gamma=375 \text{ keV}:**

\[ A = 483 \pm 32 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.229 \]
\[ \epsilon = 0.0425 \quad N_0 = 3.1245 \times 10^{20} \]
\[ K = 0.998 \quad \varphi_{av.} G = 3.0042 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 28.40 \pm 3.94 \text{ mb} \]
Set $B(1)/\gamma$: 361 keV:

\[
A = 1062 \pm 40 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \\
t_1 = 1200 \text{ sec} \quad t_2 = 50 \text{ sec} \\
t_3 = 500 \text{ sec} \quad \theta = 0.606 \\
\varepsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \\
K = 0.999 \quad \phi_{\text{av}} G = 3.0042 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma = 23.89 \pm 3.51 \text{ mb}
\]

Set $B(2)/\gamma$: 361 keV:

\[
A = 180 \pm 20 \text{ counts} \quad \lambda = 2.1216 \times 10^{-3} \text{ sec}^{-1} \\
t_1 = 1200 \text{ sec} \quad t_2 = 600 \text{ sec} \\
t_3 = 500 \text{ sec} \quad \theta = 0.606 \\
\varepsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \\
K = 0.999 \quad \phi_{\text{av}} G = 3.0042 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma = 22.55 \pm 3.89 \text{ mb}
\]

Hence, the $(n,\gamma)$ cross-section for the reaction
$^{160}\text{Gd}(n,\gamma)^{161}\text{Gd}$, at $E_n = 1.07 \pm 0.20 \text{ MeV}$ is found to be,

\[
\sigma = 25.43 \pm 3.03 \text{ mb}
\]

Neutron Energy $E_n$: $1.48 \pm 0.18 \text{ MeV}$

Set $A(1)/\gamma$: 375 keV:

\[
A = 194 \pm 20 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1}
\]
Fig. 3.12: Characteristics gamma rays of 315 KeV and 361 KeV in the decay of $^{151}$Gd and 443 KeV in the decay of $^{128}$I.
\[ t_1 = 360 \text{ sec} \quad t_2 = 60 \text{ sec} \]
\[ t_3 = 400 \text{ sec} \quad \theta = 0.229 \]
\[ \tau = 0.0425 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.998 \quad \varphi_{\text{av}} \cdot G = 2.42 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \]
\[ \sigma = 20.63 \pm 2.36 \text{ mb} \]

Set A(1)/\( \gamma \): 361 keV:

\[ A = 415 \pm 24 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 360 \text{ sec} \quad t_2 = 60 \text{ sec} \]
\[ t_3 = 400 \text{ sec} \quad \theta = 0.606 \]
\[ \tau = 0.037 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{\text{av}} \cdot G = 2.424 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \]
\[ \sigma = 19.13 \pm 2.19 \text{ mb} \]

Set B(1)/\( \gamma \): 315 keV:

\[ A = 385 \pm 26 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 300 \text{ sec} \quad \theta = 0.229 \]
\[ \tau = 0.0425 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.998 \quad \varphi_{\text{av}} \cdot G = 4.091 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \]
\[ \sigma = 19.06 \pm 2.50 \text{ mb} \]

Set B(1)/\( \gamma \): 361 keV:

\[ A = 913 \pm 34 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 300 \text{ sec} \quad \theta = 0.606 \]
\[ c = 0.037 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av} \cdot G = 4.0914 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \]

\[ t = 19.49 \pm 2.23 \text{ mb} \]

**Set B(2)/\gamma: 361 keV:**

\[ A = 258 \pm 16 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 480 \text{ sec} \]
\[ t_3 = 300 \text{ sec} \quad \theta = 0.606 \]
\[ c = 0.037 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av} \cdot G = 4.0914 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \]

\[ \sigma = 21.19 \pm 3.26 \text{ mb} \]

**Hence the average (n,\gamma) cross-section for the reaction**

\[ ^{160}\text{Gd}(n,\gamma)^{161}\text{Gd} \text{ at } E_n = 1.48 \pm 0.18 \text{ MeV} \text{ is found to be,} \]

\[ \sigma = 19.66 \pm 1.78 \text{ mb} \]

**Neutron Energy** \[ E_n: 1.89 \pm 0.17 \text{ MeV} \]

**Set A(3)/\gamma: 315 MeV:**

\[ A = 377 \pm 26 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 900 \text{ sec} \quad t_2 = 45 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.229 \]
\[ c = 0.0425 \quad \text{No} = 3.1245 \times 10^{20} \]
$E_n = 1.89 \pm 0.17 \text{ MeV}$

Set: A(1)

Fig. 313: Characteristics gamma rays of 315 KeV and 361 KeV in the decay of $^{161}\text{Gd}$ and 443 KeV in the decay of $^{128}\text{I}$. 
\[ K = 0.998 \quad \varphi_{av} \cdot G = 3.1370 \times 10^7 \text{ neutrons/cm}^2 \cdot \text{sec} \]

\[ \sigma = 19.16 \pm 2.38 \text{ mb} \]

**Set A(1)/γ1361 keV:**

\[ A = 836 \pm 33 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]

\[ t_1 = 900 \text{ sec} \quad t_2 = 45 \text{ sec} \]

\[ t_3 = 500 \text{ sec} \quad \theta = 0.606 \]

\[ \epsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \]

\[ K = 0.999 \quad \varphi_{av} \cdot G = 3.1370 \times 10^7 \text{ neutrons/cm}^2 \cdot \text{sec} \]

\[ \sigma = 13.42 \pm 2.28 \text{ mb} \]

**Set A(2)/γ1361 keV:**

\[ A = 186 \pm 19 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]

\[ t_1 = 900 \text{ sec} \quad t_2 = 555 \text{ sec} \]

\[ t_3 = 500 \text{ sec} \quad \theta = 0.606 \]

\[ \epsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20} \]

\[ K = 0.999 \quad \varphi_{av} \cdot G = 3.1370 \times 10^7 \text{ neutrons/cm}^2 \cdot \text{sec} \]

\[ \sigma = 20.14 \pm 3.24 \text{ mb} \]

**Set B(1)/γ1375 keV:**

\[ A = 406 \pm 30 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]

\[ t_1 = 1200 \text{ sec} \quad t_2 = 35 \text{ sec} \]

\[ t_3 = 706 \text{ sec} \quad \theta = 0.229 \]
\[ \varepsilon = 0.0425 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.998 \quad \varphi_{av} \cdot G = 3.0521 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 17.57 \pm 2.18 \text{ mb} \]

**Set B(1)/γ: 361 keV:**

\[ A = 1043 \pm 38 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 35 \text{ sec} \]
\[ t_3 = 706 \text{ sec} \quad \theta = 0.606 \]
\[ \varepsilon = 0.037 \quad \text{No} = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av} \cdot G = 3.0521 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 19.57 \pm 2.43 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section for the reaction \(^{160}\text{Gd}(n,\gamma)\) \(^{161}\text{Gd}\) at \(E_n = 1.89 \pm 0.17\) MeV is found to be,

\[ \sigma = 18.73 \pm 1.92 \text{ mb} \]

**Neutron Energy \(E_n\): 2.30 \pm 0.16 MeV**

**Set A(1)/γ: 315 keV:**

\[ A = 240 \pm 22 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec} \]
\[ t_3 = 600 \text{ sec} \quad \theta = 0.229 \]
\[ \varepsilon = 0.0425 \quad \text{No} = 3.1245 \times 10^{20} \]
Fig. 3.14: Characteristics gamma rays of 315 keV and 361 keV in the decay of $^{161}$Gd and 443 keV in the decay of $^{128}$I.
\[
K = 0.998 \quad \varphi_{av}\cdot\theta = 2.5192 \times 10^7 \text{ neutrons/cm}^2\text{-sec}
\]

\[\sigma = 13.44 \pm 1.79 \text{ mb}\]

**Set A(1)/γ1361 keV:**

\[
A = 605 \pm 29 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1}
\]
\[t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec}\]
\[t_3 = 600 \text{ sec} \quad \theta = 0.606\]
\[\epsilon = 0.037 \quad N_0 = 3.1245 \times 10^{20}\]
\[K = 0.999 \quad \varphi_{av}\cdot\theta = 2.5192 \times 10^7 \text{ neutrons/cm}^2\text{-sec}\]

\[\sigma = 14.63 \pm 1.95 \text{ mb}\]

**Set B(1)/γ1375 keV:**

\[
A = 415 \pm 30 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1}
\]
\[t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec}\]
\[t_3 = 800 \text{ sec} \quad \theta = 0.229\]
\[\epsilon = 0.0425 \quad N_0 = 3.1245 \times 10^{20}\]
\[K = 0.998 \quad \varphi_{av}\cdot\theta = 3.8158 \times 10^7 \text{ neutrons/cm}^2\text{-sec}\]

\[\sigma = 14.14 \pm 1.88 \text{ mb}\]

**Set B(1)/γ1361 keV:**

\[
A = 936 \pm 37 \text{ counts} \quad \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1}
\]
\[t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec}\]
\[t_3 = 800 \text{ sec} \quad \theta = 0.606\]
\[ e = 0.037 \quad N_0 = 3.1245 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av} \cdot \lambda = 3.8158 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 13.83 \pm 1.84 \text{ mb} \]

Hence the average \((n,\gamma)\) cross-section for the reaction
\[ ^{160}\text{Gd}(n,\gamma)^{161}\text{Gd} \] at \( E_n = 2.30 \pm 0.16 \text{ MeV} \) is found to be,
\[ \sigma = 13.99 \pm 1.59 \text{ mb} \]

**Neutron Energy** \( E_n : 2.85 \pm 0.15 \text{ MeV} \)

**Set** \( A(1)/\gamma: 315 \text{ keV} : \)

- \( A = 90 \pm 13 \text{ counts} \)
- \( \lambda = 1216 \times 10^{-3} \text{ sec}^{-1} \)
- \( t_1 = 1800 \text{ sec} \)
- \( t_2 = 30 \text{ sec} \)
- \( t_3 = 700 \text{ sec} \)
- \( \theta = 0.229 \)
- \( e = 0.0425 \)
- \( K = 0.998 \quad \varphi_{av} \cdot \lambda = 1.0452 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \)
- \( \sigma = 11.01 \pm 1.52 \text{ mb} \)

