Measurement of reactivity in sub-critical reactors using neutron noise methods

By

Rajeev Kumar

(Enrolment No: PHYS01201004014)

Bhabha Atomic Research Centre, Mumbai

A thesis submitted to the

Board of Studies in Physical Sciences

In partial fulfillment of requirements

For the Degree of

DOCTOR OF PHILOSOPHY

Of

HOMI BHABHA NATIONAL INSTITUTE

May, 2016

Homi Bhabha National Institute

Recommendations of the Viva Voce Board

As members of the Viva Voce Board, we certify that we have read the dissertation prepared by **Rajeev Kumar** entitled ***"Measurement of reactivity in sub-critical reactors using neutron noise methods"*** and recommend that it may be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

PKrishnani.

Date: 23/09/2016

Chairman- **Prof. P. D. Krishnani**

Date: 23/09/2016

Guide / Convener- **Prof. S. B. Degweker**

Amar Sinha

Date: 23/09/2016

Member 1- **Prof. Amar Sinha**

Date: 23/09/2016

Member 2- **Dr. H. P. Gupta**

C. Prabhakar Reddy

Date: 23/09/2016

Member 3- **Prof. C. P. Reddy**

OPsingh

Date: 23/09/2016

External Examiner- **Prof. Om Pal Singh**

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to HBNI.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it may be accepted as fulfilling the dissertation requirement.

Date: 23/09/2016

Place: Mumbai

Prof. S. B. Degweker

(Guide)

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at Homi Bhabha National Institute (HBNI) and is deposited in the Library to be made available to borrowers under rules of the HBNI.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Competent Authority of HBNI when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

Rajeev Kumar

Rajeev Kumar

DECLARATION

I, hereby declare that the investigation presented in the thesis has been carried out by me. Whenever contributions of others are involved, every efforts is made to indicate this clearly with due reference to the literature and acknowledge of collaborative research and discussions. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

Rajeev Kumar

Rajeev Kumar

List of Publications arising from the thesis

Journal

1. **Kumar Rajeev, Ali Y. and Degweker S.B. et al., (2015),** Development and testing of Neutron Pulse Time Stamping Data Acquisition System for neutron noise experiments, Nuclear instruments and methods in physics research A 770, 8–13.

2. **Kumar Rajeev, Degweker S.B., Singh K.P. et al., (2016),** Measurement of sub-critical reactivity in a heavy water reactor by neutron noise methods using a time stamping data acquisition system, Annals of nuclear energy 87, 720-727.

3. **Kumar Rajeev, Degweker S.B. et al., (2016)**, Measurement of reactivity in source driven deep sub-critical system using neutron noise methods. *(Communicated to Annals of nuclear Energy)*

Conferences

4. **Kumar Rajeev and Degweker S.B., (2011),** Reactor physics experiments in PURNIMA sub-critical facility coupled with 14 MeV neutron source, 2nd International conference on ADS and thorium utilization, Dec. 11-14, Mumbai, India.

Rajeev Kumar

Rajeev Kumar

DECLARATION

I, hereby declare that the minor corrections suggested by the examiners have been incorporated.

Dr. S.B. Degweker

(Guide)

Dedicated

To

All my Teachers

ACKNOWLEDGEMENTS

First of all I would like to express my deep and sincere gratitude to my thesis supervisor and teacher, Dr. S.B. Degweker for his invaluable guidance, constant encouragement and keen interest. I am also thankful to him for his patience during technical discussions and clarifying my doubts all through these years.

I sincerely thank Dr. P.D. Krishnani, Ex-Head, Reactor Physics Design Division for his support in my research work. I thank the members of the doctoral committee Dr. Amar Sinha, Dr. H. P. Gupta and Dr. C. P. Reddy for their critical review and suggestions during the progress review and pre-synopsis viva-voce.

Thanks are due to Shri V.M. Jolly, Shri S.K. De, Shri Sharad Verma and technical staff of AHWR critical facility for the support rendered by them in the experiment carried out in critical facility. I also thank to Dr. Tushar Roy, Shri Tarun Patel, Miss Saifali Bajpayee, Shri P. S. Adhikari, Shri Nirmal Ray and technical staff of BRAHMMA facility for their help in the experimental work.

I thank Dr. Y. S. Rana and Dr. K. P. Singh for the technical support in the research work and their help during writing of the thesis. I also thank my divisional colleagues Dr. Umasankari, Shri Amod K. Mallick for their help in the computer programming and data analysis. Thanks are also due to Shri M. Kusberker, Electronics division for providing the help in the electronics. Finally, I would like to thank my wife Asmita Sharma for her personal support throughout these years.

CONTENTS

SYNOPSIS

Experimental reactor physics is an essential element of reactor physics and plays an equally important role in the safe design and operation of nuclear reactors, as its theoretical counterpart. Approximations in modelling the reactor using various computer codes and the uncertainty in the nuclear data that goes as input into these codes contribute to the uncertainty of the theoretically computed design parameters. Reactor physics experiments provide estimates of the uncertainty in the design by comparing the measured and computed values of these parameters. Measurement of criticality related data through critical and exponential experiments and comparison between measured neutron flux and spectra with calculations are some of the methods used for validation of various computer codes used in reactor design. Integral experiments in critical test facilities allow adjustment of evaluated nuclear data of important isotopes involved in the fuel cycle as well as of structural and other materials used in nuclear reactors. Another important feature of experimental reactor physics involves measurement of reactor kinetics parameters, such as neutron lifetime, the delayed neutron fraction and the sub critical reactivity.

Sub-critical reactivity measurement / monitoring is important in assessing criticality safety margins of fissile material as it goes through various stages in the fuel cycle. It is also important in power reactors (under shut down conditions) as well as in future accelerator driven systems (ADS). ADS are attracting increasing worldwide attention due to their superior safety characteristics and their potential for burning actinide and fission product waste and energy production. India has an additional interest in ADS that is related to thorium utilization for power production. Thorium has an added advantage that it produces much less quantities of long-lived radioactive waste as compared to uranium fuel cycle.

Accurate monitoring of sub-critical reactivity (Munoz-Cobo et al., 2001) value is one of the central operational and safety issues of a future ADS. Considerable theoretical and experimental efforts are being devoted in developing methods for measuring and monitoring the sub-criticality of ADS. The fission power in ADS is directly proportional to the neutron source strength and inversely proportional to the degree of sub-criticality. To get a high power, the sub-criticality should be low. However if the reactor is operated too close to criticality, it may go critical due to addition of reactivity during operating transients such as decay of Pa^{233} to U^{233}. The reactivity variations under no circumstances should lead to criticality. Thus, sub-critical reactivity monitoring is an essential requirement for ADS operation. It decides not only the accelerator current that will be required to produce the desired power but also the margin of safety available. Therefore there has been renewed interest in methods for measuring/monitoring the sub-criticality in sub-critical systems using neutron noise techniques (Kitamura et al., 2006; Szieberth et al., 2015;Taninaka et al., 2011 a,b; Yamamoto, 2015, 2014; Becares et al., 2013).

Several low power experiments have been performed for evaluating various methods (deterministic as well as stochastic) for measuring the sub-critical reactivity MASURCA (Soule et al., 2004; Plaschy et al., 2005; Lebrat et al., 2008), YALINA thermal and booster (Gohar et al., 2009; Persson et al., 2008; Tesinsky et al., 2011), KUCA (Pyeon et al., 2007, 2008; Taninaka et al., 2011 a,b) and GUINEVERE (Uyttenhove et al., 2011; Mercatali et al., 2010). In India also, a zero power accelerator driven system BRAHMMA (Beryllium oxide Reflected

And HDPE Moderated Multiplying Assembly) (Sinha Amar et al., 2015) was commissioned recently for such experiments.

Deterministic methods of reactivity measurement involve some degree of interference with the reactor operation, which may lead to undesirable operational effects in power reactors. Reactivity meters (Shimazu et al., 2003; Shimazu and Tsuji, 2001; Shamzu and Naing, 2005) based on inverse kinetics can also be used to measure the reactivity and they do not interfere with the system operation. But such reactivity meters require calibration with respect to the critical state and may not usable in ADS since the ADS always remain sub-critical. In this context, the application of neutron noise techniques for sub-criticality measurement is viewed as a better option since these techniques are passive and do not interfere with the operation of the reactor (Behringer and Wydler, 1999; Munoz-Cobo et al., 2001).

Though the neutron noise methods are well established and have long been used for measurement of reactor kinetics parameters of critical reactors, there are some issues involved in context of the ADS. One issue is the statistical properties of the neutron source. Unlike the source due to radioactive decay present in ordinary reactors, the accelerator produced neutron source in ADS cannot be assumed to be a Poisson process. It was first pointed out by Degweker (2000, 2003) that a new theoretical approach is required to describe neutron noise in ADS. A considerable amount of theoretical work (Pazsit and Yamane, 1998; Pazsit et al., 2005; Degweker, 2000, 2003) has been carried out for understanding neutron noise in ADS and its application to measure the degree of sub-criticality. In this context, the statistical properties of an accelerator based DT reaction neutron source were measured by us and were found to be non-Poisson. (Kumar and Degweker 2011).

Another issue is the contribution of delayed neutrons and delayed photo neutrons in the reactivity measurement in heavy water moderated reactors using noise methods. Unlike light water reactors, there is significant overlap in correlation time scales of prompt neutrons and delayed / delayed photo neutrons in heavy water reactors. This issue has not been addressed in depth experimentally.

Space dependence of neutron noise method is also an issue in reactivity measurement. A general formalism based on the stochastic transport equation (Pal, 1958; Bell, 1965; Munoz Cobo et al, 2011) is commonly used to describe space dependence of noise. The space dependence of noise is often interpreted in terms of the presence of higher harmonics in the source driven sub-critical system. It was shown by Rana and Degweker (2013) that the auto correlation function shows contamination due to various higher modes if the detector locations are not chosen carefully.

The experimental work done by Rugama et al., (2002) shows that higher modes of the neutron flux contribute to the detector response. This contribution is more significant for lower K_{eff}. The effect of detector location on prompt neutron decay constant was observed experimentally. It was concluded that the contribution of higher moments of the flux must be considered and impact of these moments must be investigated. But no solution was suggested to eliminate or minimise this effect. The effect of multiple alpha modes was also discussed in the experiment carried out recently in YALINA and DELPHI sub-critical facility (Berglof Carl et al., 2011; Szieberth Mate et al., 2015).

Compared to the large number of theoretical noise studies, there has been little experimental work done in this direction and there is a need to address the issues mentioned above. The work in this thesis is an effort to address the issues discussed above, viz., the issue of modal effect in reactivity measurement using neutron noise methods in deep sub-critical systems and the effect of delayed/ delayed photo neutrons in reactivity measurements in heavy water systems. The solutions to these problems represent the main new contributions of this thesis.

With regard to the problem of reactivity measurements in heavy water moderated reactors, we describe experiments carried out in a sub-critical heavy water moderated reactor (Kumar, Degweker et al., 2016 a). The effect of delayed/ delayed photo neutrons in reactivity measurement and ways to account for these effects is explained in detail.

Toward the solution of the modal effects, observed by Rugama et al., (2002), we demonstrate a method for minimising the modal effects in experiments designed to measure the reactivity of a deep sub-critical system using neutron noise methods. The measurement (Kumar, Degweker et al., 2016 b) was carried out in the highly sub-critical assembly BRAHMMA where the estimated sub-criticality is more than 100 mk (Sinha Amar et al., 2015). This includes theoretical modelling of the sub-critical assembly BRAHMMA for the calculation of higher modes, the k_{eff}, and other kinetic parameters of the assembly. We also present a comparison between measurements and calculations, which shows quite good agreement.

The experiments described above also required a considerable amount of preparatory developmental work related to detectors and instrumentation. The main work in this area is the development and testing of a "Neutron pulse time stamping data acquisition system" (Kumar, Ali Y. et al., 2015) that enables analysis by any of the noise techniques from a single set of acquired data.

The thesis is divided into seven chapters as follows.

Chapter 1. Introduction

Chapter 1 starts with the importance of experimental reactor physics particularly the measurement of reactivity in critical and sub-critical reactors. We discuss the need of sub-criticality measurement in the context of accelerator driven systems and during fuel loading/other related scenarios in multiplying media. A brief introduction to the ADS concept is given. We discuss various stochastic and deterministic methods of reactivity measurement. A discussion on the comparative advantages / disadvantages of neutron noise methods (stochastic methods) over deterministic methods is included. We touch upon various issues involved in reactivity measurement using neutron noise methods. Finally we present two of our contributions in the area of reactivity measurement using noise methods viz., the elimination of modal effects in deep sub-critical systems and accounting for the delayed/delayed photo neutron effect in heavy water reactors.

Chapter 2. Reactivity measurement methods and review of the work done in neutron noise

A brief description of various deterministic and stochastic methods to measure the sub-critical reactivity is presented. The pulsed neutron source methods (PNS), including slope fit and area ratio analysis and the source jerk method are described among the deterministic methods. The Feynman alpha, Rossi alpha and Auto correlation function methods are described among the stochastic methods (neutron noise methods).

The theoretical and experimental work related to reactivity measurement in sub-critical systems carried out in recent years around the world (MUSE, KUCA, YELINA and many more) is reviewed. Various issues involved in these methods and the latest developments in this area are discussed. The non-Poisson characteristic of the accelerator based neutron source, which is one of the differences in critical reactor and ADS noise, is discussed briefly. We also describe the measurement carried out by us to study the statistical properties of DT reaction based neutron source (Kumar and Degweker 2011).

We also discuss the undesirable space dependent effects on reactivity measurements of sub critical systems, recent work carried out related to this modal effect is also reviewed.

Chapter 3. Development and testing of Neutron Pulse Time Stamping Data Acquisition System

This chapter describes the development of the hardware and software for the neutron pulse time stamping data acquisition system (Kumar, Ali Y. et al., 2015). Development of this data acquisition system provides us the ease of data analysis by any of the noise methods with a single experiment. We begin with a brief description of the traditional methods of data acquisition in noise and passive neutron assay (PNA). These include methods such as various combinations of gate generators, delay lines, (Boehnel K. et al., 1978; Dytlewski N., Krick M.S. et al., 1993) the shift register, the variable dead time circuit (Lambert K. and Leake J. 1979; Birkhoff G., Bondar L. et al., 1972) and neutron count frequency distribution analysers including MCS cards for the variance to mean method. Thus each of the analysis methods has its own characteristic data acquisition setup and the electronics modules required for data acquisition is specific to the method used for data analysis. This means that the entire experiment must be repeated with a different electronic setup if it is desired to perform the analysis using another method.

