INVESTIGATION OF
NEUTRON INDUCED REACTIONS

BY
Hari Mohan Agrawal
M. Sc, M. Phil (Alig.)

THESIS SUBMITTED TO
THE ALIGARH MUSLIM UNIVERSITY, ALIGARH
IN PARTIAL FULFILMENT FOR THE AWARD OF
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IN
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1979
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Certified that the work contained in this thesis is the original work of Mr. Hari Mohan Agrawal, done under my supervision.

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(Hari Mohan Agrawal)
# CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER-I :</th>
<th>INTRODUCTION</th>
<th>PAGE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER-II:</td>
<td>NEUTRON CAPTURE CROSS-SECTION IN KEV ENERGY REGION</td>
<td>10</td>
</tr>
<tr>
<td>2.1</td>
<td>INTRODUCTION</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>EXPERIMENTAL DETAILS</td>
<td>11</td>
</tr>
<tr>
<td>(i)</td>
<td>NEUTRON PRODUCTION AND IRRADIATION PROCEDURE</td>
<td>11</td>
</tr>
<tr>
<td>(ii)</td>
<td>TECHNIQUES OF MEASURING NEUTRON CROSS-SECTIONS</td>
<td>13</td>
</tr>
<tr>
<td>(iii)</td>
<td>SAMPLE PREPARATION</td>
<td>18</td>
</tr>
<tr>
<td>(iv)</td>
<td>β-COUNTING TECHNIQUE</td>
<td>19</td>
</tr>
<tr>
<td>(v)</td>
<td>ERRORS IN THE MEASUREMENT</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>EXPERIMENTAL RESULTS</td>
<td>24</td>
</tr>
<tr>
<td>2.4</td>
<td>RESULTS AND DISCUSSION</td>
<td>33</td>
</tr>
<tr>
<td>2.5</td>
<td>CALCULATIONS BASED ON STATISTICAL THEORY</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHAPTER-III : STATISTICAL THEORY CALCULATIONS OF NEUTRON-CAPTURE CROSS-SECTIONS AT 24 KEV</th>
<th>PAGE No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>INTRODUCTION</td>
</tr>
<tr>
<td>3.2</td>
<td>CALCULATIONS BASED ON STATISTICAL THEORY</td>
</tr>
<tr>
<td>3.3</td>
<td>RESULTS AND DISCUSSION</td>
</tr>
</tbody>
</table>
CHAPTER-IV: INVESTIGATION OF REACTION MECHANISMS
AND TRENDS IN (n, γ) CROSS-SECTIONS
4.1 INTRODUCTION
57
4.2 RESULTS AND DISCUSSION
59
4.3 COMMENTS ON SHELL EFFECTS
62

CHAPTER-V: STUDY OF (n, α) REACTIONS IN
KeV ENERGY REGION
5.1 INTRODUCTION
66
5.2 MEASUREMENTS OF ACTIVATION
CROSS-SECTION FOR
209Bi (n, α) 206Tl REACTION
5.3 181Ta (n, α) 178g, m Lu
73
REACTION AND ISOMERIC
STATE OF 17871Lu107
(i) INTRODUCTION
73
(ii) EXPERIMENTAL PROCEDURE
77
(iii) THE 181Ta(n, α) 178g, m Lu
77
REACTION

CHAPTER-VI: STATISTICAL ANALYSIS OF s-AND
p-WAVE NEUTRON REDUCED WIDTHS
6.1 INTRODUCTION
84
6.2 s-WAVE NEUTRON REDUCED
WIDTHS (f s)
(i) ANALYSIS
87
(ii) RESULTS AND DISCUSSION
91
6.3 ANALYSIS OF p-WAVE
NEUTRON REDUCED WIDTHS
94
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>INTRODUCTION</td>
<td>101</td>
</tr>
<tr>
<td>7.2</td>
<td>CALCULATION OF TRANSITION PROBABILITIES</td>
<td>106</td>
</tr>
<tr>
<td>7.3</td>
<td>RESULTS AND DISCUSSION</td>
<td>110</td>
</tr>
</tbody>
</table>

LIST OF PUBLICATIONS 115
ABSTRACT

Major part of the thesis deals with the investigation of neutron reaction cross-sections, particularly, \((n,\gamma)\) and \((n,\alpha)\) reactions. The work reported in the thesis has been divided into seven chapters. In the 1st chapter, a brief description of various reaction mechanisms is given.

Chapter II contains the measurements of neutron radiative capture cross-sections in KeV energy region using the facility of Van de Graaff generator at I.I.T., Kanpur (India). The experimental results have been explained within the framework of statistical theory of nuclear reactions.

In chapter III, information about \(\frac{\Gamma_D}{\Gamma} |_{p\text{-wave}}\) with respect to \(\frac{\Gamma_D}{\Gamma} |_{s\text{-wave}}\) has been extracted by fitting experimentally measured \((n,\gamma)\) cross-sections at 24 KeV using Margolis formula which is based upon statistical theory of nuclear reactions.

In chapter IV, the experimental data on \((n,\gamma)\) reaction at six neutron energies (10, 30, 100, 300 KeV, 1 and 3 MeV) have been compared with theoretical predictions based on Hauser Feshbach statistical model to get some information about other non-statistical processes.

In chapter V, cross-section measurements of \(^{209}\text{Bi}(n,\alpha)^{206}\text{Tl}\) and \(^{181}\text{Ta}(n,\alpha)^{178}\text{mLu}\) reactions in KeV energy region have been reported. Practically no earlier data on \((n,\alpha)\) reactions...
on heavy mass nuclei in KeV energy region exists. The data on $^{209}$Bi$(n,\alpha)^{206}$Tl have been used to test the validity of statistical theory of nuclear reactions. In the $^{181}$Ta $(n,\alpha)^{178}$Lu case, the ratio of cross-section for 5 min. and 25 min. activities has been measured. With the knowledge of the trend of $\sigma_{5\text{ min.}}(n,\alpha) / \sigma_{25\text{ min.}}(n,\alpha)$ vs. neutron energy ($E_n$), spins have been assigned tentatively to 5 min. and 25 min. isomers.

In chapter VI, it is shown that, contrary to wide spread opinion the s- and p-wave neutron widths do not always follow single channel Porter and Thomas distribution which was outcome of the extreme configuration mixing (compound nucleus theory).

In the last chapter, the applicability of Davydov-Rostovsky model (which is one of the model proposed to explain the collective nature of $E_2$-transitions in deformed nuclei of rare earth and actinide regions) in predicting transition probabilities of $4^+_g \rightarrow 2^+_g$, $2^+_g \rightarrow 0^+_g$ and $2^+_g \rightarrow 0^+_g$ transitions, has been tested.
CHAPTER - I

INTRODUCTION

Nuclear reactions have been studied extensively, both experimentally as well as theoretically. With the advent of the high energy accelerating machines, such as Van de Graaff generator and the cyclotron the high energy particles like protons and $\alpha$-particles have become available to produce nuclear reactions in all elements of the periodic table. Studies on cross-sections and angular distribution of the disintegration products, coupled with the various theoretical developments have led to a better understanding of the nature of the nucleus and nuclear forces. There exists two different approaches\textsuperscript{1)} viz, black box or model treatment and many body methods in nuclear Physics, to study the mechanism of interaction of nucleons with nuclei. It is simpler to handle the problem with model treatment, because in this case the dynamics of many-body system is replaced by a mathematically solvable model. Direct reaction theories, evaporation and optical model are the examples of the model treatment. Many body methods are more rigorous, where the continuous states of collision problem are treated in analogous way to the bound states of the nucleons in the nucleus. Model treatment being easier, has been most frequently applied to the nuclear phenomena. Though it is felt that many-body approach is more exact and probably a complete theory of nuclear interactions would follow the lines
of nuclear many-body approach. In the present work we shall be following the model treatment and analysing the data in terms of the compound nucleus theory.

In 1936 Bohr\textsuperscript{2}) introduced the idea of the compound nucleus model - an antithesis of the single particle model. Compound nucleus processes may conveniently be divided according to the number of compound nucleus states excited by the reaction, and this depends on the energy spread $\Delta E$ of the incident beam and on the widths $\Gamma$ and spacings $D$ of the compound nucleus states. If $\Delta E < \Gamma < D$, so that levels are well separated, the corresponding resonances in the cross-sections may be analysed by the Breit-Wigner\textsuperscript{3}) formalism. These resonances are particularly notable in $(n,\gamma)$ reaction, elastic neutron and proton scattering when the energy corresponds to that of a state of the compound nucleus, and their analysis yield important nuclear structure information.

This formalism may be extended to the case $\Delta E < \Gamma \sim D$ where two levels overlap, but becomes impracticable when more than two states are excited at the same energy. When $\Gamma > D$, so that the levels overlap strongly and the energy resolution $\Delta E < \Gamma$, the measured cross-sections fluctuate as a function of energy and it is not possible to identify the contributing resonances. The analysis of such fluctuations has been done by Ericson\textsuperscript{4,5}).

If the energy spread $\Delta E > \Gamma$, many states are excited
simultaneously but the fluctuations are no longer apparent. The resulting energy averaged cross-sections may be analyzed by statistical theory.

The statistical theory of nuclear reactions have proved very successful in predicting neutron cross-sections in the intermediate energy region over wide range of the periodic table. The general theory was presented by Wolfenstein\(^6\) and specialized for the case of inelastic scattering processes by Hauser and Feshbach\(^7\) and for capture processes by Margolis\(^8\). It is customary to divide the mechanism of nuclear reaction into two distinct processes and these contribute in different proportions depending mainly on the structure of target nucleus and incident particle energy. There are direct interaction processes which pass immediately from the initial state to the final state, and the compound nucleus process which passes through a large number of states of the compound nucleus formed by the capture of the incident particle by the target nucleus. The direct process takes place rapidly in the duration of the nuclear transit time \(\tau_{DI} \sim 10^{-22} \text{ sec.}\), and as a result the variation with energy of the corresponding cross-section is slow\(^9\). On the other hand, the second process requires the compound nucleus to attain a state of statistical equilibrium and this takes as much as a million times longer \(\tau_{CN} \sim 10^{-16} \text{ sec.}\). Consequently the excitation energy is well defined and the cross-section may change very rapidly with
incident energy, depending on particular configurations of compound nuclear states that are excited.

The domain in between the two extreme cases are the intermediate reactions as a result of the decay of compound nucleus before it attains full statistical equilibrium. Let us consider what happens when a particle approaches a nucleus, and starts the process of exciting it to a compound state. The first interaction takes place with the one nucleon in the target and the energy exchange raises the nucleon to a higher bound state, leaving a vacancy in one of the lower levels; this is a two particle one hole (2p 1h) state. The next stage in the excitation leads to the formation of a (3p 2h) state. This process continues until the energy of incoming particle is shared statistically among all nucleons of the compound nucleus. These intermediate states involving the excitation of only a few nucleon are called "doorway states" because they are the states through which the excitation must pass, the 'doors' to the compound nucleus.

Any of these doorway states has a certain probability of decaying directly back into the incident channel or into one of the open reaction channels. The total width for the decay of a doorway state may therefore be written

\[ \Gamma = \Gamma^\uparrow + \Gamma^\downarrow \]

where \( \Gamma^\uparrow \) denotes the escape width for decay back into the entrance
channel or into a direct reaction channel and \( \Gamma \) the damping width for the formation of the compound nucleus.

The statistical model of nuclear reactions has been extended by Griffin\(^{10}\) to give the probability of emission of particles at the various stages of the excitation process, and their energy distributions. These particles are called "pre-compound" and contribute to the high energy tail often found in the energy distribution of particles emitted from nuclear interactions.\(^9\)

Bulk of nuclear reaction data at thermal as well as high energy neutrons are available and have been of invaluable aid in reactor design but of limited help for statistical theory of nuclear reactions and nucleosynthesis calculations. The present work was undertaken to measure the \((n,\gamma)\) and \((n,\alpha)\) cross-sections in KeV energy region to complete and improve the earlier data. The requisite neutrons in KeV energy region were obtained from the \(^3\text{H}(p,n)^3\text{He}\) reaction using incident proton beam from Van de Graaff generator at I.I.T., Kanpur (India). The activation method has been used for these measurements. Details of flux calibration, measurement techniques and associated errors are given in chapter II. Where as the details of the individual measurements are discussed in chapter II and V.

The knowledge of neutron radiative cross-sections in the KeV energy region is of interest for the design of fast reactors as well as for the study of nuclear reaction theories.
These measurements are also useful in Astrophysics\textsuperscript{11,12}. According to stellar nucleosynthesis theory, elements heavier than iron were formed predominantly by neutron capture; the knowledge of cross-sections lead to a time scale evaluation of this process and permits the estimation of natural element abundances. In the present work capture cross-sections have been measured in KeV energy region. The published cross-section data currently available for studied isotopes are either inconsistent or in some cases non-existent over part of the energy range studied. The results of these measurements are compared with the prediction of statistical theory of nuclear reactions. Margolis formalism\textsuperscript{8} for \((n,\gamma)\) cross-section based upon statistical theory has been used (for details see chapter II).

Neutron capture cross-sections at 24 KeV for 48 nuclei with mass number \(45 \leq A \leq 232\) have also been calculated using Margolis formula\textsuperscript{8}. It is not known whether \(\langle\Omega\rangle / 2\pi\langle\gamma\rangle\), one of the input parameters) is the same for \(s\)- and \(p\)-wave neutrons. It has been shown that the assumption,

\[
\langle\gamma\rangle / \langle\Omega\rangle_{\text{p-wave}} \approx \langle\gamma\rangle / \langle\Omega\rangle_{\text{s-wave}}
\]

which has been verified experimentally for many nuclei\textsuperscript{13-16} except those in \(3p\) region\textsuperscript{13, 17}, is fairly well to reproduce the experimental cross-sections at 24 KeV and it may be further used to get information about \(\langle\gamma\rangle / \langle\Omega\rangle_{\text{d-wave}}\) with respect to \(\langle\gamma\rangle / \langle\Omega\rangle_{\text{s-wave}}\) by fitting the experimental cross-sections at higher energies (for details see chapter III).
In chapter IV, the experimental data on \((n,\gamma)\) reaction for nuclei \(A \geq 74\) at six different neutron energies (10, 30, 100, 300 keV, 1 and 3 MeV) taken from graphs given in recent BNL report (1976) have been compared with theoretical predictions based on Hauser-Feshbach statistical theory\(^7\) to get some idea about the existence of other non-statistical processes (e.g. direct/semidirect reaction). However, the inadequacy of experimental data on \((n,\gamma)\) reaction at 1 and 3 MeV neutron energies; and the choice of input parameters in statistical theory does not allow us to draw definite conclusion regarding the magnitude of non-statistical processes. This study reveals the presence of contributions to the \((n,\gamma)\) cross-section by reaction processes other than compound nucleus process. The experimental data on \((n,\gamma)\) reaction at neutron energies of 30, 300 KeV and 3 MeV have also been examined for the possible shell effects.

Cross-sections for \(^{209}\text{Bi}(n,\alpha)\)\(^{206}\text{Tl}\) reaction at two incident neutron energies and for \(^{181}\text{Ta}(n,\alpha)\)\(^{178}\text{g,m}_{\text{Lu}}\) reaction at four neutron energies have been measured for the first time. The data on \(^{209}\text{Bi}(n,\alpha)\) reaction in KeV energy region have been used to test the validity of statistical theory of nuclear reaction in predicting \(\sigma(n,\alpha)\). The reaction \(^{181}\text{Ta}(n,\alpha)\)\(^{178}\text{g,m}_{\text{Lu}}\) has been separately described in subsection (5.3) of chapter V. In this case the cross-section for 5 min. and 25 min. activities have been measured. With the knowledge of the trend of \(\frac{\sigma_{\text{5 min.}}(n,\alpha)}{\sigma_{\text{25 min.}}(n,\alpha)}\) vs. neutron energy \((E_n)\), spins have been assigned to 5 min. and 25 min. half lives.
It is well known that the absorption cross-section of neutrons with energies of few tens of electron volts has a resonance structure. The average resonance parameters \( (E_0, \Gamma_n, \Gamma, \Gamma_t, \Gamma_D) \) and their distributions are important for the statistical theory of nuclear reactions as well as for reactor physics calculations. In chapter VI the distributions of s- and p-wave neutron reduced widths for individual nucleus have been investigated. The theoretical distribution of \( \Gamma_n \) obtained in the limit of extreme configuration mixing (compound nucleus formation) was \(^{19}\) a \( \chi^2 \)-distribution with degree of freedom \( \nu = 1 \). In certain mass regions, we find that there are many nuclei for which \( \nu = 2 \). In order to explain the value of \( \nu \) other than 1 we were forced to assume that the compound nucleus component has to be supplemented by non-statistical processes.

The knowledge of nuclear reactions and of nuclear structure are complementary to each other. The more we know about the one the more we can understand about the other. In this thesis, we have mainly concentrated on nuclear reaction studies. However, in the last chapter we have dealt with Davydov-Rostovsky model \(^{20}\) in explaining the fastness of \( \frac{4^+_g}{2^+_g}, \frac{2^+_g}{0^+_g} \) and \( \frac{2^+_g}{0^+_g} \) transitions in even-even nuclei of rare earth and actinide regions.
REFERENCES:

2) N.Bohr : Nature 137 (1936) 344.

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CHAPTER - II

NEUTRON CAPTURE CROSS-SECTION IN KeV ENERGY REGION

2.1 Introduction:

The study of neutron capture cross-section is useful for understanding nuclear reaction theories, steller nucleosynthesis theories and nuclear reactor designs. Inspection of BNL reports\(^1\),\(^2\) show a definite gain in the number of capture cross-section at thermal energy as well as at high energies (MeV), but in KeV region the data are still inadequate; and for few cases it is also inaccurate. Therefore, there is still a demand to complete and improve the earlier experimental data in KeV energy region. This energy region is of special interest because of following facts:

a) In this energy region the neutron capture reaction takes place mostly through compound nucleus mechanism. The formalism for describing energy averaged compound nucleus cross-sections was originally developed by Wolfenstein\(^3\), Hauser and Feshbach\(^4\). Margolis\(^5\) and Lane and Lynn\(^6\) extended the theory for neutron capture process. Later, Moldauer\(^7\) has applied R-Matrix theory and included neutron width fluctuation corrections to calculate energy averaged cross-sections. The Margolis formalism has proved\(^8\)-\(^12\) very successful in predicting neutron capture cross-sections in KeV energy region provided the input parameters like radiation width \(\gamma\), level spacing \(D\), binding energy, target nucleus level structure and
neutron penetrabilities are well known. In the absence of complete knowledge, it is possible to extract some of these quantities from measurement of capture cross-sections as a function of neutron energy $E_n$.

b) Theories of stellar nucleosynthesis$^{13-17}$ of heavy elements predict correlations between the abundances of various elements and neutron capture cross-sections in this energy region.

c) In order to tackle the problem of poisoning of a reactor by fission products, the knowledge of neutron capture cross-section over wide energy range for many nuclei is required.$^{18}$

Present work of capture cross-section measurements in KeV energy region have got the following motivations:

a) To complete and improve $(n,\gamma)$ cross-section data in KeV region.

b) To examine the applicability of Margolis formalism in predicting $(n,\gamma)$ cross-sections in KeV region.

c) To see whether the comparison between $\sigma_{\text{expt.}}(n,\gamma)$ and $\sigma_{\text{theo.}}(n,\gamma)$ can give some more information about the energy dependence of resonance parameters e.g. radiation width $\Gamma_\gamma$ and level spacing $D$.

2.2 Experimental Details:

(i) Neutron production and irradiation procedure:

Generally $(\alpha,n)$ and $(\gamma,n)$ reactions are used for the production of neutrons, using $\alpha$-particles and $\gamma$-rays given out
from radioactive emitters. The use of these types of sources is limited to the production of neutrons at isolated energies. Another possibility is the use of accelerated charged particles like proton, deuteron, triton and $\alpha$-particles etc., obtained from charged particle accelerators. Bombardment of these accelerated charged particles on suitable target yields neutrons. The latter type of neutron sources have two fold advantages over the former ones:

a) Relatively high flux of neutrons can be obtained.
b) Neutrons can be obtained at different energies in a certain energy interval by varying the energy of the bombarding particles.

In the present work, neutrons in the KeV region were produced by the endothermic reaction $^3_1H(p,n)^2He$ i.e.,

$$^1H + ^3H \rightarrow ^2He + ^0n - 0.764 \text{ MeV} \quad \text{(1)}$$

Accelerated proton beam was obtained from the Van de Graaff accelerator at I.I.T., Kanpur (India). The tritium target consisted of 16 Ci of tritium absorbed in titanium layer on thin backing of copper (0.25 mm). The energy of the emitted neutrons at various proton energies and at different laboratory angles was taken from reference 19. All samples were irradiated at 0° to the proton beam axis. The different proton beam energies
and the corresponding emitted neutron energies, used in (n,γ) measurements are given below.

<table>
<thead>
<tr>
<th>Proton Energy ($E_p$) (MeV)</th>
<th>Neutron Energy ($E_n$) (KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>$415 \pm 15$</td>
</tr>
<tr>
<td>1.31</td>
<td>$400 \pm 70$</td>
</tr>
<tr>
<td>1.46</td>
<td>$610 \pm 20$</td>
</tr>
<tr>
<td>1.5</td>
<td>$650 \pm 20$</td>
</tr>
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There are three factors that have been considered in order to determine the uncertainty associated with a given neutron energy. They are:

a) due to thickness of the tritium - titanium target.
b) due to the finite width of the input energy ($E_p$) which is mainly caused by the degradation of the incident beam in the target material.
c) due to the angle subtended at the point neutron source by the samples studied.

The spread $\Delta E_n$ due to factor (c) is the dominating one.

(ii) Techniques of measuring neutron cross-sections:

There are two techniques generally used for the cross-section measurements:
a) Prompt particle measurement technique

b) Activation technique

Another technique which is exclusively used for $(n,\gamma)$ cross-section measurements is spherical shell transmission technique. Spherical shell transmission measurements do not depend on absolute detection efficiencies and therefore can give quite accurate capture cross-sections. But this technique has a few disadvantages, e.g., it can be used with homogenous neutron sources and requires large samples. Moreover, the correction for self shielding effects are some times difficult to evaluate in spherical shell transmission experiments.

By capturing a neutron the target nucleus is excited to a state whose excitation energy ranges from 5 to 8 MeV above the ground state as a result of binding energy of the neutron in the nucleus. This energy is generally released in a time less than $10^{-14}$ sec. in the form of gamma rays, which finally cascade to the ground state. Since this occurs for all capturing isotopes, the detection of prompt gamma rays provide perhaps a general method for capture cross-section
measurements. But in practice it is not so simple because of lack of the knowledge of prompt gamma ray spectra to such a high excitation energy, the development of efficient detectors for high energy gamma rays, and the background problem. In recent years\textsuperscript{20-22} there has been continuing development in methods for the detection of prompt capture $\gamma$-rays. Inferences about reaction mechanism may be obtained from prompt capture $\gamma$-rays spectra. Recently a search for non-statistical effects in $\gamma$-ray spectra following neutron capture has been made for incident neutron energies in the range 40 KeV to 1 MeV.