**Set** \( A(1)/\gamma: 361 \text{ keV} : \)

- \( A = 225 \pm 22 \text{ counts} \)
- \( \lambda = 3.1216 \times 10^{-3} \text{ sec}^{-1} \)
- \( t_1 = 1800 \text{ sec} \)
- \( t_2 = 30 \text{ sec} \)
- \( t_3 = 700 \text{ sec} \)
- \( \theta = 0.606 \)
- \( e = 0.037 \)
- \( K = 0.999 \quad \varphi_{av} \cdot \lambda = 1.0452 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \)
- \( \sigma = 11.92 \pm 1.64 \text{ mb} \)
Fig. 3.15: Characteristics gamma rays of 315 KeV and 361 KeV in the decay of ¹⁶¹Gd and 443 KeV in the decay of ¹²⁸I.
Hence the average $(n, \gamma)$ cross-section for the reaction $^{160}\text{Gd}(n, \gamma) \rightarrow ^{161}\text{Gd}$ at $E_n = 2.85 \pm 0.15$ MeV is found to be,

$$\sigma = 11.43 \pm 1.44 \text{ mb}$$

Table 3.4 : Activation cross-sections for the reaction $^{160}\text{Gd}(n, \gamma) \rightarrow ^{161}\text{Gd}$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy $E_n \text{ (MeV)}$</th>
<th>Cross-section $\sigma(n, \gamma) \text{ (mb)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.07 $\pm$ 0.20</td>
<td>25.43 $\pm$ 3.03</td>
</tr>
<tr>
<td>2.</td>
<td>1.48 $\pm$ 0.18</td>
<td>19.66 $\pm$ 1.78</td>
</tr>
<tr>
<td>3.</td>
<td>1.89 $\pm$ 0.17</td>
<td>18.73 $\pm$ 1.92</td>
</tr>
<tr>
<td>4.</td>
<td>2.30 $\pm$ 0.16</td>
<td>13.99 $\pm$ 1.59</td>
</tr>
<tr>
<td>5.</td>
<td>2.85 $\pm$ 0.15</td>
<td>11.43 $\pm$ 1.44</td>
</tr>
</tbody>
</table>

3.7.3 : $^{115}\text{In}(n, \gamma) \rightarrow ^{116}\text{In}$ - reaction: Specture In$_2$O$_3$ powder with purity better than 99.99% of mass 0.1610 gm and area 2.011 cm$^2$ was used as target sample. The sample was sandwiched between two KI samples of similar size and then irradiated for a certain time $t_1$ at five different neutron energies of $1.07 \pm 0.20$ MeV, $1.48 \pm 0.18$ MeV, $1.89 \pm 0.17$ MeV, $2.30 \pm 0.16$ MeV and $2.85 \pm 0.15$ MeV.
After capturing a neutron, $^{115}\text{In}$ becomes $^{116}\text{In}$ with two isomeric states of half-lives $2.16$ sec and $54.34$ min. The $2.16$ sec isomeric state decay by isomeric transition to the $54.34$ min isomeric state. The ground state of $^{116}\text{In}$ with half-life $14.1$ sec decay mainly to the ground state of $^{116}\text{Sn}$ through $\beta$-emission. However the $54.34$ min isomeric state decay by $\beta$-emission to the excited states of $^{116}\text{Sn}$ which ultimately decay to the ground state of $^{116}\text{Sn}$ giving five main $\gamma$-rays of energies $138.3$ keV, $417$ keV, $818$ keV, $1.097$ MeV and $1.293$ MeV. Among these transitions we have recorded the last four most intense $\gamma$-transitions and cross-section has been measured by counting the events under each $\gamma$-peak in every set of data, to get a more consistent cross-section values. Each $\gamma$-ray was recorded for certain time $t_3$ in the pulse height analysing mode of the multichannel analyser coupled with the heavy lead shielded $50$ c.c. Ge(Li) detector. The evidence that these gamma rays were attributed to the $54.34$ min isomeric state of $^{116}\text{In}$, the decreasing intensity of $417$ keV, $818$ keV, $1.09$ MeV and $1.29$ MeV $\gamma$-rays were plotted as a function of decay time, as shown in Fig. 3.17(b). All these $\gamma$-rays decay with a half-life of $54.34$ min, thus confirming the formation of $^{116}\text{In}$ ($T_{1/2} = 54.34$ min). A typical singles gamma spectrum of $^{116}\text{In}$ along with that of $^{128}\text{I}$ is shown in Fig. 3.16. The four most intense gamma peaks along with $443$ keV
Fig. 3.16 (a): Singles spectrum of $^{116m}$In-$^{128}$I decay produced by neutron irradiation
(b) Decay scheme of $^{116m}$In.
γ-peak in the decay of $^{128}$I standard sample were recorded in each set of irradiation at five different neutron energies and are shown in Figs. 3.18 to 3.21 for a single set. The measured cross-section corresponds to both isomeric states (2.16 sec and 54.34 min half-lives).

**Neutron Energy $E_n$: 1.07 ± 0.20 MeV**

**Set A(1)/γ1: 417 keV:**

$A = 9964 \pm 115$ counts

$t_1 = 1800$ sec  \hspace{1cm}  $t_2 = 360$ sec

$t_3 = 1000$ sec  \hspace{1cm}  $\theta = 0.284$

$\varepsilon = 0.031$

$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$\phi_{av} = 3.1450 \times 10^{7}$ neutrons/cm$^2$-sec

$\sigma = 203.31 \pm 27.32$ mb

**Set A(1)/γ1: 818 keV:**

$A = 2154 \pm 75$ counts

$t_1 = 1800$ sec  \hspace{1cm}  $t_2 = 360$ sec

$t_3 = 1000$ sec  \hspace{1cm}  $\theta = 0.121$

$\varepsilon = 0.0135$

$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$\phi_{av} = 3.1450 \times 10^{7}$ neutrons/cm$^2$-sec

$\sigma = 236.71 \pm 29.53$ mb
Fig. 3.17 (a): Characteristic gamma rays of 417 keV, 818 keV, 1.09 MeV, and 1.29 MeV in the decay of $^{116m}$In and 443 keV in the decay of $^{128I}$. (b) Typical decay curve of $^{116m}$In.
Set A(1)/γ1 1.09 MeV:

\[ A = 7608 \pm 101 \text{ counts} \]
\[ \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \]
\[ t_2 = 360 \text{ sec} \]
\[ t_3 = 1000 \text{ sec} \]
\[ \theta = 0.575 \]
\[ \epsilon = 0.0115 \]
\[ N_0 = 6.685 \times 10^{20} \]
\[ K = 0.9989 \]
\[ \varphi_{av}.G = 3.1450 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 206.51 \pm 27.40 \text{ mb} \]

Set A(1)/γ1 1.29 MeV:

\[ A = 9146 \pm 99 \text{ counts} \]
\[ \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \]
\[ t_2 = 360 \text{ sec} \]
\[ t_3 = 1000 \text{ sec} \]
\[ \theta = 0.85 \]
\[ \epsilon = 0.0095 \]
\[ N_0 = 6.685 \times 10^{20} \]
\[ K = 0.999 \]
\[ \varphi_{av}.G = 3.1450 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 205.28 \pm 27.37 \text{ mb} \]

Set A(2)/γ1 417 keV:

\[ A = 7918 \pm 102 \text{ counts} \]
\[ \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \]
\[ t_2 = 1620 \text{ sec} \]
\[ t_3 = 1000 \text{ sec} \]
\[ \theta = 0.284 \]
\[ \epsilon = 0.031 \]
\[ N_0 = 6.685 \times 10^{20} \]
\[ K = 0.9979 \]
\[ \varphi_{av}.G = 3.1450 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 211.22 \pm 27.53 \text{ mb} \]
Set A(2)/y: 815 keV:

\[
\begin{align*}
A &= 1609 \pm 65 \text{ counts} \quad \lambda = 2.125 \times 10^{-4} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \quad t_2 = 1620 \text{ sec} \\
t_3 &= 1000 \text{ sec} \\
\epsilon &= 0.0135 \\
\kappa &= 0.9988 \\
\end{align*}
\]

\[\sigma = 231.12 \pm 29.31 \text{ mb}\]

Set A(2)/y: 1.09 MeV:

\[
\begin{align*}
A &= 5888 \pm 90 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \quad t_2 = 1620 \text{ sec} \\
t_3 &= 1000 \text{ sec} \\
\epsilon &= 0.0115 \\
\kappa &= 0.9989 \\
\end{align*}
\]

\[\sigma = 208.91 \pm 28.96 \text{ mb}\]

Set A(2)/y: 1.29 MeV:

\[
\begin{align*}
A &= 6808 \pm 87 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \quad t_2 = 1620 \text{ sec} \\
t_3 &= 1000 \text{ sec} \\
\epsilon &= 0.0095 \\
\kappa &= 0.999 \\
\end{align*}
\]

\[\sigma = 197.78 \pm 27.17 \text{ mb}\]
Set $A(3)/\gamma_1$ 4.17 keV:

$A = 2385 \pm 60$ counts  \quad $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1800$ sec  \quad $t_2 = 7200$ sec

$t_3 = 1000$ sec  \quad $\theta = 0.284$

$\varepsilon = 0.031$  \quad $N_0 = 6.685 \times 10^{20}$

$\kappa = 0.9979$  \quad $\varphi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 208.30 \pm 28.46$ mb

Set $A(3)/\gamma_1$ 1.09 MeV:

$A = 1383 \pm 49$ counts  \quad $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1800$ sec  \quad $t_2 = 7200$ sec

$t_3 = 1000$ sec  \quad $\theta = 0.575$

$\varepsilon = 0.0115$  \quad $N_0 = 6.685 \times 10^{20}$

$\kappa = 0.9989$  \quad $\varphi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 219.32 \pm 28.96$ mb

Set $A(3)/\gamma_1$ 1.29 MeV:

$A = 2063 \pm 48$ counts  \quad $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1800$ sec  \quad $t_2 = 7200$ sec

$t_3 = 1000$ sec  \quad $\theta = 0.85$

$\varepsilon = 0.0093$  \quad $N_0 = 6.685 \times 10^{20}$

$\kappa = 0.999$  \quad $\varphi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 196.26 \pm 28.04$ mb
Set $A(4)/\gamma$: 417 keV:

$A = 850 \pm 39$ counts
$t_1 = 1800$ sec
$t_2 = 12420$ sec
$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$
$\theta = 0.284$
$\epsilon = 0.031$
$K = 0.9979$
$\phi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 216.08 \pm 29.94$ mb

Set $A(4)/\gamma$: 1.09 MeV:

$A = 616 \pm 31$ counts
$t_1 = 1800$ sec
$t_2 = 12420$ sec
$\eta = 0.575$
$\epsilon = 0.0115$
$N_0 = 6.685 \times 10^{20}$
$K = 0.9989$
$\phi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 208.28 \pm 29.58$ mb

Set $A(4)/\gamma$: 1.29 MeV:

$A = 717 \pm 29$ counts
$t_1 = 1800$ sec
$t_2 = 12420$ sec
$\eta = 0.85$
$\epsilon = 0.0095$
$N_0 = 6.685 \times 10^{20}$
$K = 0.999$
$\phi_{av} = 3.1450 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 198.54 \pm 29.15$ mb
Hence, the average \((n, \gamma)\) cross-section for the reaction \(^{115}\text{In}(n, \gamma) ^{116}\text{In}\) at \(E_n = 1.07 \pm 0.20\) MeV is found to be,

\[
\sigma = 209.90 \pm 24.73\text{ mb}
\]

**Neutron Energy** \(E_n = 1.48 \pm 0.18\) MeV

**Set A(1)/\(\gamma\): 417 keV:**

\[
\begin{align*}
A &= 6472 \pm 94\text{ counts} \\
t_1 &= 2100\text{ sec} \\
t_2 &= 217\text{ sec} \\
t_3 &= 500\text{ sec} \\
\epsilon &= 0.031 \\
K &= 0.9979 \\
\lambda &= 2.1255 \times 10^{-4}\text{ sec}^{-1}
\end{align*}
\]

\[
\psi_{av}G = 3.8993 \times 10^7\text{ neutrons/cm}^2\text{-sec}
\]

\[
\sigma = 173.29 \pm 18.39\text{ mb}
\]

**Set A(1)/\(\gamma\): 618 keV:**

\[
\begin{align*}
A &= 1245 \pm 57 \\
t_1 &= 2100\text{ sec} \\
t_2 &= 217\text{ sec} \\
t_3 &= 500\text{ sec} \\
\epsilon &= 0.0135 \\
K &= 0.9988 \\
\lambda &= 2.1255 \times 10^{-4}\text{ sec}^{-1}
\end{align*}
\]

\[
\psi_{av}G = 3.8993 \times 10^7\text{ neutrons/cm}^2\text{-sec}
\]

\[
\sigma = 179.51 \pm 9.69\text{ mb}
\]
Fig. 3.18: Characteristic gamma rays of 417 KeV, 818 KeV, 1.09 MeV and 1.29 MeV in the decay of $^{115m}$In and 443 KeV in the decay of $^{128I}$. 