Due to the availability of very fast electronics these days, it is possible to capture the entire time history of the neutron pulse train. It means that the stored time history of detected neutron pulses can be processed offline to perform the analysis by any noise method. It also means that a single set of experimental data can be analysed using any of the methods which simplifies the measurement process. We describe the development of a neutron pulse time stamping data acquisition system using the commercially available multi channel counter/timer card NI-6602 (www.ni.com). The card has wider functionality; therefore, customization of the card as per our requirement is described in which development of an application programming interface (API) is discussed. As expected, its utility goes beyond neutron noise studies and the system is useful in other fields like the passive neutron assay (PNA) for fissile material estimation.

We also present the performance testing of the data acquisition system by using two neutron sources that are statistically different. These are a random Poisson source (Pu-Be) and a correlated source (a nuclear reactor). The neutron sources are characterised by two noise descriptors; one is the Feynman alpha function and the other is the Auto correlation function. The experiment was carried out in the AHWR critical facility. The details of the experimental setup and specifications of the data acquisition system are given. Data analysis was carried out using these two different noise methods and the statistical properties of both the neutron sources were found as per expectation. It is concluded that performance of the data acquisition system is satisfactory. Application of the system in experimental studies of statistical properties of DT neutrons is described in the last section of the chapter.

Chapter 4. Measurement of reactivity in heavy water reactors

India has an interest in the development of Uranium-Thorium fuelled ADS including heavy water moderated thermal ADS (Degweker et al., 2013). Measurement of sub-criticality using neutron noise methods in heavy water reactors is more cumbersome than in light water reactors.

The reason is that in light water systems there is no overlap between the correlation time scales due to prompt neutron chains and those due to delayed neutrons. Data analysis is simple since only prompt neutron correlations are involved and the contribution of delayed neutrons (including delayed photo neutrons) can be ignored. But in heavy water systems there is a significant overlap between correlation time scales of prompt and delayed neutrons/ delayed photo neutrons. Therefore, in the case of heavy water reactors, contribution of delayed neutrons and delayed photo neutrons has to be accounted for a complete and correct data analysis. Relatively little work has been done in the area of experimental determination (Gotoh, 1964) of sub-criticality in heavy water systems using neutron noise methods.

In Chapter 4, the scope of reactivity measurement using neutron noise methods is expanded to heavy water systems. Reactivity was measured at various sub-critical levels in a natural uranium fueled and heavy water moderator reactor. The experiment was carried out in the AHWR critical facility (Raina V.K., Srivenkatesan R. et al., 2006). A complete description of the experimental setup and procedure is given. We also give a detailed description of the Feynman alpha and Auto correlation function method including the treatment for delayed neutrons and delayed photo neutrons. The zero power transfer function is discussed. Decay constants corresponding to correlation of prompt and delayed neutrons are obtained from a solution of coupled equations of the transfer function and its residues. Mathematically, both these noise descriptors are functions of reactor kinetics parameters like reactivity, delayed neutron fractions, neutron generation life time, and efficiency of the detector, and delayed neutron precursor decay constants.

As discussed in the previous chapter the neutron counts are stored with their time stamps in the form of a time history of events by using the data acquisition system. The procedure of getting the measured values of both the noise descriptors using the stored time history of counts is explained. The value of the reactivity is inferred by fitting the measured and calculated values of the noise descriptors. The fitting procedure adopted involves solving the coupled system of equations iteratively and is discussed in detail.

Modelling of the AHWR critical facility using the transport theory code WIMS at the lattice level and the diffusion theory based code KINFIN at the core level is described. Modelling of the system provides the calculated values of the reactivity at various levels of sub-criticality and it also provides other parameters that go as input in the data analysis, such as the prompt neutron generation time and effective delayed neutron fractions etc. We present a comparison between measured and calculated values of the reactivity by both the noise methods. It is concluded that measured values of the reactivity are in good agreement with the calculations.

Chapter 5. Theoretical basis of the method for mitigation of spatial effects in reactivity measurement of sub- critical systems

The description of the Feynman alpha and Auto correlation function methods given in the earlier chapters assumes a point model. In the context of neutron noise, such a description is strictly valid for an infinite homogeneous medium and an infinite size detector distributed throughout the medium. For a finite sized medium, localised source and detector, as well as other heterogeneities, and for taking neutron energy dependence of cross sections into account, a space and energy dependent description is necessary (Munoz Cobo et al, 2011; Rana and Degweker, 2013). This space dependent effect produces modal contamination in the measured value of the prompt neutron decay constant and needs to be eliminated or accounted for in other ways.

Chapter 5 focuses on the calculational part of the work connected with the experiments for mitigating spatial effects in reactivity measurement of sub-critical systems. We begin our discussion with a brief description of the time eign value problem in a reactor. Modelling of the BRAHMMA sub-critical assembly was done by the transport theory code WIMS at lattice level and the diffusion theory based code KINFIN at core level. The calculations provide the modal flux distribution, K_{eff} and other kinetics parameters. Knowledge of the modal flux distribution is used in eliminating the modal contamination in the measurement of the prompt neutron decay constant. The parameters such as the prompt neutron generation time and effective delayed neutron fraction which go as inputs for inferring the reactivity from the measured value of the prompt neutron decay constant are also calculated.

Chapter 6. Measurement of reactivity in BRAHMMA

This chapter discusses the experimental part of the work related to reactivity measurement in the deep sub-critical system using noise methods. We start our discussion with the preparatory activities carried out for the experiment which involved characterization of the helium filled neutron detectors. Other preparatory work carried out was the development and testing of the signal ADDER. Eight neutron detectors were used in the experiment and the signals from these detectors were combined using an ADDER module. This module was prepared and tested for its performance before employing in the experiment. The contribution of higher harmonics in the reactivity measurement is minimised by choosing the detector locations according to the modal analysis carried out earlier. A detailed discussion about the choice of the detector locations is presented. A description of the BRAHMMA facility, the experimental setup and the experimental procedure are also presented. Results of data analysis by two noise methods viz., the Feynman alpha and the Auto correlation function methods are presented. Finally we present a comparison between measurements and calculations.

Chapter 7. Summary and conclusion

Online measurement/monitoring of the reactivity is a major safety concern in context of the safe operation of accelerator driven systems. Among other methods, neutron noise methods are also being considered for this purpose. Various issues are however involved in measurement of reactivity using neutron noise based methods. This includes the effect of contribution of delayed neutrons and delayed photo neutrons in reactivity measurement in heavy water reactors and modal effects on reactivity measurement in deep sub-critical systems using noise methods. These issues have been studied in detail at a theoretical level but less so at the experimental level, and much work remains to be done. The thesis describes new methods developed by us to address these issues.

A neutron pulse time stamping data acquisition system was developed for data collection in the experiments and computational tools were also developed for the data analysis by the noise methods. The data acquisition system and data analysis tools were tested by analysing the statistical properties of two types of neutron sources.

An experiment was carried out to measure the reactivity of a sub-critical heavy water moderated reactor. This experiment enriched the field of reactivity measurement by noise methods in such systems by proper accounting of the contributions from delayed neutrons including delayed photo neutrons.

We also describe the measurement of reactivity carried out in the highly sub-critical system BRAHMMA, using neutron noise methods. The modal contamination in the measurement was minimised by choosing the neutron detectors location properly based on the calculated modal flux distribution. Comparisons between measurements and calculations show agreement within experimental error bar. Comparisons between our measurement and the results of other experiments carried out in BRAHMMA by another group using different methods are also satisfactory.

Finally we give a brief description of the scope and directions for future work in this area.

References

Bécares V., Villamarín D. et al., (2013), Validation of ADS reactivity monitoring techniques in the Yalina-Booster sub critical assembly, Annals of Nuclear Energy 53, 331–341.

Behringer K. and Wydler P., (1999), On the Problem of Monitoring Neutron Parameters of the Fast Energy Amplifier, Annals of Nuclear Energy 26, 1131.

Bell G. I., (1965), On the stochastic theory of neutron transport, Nucl. Sci. Eng., 21, 390.

Boehnel K., (1978), Determination of Plutonium in Coincidence Method, KFK2203, Karlsruhe, (54/4252), 489.

Brikhoff G. Bondar L. and Coppo N., (1972), Report EUR-4801e.

Degweker S. B., (2000), Some Variants of the Feynman Alpha Method in Critical and Accelerator Driven Sub-critical Systems, Ann. Nucl. Energy, 27(14), 1245.

Degweker S. B., (2003), Reactor Noise in Accelerator Driven Systems, Ann. Nucl. Energy, 30(2), 223.

Dytlewski N., Krick M.S. and Ensslin N., (1993), Measurement variances in thermal neutron coincidence counting, Nuclear Instruments and Methods in Physics Research A327, 469-479.

Gohar Y., Aliberti, G., Bolshinsky et al., (2009), YALINA booster subcritical assembly conversion. Trans. Am. Nucl. Soc. 101, 39–40.

Kitamura Y., Taguchi K., Yamamoto A. et al., (2006), Application of variance-to-mean technique to sub criticality monitoring for accelerator-driven sub critical reactor, International Journal of Nuclear Science and Technology, vol. 2, no. 3, pp. 266 – 284.

Kumar Rajeev and Degweker S.B., **(2011)**, Reactor Physics Experiments in PURNIMA Sub Critical Facility Coupled with 14 MeV neutron source, 2nd international conference on ADS and thorium utilization, Dec. 11-14, Mumbai, India.

Kumar Rajeev, Ali Y. and Degweker S.B. et al., (2015), Development and Testing of Neutron Pulse Time Stamping Data Acquisition System for Neutron Noise Experiments, Nuclear Instruments and Methods in Physics Research A770,8–13.

Lambert K. and Leake J., (1979), A Comparison of the VDC and Shift Register Neutron coincidence Systems for - Assay, Nuclear Materials Management VII (4), 87.

Lebrat J.F., Aliberti G., D'Angelo A. et al., (2008), Global results from deterministic and stochastic analysis of the MUSE-4 experiments on the neutronics of accelerator-driven systems. Nucl. Sci. Eng. 158 (1), 49–67.

Máté Szieberth, Gergely Klujber, Jan Leen Kloosterman et al., (2015), Measurement of multiple alpha-modes at the Delphi sub critical assembly by neutron noise techniques, Annals of Nuclear Energy 75, 146–157.

Mercatali L., Serikov A., Baeten P. et al., (2010), Design study of a fast spectrum zero-power reactor dedicated to source driven sub-critical experiments. Energy Convers. Manage. 51, 1818–1825, 2010.

Munoz Cobo J.L. et al., (2001), Sub-critical Reactivity Monitoring in Accelerator Driven Systems, Annals of Nuclear Energy, 28, 1519.

Pal L., (1958), On the theory of stochastic processes in nuclear reactors, II Nuovo Cimento, 7 (Suppl.), 25-42.

Pazsit I., Kitamura Y., Wright J. et al., (2005), Calculation of the Pulsed Feynman-Alpha Formulae and Their Experimental Verification, Annals of Nuclear Energy 32, 986.

Pazsit I. and Yamane Y., (1998), The Variance-to-Mean Ratio in Subcritical Systems Driven by a Spallation Source, Ann. Nucl. Energy, 25(9), 667.

Persson C. M., Fokau A., Serafimovich I. et al., (2008), Pulsed neutron source measurements in the subcritical ADS experiment YALINA-Booster. Ann. Nucl. Energy 35 (12), 2357–2364.

Plaschy M., Destouches C., Rimpault, G. et al., (2005), Investigation of ADS Type heterogeneities in the MUSE-4 critical configuration. J. Nucl. Sci. Technol. 42 (9), 779–787.

Pyeon C.H., Hirano Y., Misawa et al., (2007), Preliminary experiments on accelerator-driven subcritical reactor with pulsed neutron generator in Kyoto university critical assembly. J. Nucl. Sci. Technol. 44 (11), 368–1378.

Pyeon C.H., Hervault M., Misawa T et al., (2008) Static and kinetic experiments on accelerator driven system with 14 MeV neutrons in Kyoto University Critical Assembly. J. Nucl. Sci. Technol. 45 (11), 1171–1182.

Raina V.K., Srivenkatesan R. et al., (2006), Critical Facility for lattice physics experiments for the Advanced Heavy, Water Reactor and the 500MWe pressurized heavy water reactors, Nuclear Engineering and Design 236, 758–769.

Rana Y. S., Singh Arun and Degweker S. B., (2013), Diffusion Theory Based Analogue Monte Carlo for Simulating Noise Experiments in sub-critical Systems, Nucl. Sci. Eng., 174, 245.

Rugama Y., Munoz-Cobo J.L., (2002), Modal influence of the detector location for the noise calculation of the ADS, Annals of Nuclear Energy 29, 215–234.

Shamzu Y., Naing W., (2005), Some technical issues on continuous sub criticality monitoring by a digital reactivity meter during criticality approach. J. Nucl. Sci. Technol. 42, 515–524.

Shimazu Y., Tsuji M., (2001), Applicability of point reactor kinetic equations for sub criticality monitoring, Proc. Nuclear Society, Spring Meeting, Cheju, Korea

Shimazu Y., Unesaki H. and Suzuki N., (2003), Sub criticality monitoring with a digital reactivity meter, Journal of Nuclear Science and Technology, vol. 40, no. 11, pp. 970-974, November.

Sinha Amar, Roy Tushar et al., (2015), BRAHMMA: A compact experimental accelerator driven subcritical facility using D-T/D-D neutron source. Annals of Nuclear Energy 75 (2015) 590–594.

Singh K.P., Modak R.S., Degweker S.B. et al., (2009), Iterative schemes for obtaining dominant alpha-modes of the neutron diffusion equation, Annals of Nucl. Energy, 36, p.1086.

Soule R., Assal W., Chaussonnet P et al., (2004), Neutronic studies in support of accelerator-driven systems: the MUSE experiments in the MASURCA facility. Nucl. Sci. Eng. 148 (1), 124–152.

Taninaka H., Atsuko Miyoshi et al., (2011 a), Feynman alpha analysis for a thermal subcritical reactor system driven by an unstable 14 MeV neutron source, Journal of nuclear science and technology, Vol. 48, No. 9,p 1272-1280.

Taninaka H., Hashimoto K., Pyeon C.H. et al, (2011 b), Determination of subcritical reactivity of a thermal accelerator driven system from beam trip and restart experiment. J. Nucl. Sci. Technol. 48 (6), 873–879.

Toshihiro Yamamoto, (2014), Higher order mode analyses of power spectral density and Feynman-α method in accelerator driven system with periodically pulsed spallation neutron source, Annals of Nuclear Energy 66, 63–73.

Uyttenhove W., Baeten P., Vanden Eynde et al., (2011), The neutronic design of a critical lead reflected zero-power reference core for on-line sub criticality measurements in Accelerator Driven Systems. Ann. Nucl. Energy 38, 1519–1526.