In case of $(n,\alpha)$ reaction, silicon surface barrier detector is mostly used for recording prompt $\alpha$-particle spectrum. The cross-sections are obtained for the $\alpha$-branches to ground state as well as to excited states of product nucleus in contrast to the activation technique where one can only determine total $(n,\alpha)$ reaction cross-section. By looking at the $\alpha$-particle groups, level sequence of product nucleus can also be determined.

Prompt particle measurements as well as spherical shell transmission measurements, both require separated isotopes if specific reactions are to be measured.
In activation technique, cross-section is determined by following the induced activities within a specimen sample through particle bombardment. The high sensitivity with which this induced radioactivity can be detected and the individually characteristic modes of decay of each radioisotope lead to the many advantages inherent in this technique. Among these, special advantages are extremely high sensitivity, selectivity and the possibility of non-destructive analysis. Activation technique measures the cross-section for the formation of specific product. This technique is, however, limited to those product nuclei which have convenient half lives and established decay schemes. The formalism for activation measurements is outlined below.

Let a sample be irradiated by a neutron beam with flux \( \phi \). The number of target nuclei, which yield a certain radioactive reaction product (Y) on being irradiated with neutrons be \( N_o \). Then the equation which governs the growth of Y type activity during irradiation may be given as follows.

\[
\frac{dY}{dt} = \sigma_Y \phi N_o - Y \lambda \quad \cdots \cdots \cdots \cdots (2)
\]

Where \( \sigma_Y \) is the reaction cross-section and \( \lambda \) is the decay constant of the Y type nuclei. Let the irradiation be carried out for time \( t_e \). The activity of Y type nuclei at the instant when irradiation was stopped may be given as:

\[
Y_o = \sigma_Y \phi N_o \left(1 - e^{-\lambda t_e}\right) \quad \cdots \cdots \cdots \cdots (3)
\]
The disintegration rate of the Y type nuclei at any instant from the stop of irradiation is given by

\[ \frac{dY}{dt} = Y_0 e^{-\lambda t} \]  

\( \text{(4)} \)

Let \( C_t \) be the disintegration rate recorded by a certain counting device at time \( t \) from the stop of irradiation, then one can write

\[ \frac{dY}{dt} = \frac{C_t}{G_e \varepsilon} = Y_0 e^{-\lambda t} \]  

\( \text{(5)} \)

Where \( G_e \) is the geometrical efficiency of the detector. From equations (3) and (5) one can write for the reaction cross-section:

\[ \sigma_Y = \frac{C_t e^{\lambda t}}{\phi G_e \varepsilon N_0 (1 - e^{-\lambda t} \varepsilon)} \]  

\( \text{(6)} \)

In actual practice the induced activity in the sample is counted till it reaches the background counts. A graph is plotted between the log of the counting rate and time \( t \) measured from the stop of the irradiation. The graph will be a straight line and will show the half life corresponding to the product nuclei. By extrapolating the graph to zero time we get the counting rate at the instant of stop of irradiation i.e. \( C_t = 0 \). Hence one can write the following expression for \( \sigma_Y \) using equation (6)

\[ \sigma_Y = \frac{C_t = 0}{\phi G_e \varepsilon N_0 (1 - e^{-\lambda t} \varepsilon)} \]  

\( \text{(7)} \)

In some cases it is possible that there may be two or more radioactive reaction products in the irradiated sample, either
due to more than one reaction channels for the interaction of neutrons with the same isotope or due to interaction of neutrons with other stable isotopes in the natural element. In such cases the activities can be separated provided the half lives are not very close to each other. By substracting the activities one after another from the composite decay curve, one can get separate half lives each showing a certain specific activity.

(iii) Sample Preparation:

The great advantage of the activation technique which has been used to measure the cross-sections in the present work is that we do not always need enriched isotopes. The half lives enable one to assign the induced activities to the proper isotopes. Therefore, not only the metal and metallic powder were used but the oxides of the element were also used. Oxides as samples may be used due to the fact that $^{16}$O (99.76% abundant) and $^{17}$O are stable upon neutron capture. These isotopes would have to undergo a few successive neutron captures to $^{19}$O in order to show any activity. $^{18}$O, which is 0.2% abundant, becomes beta active when it captures a neutron, and the half life is 29 seconds. Because the presence of $^{18}$O in sample is nominal and the half life of $^{19}$O is short, $^\beta$-activity produced will be very weak.

Samples studied in the present work were made by uniformly spreading the powdered substances within the perspex ring of specified radius. The rings were then sandwiched between
two thin cellulose tapes. The thickness of the samples, their area of cross-section and the amount of the substance are to be chosen carefully for individual measurement. Larger amount of substances are good for improving the counting statistics, but are limited by the sample thickness (for a certain fixed area of the sample). For thicker sample self absorption of the emitted $\beta$-particles in the sample is larger. The large sample area may also reduce the sample thickness but it has got its own limitations. Large sample area can not be used in cases where the neutron source is a point source, because larger sample area is associated with larger solid angle subtended by the sample at the point source and hence larger neutron energy spread. Very large sample area may also be inconvenient from geometry consideration of the counting device. For a certain measurement, a compromise had to be made between these three things.

(iv) $\beta$-Counting Technique:

An end window beta counter of 1.75 mg/cm$^2$ window thickness shielded with 12 cm thick lead house to reduce the general background was used for $\beta$-counting. The counter was fixed in a perspex stand provided by shelves at fixed distances. Samples under investigation were fixed in a sample holder and kept in a shelf just below the window of $\beta$-counter. In order to
achieve the reproducible geometry the sample holder was kept at a fixed position. The expression used for the efficiency of the $\beta$-particles is given by

$$\varepsilon = \frac{1}{100} \left[ a e^{-\mu_1 d} + b e^{-\mu_2 d} + \ldots \right] \quad (8)$$

where $a$, $b$, $\ldots$ are the branching ratios of the various $\beta$-rays emitted; $\mu_1, \mu_2 \ldots \ldots \ldots$ are their corresponding mass absorption coefficients and $d$ is the average thickness (gm/cm$^2$) which has to be traversed by a $\beta$-particle before entering into the counter. The mass absorption coefficients corresponding to different and point energies of $\beta$-particles have been taken from reference 24.

(v) Errors in The Measurements:

An analysis of the experimental errors involved in any experimental data is very important as it indicates the reliability of the results. The pre-requisite for a meaningful comparison of the experimental data with the theory is to have an idea of errors in experimental values. Here, in the following few paragraphs the possible errors in the measurements and the corrections applied for the same have been discussed:

a) The erratic behaviour of the electronic equipment may introduce some error in the measurement. We could get rid of this by stabilizing the electronic equipment for few hours before the start of the experiment.

b) Non reproducibility of identical geometries of the irradiation and counting system, for the unknown target sample and the standard samples may introduce certain errors in the
measurements. However, fixed sample holders could minimize this error. An estimate of about $2\%$ error was made for the non-reproducibility of the geometry.

c) The inaccurate measurement of irradiation time and the time that lapses between the stop of irradiation and the start of the counting can introduce errors. Special care has been taken for isotopes of short lived activities where this error could be significant. An upper limit for this error could be put as $1\%$ in our measurements.

d) Errors may also be introduced 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 error in the weighing. The samples were having purity better than $99.9\%$. Thus the error introduced in finding the total number of nuclei due to impurities, was always less than $0.2\%$. A balance which weighed correctly up to $0.1 \text{ mg}$ was used. The maximum and the minimum errors introduced in weighing was estimated to be $0.4\%$ and $0.2\%$, respectively. Therefore, the over all error in $n_o$ was estimated to be less than $1\%$.

e) The value of the mass absorption coefficient for $\beta$-particles and of 'd' (mean thickness for absorption) may give an error in the value of $e^{-kd}$. This was estimated to be about $2\%$. 
f) Gamma ray may also be detected by the beta counter. However, the efficiency of detection of $\gamma$-rays with a beta counter is very small ($\approx 1\%$), because the counting of $\gamma$-rays depends upon the release of the secondary electrons from the walls of the counter. The estimated error due to this factor was about $2\%$. In few cases in order to apply this correction (due to counting of $\gamma$-rays by the beta counter) the counting rate measured by beta detection technique was decreased by $2\%$.

g) The half lives of the isotopes, the energies and the branching ratios of the $\beta$-particles may also introduce some error in calculating the initial activity of the sample. To minimize this error recent nuclear data sheets were consulted.

h) Error due to variation of neutron flux is a most serious error. The variation of neutron flux during irradiation, because of fluctuation in proton beam current as well as in the shape of proton beam spot will effect the standard sample and the specimen sample differently and hence care was taken to keep the neutron flux constant to within $\pm 5\%$. The runs with large beam current fluctuations were discarded. Further, in the computation of cross-sections, this small variation was also taken into consideration in the conventional manner.
i) One may expect the presence of thermal and scattered neutrons at the place of irradiation of the sample. Since at low energies the cross-sections are very high, so their presence may introduce serious errors in the measurements. In our experiment the nearest wall from the place of irradiation was at a distance of more than 10 meter and the system of irradiation was kept 'clean' having minimum scattering material nearby. Therefore the slow neutron background was reasonably small. The background neutron flux was estimated by repeating activities at distances greater than normal from the neutron source and assuming that the direct neutron flux varied inversely with the square of distance while the background neutron flux remained constant. The flux of background neutrons ($\phi_b$) with respect to the primary neutron flux ($\phi$) was found to be less than $5\%$.

j) In addition to all the above errors there will be statistical error in the counting rate. This will vary from one case to another depending upon the activity induced in the samples. In the case of $(n,\alpha)$ cross-sections measurements the magnitude of the minimum and maximum statistical error have been estimated to be $5\%$ to $10\%$; whereas in the case of $(n,\gamma)$ cross-section measurements mostly the statistical errors lie between $2\%$ to $12\%$. Method of least square fitting has been adopted in drawing straight lines corresponding to specific activities, particularly, in those cases where counting statistics are poor.
2.3 Experimental Results:

All the \((n,\gamma)\) cross-sections have been measured relative to that of \(^{127}\text{I}\). The reason for choosing \(^{127}\text{I} (n,\gamma) ^{128}\text{I}\) reaction as a standard are the following:

a) The cross-section for this reaction is known\(^1\) accurately as a function of neutron energy in KeV energy region so that standard value necessary for any given energy can be easily obtained.

b) \(^{128}\text{I}\) has a moderate half life (25 min.) and decays by beta emission to stable \(^{128}\text{Xe}\).

c) The decay scheme of \(^{128}\text{I}\) is relatively simple and well established. Moreover, \(^{127}\text{I}\) is also monoisotopic.

\(^{127}\text{I}\) was taken in the form of Potassium Iodide which when irradiated by few hundreds of KeV neutrons gives admixture of two activities \(^{128}\text{I} (25 \text{ min})\) and \(^{42}\text{K} (12.5 \text{ hrs})\). Activity of \(^{42}\text{K}\) is due to \((n,\gamma)\) reaction on \(^{41}\text{K}\). As the two activities have halflives which differ by a factor of 30, they can be easily separated without causing any sizable statistical counting error. As the natural abundance of \(^{41}\text{K}\) in KI was 6.86\%; and the duration of irradiation of the studied samples alongwith two standard samples of KI (which was selected in consideration of the halflives of the product of interest) lies between 5 min. to 25 min. for one case to another, 12.5 hrs. \(^{42}\text{K}\) activity
could not be resolved. Fig. 1 shows the half-life and decay scheme of \(^{128}\text{I}\). It is one of the figures used for the determination of neutron flux. 25 min. half life of \(^{128}\text{I}\) was obtained by substracting the background level which includes few counts due to 12.5 hrs. \(^{42}\text{K}\) activity from the composite curve (as shown in fig.1).

The natural abundances of the isotopes studied and the decay schemes of the reaction products formed by \((n,\gamma)\)
reactions were taken from recent nuclear data sheets\(^{25-30}\). All the chemicals used in our \((n,\gamma)\) measurements were obtained from m/s Johnson Mathey and Co. Ltd., London and were 99.99\% pure.

The details of various measurements are described separately for each target nucleus. The relevent part of decay schemes alongwith the decay curves for the induced activities are also given. In cases where background level is not shown in the decay curves, the curves are plotted after substracting the background counting rate. While calculating the cross-sections the decay curves were extrapolated back to zero time to find the counting rate at the stop of irradiation. For clarifying the mode of calculation the \(^{51}\text{V} \ (n,\gamma) \ ^{52}\text{V}\) reaction has been described in details.

\[
^{51}\text{V} \ (n,\gamma) \ ^{52}\text{V} \ \ \ \text{Reaction}
\]

99.9\% pure \(\text{V}_2\text{O}_5\) in powder form was used as the target material, whose area and mass were 2.545 \(\text{cm}^2\) and 0.076 gms, respectively. The sample was sandwiched between two standard
DECAY SCHEME AND HALF LIFE CURVE OF $^{52}$V
(Neutron Energy: 415±16 KeV)

$^{52}$V 2+ 20

$^{52}$Cr 25° 27

$\beta^-$

1.014 (36 %)
1.211 (9 %)
2.545 (99 %)

2.965 MeV
2.760
2.360
1.436

COUNTS IN 50 SEC

$T_{1/2} = 3.75$ MIN.

FIG. 2
samples of potassium iodide and irradiated in zero degree forward direction relative to the proton beam for 5 min. Induced activity was followed upto 32 min. After subtracting the background we got 3.75 min. activity as shown in fig. 2. The counting rate at zero time was obtained by extrapolating the resultant curve to zero time. The outline of the calculations are as follows:

Number of $^{51}$V nuclei in the sample ($n_0$) = $5.05 \times 10^{20}$

Average neutron flux obtained from induced activities in KI samples placed on the two sides of actual $V_2O_5$ sample may be given as:

$$\phi \cdot G_e = 3.258 \times 10^6 \text{ neutrons/cm}^2\text{.sec.}$$

Detection efficiency of endwindow $\beta$ counter ($\epsilon$) = 0.888

Saturation correction for the $^{52}$V activity ($1-e^{-\lambda t}$) = 0.601

Counting rate at zero time ($C_{t=0}$) = 100 counts/50 sec.

Cross-section for the reaction $^{51}$V(n,$\gamma$)$^{52}$V may be given as:

$$\frac{100}{50} \cdot \frac{3.258 \times 10^6}{(5.05 \times 10^{20}) (0.888) (0.601)} = 2.27 \times 10^{-27} \text{cm}^2$$

Total error in $\sigma$ = 15%

and so $\sigma$ = 2.27 $\pm$ 0.34 mb

$^{65}$Cu (n,$\gamma$)$^{66}$Cu — Reaction

99.9% pure CuO powder was used as the target material whose mass was 0.1272 gms. Its area was 2.011 cm$^2$. The sample was
Decay scheme and half-life curve of $^{68}$Cu
(Neutron energy 4.15 - 15 MeV)

$T_{1/2} = 5.1$ min.

Counts in 10 sec.

Time (min)
sandwiched between the standard samples (KI) and irradiated for 7 min. and 15 min. at neutron energies 415 KeV and 610 KeV, respectively. Figures 3a and 3b show the decay curves of $^{66}\text{Cu}$ with half life 5.1 min.

**Neutron Energy — 415 ±15 KeV**

\[
\begin{align*}
C_{t=0} & = 300 \quad \text{counts/100 sec.} \\
n_0 & = 2.978 \times 10^{20} \\
\varepsilon & = 0.814 \\
(1-e^{-\lambda t_e}) & = 0.606 \\
\phi \cdot G_e & = 2.576 \times 10^6 \text{ n/cm}^2 \text{ sec} \\
\sigma^- & = 7.92 \pm 0.95 \text{ mb}
\end{align*}
\]

**Neutron Energy — 610 ± 20 KeV**

\[
\begin{align*}
C_{t=0} & = 200 \quad \text{counts/50 sec} \\
n_0 & = 2.978 \times 10^{20} \\
\varepsilon & = 0.814 \\
(1-e^{-\lambda t_e}) & = 0.87 \\
\phi \cdot G_e & = 2.0611 \times 10^6 \text{ n/cm}^2 \text{ sec} \\
\sigma^- & = 9.2 \pm 0.92 \text{ mb}
\end{align*}
\]

$^{69}\text{Ga} (n,\gamma) ^{70}\text{Ga} —$ Reaction

The sample was taken in the form of Ga$_2$O$_3$ having purity better than 99.9%. The mass and area of sample were
DECAY SCHEME AND HALF LIFE CURVE OF $^{70}$Ga

(NEUTRON ENERGY 650 ± 20 KeV)

$^{70}$Ga $\rightarrow$ $^{70}$Ga $^*$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\beta^-$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\gamma$

$^{70}$Ga $^*$ $\rightarrow$ $^{70}$Ga $\alpha$
0.1022 gms and 2.011 cm². The sample was irradiated along with two standard samples for 12 min and 10 min at neutron energies 460 KeV and 650 KeV, respectively. Resultant curves (figs. 4a and 4b) of half life 21.1 min were obtained after subtracting the background which also includes few counts due to 14.2 hrs ⁷²Ga activity.

<table>
<thead>
<tr>
<th>Neutron Energy — 460 ± 10 KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{t=0}$ = 840 counts/100 sec</td>
</tr>
<tr>
<td>$n_0$ = 3.997 x10²⁰</td>
</tr>
<tr>
<td>$\epsilon$ = 0.7363</td>
</tr>
<tr>
<td>$(1-e^{-\lambda t_e})$ =0.33</td>
</tr>
<tr>
<td>$\phi . G_e$ = 2.329x10⁶ n/cm² sec</td>
</tr>
<tr>
<td>$\sigma$ =37.13 ± 3.3 mb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutron Energy — 650 ± 20 KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{t=0}$ =1100 counts/100 sec</td>
</tr>
<tr>
<td>$n_0$ =3.997x10²⁰</td>
</tr>
<tr>
<td>$\epsilon$ =0.7363</td>
</tr>
<tr>
<td>$(1-e^{-\lambda t_e})$ =0.28102</td>
</tr>
<tr>
<td>$\phi . G_e$ =3.859x10⁶ n/cm² sec</td>
</tr>
<tr>
<td>$\sigma$ =34.45 ±2.4 mb</td>
</tr>
</tbody>
</table>

$^{80}\text{Se} (n,\gamma) ^{81}\text{Ge}(18.5 \text{ min}), ^{81m}\text{Se}(57.25 \text{ min})$ — Reaction

99.9% pure selenium metal powder was bombarded along
DECAY SCHEME AND HALF LIFE CURVE OF $^{81}\text{Se}$
(Neutron Energy 610 ± 20 keV)

$\beta^{-}$ decay

$T_{1/2} = 18.5$ min.

$T_{1/2} = 57$ min.
with standard samples by neutrons of energy 610 KeV for 15 min. Measurement of activity of the sample with the beta counter was started after 4 min to allow the activities due to $^{77m}\text{Se}(17.5 \text{ sec})$ and $^{83m}\text{Se}(70 \text{ sec})$ to decay. Fig. 5 shows the decay curve with two resolved half-lives (57.25 min and 18.5 min). 25 minute activity due to $^{83}\text{Se}$ is probably very small and hence could not be separated out from the 18 min activity due to $^{81}\text{Se}$. The cross-section of $^{82}\text{Se}(n,\gamma)\ ^{83}\text{mSe}$ reaction at thermal energy is about 5 mb. At 610 KeV the contribution due to $^{83}\text{Se}(25 \text{ min})$ activity to our measured cross-section for $^{80}\text{Se}(n,\gamma)\ ^{81}\text{mSe}$ reaction, if any, is expected to be very-very small. $^{81m}\text{Se}(57 \text{ min})$ decays into the ground state by isomeric transition. The cross-section for the isomeric state and the ground state were calculated by using eqns. (15a) and (15b) of ref. 31, which are given as:

\[
\frac{(C_m)_{t=0}}{\varepsilon_{m} G_e} = \phi N_0 \sigma_m \left( \frac{\lambda_g}{\lambda_g - \lambda_m} \right) \left( 1 - e^{-\lambda_m t_e} \right)
\]

\[
\frac{(C_g)_{t=0}}{\varepsilon_{g} G_e} = \phi N_0 \left[ \sigma_g - \sigma_m \left( \frac{\lambda_m}{\lambda_g - \lambda_m} \right) \right] \left( 1 - e^{-\lambda_g t_e} \right)
\]

\[
\phi \cdot G_e = 2.060 \times 10^6 \text{ n/cm}^2 \text{ sec}
\]

\[
N_0 = 1.199 \times 10^{21}
\]

\[
\varepsilon_g = 0.488
\]

\[
\frac{\lambda_g}{\lambda_g - \lambda_m} = 1.477
\]
DECAY SCHEME AND HALF LIFE CURVE OF $^{108}_{\text{Ag}}$
(Neutron Energy $610 \pm 20$ keV)

$T_{1/2} = 2.4$ MIN.

FIG. 6
\( \left( 1-e^{-\lambda t} \right) = 0.43 \)
\( \left( 1-e^{-\lambda t} \right) = 0.18 \)

\[
\begin{align*}
(c_g)_{t=0} &= 110 \quad \text{counts/50 sec} \\
(c_m)_{t=0} &= 35 \quad \text{counts/50 sec} \\
\sigma_m &= 2.18 \pm 0.44 \quad \text{mb} \\
\sigma_g &= 5.28 \pm 0.62 \quad \text{mb}
\end{align*}
\]

107\(^{\text{Ag}}\)(n,\(\gamma\)) \(108\text{Ag} \rightarrow \) Reaction

Pure (99.9\%) metallic sheet of silver was used for the preparation of target sample. The sample whose mass and area were 0.357\,gms and 2.805\,cm\(^2\), respectively was irradiated for 7 minutes along with two standard samples. Fig.6 shows the half life curve of 108\(\text{Ag}\)

\[
C_{t=0} = 1750 \quad \text{counts/10 sec} \\
\epsilon_o = 1.146 \times 10^{-21} \\
\epsilon = 0.5416 \\
\left( 1-e^{-\lambda t} \right) = 0.8647 \\
\phi \cdot G_e = 3.6326 \times 10^6 \, \text{n/cm}^2\cdot\text{sec} \\
\sigma = 92.4 \pm 5.6 \, \text{mb}
\]

110\(^{\text{Pd}}\)(n,\(\gamma\)) \(111\text{Pd} \rightarrow \) Reaction

Thin palladium metal foil was used as the target material. The irradiation was performed for 15 minutes so
DECAY SCHEME AND HALF LIFE CURVE OF $^{113}$Pd
(NEUTRON ENERGY - 380+10)

$^{113}$Pd 172 MeV
$^{113}$I 17 MeV 20.7%
$^{111}$In 4.6 466
$^{111}$Ag 4.6

$\beta^-$ 1.5187 MeV

2.12 (96%)

$\beta^-$ (94%)

$^{7}$I 7.47 days

COUNTS IN 100 SEC.