$E_n = 1.48 \pm 0.18$ MeV

Set: A(1)
Set A(1)/γ1 1.09 MeV:

\[ A = 4774 \pm 79 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 217 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.575 \]
\[ \varepsilon = 0.0115 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9989 \quad \bar{\phi}_{av}.G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 172.38 \pm 18.35 \text{ mb} \]

Set A(1)/γ1 1.29 MeV:

\[ A = 5732 \pm 79 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 217 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.85 \]
\[ \varepsilon = 0.0095 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.999 \quad \bar{\phi}_{av}.G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 169.47 \pm 18.26 \text{ mb} \]

Set A(2)/γ1 1.17 keV:

\[ A = 5652 \pm 87 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 750 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.284 \]
\[ \varepsilon = 0.031 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9979 \quad \bar{\phi}_{av}.G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 169.49 \pm 18.26 \text{ mb} \]
Set A(2)/γ; 818 keV:

\[ A = 1094 \pm 56 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 750 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.121 \]
\[ \varepsilon = 0.0135 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9988 \quad \varphi_{av} \cdot \sigma = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 176.66 \pm 19.57 \text{ mb} \]

Set A(2)/γ; 1.09 MeV:

\[ A = 4433 \pm 75 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 750 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.575 \]
\[ \varepsilon = 0.0115 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9989 \quad \varphi_{av} \cdot \sigma = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 176.79 \pm 18.50 \text{ mb} \]

Set A(2)/γ; 1.29 MeV:

\[ A = 4916 \pm 74 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 750 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.85 \]
\[ \varepsilon = 0.0095 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{av} \cdot \sigma = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 160.55 \pm 17.96 \text{ mb} \]
Set A(3)/γ1 417 keV:

\[ A = 4254 \pm 74 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 2250 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.284 \]
\[ \varepsilon = 0.031 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9979 \quad \varphi_{\text{av}} G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 175.47 \pm 19.51 \text{ mb} \]

Set A(3)/γ1 818 keV:

\[ A = 840 \pm 47 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 2250 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.121 \]
\[ \varepsilon = 0.0135 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9988 \quad \varphi_{\text{av}} G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 186.58 \pm 20.01 \text{ mb} \]

Set A(3)/γ1 1.09 MeV:

\[ A = 3196 \pm 64 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 2250 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 0.575 \]
\[ \varepsilon = 0.0115 \quad \text{No} = 6.685 \times 10^{20} \]
\[ K = 0.9989 \quad \varphi_{\text{av}} G = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 175.35 \pm 19.50 \text{ mb} \]
Set A(3)/γ: 1.29 MeV:

\[ A = 3675 \pm 63 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 2250 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \Theta = 0.85 \]
\[ \epsilon = 0.0095 \quad N_0 = 6.685 \times 10^{20} \]
\[ K = 0.999 \quad \varphi_{\text{av}} = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 165.09 \pm 19.07 \text{ mb} \]

Set A(4)/γ: 417 keV:

\[ A = 1965 \pm 53 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 5790 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \Theta = 0.284 \]
\[ \epsilon = 0.031 \quad N_0 = 6.685 \times 10^{20} \]
\[ K = 0.9979 \quad \varphi_{\text{av}} = 3.8993 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 172.00 \pm 19.36 \text{ mb} \]

Set A(4)/γ: 1.09 MeV:

\[ A = 1572 \pm 47 \text{ counts} \quad \lambda = 2.1255 \times 10^{-4} \text{ sec}^{-1} \]
\[ t_1 = 2100 \text{ sec} \quad t_2 = 5790 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \Theta = 0.575 \]
\[ \epsilon = 0.0115 \quad N_0 = 6.685 \times 10^{20} \]
\[ K = 0.9989 \quad \varphi_{\text{av}} = 3.8933 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 183.03 \pm 19.85 \text{ mb} \]
Set $A(4)/\gamma: 1.29$ MeV:

$A = 1868 \pm 45$ counts \hspace{1cm} \lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 2100$ sec \hspace{1cm} t_2 = 5790$ sec

t_3 = 500 sec \hspace{1cm} \theta = 0.85

$\varepsilon = 0.0095 \hspace{1cm} N_0 = 6.685 \times 10^{20}$

$K = 0.999 \hspace{1cm} \varphi_{av} \cdot G = 3.8893 \times 10^7$ neutrons/cm$^2$-sec

\[ \sigma = 178.08 \pm 19.63 \text{ mb} \]

Hence, the average $(n,\gamma)$ cross-section measured for the reaction $^{115}\text{In}(n,\gamma)^{116}\text{In}$ at $E_n = 1.48 \pm 0.18$ MeV is found to be,

\[ \sigma = 173.28 \pm 15.44 \text{ mb} \]

Neutron Energy $E_n: 1.89 \pm 0.17$ MeV

Set $A(1)/\gamma: 417$ keV:

$A = 6054 \pm 91$ counts \hspace{1cm} \lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 2140$ sec \hspace{1cm} t_2 = 300$ sec

t_3 = 1000 sec \hspace{1cm} \theta = 0.284

$\varepsilon = 0.031 \hspace{1cm} N_0 = 6.685 \times 10^{20}$

$K = 0.9979 \hspace{1cm} \varphi_{av} \cdot G = 2.3670 \times 10^7$ neutrons/cm$^2$-sec

\[ \sigma = 140.98 \pm 16.25 \text{ mb} \]
$E_n = 1.89 \pm 0.17$ MeV

Set: A(1)

Fig 3.19 Characteristic gamma rays of 417 KeV, 818 KeV, 1.09 MeV & 1.29 MeV in the decay of $^{116m}$In and 443 KeV in the decay of $^{128I}$. 
Set $A(1)/\gamma$: 81.8 keV:

\[
\begin{align*}
A &= 1183 \pm 56 \text{ counts} & \lambda &= 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
\tau_1 &= 2140 \text{ sec} & \tau_2 &= 300 \text{ sec} \\
\tau_3 &= 1000 \text{ sec} & \theta &= 0.121 \\
\epsilon &= 0.0135 & N_0 &= 6.685 \times 10^{20} \\
K &= 0.9988 & \varphi_{av.0} &= 2.3670 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 148.34 \pm 17.32 \text{ mb}
\end{align*}
\]

Set $A(1)/\gamma$: 1.09 MeV:

\[
\begin{align*}
A &= 4610 \pm 76 \text{ counts} & \lambda &= 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
\tau_1 &= 2140 \text{ sec} & \tau_2 &= 300 \text{ sec} \\
\tau_3 &= 1000 \text{ sec} & \theta &= 0.575 \\
\epsilon &= 0.0115 & N_0 &= 6.685 \times 10^{20} \\
K &= 0.9989 & \varphi_{av.0} &= 2.3670 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 148.72 \pm 16.49 \text{ mb}
\end{align*}
\]

Set $A(1)/\gamma$: 1.29 MeV:

\[
\begin{align*}
A &= 4990 \pm 74 \text{ counts} & \lambda &= 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
\tau_1 &= 2140 \text{ sec} & \tau_2 &= 300 \text{ sec} \\
\tau_3 &= 1000 \text{ sec} & \theta &= 0.85 \\
\epsilon &= 0.0095 & N_0 &= 6.685 \times 10^{20} \\
K &= 0.999 & \varphi_{av.0} &= 2.3670 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 126.55 \pm 15.81 \text{ mb}
\end{align*}
\]
Hence, the average \((n,\gamma)\) cross-section measured for the reaction \(^{115}\text{In}(n,\gamma)\) \(^{116}\text{In}\) at neutron energy \(E_n = 1.89 \pm 0.17\ \text{MeV}\) is found to be,

\[
\sigma = 139.38 \pm 14.53\ \text{mb}
\]

**Neutron Energy** \(E_n: 2.30 \pm 0.16\ \text{MeV}\)

**Set** \(A(1)/\gamma: 417\ \text{keV}:

\[
\begin{align*}
A &= 5895 \pm 89\ \text{counts} & \lambda &= 2.1255 \times 10^{-4}\ \text{sec}^{-1} \\
t_1 &= 1800\ \text{sec} & t_2 &= 490\ \text{sec} \\
t_3 &= 1000\ \text{sec} & \theta &= 0.284 \\
\epsilon &= 0.031 & N_0 &= 6.685 \times 10^{20} \\
k &= 0.9979 & \varphi_{av} &\theta = 4.0982 \times 10^7\ \text{neutrons/cm}^2\text{-sec}
\end{align*}
\]

\[
\sigma = 94.91 \pm 11.95\ \text{mb}
\]

**Set** \(A(1)/\gamma: 818\ \text{keV}:

\[
\begin{align*}
A &= 1198 \pm 56\ \text{counts} & \lambda &= 2.1255 \times 10^{-4}\ \text{sec}^{-1} \\
t_1 &= 1800\ \text{sec} & t_2 &= 490\ \text{sec} \\
t_3 &= 1000\ \text{sec} & \theta &= 0.121 \\
\epsilon &= 0.0135 & N_0 &= 6.685 \times 10^{20} \\
k &= 0.9988 & \varphi_{av} &\theta = 4.0982 \times 10^7\ \text{neutrons/cm}^2\text{-sec}
\end{align*}
\]

\[
\sigma = 103.86 \pm 12.77\ \text{mb}
\]
Fig. 3.20 Characteristic gamma rays of 417 KeV, 818 KeV, 1.09 MeV & 1.29 MeV in the decay of 116mIn and 443 KeV in the decay of 128I.
Set $A(1)/\gamma_1$ 1.09 MeV:

$A = 4411 \pm 77$ counts \hspace{1cm} $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1800$ sec \hspace{1cm} $t_2 = 490$ sec

$t_3 = 1000$ sec \hspace{1cm} $\theta = 0.575$

$\varepsilon = 0.0115$ \hspace{1cm} \$N_0 = 6.685 \times 10^{20}$

$K = 0.9989$ \hspace{1cm} $\varphi_{av}G = 4.0982 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 94.45 \pm 11.94$ mb

Set $A(1)/\gamma_1$ 1.29 MeV:

$A = 5205 \pm 77$ counts \hspace{1cm} $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1300$ sec \hspace{1cm} $t_2 = 490$ sec

$t_3 = 1000$ sec \hspace{1cm} $\theta = 0.85$

$\varepsilon = 0.0095$ \hspace{1cm} \$N_0 = 6.685 \times 10^{20}$

$K = 0.999$ \hspace{1cm} $\varphi_{av}G = 4.0982 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 91.26 \pm 11.84$ mb