List of tables

List of figures

Chapter-1

Introduction

Experimental reactor physics is an essential element of reactor physics and plays an equally important role in the safe design and operation of nuclear reactors, as its theoretical counterpart. Approximations in modelling the reactor using various computer codes and the uncertainty in the nuclear data that goes as input into these codes contribute to uncertainty in the theoretically computed design parameters. Comparison of computed values of these parameters and measured values obtained from carefully conducted reactor physics experiments helps in the validation of the codes and also provides estimates of the uncertainty in the design. Measurement of criticality related data through critical and exponential experiments and comparison between measured neutron flux and spectra with calculations are some of the methods used for validation of various computer codes used in reactor design. Integral experiments in critical test facilities allow adjustment of evaluated nuclear data of important isotopes involved in the fuel cycle as well as of structural and other materials used in nuclear reactors. Another important feature of experimental reactor physics involves measurement of reactor kinetics parameters, such as neutron lifetime, the delayed neutron fraction and the sub-critical reactivity.

Measurement and monitoring of the sub-critical reactivity is very important for preventing unexpected accidents in nuclear facilities such as nuclear power reactors, fuel fabrication/ reprocessing plants and storage pools of spent fuel repositories. The subject of reactivity measurement in this area has received renewed worldwide interest in recent times. The incidents in reprocessing plant Tokaimura in 1999 (IAEA report 1999) and at Dampierre in 2001 (IAEA report 2004) have served as reminders for the need to measure / monitor the sub-criticality during core loading in power reactors and in fuel processing facilities. Another area of interest with regard to sub-critical reactivity measurement is accelerator driven systems (ADS). Developing suitable methods for reactivity monitoring in accelerator driven systems is currently an important research area of experimental reactor physics.

Accelerator driven systems are being studied around the world for energy production and for nuclear waste management. Such systems are attractive due to their superior safety characteristics as criticality related accidents can be avoided in well designed ADS. In ADS, the power is inversely proportional to the sub-criticality. To maximise the power it is desirable that ADS operation should be as close to criticality as possible. Therefore, one of the important issues related with the safe operation of ADS is the measurement and monitoring of its sub-criticality.

There are many deterministic and stochastic methods for reactivity measurement. Rod drop method, reactor period method, pulsed neutron source (PNS) [slope fit and area ratio methods], source jerk method and inverse point kinetics are some of the deterministic methods. Rossi alpha, Feynman alpha and Auto/Cross correlation function methods are among the stochastic methods. These methods will be discussed in detail in the next chapter. Various experimental studies (Soule et al., 2004; Carl-Magnus Persson et al., 2005; Pyeon et al., 2007, 2008, Gohar et al., 2009; Uyttenhove et al., 2011) have been carried out worldwide for evaluating both deterministic as well as noise methods for measuring the sub-critical reactivity.

Noise methods have the advantage of being passive i.e. they do not interfere with the reactor operation and may be viewed as a better option in some situations (Behringer and Wydler, 1999; Carta and D'Angelo, 1999; Munoz-Cobo et al., 2001). Though the neutron noise methods are well established and have long been used for measurement of reactor kinetics parameters of critical reactors, there are some unresolved issues, some of which are specific to ADS. These include the non-Poisson character of the ADS source, space dependent (modal) effects and the effect of delayed neutrons in the context of heavy water reactor systems. Compared to the large number of theoretical studies on noise in ADS (Pazsit and Yamane, 1998 a, b; Kuang and Pazsit, 2000; Behringer and Wydler, 1999; Degweker, 2000, 2003, 2007, 2010, 2011; Munoz Cobo J.L., 2008, 2011, Rana et al., 2009, 2011, 2013), there has been relatively little experimental work in this direction and there continues to be a need for more experimental work to address these issues.

The work in this thesis is an effort to address some of these issues. Specially we address the problem of modal effects in reactivity measurement using neutron noise methods in deep sub-critical systems. We also study the application of noise methods to the determination of sub-criticality in heavy water moderated systems. The solutions to these problems represent the main new contributions of this thesis (Kumar, Degweker et al., 2016 b; Kumar, Degweker et al., 2016 a). The thesis also makes a small contribution towards understanding the non-Poisson characteristic of the accelerator based neutron source (Kumar and Degweker, 2011). The thesis also describes the development and testing of a data acquisition system (Kumar, Ali Yakub et al., 2015) as a necessary pre-requisite for the experiments.

This thesis focuses on the area of reactivity measurement of sub-critical systems keeping in mind the need of accelerator driven systems in particular and hence we discuss this subject in some detail in Section 1.3. However we also briefly review the need for reactivity measurement in two other contexts, viz., nuclear power reactors and fuel processing facilities in Sections 1.1 and 1.2 respectively.

1.1 Power reactors

Measurement of reactivity in a nuclear reactor is required for monitoring shutdown margin, calibration of safety and control devices, detection of any inadvertent introduction of reactivity into the sub-critical core, quantification of the worth of fuel bundles, deciding limits on reactivity insertion by control rods etc. Also, periodic measurement of reactivity worth of control rods is one of the licensing requirements for any nuclear reactor.

Apart from normal reactor operation, monitoring of sub-criticality is required while fuel is being loaded initially in a reactor or during refueling to avoid accidental criticality of the reactor. Today there are no satisfactory methods for reactivity measurements and monitoring during core loading. In general, what is available is a system of start-up and intermediate range monitors (SIRM) that feed neutron flux signals to the safety system causing it to shut down or scram the reactor in case the amplitude of the neutron flux or the rate of increase of the flux becomes larger than specified limits. However, if the core configuration inadvertently becomes favorable for increasing the multiplication factor (Wright J., 2005), it can lead to prompt criticality. Under such circumstances the SIRM system is not good enough and it is necessary to measure the criticality during core loading to avoid a configuration that leads to an unexpected event. A suitable reactivity measurement technique when used in conjugation with suitable control electronics can help in preventing criticality accidents and can form the backbone of a criticality alarm system.

Development of an on-line, robust and in-practical technique for reactivity measurement will definitely be helpful for the safety of nuclear reactors in its various mode of operation like normal operation, fuel loading, calibration of shutdown device, in sub-critical experiments etc.

Noise methods were attempted successfully in determining the sub-critical reactivity during the core loading in PWRs in Korea (Lee E., Park D. et al., 2010).

1.2 Fuel processing facility

Apart from power reactors, the measurement of reactivity is important in fuel processing facilities. It is necessary to assess the criticality safety margins of fissile material as it goes through various stages in the fuel cycle. Recently, the topic has received attention due to incidents such as the one in Tokaimura in 1999 (IAEA report 1999) or at Dampierre in 2001 (IAEA report 2004). The criticality accident occurred at Tokaimura uranium conversion plant operated by Japan Nuclear Fuel Conversion Co., Ltd. (JCO). JCO plant processes up to 3 Te/yr of uranium enriched up to 20% in ^{235}U, which was used as fuel for the experimental fast reactor ‘‘JOYO’’ in Japan. The criticality accident occurred while pouring enriched uranium solution directly into the precipitation tank manually by buckets. The total amount of poured uranium solution was approximately seven times more than the stipulated safety limit. Furthermore, the cooling system of the tank worsened the unexpected criticality accident. The cooling water surrounding the precipitation tank reflects neutrons and makes it easier for nuclear fission to take place.

Another incident happened in France during a routine refueling of the Dampierre-4 PWR, in which, fuel assemblies were not loaded as per approved procedure. When the error was noticed near the end of the refueling sequence, the core configuration was quite different from what was intended as some of the fuel assemblies were incorrectly positioned. Under unfavorable circumstances this could have resulted in prompt criticality. Availability of some reactivity monitoring device might have avoided the accident. The two examples above illustrate the need for sub-criticality monitoring methods and explain the interest in sub-criticality measurements in this context.

Apart from critical reactors and fuel processing facilities, there is another area of interest viz. ADS, where sub-criticality measurement is important and is the focus of this thesis. The concept of ADS and the need of reactivity monitoring including various methods proposed for this purpose are discussed in the next section.

1.3 Accelerator driven systems (ADS)

Meeting the rapid increase in global energy demand is a major challenge to the world community. This large demand cannot be met by the limited fossil fuel reserves alone. Moreover there is the issue of global warming and climate change associated with emission of carbon dioxide in fossil fuel based energy. Nuclear power can make an important contribution to reducing greenhouse gases while delivering energy in increasingly large quantities required for global economic development. This has resulted in a revival of interest in nuclear energy. But production of nuclear energy through conventional critical reactors is also not devoid of problems. To be a sustainable source of energy, besides long term availability of nuclear fuel it is equally important that nuclear energy should be safe and environmentally friendly.

Presently operating reactors though fairly safe have an estimated core damage probability that is typically about 10^{-4} per reactor-year (Hill D.J etal., 1994) and there are attempts to bring it down significantly to promote large scale deployment of nuclear reactors. Various innovative reactor designs addressing the issue of safety are under development with passive safety features that significantly bring down the probability of off-site radiological consequence to the public at large.

Long term availability of fuel can be assured by breeding in fast reactors. However many countries have adopted the once through cycle rather than reprocessing and recycling the Pu in fast reactors due to their concerns with regard to proliferation. Even if one goes for the fast breeder program, the waste after reprocessing fuel contains several long lived fission products and more importantly minor actinides such as Np, Am and Cm. These are responsible for the long term radio-toxicity of the waste for over hundred thousand years. Hence there is increasing worldwide concern about the growing stockpile of high-level radioactive waste produced in nuclear reactors, which constitutes a potential threat to future generations because of its long-lived radio-toxicity.

An innovative reactor concept that is increasingly receiving worldwide interest in this context is the accelerator driven system. The accelerator driven system [for example the CERN energy amplifier design (Rubia, C. et al. 1995)] is operated as a sub-critical reactor with several passive safety features built into the design. Hence it is deemed to have superior safety characteristics as compared with critical reactors and can work as a fissile material breeder, a waste burner and as an energy amplifier. It is believed that ADS can transmute radioactive waste faster and more safely than conventional reactors and also produce energy. Thorium utilisation in ADS is another attractive feature as thorium is more proliferation resistant and the long live minor actinide component of its waste is substantially smaller.

Accelerator driven system therefore addresses many of the above concerns with respect to nuclear energy. Reflecting the worldwide interest in ADS for waste transmutation, several countries (Shvedov et al., 1997; Abderrahim et al. 2001, 2005; Kapoor, 2001; Mukaiyama et al., 2001; Gohar Y. et al., 2004, 2010) have drawn roadmaps for development of ADS. Indian interest in ADS (Degweker et al., 2010), is primarily related to the planned utilization of our large thorium reserves for future nuclear energy generation. A program for development of ADS in India was drawn up several years back (Kapoor, 2001) which includes development of a high current high energy proton accelerator, target development research and experimental and theoretical reactor physics studies on ADS. As a part of this program, a zero power accelerator driven system BRAHMMA (Beryllium oxide Reflected And HDPE Moderated Multiplying Assembly) (Sinha Amar et al., 2015) was commissioned recently for ADS related experiments and some of the experiments described in this thesis have been carried out in this facility.

1.3.1 Brief concept of ADS

The basic idea of ADS (Rubia C. et al., 1995; Kadi Y. et al., 2006) is to couple a sub-critical core with a strong spallation neutron source. Such a source produces neutrons by the interaction of high energy protons from an accelerator (LINAC or Cyclotron) on a heavy metal target such as Pb or Pb-Bi eutectic. Spallation is a nuclear reaction in which an energetic (typically 1 GeV) hadron (e.g. proton) interacts with a target nucleus producing high energy secondary particles (neutrons, protons, pions) and also leave the nucleus in a highly excited state. The high energy particles, interact with other nuclei of the target and may cause further spallation reactions or other neutron releasing reactions such as (n, 2n), (n, 3n) and fission (in case of fissionable targets). The excited nucleus de-excites by emission of additional neutrons having lower energy (typically a few MeV). While charged particles are finally absorbed in the target, the neutrons escape from the target volume and constitute the spallation neutron source. Neutrons from the source enter the sub-critical core where they undergo sub-critical multiplication as a result of fissions in the core and also produce power.

The main safety advantages of ADS are an increased margin to prompt criticality and a reduced dependence on delayed neutrons and reactivity feedbacks. The reactor need not have control rods and the power is controlled by varying the proton beam current. Because of their sub-critical operation, criticality-related accidents can be avoided in well designed ADS. These attractive features of ADS offer a great promise for effective management of nuclear waste and safe nuclear power generation.

The key advantage of ADS in using it as a transmuter/burner is that it can accommodate different types of fuel. These systems are ideally suited for burning minor actinides (MAs) (which constitute the main component of the long-lived waste) having poor safety characteristics for a critical core, such as small delayed neutron fraction, an almost zero Doppler coefficient, and a positive void reactivity effect. The enhanced safety of ADS lies in the fact that notwithstanding these poor safety characteristics of a minor actinide fuelled core, reactivity-induced transients cannot result in super criticality provided the margin to criticality is sufficiently large.

1.3.2 Requirement of sub-criticality monitoring in ADS

For commercial applications such as electricity generation, waste transmutation and fissile material breeding, the power of ADS is an important quantity. While in critical reactors the maximum power is decided by the heat removal capacity of the coolant system, the fission power in ADS is directly proportional to the external neutron source strength and inversely proportional to the degree of sub-criticality of the core (Nifenecker et al., 2003). Thus, for a given source strength (which is proportional to the proton beam current), the power output can be maximized by minimizing the sub-criticality level. However, at small sub-criticality levels, there are chances of the reactor attaining criticality due to reactivity addition under operating transients such as, temperature variation, xenon decay or decay of Pa^{233} to U^{233}. Such reactivity variations should under no circumstances lead to criticality.

Thus, monitoring of the sub-critical reactivity (Munoz-Cobo et al., 2001) is one of the central operational and safety requirement of a future ADS. In order to assure the sub-criticality of the core, a suitable reactivity monitoring system is required to determine the level of sub-criticality during the different phases of operation of ADS. The development of a reactivity monitoring system for sub-critical reactors is a major task prior to industrial scale accelerator driven systems construction.

Therefore, there has been renewed interest in methods for measuring/monitoring the reactivity in sub-critical systems. Considerable theoretical and experimental efforts are being devoted in developing methods for this purpose.

1.3.3 Reactivity measurement methods in ADS

In the context of accelerator driven systems, monitoring of reactivity should be performed on-line with a simple, accurate and robust technique. Among the available methods in experimental reactor physics, no single technique meets all these requirements (Beaten P. and Abderrahim A., 2003). Therefore a combination of different techniques has to be chosen in a way that various off-line techniques serve as a calibration method for the on-line measurement technique. Studies are being carried out worldwide towards developing suitable methods for monitoring of sub-criticality in ADS. Besides deterministic methods, noise based methods are also being evaluated for the purpose.