BACKGROUND

$T_{1/2} = 22$ MIN

FIG. 7

TIME (MIN)
that most of the activity induced in the sample may be only due to 22 min $^{111}\text{Pd}$. Some activities due to $^{109}\text{Pd}$ (13.5 hrs) and $^{111\text{m}}\text{Pd}$ (5.5 hrs) were also present, besides the general background. By subtracting total background counting rate from the composite curve the half life of 22 min was obtained, which corresponds to $^{111}\text{Pd}$ as shown in fig. 7.

$$
\begin{align*}
C_{t=0} &= 400 \text{ counts/100 sec} \\
n_o &= 1.414 \times 10^{-20} \\
\varepsilon &= 0.7054 \\
(1-e^{-\lambda t}) &= 0.3765 \\
\phi G_e &= 4.1156 \times 10^6 \\
\sigma &= 26 \pm 3.5 \text{ mb}
\end{align*}
$$

$^{154}\text{Sm(n,}\gamma)^{155}\text{Sm} \quad \text{Reaction}$

Pure (99.9\%) samarium oxide enriched in $^{154}\text{Sm}$ was used for the preparation of target sample. The sample had area and mass 2.011 cm$^2$ and 0.0252 gms, respectively. The sample was sandwiched between two standard samples and then irradiated for 10 min and 12 min at neutron energies 400 KeV and 650 KeV, respectively. The half life of 23.5 min was obtained by subtracting the background counting rate from the composite curve as shown in fig. 8a and 8b.
DECAY SCHEME AND HALF LIFE CURVE OF 155Sm
NEUTRON ENERGY (90 ± 30 kW)

$T_{1/2} = 23.5\text{ MIN.}$

$155_{Sm}$
$\beta^-$
$1.31\text{ MeV}$
$1.31(9.3\%)$

$1.62(11%)$

$2.7\text{ MeV}$
$3.51$

$3.68$

$4.04$

$4.99$

$6.96\text{ yr.}$

BACKGROUND
### Neutron Energy — 400 ± 70 KeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{t=0} )</td>
<td>740 counts/100 sec</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>( 8.5262 \times 10^{19} )</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.8548</td>
</tr>
<tr>
<td>( 1-e^{-\lambda t} )</td>
<td>0.29798</td>
</tr>
<tr>
<td>( \phi \cdot G_e )</td>
<td>( 28.541 \times 10^6 ) n/cm² sec</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>32.5 ± 4 mb</td>
</tr>
</tbody>
</table>

### Neutron Energy — 650±20 KeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{t=0} )</td>
<td>2000 counts/100 sec</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>( 8.5262 \times 10^{19} )</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.8548</td>
</tr>
<tr>
<td>( 1-e^{-\lambda t} )</td>
<td>0.2553</td>
</tr>
<tr>
<td>( \phi \cdot G_e )</td>
<td>( 10.7192 \times 10^6 ) n/cm² sec</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>37±3.5 mb</td>
</tr>
</tbody>
</table>

\( ^{198}\text{Pt}(n,\gamma)^{199}\text{Pt} \) — Reaction

0.4967 gm. spectrophotically pure platinum sponge was used for the preparation of target sample. In the usual manner, the sample was irradiated for 10 min only to avoid build up of the long lived activities. A half life of 30 min which corresponds to \(^{199}\text{Pt}\) was obtained after subtracting the background counting rate from the curve.
obtained after subtracting general background from the experimental curve as shown in fig 9.

\[ C_{t=0} = 350 \text{ counts/200 sec} \]
\[ n_0 = 1.11 \times 10^{20} \]
\[ \varepsilon = 0.26 \]
\[ (1-e^{-\lambda t}) = 0.2015 \]
\[ \phi.G_e = 3.84 \times 10^6 \text{ n/cm}^2 \text{ sec} \]
\[ \sigma = 78.3 \pm 10 \text{ mb} \]

In this case the background level shown in fig.9 may be due to longlived activities.

2.4 Results and Discussion:

Table I shows the results obtained from the present work together with the neutron energies, half lives of the products and earlier reported values at nearby energies (where ever they are known).

In \( ^{51}V \), our cross-section value is in agreement with that of Dudey et al\(^{11}\). Accurate measurement of (n,\( \gamma \)) cross-sections for structural and fuel-cladding material is essential to the understanding and description of neutron energy and flux degradation processes present in nuclear reactors. Alloys of Vaniium are one of the types of fuel-cladding materials.
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Neutron Energy (KeV)</th>
<th>Half life of product nucleus (minute)</th>
<th>Cross-section this work (mb)</th>
<th>Other results at near by energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{51}\text{V}(n,\gamma)^{52}\text{V}$</td>
<td>415±15</td>
<td>3.75</td>
<td>2.27±.34</td>
<td>402</td>
</tr>
<tr>
<td>$^{65}\text{Cu}(n,\gamma)^{66}\text{Cu}$</td>
<td>415±15</td>
<td>5.1</td>
<td>7.92±.95</td>
<td>400</td>
</tr>
<tr>
<td>$^{69}\text{Ga}(n,\gamma)^{70}\text{Ga}$</td>
<td>460±10</td>
<td>21.1</td>
<td>37.13±3.3</td>
<td>400</td>
</tr>
<tr>
<td>$^{80}\text{Se}(n,\gamma)^{81}\text{Se}$</td>
<td>610±20</td>
<td>18.5</td>
<td>5.28±.62</td>
<td>-</td>
</tr>
<tr>
<td>$^{80}\text{Se}(n,\gamma)^{81m}\text{Se}$</td>
<td>610±20</td>
<td>57.25</td>
<td>2.18±.44</td>
<td>-</td>
</tr>
<tr>
<td>$^{107}\text{Ag}(n,\gamma)^{108}\text{Ag}$</td>
<td>610±20</td>
<td>7</td>
<td>92.4±5.6</td>
<td>600</td>
</tr>
<tr>
<td>$^{110}\text{Pd}(n,\gamma)^{111}\text{Pd}$</td>
<td>380±10</td>
<td>22</td>
<td>26±3.5</td>
<td>-</td>
</tr>
<tr>
<td>$^{154}\text{Sm}(n,\gamma)^{155}\text{Sm}$</td>
<td>400±70</td>
<td>23.5</td>
<td>32.5±4</td>
<td>400</td>
</tr>
<tr>
<td>$^{198}\text{Pt}(n,\gamma)^{199}\text{Pt}$</td>
<td>475±15</td>
<td>30</td>
<td>78.3±10</td>
<td>-</td>
</tr>
</tbody>
</table>

Legend:

- $^a$ See ref. 11
- $^b$ See ref. 32
- $^c$ See ref. 33
In $^{65}$Cu and $^{154}$Sm our values of cross-section are close to the values reported by Johnsrud et al.\textsuperscript{32}). In $^{69}$Ga, cross-section values are in agreement with those of Dovbenko et al.\textsuperscript{33}). Present value of $^{107}$Ag (n,γ) $^{108}$Ag reaction cross-section is lower than the earlier reported value\textsuperscript{32}). No literature values of cross-section for $^{80}$Se(n,γ)$^{81}$Se, $^{80}$Se(n,γ)$^{81m}$Se, $^{110}$Pd(n,γ)$^{111}$Pd, and $^{198}$Pt(n,γ)$^{199}$Pt reactions are available in few hundreds of KeV region. Probably, these cross-sections are not reported yet\textsuperscript{1}).

2.5 Calculations based on statistical theory:

The theoretical values of the (n,γ) cross-sections are calculated using Margolis formula\textsuperscript{5}) based on statistical theory for comparison with the experimentally measured values in the present work. The following expression for the evaluation of (n,γ) cross-sections was used

$$
\sigma_{E}^{(n,\gamma)} = \frac{\pi J_{p}^{2}}{2(2J+1)} \sum_{J_{z}=J} \left[ \frac{\varepsilon_{J_{z}}}{1 + \xi_{J_{z}}^{2} f_{J_{z}}^{2}(E) \sum_{J_{z}'} \varepsilon_{J_{z}'}^{2} T_{J_{z}} \left( E - E_{J_{z}'} \right)} \right]
$$

where symbols have their usual meanings(for details see chapter III). The parameter $\xi_{J}$ is defined as $D_{J}/2\pi\Gamma_{\gamma}$ where $\Gamma_{\gamma}^{(z)}$ is the radiation width and $D_{J}$ is the level spacing between levels of same spin and parity. The fact that $\xi_{J}$ can be taken as independent of J is not well established. Recently, we have shown\textsuperscript{34}) that $\xi_{J}$ could be taken as independent of J to reproduce the experimental (n,γ) cross-sections at 24 KeV.
At higher neutron energies, \( J \) independence is yet to be proved and that is why we have taken different values of parameter \( \xi_2', \xi_3, 1.25 \xi_3, 1.75 \xi_3 \) (in accordance with reference 8) to evaluate the \((n, \gamma)\) cross-sections in 400-600 KeV energy range. The values of \( \xi_2' \) have been taken from low energy resonance parameters \(^{35-41})

While calculating cross-sections we have included the contribution of angular momentum of neutrons up to \( l=4 \). The \( T_l(E) \) values have been taken from "optical model neutron transmission co-efficients" due to the Perry and Buck \(^{42})

In his representation the transmission co-efficients of partial wave with projectile spin \( J \) are given by \( T^J_l(\xi) \) and the average transmission co-efficients for neutrons are defined as \(^{43})

\[
T_l(E) = \frac{(l+1)T^{J=\frac{1}{2}+\frac{1}{2}}_l(E) + lT^{J=\frac{1}{2}-\frac{1}{2}}_l(E)}{(2l+1)}
\]

The values of level density parameters 'a' and binding energy of neutron '\( B_n \)' in order to calculate \( f_{m} \) have been taken from references \(^{35}, 40 \) and \(^{44}). Energy levels in the target nucleus were taken from recent nuclear data sheets \(^{25-29}).

The results of calculations are compared with the experimental values of the cross-sections. In all cases, as can be seen from the table, the experimental data are in better agreement with the values calculated using \( 1.25 \xi \).
except $^{51}\text{V}$ where the theoretical values of cross-sections are quite high correspondings to $\xi$, $1.25\xi$ and $0.75\xi$. Probably it is due to the fact that the value of $D$ as well as $\Gamma$ obtained for $^{51}\text{V}$ from low energy resonance parameters is not correct. Relatively large level spacing is expected as $^{51}\text{V}$ has 28 neutrons. The theoretical value of the cross-section obtained by Dudey et al using Moldauer formalism at $E_n=400$ KeV is 2.7 mb. This value is close to our experimental measured value and thus confirms our doubt on the value of $\xi$. Therefore, the deviation of $\sigma_{\text{exp}}$ to $\sigma_{\text{meas}}$ for this case is not a real discrepancy. In the case of $^{110}\text{Pd}$ and $^{198}\text{Pt}$ resonance parameters are not known and hence calculations could not be extended for both nuclei.

From table II, it is clear that the theoretical values are somewhat higher than the experimental values. However, this higher trend may be due to the fact that for all nuclei except $^{51}\text{V}$, $^{80}\text{Se}$ and $^{110}\text{Pd}$ (n,\alpha) channel for 400 KeV - 600 KeV neutrons is open (from Q-value consideration). Therefore, the assumption in the derivation of Margolis formula i.e. $\Gamma = \Gamma_\gamma + \Gamma_\alpha$ is not strictly satisfied and $\sigma(n,\gamma)$ must decrease by some amount to account for the contribution of \alpha-emission width in the total width.

In view of the foregoing discussion one can conclude that statistical theory can be applied to predict neutron
### Table - II

A comparison of theoretical and experimental values of neutron capture cross-sections together with $\xi_{obs.}$ and $f$ values.

<table>
<thead>
<tr>
<th>Target Nucleus</th>
<th>Neutron energy (KeV)</th>
<th>$\sigma_{\text{expt.}}$ (mb)</th>
<th>$f$</th>
<th>$\xi$</th>
<th>$\sigma_{\text{theo.}}\xi$ (mb)</th>
<th>$\sigma_{\text{theo.}}^{1.25\xi}$ (mb)</th>
<th>$\sigma_{\text{theo.}}$ (mb)</th>
<th>$\frac{\sigma_{\text{expt.}}}{\sigma_{\text{expt.}}}$</th>
<th>$\frac{\sigma_{\text{theo.}}}{\sigma_{\text{expt.}}}$</th>
<th>$\frac{\sigma_{\text{theo.}}^{1.25\xi}}{\sigma_{\text{expt.}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{51}$V</td>
<td>415±15</td>
<td>2.27±3.4</td>
<td>.6773</td>
<td>932±326</td>
<td>13.6±4.7</td>
<td>11±3.9</td>
<td>17.2±6.7</td>
<td>5.99±2.15</td>
<td>4.9±1.94</td>
<td>7.57±3.12</td>
</tr>
<tr>
<td>$^{65}$Cu</td>
<td>415±15</td>
<td>7.92±9.5</td>
<td>.5551</td>
<td>1553±341</td>
<td>13.4±2.4</td>
<td>11.5±1.9</td>
<td>15.3±2.9</td>
<td>1.59±.31</td>
<td>1.45±.29</td>
<td>1.93±.42</td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>460±10</td>
<td>37.13±3.3</td>
<td>.5050</td>
<td>485±175</td>
<td>3±10</td>
<td>26±8.5</td>
<td>40±13.4</td>
<td>.83±.26</td>
<td>.7±.23</td>
<td>1.07±.37</td>
</tr>
<tr>
<td>$^{80}$Se</td>
<td>610±20</td>
<td>7.46±.75</td>
<td>.3366</td>
<td>2101±766</td>
<td>20±7</td>
<td>17±6</td>
<td>28±9</td>
<td>2.58±.97</td>
<td>2.28±.83</td>
<td>3.75±1.26</td>
</tr>
<tr>
<td>$^{107}$Ag</td>
<td>610±20</td>
<td>92±4±5.6</td>
<td>.3363</td>
<td>40±11</td>
<td>114±28</td>
<td>93±24</td>
<td>137±25</td>
<td>1.23±.31</td>
<td>1.006±.26</td>
<td>1.48±.28</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>380±10</td>
<td>26±3.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(Contd.)
capture cross-sections in few hundreds of KeV region provided the values of resonance parameters and their energy dependence (J-dependence) are precisely known. In the present work, the data points were too meagre to draw any definite conclusion regarding $J$-dependence of $\xi$. 
REFERENCES:

CHAPTER - III

STATISTICAL THEORY CALCULATIONS OF NEUTRON CAPTURE CROSS-SECTIONS AT 24 KeV

3.1 Introduction:

Nuclear reactions data have been investigated primarily to obtain knowledge about nuclear structure and reaction mechanism. The cross-sections in the KeV energy region are useful in the design of fast reactors as well as in the study of cosmological theory of element formation in the universe.1) To understand clearly the element building formation, neutron capture cross-sections data are required in the KeV energy region. Unfortunately, capture cross-sections in the KeV region are known at isolated energies; and these are also not known for all isotopes because most of these cross-sections have been measured using activation technique. This technique is limited to those cases where the life time of product nucleus is neither very short nor very long. In order to understand nucleosynthesis theory Allen et al2) used empirical expressions for finding the neutron-capture cross-sections at 30 KeV where they were not known experimentally. For this reason, the need may arise for calculating the cross-sections in those cases when they are not known from experiment.

In this energy region the neutron-capture reaction
takes place mostly through compound nucleus mechanism. The only problem in evaluating the cross-sections for this kind of reaction is the precise knowledge of the parameters involved in the theoretical formula. No systematic calculations of the cross-section have been done so far in this energy region. Miskel et al.\textsuperscript{3)} have calculated the capture cross-sections for $^{180}$Hf, $^{181}$Ta, $^{186}$W, $^{197}$Au and $^{232}$Th nuclei in the energy region of 0.03 to 4 MeV. These workers have taken three different values of the parameter $\xi$ i.e. 1.25 $\xi$, 0.5 $\xi$ and 0.75 $\xi$ (where $\xi = \langle D \rangle / 2\pi \langle \Omega \rangle$, $\langle D \rangle$ is the average level spacing and $\langle \Omega \rangle$ is the average radiation width) in these calculations. Chaubey and Sehgal\textsuperscript{4)} have calculated the parameter $\xi$ at 24 KeV for a number of cases.

In the present work, neutron total capture cross-sections at 24 KeV for 48 nuclei with mass number $45 < A < 232$ have been calculated on the basis of statistical theory. We have used the expression of Margolis\textsuperscript{5)} for these calculations. It is not known whether $\xi$ is same for s- and p-wave neutrons. We have performed these calculations assuming (a) that $\langle \Omega \rangle / \langle D \rangle$ is same\textsuperscript{5,6)} for s-, p- and d-wave neutrons (b) that $\langle \Omega \rangle / \langle D \rangle$ for p- and d-wave is $(2J+1)$ time\textsuperscript{7,8,9)} that of the s-wave, assuming $\langle \Omega \rangle$ to be same\textsuperscript{9)} for s-, p- and d-wave neutrons. The present work is devoted to presenting these theoretical values alongwith the experimental data. It is concluded that $\langle \Omega \rangle / \langle D \rangle$ is the same for s- and p-wave neutrons.
3.2 Calculations Based on Statistical Theory:

The statistical theory of nuclear reactions is based on two main assumptions: (a) Bohr picture of the compound nucleus formation holds true, and (b) there is an overlapping of the levels at the excitation energy where the compound nucleus is formed. At higher energies of incident neutrons (> 1 MeV) the second assumption will hold good but the first assumption may not be completely valid because of a small contribution due to the non-compound processes as shown in chapter IV. In few hundreds of KeV energy region, both assumptions are expected to be valid and that is why Margolis formula based upon statistical theory has been used in predicting (n,γ) cross-sections in preceding chapter. At 24 KeV the first assumption is completely valid whereas the assumption (b) also seems to be valid provided the energy spread of the incident neutron beam is greater than the spacing of the levels so that many compound states are simultaneously excited. Margolis has derived an expression for the (n,γ) cross-section based on the statistical theory. A brief outline of Margolis formalism may be given as follows.

Let 'l' be the spin of the target nucleus. This spin combines with the neutron spin to give us a "channel spin" $j = \frac{l+1}{2}$. The components (m) of j along the Z-axis (the direction of the incident neutron beam) are $-j$, $-(j+1)$...
\[ \sigma(l,j,J,m,E) = (2l+1)\pi \lambda^2 T_l(E) |\mathcal{C}(l\,|\,0\,|\,J\,m)|^2 \]  

where \( \lambda \) is the wavelength of the incident neutron, \( \mathcal{C}(l\,|\,0\,|\,J\,m) \) is the Clebsch-Gordan coefficient relating to the probability that \( l \) and \( j \) with Z-component 0 and \( m \) combine vectorially to give spin \( J \) with Z-component \( m \), and \( T_l(E) \) is the transmission coefficient for the neutrons.

Now the partial decay probability of the compound state with spin \( J \) and excitation energy \( (B+E) \) (\( B \) is the last neutron binding energy in the compound nucleus) through \( \gamma \)-emission may be given as:

\[ \sigma(l,j,J,m,E) \times \left[ \frac{\Gamma_{\gamma}(B+E)}{\Gamma(B+E)} \right] \]

where \( \Gamma_{\gamma}(E+B) \) and \( \Gamma(B+E) \) are the partial radiation width and total width respectively of the compound state with spin \( J \) and excitation energy \( (E+B) \). Summing expression (2) over the possible \( J \)'s and \( l \)'s, and averaging over all \( j \) and \( m \) one gets

\[ \sigma_{\text{tot}} = \frac{\pi A^2}{\lambda (2I+1)} \sum_{l=0}^{\infty} T_l(E) \left[ \sum_{J=0}^{\infty} \frac{E_{Jl}^\gamma (2J+l)}{\Gamma_{\gamma}(B+E)} \left( \frac{\Gamma_{\gamma}(B+E)}{\Gamma(B+E)} \right) \right] \]
Margolis used a form of level density $\rho(E)$ at excitation energy $E$ on the basis of Fermi gas model

$$\rho(E) = C \exp \left[2(aE)^{1/2}\right] \quad \ldots \ldots (4)$$

where

$$\epsilon_{J}^{\pm} = 2, \text{ if both } j_1 \text{ and } j_2 \text{ satisfy } |J-1| \leq j_1, j_2 \leq J+1$$

$$= 1, \text{ if } j_1 \text{ or } j_2 \text{ (not both) satisfies } |J-1| \leq j \leq J+1$$

$$= 0, \text{ otherwise}$$

The expression derived by him is given by

$$\Gamma_n^{(J)}(E')/\Gamma_n^{(J)}(B+E) = \frac{R_B+E}{\Delta I} T_1(E') f_{\Delta I}(E) \ldots \ldots (5)$$

where $\Gamma_n^{(J)}(E')$ is the width for the neutron emission of angular momentum $l'$ and energy $E'$ from the compound state of spin $J$ and excitation energy $(B+E)$ and $B+E$

$$f_{\Delta I} = \frac{\int_0^\Delta e^{2\Delta I+1} \rho(B-\varepsilon)d\varepsilon}{\int_0^\Delta e^{2\Delta I+1} \rho(B+E-\varepsilon)d\varepsilon} \ldots \ldots (6)$$

$\Delta I$ being the multipolarity of the $\gamma$-rays emitted and

$$T_1(E') = D^J(B)/2\pi \Gamma^{(J)}(B) \ldots \ldots (7)$$

where $D^J(B)$ is the spacing of the compound nucleus levels of spin $J$ at excitation energy $(B)$.

On the assumption that at the value of the excitation energy concerned compound nucleus can decay by neutron emission or by $\gamma$-emission one can write for $(n,\gamma)$ reaction cross-section using equations (3) and (5),

$$\sigma_{n,\gamma}^{(J)}(n,\gamma) = \frac{\pi}{2(2I+1)} \sum_{\ell=0}^{2I+1} \left\{ T_1(E') \sum_{j} \frac{\epsilon_{J}^{j} (2J+1)}{\epsilon_{j}^{+} + \epsilon_{j}^{-} f_{\Delta I}(E) \sum_{r} \epsilon_{j}^{r} T_1(E-E_n)} \right\} \ldots \ldots (8)$$
where \( E_n \) is the energy of the \( n \)th excited state of the target nucleus and \( j_n = i_n + \frac{1}{2} \), where \( i_n \) is the spin of the \( n \)th excited state of the target nucleus. The sum over \( l' \) includes only those values for which parity of the system remains conserved. The sum over \( E_n \) includes only those states for which \( E_n < E \).