Set $A(2)/\gamma_1$ 417 keV:

$A = 2817 \pm 63$ counts \hspace{1cm} $\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$

$t_1 = 1800$ sec \hspace{1cm} $t_2 = 4140$ sec

$t_3 = 1000$ sec \hspace{1cm} $\theta = 0.284$

$\varepsilon = 0.031$ \hspace{1cm} \$N_0 = 6.685 \times 10^{20}$

$K = 0.9979$ \hspace{1cm} $\varphi_{av}G = 4.0982 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 98.52 \pm 12.05$ mb
Set $A(2)/\gamma$: 1.09 MeV:

\begin{align*}
A &= 2083 \pm 53 \text{ counts} \\
\lambda &= 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \\
t_2 &= 4140 \text{ sec} \\
t_3 &= 1000 \text{ sec} \\
\theta &= 0.575 \\
\epsilon &= 0.0115 \\
N_0 &= 6.685 \times 10^{20} \\
K &= 0.9989 \\
\sigma_{av.\epsilon} &= 4.0982 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \\
\sigma &= 96.89 \pm 12.00 \text{ mb}
\end{align*}

Set $A(2)/\gamma$: 1.29 MeV:

\begin{align*}
A &= 2429 \pm 52 \text{ counts} \\
\lambda &= 2.1255 \times 10^{-4} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \\
t_2 &= 4140 \text{ sec} \\
t_3 &= 1000 \text{ sec} \\
\theta &= 0.85 \\
\epsilon &= 0.0095 \\
N_0 &= 6.685 \times 10^{20} \\
K &= 0.999 \\
\sigma_{av.\epsilon} &= 4.0982 \times 10^7 \text{ neutrons/cm}^2\cdot\text{sec} \\
\sigma &= 92.52 \pm 11.88 \text{ mb}
\end{align*}

Hence, the average $(n,\gamma)$ cross-section measured for the reaction $^{115}\text{In}(n,\gamma)^{116}\text{In}$ at $E_n = 2.30 \pm 0.16 \text{ MeV}$ is found to be,

\[\sigma = 95.48 \pm 10.73 \text{ mb}\]
Neutron Energy $E_n$: 2.85 ± 0.15 MeV

**Set A(l)/γ: 417 keV:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>4850 ± 85 counts</td>
<td>$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$</td>
</tr>
<tr>
<td>$t_1$</td>
<td>4200 sec</td>
<td>$t_2 = 180$ sec</td>
</tr>
<tr>
<td>$t_3$</td>
<td>2000 sec</td>
<td>$\theta = 0.284$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.031</td>
<td>$N_0 = 6.685 \times 10^{20}$</td>
</tr>
<tr>
<td>$K$</td>
<td>0.9979</td>
<td>$\phi_{av}G = 1.2511 \times 10^7$ neutrons/cm$^2$-sec</td>
</tr>
</tbody>
</table>

$\sigma = 71.29 \pm 9.84$ mb

**Set A(l)/γ: 818 keV:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>901 ± 54 counts</td>
<td>$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$</td>
</tr>
<tr>
<td>$t_1$</td>
<td>4200 sec</td>
<td>$t_2 = 180$ sec</td>
</tr>
<tr>
<td>$t_3$</td>
<td>2000 sec</td>
<td>$\theta = 0.121$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.0135</td>
<td>$N_0 = 6.685 \times 10^{20}$</td>
</tr>
<tr>
<td>$K$</td>
<td>0.9988</td>
<td>$\phi_{av}G = 1.2511 \times 10^7$ neutrons/cm$^2$-sec</td>
</tr>
</tbody>
</table>

$\sigma = 77.31 \pm 10.38$ mb

**Set A(l)/γ: 1.09 MeV:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>3598 ± 72 counts</td>
<td>$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$</td>
</tr>
<tr>
<td>$t_1$</td>
<td>4200 sec</td>
<td>$t_2 = 180$ sec</td>
</tr>
<tr>
<td>$t_3$</td>
<td>2000 sec</td>
<td>$\theta = 0.575$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.0115</td>
<td>$N_0 = 6.685 \times 10^{20}$</td>
</tr>
<tr>
<td>$K$</td>
<td>0.9989</td>
<td>$\phi_{av}G = 1.2511 \times 10^7$ neutrons/cm$^2$-sec</td>
</tr>
</tbody>
</table>

$\sigma = 76.26 \pm 9.98$ mb
$E_n = 2.85 \pm 0.15 \text{ MeV}$

Set: $A(1)$

![Graph showing gamma rays](image)

Fig. 3.21: Characteristic gamma rays of 417 KeV, 818 KeV, 1.09 MeV & 1.29 MeV in the decay of $^{116}\text{mIn}$ and 443 KeV in the decay of $^{128}\text{I}$. 
Set A(1)/γ: 1.29 MeV:

\[ \begin{align*}
A &= 4394 \pm 70 \text{ counts} \\
t_1 &= 4200 \text{ sec} \\
t_2 &= 180 \text{ sec} \\
t_3 &= 2000 \text{ sec} \\
\epsilon &= 0.0095 \\
K &= 0.999 \quad \phi_{av} G = 1.2511 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 76.25 \pm 9.98 \text{ mb}
\end{align*} \]

Set A(2)/γ: 417 keV:

\[ \begin{align*}
A &= 2549 \pm 65 \text{ counts} \\
t_1 &= 4200 \text{ sec} \\
t_2 &= 3660 \text{ sec} \\
t_3 &= 2000 \text{ sec} \\
\epsilon &= 0.031 \\
K &= 0.9979 \quad \phi_{av} G = 1.2511 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 78.51 \pm 10.04 \text{ mb}
\end{align*} \]

Set A(2)/γ: 618 keV:

\[ \begin{align*}
A &= 488 \pm 38 \text{ counts} \\
t_1 &= 4200 \text{ sec} \\
t_2 &= 3660 \text{ sec} \\
t_3 &= 2000 \text{ sec} \\
\epsilon &= 0.0135 \\
K &= 0.9988 \quad \phi_{av} G = 1.2511 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 87.75 \pm 10.79 \text{ mb}
\end{align*} \]
Set $A(2)/\gamma$: 1.09 MeV:

$A = 1759 \pm 51$ counts  
$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$  
$t_1 = 4200$ sec  
$t_2 = 3660$ sec  
$t_3 = 2000$ sec  
$\theta = 0.575$  
$\varepsilon = 0.0115$  
$N_0 = 6.685 \times 10^{20}$  
$K = 0.9988$  
$\phi_{av}G = 1.2511 \times 10^7$ neutrons/cm$^2$-sec  

$\sigma = 78.11 \pm 10.02$ mb

Set $A(2)/\gamma$: 1.29 MeV:

$A = 2163 \pm 50$ counts  
$\lambda = 2.1255 \times 10^{-4}$ sec$^{-1}$  
$t_1 = 4200$ sec  
$t_2 = 3660$ sec  
$t_3 = 2000$ sec  
$\theta = 0.85$  
$\varepsilon = 0.0095$  
$N_0 = 6.685 \times 10^{20}$  
$K = 0.999$  
$\phi_{av}G = 1.2511 \times 10^7$ neutrons/cm$^2$-sec  

$\sigma = 71.01 \pm 9.84$ mb

Hence, the average $(n, \gamma)$ cross-section measured for the reaction $^{115}$In$(n, \gamma) \ ^{116}$In at neutron energy $E_n = 2.85 \pm 0.15$ MeV is found to be,

$\sigma = 76.16 \pm 9.02$ mb
Table 3.5: Activation cross-sections for the reaction \( ^{115}\text{In}(n,\gamma)^{116m}\text{In} \).

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy, ( E_n [\text{MeV}] )</th>
<th>Cross-section ( \sigma(n,\gamma) [\text{mb}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.07 ( \pm ) 0.20</td>
<td>208.90 ( \pm ) 24.73</td>
</tr>
<tr>
<td>2.</td>
<td>1.48 ( \pm ) 0.18</td>
<td>173.28 ( \pm ) 15.44</td>
</tr>
<tr>
<td>3.</td>
<td>1.89 ( \pm ) 0.17</td>
<td>139.38 ( \pm ) 14.53</td>
</tr>
<tr>
<td>4.</td>
<td>2.30 ( \pm ) 0.16</td>
<td>95.48 ( \pm ) 10.73</td>
</tr>
<tr>
<td>5.</td>
<td>2.85 ( \pm ) 0.15</td>
<td>76.16 ( \pm ) 9.02</td>
</tr>
</tbody>
</table>

3.7.4 \( ^{103}\text{Rh}(n,\gamma)^{104m}\text{Rh} \) reaction: 99.99\% spectrographically pure rhodium powder of mass 0.07235 gm and area 2.011 cm\(^2\) was used as target. The sample was irradiated along with two standard samples for a certain time \( t_1 \) at five different neutron energies in each set. The \((n,\gamma)\) cross-section measured here for \( ^{103}\text{Rh} \) is only for 4.34 min isomeric state \( ^{104m}\text{Rh} \). The isomeric state \( ^{104m}\text{Rh} \) decays through the isomeric transitions to the ground state of \( ^{104}\text{Rh} \). The most intense \( \gamma \)-ray transition is of 51 keV which is used for measuring the present cross-section values.

The evidence for the origin of 51 keV \( \gamma \)-ray was also sought by plotting the decreasing intensity of the 51 keV
Fig. 3.22:
(a) Singles spectrum of $^{104}$mRh + $^{128}$I decay produced by neutron irradiation
(b) Decay scheme of $^{104}$Rh
γ-ray as a function of decay time which yielded a half-life of 4.34 min (Fig. 3.23). The decay scheme of $^{104}$Rh and a singles spectrum of $^{104m}$Rh along with that of $^{128}$I is also shown in Fig. 3.22. The characteristic γ-ray of 51 keV in the decay of $^{104m}$Rh for each irradiation energy shown in Fig. 3.23 to 3.27 for a single set. The values of the parameters involved at different neutron energies for the calculation of the cross-section are given with each set.