As an on-line measurement technique, the current-to-flux ratio as a reactivity indicator is the most simple and robust solution. The current-to-flux method, which is a deterministic method is based on the fact that in a sub-critical multiplying medium with a driving source, the flux level is proportional to the driving source intensity, hence the beam current, and the reactivity level. However, since the proportionality constant depends on a number of core-dependent parameters and detector characteristics, this current-to-flux indicator has to be calibrated on a regular basis; in other words, we can say that an absolute measurement of sub-criticality is necessary. In principal, absolute sub-criticality measurement can be carried out by any of the deterministic or stochastic methods but noise methods are viewed as a better option for this purpose which will be explained subsequently.

The pulsed neutron source methods (PNS), including slope fit and area ratio analysis and the source jerk method are some of the deterministic methods under consideration. But the problem with the deterministic methods is that employing them for reactivity measurement involves some degree of interference with the reactor operation, which may lead to undesirable operational effects in the power reactors. Another problem is that pulsing of the neutron source may have undesirable thermal cycling on the reactor components particularly in case of heavy water moderated systems. Hence these methods may be applied in fast systems but not for online reactivity measurement in thermal power reactors moderated by heavy water.

Another very popular technique of reactivity measurement among deterministic methods is based on inverse point kinetics. Reactivity meters (Shimazu and Tsuji, 2001; Shimazu et al., 2003; shamzu and Naing, 2005) based on inverse point kinetics are used to measure the reactivity. Unlike other deterministic methods discussed above, such a reactivity meter does not interfere with the system operation. But there are some difficulties associated with a digital reactivity meter for sub-criticality monitoring in ADS. For example, the applicability of the point reactor kinetic equations must be verified (or corrected for) for the system since neutron flux distribution is dependent on the degree of sub-criticality. Another limitation is that use of this technique calls for the calibration of the reactivity meter with respect to the known level of reactivity.

Stochastic methods (noise methods) have long been used (MMR Williams, 1973) to measure reactor kinetic parameters like, prompt neutron generation life time, delayed neutron fraction and sub-critical reactivity. Considering the above mentioned limitations of the deterministic methods, the application of neutron noise techniques for absolute sub-criticality measurement is viewed as a better option in comparison with deterministic methods since noise methods are passive and do not interfere with the operation of the reactor (Behringer and Wydler, 1999; Munoz-Cobo et al., 2001, Rana and Degweker 2007) and can measure the absolute value of the reactivity.

Though the neutron noise methods are well established, there are some issues involved in the context of ADS. The noise in ADS is different from that in critical reactors (Degweker 2000, 2003). One issue is the statistical properties of the neutron source. Unlike the source due to radioactive decay present in ordinary reactors, the accelerator produced neutron source in ADS cannot be assumed to be a Poisson process. It was first pointed out by Degweker (2000, 2003) that a new theoretical approach is required to describe neutron noise in ADS.

Space dependence of reactivity measurements in sub-critical systems by neutron noise methods is another major issue. The effect is more significant and serious in deep sub-critical system (Rugama et al., 2002). The space dependent effects can be viewed as the presence of higher modes of the flux distribution. In practical applications of the noise techniques in ADS, the effect of the higher order modes is a major problem.

The third issue is the contribution of delayed neutrons and delayed photo neutrons particularly in reactivity measurement in heavy water moderated reactors using noise methods. Unlike fast &light water reactors, there is a significant overlap in the correlation time scales of prompt neutrons and delayed neutrons / delayed photo neutrons in heavy water reactors. The prompt neutron kinetics cannot be clearly separated from the delayed neutron kinetics (Behringer K. et al., 1975). The effect of delayed neutrons should be considered in measurement of kinetic parameters in heavy water moderated reactors (Albrecht 1962).This issue has not been addressed in depth experimentally.

There are several similarities between the sub-criticality measurements during core loading and in ADS. To measure reactivity during core loading one needs an external source analogous to the driving source in ADS. In addition, since both systems are sub-critical, their neutron kinetic characteristics are similar. Therefore, similar reactivity measurement methods can be used for both the cases.

1.4 The scope of this thesis

The work described in this thesis generally relates to the problem of sub-criticality measurement by noise methods. The work includes major contributions in extending the scope of application of noise methods in two areas viz., reactivity measurement in source driven deep sub-critical systems (Kumer, Degweker et al., 2016 b) and in heavy water moderated systems (Kumar, Degweker et al., 2016 a).

It is demonstrated that the undesirable modal effects on measurement of the prompt neutron decay constant is very significant in a deep sub-critical system. However, it can be considerably mitigated if not completely eliminated by designing the experiment carefully as regards the number of detectors and their locations. This way, the contribution of higher modes can be largely eliminated at the stage of data collection itself. This is a better way of addressing the issue of modal contamination in comparison with other methods wherein the significant higher modes are accounted for in the data analysis by adopting a multi exponential fitting to the data (Carl Berglof et al., 2011)**.** In this latter approach, a large number of unknown parameters need to be estimated (the amplitudes and the value of alphas). Such an estimation is obviously rather difficult and the measured value of alpha may have large errors. *The method demonstrated in the thesis avoids the appearance of multiple exponentials by eliminating the higher modes from the measured data itself, and represents one of the major new contributions described in the thesis.*

The thesis extends the scope of noise methods in reactivity measurement in heavy water systems. The effect of delayed neutrons / delayed photo neutrons were included in a rigorous analysis of an experiment carried out in a zero power heavy water moderated reactor. The analysis demonstrates that there is substantial improvement in the estimated reactivity by including the effect of delayed neutrons and delayed photo neutrons. *This is the second major contribution of the thesis.*

The data acquisition system employed in the experiments reported in this work was different from the conventional electronics used in noise experiments. A "Neutron pulse time stamping data acquisition system" was developed (Kumar, Ali Yakub et al., 2015) for the purpose of the experiments. The main advantage of such a system is that it records the complete history of detected neutrons (counts) and hence permits noise analysis by any of the methods developed for this purpose using the data obtained in a single run (and hence permits inter method comparison). Earlier data acquisition systems were specific to a particular method and required not only multiple electronic systems but also required the experiment to be repeated for each method. The thesis discusses the development and testing of this data acquisition system. As an additional application of the time stamping data acquisition system, we also describe an attempt to infer the statistical properties of an accelerator based DT neutron source (Kumar and Degweker, 2011) by various methods of noise analysis using the data acquisition system. *The development of the data acquisition system and its application to study the statistical properties of the accelerator based neutron source represents the third major new contribution described in the thesis.*

Reactivity measurement methods and review of the work done in neutron noise

2.1 Introduction

Reactivity measurement of a system containing fissile material in some configuration can be carried out by employing various deterministic or stochastic methods. The pulsed neutron source methods (PNS), including slope fit and area ratio analysis, the source jerk method, digital reactivity meter based on inverse point kinetics, rod drop and period measurement are some of the deterministic methods. The Feynman alpha, Rossi alpha and Auto/Cross correlation function methods fall in the category of stochastic methods (neutron noise methods).

However, most of these methods have difficulties that have limited their use for practical in-plant applications. Many of these methods depend on absolute detector efficiency which may change with time and thereby affect accuracy. Neutron source multiplication methods and inverse point kinetics methods can only be used when the degree of sub-criticality is known in one reference reactor configuration. But the advantage of the digital reactivity meter which works on the principle of inverse point kinetics is that it can continuously give real time reactivity and it can monitor the reactivity even under transient conditions. The neutron noise analysis methods such as the Feynman alpha and Rossi alpha are traditionally used for determination of reactor kinetic parameters and can be employed for sub-criticality determination if other kinetics parameters are known. Noise methods require analysis of a certain length of a time sequence of data to estimate the sub-criticality using complicated statistical theory and may not be useful in transient state. Noise methods may suffer from large statistical errors in certain situations.

Some of the deterministic and noise methods will be described in this chapter. A more detailed review and literature survey of the theoretical and experimental work in neutron noise will also be presented as this forms the main subject of the thesis. Special emphasis is placed on the work related to reactivity measurement using noise methods in the context of ADS.

2.2 Deterministic methods

Among deterministic methods, there are two basic experimental techniques for reactivity measurement, viz., kinetic and static. Among static methods, we discuss the sub-critical multiplication method. Three types of kinetic techniques, namely, asymptotic period measurements, rod drop method and source perturbation techniques like pulsed neutron source (slope fit and area ratio methods), and the source jerk method, are discussed.

2.2.1 Neutron source multiplication method

The neutron source multiplication method (NSM) is one of the simplest and the most straightforward method for reactivity measurement. If M is the neutron count rate (in cps) measured by a detector, ε is the absolute detector efficiency, S is the intensity of the neutron source (in neutrons/s) and k is the effective multiplication factor for a sub-critical reactor then:

$$M = \epsilon S(1 + k + k^2 + k^3 + \ \ldots\ldots..) = \frac{\epsilon S}{(1-k)} \tag{2.1}$$

The sub-criticality can be determined by observing the value of M if ϵ and S are known.

However, in real situation, S serves not only the fundamental mode but contributes to the higher modes also. Thus it introduces inaccuracy into the calculations. The detector efficiency may also drift with time. Furthermore, the right hand side of the Eq. (2.1) consists of three unknowns ε, S and k. To obtain k, accurate estimates of S and ε are required. This is not easy in most circumstances. The requirement of S and ε can however be eliminated if we carry out measurement of the count rates at two different values of k (say k_1 and k_2) and take the ratio of the counts at these two levels of sub-criticality. From Eq. (2.1) we obtain,

$$\frac{M_1}{M_2} = \frac{1-k_2}{1-k_1} \tag{2.2}$$

Eq. (2.2) requires a knowledge of k at some level (called the reference level) of sub-criticality and observations of count rates at this level as well as the level for which the sub-criticality is being measured. In other words, k_1 should be known and M_1 and M_2 should be observed in order to estimate k_2. This is called calibration of the instrumentation system at some known steady state.

The modified source multiplication method (MSM) with a fundamental mode extraction was proposed by Masashi Tsuji (2013). This method consists of a two step correction process: (1) extraction of the fundamental mode from measured data and (2) importance and spatial corrections for perturbations induced in the distributions of the neutron importance field and the fundamental mode. The feasibility of the proposed method has been verified through numerical analyses. These analyses showed that the proposed method could estimate the sub-criticality accurately, although with the limitation that the neutron multiplying system was small in size and that the reactivity addition was homogeneous. The method also requires a knowledge of the reactivity of a reference sub-critical state.

2.2.2 Digital reactivity meter: Inverse point kinetic method

Conventional digital reactivity meter based on inverse point kinetic equations can continuously measure real time reactivity. It can monitor the reactivity even under transient conditions (Shimazu and Tshuji, 2001). The reactivity measurement is basically done by solving the problem that is inverse to that of solving the point kinetic equations.

The point rector kinetics equations are,

$$\frac{dn}{dt} = \frac{(\rho-\beta)}{\Lambda} n + \sum_{i=1}^{6} \lambda_i c_i + S \tag{2.3}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i c_i \ \ (\mathrm{i} = 1 \text{ to } 6) \tag{2.4}$$

Here Λ is the prompt neutron generation time, β_i , λ_i are the delayed neutron fraction and decay constant respectively in the ith delayed neutron group. ρ is the reactivity, C_i is the precursors concentration in the ith group and S is the neutron source strength (neutron per sec). The direct problem involves obtaining n and C_i as functions of time when λ_i , β_i and Λ are known and ρ is given as a function of time. Assuming that the detector counts are proportional to n, the inverse problem is to find ρ as a function of time assuming λ_i , β_i and Λ are known. This can be done by solving the precursor equations (2.4) in terms of the neutron number and substituting in (2.3). We obtain the following equations.

$$C_i = C_{i0} \exp(-\lambda_i t) + \frac{\beta_i}{\Lambda} \int_0^t \exp[-\lambda_i (t - t')] \, n(t') dt' \tag{2.5}$$

$$\frac{dn}{dt} = \frac{(\rho-\beta)}{\Lambda} n + \sum_{i=1}^{6} \lambda_i \left[C_{i0} \exp(-\lambda_i t) + \frac{\beta_i}{\Lambda} \int_0^t \exp[-\lambda_i (t - t')] \, n(t') dt' \right] + S \tag{2.6}$$

If the external source strength is small compared to the delayed precursor decay rate, the above equation [Eq. (2.6)] can be solved for the reactivity in terms of the time derivative of $n(t)$, the value of $n(t)$, and an integral over time of various values of $n(t)$. If the source is however strong then a correction term amounting to ϵS (where ϵ is the detection efficiency) will have to be added..

The formulation of point kinetics essentially assumes that the shape of the neutron flux in space and energy remains unchanged with time, which is not the case with sub-critical reactors. The shape of the neutron flux distribution changes with sub-criticality (Rubia C., 1995). Secondly, the digital reactivity meter assumes that the neutron flux distribution is in the fundamental mode of the neutron diffusion equation. In reality, the neutron flux distribution contains higher harmonics which are quite significant in a sub-critical reactor. Thirdly, it is necessary to know the accurate initial neutron source strength in order to solve the inverse point kinetic equations, which is difficult. Unlike in a critical reactor, the source term (other than fission) cannot be neglected in sub-criticality monitoring as it is the source term that gives rise to the asymptotic flux profile. Also, the fluctuation of the neutron signal measured in sub-critical system is quite large because of the low measured flux level in general.

A possible solution to the above problems was suggested by Shimazu et al., (2003). They showed that if for a sub-critical reactor a location for detector can be found out where equation (2.1) holds then the reactivity meter can calculate the corresponding sub-criticality based on the solution of the inverse point reactor kinetic equations. Such a detector location can be found out by analytical calculations in advance. The unknown neutron source strength can be estimated by knowing the flux level and sub-criticality at a stable initial condition. The fluctuation of the estimated sub-criticality can be sufficiently reduced by using appropriate filtering techniques (W.

Naing, M. Tsuji and Y. Shimazu, 2005). However, such a solution was validated for small systems where reactivity was added homogeneously. In systems, particularly large ones or those in which localized reactivity addition is expected, a more precise theory needs to be developed.

2.2.3. Rod drop method

This method is based on the change in the neutron flux due to a nearly step insertion of reactivity caused by rapid insertion of one or more rods by dropping when the reactor is in a critical state. This method is generally used for calibrating the control rods in a reactor. The control rod is suddenly dropped by a known distance into the core, causing a step decrease (prompt drop) in the reactivity. Instantaneous flux as a function of time is recorded after dropping the rod in the reactor. If Φ_0 is the neutron flux in the steady state and Φ is the value a short time after the prompt drop, when the prompt transient has died out, it follows from the reactor kinetics equations that reactivity change ρ resulting from the insertion of the rod is given approximately (Profio A.E., 1976).

$$\rho = \left(1 - \frac{\Phi_0}{\Phi}\right)\beta \qquad (2.7)$$

The rod-drop method is advantageous because it requires no extra equipment and is very quick to perform. It can easily and safely measure large amounts of reactivity. However the method has the disadvantage that the rod drop time is not instantaneous as is theoretically assumed, therefore limiting the accuracy of the method.