While calculating cross-sections we have included the contribution of angular momentum of neutrons up to \( l = 2 \), as only s- and p-wave neutrons contribute predominantly to the capture cross-section at 24 keV in most of the target nuclei\(^9\). The neutrons transmission coefficients were calculated using the data of Campbell et al.\(^{11}\) We have taken the spherical complex well potential with diffuse edges\(^3\) and the value of nuclear radius as \( R = (1.25 A^{1/3} + 0.5) \) fermis in the calculations of \( T_1 \). It is assumed\(^{12}\) that dipole radiation predominates over other higher multipoles, the ratio of the two is of the order of \( 10^{-5} \). Different values of level density parameter \( a \), neutron binding energy \( B \) and pairing energy \( \Delta \), corresponding to different isotopes have been taken from the results of Gilbert and Cameron\(^{13}\) and Baba\(^{18}\). There was no significant variation in the values of \( f_{\Delta I} \) for different isotopes. Most of these values lie between 0.93 to 0.97. However, we have taken different values of \( f_{\Delta I} \) for different isotopes in our calculations. We also calculated \( f_{\Delta I} \) for \(^{197}\)Au assuming quadrupole radiations. This value of \( f_{\Delta I} = 0.975 \) is very
close to $f_{\Delta I} = 0.953$ for dipole radiations, therefore, our results are not effected in the presence of a small admixture of quadrupole radiations.

$\xi_J$ is defined as $D_J / 2\pi \Gamma_r^{(\tau)}$ where $\Gamma_r^{(\tau)}$ is the radiation width and $D_J$ is the level spacing between levels of same spin and parity. We have done two sets of calculations of the capture cross-sections once taking into account $J$-dependence of $\xi$ through $D_J$ and another taking $\xi$ to be independent of $J$. $\xi'$ and $\xi$ denote the value with and without $J$-dependence.

The parameter $\xi$ was calculated by taking the average value of level spacing $D$ and radiation width $\Gamma_r$ from the recently known resonance parameters\textsuperscript{14-19,9).} While calculating $\xi$ the average level spacing $D$ for zero spin target nuclei was taken to be equal to the observed level spacing, whereas for non-zero spin target nuclei the average level spacing was taken to be twice that of the observed level spacing\textsuperscript{4,20).} It has been shown\textsuperscript{21) that $<\Gamma>$ and $<D>$ do not change significantly up to 100 KeV of incident neutron energy and hence these low energy resonance parameters can be safely used at 24 KeV.

The $s$-wave contributions to capture cross-section has been calculated using $s$-wave resonance parameters available in literature\textsuperscript{14-19)\textsuperscript{).}} The $p$-wave contributions have been calculated following two different approaches:

(a) that $<\Gamma_D>$ is same\textsuperscript{5,6) for s-, p- and d-wave neutrons.
(b) that $<\Gamma>/<D>$ for p- and d-wave is $(2J + 1)$ times\textsuperscript{7-9) that of the s-wave, assuming $<\Gamma>$ to be same\textsuperscript{9}) for s-, p- and d-wave neutrons.
Table 1. A comparison of theoretical and experimental values of neutron capture cross-sections at 24 k.eV together with the \( \xi_{\text{exp}} \) values.

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>( \xi_{\text{theo}} )</th>
<th>( (\sigma_{\text{theo}})_c ) (mb)</th>
<th>( (\sigma_{\text{exp}})_c ) (mb)</th>
<th>( (\sigma_{\text{exp}})_c ) (mb)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{2} \text{H} )</td>
<td>1553 ± 252 (18, 15)</td>
<td>55 ± 13</td>
<td>82 ± 17</td>
<td>51 ± 7 (2)</td>
<td>1.08 ± 0.29</td>
</tr>
<tr>
<td>( ^{2} \text{He} )</td>
<td>1900 ± 259 (18, 15)</td>
<td>53 ± 14</td>
<td>99 ± 21</td>
<td>58 ± 3 (2)</td>
<td>0.91 ± 0.24</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>613 ± 107 (18, 17)</td>
<td>178 ± 18</td>
<td>245 ± 29</td>
<td>112 ± 9 (22-28)</td>
<td>1.14 ± 0.18</td>
</tr>
<tr>
<td>( ^{2} \text{O} )</td>
<td>1533 ± 341 (18, 19)</td>
<td>53 ± 13</td>
<td>112 ± 15</td>
<td>44 ± 5 (28-23, 26)</td>
<td>1.2 ± 0.29</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>485 ± 175 (18, 17)</td>
<td>181 ± 60</td>
<td>337 ± 93</td>
<td>150 ± 35 (2)</td>
<td>1.2 ± 0.48</td>
</tr>
<tr>
<td>( ^{2} \text{O} )</td>
<td>438 ± 118 (18, 19)</td>
<td>195 ± 45</td>
<td>454 ± 50</td>
<td>140 ± 35 (2)</td>
<td>1.39 ± 0.46</td>
</tr>
<tr>
<td>( ^{2} \text{Mg} )</td>
<td>216 ± 13 (18, 15)</td>
<td>752 ± 54</td>
<td>1320 ± 71</td>
<td>565 ± 115 (2)</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>( ^{2} \text{Mg} )</td>
<td>57 ± 12 (18, 16)</td>
<td>987 ± 139</td>
<td>1450 ± 144</td>
<td>760 ± 65 (4, 39)</td>
<td>1.29 ± 0.2</td>
</tr>
<tr>
<td>( ^{2} \text{Mg} )</td>
<td>71 ± 15 (17, 13)</td>
<td>255 ± 130</td>
<td>1236 ± 134</td>
<td>555 ± 65 (4, 23)</td>
<td>1.54 ± 0.3</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>2101 ± 766 (12, 19)</td>
<td>48 ± 12</td>
<td>96 ± 26</td>
<td>23 ± 14 (2)</td>
<td>2.006 ± 0.37</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>1400 ± 254 (18, 19)</td>
<td>270 ± 32</td>
<td>231 ± 42</td>
<td>181 ± 35 (23)</td>
<td>0.66 ± 0.21</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>2292 ± 687 (18, 19)</td>
<td>34 ± 5</td>
<td>69 ± 10</td>
<td>27 ± 5 (2)</td>
<td>1.26 ± 0.29</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>777 ± 1433 (4)</td>
<td>22 ± 6</td>
<td>49 ± 13</td>
<td>24 ± 6 (2)</td>
<td>0.91 ± 0.32</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>117 ± 24 (13, 19)</td>
<td>471 ± 54</td>
<td>609 ± 51</td>
<td>320 ± 35 (2)</td>
<td>1.49 ± 0.22</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>2165 ± 520 (16)</td>
<td>555 ± 12</td>
<td>115 ± 22</td>
<td>35 ± 14 (2)</td>
<td>0.5 ± 0.16</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>600 ± 254 (15, 19)</td>
<td>162 ± 45</td>
<td>195 ± 32</td>
<td>162 ± 46 (2)</td>
<td>1 ± 0.4</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>288 ± 42 (15, 19)</td>
<td>276 ± 30</td>
<td>436 ± 74</td>
<td>115 ± 46 (2)</td>
<td>2.4 ± 0.98</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>298 ± 40 (11, 17)</td>
<td>991 ± 192</td>
<td>1037 ± 183</td>
<td>1332 ± 24, (2)</td>
<td>0.75 ± 0.18</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>53 ± 10 (13, 17)</td>
<td>787 ± 104</td>
<td>835 ± 98</td>
<td>765 ± 60 (4, 25)</td>
<td>1.02 ± 0.15</td>
</tr>
<tr>
<td>( ^{2} \text{Ne} )</td>
<td>200 ± 15 (18, 19)</td>
<td>600 ± 15</td>
<td>1500 ± 45</td>
<td>586 ± 105 (22, 23, 4)</td>
<td>1.02 ± 0.18</td>
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<tr>
<td>( ^{2} \text{Ne} )</td>
<td>167 ± 24 (13, 19)</td>
<td>21 ± 6</td>
<td>178 ± 13</td>
<td>120 ± 11 (2)</td>
<td>1.27 ± 0.3</td>
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<tr>
<td>( ^{2} \text{Ne} )</td>
<td>16 ± 4 (13, 19)</td>
<td>1751 ± 93</td>
<td>976 ± 100</td>
<td>847 ± 57 (2)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>53 ± 12 (13, 15)</td>
<td>815 ± 154</td>
<td>865 ± 152</td>
<td>805 ± 45 (2)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>11389 ± 5488 (18, 9)</td>
<td>15 ± 5</td>
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<td>13 ± 6 (9)</td>
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<td>( ^{2} \text{Ne} )</td>
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<td>50 ± 7 (23, 24)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>4301 ± 1590 (9)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>2120 ± 390 (9)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>315 ± 58 (15, 19)</td>
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<td>318 ± 18</td>
<td>170 ± 40 (21, 23)</td>
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<td>( ^{2} \text{Ne} )</td>
<td>902 ± 36 (13, 9)</td>
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<td>654 ± 53 (9, 4, 23)</td>
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<tr>
<td>( ^{2} \text{Ne} )</td>
<td>324 ± 38 (13, 9)</td>
<td>515 ± 70</td>
<td>715 ± 69</td>
<td>514 ± 44 (9, 4, 23)</td>
<td>0.57 ± 0.05</td>
</tr>
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</table>
3.3 Results:

The results of the present calculations are summarized in Table I. In column Ist and IIInd are given the target nucleus and the values of \( \xi \) for different isotopes. The third and fourth columns contain the computed cross-sections corresponding to \( \xi \) and \( \xi' \) (\( = <D>/2\pi \xi' (2l+1) \)), respectively. The errors in the calculated cross-section values are due to errors present in the value of resonance parameters. Various experimental values\(^ {22-30} \) of total capture cross-sections mostly obtained by activation technique using Sb-Be Photo-neutron source, which has an energy spread 5KeV\(^ {28} \), have been suitably averaged in Vth column of table I. Some of the average values of \( \sigma_{\text{expt.}} \) have been taken from ref.2. The search is not claimed to be exhaustive, but it is believed that no important data have been missed. In \(^{79}\text{Br},^{85}\text{Rb},^{108}\text{Pd},^{109}\text{Ag},^{114}\text{Cd},^{115}\text{In},^{133}\text{Cs},^{164}\text{Dy},^{184}\text{W},^{181}\text{Ta} \) and \(^{209}\text{Bi} \) values of \( \sigma_{\text{expt.}} \) are the sum of the cross-sections for the isomeric and the ground states, and thus are total capture cross-sections. The ratio of the theoretical values to those of experimentally measured cross-sections have been presented in the VIth and VIIth column of the table. Fig.1 illustrates the behaviour of \( \frac{\sigma_{\text{theo.}}}{\sigma_{\text{expt.}}} \) and \( \frac{\sigma_{\text{theo.'}}}{\sigma_{\text{expt.'}}} \) versus the neutron number \( N \) in the target nucleus.

Practically for all cases given in table I, the contribution of the d-wave to capture cross-section is very
FIG. 1

NUMBER N OF THE TARGET NUCLEUS

Plot of the ratios \( \frac{\text{theo}}{\text{exp}} \) and \( \frac{\text{theo}}{\text{exp}} \) vs. the neutron.
small in comparison with s- and p-wave, so it is difficult to say whether \( \langle \eta \rangle / \langle \delta \rangle \) for d-wave is same that of s-wave. However, the contribution of p-wave to the capture cross-section is either comparable or more than s-wave contribution in most of the cases, therefore, it is easy to verify whether \( \langle \eta \rangle / \langle \delta \rangle \) is the same for s- and p-wave. It is clear from the Fig.1 that most of the points are closer to the line corresponding to the ratio 1, within experimental uncertainties, when \( \xi \) is taken to be independent of \( J \); thus confirming that \( \langle \eta \rangle / \langle \delta \rangle \) is the same for s- and p-wave. From table it is clear that difference between \( \langle \sigma_{\text{theo}} \rangle \) and \( \langle \sigma_{\text{theo}} \rangle \) for nuclei 98-100Mo, 107-109Ag, 114Cd, 115In, 127I, 133Cs is not significant and therefore it is difficult to verify the relation \( \langle \eta \rangle / \langle \delta \rangle \) \( \approx \) \( \langle \eta \rangle / \langle \delta \rangle \) for these cases.

It may be remarked that \( \langle \eta \rangle \) and \( \langle \delta \rangle \) can independently change for p-wave keeping the ratio \( \langle \eta \rangle / \langle \delta \rangle \) to be the same. Allen et al.\(^{31}\) have proved for \( ^{56}\text{Fe} \) that \( \langle \eta \rangle / \langle \delta \rangle \) has the value \( \approx 0.06 \pm 0.0017 \) and \( 0.0428 \pm 0.012 \) for s- and p-wave, respectively. Stieglietz et al.\(^{32}\) have studied p-wave resonances of \( ^{52}\text{Cr} \). They have found that average radiation width \( \langle \eta \rangle \) for the p-wave resonances is nearly three times smaller than the \( \langle \eta \rangle \) for the s-wave resonances. Assuming that the average level spacing obeys a law or \( (2J+1)^{-1} \), \( D_{J=1} \) will be three times smaller than \( D_{J=0} \). Thus \( \langle \eta \rangle / \langle \delta \rangle \) for the p-wave resonances will remain same as that
of $s$-wave resonances for $^{52}$Cr. Musgrove et al.\textsuperscript{33} have shown that $\frac{\langle r \rangle}{\langle D \rangle}$ is nearly same for $s$- and $p$-wave resonances in $^{40}$Ca.

Finally, we would like to point out that the assumption $[\frac{\langle r \rangle}{\langle D \rangle}]_{p\text{-wave}} \simeq [\frac{\langle r \rangle}{\langle D \rangle}]_{s\text{-wave}}$, which has been verified experimentally for many nuclei\textsuperscript{16, 31-33} except three in $3P$ region\textsuperscript{16, 34}, is fairly well to reproduce the experimental cross-sections and it may be further used to get information about $[\frac{\langle r \rangle}{\langle D \rangle}]_{d\text{-wave}}$ with respect to $[\frac{\langle r \rangle}{\langle D \rangle}]_{s\text{-wave}}$ by fitting the experimental cross-sections at higher energies.
REFERENCES:

1) E.M.Burbidge et al. : Rev. Mod. Phys. 29 (1957) 547.

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CHAPTER - IV
INVESTIGATION OF REACTION MECHANISMS AND TRENDS IN
\( (n,\gamma) \) CROSS-SECTIONS

4.1 Introduction:

Early work on neutron capture showed the existence of narrow resonances and led to Bohr's compound nucleus hypothesis\(^1\). This, in turn, was the basis of the statistical theory of nuclear reactions\(^2,3\) which proved very successful\(^4-8\) in predicting \((n,\gamma)\) cross-sections over wide energy range (few tens of KeV to \(3-4\) MeV). The importance of other reaction mechanisms was considered by Lane and Lynn\(^9,10\) who introduced hard sphere or direct capture, and channel or valance capture. These processes arise from the overlap of initial and final state wave functions in the external region of the target nucleus, which acts as an inert core\(^11\).

The experimental data available for the discussion of the capture mechanism are \(\gamma\)-ray spectra\(^12,13\) emitted in the capture of neutrons of different energies. In the first theoretical investigations, an attempt was made to explain with the aid of the direct capture the presence of high-energy lines in the spectra of the capture gamma rays from the reaction \((n,\gamma)\) with thermal neutrons by nuclei with \(A\approx50\) and \(A\approx200\). These lines correspond to El transitions of the product nucleus from the capture state to the lower p-level\(^10,14-16\). Later, it was found\(^17,18\) that the cross-
A comparison of experimental and theoretical values of neutron capture cross section at 10, 30, 100, 300 keV, 1 and 3 Mev.

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58
section of the direct capture is too small and does not exceed 0.1 b in nuclei with A≈50.

In the present work, an attempt has been made to shed light on the capture mechanism by comparing \( \sigma_{\text{expt.}} \) with \( \sigma_{\text{theo.}} \) (n,γ). At present, a bulk of neutron capture cross-section data are available along with the theoretical values based upon statistical theory of nuclear reactions. The experimental data on (n,γ) cross-sections have also been examined to find any possible "shell effects".

4.2 Results and discussion:

Large discrepancies in the experimental results reported by different group of workers might put a limit to the establishment of reaction mechanisms. That is why we have taken cross-section value from graphs given in recent BNL report\(^{19}\) along with \( \approx 15\% \) error. This choice of error limit ensures us the reliability of \( \sigma(n,\gamma) \) values as this limit covers the range of clusters of experimental points (through which curves have been drawn in BNL report). Table I gives the experimental values of (n,γ) cross-section together with the theoretical values at incident energies \( E_n = 10, 30, 100, 300 \text{ KeV}, 1 \) and 3 MeV for nuclei A>85. The ratios \( \frac{\sigma_{\text{expt.}}(n,\gamma)}{\sigma_{\text{theo.}}(n,\gamma)} \) at these energies have been plotted against the compound nucleus mass (A). Figures 1 and 2 display these plots.
$E_n = 3$ MeV

$E_n = 1$ MeV

$E_n = 300$ KeV
Gross features of \( \frac{\sigma_{\text{theo}}(n,\gamma)}{\sigma_{\text{expt}}(n,\gamma)} \) vs. A curves are same at \( E_n = 10, 30 \) and 100 KeV. That is, the data points are scattered around the line corresponding to the ratio one (Fig.1). At 300 KeV, a cluster of points at \( A > 150 \) is present below the line corresponding to the ratio 1. At 1 MeV and 3 MeV, except few data points, all points lie below the line corresponding to ratio unity. This tendency is probably indicative of the increasing importance of non-statistical processes in the capture mechanism. At higher energies the cross-section for radiative capture via compound nucleus formation are strongly reduced due to the competition from other modes of decay. It has been shown \(^8\) that compound nucleus model fails to predict capture cross-section at \( E_n \approx 1.4 \) MeV. In other words non-statistical processes contribute largely to the \( (n,\gamma) \) cross-sections at \( E_n \approx 1.4 \) MeV. At 3 MeV it is inferred from Fig.(2) that at least 20-30\% of cross-section should be added from non-statistical processes to the compound nucleus contribution in order to get an agreement of \( \sigma_{\text{expt.}} \) with \( \sigma_{\text{theo.}} \) within a factor of two or better.

The theoretical values are valid to roughly a factor of two \(^{20}\). The factor of two may be due to the fact that the statistical model cross-sections are parameter dependent, especially the level density expression play an
important role. Some attempts to check the level density models through fitting the cross-sections have been made\textsuperscript{21)\textsuperscript{21}}. The level density expression (Back-Shifted Fermi Gas Formula) used in the present calculations is given by\textsuperscript{20)}

\[ \rho(\varepsilon', J', \pi') = \rho_{\text{bt}}(\varepsilon') f(\varepsilon', J', \pi') \]

Where \( \rho_{\text{bt}}(\varepsilon') = \frac{482}{A^5/6} \exp\left(2\sqrt{a(\varepsilon'-\delta)}\right)/(\varepsilon'-\delta)^{3/2} \text{ MeV}^{-1} \)

where \( \rho_{\text{bt}}(\varepsilon') \) is the total nuclear level density in the nucleus of atomic mass \( A \) and moment of inertia \( J \) at the excitation energy \( \varepsilon' \), \( f(\varepsilon', J', \pi') \) is the distribution of spins and parities at that energy normalized so that the sum over all spins and parities is unity and 'a' and 'δ' are two nuclear parameters which are determined empirically. The above level density formula does not take into account shell effects properly. For reactions involving nuclei near closed shells, for which low nuclear level density is expected, the reader has been advised\textsuperscript{20)\textsuperscript{20}} to seek an alternate source of nuclear data.

In conclusion we can say that the statistical model is a very useful concept for low energy (n,γ) reactions. We expect it to begin to break down at \( \gtrsim 3 \text{ MeV} \) due to the onset of non-statistical processes (e.g. direct reactions). Much more experimental data along with theoretical developments would enable one to draw definite conclusions regarding the magnitude of non-statistical processes in MeV energy region.
FIG. 6
NEUTRON NUMBER

2-MAY CAPTURE CROSS SECTIONin mb

Z ODD

Ag In
Sb
As
Rb
Cl
Ho
Ir
Au

10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}

20 20 50 92 126
4.3 Comments on Shell effects:

It is apparent from figures 3 and 4 that the experimental data on \((n,\gamma)\) at 30 KeV show separate systematic trends with neutron number for even and odd-Z nuclei. The odd-Z nuclei, generally limited to two isotopes exhibit pronounced minima at the magic neutron numbers \(N=20, 50, 82\) and 126. A similar effect is observed for the even-Z nuclei but less pronounced because of complex situation as a result of large number of isotopes. Isotopic cross-sections at 300 KeV (wherever they are available) are plotted against neutron numbers for odd-Z nuclei. The cross-sections are seen to increase immediately after neutron shell is filled. In contrast to the marked minima at \(N=20, 50, 82\) and 126 the magic neutron number 28 appears to have little effect on KeV cross-sections.

It was thought worthwhile to see whether the shell effects remain unaffected as the energy \(E_n\) increases. In pursuit of this goal we have also plotted the cross-section for odd-Z nuclei at 3 MeV against neutron number.

It is clear from these figures (3-6) that shell effects are clearly apparent at low energies (up to 300 KeV) but seem to be on the verge of disappearing at high energies (> 3 MeV). The knowledge of level density plays an important
role in the statistical theory. The decreasing tendency of observed shell effects in \((n,\gamma)\) data, if interpretable within the framework of statistical theory, may also be due to the fact that at high excitation energy shell effects on level density tend to disappear\(^{22}\).
REFERENCES:

9. J.E. Lynn: Theory of neutron resonance reactions,
11. J.R. Bird et al.: Proc. Int. Conf. of interaction of
    neutrons with nuclei, Lowell (1976) p. 76.
    2 (1956) 769.
CHAPTER - V

STUDY OF (n,α) REACTIONS IN KeV REGION

5.1 Introduction:

The measurement of the (n,α) reaction on heavy nuclei is a difficult experimental task because of the extremely small cross-sections for this reaction and the large γ-ray background in the other competing reactions. Except for low mass nuclei practically no experimental data on (n,α) reactions in KeV region exists to prove or to disprove the validity of statistical theory of nuclear reactions in predicting (n,α) cross-sections. For this reason, the need arises for measuring the cross-sections for (n,α) reaction.

The present work provides the value of cross-section of $^{209}$Bi(n,α)$^{206}$Tl reaction at two incident neutron energies for the first time. The $^{209}$Bi target is a promising target for low energy neutron initiated (n,α) reaction as the Q-value of (n,α) reaction for this is quite high (9.633 MeV). These values of the cross-sections have been compared with the theoretical values based on Hauser Feshback Statistical model.

In addition to it, the isomeric cross-section ratios for $^{181}$Ta (n,α) $^{178g}$mLu reaction at four neutron energies have been measured. With the knowledge of the trend of
The spins have been assigned to 5 min. and 25 min. isomeric states. Details are separately given in section (5.3) of this chapter.

5.2 Measurements of Activation Cross-section for \( ^{209}\text{Bi} (n,\alpha) ^{206}\text{Tl} \) reaction:

Spectrographically pure \( \text{Bi}_2\text{O}_3 \) powder was sandwiched between two thin pieces of cellotape. The area of the sample was a circle of 1.6 cm. diameter. Since most of the cross-sections for \( (n,\alpha) \) reaction are rather low, somewhat thick sample (0.2445 gm/cm\(^2\)) in comparison to \( (n,\gamma) \) measurements was taken. The requisite neutrons were obtained from the \( ^3\text{H}(p,n)^3\text{He} \) reaction using incident proton beam from Van de Graaff generator at I.I.T., Kanpur (India). The tritium target consisted of 16 Ci of tritium absorbed in titanium layer on thin backing of copper (~0.25 mm.). The circulation of high pressure chilled water around the tritium target to remove the local heating permitted beam currents as large as 50 \( \mu \text{A} \) for a duration of 15-20 min. without experiencing any serious deterioration of tritium target.