**Neutron Energy**: $1.07 \pm 0.20$ MeV

**Set A(1):**

\[
\begin{align*}
A & = 4144 \pm 84 \text{ counts} \\
\lambda & = 2.6613 \times 10^{-3} \text{ sec}^{-1} \\
t_1 & = 1200 \text{ sec} \\
t_2 & = 40 \text{ sec} \\
t_3 & = 500 \text{ sec} \\
\theta & = 0.483 \\
\varepsilon & = 0.1175 \\
N_0 & = 8.5024 \times 10^{20} \\
K & = 0.818 \\
\sigma_{av.0} & = 2.9482 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma & = 14.94 \pm 2.07 \text{ mb}
\end{align*}
\]

**Set A(2):**

\[
\begin{align*}
A & = 1001 \pm 54 \text{ counts} \\
\lambda & = 2.6613 \times 10^{-3} \text{ sec}^{-1} \\
t_1 & = 1200 \text{ sec} \\
t_2 & = 600 \text{ sec} \\
t_3 & = 500 \text{ sec} \\
\theta & = 0.483 \\
\varepsilon & = 0.1175 \\
N_0 & = 8.5024 \times 10^{20}
\end{align*}
\]
Fig. 3.23 (a) Characteristic gamma ray of 51 KeV in the decay of 128I. (b) Typical decay curve of 104mRh.
\( K = 0.818 \quad \varphi_{av} G = 2.94820 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \)

\( \sigma = 16.02 \pm 2.42 \text{ mb} \)

**Set A(1):**

\( A = 297 \pm 35 \text{ counts} \quad \lambda = 2.6613 \times 10^{-3} \text{ sec}^{-1} \)

\( t_1 = 1200 \text{ sec} \quad t_2 = 750 \text{ sec} \)

\( t_3 = 300 \text{ sec} \quad \theta = 0.483 \)

\( \varepsilon = 0.1175 \quad N_0 = 8.5024 \times 10^{20} \)

\( K = 0.818 \quad \varphi_{av} G = 1.7897 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \)

\( \sigma = 15.61 \pm 2.36 \text{ mb} \)

Hence, the average \((n,\gamma)\) cross-section for the reaction \(^{103}\text{Rh}(n,\gamma)\) \(^{104}\text{Rh}\) at \(E_n = 1.07 \pm 0.20 \text{ MeV}\) is found to be as,

\( \sigma = 15.40 \pm 1.39 \text{ mb} \)

**Neutron Energy:** \(1.48 \pm 0.18 \text{ MeV}\)

**Set A(1):**

\( A = 1472 \pm 50 \text{ counts} \quad \lambda = 26613 \times 10^{-3} \text{ sec}^{-1} \)

\( t_1 = 1200 \text{ sec} \quad t_2 = 50 \text{ sec} \)

\( t_3 = 300 \text{ sec} \quad \theta = 0.483 \)

\( \varepsilon = 0.1175 \quad N_0 = 8.5024 \times 10^{20} \)
Fig. 3.24: Characteristic gamma ray of 51 KeV in the decay of $^{104m}$Rh and 443 KeV in the decay of $^{128I}$. 

$E_n = 1.48 \pm 0.18$ MeV 

Set: B(1)
\[ K = 0.818 \quad \varphi_{av} \cdot G = 1.849 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 11.58 \pm 1.33 \text{ mb} \]

Set A(2):

\[ A = 622 \pm 35 \text{ counts} \quad \lambda = 2.6613 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 370 \text{ sec} \]
\[ t_3 = 300 \text{ sec} \quad \theta = 0.483 \]
\[ \varepsilon = 0.1175 \quad \text{No} = 8.5024 \times 10^{20} \]
\[ K = 0.818 \quad \varphi_{av} \cdot G = 1.8491 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 11.51 \pm 1.49 \text{ mb} \]

Set B(1):

\[ A = 2807 \pm 65 \text{ counts} \quad \lambda = 2.6613 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 600 \text{ sec} \quad t_2 = 25 \text{ sec} \]
\[ t_3 = 200 \text{ sec} \quad \theta = 0.483 \]
\[ \varepsilon = 0.1175 \quad \text{No} = 8.5024 \times 10^{20} \]
\[ K = 0.818 \quad \varphi_{av} \cdot G = 5.5901 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 10.99 \pm 1.26 \text{ mb} \]

Set B(2):

\[ A = 1646 \pm 47 \text{ counts} \quad \lambda = 2.6613 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 600 \text{ sec} \quad t_2 = 230 \text{ sec} \]
\[ t_3 = 200 \text{ sec} \quad \theta = 0.483 \]
Neutron Energy $E_n : 1.89 \pm 0.17$ MeV

Set A(1):

$A = 2189 \pm 61$ counts \hspace{1cm} $\lambda = 2.6613 \times 10^{-3}$ sec$^{-1}$

$t_1 = 1200$ sec \hspace{1cm} $t_2 = 40$ sec

t_3 = 500 sec \hspace{1cm} \theta = 0.483

$\epsilon = 0.1175$ \hspace{1cm} $N_0 = 8.5024 \times 10^{20}$

$K = 0.818$ \hspace{1cm} $\phi_{av} \cdot \sigma = 2.4241 \times 10^7$ neutrons/cm$^2 \cdot$sec

$\sigma = 9.59 \pm 1.19$ mb

Set A(2):

$A = 525 \pm 40$ counts \hspace{1cm} $\lambda = 2.6613 \times 10^{-3}$ sec$^{-1}$

$t_1 = 1200$ sec \hspace{1cm} $t_2 = 590$ sec

t_3 = 500 sec \hspace{1cm} \theta = 0.583

$\epsilon = 0.1175$ \hspace{1cm} $N_0 = 8.5024 \times 10^{20}$

$K = 0.818$ \hspace{1cm} $\phi_{av} \cdot \sigma = 2.4241 \times 10^7$ neutrons/cm$^2 \cdot$sec

$\sigma = 9.95 \pm 1.37$ mb

Hence, the average $(n,\gamma)$ cross-section for the reaction $^{103}\text{Rh}(n,\gamma)^{104}\text{Rh}$ at $E_n = 1.89 \pm 0.17$ MeV is found to be,

$\sigma = 9.72 \pm 1.10$ mb
Fig. 3.25: Characteristic gamma ray of 51 KeV in the decay of $^{104}$mRh and 443 KeV in the decay of $^{128}$I.

$E_n = 1.89 \pm 0.17$ MeV
Set: B(1)
Neutron Energy: $2.30 \pm 0.16$ MeV

Set A(1):

$A = 3334 \pm 74$ counts \hspace{1cm} $\lambda = 2.6613 \times 10^{-3}$ sec$^{-1}$
$t_1 = 1800$ sec \hspace{1cm} $t_2 = 40$ sec
$t_3 = 800$ sec \hspace{1cm} $\theta = 0.483$
$c = 0.1175$ \hspace{1cm} $N_0 = 8.5024 \times 10^{20}$
$K = 0.818$ \hspace{1cm} $\varphi_{av}G = 2.4068 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 11.89 \pm 1.58$ mb

Set B(1):

$A = 2849 \pm 73$ counts \hspace{1cm} $\lambda = 2.6613 \times 10^{-3}$ sec$^{-1}$
$t_1 = 2610$ sec \hspace{1cm} $t_2 = 35$ sec
$t_3 = 800$ sec \hspace{1cm} $\theta = 0.483$
$c = 0.1175$ \hspace{1cm} $N_0 = 8.5024 \times 10^{20}$
$K = 0.818$ \hspace{1cm} $\varphi_{av}G = 2.1529 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 11.13 \pm 1.48$ mb

Hence, the average $(n, \gamma)$ cross section for the reaction $^{103}$Rh$(n, \gamma)^{104}$Rh at $E_n = 2.30 \pm 0.16$ MeV is found to be,

$\sigma = 11.48 \pm 1.38$ mb
Fig. 3.26: Characteristic gamma ray of 51 KeV in the decay of $^{104m}$Rh and 443 KeV in the decay of $^{128I}$. 

Energy: $E_n = 2.30 \pm 0.16$ MeV 
Set: B(1)
Neutron Energy: $2.85 \pm 0.15$ MeV

Set A(1):

$$A = 1353 \pm 54 \text{ counts} \quad \lambda = 2.6613 \times 10^{-3} \text{ sec}^{-1}$$

$$t_1 = 1960 \text{ sec} \quad t_2 = 20 \text{ sec}$$

$$t_3 = 800 \text{ sec} \quad \theta = 0.483$$

$$\varepsilon = 0.1175 \quad N_0 = 8.5024 \times 10^{20}$$

$$K = 0.818 \quad \varphi_{av} \cdot G = 1.2553 \times 10^7 \text{ neutrons/cm}^2\text{-sec}$$

$$\sigma = 8.75 \pm 1.12 \text{ mb}$$

Hence, the average $(n,\gamma)$ cross-section for the reaction $^{103}\text{Rh}(n,\gamma)^{104}\text{Rh}$ at neutron energy $E_n = 2.85 \pm 0.15$ MeV is found to be,

$$\sigma = 8.75 \pm 1.21 \text{ mb}$$

Table 3.6: Activation cross-sections for the reaction $^{103}\text{Rh}(n,\gamma)^{104}\text{Rh}$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy $E_n$ [MeV]</th>
<th>Cross-section $\sigma (n,\gamma)$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$1.07 \pm 0.20$</td>
<td>$15.40 \pm 1.93$</td>
</tr>
<tr>
<td>2.</td>
<td>$1.48 \pm 0.18$</td>
<td>$11.38 \pm 1.02$</td>
</tr>
<tr>
<td>3.</td>
<td>$1.89 \pm 0.17$</td>
<td>$9.72 \pm 1.10$</td>
</tr>
<tr>
<td>4.</td>
<td>$2.30 \pm 0.16$</td>
<td>$11.48 \pm 1.38$</td>
</tr>
<tr>
<td>5.</td>
<td>$2.85 \pm 0.15$</td>
<td>$8.75 \pm 1.21$</td>
</tr>
</tbody>
</table>
En = 2.85 ± 0.15 MeV
Set: A(1)

Fig. 3.27. Characteristic gamma ray of 51 KeV in the decay of $^{104}\text{mRh}$ and 443 KeV in the decay of $^{128}\text{I}$. 
Purified (99.9%) manganese powder was used for the preparation of the sample target. The sample whose mass and area was 0.4383 g and 2.011 cm² respectively, was irradiated along with two standard samples in the zero-degree forward direction with the proton beam by placing it at 2.5 cm distance from the tritium target. Manganese is a monocisotopic element and hence the activity produced in the sample due to neutron irradiation was of $^{56}$Mn. It decays through $\gamma$-emission to the excited states of $^{56}$Fe. Most intense $\gamma$-ray in the decay of $^{56}$Mn is of 0.847 MeV which has been made use of, for the measurement of $^{55}$Mn(n,\(\gamma\)) $^{56}$Mn cross-section. The decay scheme of $^{56}$Mn is shown in Fig. 3.29(b). To be sure whether this gamma ray was attributed to the 2.578 hrs activity of $^{56}$Mn, the decreasing intensity of this gamma ray was plotted as a function of decay time which gave a half-life of 2.578 hrs (shown in Fig. 3.28). Similar irradiations were performed at different neutron energies and events under this 0.847 MeV peak were recorded for the calculation of $^{55}$Mn(n,\(\gamma\)) $^{56}$Mn reaction cross-section at the five neutron energies. The characteristic $\gamma$-ray of 847 keV in the decay of $^{56}$Mn and 443 keV in the decay of $^{128}$I for each neutron energy are shown in Figs. 3.28 to 3.32 for a single set.
Fig. 3.28 (a) Characteristic gamma ray of 847 keV in the decay of $^{56}$Mn and 443 keV in the decay of $^{128}$I. (b) Typical decay curve of $^{56}$Mn.
Fig. 3.29 (a) Characteristic gamma ray of 847 KeV in the decay of $^{56}$Mn and 443 KeV in the decay of $^{128}$I. (b) Decay scheme of $^{56}$Mn.
Neutron Energy $E_n = 1.07 \pm 0.20$ MeV

**Set A(1):**

$A = 2857 \pm 56$ counts \hspace{1cm} $\lambda = 7.4612 \times 10^{-5}$ sec$^{-1}$

