CHAPTER 8

Summary and Conclusions

The development of ADS systems and advanced reactor programme requires significant amount of new and improved nuclear data in extended energy regions as well as for a variety of new materials. Nuclear data of actinides, minor actinides and fission products are also crucial in international formulation of radioactive transport regulations. These requirements demonstrate the immediate need for experimental research, the result of which would be incorporated with the basic nuclear data.

In the present thesis, the yields of various fission products in the neutron-induced fission of ^{232}Th have been determined using recoil catcher and off-line gamma-ray spectrometric technique with average energies of 5.42 MeV, 7.75 MeV and 10.09 MeV. The present measured yields of the different fission products in the neutron-induced fission of ^{232}Th with average energies of 5.42 MeV and 7.75 MeV have been compared with the similar data of mono-energetic neutrons of comparable energy from literature and are found to be consistent. The effect of nuclear structure on fission products yields as a function of neutron energy has been examined.

The ^{232}Th(n, γ) ^{233}Th reaction cross-section has been determined using an activation and off-line γ-ray spectrometric technique at average neutron energies of 3.7±0.3 MeV, 5.9±0.6 MeV, 9.85±0.38 MeV and 15.5±0.7 MeV. Further, the ^{232}Th(n, 2n) ^{231}Th reaction cross-section has also been determined at average neutron energies of 9.85±0.38 MeV and 15.5±0.7 MeV using the same technique. The neutron beam was obtained from the ^{7}Li(p, n) reaction by using the proton beam main line at 6 meter above the analyzing magnet of the BARC-TIFR Pelletron Facility to utilize the maximum proton current from the accelerator.

^{233}Pa is an important intermediary in the thorium based fuel cycle and thus its fission cross section is a key parameter in the modeling of AHWR and ADS. Therefore, the ^{233}Pa($2n_{th}$, f) cross-section has been experimentally determined using a fission track-technique. The radiochemical separation of ^{233}Pa from irradiated Thorium Nitrate was performed at Radiochemistry Division, Radiological Laboratory (RLG), B.A.R.C, Mumbai, India.

The $^{94}Zr(n,\gamma)^{95}Zr$ and $^{90}Zr(n,p)^{90}Y^{m}$ reaction cross-sections have been measured at neutron energies (E_n) of 2.45 MeV and 9.85 ± 0.38 MeV (average) using activation and off-line γ-ray spectrometric technique. The "thermal neutron" activation cross-sections of $^{94}Zr(n,\gamma)^{95}Zr$ and $^{96}Zr(n,\gamma)^{97}Zr$ reactions were also measured using the same technique. The experiments were carried out using APSARA reactor, Purnima Neutron Generator at BARC and at BARC-TIFR Pelletron facility, Mumbai, India.

The measured cross-sections have been generated theoretically using nuclear model based computer code TALYS 1.2 and compared with experimental data. Further, the experimentally measured neutron cross-sections data were also compared with latest available evaluated nuclear data libraries from ENDF/B-VII, JENDL 4.0, JEFF 3.1 and TENDL 2010.

The present experimentally measured neutron-induced reaction and fission cross-section data have been compiled into IAEA-EXFOR data base. In addition to this, the Indian experimentally measured nuclear physics data from various Indian laboratories and Institutions have also been compiled into IAEA-EXFOR database as per NDS, IAEA guidelines and requirements.

The following conclusions have been drawn from the entire present work:

- The yields of seven, fourteen and sixteen fission products in neutron-induced fission of ^{232}Th at average neutron energy of 5.42 MeV, 7.75 MeV and 10.09 MeV were determined using recoil catcher and off-line gamma ray spectrometric technique. The yields of fission products at average neutron energy of 10.09 MeV were determined for the first time.

- The experimentally measured fission yield data at average neutron energy of 5.42 MeV, 7.75 MeV and 10.09 MeV are in general agreement with the neutron-induced fission data of ^{232}Th for mono-energetic neutron of 5.9 MeV, 7.6 MeV and 8.0 MeV, respectively.

- The yields of fission products around mass number 134 -135, 139 -140 and 144 -145 and their complementary products are slightly higher than the yields of other fission products. This shows the effect of nuclear structure even at higher neutron energy.

- The $^{232}Th(n, \gamma)$ reaction cross-sections are determined for the first time using the neutron activation technique at average E_n = 3.7±0.3 MeV, 5.9±0.6 MeV, 9.85±0.38 MeV and 15.5±0.7 MeV whereas the $^{232}Th(n, 2n)$ reaction cross-section was re-measured at average E_n = 9.85±0.38 MeV and 15.5±0.7 MeV using the same technique.

