Chapter 7

Summary, Conclusions and Future Work

7.1 Summary and Conclusions

The present Ph.D. thesis concerns a systematic experimental and theoretical study of the $(n, 2n)$ and (n, p) reactions channel for the isotopes: ^{48}Ti, ^{51}V, ^{52}Cr, ^{65}Cu, ^{76,77,78,80}Se, ^{103}Rh, ^{121}Sb and ^{123}Sb, which belong to low mass to heavy mass region. Neutron induced reaction cross sections were measured at different higher neutron beam energies ranging from 7.87 to 19.81 MeV via the activation technique relative to the $^{27}\mathrm{Al}(n, \alpha)^{24}\mathrm{Na}$ monitor reaction. The neutron irradiations were performed at the 6 m setup of the 14UD BARC-TIFR Pelletron Accelerator facility at Mumbai, India. These high energy quasi-monoenergetic neutrons were produced via the $^{7}\mathrm{Li}(p, n)$ reaction. After the irradiation process, the induced activities of the samples were measured offline via high-resolution γ-ray spectrometry using the HPGe detector. One of the most important contributions of present thesis work is the addition of experimental data at higher energy, as well as a detailed description of the uncertainties in measured cross sections using covariance analysis method. In the present measurements, the uncertainties in the HPGe detector efficiency and measured cross section were calculated using the covariance analysis method along with the covariance matrix and correlation matrix. Besides this, the correction factors due to the low energy background neutron contribution, self-attenuation of the γ-ray, geometry and coincidence summing effect were considered in the data analysis. The present experimental results are summarized in Tables 3.5 to 3.9 [Chapter 3].

It was found that the existing literature data of the $(n, 2n)$ reaction for the isotopes: ^{103}Rh, ^{121}Sb and ^{123}Sb shows significant discrepancies and most of the measurements were in the range of 13-15 MeV. The present measurements of the $^{121}\mathrm{Sb}(n, 2n)^{120}\mathrm{Sb}^{m}$ and $^{123}\mathrm{Sb}(n, 2n)^{122}\mathrm{Sb}$ reactions cross sections are performed at 12.50, 15.79 and 18.87 MeV energies, at these energies very limited experimental data are available in literature. Our results follow the trend of previously existing literature datasets [see Fig. 5.1(a) and Fig. 5.3(c)] and the new data points at 12.50, 15.79 and 18.87 MeV provide information on the shape of the excitation function. Similarly, the $^{103}\text{Rh}(n, 2n)^{102}\text{Rh}^{\text{g}}$ and $^{103}\text{Rh}(n, 2n)^{102}\text{Rh}^{\text{m}}$ reactions cross sections were measured at 16.86 and 19.89 MeV energies. It was observed that the previous measurements of the isomeric state cross section are only limited to a narrow energy range of 13.5–15.0 MeV, whereas the ground state cross sections are measured by several authors from threshold to 24 MeV energies, it's also demonstrated significant discrepancies. The present measurements at 16.86 and 19.89 MeV are new higher energies data points and following the trend of existing literature data for ground and isomeric state [see Fig. 5.6 and Fig. 5.7]. These cross sections values of rhodium and antimony fill the gap that existed in literature data at present energies region.

Furthermore, the existing literature data of the (n, p) reaction for the isotopes: ^{51}V and ^{65}Cu are available from the threshold to 20 MeV energies. This existing data shows significant discrepancies above 13 MeV, whereas at lower energies all measurements are agree to each other. The present data for the $^{51}\text{V}(n, p)^{51}\text{Ti}$ reaction cross section at 7.87, 13.05 and 16.98 MeV are following the trend of previously existing literature datasets [see Fig. 6.1]. Concerning the $^{65}\text{Cu}(n, p)^{65}\text{Ni}$ reaction cross section, our results at higher 13.52, 16.86 and 19.89 MeV energies are agreed with previously existing datasets, while the new data at 19.89 MeV are second measurements of the cross section [see Fig. 6.2]. The experimental results on the $\text{Se}(n, p)\text{As}$ reaction are new since no higher energy data exists for Se isotopes in literature. Most of the previous experiments were performed using small-volume NaI (Tl) detectors with low resolution and efficiency in the 13-15 MeV region and shows significant discrepancies. The present measurements at 13.52 MeV are following the trend of existing literature data [see Fig. 6.3] and the cross sections were measured for the first time at 16.86 and 19.89 MeV energies. However, our results of the $^{76}\text{Se}(n, p)^{76}\text{As}$ reaction cross section at 10.52 MeV shows good agreement with literature data, whereas $^{78}\text{Se}(n, p)^{78}\text{As}$ reaction cross section shows lower value compared to literature data. It is observed that our experimental results are not sufficient to provide the information on shape of the excitation function. Therefore, more experimental data are required at lower and higher energies of the (n, p) reaction for Se isotopes.