$t_1 = 3180$ sec \hspace{1cm} $t_2 = 390$ sec

$t_3 = 3000$ sec \hspace{1cm} $\theta = 0.9837$

$\epsilon = 0.013$ \hspace{1cm} $N_0 = 46,9027 \times 10^{20}$

$K = 0.9985$ \hspace{1cm} $\phi_{av} \cdot G = 1.1130 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 7.72 \pm 1.01$ mb

**Set A(2):**

$A = 1350 \pm 40$ counts \hspace{1cm} $\lambda = 7.4612 \times 10^{-5}$ sec$^{-1}$

$t_1 = 3180$ sec \hspace{1cm} $t_2 = 5820$ sec

$t_3 = 200$ sec \hspace{1cm} $\theta = 0.9837$

$\epsilon = 0.013$ \hspace{1cm} $N_0 = 46,9027 \times 10^{20}$

$K = 0.9985$ \hspace{1cm} $\phi_{av} \cdot G = 1.11304 \times 10^7$ neutrons/cm$^2$-sec

$\sigma = 7.92 \pm 1.03$ mb

Hence, the average $(n, \gamma)$ cross-section measured for the reaction $^{55}$Mn$(n, \gamma)^{56}$Mn at $E_n = 1.07 \pm 0.20$ MeV is found to be,

$\sigma = 7.82 \pm 0.97$ mb
Neutron Energy $E_n : 1.48 \pm 0.18$ MeV

Set A(1):

\begin{align*}
A &= 473 \pm 26 \text{ counts} \quad \lambda = 7.4612 \times 10^{-5} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \quad t_2 = 2445 \text{ sec} \\
t_3 &= 2046 \text{ sec} \quad \theta = 0.9887 \\
c &= 0.013 \quad N_0 = 46.9027 \times 10^{20} \\
k &= 0.9985 \quad \phi_{av} G = 0.8716 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 4.53 \pm 0.52 \text{ mb}
\end{align*}

Hence, the average $(n,\gamma)$ cross-section measured for the reaction $^{55}\text{Mn}(n,\gamma) ^{56}\text{Mn}$ at $E_n = 1.48 \pm 0.18$ MeV is found to be,

\[ \sigma = 4.53 \pm 0.52 \text{ mb} \]

Neutron Energy $E_n : 1.89 \pm 0.17$ MeV

Set A(1):

\begin{align*}
A &= 1370 \pm 43 \text{ counts} \quad \lambda = 7.4162 \times 10^{-5} \text{ sec}^{-1} \\
t_1 &= 1800 \text{ sec} \quad t_2 = 1650 \text{ sec} \\
t_3 &= 3000 \text{ sec} \quad \theta = 0.9887 \\
c &= 0.013 \quad N_0 = 46.9027 \times 10^{20} \\
k &= 0.9985 \quad \phi_{av} G = 1.9218 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \\
\sigma &= 3.96 \pm 0.47 \text{ mb}
\end{align*}
En = 1.89 ± 0.17 MeV
Set : A(1)

Fig. 3.30: Characteristic gamma ray of 847 keV in the decay of $^{56}$Mn and 443 keV in the decay of $^{128}$I.
Set A(2):

\[ A = 280 \pm 20 \text{ counts} \quad \lambda = 7.4612 \times 10^{-5} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \quad t_2 = 9210 \text{ sec} \]
\[ t_3 = 1022 \text{ sec} \quad t = 0.9887 \]
\[ \varepsilon = 0.013 \quad No = 46.9027 \times 10^{20} \]
\[ K = 0.9985 \quad \varphi_{av} G = 1.9218 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 3.88 \pm 0.48 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{55}\text{Mn}(n, \gamma) ^{56}\text{Mn}\) at \(E_n = 1.89 \pm 0.17 \text{ MeV}\) is found to be,

\[ \sigma = 3.93 \pm 0.43 \text{ mb} \]

**Neutron Energy** \(E_n = 2.30 \pm 0.16 \text{ MeV} \)

Set A(1):

\[ A = 846 \pm 34 \text{ counts} \quad \lambda = 7.4612 \times 10^{-5} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \quad t_2 = 1320 \text{ sec} \]
\[ t_3 = 2000 \text{ sec} \quad t = 0.9887 \]
\[ \varepsilon = 0.013 \quad No = 46.9027 \times 10^{20} \]
\[ K = 0.9985 \quad \varphi_{av} G = 2.7107 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 2.64 \pm 0.35 \text{ mb} \]
$E_n = 2.30 \pm 0.16 \text{ MeV}$

Set: A(1)

Fig. 3.31: Characteristic gamma ray of 847 KeV in the decay of $^{56}\text{Mn}$ and 443 KeV in the decay of $^{128}\text{I}$. 
Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{55}\text{Mn}(n, \gamma)\) \(^{56}\text{Mn}\) at neutron energy, \(E_n = 2.30 \pm 0.16\) MeV is found to be,

\[\sigma = 2.64 \pm 0.35\text{ mb}\]

**Neutron Energy** \(E_n = 2.85 \pm 0.15\) MeV

**Set A(1):**

\[\begin{align*}
A &= 686 \pm 32 \text{ counts} \\
\lambda &= 7.4612 \times 10^{-5} \text{ sec}^{-1} \\
t_1 &= 3300 \text{ sec} \\
t_2 &= 1380 \text{ sec} \\
t_3 &= 2000 \text{ sec} \\
\theta &= 0.9887 \\
\epsilon &= 0.013 \\
N_0 &= 46.9027 \times 10^{20} \\
\kappa &= 0.9985 \\
\phi_{av} \cdot G &= 1.2936 \times 10^{7} \text{ neutrons/cm}^2\text{-sec}
\end{align*}\]

\[\sigma = 2.08 \pm 0.29\text{ mb}\]

Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{55}\text{Mn}(n, \gamma)\) \(^{56}\text{Mn}\) at neutron energy \(E_n = 2.85 \pm 0.15\) MeV is found to be,

\[\sigma = 2.08 \pm 0.29\text{ mb}\]
En = 2.85 ± 0.15 MeV
Set: A(1)

Fig. 3.32: Characteristic gamma ray of 847 KeV in the decay of $^{56}$Mn and 443 KeV in the decay of $^{128}$I.
Table 3.7: The activation cross-sections for the reaction \( ^{55}\text{Mn}(n,\gamma)\ ^{56}\text{Mn} \).

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Neutron Energy, ( E_n ) [MeV]</th>
<th>Measured cross-section ( \sigma(n,\gamma) ) [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.07 ( \pm ) 0.20</td>
<td>7.82 ( \pm ) 0.97</td>
</tr>
<tr>
<td>2.</td>
<td>1.48 ( \pm ) 0.18</td>
<td>4.53 ( \pm ) 0.52</td>
</tr>
<tr>
<td>3.</td>
<td>1.89 ( \pm ) 0.17</td>
<td>3.93 ( \pm ) 0.43</td>
</tr>
<tr>
<td>4.</td>
<td>2.30 ( \pm ) 0.16</td>
<td>2.64 ( \pm ) 0.35</td>
</tr>
<tr>
<td>5.</td>
<td>2.85 ( \pm ) 0.15</td>
<td>2.08 ( \pm ) 0.29</td>
</tr>
</tbody>
</table>

3.7.6 \( ^{51}\text{V}(n,\gamma)\ ^{52}\text{V} \) reaction:

The spectpure powder of \( \text{V}_2\text{O}_5 \) with purity better than 99.99\% was used for the preparation of the samples. Two samples of masses 0.12495 gm, 0.09589 gm and area 2.011 cm\(^2\) each were used as targets. In the natural vanadium sample, the abundance of \( ^{51}\text{V} \) is 99.75\%. Another stable isotope is \( ^{50}\text{V} \) whose abundance is only 0.25\%, moreover, its end product in the \( (n,\gamma) \) reaction is stable. These two samples were irradiated along with standard sample in between them for a certain time \( t_1 \) at the five different neutron energies in each set. The characteristic
Fig. 3.33(a): Singles spectrum of $^{52}_{V}$ $^{128}_{1}$ decay produced by neutron irradiation
(b) Decay scheme of $^{52}_{V}$. 
gamma ray line of 1.434 MeV in the decay of $^{52}\text{V}$, produced by the reaction $^{51}\text{V}(n,\gamma)\,^{52}\text{V}$, was sorted out and the counts under this photopeak were recorded in PHA mode of the multichannel analyser, coupled with the high resolution Ge(Li) detector, for a particular time $t_3$. The decay scheme of $^{52}\text{V}$ and the recorded singles spectrum of $^{52}\text{V}$ along with $^{128}\text{I}$ are shown in Fig. 3.33. To be sure that the gamma-ray peak appeared at energy 1.434 MeV is only due to the decay of $^{52}\text{V}$, the counts under the photopeaks were recorded at subsequent time intervals during its decay upto several half-lives and are plotted in Fig. 3.34.

The characteristic gamma ray of 1.434 MeV in the decay of $^{52}\text{V}$ and 443 keV in the decay of $^{128}\text{I}$ are shown in Figs. 3.34 to 3.38 at each neutron energy, for a single set.

**Neutron Energy** $E_n : 1.07 \pm 0.20$ MeV

**Set A(1):**

$A = 645 \pm 26 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1}$

$t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec}$

$t_3 = 586 \text{ sec} \quad \theta = 1$

$\varepsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20}$

$K = 0.9987 \quad \varphi_{av}.G = 3.9712 \times 10^7 \text{ neutrons/cm}^2\text{-sec}$

$\sigma = 2.71 \pm 0.30 \text{ mb}$
$E_n = 1.07 \pm 0.20 \text{ MeV}$

Set: A(1)

Fig. 3.34 (a) Characteristic gamma ray of 1.434 MeV in the decay of $^{52}V$ and 443 keV in the decay of $^{128}I$.

(b) Typical decay curve of $^{52}V$. 

