Chapter 7

Summary & Conclusion

The measurement of neutron induced reaction cross section was performed within the neutron energy range of 1 to 20 MeV for the reactor-based application and reported in the present study. The cross section of proton induced reactions was reported for the application of reactor and astrophysics within 1 to 16 MeV of proton energy in the present study. The experiment for the neutron induced reactions has been performed using the neutron activation analysis (NAA) technique via offline γ-ray spectrometry at 16 UD BARC-TIFR Pelletron Facility, Mumbai, India. The HPGe detector of p-type is used for the γ ray counting. The neutrons of the desired energies were generated using ^{7}Li(p, n) reactions. The experiment on proton induced reaction was performed using the stacked foil activation technique with the same experimental facility and the detector setup of the neutron irradiation experiment. The theoretical calculations were performed using statistical model codes TALYS, EMPIRE and ALICE using the latest version of the codes. The comparison of obtained experimental results shows good agreement with the previously published experimental data of EXFOR, with available evaluated data library, and theoretical calculations.

Further, the theoretical study has been carried out for the deuteron induced reactions for some chemical elements of the periodic table which have importance in the field of nuclear physics and technology as well as in nuclear medicines. The latest versions of nuclear model codes TALYS, EMPIRE, and ALICE have been utilized for the cross section calculation. The cross section was also calculated using the (d, 3n) empirical formula of Y. Kavun (2020) at 20 MeV of deuteron energy. The theoretically calculated cross sections were compared with the value of cross section calculated by Y. Kavun's formula and the EXFOR database and show good agreement with each other.

7.1 Neutron induced reactions

The cross sections of ^{115}In(n, n')^{115m}In, ^{232}Th(n, f)^{97}Zr, and ^{238}U(n, f)^{97}Zr reactions are reported for 16.63 ± 0.95, 12.47 ± 0.825, 8.96 ± 0.77, and 5.08 ± 0.165 MeV of neutron energies. While the cross sections of ^{197}Au(n, 2n)^{196}Au reaction were reported at 12.47 ± 0.825, 8.96 ± 0.77 MeV of energies. The theoretical calculations of TALYS were performed using all the six-level density models but the best-fitted model was adopted for the comparison. The cross sections of ^{232}Th(n, f)^{97}Zr, and ^{238}U(n, f)^{97}Zr reactions were calculated using the available sample file of TALYS-1.9. The conclusion is stated below.

- The measured cross sections of ^{197}Au(n, 2n)^{196}Au, ^{232}Th(n, f)^{97}Zr, and ^{238}U(n, f)^{97}Zr reactions are compared with the recent experimental data extracted from the EXFOR data library, with other available standard evaluated libraries such as ENDF/B-VIII.0, JEFF-3.3, JENDL-4.0, CENDL-3.1, IRDFF II, and TENDL-2017, and TALYS data. While the cross sections of ^{115}In(n, n')^{115m}In reaction is compared with the EXFOR database and theoretical predictions of TALYS-1.9.
- The measured cross-section data follow the general trend of the existing experimental data and theoretical predictions of TALYS-1.9.
- It may be concluded that the present data shows an overall satisfactory agreement with available experimental data of the EXFOR database as well as with theoretical predictions.
- The studied reactions are widely used as neutron flux monitor reactions for the estimation of neutron flux in the NAA technique.

7.2 Proton induced reactions

Cadmium has been chosen for the proton induced reaction. A stacked foil activation technique followed by off-line γ-ray spectroscopy was used to carry out the present work. The proton flux was calculated by keeping the current constant throughout the experiment.

The uncertainty in the cross section was measured using the quadratic sum of the partial statistical and systematic errors which is found to be $\leq$ 10 %. ^{114}Cd(p, γ)^{115m}In, and ^{114}Cd(p, n)^{114m}In reactions have been studied for the nuclear reactor and astrophysical applications for up to 16 MeV of proton energy. ^{112}Cd(p, γ)^{113m}In reaction has been studied for the astrophysical energy range. The astrophysical S factor has been also calculated for these reactions. Theoretical calculations were performed using Hauser-Feshbach (HF) statistical model calculations of the latest version of TALYS. Further, the cross section of ^{110}Cd(p, n)^{110g}In, and ^{110}Cd(p, 2n)^{109}In reactions have been measured for 14.14 MeV of proton energy for reactor applications. A theoretical study has been carried out for ground and metastable state populations of (p, n) and (p, 2n) reaction channels by utilizing the nuclear model code TALYS-1.95, EMPIRE-3.2.3, and ALICE-2014. The conclusion drawn from the analysis is as follows:

- A multidisciplinary work is carried out in the field of nuclear reactors and astrophysics by measuring the cross sections for ^{114}Cd(p, γ)^{115m}In and ^{114}Cd(p, n)^{114m}In reactions for three different proton energies, 14.26 $\pm$ 2.03, 10.18 $\pm$ 2.15, and 4.90 $\pm$ 2.40 MeV in the laboratory frame. The astrophysical S factor was also determined for all three energies in the centre-of-mass frame. The presently measured data are compared with 96 different combinations of the TALYS models and it is found the measured data are in good agreement with available experimental data of the EXFOR database and with the data obtained from nuclear model code TALYS -1.95 for both reactions. The present work will enhance the nuclear data library of proton-induced nuclear reactions for reactor applications. Also, the present work is a contribution to the astrophysical p process which is one of the important process to understand the formation of neutron deficient isotopes.