An end window \( \beta \)-counter, whose window thickness was 1.75mg/cm\(^2\), was used for detecting the \( \beta \)-particles. The counter was shielded by a lead house to reduce the general background. The sample was irradiated in zero degree forward
BACKGROUND DUE TO $^{210}\text{Bi}$ ($T_{1/2} = 5\text{ d}$)

$T_{1/2} = 4.3\text{ min}$

COUNTS/100 SEC.

FIG. 2 TIME (MIN)
direction relative to the proton beam. The position of sample with respect to neutron source had to be very close to get substantial counts due to activity produced from \((n,\alpha)\) reaction. However, it resulted in a large energy spread \(\Delta E_n\) of the neutrons.

Figures 1 and 2 show the decay curves of the products due to the \((n,\alpha)\) and \((n,\gamma)\) reactions. By subtracting the background of 5d \((n,\gamma)\) activity due to \(^{210}\)Bi from the composite curve, we obtained a half life of 4.3 min., which corresponds to the activity of \(^{206}\)Tl. As \(^{209}\)Bi is mono-isotopic, the admixture of other \(\beta\)-activities is not possible.

The following expression was used for finding the cross-section

\[
\sigma(n,\alpha) = \frac{C_0}{(\phi G_e) \varepsilon (1-e^{-\lambda t})n_0}
\]

where \(C_0\) corresponds to the counting rate at zero time for the product activity produced by \((n,\alpha)\) reaction; \((\phi G_e)\), \(n_0\), \(\lambda\) correspond to the flux of neutrons at the place of irradiation of the sample, the number of nuclei in the target, and the decay constant for product nuclei formed by \((n,\alpha)\) reaction, respectively; and 't' is time of irradiation of the sample. In calculating the detection efficiency \(\varepsilon\), corrections for the finite thickness of the target as well as
the window thickness of the $\beta$-counter were also taken into account. Neutron flux on both sides of the sample was calculated by using two standard samples of potassium iodide, one on each side of the specimen sample during irradiation with neutrons. The average of these two values of neutron flux was used for the measurement of the cross-sections. While calculating the flux, the cross-sections for $^{127}\text{I} \,(n,\gamma)\, ^{128}\text{I}$ reaction at 340 KeV and 575 KeV were taken to be 0.17 b, and 0.12 b, respectively from BNL report (1976). Details of individual measurements at different energies are given below.

<table>
<thead>
<tr>
<th>Neutron energy — 340 ± 150 KeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>= 0.7</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>= 0.3356</td>
</tr>
<tr>
<td>$n_0$</td>
<td>= $1.272 \times 10^{21}$</td>
</tr>
<tr>
<td>$(\phi G_e)$</td>
<td>= $16.29 \times 10^8$</td>
</tr>
<tr>
<td>$(1-e^{-\lambda t})$</td>
<td>= 0.8</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>= $1.26 \pm 0.18$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutron energy — 575±235 KeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>= 0.96</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>= 0.3356</td>
</tr>
<tr>
<td>$(\phi G_e)$</td>
<td>= $14.83 \times 10^8$</td>
</tr>
<tr>
<td>$(1-e^{-\lambda t})$</td>
<td>= 0.98</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>= $1.55 \pm 0.23$</td>
</tr>
</tbody>
</table>
Table-I gives the experimental values of cross-section for $^{209}\text{Bi} (n,\alpha) ^{206}\text{Tl}$ reaction along with the theoretical values based on Hauser Feshbach statistical model of nuclear reactions. The experimental values are $\approx 10^4$ times larger than the theoretical values. The present values are also high when compared with the value ($\approx 3$ b) reported by Emsallem et al. for $^{209}\text{Bi} (n,\alpha_n)$ reaction at thermal energy. Where $\sigma(n,\alpha_n)$ corresponds to the cross-section when the $\alpha$-particle feeds the ground state of the product nucleus. The present work proved rewarding to support one of the two reported values of cross-section of $^{209}\text{Bi} (n,\alpha)$ $^{206}\text{Tl}$ reaction at thermal energy. Alam and Sehgal looked for this reaction induced by thermal energy neutrons using $\beta$-counting technique and obtained $\sigma_\alpha = 1.45 \mu$b (as quoted in ref.3). Emsallem et al used a gold silicon surface barrier detector to detect $\alpha$-particles directly from the above reaction at the same energy and obtained $\sigma_\alpha < 3$ b. The difference between these two values is quite big. Our work supports the latter one.

The large discrepancy between the values reported by Alam and Sehgal and by A. Emsallem (as shown in table 2 of ref.3) may be due to the following facts:
(1) The sample might have picked up some impurity at the time of irradiation in the thermal column. It seems that the samples were irradiated by placing them in the pit (located in the thermal column). In that case it is possible that sample might have picked up some contamination with nearly the same life time. The counting rate in this case was small and hence the chances of the impurity being discriminated is also very small. This might be one of the possible reasons for extremely large value of cross-section reported by Alam and Sehgal.

(2) The sample purity though purchased from Johnson Mathey and Co., Ltd., London with 99.9% purity may be a point to be worried.

(3) The long-lived activity has not been followed up to the desired level and the problem of background has not been tackled convincingly.

It has been pointed out\(^5\) that experimental values \(\sigma_{\text{exp.}}\) of \((n,\alpha)\) reaction are much larger than the predictions of statistical model of nuclear reactions for nuclei of mass \(\gtrsim 130\) and the pre-existence of \(\alpha\)-particle within the nucleus was suggested and its emission was treated just like that of a nucleon.

The present disagreement between \(\sigma_{\text{exp.}}(n,\alpha)\) and \(\sigma_{\text{hess.}}(n,\alpha)\) may be due to the presence of contributions to the cross-section.
TABLE - I

Comparison of $\sigma_{\text{exp.}}(n,\alpha)$ and $\sigma_{\text{theor.}}(n,\alpha)$ for $^{209}\text{Bi}(n,\alpha)^{206}\text{Tl}$ Reaction

<table>
<thead>
<tr>
<th>Energy of Neutron ($E_n$) (KeV)</th>
<th>$\sigma_{\text{exp.}}(n,\alpha)$ ($\mu$b)</th>
<th>$\sigma_{\text{theor.}}(n,\alpha)$ ($\mu$b) $\times 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$340 \pm 150$</td>
<td>$1.26 \pm .18$</td>
<td>$6.5 \pm 2.5$</td>
</tr>
<tr>
<td>$575 \pm 235$</td>
<td>$1.55 \pm .23$</td>
<td>$13 \pm 7.0$</td>
</tr>
</tbody>
</table>
by reaction processes other than compound nucleus process e.g. preformed emission. The veracity of this conclusion calls for increasing amount of experimental data in KeV region.

5.3 $^{181}$Ta (n,$\alpha$) $^{178}$g$_m$$^{107}$Lu Reaction and isomeric states of $^{178}$g$_m$$^{107}$Lu:

(i) Introduction:

According to Gallanger and Moszkowski$^6$ the ground state of deformed odd-odd nuclei could be represented by two particle state of the last odd proton and last odd neutron. In $^{178}$Lu nucleus the last (71 st) proton and last (107 th) neutron are known to occupy the $7^+2[404]$$\downarrow$ and $9^+/2[624]$$\uparrow$ Nilsson states, respectively. On the basis of coupling rule$^6$ the spin and parity of ground state is

$$p \ 7^+2[404]$$\downarrow\ -n 9^+2[624]$$\uparrow \rightarrow 1^+(\Sigma=1)$$

gallanger$^7$ has extended the applicability of the coupling rule to the low lying intrinsic states of both odd-odd and even-even deformed nuclei. The Nilsson orbital ordering adjacent to $Z = 71$ and $N = 107$ are given as follows:

<table>
<thead>
<tr>
<th>Z</th>
<th>Nilsson orbital</th>
<th>N</th>
<th>Nilsson orbital</th>
</tr>
</thead>
<tbody>
<tr>
<td>69</td>
<td>$1^+[411]$$\downarrow$</td>
<td>105</td>
<td>$7^+/2[514]$$\downarrow$</td>
</tr>
<tr>
<td>71</td>
<td>$7^+/2[404]$$\downarrow$</td>
<td>107</td>
<td>$9^+/2[624]$$\uparrow$</td>
</tr>
<tr>
<td>73</td>
<td>$9^+/2[514]$$\uparrow$</td>
<td>109</td>
<td>$1^−/2[510]$$\downarrow$</td>
</tr>
</tbody>
</table>
Coupling scheme produces spins of 7−, 8+ and 9− for isomeric state:

\[
p^{7/2} \left[ {404} \right] \downarrow + n^{7/2} \left[ {514} \right] \downarrow \rightarrow 7^{-}
\]

\[
p^{7/2} \left[ {404} \right] \downarrow + n^{9/2} \left[ {624} \right] \uparrow \rightarrow 8^{+}
\]

\[
p^{9/2} \left[ {514} \right] \uparrow + n^{9/2} \left[ {624} \right] \uparrow \rightarrow 9^{-}
\]

There are various discrepancies in the experimental data which does not give a consistent picture of decay scheme. Different half-lives \{22^{8-10}, 10^{9}, 18.7^{11}, 4.5^{10}, 19^{12}, 30^{13-16}, 16^{13}, 5^{14}, 28.4^{17}, 23^{16}, \text{and} 22.7 \text{minute}^{17}\} have been reported. Isomeric pairs of $^{178}$Lu nucleus with half lives of 22 and 4.5 min.\(^{10}\), 30 and 16 min.\(^{13}\), 5 and 30 min.\(^{14}\), 30 and 23 min.\(^{16}\), and 28.7 and 22.7 min.\(^{17}\) for the ground and isomeric states, respectively, have been proposed. More recently, Alam and Sehgal\(^{18}\) obtained half-lives of 25 and 5 mins for the ground and isomeric states of $^{178}$Lu nucleus, respectively. These isomeric states were produced by different reactions as shown in Table II.
<table>
<thead>
<tr>
<th>Target Nucleus</th>
<th>Reaction</th>
<th>Product Nucleus</th>
<th>Spin and half life</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{181}_{\text{Ta}}$</td>
<td>$(n,\alpha)$</td>
<td>$^{178g}_{\text{Lu}}$</td>
<td>$1^+$, $5 \text{ min}$</td>
<td>H.Bakhru and S.K.Mukherjee (1964)</td>
</tr>
<tr>
<td>Enriched $^{179}_{\text{Hf}}$</td>
<td>$(\gamma,p)$</td>
<td>$^{178g}_{\text{Lu}}$</td>
<td>$1^+$, $30 \text{ min}$</td>
<td>T.Tamura (1967)</td>
</tr>
<tr>
<td>Enriched $^{176}_{\text{Yb}}$</td>
<td>$(t,p)$</td>
<td>$^{178}<em>{\text{Yb}} (7^+ \text{ min})$ decays to $^{178g}</em>{\text{Lu}}$</td>
<td>$1^+$, $28.4 \text{ min}$</td>
<td>C.J.orth et al. (1973)</td>
</tr>
<tr>
<td>Enriched $^{176}_{\text{Yb}}$</td>
<td>$(t,n)$</td>
<td>$^{178m}_{\text{Lu}} (7^-,8^+,9^-) 22 \text{ min}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{181}_{\text{Ta}}$</td>
<td>$(n,\alpha)$</td>
<td>$^{178g}_{\text{Lu}}$</td>
<td>$7^-$, $25 \text{ min}$</td>
<td>J.Alam and M.L.Sehgal (1974)</td>
</tr>
</tbody>
</table>

From table II, it is interesting to note that the 22 min. $^{178}_{\text{Lu}}$ isomer could not be produced through $^{181}_{\text{Ta}}(n,\alpha)^{178}_{\text{Lu}}$ reaction. To confirm it as well as to resolve the inconsistency in assigning spins to $^{178}_{\text{Lu}}$ isomers we have produced $^{178g,m}_{\text{Lu}}$. 
from $(n,\alpha)$ reaction on $^{181}$Ta, using neutrons of four different energies. The measurement of isomeric cross-section ratios $\left\{ \frac{\sigma_{5\text{min}}(n,\alpha)}{\sigma_{25\text{min}}(n,\alpha)} \right\}$ at different neutron energies may provide valuable information about the spins of isomeric states. The trend between the ratio $\left\{ \frac{\sigma_{5\text{min}}(n,\alpha)}{\sigma_{25\text{min}}(n,\alpha)} \right\}$ vs. $E_n$ (neutron energy) would decide whether 5 min state is high angular momentum state. So far no attempt has been made to measure the ratio $\frac{\sigma_{5\text{min}}(n,\alpha)}{\sigma_{25\text{min}}(n,\alpha)}$ at different neutron energies.

Due to the large difference between spins of isomeric states, viz., $1^+$ for ground state and $[7^-, 8^+, 9^+]$ for isomeric state, the $\gamma$-ray transition probability for the isomeric transition is expected to be very small and that is why no isomeric transition could be observed$^{17}$ and energy difference between the two isomeric states could not be determined directly.

In the earlier work from this lab$^{18}$, an attempt was made to get an information about the isomeric states of $^{178}$Lu through a study of the cross-sections for the production of 25 min and 5 min life time by $^{181}$Ta $(n,\alpha)$ $^{178}$Lu reaction, using thermal neutrons from Apsara Reactor at Bombay (India). By equating the experimental isomeric cross-section ratio $\left\{ \frac{\sigma_{5\text{min}}(n,\alpha)}{\sigma_{25\text{min}}(n,\alpha)} = 2.7 \pm 0.3 \right\}$ to the calculated isomeric
cross-sections for different spin pairs according to
Gallanger\(^6\), four possible calculated isomeric states of
\(^{178}\text{Lu}\) were suggested. On the basis of Bakhru and Mukherjee's
work\(^{14}\), the possibility of 25 min \(^{178}\text{Lu}(1^+)&&\) and 5 min \(^{178}\text{Lu}(8^+)\)
was ruled out. However, in the light of available data published
after 1964 and present work, this pair of spins for the isomers
of \(^{178}\text{Lu}\) nucleus can not be discarded.

(ii) Experimental Procedure:

The requisite neutrons were obtained from the
\(^3\text{H}(p,n)^3\text{He}\).reaction using incident proton beam of energy\(> 1.46 \text{ MeV}\)
from Van-de-Graaff generator at I.I.T., Kanpur (India). The
tritium target consisted of \(16\text{Ci}\) of tritium absorbed in
titanium layer on a thin backing of copper. The sample to be
irradiated was circular having \(1.6 \text{ cm}\) diameter. The neutron
flux at the place of irradiation was of the order \(\approx 10^8 \text{ neutrons/cm}^2/\text{sec}\).

The element tantalum was spectrographically pure
having purity better than 99.9\% and was obtained from M/S.
Johnson Math\(x\)ey and Co., Ltd., London. The details regarding
the sample preparation, counter shielding etc. have been
discussed in chapter II.

(iii) The \(^{181}\text{Ta}(n,\alpha)^{178}\gamma\text{mLu}\) Reaction:

Pure (99.9\%) tantalum metallic sheet of thickness
FIG. 2

Counts (90 sec)

Time (min)

2.5 min

5 min

$E_n = 0.5 \pm 0.1$ keV
5 mm was used for the preparation of target sample. The sample was irradiated by neutrons of four energies. Figs (1-4) show the decay curves due to (n,\(\alpha\)) and (n,\(\gamma\)) reactions. When the background activity due to \(^{182}\text{Ta} (T_{1/2} = 115\) days) is subtracted from figs, the tail of the resultant curves gave 25 min half life as shown in figs. After extrapolating the 25 min activity to zero time and subtracting these curves from the resultant curves, a half life of 5 min was also obtained.

The following equation has been used to calculate the isomeric cross-section ratio:

\[
\frac{\sigma_{25\ min}(n,\alpha)}{\sigma_{5\ min}(n,\alpha)} = \frac{C_{o5}}{C_{o25}} \cdot \frac{(1-e^{-t_{5}/t})}{(1-e^{-t_{25}/t})} \cdot \frac{\epsilon_{25}}{\epsilon_{5}}
\]

Neutron Energy = 270 ± 100 KeV

a. Due to 5 min activity

Counting rate per second at zero time \((C_{o5})\) = 0.46
Detection efficiency of \(\beta\)-counter \((\epsilon_{5})\) = 0.459
Saturation correction for \(^{178}\text{Lu}\) activity \((1-e^{-t_{5}/t})\) = 0.875

b. Due to 25 min activity

Counting rate per second at zero time \((C_{o25})\) = 0.37
Detection efficiency of \(\beta\)-counter \((\epsilon_{25})\) = 0.30
Saturation correction for \(^{178}\text{Lu}\) activity \((1-e^{-t_{25}/t})\) = 0.34
\[ \sigma(n,\alpha) \text{ for 5 min activity} = \frac{0.46 \times 0.34 \times 0.3}{0.37 	imes 0.875 \times 0.459} \]

\[ \frac{\sigma_{5 \text{ min}}(n,\alpha)}{\sigma_{25 \text{ min}}(n,\alpha)} = 0.32 \pm 0.067 \]

**Neutron Energy** = 615 ± 110 KeV

a. Due to 5 min activity

\[ C_{5} = 0.26 \]
\[ \epsilon_{5} = 0.459 \]
\[ (1-e^{-\lambda_{5} t}) = 0.875 \]

b. Due to 25 min activity

\[ C_{25} = 0.18 \]
\[ \epsilon_{25} = 0.30 \]
\[ (1-e^{-\lambda_{25} t}) = 0.34 \]

\[ \frac{\sigma_{5 \text{ min}}(n,\alpha)}{\sigma_{25 \text{ min}}(n,\alpha)} = 0.3723 \pm 0.085 \]

**Neutron Energy** = 690 ± 120 KeV

a. Due to 5 min activity

\[ C_{5} = 1.35 \]
\[ \epsilon_{5} = 0.459 \]
\[ (1-e^{-\lambda_{5} t}) = 0.9864 \]
b. Due to 25 min activity

\[ C_{025} = 1.30 \]
\[ \varepsilon_{25} = 0.30 \]
\[ (1-e^{-\frac{A_5}{t}}) = 0.5769 \]
\[ \frac{\sigma_{5 \text{ min}} (n,\alpha)}{\sigma_{25 \text{ min}} (n,\alpha)} = 0.4026 \pm 0.06 \]

Neutron Energy \[ = 875 \pm 125 \text{ KeV} \]

a. Due to 5 min activity

\[ C_{05} = 1.70 \]
\[ \varepsilon_{5} = 0.459 \]
\[ (1-e^{-\frac{A_5}{t}}) = 0.967 \]

b. Due to 25 min activity

\[ C_{025} = 0.82 \]
\[ \varepsilon_{25} = 0.30 \]
\[ (1-e^{-\frac{A_5}{t}}) = 0.499 \]
\[ \frac{\sigma_{5 \text{ min}} (n,\alpha)}{\sigma_{25 \text{ min}} (n,\alpha)} = 0.7076 \pm 0.12 \]

The measured values of \[ \frac{\sigma_{5 \text{ min}} (n,\alpha)}{\sigma_{25 \text{ min}} (n,\alpha)} \] as well as neutron energies are listed in Table III.
PLOT OF THE RATIO $\frac{\sigma - 5 \text{min} [n, \alpha]}{\sigma - 25 \text{min} [n, \alpha]}$ Vs. NEUTRON ENERGY

FIG. 5
The measured values of the isomeric cross-section ratio are plotted in fig. 5 as a function of $E_n$. It is clear from the figure that cross-section ratio increases with the energy of the neutron. From this trend it may be inferred that 5 min state should be high spin state as the neutron energy increases higher angular momentum start taking part, and the probability of population of high spin state will be more than that of low spin state.

In the earlier work, Alam and Sehgal\textsuperscript{18} proposed four possible calculated isomeric state of $^{178}$Lu by equating the experimental isomeric cross-section ratio \( \frac{\sigma_{5 \text{ min}}(n,\alpha)}{\sigma_{25 \text{ min}}(n,\alpha)} = 2.7 \pm 0.3 \) measured at thermal neutron energy.
Fig. 6. Possible positions of the isomeric states of $^{178}$Lu which will give the same theoretical isomeric cross section ratio as the experimental measured value ($\sigma_{isom}(n,\alpha)/\sigma_{tot}(n,\alpha) = 2.7 \pm 0.3$).
to the calculated isomeric cross-sections for different spin pairs. Fig. 6 shows different possible calculated isomeric states of $^{178}$Lu. Present work rules out the possibilities (a) and (c) in fig. 6. From an analysis of $\beta$-decay$^{16}$, $\beta$-\(\gamma\) and \(\gamma\)-\(\gamma\) coincidence experiments$^{15-17}$, and also from the consideration of coupling rule of Nilsson states$^{6,7}$, it is well established that the spin of ground state of $^{178}$Lu nucleus should be $1^+$ and hence the possibility (6d) shown in Fig. (6) is also ruled out. The sets of spins $1^+$, $7^-$ and $1^+$, $9^-$ for isomeric states have not been considered in earlier work$^{18}$. Tsutomu Tamura has suggested$^{16}$ $7^-$ for the isomeric state of $^{178}$Lu having halflife of 23 minutes. In the present case 5 min. life time also corresponds to some high spin state in $^{178}$Lu. Obviously it can not have $7^-$ spin. The probable spins for the 5 min. isomeric state are $8^+$, $9^-$ due to the coupling of $p[404] \uparrow$ and $n[624] \uparrow$; and $p[514] \uparrow$ and $n[624] \uparrow$ configurations, respectively. It is not possible to say whether this state is below or above 23 min. $^{178}$Lu ($7^-$) state. But the energy difference between 23 min. $^{178m}$Lu ($7^-$) and 5 min. $^{178m}$Lu ($8^+$, $9^-$) must be very small otherwise isomeric transition between these two must have been observed. If this energy difference happens to be large then it would not be possible to explain both 5 min. and 23 min. isomeric states.
REFERENCES:

CHAPTER VI

STATISTICAL ANALYSIS OF S- AND P-WAVE NEUTRON REDUCED WIDTHS

6.1 Introduction:

It is well known that the absorption cross-section of neutrons with energies of few tens of electron volts has resonances structure. The resonances correspond to the excited level of the compound nucleus with life time ranging from $10^{-18}$ sec. to $10^{-14}$ sec. which is an extremely long time in terms of nuclear transit time ($\sim 10^{-22}$ sec.). The aim of the resonance analysis is to determine the following parameters: the energy of the resonance ($E_0$), the neutron width ($\Gamma_n$), the total width ($\Gamma$), the total radiation width ($\Gamma_r$), the fission width ($\Gamma_f$) and the level spacing ($D$). The time of flight technique is mostly used to study neutron resonances. In the recent years, both the quantity and quality of neutron cross-section data have increased rapidly as a result of developments of the time of flight method\(^1\), such as the increase in the intensity of the pulsed neutron sources, improved detectors, large multichannel analyzers and the availability of larger samples of enriched isotopes. The average resonance parameters and their distributions are important for the statistical theory of nuclear reactions as well as for reactor physics calculations. In the present work we have studied the distribution of s- and p-wave neutron reduced widths.
6.2 S-wave neutron reduced widths ($\Gamma_n^0$):

The knowledge of $\chi^2$ distribution of neutron reduced widths is of great importance in the theory of nuclear reactions as well as nuclear engineering. The value of degree of freedom $\nu$ associated with $\chi^2$ distribution of the reduced widths of a nucleus enters as one of the input data in the Moldauer theory\(^1\) for the evaluation of ($n,n'$) reaction yields. The mathematical form of the distribution of the individual s-wave neutron reduced widths was established by Porter and Thomas\(^2\), who gave a theoretical basis for the distribution. They reasoned that since the levels in the compound nucleus are of very complicated nature, the phases of the wave functions of the contributing states would be distributed randomly. This would result in a gaussian distribution of $\Gamma_n^0$ and hence a $\nu=1$ distribution in $\Gamma_n^0$. The fact that the neutron reduced widths ($\Gamma_n^0$) distribution obeyed a $\nu=1$ distribution seemed very reasonable since there is only one exit channel in the scattering process for these low energy neutrons. This picture can readily be applied to the total radiation width $\Gamma_\gamma$. Because a level can decay by many exit channels one would expect the total $\Gamma_\gamma$ to follow a distribution with a large $\nu$. The expression for chi-squared distribution with one degree of freedom ($\nu=1$) is

$$ P(x, \nu) = \frac{(\frac{\rho}{\nu})^{\nu-1}}{\Gamma(\nu)} \rho^x e^{-\rho x} \, dx, $$

where

$$ x = \frac{\Gamma_n^0}{\Gamma_n^\nu}, \quad \rho = \frac{\nu}{2}. $$

The above distribution satisfied the reduced neutron widths
available at that time for different isotopes. Later, Garrison\textsuperscript{4}) studied the problem in the same way as Porter and Thomas. For his investigation he combined the reduced neutron widths for some nuclei and concluded the $\mathcal{V}=1$ distribution. This method of analysis could not reveal departure, if any for individual nucleus, from the P.T. distribution\textsuperscript{3}).