$T_{1/2} = 3.76 \text{ min}$
Set A(2):

\[ A = 108 \pm 11 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 690 \text{ sec} \]
\[ t_3 = 907 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \varphi_{av.0} = 3.9712 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 2.80 \pm 0.48 \text{ mb} \]

Set B(1):

\[ A = 602 \pm 25 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 40 \text{ sec} \]
\[ t_3 = 574 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \varphi_{av.0} = 3.2953 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 2.89 \pm 0.42 \text{ mb} \]

Set B(2):

\[ A = 101 \pm 11 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 630 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \varphi_{av.0} = 3.2953 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 3.13 \pm 0.54 \text{ mb} \]
Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{51}\text{V}(n, \gamma)^{52}\text{V}\), at \(E_n = 1.07 \pm 0.20\) MeV is given as:

\[
\sigma = 2.84 \pm 0.36 \text{ mb}
\]

**Neutron Energy \(E_n\): 1.48 \pm 0.18\) MeV

**Set A(1):**

\[
\begin{align*}
A &= 141 \pm 12 \text{ counts} \\
\lambda &= 3.0718 \times 10^{-3} \text{ sec}^{-1} \\
t_1 &= 1200 \text{ sec} \\
t_2 &= 30 \text{ sec} \\
t_3 &= 400 \text{ sec} \\
\epsilon &= 0.0093 \\
\theta &= 1 \\
\gamma &= 0.9989 \\
\end{align*}
\]

\[
\text{\(\bar{P}_{av} \cdot G\) = 2.7689 \times 10^7 \text{ neutrons/cm}^2\text{-sec}}
\]

\[
\sigma = 2.11 \pm 0.26 \text{ mb}
\]

**Set B(1):**

\[
\begin{align*}
A &= 333 \pm 18 \text{ counts} \\
\lambda &= 3.0718 \times 10^{-3} \text{ sec}^{-1} \\
t_1 &= 1200 \text{ sec} \\
t_2 &= 50 \text{ sec} \\
t_3 &= 222 \text{ sec} \\
\epsilon &= 0.0093 \\
\theta &= 1 \\
\gamma &= 0.9987 \\
\end{align*}
\]

\[
\text{\(\bar{P}_{av} \cdot G\) = 4.3357 \times 10^7 \text{ neutrons/cm}^2\text{-sec}}
\]

\[
\sigma = 2.37 \pm 0.29 \text{ mb}
\]
En = 1.48 ± 0.18 MeV

Set: B(1)

Fig. 3.35: Characteristic gamma ray of 1.434 MeV in the decay of 52V and 443 keV in the decay of 128I.
Set B(2):

\[ A = 276 \pm 17 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 300 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \Theta = 1 \]
\[ \epsilon = 0.0093 \quad \text{No} = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \varphi_{av} \cdot G = 4.3357 \times 10^{7} \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 2.35 \pm 0.36 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{51}V(n, \gamma)\) \(^{52}V\), at \(E_n = 1.48 \pm 0.18 \text{ MeV}\) is given as:
\[ \sigma = 2.25 \pm 0.22 \text{ mb} \]

**Neutron Energy** \(E_n : 1.89 \pm 0.17 \text{ MeV} \)

Set A(1):

\[ A = 218 \pm 15 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1300 \text{ sec} \quad t_2 = 60 \text{ sec} \]
\[ t_3 = 525 \text{ sec} \quad \Theta = 1 \]
\[ \epsilon = 0.0093 \quad \text{No} = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \varphi_{av} \cdot G = 1.6431 \times 10^{7} \text{ neutrons/cm}^2\text{-sec} \]
\[ \sigma = 1.77 \pm 0.23 \text{ mb} \]
Fig 3.36: Characteristic gamma ray of 1.434 MeV in the decay of $^{52}$V and 443 KeV in the decay of $^{128}$I.
Set B(1):

\[ A = 179 \pm 13 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1200 \text{ sec} \quad t_2 = 30 \text{ sec} \]
\[ t_3 = 500 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \phi_{av} \cdot G = 1.6183 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 1.79 \pm 0.23 \text{ mb} \]

Hence, the average \((n,\gamma)\) cross-section measured for the reaction \(^{51}\text{V}(n,\gamma)^{52}\text{V}\), at \(E_n = 1.89 \pm 0.17\) MeV is given as,

\[ \sigma = 1.78 \pm 0.20 \text{ mb} \]

\textbf{Neutron Energy} \(E_n = 2.30 \pm 0.16\) MeV

Set A(1):

\[ A = 199 \pm 14 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1800 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 802 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \phi_{av} \cdot G = 1.7894 \times 10^7 \text{ neutrons/cm}^2\text{-sec} \]

\[ \sigma = 1.61 \pm 0.22 \text{ mb} \]
En = 2.30 ± 0.16 MeV
Set: A(1)

Fig. 3.37: Characteristic gamma ray of 1.434 MeV in the decay of $^{52}$V and 443 KeV in the decay of $^{128}$I.
Set B(1):

\[ A = 214 \pm 15 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 1830 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 894 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \phi_{\text{av} \cdot G} = 1.7957 \times 10^7 \text{ neutrons/cm}^2 \text{ -sec} \]

\[ \sigma = 1.68 \pm 0.23 \text{ mb} \]

Hence, the average \((n, \gamma)\) cross-section measured for the reaction \(^{51}\text{V}(n, \gamma) \rightarrow ^{52}\text{V}\), at \(E_n = 2.30 \pm 0.16 \text{ MeV}\) is given as,

\[ \sigma = 1.64 \pm 0.20 \text{ mb} \]

**Neutron Energy** \(E_n : 2.85 \pm 0.15 \text{ MeV} \)

Set A(1):

\[ A = 52 \pm 6 \text{ counts} \quad \lambda = 3.0718 \times 10^{-3} \text{ sec}^{-1} \]
\[ t_1 = 900 \text{ sec} \quad t_2 = 50 \text{ sec} \]
\[ t_3 = 600 \text{ sec} \quad \theta = 1 \]
\[ \epsilon = 0.0093 \quad N_0 = 29.2854 \times 10^{20} \]
\[ K = 0.9987 \quad \phi_{\text{av} \cdot G} = 0.8905 \times 10^7 \text{ neutrons/cm}^2 \text{ -sec} \]

\[ \sigma = 0.92 \pm 0.13 \text{ mb} \]
Fig. 3.38: Characteristic gamma ray of 1.434 MeV in the decay of $^{52}$V and 443 KeV in the decay of $^{128}$I.
Hence, the average \((n,\gamma)\) cross-section for the reaction \(^{51}\text{V}(n,\gamma)\) \(^{52}\text{V}\) at \(E_n = 2.85 \pm 0.15\) MeV is obtained as

\[
\sigma = 0.92 \pm 0.13 \text{ mb}
\]

Table 3.8: Activation cross-sections for the reaction \(^{51}\text{V}(n,\gamma)\) \(^{52}\text{V}\).

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy, (E_n) (MeV)</th>
<th>Cross-section (\sigma(n,\gamma)) [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.07 (\pm) 0.20</td>
<td>2.84 (\pm) 0.35</td>
</tr>
<tr>
<td>2.</td>
<td>1.43 (\pm) 0.18</td>
<td>2.25 (\pm) 0.22</td>
</tr>
<tr>
<td>3.</td>
<td>1.89 (\pm) 0.17</td>
<td>1.78 (\pm) 0.20</td>
</tr>
<tr>
<td>4.</td>
<td>2.30 (\pm) 0.16</td>
<td>1.64 (\pm) 0.20</td>
</tr>
<tr>
<td>5.</td>
<td>2.85 (\pm) 0.15</td>
<td>0.92 (\pm) 0.13</td>
</tr>
</tbody>
</table>

3.8 Results and Discussion:

The capture cross-sections for the reactions \(^{160}\text{Gd}(n,\gamma)\) \(^{161}\text{Gd}\), \(^{154}\text{Sm}(n,\gamma)\) \(^{155}\text{Sm}\), \(^{115}\text{In}(n,\gamma)\) \(^{116}\text{In}\), \(^{103}\text{Rh}(n,\gamma)\) \(^{104}\text{Rh}\), \(^{55}\text{Mn}(n,\gamma)\) \(^{56}\text{Mn}\) and \(^{51}\text{V}(n,\gamma)\) \(^{52}\text{V}\) are measured at five neutron energies of 1.07 \(\pm\) 0.20 MeV, 1.48 \(\pm\) 0.18 MeV, 1.89 \(\pm\) 0.17 MeV, 2.30 \(\pm\) 0.16 MeV and
2.85 ± 0.15 MeV. These cross-section values are tabulated in Table 3.9. These data together with the results of previous investigations\(^9\) (wherever available) are shown in Figures 3.39 to 3.44. These measurements provide a means for testing the accuracy of the statistical theory of nuclear reactions, which is widely used with varying degrees of success to predict nuclear properties including energy averaged cross-sections. The experimental measurements are also useful for the choice of structural and fuel cladding materials in the design of fast nuclear reactors.

The vertical error bars in our experimental results indicate the r.m.s. standard deviation in the values of the cross-sections and the horizontal bars represent the neutron energy spread associated with each data points. The solid curves in Figs. 3.39, 3.40, 3.43 and 3.44 represent the statistical theory calculations due to Holmes et.al.\(^12\) (See Chapter II, sec. 2.1.1).

In the present cross-section measurements, enriched isotopes of \(^{160}\text{Gd}\) and \(^{154}\text{Sm}\) were used as samples, while rest of the cross-sections were measured using spectrographically pure samples with purity better than 99.99\%.

Gadolinium is one of the important elements as far as reactor design is concerned. It is used in the control
Fig 3.39. Capture Cross-sections for the reaction $^{160}\text{Gd}(n,\gamma)^{161}\text{Gd}$ as a function of Neutron Energy.
Fig. 3-40: Capture Cross-sections for the reaction $^{154}_{\text{Sm}}(n,\gamma)^{155}\text{Sm}$ as a function of Neutron Energy.
Fig. 3.41: Capture Cross-sections for the reaction $^{115\text{In}}(n,\gamma)^{116\text{mIn}}$ as a function of Neutron Energy.
\[ ^{103}\text{Rh}(n,\gamma)^{104m}\text{Rh} \]

<table>
<thead>
<tr>
<th>En (MeV)</th>
<th>( \sigma_{n\gamma} ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07 ± 0.20</td>
<td>15.40 ± 1.93</td>
</tr>
<tr>
<td>1.48 ± 0.18</td>
<td>11.38 ± 1.02</td>
</tr>
<tr>
<td>1.89 ± 0.17</td>
<td>9.72 ± 1.10</td>
</tr>
<tr>
<td>2.30 ± 0.16</td>
<td>11.48 ± 1.38</td>
</tr>
<tr>
<td>2.85 ± 0.15</td>
<td>8.75 ± 1.21</td>
</tr>
</tbody>
</table>

**Fig. 3.42:** Capture Cross-sections for the reaction \( ^{103}\text{Rh}(n,\gamma)^{104m} \) as a function of Neutron Energy.
Fig. 3.44: Capture Cross-sections for the reaction $^{51}\text{V}(n,\gamma)^{52}\text{V}$ as a function of Neutron Energy.
Table 3.9
Neutron Activation Cross-sections Measured at Five Neutron Energies

<table>
<thead>
<tr>
<th>Neutron Energy (En) [MeV]</th>
<th>Measured Cross-sections (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>160Gd(n,γ)</td>
</tr>
<tr>
<td>1.07±0.20</td>
<td>25.43 ± 3.03</td>
</tr>
<tr>
<td>1.48±0.18</td>
<td>19.66 ± 1.78</td>
</tr>
<tr>
<td>1.89±0.17</td>
<td>18.73 ± 1.92</td>
</tr>
<tr>
<td>2.30±0.16</td>
<td>13.99 ± 1.59</td>
</tr>
<tr>
<td>2.85±0.15</td>
<td>11.43 ± 1.49</td>
</tr>
</tbody>
</table>

* (54.34 min < 2.16 sec) isomeric states

** 4.35 min isomeric state
red of the reactors$^{13,14}$. The capture cross-section for for the reaction$^{160}$Gd$^*(n,\gamma)$ $^{161}$Gd has been measured probably for the first time in the above energy region. Table 3.10 and Figure 3.45 show that agreement between experimental and theoretical cross-section values$^{12}$) upto about 3 MeV energy is quite good and hence the mode of reaction which takes place upto this energy is well predictable within the framework of statistical theory.

