8.1 Conclusion

The research work of this thesis is a part of following long term goals: To promote generation of covariances in nuclear data science experiments in the Indian context and nuclear data evaluation in the Indian context.

The covariance analysis can be viewed, either as a mandatory procedure from the perspective of probabilistic reasoning or as a most valuable information required from the application point of view (e.g. covariances are important in assessing confidence margins in design parameters of nuclear systems apart from the basic quantification of errors in the form of covariances). In this thesis, both the experiment and the covariance analysis of the data obtained from the experiment are given equal importance. The publications of an experimental result without a complete specification of uncertainties in the form of covariances is incomplete.
Chapter 8. Conclusion and future work.

The covariance analysis in the context of nuclear physics experiment assumes greater importance, since, experiments such as determination of reaction cross sections, require huge resources, and therefore, the detailed information documented by the experimenter is precious, so as not to lose the valuable information on the costly experiment.

The present work has been expected, in the Indian context, to set a trend for all experimental nuclear physicists to incorporate a detailed covariance information in their publications of research output. We present detailed treatment of the measurement and covariance analysis of $^{58}Ni(n, p)^{58}Co$ reaction cross-section determination, relative to cross-section for the formation of the fission product $^{97}Zr$ in the $^{232}Th(n, f)$ and $^{238}U(n, f)$ reactions at three effective neutron energies $E_n = 5.88 \pm 0.12, 10.11 \pm 0.06$ and $15.86 \pm 0.12$ MeV, respectively.

We discuss, generation of covariance information using partial uncertainties and micro-correlations. We present necessary data and step by step simplification, in the following context:

1. Efficiency calibration of HPGe detector with respect to $\gamma$-lines from standard $^{152}Eu$ source.

2. Efficiency of the HPGe detector with respect to characteristic $\gamma$-lines from the reaction products $^{58}Co^*$ and $^{97}Zr^*$.

3. Reaction rates in the $^{58}Ni(n, p)^{58}Co$, $^{232}Th(n, f)$ and $^{238}U(n, f)$ reactions.

4. Ratio of reaction rates at three effective neutron energies $E_n = 5.88 \pm 0.12, 10.11 \pm 0.06$ and $15.86 \pm 0.12$ MeV:
   
   (a) Ratio of reaction rate in the $^{58}Ni(n, p)^{58}Co$ to that of reaction rate in $^{232}Th(n, f)$ reaction at each of the three effective neutron energies.

   (b) Ratio of reaction rate in the $^{58}Ni(n, p)^{58}Co$ to that of reaction rate in $^{238}U(n, f)$ reaction at each of the three effective neutron energies.

5. Normalization:
Chapter 8. Conclusion and future work

(a) Neutron induced reaction cross-section of $^{58}Ni(n,p)^{58}Co$ reaction, normalized to the cross-section for the formation of the fission product $^{97}Zr$ in the $^{232}Th(n,f)$ reaction, at each of the three effective neutron energies.

(b) Neutron induced reaction cross-section of $^{58}Ni(n,p)^{58}Co$ reaction, normalized to the cross-section for the formation of the fission product $^{97}Zr$ in the $^{238}U(n,f)$ reaction, at each of the three effective neutron energies.

6. Weighted averaging of equivalent data, where, by equivalent data, we mean neutron induced reaction cross-section of $^{58}Ni(n,p)^{58}Co$ reaction, normalized to the cross-section for the formation of fission product $^{97}Zr$ in the $^{232}Th(n,f)$ and $^{238}U(n,f)$ reaction, at each of the three effective neutron energies. Additionally, we illustrate $\chi^2$-scaling, when $\chi^2$ value obtained in the weighted averaging of equivalent data is higher than the expected.

Additionally, we discuss neutron spectrum features in the context of $^7Li(p,n)$ neutron production reaction, which is a quasi mono-energetic neutron source at higher incident proton energies. We present simple derivation of correction factor to account for neutron spectrum features in the relative cross-section measurement. Since, we employed quasi mono-energetic neutron source, we base our calculations on the effective neutron energies. Since, cross-section is a function of neutron energy, the selection of standard cross-section data and our inference on the neutron induced reaction cross-section of $^{58}Ni(n,p)^{58}Co$ reaction is strongly influenced by effective neutron energies. i.e., The effective neutron energies play important role in the covariance analysis of $^{58}Ni(n,p)^{58}Co$ reaction cross-section. The $\chi^2$-value obtained in the weighted averaging of equivalent data is sensitive to effective neutron energies.