In conclusion, the present measurements were compared with the literature data taken from the EXFOR database and evaluations of the latest libraries taken from the ENDF database and these new measurements are agreed and following the trend of the previous literature and evaluated data. A systematic study from the formula concludes that, the formulae of the Chatterjee, Lu and Fink, Bychkov and Luo reproduce the $(n, 2n)$ reaction cross section of the

Antimony and Rhodium isotopes very well except for the Habbani formula. Similarly, the (n,p) reaction cross section of the Vanadium, Copper, and Selenium from the systematic formulae of the Kasugai, Levkovski, Habbani and Luo show good agreement with the literature data.

Statistical calculations were performed using statistical reaction TALYS (ver. 1.9) and EMPIRE (ver. 3.2.3) codes. The present experimental data and the previous ones were used to validate the theoretical calculations of both codes by considering the level density, optical potential, γ-ray strength functions and pre-equilibrium models. In theoretical calculations, the impacts of various combinations of the nuclear input parameters of different level density models, optical model potentials, and pre-equilibrium models were considered in the present measurements for study of the $(n,2n)$ and (n,p) reactions for the isotopes: ^{48}Ti, ^{51}V, ^{52}Cr, ^{65}Cu, ^{76,77,78,80}Se, ^{103}Rh, ^{121}Sb and ^{123}Sb. These obtained theoretical cross sections were found to be similar to the measured experimental data when specific level density models were applied. If multiple models are considered for the phenomenological and microscopic level densities, the estimated excitation functions show the greatest differences. The models of pre-equilibrium emission, optical model potentials and the γ-ray strength functions of the E1 transition were used in combination with various models of the phenomenological and microscopic level density models to enhance the performance of the estimated excitation functions for the present measurements and literature data. It was found that the excitation functions of the present reactions did not significantly alter when the optical Koning-Delaroche (KD) potential was swapped out by the semi-microscopic Bauge optical potential model. Moreover, the impacts of optical model potential and γ-ray strength functions were much less than those of nuclear level densities. It is observed that, the different preequilibrium models are important at higher energy to reproduce the experimental results. In general terms, both EMPIRE and TALYS codes gave quite satisfying results for the reproduction of the total, ground and isomeric states cross sections. The following remarks can be drawn from theoretical calculations of both the codes for the present thesis work:

- **^{51}V$(n,p)^{51}$Ti reaction:** The theoretical calculations were obtained from the TALYS code with input parameters adjustment of different level density models and preeqmode 2 (exciton model) and KD local potential show good agreement with the present work and the available literature data.