The $(n,\gamma)$ cross-section for the reaction$^{154}$Sm $(n,\gamma)$ $^{155}$Sm is also measured using enriched sample. Only one earlier measurement for this reaction has been reported by Johnsrud et.al.$^{15}$) using natural samarium oxide and also using NaI(Tl) detector. Their values are in general lower by about 20% from our measurements. However, the agreement between experimental and theoretical results$^{12}$) are quite good.

Alloys of vanadium is one of the fuel cladding and structural materials being considered for future fast reactors designing. Speepure samples were used for the $^{52}$V$(n,\gamma)$ $^{52}$V cross-section measurements. Our measured values are generally higher than the measurements of Johnsrud et.al.$^{15}$) except at 2.85 MeV energy, where the agreement is quite good [Fig. 3.44]. However, the measurements by Dudey et.al.$^{16}$) who have measured $(n,\gamma)$ cross-section upto 1.5 MeV neutron energy are somewhat
closer to our measurements. The values of Dudey et al.\textsuperscript{16} do not show any systematic variation in this energy region as is clear from Figure 3.45.

Indium is also an important metal being used in the breeder reactors as a fuel in the form of Th-In and Pu-In alloys\textsuperscript{13,14}. The isomeric cross-section \( ^{115}\text{In} (n,\gamma)^{116}\text{In} \) for the two isomeric states (54.34 min, 2.16 sec) have been measured. Two earlier measurements are available in this energy region. Johnsrud et al.\textsuperscript{15} have measured the isomeric cross-sections using NaI(Tl) detector. Their values are comparable with our measurements within experimental limits. However, the data points measured by Menlove et al.\textsuperscript{17} in the above energy region are in fair agreement with our data points.

Rhodium is one of the important members of the elements being used in control rod designing\textsuperscript{13,14}. The cross-sections for the reaction \( ^{103}\text{Rh}(n,\gamma)^{104}\text{Rh} \) for 4.55 min isomeric states, have been measured probably for the first time in the above energy region. At neutron energies below 1.5 MeV, only one measurement by Cox\textsuperscript{18} using beta detection technique is available in the literature. His cross-section value at 1.49 MeV is in good agreement with our measured value at 1.48 MeV, while below this energy his values are lower by about 30\% from ours.
The alloys of zirconium with manganese is used as one of the structural material in the nuclear power reactors\textsuperscript{13,14}. A few previous measurements for the reaction \( ^{55}\text{Mn}(n,\gamma)^{56}\text{Mn} \) are available in the literature in the above energy region, but our measured cross-section values are quite high at 1.07 MeV. It is higher by a factor of two to three than the previous measurements of Stavissky and Tolstikov\textsuperscript{19} and Johnsrud et al.\textsuperscript{15}. At other energies our results are somewhat closer to the measurement of Johnsrud et al.\textsuperscript{15}. At 2.85 MeV neutron energy, our cross-section value is in good agreement with the result of Dovbenko et al.\textsuperscript{20}, but is smaller by about 30\% from the result of Leipunske\textsuperscript{y} et al.\textsuperscript{21}. Our experimentally measured cross-section values for the reaction \( ^{55}\text{Mn}(n,\gamma)^{56}\text{Mn} \) are generally higher by a factor of 2 to 4 than the theoretical values\textsuperscript{12} in the above energy region.

To extract some definite conclusion about the reaction mechanism which reproduce the experimental cross-section data in the above energy region, we have compared our measured values of \( \sigma_{\text{exp}}(n,\gamma) \) with the theoretical calculations of Holmes et al.\textsuperscript{12}, which is based upon the statistical theory. Out of six nuclei studied in the present work we have made the comparison for the four nuclei, i.e., \( ^{160}\text{Gd}, ^{154}\text{Sm}, ^{55}\text{Mn} \) and \( ^{51}\text{V} \) whose total \( (n,\gamma) \)
### Table 3.10: The \((n, \gamma)\) activation cross-section for the reaction \(^{160}\text{Gd}(n, \gamma)^{161}\text{Gd}\)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy ((E_n)) [MeV]</th>
<th>(\sigma_{\text{exp}}(n, \gamma)) [mb]</th>
<th>(\sigma_{\text{theo}}(n, \gamma)) [mb]</th>
<th>(\frac{\sigma_{\text{exp}}(n, \gamma)}{\sigma_{\text{theo}}(n, \gamma)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07 ± 0.20</td>
<td>25.43 ± 3.03</td>
<td>23.4</td>
<td>1.09 ± 0.13</td>
</tr>
<tr>
<td>2</td>
<td>1.48 ± 0.18</td>
<td>19.66 ± 1.78</td>
<td>24.4</td>
<td>0.81 ± 0.07</td>
</tr>
<tr>
<td>3</td>
<td>1.89 ± 0.17</td>
<td>18.73 ± 1.92</td>
<td>22.2</td>
<td>0.84 ± 0.09</td>
</tr>
<tr>
<td>4</td>
<td>2.30 ± 0.16</td>
<td>13.99 ± 1.59</td>
<td>17.4</td>
<td>0.80 ± 0.09</td>
</tr>
<tr>
<td>5</td>
<td>2.85 ± 0.15</td>
<td>11.43 ± 1.44</td>
<td>10.6</td>
<td>1.08 ± 0.14</td>
</tr>
</tbody>
</table>

### Table 3.11: The \((n, \gamma)\) activation cross-section for the reaction \(^{154}\text{Sm}(n, \gamma)^{55}\text{Sm}\)

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy ((E_n)) [MeV]</th>
<th>(\sigma_{\text{exp}}(n, \gamma)) [mb]</th>
<th>(\sigma_{\text{theo}}(n, \gamma)) [mb]</th>
<th>(\frac{\sigma_{\text{exp}}(n, \gamma)}{\sigma_{\text{theo}}(n, \gamma)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07 ± 0.20</td>
<td>50.49 ± 6.16</td>
<td>33.5</td>
<td>1.51 ± 0.18</td>
</tr>
<tr>
<td>2</td>
<td>1.48 ± 0.18</td>
<td>48.16 ± 4.52</td>
<td>30.5</td>
<td>1.58 ± 0.15</td>
</tr>
<tr>
<td>3</td>
<td>1.89 ± 0.17</td>
<td>45.88 ± 5.69</td>
<td>33.6</td>
<td>1.37 ± 0.17</td>
</tr>
<tr>
<td>4</td>
<td>2.30 ± 0.16</td>
<td>23.28 ± 3.45</td>
<td>34.1</td>
<td>0.83 ± 0.10</td>
</tr>
<tr>
<td>5</td>
<td>2.85 ± 0.15</td>
<td>24.08 ± 3.32</td>
<td>27.0</td>
<td>0.89 ± 0.12</td>
</tr>
</tbody>
</table>
Table 3.12 : The $(n, \gamma)$ activation cross-section for the reaction $^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy $(E_n)$ [MeV]</th>
<th>$\sigma_{\text{exp}}(n, \gamma)$ [mb]</th>
<th>$\sigma_{\text{theo}}(n, \gamma)$ [mb]</th>
<th>$\sigma_{\text{exp}}(n, \gamma)/\sigma_{\text{theo}}(n, \gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.07 \pm 0.20$</td>
<td>$7.82 \pm 0.97$</td>
<td>$1.8$</td>
<td>$4.34 \pm 0.54$</td>
</tr>
<tr>
<td>2</td>
<td>$1.48 \pm 0.18$</td>
<td>$4.53 \pm 0.52$</td>
<td>$1.4$</td>
<td>$3.23 \pm 0.37$</td>
</tr>
<tr>
<td>3</td>
<td>$1.89 \pm 0.17$</td>
<td>$3.93 \pm 0.43$</td>
<td>$1.2$</td>
<td>$3.27 \pm 0.36$</td>
</tr>
<tr>
<td>4</td>
<td>$2.30 \pm 0.16$</td>
<td>$2.64 \pm 0.35$</td>
<td>$1.0$</td>
<td>$2.64 \pm 0.35$</td>
</tr>
<tr>
<td>5</td>
<td>$2.85 \pm 0.15$</td>
<td>$2.08 \pm 0.29$</td>
<td>$0.8$</td>
<td>$2.60 \pm 0.36$</td>
</tr>
</tbody>
</table>

Table 3.13 : The $(n, \gamma)$ activation cross-section for the reaction $^{51}\text{V}(n, \gamma)^{52}\text{V}$

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Neutron Energy $(E_n)$ [MeV]</th>
<th>$\sigma_{\text{exp}}(n, \gamma)$ [mb]</th>
<th>$\sigma_{\text{theo}}(n, \gamma)$ [mb]</th>
<th>$\sigma_{\text{exp}}(n, \gamma)/\sigma_{\text{theo}}(n, \gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.07 \pm 0.20$</td>
<td>$2.85 \pm 0.35$</td>
<td>$1.90$</td>
<td>$1.50 \pm 0.18$</td>
</tr>
<tr>
<td>2</td>
<td>$1.48 \pm 0.18$</td>
<td>$2.25 \pm 0.22$</td>
<td>$1.93$</td>
<td>$1.17 \pm 0.11$</td>
</tr>
<tr>
<td>3</td>
<td>$1.89 \pm 0.17$</td>
<td>$1.78 \pm 0.20$</td>
<td>$1.15$</td>
<td>$1.55 \pm 0.17$</td>
</tr>
<tr>
<td>4</td>
<td>$2.30 \pm 0.16$</td>
<td>$1.64 \pm 0.20$</td>
<td>$1.04$</td>
<td>$1.58 \pm 0.19$</td>
</tr>
<tr>
<td>5</td>
<td>$2.85 \pm 0.15$</td>
<td>$0.92 \pm 0.13$</td>
<td>$1.06$</td>
<td>$0.87 \pm 0.13$</td>
</tr>
</tbody>
</table>
cross-sections are measured. For the other two nuclei $^{115}$In and $^{103}$Rh we have measured only isomeric state cross-section, hence no comparison could be made for these two cases.

Tables 3.10 to 3.13 give the experimentally measured values of $(n,\gamma)$ cross-section together with the theoretical values at the above five incident neutron energies. The experimental and theoretical cross-section ratio $\sigma_{\text{exp}}(n,\gamma)/\sigma_{\text{theo}}(n,\gamma)$ have been plotted as a function of neutron energies for the reactions $^{160}$Gd$(n,\gamma)^{161}$Gd, $^{154}$Sm$(n,\gamma)^{155}$Sm, $^{55}$Mn$(n,\gamma)^{56}$Mn and $^{51}$V$(n,\gamma)^{52}$V, and are displayed in Fig. 3.45. The theoretical values of the cross-sections are in agreement with the experimental values within a factor of two. The factor of two may be due to the fact that the statistical model calculations are parameter dependent$^{12,22}$, specially the calculation of level density which plays an important role.

Hence, it is inferred that statistical theory is quite acceptable in the above energy region, and the reactions takes place mostly through the compound nucleus formation mechanism. Therefore, the $(n,\gamma)$ cross-section can be well predicted by statistical theory of nuclear reaction up to 3 MeV neutron energy, in contrast to the suggestions of few workers$^{6,7}$ that in this energy region the contribution due to non-statistical processes is also present in the cross-section. Our finding supports the work of Lindholm et.al.$^{24}$. 
Fig. 3.45: $\frac{\sigma_{\text{exp}}(n,\gamma)}{\sigma_{\text{theo}}(n,\gamma)}$ versus Neutron Energy
References


