Chapter 6

Summary, Conclusions and Future work

6.1 Summary and Conclusions

The accurate knowledge of the cross section and excitation function of neutron induced reactions are of interest from different perspectives such as nuclear reaction theory (models), fission and fusion reactor technology, reactor design and control, neutron fluence monitoring, neutron therapy (medical), activation and prompt radiation analysis and nucleo-synthesis in stars. Thus neutron capture cross section data becomes not only important for the studies of nuclear reaction mechanisms and astrophysics, but also for nuclear technology applications. Further, compound nuclear cross sections for reactions involving neutrons and light charged particles on target nuclei across the isotopic chart, with energies ranging from a few keV to tens of MeV are also important in many of the above mentioned applications.

The basic structure of the present thesis is to study of neutron induced reaction cross section measurement for fusion-fission reactor materials. The measurement studies were covered in the fast neutron energy region in between 0.6 to 20 MeV. In the present thesis work, the cross sections of (n,γ), (n,2n) and (n,p) reactions of structural and first wall materials were studied using the neutron activation analysis technique followed by offline γ-ray spectroscopic technique. The target materials for the studies were isotopes of W, Zr, Nb, Sr and Rb materials which are prime candidate materials for plasma facing components, superconducting magnets, shielding, cladding and structural materials in fusion-fission reactors and also used on Accelerator Driven Subcritical Systems (ADSS). Theoretical calculations for the reactions were also done by selection of various nuclear reaction models. The quasi monoenergetic neutrons of desired energies were produced by ^{7}Li(p,n)^{7}Be reaction. The experimental work of neutron energies 0.6 to 3.2 MeV was performed at facilities available at FOTIA-BARC and neutron energies of 10 to 20 MeV were performed at BARC-TIFR Pelletron facility.

The summary of the present thesis work is as follows:

- The spectrum averaged cross section ^{186}W(n,γ)^{187}W reaction was measured at averaged neutron energies of 0.61 ± 0.01 , 2.11 ± 0.02 and 3.13 ± 0.02 MeV relative to

^{115}In(n,n')^{115m}In monitor reaction cross section. Multiple cross section values were reported in this energy range but no cross section data available with uncertainties, covariance and correlation matrix. The uncertainties in the cross section values were obtained by covariance analysis and found to be within the range of 8 – 20 %. The measured results were consistent with the previously reported data and are in good agreement with ENDF/B-VIII.0 and EMPIRE 3.2 data.

Measurement of ^{90}Zr(n,2n)^{89}Zr and ^{90}Zr(n,p)^{90m}Y reactions cross section

- The ^{90}Zr(n,p)^{89m}Y reaction cross section was measured at 10.95 ± 0.45, 13.97 ± 0.68, 16.99 ± 0.53 and 20.02 ± 0.58 MeV energies. The ^{115}In(n,n')^{115m}In reaction was used as monitor reaction. The details of uncertainty propagation from various attributes in the activation formula have been performed using covariance analysis. The uncertainties with covariance analysis were found within limit of 15-25 %. The present results were found in good agreement with both the previously reported and evaluated data. TALYS 1.9 and EMPIRE-3.2.2 with optimized input parameters were used for the comparison, in which TALYS-1.9 results were found to be in good agreement with the measured results.

- The ^{90}Zr(n,2n)^{89}Zr reaction cross section was determined at 13.97 ± 0.68, 16.99 ± 0.53 and 20.02 ± 0.58 MeV energies relative to ^{27}Al(n,α)^{24}Na monitor reaction cross section. The cross section values of ^{90}Zr(n,2n)^{89}Zr reaction were reported with uncertainties, covariance and correlation matrix. The uncertainties with covariance analysis were found within limit of 14-16 %. The measured cross section values are consistent with the earlier published data, evaluated data from ENDF/B-VIII.0, JENDL-4.0, JEFF-3.3 and ROSFOND-2010 libraries and predicted data using codes TALYS-1.9 and EMPIRE-3.2.2.

Measurement of ^{93}Nb(n,2n)^{92m}Nb and ^{88}Sr(n,2n)^{87m}Sr reaction cross sections

- The ^{93}Nb(n,2n)^{92m}Nb reaction cross section was measured at average neutron energies of 13.97 ± 0.68 and 20.02 ± 0.58 MeV relative to ^{27}Al(n,α)^{24}Na monitor reaction cross section. The uncertainties in the cross section measurements were found within the range of 4-5 %. Theoretically the cross section was calculated by using different level density models in TALYS 1.9 code. The comparison of the reaction cross section

indicates that the results are underestimated compared with the literature data, evaluated data and predicted data by the TALYS-1.9 code.