- **^{65}Cu$(n, p)^{65}$Ni reaction:** The behaviour of the excitation function was improved by combining phenomenological and microscopic level densities models with the KD local, global and dispersive optical potential, the Kopecky and Uhl γ-strength functions, exciton model (preeqmode 3) with the appropriate adjustments of the 'ctable' and 'ptable' level densities input parameters and considering the asys, gshell and deltaW in TALYS theoretical calculations. Similarly, the EMPIRE calculations were improved combining level densities models with the KD local optical potential, the Standard Lorentzian (SLO) and Modified Lorentzian (MLO1) γ-strength functions, Multi-Step-Compound (MSC) and exciton model (PCROSS) with the appropriate adjustments of the ATILNO, GDIV, STMRO, GTILNO and PCROSS input parameters.
- **^{48}Ti$(n, p)^{48}$Sc reaction:** We have shown that the trend of the experimental data can be reproduced with a statistical model TALYS code with appropriate adjustments made to the microscopic level density parameters 'ctable' and 'ptable' with the semi-microscopic optical potential of the Bauge *et al.*, exciton pre-equilibrium model and a microscopic model for the strength functions based on Hartree-Fock-Bogolyubov calculations. Similarly, the appropriate adjustments were made to the phenomenological level density parameters alphald, betald and gammald with dispersion optical potential and exciton preequilibrium models to reproduce the experimental data.
- **^{52}Cr$(n, p)^{52}$V reaction:** The behaviour of the phenomenological and microscopic level densities model was improved by combining it with the KD local and global optical potential and the Kopecky and Uhl γ-strength functions with the appropriate adjustments of the alphald, betald and gammald, 'ctable' and 'ptable' level densities input parameters.
- **^{121}Sb$(n, 2n)^{120}$Sb$^{m,\ g,\ t}$ and ^{123}Sb$(n, 2n)^{122}$Sb$^{m,\ g,\ t}$ reactions:** The theoretical cross sections for the isomeric, ground, total and isomeric cross section ratio were improved combining level densities models with the KD local optical potential, Kopecky–Uhl generalized Lorentzian γ-strength functions and exciton (preeqmode 2) preequilibrium model. Similarly, the EMPIRE calculations were improved combining level densities models with the KD global optical potential, the Brink–Axel γ-strength functions, Multi-Step-Compound (MSC), multistep direct (MSD) and exciton model (PCROSS).
- **^{103}Rh$(n, 2n)^{102}$Rh$^{m,\ g,\ t}$ reaction:** The theoretical results for the isomeric, ground, total and isomeric cross section ratio based on the phenomenological and microscopic level

density models with default calculations are showing good agreement with the present measurements and existing literature data.

- **Se(n, p)As reaction:** The default theoretical cross sections for the above reactions using both the codes with multiple option of level densities, preequilibrium, γ-ray strength functions and optical potential models are showing significant difference in calculations. Therefore, theoretical calculations with parameters adjustment are required to reproduce the (n, p) reaction cross section for Se isotopes in future work.

Although the theoretical results of present thesis work for the ^{48}Ti$(n, p)^{48}$Sc, ^{51}V$(n, p)^{51}$Ti, ^{52}Cr$(n, p)^{52}$V, ^{65}Cu$(n, p)^{65}$Ni, ^{76}Se$(n, p)^{76}$As, ^{77}Se$(n, p)^{77}$As, ^{78}Se$(n, p)^{78}$As, ^{80}Se$(n, p)^{80}$As, ^{103}Rh$(n, 2n)^{102}$Rh, ^{103}Rh$(n, 2n)^{102}$Rh^{m}, ^{103}Rh$(n, 2n)^{102}$Rh^{g}, ^{121}Sb$(n, 2n)^{120}$Sb^{m} and ^{123}Sb$(n, 2n)^{122}$Sb reactions cross sections will also help to improve the theoretical calculations.

7.2 Future work

In the present thesis, the experimental studies for $(n, 2n)$ and (n, p) reactions cross sections were performed up to 20 MeV incident neutron energies. In the future, the extension of similar work at higher energies to produce precise nuclear data above 20 MeV will be interesting to investigate the energy dependence of cross section. These obtained measurements can be used to investigate the optimum combinations of theoretical models of ALICE, COH3, TALYS and EMPIRE statistical simulation codes, and remarks can be made about the behaviour of the models at higher incident neutron energies. The model selection combinations that best reproduce the measurements using theoretical calculations can be helpful to examine how sensitive the calculations can be when alternative models will be considered in theoretical calculations. In this way, a strong conclusion will be drawn for the cross section calculations at higher energies.

In the future, the cross section measurements of the neutron and proton induced reactions for the p-nuclei (Z= 34 to 80) will be quite interesting from astrophysics point of view and focus on the further details of the theoretical calculations for p-nuclei. Similarly, it will be also interesting to extend the cross section measurements for the astrophysical s-process and r-process which are responsible for the synthesis of the heavy elements above the iron nuclei and the calculations of nuclear reaction rates for these nuclei. Furthermore, the cross section measurements for short-lived nuclei are a major challenge for nuclear physics and astrophysics. In general, the cross section measurements are performed using direct methods that involve incident neutrons or protons and stable target combinations. However, in the case of short-lived nuclei the cross sections must be determined using indirect methods and several indirect methods have been mentioned including the surrogate reaction method, the Trojan Horse approach, Coulomb dissociation, asymptotic normalisation coefficient, and the Oslo and β-Oslo method for cross sections measurements. Therefore, in future research work, it will be also interesting to extend the cross section measurements for the short lived nuclei.