Recently, Sharma and Raj\textsuperscript{5}) determined the value of degree of freedom ($\mathcal{V}$) appropriate to individual nuclei. They pointed out the possibility of structure effect in the value of $\mathcal{V}$. No definite conclusion could be drawn by them because they analysed insufficient number of cases (e.g. 20 nuclei). For 25\textsuperscript{o} of the cases studied by them, the widths ($\Gamma_n^0$) were known for less than 25 levels, the statistically insignificant number of s-levels. However, in the later publication they reported\textsuperscript{6}) the analysis on $\Gamma_n^0$ for 22 nuclei and found six cases for which the value of $\mathcal{V}$ was 2. No explanation has been suggested by them for this higher value of $\mathcal{V}$.

In the present work, an attempt has been made to determine the value of $\mathcal{V}$ appropriate to individual nuclei. The analysis has been undertaken for those nuclei where more than thirty reduced neutron widths are known. It is shown that, contrary to wide spread opinion, the s-wave reduced neutron widths do not always follow single channel Porter Thomas distribution. Possible explanation for this deviation has been given.
(i) Analysis:

During the last few years a lot of new improved experimental data on $\Gamma_n^0$ have been accumulated. To analyse this experimental data, the maximum likelihood method has been used to determine the value of $\nu$. In the present analysis the statistical weight factor (g) was assumed to be $1/2$, except for zero spin target nuclei, where it is known to be unity.

The nucleus $^{177}\text{Hf}$ is one of the few examples where an almost complete $J$ (total angular momentum) determination of large set of neutron resonances has been achieved\textsuperscript{7}). For $^{177}\text{Hf}$ nucleus, $(g \Gamma_n^0)$ values are known for 133 resonances. We find that the degree of freedom $\nu$ in this case comes out to be ($1.44\pm0.15$) when the value of g is taken as $1/2$. For most of these resonances, J assignment is also known. From these J values the exact value of g has been determined for each resonance. Using these exact value of g for each resonance, the value of $\nu$ has also been deduced which comes out to be ($1.32\pm0.14$). It is clear from this example that assuming $g=1/2$ in the present analysis is quite safe.

Thus we find that the value of $\nu$ is not very sensitive to the uncertainty in g values for odd nuclei because the reduced neutron widths varies over a much larger range than one would have been from the two possible g values in odd A nuclei. In the present work, the uncertainty in the value of $\Gamma_n^0$ has also not been taken into account. It has been shown\textsuperscript{4})
that $\Gamma_\nu$ distribution is too broad to be sensitive to the uncertainty in $\Gamma_\nu$. For a particular nucleus the value of $\nu = 2\rho$, the degree of freedom of $\chi^2$ distribution of neutron reduced widths, hereafter referred to as $\Gamma$, was determined by Porter-Thomas procedure\textsuperscript{3)} which is as follows:

The general expression for the $\chi^2$-distribution is given as

$$P(x, \rho) \, dx = \Gamma(\rho)^{-1} (\rho x)^{\rho-1} e^{-\rho x} \, dx \quad ... (1)$$

where $\nu = 2\rho$ is called the degree of freedom of the $\chi^2$-distribution and $\Gamma(\rho)$ the Gamma function. For a few $\nu$-values the distribution functions $P(x, \rho)$ are shown in Fig.1. It can be noted from this figure that $P(x, 1)$ and $P(x, 2)$ do not differ much in the region of high value of $x(=r'/\langle r' \rangle)$ but are appreciably different in the lower side. Further it is obvious from Eq.(1) that $\langle x \rangle = 1$ and the variance of $x$ (Var $x = \langle x^2 \rangle - \langle x \rangle^2$) is equal to $\rho^{-1}$, that is, as $\nu$ increases the distribution becomes narrower and centered about unity.

The most probable value of $\rho$(hence $\nu$) is determined by the solution of the transcendental equation\textsuperscript{8,9)}

$$\frac{1}{m} \sum \left( \frac{\Gamma_i}{\langle r' \rangle} \right) - F(\rho) = 0 \quad ... (2)$$

where

$$F(\rho) = \psi(\rho) - \ln(\rho)$$

$$\psi(\rho) = \frac{d}{d\rho} \ln [\Gamma(\rho)]$$

and $m$ is the total number of neutron reduced widths. The value of $F(\rho)$ is taken from graphical relation between $F(\rho)$ and $\nu$\textsuperscript{3).} The standard error in the estimate of $\nu$ is given by
Fig 2.

ENERGY (eV)

NUMBER OF LEVELS

Cumulative sum of levels as a function of energy.

<ΔS> = 4.5 eV

179 He
the variance of \( \lambda \).

\[
\text{Var} \, \lambda = 2 \, m^{-1} \left[ \psi'(p) - p^{-1} \right]^{-1} \quad \ldots \ldots \quad (3)
\]

where \( \psi'(p) = \frac{d}{dp} \left[ \psi(p) \right] = \frac{d}{dp} \left[ \mathcal{F}(p) + \ln(p) \right] \)

The value of \( \lambda \) is sensitive to the missed levels and to the statistical sample. Plots of the cumulative number of levels up to energy \( E \), vs. \( E \) were drawn. Fig. 2 is a specimen plot for \(^{179}\text{Hf}\) nucleus. A plot of this kind is expected to be a straight line provided levels are not missed and the slope gives the average level spacing for \( s \)-levels \( \langle D_s \rangle \). The region up to 400 eV has a slope which gives \( \langle D_s \rangle = 4.5 \) eV, followed by decreasing slope at higher energies where an increasing fraction of weak levels might have been missed. For this case, we have taken data only up to energy 400 eV. These plots also take care of the presence of levels due to \( p \)-wave neutrons.

In case, \( p \)-wave resonances are considerably mixed with \( s \)-levels the slope of straight line \( \langle D_p \rangle \) should be three times the slope of \( s \)-wave \( \langle D_s \rangle \) in accordance with \((2l+1)\) dependence of level spacing. Similar plots were drawn for all those cases where \( \lambda \) was not one. In each case, levels have been considered only up to the energy where first slope \( \langle D_s \rangle \) ends in order to find out the value of \( \lambda \) which is not contaminated by missed resonances.

Equation (2) determines \( \lambda \) accurately when \( m \) is sufficiently large. The sample sizes available for various nuclei are still not large and a correction must be made for
a possible difference of the sample average \( \bar{r} = \frac{\Sigma r_i}{m} \) from the population average \( <r> \). The function \( \phi \) is then formed such that

\[
\phi = \frac{1}{m} \sum_i \ln \left( \frac{r_i}{\bar{r}} \right) + F(m\rho) - F(\rho) \quad \text{..... (4)}
\]

One then gets from Eq. (4) and

\[
P(r, \rho) \, dr = \Gamma(m\rho)^{-1} (m\rho \bar{r} / <r>)^{m\rho-1} \exp\left( -m\rho \bar{r} / <r> \right) \, dr(\ln[m\rho \bar{r} / <r>]) \quad \text{..... (5)}
\]

that \( <\phi> = 0 \) and

\[
\text{Var} \phi = m^{-1} \psi'(\rho) - \psi'(m\rho) \quad \text{.............. (6)}
\]

The Centre-Limit theorem states that as \( m \) increases the distribution for \( \phi \) approaches normality which means that

\[
P(\phi) \, d\phi \rightarrow (2\pi \text{Var} \phi)^{-1/2} \exp\left( -\phi^2 / 2\text{Var} \phi \right) \, d\phi
\]

while analysing the sample it is assumed that \( m \) is large enough to test the hypothesis that \( \bar{r} \) follows a \( \chi^2 \)-distribution with the degree of freedom \( 2m\rho \) and hence \( r_i \) has a degree of freedom \( 2\rho = \nu \).

To test this hypothesis the probability integral (error function)

\[
I = \int_{-\infty}^{\phi/(\text{Var} \phi)^{1/2}} \exp\left( -z^2 / 2 \right) \, dz; \quad a = \phi/(\text{Var} \phi)^{1/2} \quad \text{..... (7)}
\]

is evaluated. At the 5\% level of reliability \( 11) \) if \( I(5) > 0.95 \) (or \( a^2 < 3.6 \) for a given value \( \phi \)), the hypothesis of a \( \chi^2 \) distribution with this degree of freedom is considered to be true.

(ii) Result and Discussion:

The results of the analysis are shown in table I. Most of the nuclei have either \( \nu = 1 \) or \( \nu = 2 \). However, there
Degree of freedom $\gamma$ vs. mass number $A$.

- Odd $A$ nuclei
- Even $A$ nuclei

**FIG. 3**
are two nuclei, viz, $^{113}$In and $^{123}$Te for which $\nu > 3$. Table also shows the corresponding results of testing of the hypothesis at $5\%$ level of reliability. It can be noted that the hypothesis for most of the nuclei is consistent either with $\nu = 1$ or $\nu = 2$ but there are cases ($16\%$) for which the hypothesis is consistent both with $\nu = 1$ and $\nu = 2$. The reason for the latter cases may be due to the inadequate sample of $\Gamma'$. As is evident from Fig. 3 many points lie around the line corresponding to $\nu = 1$, thus confirming the P.T. distribution for $\Gamma'$. However, in the mass regions $A \approx 50$ and $A \gg 150$ we find that there are many nuclei for which $\nu = 2$.

In earlier analysis$^{12-16}$, P.T. distribution was assumed to represent the distribution of reduced neutron widths correctly. Any deviation of the experimental data from the P.T. distribution was explained either due to some missed resonances having small $\Gamma^p$ or due to the inclusion of some p-wave resonances. This is because the inclusion of p-wave resonances reduces the value of $\nu$ and the omission of some resonances of smaller $\Gamma^p$ leads to a higher value of $\nu$. The data$^{10}$ which have been analyzed here are of much better quality than the data examined by earlier workers$^{3-5}$. Also, the inaccuracy in the value of $\nu$ because of missing levels as well as sample sizes has been almost taken care of. Therefore, it is worthwhile to establish a departure from the P.T. distribution in the mass regions $A \approx 50$ and $A \gg 150$. 
The analysis of the distribution of experimental reduced widths by Porter and Thomas (1956) confirmed the \( \chi^2 \)-distribution with \( \nu = 1 \) thus confirming the assumption of independent, normally distributed and real reduced width amplitudes. It is important to note that the value of \( \nu > 1 \) has not been completely ruled out by them\(^3\). If the reduced widths amplitudes were regarded essentially complex with real and imaginary parts which are distributed normally, the reduced neutron widths would follow a distribution with characteristic some where between a \( \chi^2 \)-distribution with one and with two degrees of freedom, depending on relative magnitudes and correlations of real and imaginary parts.

Possible explanations for \( \nu = 2 \) may be as follows. If we have a pure compound nucleus reaction the cross-section to a single state should fluctuate essentially like a P.T. distribution\(^3\). The departure from P.T. distribution at once indicates the contributions to the cross-section due to other non-statistical reaction channels (e.g. direct reaction). Structure in gamma ray spectra from thermal neutron capture was the first evidence found for non-statistical processes in neutron capture. An excess of high energy gamma rays even at low energy of neutrons was observed in mass regions \( A \approx 50-60 \) and \( A \approx 200 \). For most of nuclei around \( A \approx 50 \) and \( A > 150 \) the value of \( \nu \) is two and thus may be due to the presence of non-statistical processes in addition to the compound nucleus process.
The nuclei in mass regions $A \gtrsim 150$ are considerably deformed. It may be expected that a single resonance splits into two components, due to spheroidal shape. Thus the reduced neutron width measured in an experiment is actually the sum of two independent widths, one for each splitted resonance. If we assume equal population of both components, the reduced neutron widths would obey a $\chi^2$-distribution with two degrees of freedom.

6.3 Analysis of $p$-wave neutron reduced widths ($\Gamma_n^1$):

It has been usually assumed\textsuperscript{4,20,21} that the experimental $p$-wave neutron reduced widths ($\Gamma_n^1$) obey a Porter-Thomas distribution ($\chi^2$-distribution with degree of freedom $\nu=1$). Shapiro\textsuperscript{22} raised the question whether reduced neutron widths follow a $\chi^2$-distribution with $\nu=1$ or their distribution should be narrower. However, he favoured the latter possibility. Solution of this problem would be an important step towards a better understanding of spin dependence and structure of wave functions of states involving in a nuclear reaction\textsuperscript{23}.

One of the means for solving the above problem is to study the distribution of $\Gamma_n^1$. No attempt has been made so far to analyse the reduced widths $\Gamma_n^1$. In the present work, we have analysed the widths $\Gamma_n^1$ for nuclei (for which experimental data are available) within the framework of Porter and Thomas\textsuperscript{3}.

The $p$-wave neutron reduced widths were determined using the recently compiled\textsuperscript{10,23} value of $g\Gamma_n^1$ and dividing by
an average value of \('g'\). For $^{88}$Sr nucleus, \('g'\) values are known for 35 p-wave resonances. We find that the degree of freedom in this case comes out to be $(2 \pm 0.37)$ when the average value of \('g'\) is taken. Using the exact values of \('g'\) for each resonance, the value of \(\nu\) has also been deduced which comes out to be $(2.1 \pm 0.5)$. It is clear from this example that assuming average value of \('g'\) in the present analysis is quite safe for even-even nuclei. It has been also shown by Harvey\textsuperscript{25}) that $\Gamma^n$ distribution is too broad to be sensitive to the uncertainty in \('g'\) values.

In table II, we have presented the result of our analysis. It is clear from the table that the degree of freedom \(\nu\) varies from nucleus to nucleus. For most of these nuclei, the value of \(\nu\) appears to be larger than one would expect from simplest considerations. However, $^{39}$K, $^{94}$Mo and $^{103}$Rh are exceptions.

In the earlier work\textsuperscript{14, 20, 21}) the single channel P.T. distribution has been considered to represent correctly the distribution of $\Gamma^n$, and any deviation of experimental data from P.T. distribution has been expected either due to the inclusion of d-wave neutron reduced widths or due to the possibility of undetectable small widths. However, the present work does not seem to support such arguments. For instance take the case $^{232}$Th, $^{238}$U and $^{88}$Sr which have got a considerable number of $\Gamma^n$. The higher value of \(\nu\) for these cases cannot be attributed only to the omission of some small widths.
In this work, we want to emphasize that besides the facts such distributions are sensitive to the lack of missed levels and to the statistical sample, there may be other reasons for the deviation of experimental data from single channel P.T. distribution\textsuperscript{3).}

In general, we can have $J = \frac{1}{2} + \ell + \frac{1}{2} = 3, 4, 5$ or 6 for $^{209}$Bi and $^{93}$Nb nuclei. For p-neutrons, either $p_{3/2}$ or $p_{1/2}$ interactions may be present. Both $p_{3/2}$ and $p_{1/2}$ may contribute to $J = 4$ and 5, but only $p_{3/2}$ to $J = 3$ or 6. Thus, in an ordinary experiment with unpolarized beam and unpolarized target, the measured neutron widths $[\Gamma_{n}^{1}(J=4, 5)]$ is actually the sum of two widths $\Gamma_{n}^{1}$ and $\Gamma_{n}^{1}$ corresponding to $p_{3/2}$ and $p_{1/2}$ interactions. Therefore, it appears likely that $\Gamma_{n}^{1}(J=4, 5)$ should follow a distribution with characteristic somewhere between a $\chi^{2}$-distribution with one and with two degrees of freedom depending on relative magnitudes of $\Gamma_{n}^{1}$ and $\Gamma_{n}^{1}$. This situation is in contrast to single channel P.T. distribution mostly followed by s-wave neutron reduced widths ($\Gamma_{n}^{s}$) or widths resulting from p-wave neutrons on $I = 0$ target nuclei.

If we have pure compound nucleus reaction, the cross-section to a single state should fluctuate essentially like a single channel P.T. distribution\textsuperscript{3).} Any departure from it may be due to the presence of contributions to the cross-section by reaction processes other than compound nucleus process.
Analysis of much reliable data would establish either of two important facts: (a) an appreciable correlation between $\Gamma_1$ and $\Gamma_2$ or a large difference in their average magnitudes, (b) independent evidence for the existence of reaction processes e.g. direct capture and semi-direct capture in addition to the compound nucleus process in the same way as neutron-capture $\gamma$-ray spectra reveal\(^{18}\).

Our interest in this topic will gain momentum in future with the operation of variable energy cyclotron (VEC) in our country which would enable us to measure the neutron reduced widths.
<table>
<thead>
<tr>
<th>Nucleus ( (J^\pi) )</th>
<th>Number of p-wave neutron reduced widths</th>
<th>( \nu )</th>
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<td>( ^{40} \text{Ar} ) ( (0^+) )</td>
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<td>( 1.94 \pm 0.524 )</td>
</tr>
<tr>
<td>( ^{39} \text{K} ) ( (3/2^+) )</td>
<td>28</td>
<td>( 1.25 \pm 0.282 )</td>
</tr>
<tr>
<td>( ^{40} \text{Ca} ) ( (0^+) )</td>
<td>25</td>
<td>( &gt;3 )</td>
</tr>
<tr>
<td>( ^{88} \text{Sr} ) ( (0^+) )</td>
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<td>( 2.0 \pm 0.37 )</td>
</tr>
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<td>( ^{89} \text{Y} ) ( (1/2^-) )</td>
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<td>( 1.83 \pm 0.53 )</td>
</tr>
<tr>
<td>( ^{92} \text{Mo} ) ( (0^+) )</td>
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<td>( 2.53 \pm 0.43 )</td>
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<td>( ^{93} \text{Nb} ) ( (9/2^+) )</td>
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<td>( 1.89 \pm 0.33 )</td>
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<tr>
<td>( ^{94} \text{Mo} ) ( (0^+) )</td>
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<td>( 0.95 \pm 0.29 )</td>
</tr>
<tr>
<td>( ^{98} \text{Mo} ) ( (0^+) )</td>
<td>49</td>
<td>( 2.18 \pm 0.39 )</td>
</tr>
<tr>
<td>( ^{103} \text{Rh} ) ( (1/2^-) )</td>
<td>21</td>
<td>( 1.62 \pm 0.43 )</td>
</tr>
<tr>
<td>( ^{207} \text{Pb} ) ( (1/2^-) )</td>
<td>17</td>
<td>( &gt;3 )</td>
</tr>
<tr>
<td>( ^{209} \text{Bi} ) ( (9/2^-) )</td>
<td>26</td>
<td>( 2.27 \pm 0.56 )</td>
</tr>
<tr>
<td>( ^{232} \text{Th} ) ( (0^+) )</td>
<td>105</td>
<td>( &gt;3 )</td>
</tr>
<tr>
<td>( ^{238} \text{U} ) ( (0^+) )</td>
<td>73</td>
<td>( &gt;3 )</td>
</tr>
</tbody>
</table>
REFERENCES:

22. F.L.Shapiro : Lecture in the All Union Summer School of Nuclear Spectroscopy in Nuclear Reactions(Obninsk, Physics and Power Engineering Institute) 1966.
7.1 Introduction:

In spite of the great successes of the shell model in the prediction of ground state spins, parities, $\alpha$ and $\beta$ decay systematics and so forth, this model still has exhibited many limitations. For example, experimentally observed nuclear quadrupole moments are in most cases much larger than the shell model predictions, especially, in the regions between closed shells; the transition probabilities of low lying states exceed the single particle estimates. These observations led to the development of various collective models dealing with a motion where many nucleons move coherently with well defined phases. In fact two basically different models emerged, viz, low energy collective model and high energy collective model (giant resonances). The first of these deals with collective surface degrees of freedom and thus with low energy collective rotations and vibrations of nuclei. Bohr and Mottelson\(^1\)\(^-\)\(^4\)) dealt with both collective and single particle phenomena and established the important conceptual bases for work in this area.

The low energy spectra of the even-even nuclei exhibit a sequence of states with $I\pi = 0^+_g, 2^+_g, 4^+_g \ldots \ldots \ldots \ldots \ldots$ and
energies approximately following an $I(I+1)$ law in certain regions of $A$, namely, from $A = 19$ to 28, from 150 to 196, for $A \geq 222$ and for neutron deficient Ba and Ce isotopes. The excitation energy of $2^+$ state is observed to be of the order 100 KeV in even-even nuclei for which proton and neutron numbers are far from being magic. This excitation energy is considerably smaller than the single particle (nucleon) excitations between shells or subshells which are of the order of 5-6 MeV between shells and $\gg 1$ MeV between subshells. This fact coupled with a spin dependence $I(I+1)$ in the position of the energy levels suggests immediately the rotational character of the states by analogy with molecular Physics. A symmetric rotator will have rotational energies $E_I = I(I+1) \hbar^2/2J$, where $J$ is the moment of inertia.