2.2.4. Asymptotic period measurement

The asymptotic period method is the method most frequently used to calibrate control rods (Stacey W. 2001). The reactivity of the system is related to the stable reactor period (The time required for the power to change by a factor e) through the inhour equation, derived from point reactor kinetics [Eqs. (2.3 & 2.4)]. The general form of the inhour equation which is a relation between the reactivity and the stable reactor period is given as follows.

$$\rho = \frac{l}{T_p} + \sum_{i=1}^{6} \frac{\beta_i}{1+\lambda_i T_p} \tag{2.8}$$

Here l is the neutron life time and T_p is the reactor period. All other symbols are the same as defined earlier in this chapter. The reactivity can be inferred from the measured value of the reactor period provided the values of l, β_i, and λ_i are known. For very small reactivities the period is long and the above Eq. reduces to the form

$$\rho = \frac{l+\sum\frac{\beta_i}{\lambda_i}}{T_p} \tag{2.9}$$

The reactivity is inversely proportional to the period and hence it is called “in-hour” equation.

The control rods are calibrated by the following procedure. The reactor is brought to criticality with the rod to be calibrated fully inserted. The rod to be calibrated is withdrawn a small distance and the transients are allowed to die out. The stable period is then observed from the period meter or the linear power meter. One advantage of this method is that it requires no extra equipment. Another major advantage is that the higher mode and the detector location have no effect since the higher modes are allowed to die away.

2.2.5 Pulsed neutron source (PNS) method

In a sub-critical system, it is possible to determine the reactivity of the core by analysing the response of a neutron detector after a neutron pulse is injected. Reactivity is determined by investigating the neutron flux decay during repeated injection of neutron pulses at a constant frequency. After a large number of neutron pulses, the delayed neutron precursors come into equilibrium with the average neutron flux. These delayed neutron precursors will decay at a constant rate which will produce a constant delayed neutron background, but the prompt neutrons show very fast time dependent behavior. By operating the neutron generator in pulse mode and registering the detector signals after each pulse, histograms of pulses are produced by adding data from all pulses to each other. The net result of the experiment is that we get a curve as shown in Fig. 2.1. There are two methods used for analyzing the PNS experiment namely the slope fit method (Keepin, 1965) and the area ratio method (Sjostrand, 1956). MUSE experiment (Soule et al., 2004) showed that space and energy effects may introduce some bias in the results and detailed computer simulations should be used to take into account the spatial and energy effects. The PNS experiments in YALINA (Carl-Magnus Persson et al, 2005) were found to be in good agreement with those obtained by Monte Carlo calculations. The experiments showed that the slope fit method gives better results compared to the area ratio method. However, in certain situations such as deep sub-critical system and fast system with reflector, it may be difficult to find the correct slope. The correction for spatial spread in the area ratio method was applied in the sub-criticality measurements in YALINA by Talamo et al., (2013). The method of correction was based on a recipe given in the book by Bell and Glasstone, (1970).

In the area ratio method proposed by Sjostrand, the reactivity of the system can be found using the following formula.

$$\frac{\rho}{\beta} = -\frac{A_p}{A_d} \tag{2.10}$$

Here ρ is the reactivity, β is the delayed neutron fraction, A_p is the area under the prompt neutron decay curve and A_d is the area under the delayed neutron counts (Fig. 2.1). The figure shows two different regions. The first region has a rapid variation of the flux which corresponds to the prompt response of the reactor. While in the second region the flux variation with the time is so slow that it is practically constant on the time scale shown in the figure.

The slope-fit method explores the prompt response of the reactor. After the transient due to higher modes died out, the fall in the flux is approximately given as

$$n_p = n_0\, exp(-\alpha t) \tag{2.11}$$

The prompt neutron decay constant can be obtained by fitting the fall of the flux to an exponential function. The slope of the fitted curve gives the value of the prompt neutron decay constant (α). This is why the method is called the “slop fit”. The reactivity can be inferred from the prompt neutron decay constant using the following relation, provided the calculated values of the prompt neutron generation time (Λ) and delayed neutron fraction are known.

$$\alpha = \frac{\rho - \beta}{\Lambda} \tag{2.12}$$

2.2.6 Source jerk method

The source jerk method (Keepin, 1965) is a dynamic method based on the utilisation of a time dependent external source for reactivity determination. In this technique, the external source is used to build a steady level of the neutron and population of the precursors in a sub-critical system. The source is suddenly removed from the system. Let us define the steady state neutron flux level in the core by n_0. After sudden removal of the external neutron source, the flux decreases rapidly and reaches a level n_1.The reactivity in dollars is then given by

$$\frac{\rho}{\beta} = \frac{n_0 - n_1}{n_1} \tag{2.13}$$

The efficiency of the source jerk experimental technique for assessing a sub-critical level was tested in RACE experiments (Jammes, Christian C. et al., 2006) by causing the transient through the neutron generator shutdown (SJ-Gen) and the standard source jerk technique (SJ-Cf) using the Cf^{252} source**.** Among the methods used for reactivity determination, the source jerk method provided less satisfactory results.

2.3 Stochastic methods

The temporal behaviour of neutrons in a nuclear reactor can be described as a stochastic process. The study of this stochastic process forms the subject of reactor noise. The subject is very old; indeed it is as old as reactor physics itself. The subject can broadly be divided in two parts viz., zero power reactor noise and power reactor noise.

Zero power reactor noise arises due to the inherent random interactions of neutrons with nuclei and the fission chain multiplication produced correlations. When a neutron is injected into a system from an extraneous source, it randomly undergoes a number of events such as fission, scattering, capture or detection. The time between nuclear events is a random variable. The probabilities for various events such as capture, fission etc also introduces randomness. The number of neutrons produced in the fission is also random. These neutron fluctuations caused by the above types of sources due to inherent nuclear effects are reflected in the output of a detector, monitoring the neutron population of a reactor in its steady state. These fluctuations in the detector output around a mean value are referred to as a neutron noise signal. Reactor noise methods are important because one can obtain dynamic information from measurements at steady state. The experimental methods in zero power noise have been traditionally used in measurement of reactor kinetic parameters like delayed neutron fractions, lifetimes of neutrons and reactivity etc. Similarly methods are also used in the estimation of fissile material which belong to the area of passive neutron assay (PNA) (Lestonea J.P. et al., 2002). Power reactor noise on the other hand studies the neutronic and other reactivity fluctuations associated with vibration of fuel and control rods due to turbulent coolant flow, formations and collapse of voids and temperature fluctuations, and is used for online monitoring of the health of the power plant.

Data analysis in neutron noise experiments at low power is based on neutron pulse counting. The whole counting interval is divided into a large number of small time-bins. The fluctuations in the number of counts in time-bins or the correlation between counts of neighboring time-bins are directly related to the sub-criticality of the system. Some of the noise methods particularly Rossi alpha, Feynman alpha and Auto correlation function method are described here.

2.3.1 Rossi alpha method

The method was proposed by Bruno Rossi (1944) and is based on measurement of the probability $P(t_2/t_1)dt_2$ of detecting a neutron between times t_2 and t_2+dt_2 given that there has been a detection at some earlier time t_1. While, in general, this is a function of both the time variables t_1 and t_2, for a stationary system this is a function of the time difference $\tau=t_2-t_1$. Theoretical analysis (Orndoff, 1957; Babala, 1967) shows that in the point model, the probability of detecting a neutron can be written as follows.

$$P(t_2/t_1)dt_2 = N_0 + \frac{\epsilon\overline{\nu(\nu-1)}}{2\overline{\nu}^2}\alpha\frac{k_p^2}{(1-k_p)^2}e^{-\alpha\tau} \tag{2.14}$$

where $\tau=t_2-t_1$ and N_0 is the average count rate, k_p is the prompt neutron multiplication factor, α is the prompt neutron decay constant, ε is the detector efficiency, $\overline{\nu}$ and $\overline{\nu(\nu-1)}$ are the first and second moments of the distribution of the number of neutrons in a fission respectively.

It is clear that the probability consists of two parts: the first on account of neutrons which are uncorrelated with the one observed at t_1 (the so called 'accidental' coincidences) and, the second due to neutrons which are correlated with the one observed at t_1. In the point model (valid for small systems and systems not too far from critical), it is possible to derive the following expression for this probability distribution:

$$P(\tau) = A + Be^{-\alpha\tau} \tag{2.15}$$

Where $\tau = t_2 - t_1$. The prompt neutron decay constant α is determined by fitting the measured distribution to the above function. The method works better in systems where the power is very low so that the contribution of the first term is not overwhelmingly large compared to that of the second term. At higher powers, the auto-correlation or cross-correlation function method described in this chapter performs better.

The probability is traditionally measured by the use of delayed coincidence counting circuits (Saito, 1979) but with modern fast electronics, it is possible to simply record the entire time history of counts in a detector and the required probability distribution can be obtained by an off-line analysis of the recorded data (Kumar, Ali Y. et al., 2015).

2.3.2 Feynman alpha (Variance to mean ratio) method

This method was proposed by Feynman (1956). It is a technique to determine reactor kinetics parameters from the relative variance (Variance to mean,V/m) of neutron counts collected over a period of time. For a neutron source like Am-Be, where radioactive decay events are not correlated with one another, the detected neutron counts are independent of one another. In this case the value of V/m is unity as the detected events follow Poisson statistics and remains unity irrespective of the count collection time interval (t). But in the case of neutrons coming from a correlated source such as a nuclear reactor, the statistics are different. Due to the multiplicity of the neutrons emitted in a fission event, the neutrons of a multiplying chain are correlated in time with one another and the V/m value is not equal to unity. The presence of correlations increases the variance and the value of V/m deviates from unity as per the following equation.

$$\frac{V}{m} = 1 + \varepsilon \frac{\overline{\nu(\nu-1)}}{(\overline{\nu})^2(\rho-\beta)^2}\left(1 - \frac{1-e^{-\propto t}}{\propto t}\right) \tag{2.16}$$

Here ε is the detector efficiency, ν is the multiplicity of the fission event, β is the delayed neutron fraction, *t* is the counting time interval and α is the prompt neutron decay constant approximately given by

$$\propto = \frac{\rho-\beta}{\Lambda} \tag{2.17}$$

Here Λ is the prompt neutron generation time.

The method consists of repeatedly measuring number of counts in a time interval of length t. This is used to calculate the variance (V) and the mean (m) of the number of counts in an interval of length t. The experiment is repeated for various interval lengths. The ratio V/m is plotted as a function of time interval length t.

By fitting the plot of V/m obtained from the measured data to Eq. (2.16), prompt neutron decay constant α can be obtained. Sub-critical reactivity ρ can be inferred from the measured value of neutron decay constant using Eq. (2.17) provided the value of delayed neutron fraction β and neutron generation time Λ are known. The method works best when detection efficiency is high so that the magnitude of the amplitude part of the second term is significant compared to unity.

2.3.3 Auto correlation function

The output from a neutron detector in a steady-state reactor has fluctuations in the count rate over a mean value. The Auto correlation function (ACF) Φ of the number of neutrons in the reactor at a given time (t) with that at a later time (τ) is defined as

$$\Phi(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{+T} dt(N(t)(N(t+\tau) \tag{2.18}$$

Thus we take the product of two values of N at different times separated by τ (lag) and integrate over the sample length 2T. In principle one should choose an infinite sample length but in practice, we must use a sample of finite length T which is large compared with the inverse of the longest decay time of the system and which provides enough data to yield adequate statistics. If we use $N(t) - \bar{N}$ instead of N(t) in the above equation, we obtain what is called the Auto covariance function (ACV).

$$\Phi'(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} dt((N(t) - \bar{N})((N(t+\tau) - \bar{N}) \qquad (2.19)$$

Here $\bar{N}$ is the average value of neutron counts N(t). It is shown (Williams M.M.R. 1973) that when τ is short compared to delayed neutron decay times, the point model of reactor noise gives the following expression for the Auto covariance.

$$\Phi'(\tau) = \epsilon \lambda_f \bar{N}(\delta(t) + \varepsilon \frac{\overline{\nu(\nu-1)}}{2\Lambda(\beta-\rho)} e^{-\alpha\tau}) \qquad (2.20)$$

Here λ_f is the probability of fission per unit time. All other symbols are the same as in Eq. 2.16 & 2.17. The first term is the detector noise. We see therefore that from an apparently random signal we can deduce the prompt neutron decay constant (α). By fitting the measured profile of Auto covariance function to Eq. (2.20) the prompt neutron decay constant (α) can be obtained. The sub-critical reactivity ρ can be inferred from the measured value of the prompt neutron decay constant using Eq. (2.17) provided the values of delayed neutron fraction (β) and neutron generation time (Λ) are known from calculations.

2.3.4 Other methods

A variant of the Feynman alpha method has been proposed by Bennett (1960) and is commonly referred to as Bennett variance technique. Based on computation of variance from cross-correlation of count rates in two successive time intervals, the author derived an expression for variance to mean ratio which does not diverge as the reactor approaches criticality. Similar to correlation function method, a method based on polarity correlation function has been proposed by Veltman et al., (1961) and Dragt (1966b). Other methods for measurement of prompt neutron decay constant include the interval distributions method (Babala, 1966) and the dead time method (Srinivasan, 1967; Srinivasan and Sahni, 1967). The Cf^{252} method was developed and studied intensively by Mihalczo (1974, 1990) for measuring the degree of sub-criticality.

2.4. Review of the work done in neutron noise methods

2.4.1 Early theoretical studies

Reactor noise theory deals with the time evolution of the state of a reactor. The term state of the reactor depends upon the level of description of the system under consideration. Once the state of the reactor is defined, a probability function is defined which gives the probability that the reactor is in that particular state. The evolution of the system in time is then described by the time evolution of the probability function. The theoretical approach to the problem can be classified broadly into the forward equation approach (Courant and Wallace 1947; Pluta 1962), and the backward equation approach (Pal 1958, Bell 1965). Although intuitively less obvious than the forward approach, the backward equation methodology is simpler. Other approach adopted include the Langevin methods (Moore 1963), Branching process theory (Babla 1966, Saito 1967) and the quantum Liouville Equation (Burger 1969). The point model commonly used to interpret the noise experiments is attractive since it involves a description in terms of a few parameters which can be easily measured. However a complete theory should include space and energy effects also. Point kinetics works well when we can assume that only the fundamental mode exists.