We irradiated two monitor foils (natural uranium and thorium foils) along with an unknown sample (Nickel foil) at each of the three effective neutron energies. The rational is to understand the effect of systematic error. Ideally, we expect, similar values of neutron induced reaction cross-section of $^{58}Ni(n,p)^{58}Co$ reaction, normalized to the cross-section for the formation of fission product $^{97}Zr$ in the $^{232}Th(n,f)$ and $^{238}U(n,f)$ reaction, respectively, at each of the the three effective neutron energies. The difference
between the neutron induced reaction cross-section of $^{58}Ni(n, p)^{58}Co$ reaction, normalized to the cross-section for the formation of fission product $^{97}Zr$ in the $^{232}Th(n, f)$ reaction and the neutron induced reaction cross-section of $^{58}Ni(n, p)^{58}Co$ reaction, normalized to the cross-section for the formation of fission product $^{97}Zr$ in the $^{238}U(n, f)$ reaction, at each of the three effective neutron energies, is attributed to the effect of systematic errors. The advantage is that, the true value of the neutron induced reaction cross-section of $^{58}Ni(n, p)^{58}Co$ reaction, is constrained within the interval equal to the difference between the neutron induced reaction cross-section of $^{58}Ni(n, p)^{58}Co$ reaction, normalized with respect to two different monitors.

The rational of two monitors in a relative measurement presented in previous paragraph, enabled us to discuss weighted averaging of equivalent data and to extract our best knowledge of the neutron induced reaction cross-section of $^{58}Ni(n, p)^{58}Co$ reaction, at each of the three effective neutron energies, along with covariance information, presented in Table 8.1.

<table>
<thead>
<tr>
<th>$E_n$ MeV</th>
<th>$\sigma(E_n)$ (mb)</th>
<th>$V_n \times 10^{-4}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.588 ± 0.12</td>
<td>485 ± 38</td>
<td>14.52 01.38 00.42</td>
<td>3.61</td>
</tr>
<tr>
<td>1.101 ± 0.06</td>
<td>656 ± 40</td>
<td>01.38 16.28 00.55</td>
<td>2.73</td>
</tr>
<tr>
<td>15.86 ± 0.12</td>
<td>194 ± 14</td>
<td>00.42 00.55 02.20</td>
<td>1.31</td>
</tr>
</tbody>
</table>

The $\chi^2$ values presented in Table 8.1 are supposed to be $\approx 1$, the higher $\chi^2$ values indicates the effect of systematic error in action. Since, we have included all known information of systematic errors in the covariance analysis, we proceed with adhoc method of scaling or adjusting covariance information presented in Table 8.1 to achieve expected $\chi^2$-value. The corresponding result is presented in Table 8.2.

Our best knowledge of $^{58}Ni(n, p)^{58}Co$ reaction cross-section at effective neutron energies $E_n = 5.88\pm0.12, 10.11\pm0.06$ and $15.86\pm0.12$ MeV, along with covariance information, presented in Table 8.1 or Table 8.2, is a new contribution to the $^{58}Ni(n, p)^{58}Co$ reaction cross-section data. In the present work, we strive our best to cover elements
Chapter 8. Conclusion and future work.

Table 8.2: The adjusted best values of $^{58}\text{Ni}(n,p)^{58}\text{Co}$ reaction cross-section at effective neutron energies $E_n = 5.88 \pm 0.12, 10.11 \pm 0.06$ and $15.86 \pm 0.12$ MeV, with covariance matrix $V_{ns}$.

<table>
<thead>
<tr>
<th>$E_n$ MeV</th>
<th>cross-section $\sigma(E_n)$ (mb)</th>
<th>$V_{ns} \times 10^{-4}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>05.88 ± 0.12</td>
<td>485 ± 72</td>
<td>52.41 04.34 00.92</td>
<td>≈ 1</td>
</tr>
<tr>
<td>10.11 ± 0.06</td>
<td>656 ± 66</td>
<td>44.45 04.34 01.04</td>
<td>≈ 1</td>
</tr>
<tr>
<td>15.86 ± 0.12</td>
<td>193 ± 16</td>
<td>00.92 01.04 02.88</td>
<td>≈ 1</td>
</tr>
</tbody>
</table>

of data reduction and data evaluation in the context of relative cross-section determination, in order to motivate and promote generation of covariances in nuclear data science experiments and nuclear data evaluations in the Indian context.

8.2 Future Work

It is expected that, as a general culture, the task of covariance generation in all nuclear data science experiments in India will be followed. The detailed description of uncertainties in nuclear experiments are very important for providing a full description of uncertainties and for propagation in nuclear data evaluations to provide Indian recommended values of nuclear data for Indian nuclear applications. Evaluation of nuclear data has to started in a modest way for Indian nuclear applications.

The present work in this thesis is only a small beginning when compared to needs and future scope of work in the Indian context. The indigenous efforts in India on covariances, as a near and future scope, propose to cover and influence broadly the following industrial scale activities on covariances:

1. Generation of covariances in hundreds of nuclear data physics experiments including in surrogate reactions.

2. Promotion and use of nuclear data covariances for lakhs of nuclear reactions in raw data compilations in EXFOR format.

3. Cross-section evaluations include use of nuclear models, statistical inference tools, and covariances based on nuclear models.
4. Understanding formats and procedures for covariances and their use; Processing of covariances for use in reactor design calculations (Monte Carlo or multigroup discrete ordinates) in advanced reactor applications.


6. Use of covariances to define error margins due to uncertainties in nuclear data and adjustment of cross-sections. Perspectives on uncertainties in quantities other than nuclear data, affecting target accuracy in advanced reactor designs.

7. Creation of Indian experimental benchmarks with specification of uncertainties in system characterization. Integral experiments with covariances.