- The cross-section and S-factor values were measured at 4.86 MeV of proton energy for ^{112}Cd(p, γ)^{113m}In reaction and compared with the 96 combinations of the TALYS models. The measured cross-section data point as well as the astrophysical S-factor lie in the shaded region of TALYS-1.95 and are in good agreement TENDL-2019 library.

- The activation cross section was measured for ^{110}Cd(p, n)^{110g}In, and ^{110}Cd(p, 2n)^{109}In reactions at 14.14 $\pm$ 2.03 MeV of proton energy and compared with the phenomenological and microscopic level density model of TALYS, and EMPIRE as well as with the default model of ALICE. For ^{110}Cd(p, n)^{110g}In reaction, the phenomenological BFM model of TALYS was modified with the level density and spin-cut-off parameter which shows good resemblance with presently measured data, EMPIRE data, and with previously reported data of EXFOR. Further, to achieve a good resemblance of measured data with a microscopic model, the combination of HFB LD + FHMS + Lorentzian ver. 3 γ SF of EMPIRE was adopted. A systematic study has been carried out for metastable state and total cross section for ^{110}Cd(p, n)^{110}In reaction using TALYS, EMPIRE, and ALICE codes, and comparison with previously reported data shows good agreement. Further, the data produced using a default model of ALICE-2014 code are under/over-predicted for the reaction. The cross section ratio (σ_g/σ_m) has been also studied theoretically for the ^{110}Cd(p, n)^{110}In reaction which shows a compound nucleus mechanism.

7.3 Deuteron induced reaction

The cross sections of ^{112}Cd(d, 3n)^{111}In, ^{141}Pr(d, 3n)^{140}Nd, ^{167}Er(d, 3n)^{166}Tm, ^{197}Au(d, 3n)^{196}Hg and ^{209}Bi(d, 3n)^{208}Po reactions were predicted using theoretical model codes such as TALYS-1.95, EMPIRE-3.2.3, and ALICE-2014 within the incident deuteron energy range of threshold energy to 50 MeV. The cross section of all the reactions was also calculated with the newly developed (d, 3n) formula of Kavun (2020) at 20 $\pm$ 1.5 MeV of deuteron energy. These results were compared with the previously reported experimental data of the EXFOR database. The conclusion drawn from the analysis is as follows:

- For ^{112}Cd(d, 3n)^{111}In reaction, the results of TALYS, EXFOR and Y. Kavun's empirical formula are more compatible. However, the EMPIRE predicts slightly lower values but shows the same trend as other results. Predictions of ALICE are well matched at lower energy ranges and lower predicted for higher energy ranges. For ^{141}Pr(d, 3n)^{140}Nd reaction, all the predictions show the same trend and the data of TALYS and EXFOR are quite compatible. For the ^{167}Er(d, 3n)^{166}Tm reaction, more compatible results were obtained up to around 20 MeV. The (d, 3n) Y. Kavun (2020) formula for the ^{197}Au(d, 3n)^{196}Hg and ^{209}Bi(d, 3n)^{208}Po reactions gave slightly higher values and deviated a little from the theoretical and experimental values.
- Overall, the cross section value obtained from Y. Kavun's empirical formula shows more resemblance with TALYS data and the EXFOR data. EMPIRE code predicts cross section values lower compared to TALYS and EXFOR data. Predictions of the

ALICE code are well-matched at lower energy with TALYS and EXFOR data, but it predicts a lower value for the increasing energy.

- This study is important for validating the data and determining the accuracy of the reaction models. Although it is difficult to understand these processes, their study is increasing day by day.

7.4 Future plans

In the present thesis, the reaction cross sections were calculated for incident neutrons up to 20 MeV and for the incident proton up to 16 MeV of energy for the reaction where data are scarce or discrepancy in data is observed. Some of the reactions are not explored yet or the previously published data are very old so similar work can be carried out for those reactions. Also, the data on neutron induced reactions are not available for the several isotopes, especially for the unstable isotopes and the research work will be carried out for those isotopes.

Further, the charged particle and neutron induced reactions can be studied for the astrophysical processes for Gamow energy range at the high current and low energy accelerators. So, the neutron induced reactions will be considered to understand the astrophysical s & r processes, while charged particle induced reactions will be studied to understand p process. The exploration of the astrophysical parameters are important for these processes. Also, the simulation of proton energy degradation and detector efficiency can be performed using the MCNP and GEANT4 simulation tool kit.