The earlier attempts made to understand the space energy dependence includes the work by Pal (1958, 1962). Matthes (1966) showed that the backward Kolmogorov equation for the space energy dependent problem is the stochastic transport equation. A complete formalism for space energy effects in reactor noise was given by Bell (1965) which includes the effect of source, delayed neutrons, detectors and anisotropic scattering. The forward equation approach to the problem of space dependence was given by Raiveski (1958) and generalized by Matthes (1962) to include the energy dependence. A more fundamental approach of deriving the equation for space-energy dependant stochastic kinetics starts from the quantum Liouville equation (Osborn and Yip 1966). A more general forward equation approach in continuous space-energy variables was developed by Degweker (1994). The Langevin method for studying the reactor noise was first introduced in the point model by Cohn (1960) and was applied for space dependent problem by Morre (1963) and developed considerably by Saito (1967).

2.4.2 Early experimental methods

Coming to experimental methods in reactor noise, the kinetics parameters are obtained by analysing the fluctuations in the output of a detector placed in the nuclear reactor. A large number of experimental and analytical techniques were developed during sixties for studying the zero power reactor noise. Some of these techniques like Feynman alpha method (Feynman 1944), Rossi alpha method (Bruno Rossi 1944), Auto correlation function, Cross correlation between detector and source signal and cross power spectral density method are there and some of them have been discussed earlier in this chapter. Also there are methods based on probability of counts like frequency distribution (Pacilio 1969), time interval distribution (Babala 1967). The dead time methods were proposed by Srinivasan and Sahani (1967) in the context of reactor noise analysis for the measurement of alpha. In these methods, a dead time circuit is introduced into the circuit before the pulse goes to the counting system. Around the same time Babala

(1966) also gave expression for the count rate and V/m ratio in the presence of non-extendable dead time.

2.4.3 Application to reactivity measurement in highly sub-critical systems

There was a considerable interest in measurement and monitoring the reactivity of highly sub-critical system in the eighties & nineties. This was mainly due to increasing concern for criticality safety margins in storing and processing facilities of fissile materials. Another reason was that experiments can be carried out in highly sub-critical systems with less concern for safety as compared to systems close to the criticality. Another advantage is that criticality data of certain actinides such as Np, Am, Cm etc. can be verified, where it may not be possible to have enough fissile material to carry out the criticality experiment. The measurement of reactivity of highly sub-critical system is difficult and most of the above mentioned techniques have been applied to systems close to critical. The reason is that flux level is very low; hence detection of the correlations is difficult. Further the flux distribution in such system is far from fundamental mode hence the method suffers from the spatial effects. Finally a calibration of the system at critical is either not available or is not valid far away from criticality.

A remedy was offered by Cf^{252} method reported by Mihalezo (1974) to have been used successfully on a wide range of sub-critical system down to a K_{eff} of 0.5. The principle advantages of the method are that it does not require the calibration near delayed critical and is independent of the efficiency of the detector and source strength. The method however requires specialized fission chamber with Cf^{252} deposited on one of the electrodes.

2.4.4 Application in non destructive assay

The subject neutron noise also finds application in passive non-destructive assay (PNA) of plutonium. Plutonium being a fissile material is strategically important. Proper accounting of the materials calls for regular checks. Being radiotoxic it is mandatory to contain it in the sealed containers. Therefore it is important to have methods to determine the quantity of materials by non destructive means. In non destructive assay, the quantity of plutonium is estimated by studying the correlations in the neutrons emitted in the spontaneous fission of Pu^{240} which is always presents to some extent. Besides safeguards, such methods can also be applied in the monitoring of plutonium contaminated wastes (Birkhoff 1985). The basic principles used in PNA are similar to those already discussed earlier for reactor noise analysis. The difference lies mainly in that self multiplication is usually much smaller in Pu samples than in reactors close to critical and therefore the chains are much smaller. Detection efficiencies have to be much higher than in reactor noise analysis. This necessitated the development of the well type high level neutron coincidence counter (HLNCC) (Sher 1980).

The dead time method is the earliest technique used for the PNA of plutonium. The method was introduced by Jacquesson (1963). The gated scalar method was later developed for Pu^{240} estimation at BNL by Sher (1980) for application in nuclear safeguard. An improved version of the dead time system, the variable dead time counter (VDC) was later built by Birkhoff (1972). Another technique based on shift register was developed by Bohnel (1975). The shift register based system essentially gives two quantities viz. the total count rate and the real coincidence count rate; the coincident counts are proportional to the quantity of Pu^{240}. The shift register technique was modified to include a multiplicity decoding unit (Swansen 1982). In this modified technique, multiplicity distribution of counts is also registered apart from total and coincidence counts. The system described by Krick and Swansen (1984) can sort multiplicity from 0 to 8.

A theory based on the super fission model was proposed by Bohnel (1985) to account for self multiplication effects. A method was developed by Degweker (1989) for deriving formulae relating measured quantities to the system parameters via the n interval PGF of detected neutrons. The technique can take care of dead time problems as well. Together with the super fission model, the n interval probability generating function (PGF) provides a sufficiently general framework for discussing every conceivable experimental situation including dead time effects. In this sense it constitutes a unified theory of passive neutron assay.

2.4.5 Reactivity measurement in sub-critical reactors

Suggestions for using the neutron noise for measuring reactor kinetics parameters were made as early as the Manhattan project and noise based methods such as Feynman alpha and Rossi alpha, among others, were further developed during the 1950s and 1960s to determine the reactivity of a sub-critical system (Saito, 1979). Neutron noise methods have been used to measure the reactor kinetic parameters in many reactor systems over the years: (Karam, 1964, 1965; Busch and Spriggs, 1994; Hashimoto et al., 1996; Wallerbos and Hoogenboom, 1998; Soule et al., 2004; Kitamura et al., 2006; Kuramoto et al., 2007). Reactivity measurement was carried out during fuel loading in the PWRs in Korea (Lee E. Park D. et al., 2010) using noise methods.

The recent interest in accelerator driven systems and the necessity of monitoring their degree of sub-criticality has created a renewed interest in noise methods for this purpose. Noise techniques have been suggested (Behringer and Wydler, 1999; Carta and D'Angelo; 1999

Munoz Cobo et al., 2001) for monitoring the sub-criticality of ADS. Since noise methods do not cause any perturbation of the system, they might be more suitable for the purpose (Degweker and Rana, 2007). A considerable amount of theoretical work (Pazsit and Yamane 1998; Degweker, 2000, 2003; Pazsit et al., 2005; Toshihiro Yamamoto 2011; 2014,2015; Jose-Luis, Munoz Cobo et al., 2011; Rana and Degweker 2013, Singh K.P and Degweker 2014) has been carried out for understanding neutron noise in ADS and its application to measure the degree of sub-criticality.

In order to develop suitable methods for measurement and monitoring the sub-criticality of ADS, low power experiments (Andriamonje et al., 1995; Soule et al., 2004; Carl-Magnus Persson et al., 2005; Kitamura et al., 2006; Bécares et al., 2013) have been carried out. Other parameters pertaining to operation of a future ADS have also been studied in FEAT and TRADE experiments (Andriamonje et al, 1995; Imel et al, 2004). The Guinevere experimental facility in Belgium has become operational (Billebaud et al., 2009). Measurements have been carried out at the Kyoto University Critical Assembly (KUCA) (Kitamura Y. et al., 2004,2006; Taninaka H. et al., 2011a,b) and also at YALINA (Gohar Y. et al 2009).

There are some issues related to the reactivity measurement using noise methods which were discussed briefly in Chapter-1. We have tried to address some of these issues in this thesis. In the following sub-section, we will review the work done by various researchers to address these issues and also mention about our contribution briefly. The review of the work related to spatial/modal effects is emphasised .

Space dependent effects

The basic point kinetics noise theory is strictly valid for an infinite homogeneous medium with an infinite detector. In a realistic neutron multiplying system, however, there exists a space and energy variation of variables; moreover the source and detector are localised. All this gives rise to space dependent effects in measurements. These effects need to be considered for correct estimation of sub- criticality.

Earlier experiments and theoretical investigations indicated the existence of multiple alpha modes in sub-critical systems (Karam, 1964; Busch and Spriggs, 1994) and was explained by the two-region kinetics model (Avery, 1958; Cohn, 1962). A theory has also been developed for the Feynman alpha method with two energy groups (Pál and Pázsit, 2012) and two geometry regions (Anderson et al., 2012; Chernikova et al., 2014). In the case of Rossi alpha, it is known that an arbitrary number of alpha-modes can be incorporated as a series of exponentials by formulating the time-dependent Boltzmann equation as an eigenvalue problem (Borgwaldt et al., 1965). As proposed by Kuramoto et al., (2007), the relation between the alpha modes and the reactivity is non-linear at deep sub-criticality. Hence, obtaining the reactivity value from noise measurements with multiple alpha modes is not a straightforward task. If modal contamination due to higher harmonics is not addressed in noise experiment, faulty conclusions regarding the reactivity might be drawn.

In near-critical systems, the ratios of contribution of the higher order modes to that of the fundamental mode become small. In this case, the effect of the higher order modes is insignificant. On the other hand, α values measured by the Feynman alpha method differ from the fundamental mode α value as the sub-criticality becomes larger (Misawa et al.,1990). This is due to the fact that the ratios of contribution of higher order modes to that of the fundamental mode are large and the effects of the higher order modes become significant. Therefore, for accurate estimation of sub-criticality, it is important to identify the effects of higher order modes in a sub-criticality measurement and apply suitable corrections for the same.

The space dependence of neutron noise was investigated by Rugamma et al., (2002) in a source-driven sub-critical system. The prompt neutron decay constant was measured and it was found to be dependent on the detector location because of the influence of higher modes of the neutron flux. The observation was supported by coupled LAHET/MCNP–DSP simulations and a simplified one-group, two-dimensional model of the ADS. Both the calculations demonstrated that higher modes of the neutron flux contribute to the detector response. It was also observed in the work that the contribution of higher modes is most significant for lower k_{eff} values. The results of this work demonstrated that care must be taken when interpreting any sub-critical measurements that rely upon the prompt neutron decay constant to determine the reactivity of an ADS. The contribution of the higher modes of the neutron flux must be considered and the impact of these higher modes must be investigated.

Determination of lambda-mode eigen value separation of a thermal accelerator driven system was carried out by Taninaka H. (2010). In such a thermal sub-critical system, a localized neutron source with the target placed in the core region, the spatial effects are significant and this results in a failure of the point kinetics model. It was suggested in this paper that from the viewpoint of practical operation of thermal ADS, it is preferable to evaluate the eigen value separation and quantify the spatial effects.

Neutron noise measurements were performed in a heterogeneous sub-critical system (Carl Berglof et al., 2011). It was shown that the traditional single alpha-mode formulations of the Rossi and Feynman alpha method were not applicable due to the presence of higher alpha modes. Formalisms taking into account multiple alpha modes were applied. Instead of a single exponential, multiple exponential fitting gave better results and three alpha-modes could be identified. In this work by Carl Berglof et al., (2011), the applicability of the multiple alpha-mode approach is verified on neutron noise data from the strongly heterogeneous sub-critical YALINA core at various sub-criticality levels. It was observed in this work that for the deep sub-critical configuration, there is a noticeable deviation from the fundamental mode.

It was pointed out by Carl Berglof et al., (2011) that care must be taken when analyzing noise experimental data from heterogeneous systems during core loading procedures and it is important to identify possible contributions from higher alpha modes. Otherwise, the analysis will give a faulty estimation of the core reactivity.

A model based on stochastic transport theory was recently proposed, allowing a thorough analytical treatment of multiple alpha-modes for both the Rossi alpha and the Feynman alpha method (Muñoz-Cobo et al., 2011). An important conclusion drawn is that in presence of the higher modes, the Feynman alpha function cannot be deduced from the Rossi alpha formula performing the double integration as done in the papers of Soule et al., (2004) and Munoz-Cobo et al., (2008). However, this has been questioned by Degweker & Rudra (2016).

The effect of higher order modes on the Feynman Y function was investigated by Toshihiro Yamamoto, (2011). It was observed that if a detector is positioned at the node of the 1st order mode, the result may be better. On the other hand, in a deeply sub-critical system, the Feynman alpha function is seriously contaminated by the higher order modes, and applying the conventional Feynman alpha formula may give an unacceptable result. In case one wishes to minimise the modal effects in reactivity measurement of ADS, one must choose the detector position properly. (Uyttenhove W. et al., 2012).

It may be possible to carry out a pulsed neutron source experiment successfully to measure the reactivity of a deep sub-critical system (k_{eff}=0.9), but noise experiments for determining alpha in such cases are likely to face difficulties in interpretation because of much greater modal contamination effects (Rana and Degweker 2013).

Higher order mode analyses of the power spectral density and the Feynman alpha function in ADS were reported by Toshihiro Yamamoto (2014). A theoretical formula that considers the effects of higher order modes of the correlated and uncorrelated components in the Feynman Y function for ADS was derived in this work.

Measurement of multiple α-modes at the Delphi sub-critical assembly by neutron noise techniques was carried out by Máté Szieberth et al., (2015). The objective of the measurements was to examine the influence of the source distribution and the detector position on the prompt neutron decay constant obtained using the different neutron noise methods. The α values obtained from a single α-fit show strong bias depending both on the detector position and on the source distribution. This is due to the presence of higher modes in the system. The higher α-modes have been observed by fitting functions describing dual α-modes.

The experimental and theoretical studies carried out so far have confirmed the undesirable effects of higher modes on reactivity measurements in sub-critical systems specially in the case of deep sub-criticality. In some of the experiments discussed above, the issue of modal effects was addressed by accounting for the effect of higher modes by using the multi exponential fitting (Carl Berglof et al., 2011). Another solution, vig. the extraction of the fundamental mode was proposed in the theoretical work of Tsuji M. et al., (2003). A better way to address the modal contamination would be to design the experiment in such a way that the effect of these higher modes can be eliminated from the measurement itself rather than taking it into account in the data analysis after the measurement.

In a recent theoretical work by Ran and, Degweker(2013) it was shown mathematically and verified by Monte Carlo simulations that it is possible to select the detector positions in such a way that the modal contamination of many of the higher modes immediately above the fundamental mode can be eliminated. This idea was implemented experimentally in this thesis. The r*eactivity of a deep sub-critical system was measured and it is demonstrated that the contamination of higher modes can be mitigated if not completely eliminated by choosing the detector locations strategically (Kumar, Degweker et al., 2016 b). This experimental demonstration is one of the major new contributions of this thesis.*

Effect of delayed neutrons in heavy water systems

Another issue is the contribution of delayed neutrons and delayed photo neutrons in reactivity measurement in heavy water moderated reactors using noise methods. Unlike light water reactors, there is significant overlap in correlation time scales of prompt neutrons and delayed neutron / delayed photo neutrons in heavy water reactors. Consequently the prompt neutron kinetics cannot be separated from that of the delayed neutrons (Behringer K., Phildius J. et al., 1975). Therefore, in the case of heavy water reactors, the contribution of delayed neutron and delayed photo neutrons must be taken into account for a complete and correct data analysis.