- The ^{88}Sr(n,2n)^{87m}Sr reaction cross section was calculated experimentally at averaged neutron energies of 13.97 ± 0.68 and 16.99 ± 0.53 MeV. The uncertainties in the cross section measurements were found within the range of 6-7 %. The cross section value at 13.97 ± 0.68 MeV was consistent with the reported data and TALYS 1.9 data while at 16.99 ± 0.53 MeV, the cross section value was in good agreement with the JENDL/AD-2017 and TALYS-1.9 data.

Measurement of ^{85}Rb(n,p)^{85m}Kr and ^{85}Rb(n,2n)^{84m}Rb reactions cross section

- The cross section of ^{85}Rb(n,p)^{85m}Kr reaction was determined at average neutron energies of 12.97 ± 0.51, 15.72 ± 0.60, 16.73 ± 0.66 and 18.99 ± 0.74 MeV relative to ^{27}Al(n,α)^{24}Na reference monitor reaction cross section. The uncertainties in the cross section were found within the range of 5-7 %. The present results were overestimated with the previously reported data and evaluated data from JENDL-5 and EAF-2010.

- The cross section of ^{85}Rb(n,2n)^{84m}Rb reaction was determined at average neutron energies of 12.97 ± 0.51, 15.72 ± 0.60, 16.73 ± 0.66 and 18.99 ± 0.74 MeV. The uncertainties in the cross section were found within the range of 6-8 %. The reported data for ^{85}Rb(n,2n)^{84m}Rb reaction was scattered from threshold to 20 MeV neutron energies. The measured cross section values were in accordance with the reported data and overestimated with the evaluated data and TALYS-1.9 data.

6.2 Future Work

Measurement of nuclear reaction cross sections for reactor and astrophysical applications.

The cross section data for several structural and actinide materials have been determined using different methods for use in both fusion and fission applications. However, not all required data can be directly measured or calculated due to certain difficulties. For example, the energy regime relevant to a particular application is often inaccessible. Similarly, the given reaction might involve unstable nuclei as targets which are either difficult to produce or they are short-lived. Theoretical calculations too have their limitations.

One of the prime examples in the field of nuclear astrophysics in which compound nuclear reaction cross section plays a crucial role in the understanding of the synthesis of heavy elements (A>56) by s- and r- processes. There is also nuclei that are a group of stable nuclei heavier than Iron that lie on the neutron deficient side of the stability valley between ^{74}Se and ^{196}Hg. Several studies have been carried out on cross section measurements of proton capture reactions relevant to the p-process. Similarly reliable rates for neutron reaction along the s-process path are important input parameters for stellar models; for example neutron capture on s-process branch points. In the case of r-process, model predictions require neutron capture rates for nuclei far off from stability. The cross sections for both compound and direct capture mechanisms are required. Efforts have been made by different groups for such measurements, for example, Wallner et al. had reported precise measurement of (n,γ) cross sections on ^{54}Fe using accelerator mass spectroscopy.

Among the several indirect methods that have been employed in the past two decades, the complementary method called the surrogate nuclear reaction method has evolved as a very useful and reliable method for determining the cross section for compound nuclear reactions that involve difficult-to-produce targets. In a compound reaction, target and projectile nuclei combine to form a highly excited, intermediate system, the compound nucleus (CN), which subsequently decays. The formation and decay of a CN are considered to be independent of each other in first order (''Bohr hypothesis''). In the surrogate method, experimental information on the decay of the required CN (B*) occurring in the reaction of interest (a + A s B*s c + C) is obtained by producing the compound nucleus (B*) via an alternative, ''surrogate'' reaction (d + D s b + B*) that involves a projectile-target combination (d + D) that is experimentally more accessible.

The decay of the compound nucleus thus formed is observed in coincidence with the outgoing direct reaction particle (b in this case). This surrogate approach, originally introduced in 1970's has received renewed attention in the recent times and a large number of surrogate experiments aimed at obtaining (n,f), (n,γ), (n,x) cross sections have been carried out over the years. The kinetic energy of the neutron is related to the excitation energy of the compound nucleus (E_{ex}) via $E_n=(1+1/A)(E_{ex} - S_n)$, Here S_n is the neutron separation energy of nucleus $^{A+1}$Z. The compound nucleus formation probability can be calculated using neutron-nucleus effective interaction with reasonable accuracy and decay probability is constrained by experiment.

In this study, we propose to measure the reaction cross section by direct neutron irradiation as well as by the complementary method, the surrogate nuclear reaction method, which aims at

determining reaction cross sections for compound-nuclear reactions that involve difficult-to-produce targets.