The regions in which the rotational spectra occur correspond to ground state configurations with many particles outside of closed shells. While the closed shell configurations prefer the spherical symmetry, the orbits of the particles outside the closed shells are strongly anisotropic and drive the system away from spherical symmetry. These nuclei are said to be rotational nuclei or deformed since only deformed nuclei can have a moment of inertia. Rainwater observed that if the nuclei are assumed to have spheroidal shapes, then the many protons in the nucleus can give large values of the quadrupole moment as were found experimentally.

The rotational mode of excitation corresponds to the
Fig. S1. Schematic diagram for angular momenta in deformed nuclei.
rotation of the nucleus in space about an axis perpendicular to the axis of symmetry. The orientation of a body in three dimensional space involves three angular variables, such as Euler angles \( \omega = \phi, \theta, \psi \) and three quantum numbers are needed in order to specify the state of motion. The total angular momentum \( I \) and its component \( M = I_z \) on a space fixed axis provide two of these quantum numbers; the third may be obtained by considering the components of \( I \) with respect to (intrinsic) body-fixed co-ordinate system with orientation \( \omega \). The eigen values of \( I_3 \) are denoted by \( K \) and have same ranges of values as does \( M \),

\[ K = I, I - 1, \ldots, -I. \]

The angular momentum coupling scheme for the deformed nuclei is shown in Fig.1. The \( z \)-axis belong to a co-ordinate system fixed in the laboratory, while the \( 3 \)-axis is part of a body-fixed co-ordinate system.

In the nucleus, the possibility of collective shape oscillations (vibrations) is strongly suggested by the fact that some nuclei are found to have non-spherical equilibrium shapes, whereas others, such as closed shell nuclei, have an equilibrium with spherical shape. One might thus expect to find intermediate situations in which the shape undergoes rather large fluctuations away from the equilibrium shape. Indeed, a striking feature of the energy spectra of almost all nuclei is the occurrence of low lying states that are strongly
Fig. 2. Typical band structure for a deformed even-even nucleus.
excited by electric quadrupole process. In the regions of non spherical nuclei, these states are members of a rotational band, but for the remaining nuclei, it appears that we are dealing with collective vibrations in the nuclear shape. The vibrational excitations are classified into two types for the assumed axially symmetric shape of the nucleus: one is gamma band and the other is beta band. Beta-vibrations which are similar to the breathing modes in molecules preserve the axial symmetry. The gamma-vibrations which result in a wave-like motion around the equator of the nucleus break the axial symmetry and lead to nuclear shapes of ellipsoidal type. Each of these vibrational states would have a rotational spectrum based on it with spin sequence $0^+, 2^+, 4^+$ .... for the beta-states and $2^+, 3^+, 4^+$ .... for the gamma-states. The typical band structure of a deformed nucleus is shown in figure 2.

In any quantal system, there will be fluctuations in the shape, which involve momentary excursions away from axial symmetry. If the system possesses a stable equilibrium shape that deviates from axial symmetry, it becomes possible to go a step further in the separation between rotational and intrinsic motion and to consider collective rotations about all axes of the intrinsic structure. The study of rotational motion in nuclei with asymmetric shape is potentially a field of broad scope. The possibility of exploiting the asymmetric rotor in the interpretation of nuclear spectra has been especially emphasized by Davydov and co-workers.\textsuperscript{6,7}
Davydov and Filippov\textsuperscript{6)} have proposed a model for deformed nuclei in which they assume that the rotation of the nucleus takes place without change of the intrinsic state. The equilibrium shape of the nucleus is like a triaxial ellipsoid and is determined by the two parameters $\beta_0$ and $\gamma_0$, where $\beta_0$ is the deformation parameter and $\gamma_0$ is the nonaxiality parameter which determines the deviation from the axial symmetry. The axial symmetry of the nucleus represents a degenerate situation with two equal moments of inertia and a deviation from the symmetry increases one of these moments of inertia at the expense of the other. The nucleus rotates about the axis with the largest moment of inertia. Later, Davydov and Rostovský\textsuperscript{8)} have treated the problem of collective excitation by taking into account the interactions of the rotations with $\beta$ and $\gamma$ vibrations.

A few years ago, attempts were made\textsuperscript{9-11)} to establish a correlation between the experimental and theoretical transition probabilities of $\frac{4^+}{g} \rightarrow \frac{2^+}{g}$, $\frac{2^+}{g} \rightarrow \frac{0^+}{g}$ and $\frac{2^+}{g} \rightarrow \frac{0^+}{g}$ transitions. They reported that the factor $F_{DR}(=B(E_2)_{\text{exp.}}/B(E_2)_{DR})$ increases slowly with the increase in the value of non-axiality parameter '$\gamma_0$'. However, for transitions between $\frac{4^+}{g} \rightarrow \frac{2^+}{g}$ and $\frac{2^+}{g} \rightarrow \frac{0^+}{g}$, the data points were too meagre to draw any reliable conclusion.

It was also reported earlier\textsuperscript{12)} that the factor $F_{SP}(=B(E_2)_{\text{exp.}}/B(E_2)_{SP})$ decreases gradually with the increase of $\gamma_0$. The above trends could be established on the basis of the then available
experimental data. Theoretical calculations of $E_2$-transition probabilities within the framework of DR model could not be extended to other deformed nuclei for which relevant experimental informations were not present. During the last few years a lot of new experimental data have become available in the mass region $150 \leq A \leq 196$ and $A > 230$. So a reexamination of the trends of $B(E_2, 2^+_g \rightarrow 0^+_g)_{\exp} / B(E_2, 2^+_g \rightarrow 0^+_g)_{DR}$ vs $\gamma_0$, $B(E_2, 4^+_g \rightarrow 2^+_g)_{\exp} / B(E_2, 4^+_g \rightarrow 2^+_g)_{DR}$ vs $\gamma_0$, $B(E_2, 2^+_g \rightarrow 0^+_g)_{\exp} / B(E_2, 2^+_g \rightarrow 0^+_g)_{SP}$ vs $\gamma_0$ is considered worthwhile. In addition to it, mathematical relations, which could represent the above trends, have been proposed.

7.2 Calculation of Transition Probabilities:

The expressions due to the DR model$^3$ for the reduced $E_2$-transition probabilities inside the ground rotational band as well as from the $2^+_g$ state of $K = 2$ vibrational band to $0^+_g$ state of ground rotational band are given by,

$$B(E_2, \frac{J'}{g} \rightarrow \frac{J}{g}) = 5e^2 Q_0^2 / 16\pi (2J_g J_g' e^{J_g J_g'})^2 (1-1/S)(1-9S/4q^2)^2, \quad (1)$$

$$B(E_2, 2^+_g \rightarrow 0^+_g) = e^2 Q_0^2 / 16\pi 1/S(1-3/2S)x(1-9S/4q^2)^2, \quad (2)$$

where

$$Q_0^2 = 3Z R_0^2 / 5\pi$$

$$S = E_{2\gamma} / E_{2g}$$

$$q = E_{0g} / E_{2g}$$

$$R_0 = r_o A^{1/3}$$

where

$$r_o = 1.2 \text{ fm}.$$  

Here $E_{2g}$ is the energy of the $2^+_g$ state of ground state rotational band, $E_{2\gamma}$ is the energy of $2^+_g$ state of
$\gamma$-vibrational band and $E_{0^p}$ is the energy of $0^+ \text{ state of}$
$\beta$-vibrational band. The $(2j00|j'0)$ are the Clebsch-Gordan
Coefficients in the notation $(2jmm|j'm')$. The values of
parameters 's' and 'q' have been calculated using experimentally
known energy levels recently compiled by Sakai and Rester\textsuperscript{13}).
It is worth noting that the present compilation is up to date
and special care has been taken in assigning the states to
pertinent bands. In order to avoid the theoretical values of
'\beta_o' based on different models, the experimental values of
equilibrium deformation parameter '\beta_o' have been used in the
present calculations. These values of '\beta_o' correspond to
experimental transition probabilities. Using the above relations
$E_2$ transition probabilities between $4^+_g \rightarrow 2^+_g$, $2^+_g \rightarrow 0^+_g$ and
$2^+_g \rightarrow 0^+_g$ have been calculated for all nuclei in deformed region
(for which the required data are available). In the Davydov
Filippov model\textsuperscript{6}), the energy ratio $R(4)$ ($=E_{4^+_g}/E_{2^+_g}$), is indeed
restricted by $10/3< R(4)< 8/3$. However, the ratio can be smaller
than 8/3 in Davydov Chaban\textsuperscript{7}) and Davydov Rostovsky\textsuperscript{8}) model
because of the fact that energy levels are pushed down by
some perturbation such as rotation-vibration interaction.
In the present work, no nucleus has been neglected merely
because the ratio $R(4)$ for it is smaller than 8/3. The single
particle reduced transition probabilities have been calculated
by following relation\textsuperscript{14})
\[ B(E_2, 2^+_g \rightarrow 0^+_g) = .062 A^{14/3} e^{-2 x 10^{-52} cm^4} \]
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Note: The table entries include additional columns for various properties, but they are not visible in the provided image.
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The experimental transition probabilities have been taken from the literature\textsuperscript{15-19}.

7.3 Results and Discussion:

The results of the present calculations are given in Table I. Figure 3 shows the behaviour of the ratios $F_{\text{SP}}$ and $F_{\text{DR}}$ against the non-axiality parameter $\gamma'$ determined from the ratios $R_{\gamma}(2)^{6}$. From upper part of Fig. 3 it is clear that the value of factor $F_{\text{SP}}$ decreases as the value of asymmetry parameter $\gamma'$ increases from 0° to 30°. The increase in the value of $\gamma'$ follows the change from rotational limit (strongly deformed nuclei) to vibrational limit (almost spherical nuclei). The difference between single particle estimate and experimental rate is quite large in well deformed region. This is not surprising because the single particle model is not applicable to deformed nuclei where there are large number of nucleons outside the closed shells. The solid line is drawn to focus the attention to the fact that most of the points may be represented by the equation.

$$\gamma' = c \log F_{\text{SP}} + d$$

where $c = -(28.5 \pm 1.3)$ and $d = (76.28 \pm 3.3)$ from the method of least square fit.

The lower part of Fig. 3 confirms a slightly increasing trend in the value of $F_{\text{DR}}$ against $\gamma'$, observed by Rajput and Augusthy\textsuperscript{9}). The above trend may be represented by straight line:

$$\gamma' = a \log F_{\text{DR}} + b$$
Fig 4 (a) The ratio $BE_{g2}, 4^2_g - 2^2_g \lambda_{max} / BE_{g2}, 4^2_g - 4^2_g \lambda_{max}$ vs the nonaxiality parameter $\lambda_{max}$.
(b) The ratio $BE_{g2}, 2^+ - 0^+_h \lambda_{max} / BE_{g2}, 2^+ - 0^+_h \lambda_{max}$ vs the nonaxiality parameter $\lambda_{max}$. 
where \( a = (64.5 \pm 2.9) \) and \( b = -(29.5 \pm 1.4) \) from least square fitting procedure.

It is apparent from the Fig. 3 that the value of the factor \( F_{DR} \) changes smoothly from one isotope to another. However the factor \( F_{DR} \) changes sharply in Sm and Ga. It may be due to the transition from the almost spherical to the well deformed nuclei between 88 and 90 neutrons\(^{20}\) provided proton number \( Z \leq 66^{21} \).

In Fig. 4(a) and (b) the ratios \( B(E_2, \frac{1}{g} \rightarrow 2^+_{g})_{DR} \) and \( B(E_2, \frac{1}{g} \rightarrow 0^+_{g})_{DR} \) have been plotted against the non-axiality parameter \( \gamma \). In these figures, the errors have not been shown. The errors in experimental rates are about \( 20\% \). It is clear from these figures that the value of the ratios increases with \( \gamma \). The increasing trends could be represented by equations:

\[
\gamma = a' \log \{ \frac{B(E_2, \frac{1}{g} \rightarrow 2^+_{g})_{exp}}{B(E_2, \frac{1}{g} \rightarrow 2^+_{g})_{DR}} \} + b',
\]

and

\[
\gamma = a'' \log \{ \frac{B(E_2, 2^+ \rightarrow 0^+_{g})_{exp}}{B(E_2, 2^+ \rightarrow 0^+_{g})_{DR}} \} + b',
\]

where \( a' = (68.96 \pm 9.5) \), \( a'' = (18.58 \pm 3.45) \), \( b' = -(30.8 \pm 4.8) \) and \( b'' = (6.96 \pm 2.64) \) from least square fitting procedure.

It is apparent from the Table I as well as from the
slopes of fitted lines that the agreement between experimental values and the DR predictions for $2^+_g \rightarrow 0^+_g$ transition is better than that of $4^+_g \rightarrow 2^+_g$ and $2^+_g \rightarrow 0^+_g$ transitions. The abnormal behaviour in the ratio of $B(E2, 2^+_g \rightarrow 0^+_g)_{\text{exp}} / B(E2, 2^+_g \rightarrow 0^+_g)_{\text{DR}}$ vs. $\gamma$ of $^{152}\text{Sm}$ and $^{154}\text{Gd}$ may be due to critical neutron number 90.

From the Table, it is clear that the model does not reproduce fairly well the absolute experimental rates. For all cases, the DR model predicts somewhat smaller values of $E2$ transition probabilities compared to experimental rates. The disagreement between theoretical estimates to experimental rates can be brought down by treating the unit radius ($r_o$) as a free parameter. The deviations could be reduced to 50% when the values of $r_o$ was taken to be 1.5 instead of 1.2 fm. in the calculations. It is interesting to note that the value of $r_o$ (=1.5 fm.) is equal to that obtained by Satchler from the optical model analysis of $\alpha$-particle scattering for various elements.
REFERENCES:

13. M. Sakai and A. C. Rester: to be published in Atomic Data and Nuclear Data Tables.
List of Publications


(iv) Statistical Analysis of s-wave Neutron Reduced Widths: H.M. Agrawal, V.P. Varshney and M.L. Sehgal (under publication) Nuovo Cimento, Italy.

(v) Measurement of $(n,\gamma)$ reaction Cross-sections for $^{154}\text{Sm}$ at $470 \text{ KeV}$ and $680 \text{ KeV}$; and for $^{110}\text{Pd}$ at $380 \text{ KeV}$: H.M. Agrawal et al.: Presented in the NP and SSP Symposium held at I.I.T., Bombay, Dec. 28-31 (1978).

(vi) Activation Cross-section for $^{209}\text{Bi}(n,\alpha)^{206}\text{Tl}$ reaction: H.M. Agrawal et al.: (under publication) Z.Physik, Germany.

(vii) $^{181}\text{Ta}(n,\alpha)^{178}\text{m}^g\text{Lu}$ Reaction and Isomeric States: H.M. Agrawal, Mohd. Wasim and M.L. Sehgal (under publication) Nucl. Phys. A, Holland.

XXX XXX XXX
§1. Introduction

Transition probabilities of the $E_2$-transitions from $4^+_g$ to $2^+_g$ state and $2^+_g$ to $0^+_g$ state in even-even deformed nuclei in mass region $150 < A < 196$ and $A > 230$ have been studied by several researchers. $E_2$-transitions are almost everywhere much faster than single particle allows. This fastness suggests a sort of collective motion of the nucleons inside the nucleus. Several phenomenological nuclear models$^{1-4}$ have been proposed to explain the collective behaviour of these transitions. Among these the asymmetric rotor model$^{5-7}$ is one of the successful models. In this model it is assumed that the rotation of the nucleus takes place without change of the intrinsic state. The equilibrium shape of the nucleus is like a triaxial ellipsoid and is determined by the two parameters $\beta_0$ and $\gamma_0$, where $\beta_0$ is the deformation parameter and $\gamma_0$ is the nonaxiality parameter which determines the deviation from the axial symmetry. Later, Davydov and Rostovsky$^8$ have treated the problem of collective excitation by taking into account the interactions of the rotations with $\beta$ and $\gamma$ vibrations.

A few years ago, attempts were made$^9-11$ to establish a correlation between the experimental and theoretical transition probabilities of $4^+_g - 2^+_g$, $2^+_g - 0^+_g$ and $2^+_g - 0^+_g$ transitions. They reported that the factor $F_{DR} = B(E_2)_{exp}/B(E_2)_{DR}$ increases slowly with the increase in the value of non-axiality parameter $\gamma_0$. However, for transitions between $4^+_g - 2^+_g$ and $2^+_g - 0^+_g$, the data points were too meagre to draw any reliable conclusion. It was also reported earlier$^8$ that the factor $F_{SR} = B(E_2)_{exp}/B(E_2)_{SR}$ decreases gradually with the increase of $\gamma_0$. The above trends could be established on the basis of the then available experimental data. Theoretical calculations of $E_2$-transition probabilities within the framework of DR model could not be extended to other deformed nuclei for which relevant experimental informations were not present. During the last few years a lot of new experimental data have become available in the mass region $150 < A < 196$ and $A > 230$. So a reexamination of the trends of $B(E_2, 4^+_g - 2^+_g)_{exp}/B(E_2, 4^+_g - 2^+_g)_{DR}$ vs $\gamma_0$, $B(E_2, 4^+_g - 2^+_g)_{exp}/B(E_2, 4^+_g - 2^+_g)_{SR}$ vs $\gamma_0$, $B(E_2, 2^+_g - 0^+_g)_{exp}/B(E_2, 2^+_g - 0^+_g)_{DR}$ vs $\gamma_0$ and $B(E_2, 2^+_g - 0^+_g)_{exp}/B(E_2, 2^+_g - 0^+_g)_{SR}$ vs $\gamma_0$ is considered worthwhile. In addition to it, mathematical relations, which could represent the above trends, have been proposed.

§2. Calculation of Transition Probabilities

The expressions due to the DR model$^8$ for the reduced $E_2$ transition probabilities inside the ground rotational band as well as from the $2^+$ state of $K=2$ vibrational band to $0^+$ state of ground rotational band are given by,

$$B(E_2, J_g^+ - J_g^0) = 5e^2Q_0^2/16\pi(2J_g^0/J_g^0)^2(1-1/S) \times (1-2S/3q^2)$$

(1)

$$B(E_2, 2^+_g - 0^+_g) = e^2Q_0^2/16\pi(1-3/2S) \times (1-9S/4q^2)^2.$$  

(2)
where

\[ Q_0 = 3ZR_0^3/\sqrt{5\pi} \]
\[ S = E_{2\gamma}/E_{0\beta} \]
\[ q = E_{0\beta}/E_{2\gamma} \]
\[ R_0 = r_0 A^{1/3} \]

Here \( E_{2\gamma} \) is the energy of the 2\(^+\) state of ground state rotational band, \( E_{2\gamma} \) is the energy of 2\(^+\) state of \( \gamma \)-vibrational band and \( E_{0\beta} \) is the energy of 0\(^+\) state of \( \beta \)-vibrational band. The \( (2J00\mid J'\rangle J') \) are the Clebsch-Gordan Coefficients in the notation \( (2J00\mid J'm') \). The values of parameters 'S' and 'q' have been calculated using experimentally known energy levels recently compiled by Sakai and Rester\(^5\). It is worth noting that the present compilation is up to date and special care has been taken in assigning the states to pertinent bands. In order to avoid the theoretical values of \( \beta_0 \) based on different models, the experimental values of equilibrium deformation parameter \( \beta_0 \) have been used in the present calculations. These values of \( \beta_0 \) correspond to experimental transition probabilities. Using the above relations \( E_2 \) transition probabilities between \( 4_s^+ \rightarrow 2_s^+ \), \( 2_s^+ \rightarrow 0_s^+ \) and \( 2_s^+ \rightarrow 0_s^+ \) have been calculated for all nuclei in deformed region (for which the required data are available). The single particle reduced transition probabilities have been calculated by following relation\(^1\)

\[ B(E_2, 2_s^+ \rightarrow 0_s^+) = 0.062 A^{4/3} \times 10^{-52} \text{ cm}^4 \]  

(3)

The experimental transition probabilities have been taken from the literature.\(^1\)

§3. Results and Discussion

The results of the present calculations are given in Table I. Figure 1 shows the behaviour of the ratios \( F_{SP} \) and \( F_{DR} \) against the non-axiality parameter \( \gamma_0 \) determined from the ratios \( R_0(2)\).\(^3\) From upper part of Fig. 1 it is clear that the value of factor \( F_{SP} \) decreases as the value of asymmetry parameter \( \gamma_0 \) increases from 0° to 30°. The increase in the value of \( \gamma_0 \) follows the change from rotational limit (strongly deformed nuclei) to vibrational limit (almost spherical nuclei). The difference between single particle estimate and experimental rate is quite large in well deformed region. This is not surprising because the single particle model is not applicable to deformed nuclei where there are large number of nucleons outside the closed shells. The solid line is drawn to focus the attention to the fact that most of the points may be represented by the equation,

\[ \gamma_0 = c \log F_{SP} + d \]

where \( c = -(28.5 \pm 1.3) \) and \( d = (76.28 \pm 3.3) \) from the method of least square fit.

The lower part of Fig. 1 confirms a slightly increasing trend in the value of \( F_{DR} \) against \( \gamma_0 \), observed by Rajput and Augusthy.\(^5\) The above trend may be represented by straight line:

\[ \gamma_0 = a \log F_{DR} + b \]

where \( a = (64.5 \pm 2.9) \) and \( b = (29.5 \pm 1.4) \) from least square fiting procedure.

It is apparent from the Fig. 1 that the value of the factor \( F_{DR} \) changes smoothly from one isotope to another. However, the factor \( F_{DR} \) changes sharply in Sm and Ga. It may be due the transition from the almost spherical to the well deformed nuclei between 88 and 90 neutrons\(^6\) provided proton number \( Z \leq 66\).\(^7\)

In Fig. 2(a) and (b) the ratios \( B(E_2, 4_s^+ \rightarrow 2_s^+) \) \( \exp \) / \( B(E_2, 4_s^+ \rightarrow 0_s^+) \) \( \exp \) and \( B(E_2, 2_s^+ \rightarrow 0_s^+) \) \( \exp \) / \( B(E_2, 2_s^+ \rightarrow 0_s^+) \) \( \exp \) have been plotted against the non-axiality parameter \( \gamma_0 \). In these figures, the errors have not been shown. The errors in experimental rates are about 20%.\(^8\) It is clear from these figures that the value of the ratios increases with \( \gamma_0 \). The increasing trends could be represented by equations:

\[ \gamma_0 = a' \log \left\{ B(E_2, 4_s^+ \rightarrow 2_s^+) \exp \right\} / \left\{ B(E_2, 4_s^+ \rightarrow 2_s^+) \exp \right\} + b', \]

and

\[ \gamma_0 = a'' \log \left\{ B(E_2, 2_s^+ \rightarrow 0_s^+) \exp \right\} / \left\{ B(E_2, 2_s^+ \rightarrow 0_s^+) \exp \right\} + b'', \]

where \( a' = (68.96 \pm 9.5) \), \( a'' = (18.58 \pm 3.45) \) \( b' = -(30.8 \pm 4.8) \) and \( b'' = (6.96 \pm 2.64) \) from least square fitting procedure.