Measurement of neutron life time in heavy water system was carried out by Gotoh Y, (1964). In this work, the data analysis was performed over a short time interval so that contribution from delayed / delayed photo neutrons can be avoided in the data analysis. But ignoring the data on long time scales adds to the error in the measurement. The paper concluded that precision in the results can be improved by including delayed neutrons in the data analysis. This issue has not been addressed in depth experimentally and relatively little work has been done in the area of experimental determination of sub-criticality in heavy water systems using neutron noise methods. We studied this aspect experimentally in this thesis because heavy water moderated reactors , (for example one way coupled ADS) are also being considered as candidates for ADS.

One of the outcomes of this thesis is that the scope of reactivity measurement using noise methods is expanded to heavy water systems. The reactivity was measured in a heavy water moderated experimental reactor and the contribution of delayed neutrons / delayed photo neutrons was included in the data analysis (Kumar, Degweker et al., 2016 a)

Statistical properties of the neutron source in ADS

In the earlier publications (Pazsit and Yamane, 1998 a, b; Kuang and Pazsit, 2000; Behringer and Wydler, 1999), the authors assumed that the ADS source was a continuous Poisson source and that the main difference from traditional reactors was that in each source event spallation reaction produces a large number of neutrons having a multiplicity distribution with a large mean and a large second factorial moment. Such a situation is very similar to that of a spontaneous fission source and has been studied in detail by Munoz Cobo and Difilippo (1988).

However, the difference between critical reactor noise and ADS noise goes beyond the large multiplicity of spallation reaction and is due to the statistical properties of the source. Unlike the source due to radioactive decay, present in ordinary reactors, the accelerator produced neutron source in ADS cannot be assumed to be a Poisson process. One reason is the complex chain of events in the ion source, bunching & acceleration may give rise to non-Poisson statistics. Another reason is that a practical accelerator, in how so ever steady operation, is expected to show small fluctuations in current which can lead a non-Poisson distribution of the number of particles in a pulse (Degweker and Rana, 2007). The measurement of the number of protons per pulse during the TARC experiment by Abanades et al., (2002) showed clear experimental evidence of non-Poisson character of the ADS source. A second piece of evidence can be seen in the experimental study by Taninaka H. et al. (2011b). A third piece of evidence was deduced by Rana and Dgweker (2009) from the experimental data of Pazsit et al (2005). A new theoretical approach for a periodically pulsed non-Poisson source was proposed by Degweker (2000, 2003). The theory has, since then, been considerably expanded by Rana and Degweker (Degweker and Rana, 2007, 2011; Rana and Degweker, 2009, 2011).

We have tried to experimentally determine the non-Poisson characteristic of an accelerator based source. Statistical properties of DT neutrons were measured in an experiment conducted by us (Kumar and Degweker, 2011). This is the third new contribution of this thesis.

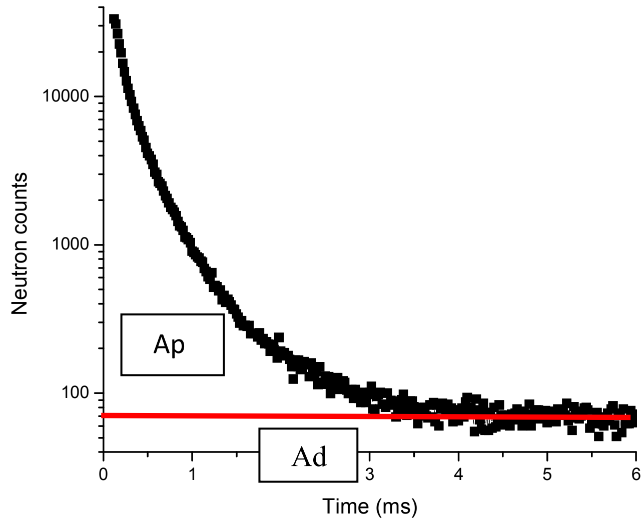

Fig. 2.1 Decay profile of Neutron counts in a PNS experiment

Chapter-3

Development and testing of Neutron Pulse Time Stamping Data Acquisition System

3.1. Introduction

As discussed earlier in Chapter-2, there are several apparently different techniques such as the Feynman alpha, Rossi alpha and Auto correlation function method which have been used for carrying out the statistical correlation analysis in neutron noise over the past decades. Very similar techniques find applications in the non destructive assay of plutonium and form the field of passive neutron assay (PNA). Correlations appear among detected pulses due to simultaneously emitted neutrons in the spontaneous fission of nuclides such as plutonium (Pu^{240}). A study of such correlations can be used to estimate the mass of plutonium and forms the subject of passive neutron assay (Lestonea J.P et al., 2002; Boehnel K., 1978). In the field of PNA, several methods such as the shift register, the variable dead time and the variance methods have been used (Birkhoff G. et al., 1972).

Traditionally the electronics modules used for data acquisition and analysis is specific to the method used for data analysis. In this chapter we describe a data acquisition scheme developed by us, which is independent of the specific analysis method and can therefore be used for all of them. Thus a single set of measured data can be analysed by any of the method and, makes measurement easier and economical in terms of efforts and cost. The neutron time stamping data acquisition system is based on a timer card and an application programming interface (API). The system has been successfully tested with two statistically different types of known neutron sources, namely a random Poisson source (Pu-Be) and a correlated source (a nuclear reactor). The description in this chapter goes beyond the development and testing of the system. We also describe the measurement of the statistical properties of an accelerator based DT neutron source as an application of this data acquisition system. As mentioned in Chapter-1&2, the neutron noise in accelerator driven systems is different than in a critical reactor noise due to the non-Poisson character of the accelerator based neutron source (Degweker 2003). For this reason, statistical properties of DT neutron source were studied experimentally by employing this data acquisition system. (Kumar and Degweker, 2011). The data acquisition system acquires and stores neutron counts with its time stamp in a continuous mode with practically no limitation on the file size. Needless to say, the utility of the system is not limited to reactor noise and it can be employed in the PNA of plutonium as well.

3.2. Data acquisition system

Due to the availability of very fast electronics these days, it is possible to capture the entire time history of the neutron pulse train. This can be stored in a computer for subsequent off line analysis. Sophisticated PCI based counter/timer data acquisition cards are available which can register each neutron pulse with its time stamp. The commercially available multi channel counter/timer card NI-6602 is used in the development of this data acquisition system. The system is described here in two parts; the hardware part gives details of the timer card while the software part gives details of an application programming interface (API).

3.2.1 Counter/timer card

This is a versatile card which can be used for a wide variety of measurement solutions including measuring a number of time-related quantities and counting events. The NI-6602 counter/timers use the NI-TIO ASIC chip specifically designed to meet the counting and timing requirements of measurement applications that are beyond the capabilities of off-the-shelf components. The wider functionality and simple programming interface make this card the best choice for counting and timing applications.

The card has a feature of buffered operation which enables it for continuous buffered event counting. It results in storing the continuous pulse train and this feature is useful in statistical analysis of count events in the time domain. That is why this card was chosen for data acquisition in the noise experiments carried out by us. An application programming interface was developed (API) to acquire and store the data in the required format.

Counter/Timers

The NI-6602 counter/timer (Fig. 3.1) devices are readily integrated into measurement systems and are software-compatible. The card offers up to eight counter/timers and up to 32 lines of 5 V TTL/CMOS-compatible digital I/O. The size of the counter is 32-bits which means that it can count up to 2^{32}-1 or 4,294,967,295 before it rolls over. The maximum source frequency is a very important parameter which represents the speed of the fastest signal the counter can count. It also decides the time resolution of the event registering devise. This card uses an 80 MHz counter clock which can therefore count pulses that are 12.5 ns ($1/80 \times 10^6$) apart, This gives a time resolution better than 0.1 micro sec. Each counter has a gate, up/down, and source signal, which can be controlled by external or internal signals. Each counter has one output that can be routed externally or to other counters on the device. 20 MHz and 100 kHz time bases are available on each device for use with each counter/timer. In addition, an 80 MHz time base is available on the NI-6602 and NI-6608 devices. A hardware trigger can be used to start multiple counters simultaneously

Buffered Operations and DMA

This card can capture numerous data points without dead times. These types of measurements, called buffered operations, are valuable in applications related to the statistical analysis. For instance, when one configures a counter for buffered period measurement, data is moved from the counter into a buffer and the event/count is registered with its time stamp. Each edge that initiates a measurement also causes a transfer of the count into the buffer, as shown in Fig. 3.2. With buffered operations; data is transferred to the computer memory using DMA (direct memory access).

Accessories

BNC-2121 (Fig. 3.3) is a connector block with BNC and spring terminal connections and is used for easy connection of I/O signals to counter/timer devices. The BNC-2121 offers spring terminals, as well as eight dedicated and six user-defined BNC connectors, which provide access to all I/O signals. This connector block is also a full-featured test accessory that provides pulse-train, trigger, and quadrature encoder signals. The dimensions of the block are 26.7 X 11.2 X 5.5 cm (8.0 X 4.4 X 2.2 in.)

3.2.2 Development of application programming interface (API)

The NI-6602 card used in the data acquisition system has wider functionality and hence it is necessary to customize it for our application. This includes proper configuration and development of an application programming interface. Such an interface has been developed to store the time stamped neutron counts in the desired format. VISUAL BASIC was used for the programming and the data is stored in ASCII format in a file. The NI card is configured in the buffered mode. The TTL pulse output from a single channel analyser (SCA) is connected to the gate of the counter and its internal 80 MHz clock is connected to the source of the counter. The resolving time of the counter is 12.5 ns. The array buffer size is set to $2X10^6$. The program requires the total time duration of data collection as an input. The data is stored using dynamic memory allocation. The programme estimates the event rate and depending upon the length of the counting period set by the user, it decides the array size to be used. At the end of the counting, the data acquired in the buffer is stored in a file. The file consists of two one dimensional arrays. The first contains the sequential neutron detection event numbers and second contains the corresponding detection event time in micro seconds. A section of a typical data record is shown in Table-3.1. The data is stored in a text file and there is practically no limitation on the size of the file that may be generated.

3.3 Advantage of the present data acquisition system

The data acquisition system described here is a better than conventional data acquisition electronics used in the noise experiments in many ways. As mentioned earlier that neutron noise as well as passive neutron assay can be analysed by several apparently different methods. Traditionally each of these methods has its own characteristic data acquisition setup. Depending on the method used for the analysis, various combinations of gate generators, delay lines, shift register coincidence circuits and variable dead time circuits (Boehnel K., 1978; Lambert K. and Leake J., 1979; Dytlewski N. et al., 1993; Birkhoff G. et al., 1972) were used in the past to acquire data in the experiments. Thus the configuration of electronics modules for acquisition of data is specific to the theoretical method used for the data analysis. This means that the entire experiment must be repeated with a different electronic setup if it is desired to perform the analysis using another method.

But the availability of a time stamping data acquisition system makes life easy. The advantage of using such a system is that the time history of detected neutron pulses can be processed offline to perform the analysis by any of the noise methods. Offline analysis also means that a single set of experimental data can be analysed using any of the methods. The ease in data analysis by various methods using this time stamping system is demonstrated here taking the Feynman alpha, Rossi alpha and Auto correlation function methods as examples.

3.3.1 Feynman alpha method

A brief description of the Feynman alpha method was given in Section 2.3.2. The relative variance which is a statistical property of the neutron source is given by Eq. (2.16) of Chapter-2. The value of α is obtained by fitting the measured value of V/m to Eq. (2.16). A typical plot of the V/m ratio is shown in Fig. 3.4. For the Feynman alpha method, traditionally, neutron counts are collected repeatedly over several time intervals each of length t. The counts recorded in each of these intervals have a statistical spread. This can be converted into a frequency distribution of counts. The variance (V) and mean (m) are obtained from this frequency distribution. The ratio V/m gives one point corresponding to the time interval t of the plot shown in Fig. 3.4. This procedure is repeated by varying the interval length (t) to get the V/m values as a function of time period t and this gives us the Feynman alpha distribution.

The use of our data acquisition system makes the experiment simpler. Neutron counts are registered with their time stamp for a long time duration (T) in one shot. To get the variance and mean for a time interval of length t, the entire data record is divided into n equal segments each of length t such that n equals T/t. The mean and variance of the neutron counts contained in these n segments are estimated and the ratio V/m is calculated. This will give the V/m ratio corresponding to a time interval of length t. The procedure is repeated using different values of t, which give us V/m as a function of t. In recent years the experiment is carried out using multi channel scalar (MCS) cards for measuring the Feynman alpha distribution which simplifies the procedure considerably. However, The MCS card performs only a single function and the data acquired using this card cannot be analyzed by other methods.

3.3.2 Rossi alpha method

In the Rossi alpha method, one seeks to measure the probability of obtaining a neutron count in an infinitesimal time interval dt_2 around time t_2 given that a count has been detected at an earlier time t_1. For the stationary situation this can be considered a function of the time difference ($t=t_2-t_1$) and expressed as a sum of random and correlated parts Eq. (2.15) as was described in Section 2.3.1.

Traditionally the probability is measured by using delayed coincidence counting circuits (Dytlewski N., Krick M.S. et al., 1993). One has to set the gate width depending on parameters like the prompt neutron decay constant of the system and the neutron count rate. The measurement has to be repeated for different values of the gate width.

However, with our data acquisition system, it is possible to record the neutron counts with their time stamp, and the probability distribution can be obtained by an off-line analysis of the time history of neutrons. Keeping the first count as a reference and treating the time of it's occurrence as zero, we observe how many counts are falling in successive time intervals [0, Δt], [Δ t, 2Δt], [2Δt, 3Δt]... and so on. The counts obtained are stored in channel numbers 1,2,3 .. and so on, where Δt is the channel width. The process is repeated treating the second count as a reference count and adding the number of counts falling in each channel to the number already present in that channel. This process is continued by changing the reference count progressively till all counts are covered. The distribution of the number of neutron counts in the channel n is proportional to the probability of occurrence of a neutron count at the time $t=(n-1/2)\ \Delta t$, given that a neutron was detected at time zero. The channel width Δt must be chosen to be small compared to the correlation time we wish to measure (inverse of α). It is also chosen to be small so that the number of counts in each bin is either zero or 1.

3.3.3 Auto correlation function (ACF)

This method is similar in principle to the Rossi alpha method, but both the recording and analysis of the data are different. Here we seek to measure the Auto correlation function (ACF) Φ of the number of neutrons in the system at a given time (t) with that at a later time (τ) and is given by Eq. (2.18) of Section 2.3.3.