- The experimental $^{232}Th(n, \gamma)$ reaction cross-sections from present work are in good agreement with the evaluated data from ENDF/B-VII, JENDL-4.0 and JEFF-3.1 at average E_n = 3.7±0.3 MeV, 5.9±0.6 MeV, 9.85±0.38 MeV and 15.5±0.7 MeV. For the $^{232}Th(n, 2n)$ reaction cross-section at average E_n = 9.85±0.38 MeV and 15.5±0.7 MeV, the experimental value lies within the range of the evaluated data.

- The $^{232}Th(n, \gamma)$ and ^{232}Th (n, 2n) reaction cross-sections are calculated theoretically using TALYS 1.2 code and found to be consistent with the experimentally measured data.

- The experimentally measured $^{232}Th(n, \gamma)$ reaction cross-section at E_n = 14.5 MeV by Perkin at all, is now excluded since the measurement at E_n = 15.5 MeV gives more reasonable results.

- The measurement of $^{232}Th(n, \gamma)$ reaction cross-section at E_n = 7 or 8 MeV becomes mandatory in the future to better constrain the model which will have an impact also on evaluations since they are largely based on TALYS calculations.

- The $^{233}Pa(2n_{th}, f)$ cross-section has been experimentally determined for the first time using a fission track-technique. It was found to be 4834±57 barns.

- The $^{233}Pa(2n_{th}, f)$ cross-section was found to be 4834±57 barns, which is significantly high and thus it is very important for ^{232}Th-^{233}U based fuel in advanced heavy water reactors (AHWR) and accelerator driven sub-critical systems (ADS).

- The $^{233}Pa(2n_{th},f)$ cross section was calculated theoretically using the TALYS 1.2 computer code and found to be in good agreement with the experimental value after normalization with respect to $^{241}Am(2n_{th}, f)$.

- The $^{233}Pa(2_{nth}, f)$ fission cross-section has immense importance from a neutronics and physics point of view for the design of AHWR and ADS.

- The $^{94}Zr(n,\gamma)^{95}Zr$ reaction cross-sections is measured for the first time at neutron energy of 2.45 MeV using neutron activation and off-line γ-ray spectrometric technique.
- The $^{94}Zr(n,\gamma)^{95}Zr$ reaction cross-section at neutron energy of 2.45 MeV is higher than JENDL 4.0 and lower than ENDF/B-VII, while it is in fair agreement with TENDL 2010.
- The $^{94}Zr(n,\gamma)^{95}Zr$ and $^{96}Zr(n,\gamma)^{97}Zr$ reaction cross-sections are re-measured at thermal neutron energy. The experimentally measured cross-sections for the $^{94}Zr(n,\gamma)^{95}Zr$ and $^{96}Zr(n,\gamma)^{97}Zr$ reactions at thermal neutron energy are found to be very close with the evaluated data from ENDF/B-VII, JENDL 4.0 and TENDL 2010.
- The measured $^{90}Zr(n,p)^{90}Y^{m}$ reaction cross-sections at average neutron energy of 9.85 ± 0.38 from the present work is found consistent with data available in IAEA-EXFOR database .
- The present measurements have added new data points to the existing database.
- The author has contributed more than 30 new Indian Exfor entries in IAEA-EXFOR database as required by NDS, IAEA.
- The IAEA-EXFOR nuclear data compilation of the Indian experimental nuclear physics data will be continued in future as an important task of NDPCI.

Future Outlook:

Determining reaction cross sections on unstable nuclear species is a major challenge for nuclear physics and nuclear astrophysics. Many of these nuclei are too difficult to produce with currently available experimental techniques or too short-lived to serve as targets in present day set-ups. Some nuclear reactions will remain un-measurable even at upcoming and planned radioactive beam facilities. It is therefore important to explore alternative methods for determining reaction cross sections on unstable nuclei. Therefore, the research will be carried out in the framework of the "Surrogate Nuclear Reaction Technique", an indirect method for determining compound-nuclear reaction cross sections. Surrogate experiments employ reactions different from but related to the desired reaction and can thus often avoid the difficulties associated with extremely short-lived target nuclei. The design of nuclear reactors capable to incinerate minor actinides requires a good knowledge of neutron-induced cross sections. However, the enormous specific activities of these nuclei complicate the direct measurements of these cross sections. Therefore, the surrogate reaction technique can be used to measure the neutron- induced reactions of these actinides.