It is apparent from the Table I as well as from the slopes of fitted lines that the agree-
Fig. 1. Plots of the ratios \( \frac{B(E_2, \, 2^+_2 \to 0^+_1)}{B(E_2, \, 2^+_2 \to 0^+_2)_{\text{orb}}} = F_{\text{orb}} \) and \( \frac{B(E_2, \, 2^+_4 \to 0^+_4)}{B(E_2, \, 2^+_2 \to 0^+_2)_{\text{sr}}} = F_{\text{sr}} \) vs the nonaxiality parameter \( \gamma_0 \).
<p>| S. N. | Nucleus | $B(E_{2}, 2_{1}^{+}ightarrow 0_{1}^{+})$ ($\text{e}^{2} \cdot 10^{-48} \text{cm}^{4}$) | $B(E_{2}, 2_{1}^{+}ightarrow 0_{1}^{+})$ $\frac{DR}{Exp.}$ ($\text{e}^{2} \cdot 10^{-48} \text{cm}^{4}$) | $B(E_{2}, 4_{1}^{+}ightarrow 2_{1}^{+})$ $\frac{DR}{Exp.}$ ($\text{e}^{2} \cdot 10^{-48} \text{cm}^{4}$) | $B(E_{2}, 2_{1}^{+}ightarrow 0_{1}^{+})$ $\frac{DR}{Exp.}$ ($\text{e}^{2} \cdot 10^{-48} \text{cm}^{4}$) | $B(E_{2}, 2_{1}^{+}ightarrow 0_{1}^{+})$ $\frac{DR}{Exp.}$ ($\text{e}^{2} \cdot 10^{-48} \text{cm}^{4}$) | $\gamma_{0}$ |
|------|---------|---------------------------------|-----------------|-----------------|-----------------|-----------------|------|
| 1.   | $^{147}$Sm | .268 ± .01a | .0396 | .2265 | .016c | .00339 | 20.4 |
| 2.   | $^{147}$Sm | .67 ± .016a | .1585 | 1c | .2348 | .026c | .00455 | 13.26 |
| 3.   | $^{150}$Sm | .868 ± .026a | .227 | 1.2c | .3242 | .013c | .00874 | 9.6 |
| 4.   | $^{152}$Cd | .318 ± .03a | .0201 | .37 | .016c | .01327 | 21.44 |
| 5.   | $^{152}$Gd | .736 ± .04a | .164 | 1.2c | .2348 | .026c | .00455 | 13.9 |
| 6.   | $^{152}$Gd | .93 ± .04a | .232 | 1.3c | .326 | .012c | .01198 | 11.05 |
| 7.   | $^{152}$Gd | 1.03 ± .05a | .259 | 1.3c | .37 | .016c | .01327 | 10.31 |
| 8.   | $^{152}$Dy | .768 ± .054a | .137 | 1.3c | .33 | .154 | 12.78 |
| 9.   | $^{152}$Dy | .94 ± .07a | .235 | 1.3c | .33 | .014c | .01659 | 11.89 |
| 10.  | $^{152}$Dy | .95 ± .06a | .237 | 1.5c | .33 | .014c | .01659 | 11.89 |
| 11.  | $^{152}$Dy | 1.01 ± .03a | .225 | 1.5c | .334 | .031c | .01665 | 9.59 |
| 12.  | $^{152}$Er | .33 ± .02a | .0622 | .53c | .0886 | .2342 | 18.74 |
| 13.  | $^{152}$Er | .55 ± .03a | .0774 | .87c | .11 | .1857 | 15.07 |
| 14.  | $^{152}$Er | .83 ± .04a | .1229 | 1.2c | .175 | .01103 | 11.53 |
| 15.  | $^{152}$Er | .98 ± .05a | .249 | 1.4c | .334 | .036c | .197 | 12.9 |
| 16.  | $^{152}$Er | 1.04 ± .07a | .2217 | 1.4c | .334 | .036c | .197 | 12.9 |
| 17.  | $^{152}$Er | 1.15 ± .04a | .319 | 1.7c | .454 | .027c | .02013 | 12.66 |
| 18.  | $^{152}$Er | 1.15 ± .044a | .319 | 1.6c | .45 | .027c | .02013 | 12.66 |
| 19.  | $^{152}$Er | 1.106 ± .03a | .291 | 1.6c | .45 | .027c | .02013 | 12.66 |
| 20.  | $^{152}$Yb | .93 ± .035c | .219 | 1.3c | .313 | .02c | .00114 | 9.26 |
| 21.  | $^{152}$Yb | 1 ± .05c | .238 | 1.52c | .344 | .0198 | 10.8 |
| 22.  | $^{152}$Yb | 1.09 ± .05a | .272 | 1.52c | .344 | .0198 | 10.8 |
| 23.  | $^{152}$Yb | 1.104 ± .05a | .298 | 1.47 | .447 | .006c | .006814 | 9.26 |
| 24.  | $^{152}$Yb | 1.198 ± .05a | .315 | 1.6c | .447 | .006c | .006814 | 9.26 |
| 25.  | $^{152}$Yb | 1.15 ± .056a | .319 | 1.7c | .453 | .006c | .006814 | 9.26 |
| 26.  | $^{152}$Hf | .94 ± .07a | .236 | 1.6c | .447 | .006c | .006814 | 9.26 |
| 27.  | $^{152}$Hf | .98 ± .064a | .235 | 1.6c | .447 | .006c | .006814 | 9.26 |
| 28.  | $^{152}$Hf | 1.08 ± .05a | .284 | 1.6c | .447 | .006c | .006814 | 9.26 |
| 29.  | $^{152}$Hf | .924 ± .05a | .225 | 1.6c | .447 | .006c | .006814 | 9.26 |</p>
<table><thead><tr><th></th><th></th><th></th><th></th><th></th><th></th><th></th></tr>
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<tr><td>45.</td><td>$^{170}$Hg</td><td>$0.284 \pm 0.04a$</td><td>$0.0333$</td><td></td><td></td><td></td></tr>
<tr><td>46.</td><td>$^{232}$Th</td><td>$1.41 \pm 0.112a$</td><td>$0.332$</td><td></td><td></td><td></td></tr>
<tr><td>47.</td><td>$^{231}$Th</td><td>$1.6 \pm 0.4a$</td><td>$0.405$</td><td>$2.24c$</td><td>$0.57$</td><td>$0.0246d$</td></tr>
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<tr><td>52.</td><td>$^{235}$U</td><td>$2.376 \pm 0.05a$</td><td>$0.452$</td><td></td><td></td><td></td></tr>
<tr><td>53.</td><td>$^{236}$Pu</td><td>$2.516 \pm 0.07a$</td><td>$0.708$</td><td></td><td></td><td></td></tr>
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<tr><td>56.</td><td>$^{239}$Cm</td><td>$3.0 \pm 0.09a$</td><td>$0.566$</td><td></td><td></td><td></td></tr>
<tr><td>57.</td><td>$^{240}$Cm</td><td>$3.0 \pm 0.11a$</td><td>$0.577$</td><td></td><td></td><td></td></tr></tbody></table>

ment between experimental values and the DR predictions for $2^+_g \rightarrow 0^+_g$ transition is better than that of $4^+_g \rightarrow 2^+_g$ and $2^+_g \rightarrow 0^+_g$ transitions. The abnormal behaviour in the ratio of $B(E2, 2^+_g \rightarrow 0^+_g)_{\text{exp}}/B(E2, 2^+_g \rightarrow 0^+_g)_{\text{DR}}$ vs $\gamma_0$ of $^{152}\text{Sm}$ and $^{154}\text{Gd}$ may be due to critical neutron number $90$.\(^{18}\)

From the Table, it is clear that the model does not reproduce fairly well the absolute experimental rates. For all cases, the DR model predicts somewhat smaller values of $E_2$ transition probabilities compared to experimental rates. The disagreement between theoretical estimates to experimental rates can be brought down by treating the unit radius ($r_0$) as a free parameter. The deviations could be reduced to 50\% when the values of $r_0$ was taken to be 1.5 instead of 1.2 fm. in the calculations. It is interesting to note that the value of $r_0$ (=1.5 fm.) is equal to that obtained by Satchler\(^{19}\) from the optical model analysis of $\alpha$-particle scattering for various elements.

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**References**

1) K. Alder, A. Bohr, T. Huus, B. Mottelson and
4) A. S. Davyдов and V. S. Rostovsky: Nuclear Phys. 60 (1964) 529.
9) M. Sakai and A. C. Rester: to be published in Atomic Data and Nuclear Data Tables.
Statistical Theory Calculations of Neutron-Capture Cross-Sections at 24 keV

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Neutron-capture cross-sections are calculated using Margolis formula based on statistical theory at 24 keV for 48 nuclei, using low energy resonance parameters. In these calculations we have taken into account the contribution due to \(s\)-, \(p\)- and \(d\)-wave neutrons. In general, the agreement between the theoretical and the experimental cross-sections for the cases enumerated is satisfactory, when \(\langle r, y \rangle / \langle \sigma \rangle \) is taken to be the same for \(s\) and \(p\)-wave neutrons.

§1. Introduction

Nuclear reactions data have been investigated primarily to obtain knowledge about nuclear structure and reaction mechanism. The cross-sections in the keV energy region are useful in the design of fast reactors as well as in the study of cosmological theory of element formation in the universe.\(^{1}\) To understand clearly the element building formation, neutron capture cross-sections data are required in the few tens of keV energy region. Unfortunately, capture cross-sections in the keV region are known at isolated energies; and these are also not known for all isotopes because most of these cross-sections have been measured using activation technique. This technique is limited to those cases where the life time of product nucleus is neither very short nor very long. In order to understand nucleosynthesis theory Alien et al.\(^{2}\) used empirical expressions for finding the neutron-capture cross-sections at 30 keV where they were not known experimentally. For this reason, the need may arise for calculating the cross-sections in those cases when they are not known from experiment.

In this energy region the neutron-capture reaction takes place mostly through compound nucleus mechanism. The only problem in evaluating the cross-sections for this kind of reaction is the precise knowledge of the parameters involved in the theoretical formula. No systematic calculations of the cross-section have been done so far in this energy region. Miskel et al.\(^{3}\) have calculated the capture cross-sections for \(^{184}\)Hf, \(^{181}\)Ta, \(^{186}\)W, \(^{197}\)Au and \(^{232}\)Th nuclei in the energy region of 0.03 to 4 MeV. These workers have taken three different values of the parameter \(\xi\) i.e. 1.25\(\xi\), \(\xi\) and 0.75\(\xi\) (where \(\xi = \langle D \rangle / 2 \pi \langle r, y \rangle\), \(\langle D \rangle\) is the average level spacing and \(\langle r, y \rangle\) is the average radiation width) in these calculations. Chaubey and Sehgal\(^{4}\) have calculated the parameter \(\xi\) at 24 keV for a number of cases.

In the present work, neutron total capture cross-sections at 24 keV for 48 nuclei with mass number \(45 < A < 232\) have been calculated on the basis of statistical theory. We have used the expression of Margolis\(^{5}\) for these calculations. It is not known whether \(\xi\) is same for \(s\) and \(p\)-wave neutrons. We have performed these calculations assuming (a) that \(\langle r, y \rangle / \langle \sigma \rangle\) is same\(^{5,6}\) for \(s\), \(p\) and \(d\)-wave neutrons (b) that \(\langle r, y \rangle / \langle D \rangle\) for \(p\)- and \(d\)-wave is \((2J + 1)\) time\(^{7,9}\) that of the \(s\)-wave, assuming \(\langle r, y \rangle\) to be same\(^{9}\) for \(s\), \(p\) and \(d\)-wave neutrons. The present paper is devoted to presenting these theoretical values along with the experimental data. It is concluded that \(\langle r, y \rangle / \langle D \rangle\) is the same for \(s\) and \(p\)-wave neutrons.

§2. Calculations Based on Statistical Theory

The statistical theory of nuclear reactions is based on two main assumptions: (a) Bohr picture of the compound nucleus formation holds true, and (b) there is an overlapping of the levels at the excitation energy where the compound nucleus is formed. In keV energy
region the first assumption is completely valid whereas the assumption (b) also seems to be valid provided the energy spread of the incident neutron beam is greater than the spacing of the levels so that many compound states are simultaneously excited.

The following expression for \((n, \gamma)\) cross-section, using statistical theory, was used:

\[
\sigma_{n\gamma}(n, \gamma) = \frac{\pi \hbar^2}{2(2I+1)} \sum_{I'=0}^\infty \left[ T_i(E) \sum_{j'=0}^\infty \frac{e_j(2J+1)}{1 + \xi \gamma_{AI}(E) \sum_j \frac{e_j(2J+1)}{j+1} T_j(E - E_n)} \right],
\]

where \(I\) is the spin of the target nucleus, \(J\) is the channel spin, \(J\) is the spin of a level in the compound nucleus, \(2\pi \hbar\) is the deBroglie wavelength of the incident neutron, \(E_n\) is the energy of the \(n\)th excited state, \(T_i\) is the transmission coefficient for the \(l\)-th partial wave, \(l\) is the angular momentum of the emitted neutron and \(e_j\) is the statistical factor.

While calculating cross-sections we have included the contribution of angular momentum of neutrons up to \(l=2\), as only \(s\)- and \(p\)-wave neutrons contribute predominantly to the capture cross-section at 24 keV in most of the target nuclei.\(^9\) The neutron transmission coefficients were calculated using the data of Campbell et al.\(^10\) we have taken the spherical complex well potential with diffuse edges and the value of nuclear radius as \(R=(1.25 A^{1/3} + 0.5)\) fermis in the calculations of \(T_i\).

The factor \(\gamma_{AI}\) in the expression (1), which accounts for the energy and level density dependence of the width \(\Gamma_j\), is given by

\[
\gamma_{AI} = \int_0^{B'} e^{2\Delta I + 1} \rho(B - \epsilon) d\epsilon \int_0^{B + E} e^{2\Delta I + 1} \rho(B + E - \epsilon) d\epsilon,
\]

where \(B'\) is the effective neutron binding energy which takes into account the pairing effect, \(E\) is the energy of incident neutron, and the level density \(\rho(E')\) at excitation energy \(E'\) on the basis of Fermi gas Model, is given by

\[
\rho(E') = \frac{\mathcal{N}}{\sqrt{2\pi}} e^{-E'/T},
\]

where \(E\) and \(2\Delta I\) are the energy and multipole order, respectively, of the \(\gamma\)-radiation emitted in the decay of the compound nucleus. It is assumed\(^11\) that dipole radiation predominates over other higher multipoles, the ratio of the two is of the order of \(10^{-2}\). Different values of level density parameter \(a\), neutron binding energy \(B\) and pairing energy \(A\), corresponding to different isotopes have been taken from the results of Gilbert and Cameron,\(^12\) and Baba.\(^13\) There was no significant variation in the values of \(\gamma_{AI}\) for different isotopes. Most of these values lie between 0.93 to 0.97. However, we have taken different values of \(\gamma_{AI}\) for different isotopes in our calculations.

We also calculated \(\gamma_{AI}\) for \(^{197}\)Au assuming quadrupole radiations. This values of \(\gamma_{AI} = 0.975\) is very close to \(0.953\) for dipole radiations, therefore, our results are not affected in the presence of a small admixture of quadrupole radiations.

The \(J\)-wave contribution to capture cross-section has been calculated using \(J\)-wave resonance parameters available in literature.\(^12\) The \(s\)-wave contributions have been calculated following two different approaches:

(a) that \(\langle \Gamma_j \rangle / \langle D \rangle\) is same\(^5\) for \(s\)-, \(p\)-...
and d-wave neutrons.

(b) that \( \langle \Gamma_s \rangle / \langle D \rangle \) for p- and d-wave is 
\((2J+1)\) times\(^{29} \) that of the s-wave, assuming 
\( \langle \Gamma_s \rangle \) to be same\(^9 \) for s-, p- and d-wave neutrons.

§3. Results

The results of the present calculations are summarized in Table I. In column first and second are given the target nucleus and the values of \( \xi \) for different isotopes. The third and fourth columns contain the computed cross-sections corresponding to \( \xi \) and \( \xi' \) 
\( (= \langle D \rangle / 2\pi \Gamma_s (2l+1)) \) respectively. The errors in the calculated cross-section values are due to errors present in the value of resonance parameters. Various experimental values\(^{21-29} \) of total capture cross-sections mostly obtained by activation technique using \( 5b-Be \) photon-neutron source, which has an energy spread 5 keV,\(^{27} \) have been suitably averaged in fifth column of Table I. Some of the average values of \( \sigma_{\text{expt.}} \) have been taken from ref. 2. The search is not claimed to be exhaustive, but it is believed that no important data have been missed. In \( 79\text{Br}, 85\text{Rb}, 106\text{Pd}, 109\text{Ag}, 114\text{Cd}, 115\text{In}, 133\text{Cs}, 164\text{Dy}, 184\text{W}, 181\text{Ta} \) and \( 209\text{Bi} \) values of \( \sigma_{\text{expt.}} \) are the sum of the cross-sections for the isomeric and the ground states, and thus are total capture cross-sections. The ratio of the theoretical values to those of experimentally measured cross-sections have been presented in the sixth and seventh column of the Table. Figure 1 illustrates the behaviour 

\[ \text{(a)} \quad \langle \Gamma_s \rangle / \langle D \rangle \text{ versus the neutron number } N \text{ in the target nucleus.} \]

Practically for all cases given in Table I, the contribution of the d-wave to capture cross-section is very small in comparison with s- and p-wave, so it is difficult to say whether \( \langle \Gamma_s \rangle \) for d-wave is same as that of s-wave. However, the contribution of p-wave to the capture cross-section is either comparable or more than s-wave contribution in most of the cases, therefore, it is easy to verify whether \( \langle \Gamma_s \rangle / \langle D \rangle \) is the same for s- and p-wave. It is clear from the Fig. 1 that most of the points are closer to the line corresponding to the ratio 1, within experimental uncertainties, when \( \xi \) is taken to be independent of \( J \); thus confirming that \( \langle \Gamma_s \rangle / \langle D \rangle \) is the same for s- and p-wave. From Table it is clear that difference between \( \langle \sigma_{\text{theor.}} \rangle \) and \( \langle \sigma_{\text{theor.}} \rangle \) for nuclei \( 98-100\text{Mo}, 107-109\text{Ag}, 114\text{Cd}, 115\text{In}, 127\text{Tl}, 133\text{Cs} \) is not significant and therefore it is difficult to verify the relation \( \langle \Gamma_s \rangle / \langle D \rangle \rangle_{\text{p-wave}} \approx \langle \Gamma_s \rangle / \langle D \rangle \rangle_{\text{d-wave}} \) for these cases.

It may be remarked that \( \langle \Gamma_s \rangle \) and \( D \) can independently change for p-wave keeping the ratio \( \langle \Gamma_s \rangle / \langle D \rangle \) to be the same. Allen et al.\(^{30} \) have proved for \( 56\text{Fe} \) that \( \langle \Gamma_s \rangle / \langle D \rangle \) has the value \( \approx 0.06 \pm 0.0017 \) and \( \approx 0.0428 \pm 0.012 \) for s- and p-wave respectively. Stieglitz et al.\(^{31} \) have studied p-wave resonances of \( 52\text{Cr} \). They have found that average radiation width \( \langle \Gamma_s \rangle \) for the p-wave resonances is nearly three times smaller than the \( \langle \Gamma_s \rangle \) for the s-wave resonances. Assuming that the

\[ \text{Fig. 1. Plot of the ratios } \langle \sigma_{\text{theor.}} \rangle / \langle \sigma_{\text{expt.}} \rangle \text{ and } \langle \sigma_{\text{theor.}} \rangle / \langle \sigma_{\text{expt.}} \rangle \text{ vs the neutron number } N \text{ of the target nucleus.} \]
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<th>Target nucleus</th>
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<th>$(\sigma_{\text{dual}})_1$</th>
<th>$(\sigma_{\text{dual}})_2$</th>
<th>$(\sigma_{\text{extrap}})$</th>
<th>Ratio</th>
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average level spacing obeys a law of $(2J + 1)^{-1}$, $D_{J+1}$ will be three times smaller than $D_{J=0}$. Thus $\langle \Gamma_y \rangle / \langle D \rangle$ for $p$-wave resonances will remain same as that of $s$-wave resonances for $^{52}\text{Cr}$.

Musgrove et al.\(^{32}\) have shown that $\langle \Gamma_y \rangle / \langle D \rangle$ is nearly same for $s$- and $p$-wave resonances in $^{40}\text{Ca}$.

Finally, we would like to point out that the assumption $\langle \Gamma_y \rangle / \langle D \rangle_{p\text{-wave}} \approx \langle \Gamma_y \rangle / \langle D \rangle_{s\text{-wave}}$, which has been verified experimentally for many nuclei\(^{15,30-32}\) except those in 3p region\(^{15,33}\) is fairly well to reproduce the experimental cross-sections at 24 keV and it may be further used to get information about $\langle \Gamma_y \rangle / \langle D \rangle_{s\text{-wave}}$ by fitting the experimental cross-sections at higher energies.

Acknowledgement

We are thankful to Professor Zillur Rahman Khan for his kind interest in the present work. One of the authors (H.M.A.) is thankful to U.G.C. for providing research fellowship.

References

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STATISTICAL ANALYSIS OF NEUTRON-REDUCED WIDTHS

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The mathematical form of the distribution of the individual neutron reduced widths was established by Porter and Thomas\(^1\). Such a distribution is represented by the chi-squared distribution with one degree of freedom \(\nu = 1\): \(p(x, \nu) = \frac{(f_r)^{\nu-1}}{\Gamma(\nu)} e^{-x f_r} dx\), where \(x = \frac{x^2}{f_r}\), \(\nu = 1\). Later, Garrison\(^2\) studied the problem in the same way as Porter and Thomas. For this investigation he combined the reduced neutron widths for some nuclei and concluded the \(\nu = 1\) distribution. This method of analysis could not reveal departure, if any, for individual nuclei, from the P.T. distribution. Recently, Sharma and Raj\(^3\) determined the value of degree of freedom \(\nu\) corresponding to individual nuclei. They pointed out the possibility of structure effect in the value of \(\nu\). No definite conclusion could be drawn by them.

In this paper, we have made an attempt to determine the values of \(\nu\) appropriate to individual nuclei. The analysis has been undertaken for nuclei for which sufficient number of resonances are known. The maximum likelihood method has been used to determine the value of \(\nu\).

In the present work, the statistical weight factor \(g\) is assumed to be 1/2, except for zero spin target nuclei, where it is known to be unity. In mass regions \(A < 55\) and \(A > 150\) we find that there are many nuclei for which \(\nu\) is \(\approx 2\).

In the earlier work any deviation from such a distribution was explained either by the inclusion of \(p\)-wave resonances or by the possibility of some resonances not being observed. Because of good energy resolution, during last few years some missed resonances having small \(R\) as well as \(p\)-wave induced resonances have been detected. The data which have been analyzed here are quite accurate to establish a departure from the P.T. distribution in the mass regions \(A < 55\) and \(A > 150\). Possible explanations for this departure are given on the basis of nuclear reaction theory as well as nuclear structure.

REFERENCES

KEYWORDS
P.T. distribution, Neutron-reduced width