Traditionally the Auto correlation function is measured using an electronic circuit which takes the neutron pulse train as input and gives the function defined in Eq. (2.18) as the output. The value of the input signal at a time t is multiplied with the value of the function at time $t+\tau$ using an AND gate. The product is then integrated over the entire time of measurement (T) using an integrator circuit. The process has to be repeated for the next value of τ. The configuration of electronic modules, their parameter setting and the data acquired is specific to this method. On the other hand using the data acquisition system described in this chapter the time history of all neutron counts is available and the Auto correlation function can be obtained by performing an offline analysis. This can be done by binning the neutron time history and using a discretised form of Eq. (2.18) given in Section 2.3.3.We write.

$$< N(t)N(t+\tau) >= \frac{1}{n}\sum_{i}^{n} N_i N_{(i+k)} \tag{3.1}$$

Where N_i represents the number of neutron counts in the i^{th} bin. If each bin is of size Δt, then $\tau = k\Delta t$. Our data acquisition system helps in doing away with the complicated electronics required to acquire the data to be analyzed by Auto correlation function methods.

3.4. Testing of the data acquisition system

Testing of the data acquisition system was carried out by studying the statistical properties of two different types of neutron sources with known properties namely a Pu-Be neutron source (random) and the zero power nuclear reactor (correlated). The Feynman alpha distribution and the Auto correlation function method are the two descriptors used to study the statistics of the neutron sources.

3.4.1 Experimental setup

For the experiment with a random Poisson source, a one mili Curi (1mCi) Pu-Be neutron source was wrapped in 5 cm of high density polyethylene (HDP) to thermlise the neutrons. The BF_3 neutron detector was placed in close contact with the wrapping. The experimental setup and the nuclear instrumentation are shown in Fig. 3.5. The BF_3 detector tube is configured in the proportional region with a HV of 1700 Volt. The detector tube is coupled to a pre-amplifier. The pre-amplifier output is sent to a spectroscopy amplifier for pulse shaping. The amplifier output is connected to a single channel analyzer (SCA) which is used as a discriminator. The output of the SCA is a TTL pulse which is fed to the time stamping data acquisition system.

For testing the data acquisition system with a correlated source, the BF_3 detector was placed in the reflector region of a zero power reactor. The reactor is a critical facility commissioned for the validation of the physics design of the thorium fuel based advanced heavy water reactor (AHWR) (Raina V.K. et al., 2006). The neutron detector tube was placed in the ion chamber housing location in the bottom reflector. The associated electronics was placed outside the reactor cavity. A schematic of the experimental setup is shown in Fig. 3.6. The electronics is the same as in the earlier case of the Pu-Be neutron source. It was ensured that the neutron count rate is not very high (<1.0e+4 per sec), so as to avoid excessive dead time loses or detector saturation. The reactor was operated at two different levels of sub-criticality, and three sets of data were taken for each level. The sub-criticality levels 1 and 2 correspond to reactivities of about -1 and -2 mK respectively. Neutron counts were collected for about 30 mins for each of the data sets.

3.4.2 Detector and electronics

The detector used was a BF_3 neutron detector tube with a sensitivity of 44 cps/nv. The health of the detector and the associated electronics was tested prior to employing it in the experiment. The details of the electronics are as follows:

1. Pre Amplifier: PEA-6, Charge sensitive (Wissel)
2. Spectroscopy Amplifier: N 968 (CAEN)
3. Discriminator: SCA 103 (FASTCOM)
4. High voltage supply: NHQ 105 M (FASTCOM)
5. Low voltage power supply (FASTCOM 7018)

3.4.3 Data analysis

The neutron counts for each data set were stored in two columns where the serial numbers of the counts form the first column and their detection times (micro sec) form the second column as shown in (Table 3.1). The last entry in the record is 25 and 6465.7, which means that 25^{th} neutron count was detected at 6465.7 micro sec.

As mentioned earlier, the data analysis was performed using two neutron noise methods, namely the Feynman alpha distribution and the Auto correlation function. The data obtained in the case of correlated (reactor) neutron source were analysed using the Feynman alpha distribution as described in Section 3.3.1 The V/m ratios were obtained for time intervals ranging from 1 mili sec upto 1 sec in steps of 1 mili sec. The range of time intervals chosen is of the order of the inverse of the prompt neutron decay constant (α^{-1}). A similar analysis was carried out for the Pu-Be neutron source with time intervals in the range of 1 mili sec to 1 sec in steps of 1 mili sec. The measured profile of the relative variance for the correlated neutron source in case of sub-critical levels 1 &2 and for the Pu-Be neutron source are given in Figs. 3.7 & 3.8.

The analysis for obtaining the Auto correlation function in the case of the correlated (reactor) neutron source was performed as described in Section 3.3.3 The time stamped neutron pulse train was divided in bins of width 10 mili sec (Δt) each. The bin width of 10 ms gave better statistics compared to that for a lower bin width of 1 mili sec. The fluctuations in the latter case were unacceptably large. It should be noted that analysis with different bin widths was possible using the same data because neutron counts were available with their time stamps (raw data). In the case of a traditional data acquisition system, if one wishes to analyse the data with a different bin width, the data has to be collected all over again. The Auto correlation function was also obtained for the Pu-Be neutron source, in which the value of τ was taken from 10 mili sec to 1 sec in steps of 10 mili sec. The measured Auto correlation functions for sub-critical levels 1 and 2 and for the Pu-Be neutron source are shown in Figs. 3.9 & 3.10. The first term in Eq. (2.20) which is a delta function is left out; only second term ($\tau \neq 0$) is plotted.

3.5 Results and discussion

Let us have a look at the statistical properties of two statistically different neutron sources used in the testing. For a neutron source like Pu-Be, where the radioactive decay is not correlated, the detected neutron counts are independent of one another. In this case the value of the relative variance (V/m) is unity as the detected events follow Poisson statistics and remains unity irrespective of the length of time interval (t) used for collecting the neutron counts. But in the case of neutrons coming from the nuclear reactor, the statistics is different. Due to the multiplicity of the neutrons emitted in a fission event, the neutrons of a multiplying chain are correlated in time with one another and the V/m value is not equal to unity. The presence of correlations increases the variance and hence the value of V/m deviates from unity. As can be seen from Eq. (2.16), the deviation increases with the count collection time (t), and saturates on a time scale of the order of the inverse of the prompt neutron decay constant. Fig 3.4 shows a plot of the relative variance against time interval as expected on the basis of Eq. (2.16).

It can be seen from Figs 3.7 & 3.8 that in the case of neutrons from the reactor (fission source), the measured profile of the V/m ratio as a function of time is qualitatively similar to the one which is expected theoretically (Fig. 3.4). In both the cases, sub-criticality level 1 and 2 (Figs 3.7 & 3.8) the value of the V/m is more than unity. This is as expected since the neutron counts are correlated due to the fission chain multiplicity and that the distribution is not Poisson in nature.

The profile of the V/m is similar at the two levels of sub-criticality which indicates reproducibility of the measurements. The maximum value of V/m is less in the case of sub-criticality level-2 compared to that at the level-1 as the reactor was more sub-critical in level-2. This is again as expected from Eq. (2.16). In the case of neutrons from the Pu-Be source the value of V/m is unity irrespective of the time interval length, which means that neutrons are not correlated with one another and follow the Poisson statistics, as is expected for a Pu-Be source.

The Auto correlation function shown in Figs 3.9 & 3.10 belongs to the two levels of sub-criticality. It can be seen that in the case of neutrons from the reactor, the Auto correlation function is non zero and falls exponentially which shows that neutrons from the reactor are in temporal correlation with one another and the correlation decreases exponentially with time. The maximum value of the ACF is less in the case of sub-criticality level-2 compared to that in level-1 as the reactor was more sub-critical in level 2. In the case of the Pu-Be source, the Auto correlation function is zero irrespective of the time interval length. This shows that the neutrons from the Pu-Be source are uncorrelated with one another. It is clear from the above discussion that the measured profiles of both, the V/m and the ACF obtained using the data acquisition system agree with what is expected from theoretical consideration in case of both types of neutron sources. This demonstrates the satisfactory performance of the data acquisition system.

3.6 Application of the system in studying the statistical properties of DT neutrons.

After getting the satisfactory performance of the data acquisition system, statistical properties of the DT neutron source were studied experimentally by employing the system. The experimental setup used for this experiment was similar to the one described above in case of the random Poisson source, except for the fact that the random Poisson source was replaced by the neutron generator (Fig. 3.11). The neutron detector was wrapped in a 1 inch thick cylindrical cavity of polyethylene to increase the response of the detector for 14 MeV neutrons emitted from the DT reaction.

Data analysis was done by Feynman alpha and Auto correlation function method. The V/m ratios were obtained for time intervals length ranging from 10 mili sec upto 1000 mili sec in steps of 10 mili sec (Fig. 3.12). It can be seen from the plot that the relative variance is deviating from unity indicating non poisson behaviour. The Auto correlation function was obtained for the values of time lag (τ) ranging from 1 mili sec to 5000 mili sec in steps of 1 mili sec (Fig. 3.13). The Auto correlation function is non zero and has a profile of an exponentially decaying sinusoidal function. Both the noise descriptors show the presence of long time correlations.

Presence of short time correlation

The presence of short time correlation (few tens of micro sec) could not be studied using Auto correlation function method. The reason is that efficiency of the detector in the given experimental set up is very low, therefore, short time correlations might be masked in the larger fluctuations of detector counts. To study the presence of short time correlations, the real and accidental coincidences [(R+A) and A] method is used. In this method, for each detected neutron, all counts falling in an interval Δt following any count are tallied in the R+A bin. Counts falling in an identical sized time interval after a long delay τ is tallied in the A bin. The first set constitutes the sum of correlated and accidental coincidences (R+A) while the second set constitutes accidental coincidences A. Subtraction the set 2 from the set 1[(R+A)-A] gives the counts due to the short time correlations (Fig. 3.14). A pre delay time (t_d) of 10 micro sec was used for each interval. In the present case, the value of τ was chosen to be 100 micro sec, and [(R+A-A)] were obtained for Δt values ranging from 10 to 100 micro sec in steps of 10 micro sec and the same are plotted in Fig. 3.15. It can be seen that short time correlations are also present, which are on the time scale of few tens of micro secs. Thus long time as well as short time correlations was found in the data analysis. Therefore, it can be stated that the statistical properties of DT neutron source are different from that of a Poisson source.

Table-3.1: A section of data file containing the time stamped neutron counts

Neutron No.	Time (micro sec)
1	90.0
2	197.5
3	424.1
4	446.2
5	834.4
6	1267.9
7	1312.2
8	1569.8
9	1905.9
10	3009.9
11	3442.0
12	3538.6

13	4228.9
14	4289.9
15	4355.3
16	4485.1
17	4505.0
18	4596.2
19	4865.9
20	4926.5
21	5002.3
22	5091.9
23	5351.8
24	5457.2
25	6465.7

Fig. 3.1 View of Ni-6602 card

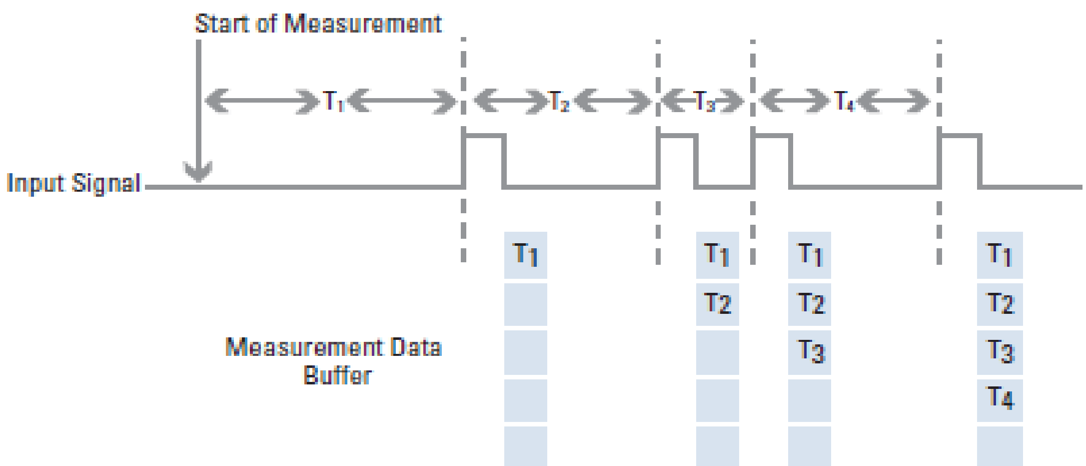

Fig.3.2 Schematic of pulses registered with time stamp

Fig. 3.3 BNC Connector block

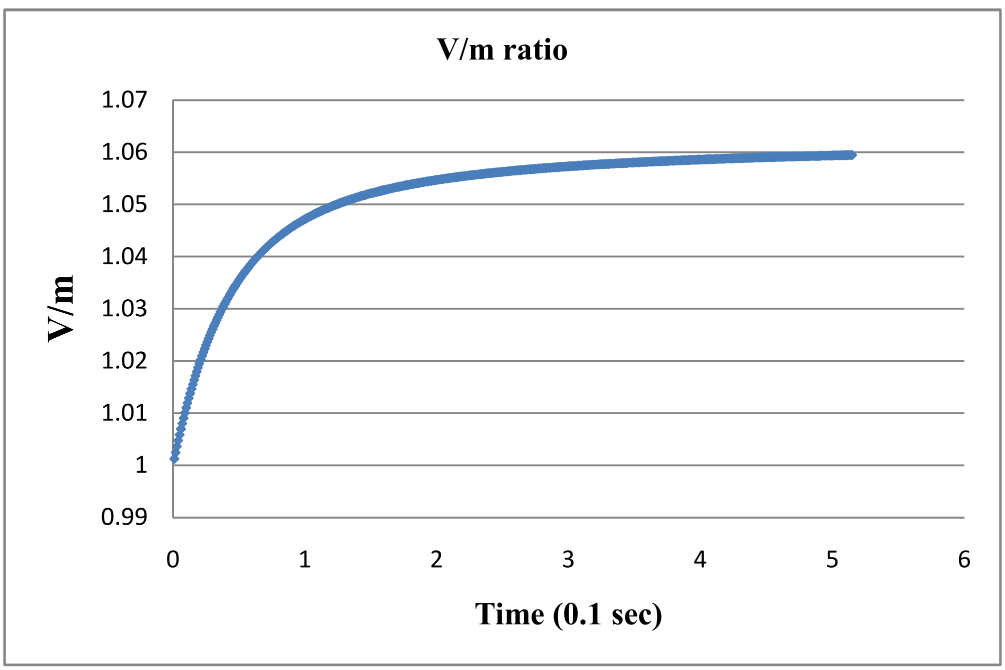

Fig. 3.4 Plot of V/m obtained theoretically from Feynman alpha distribution

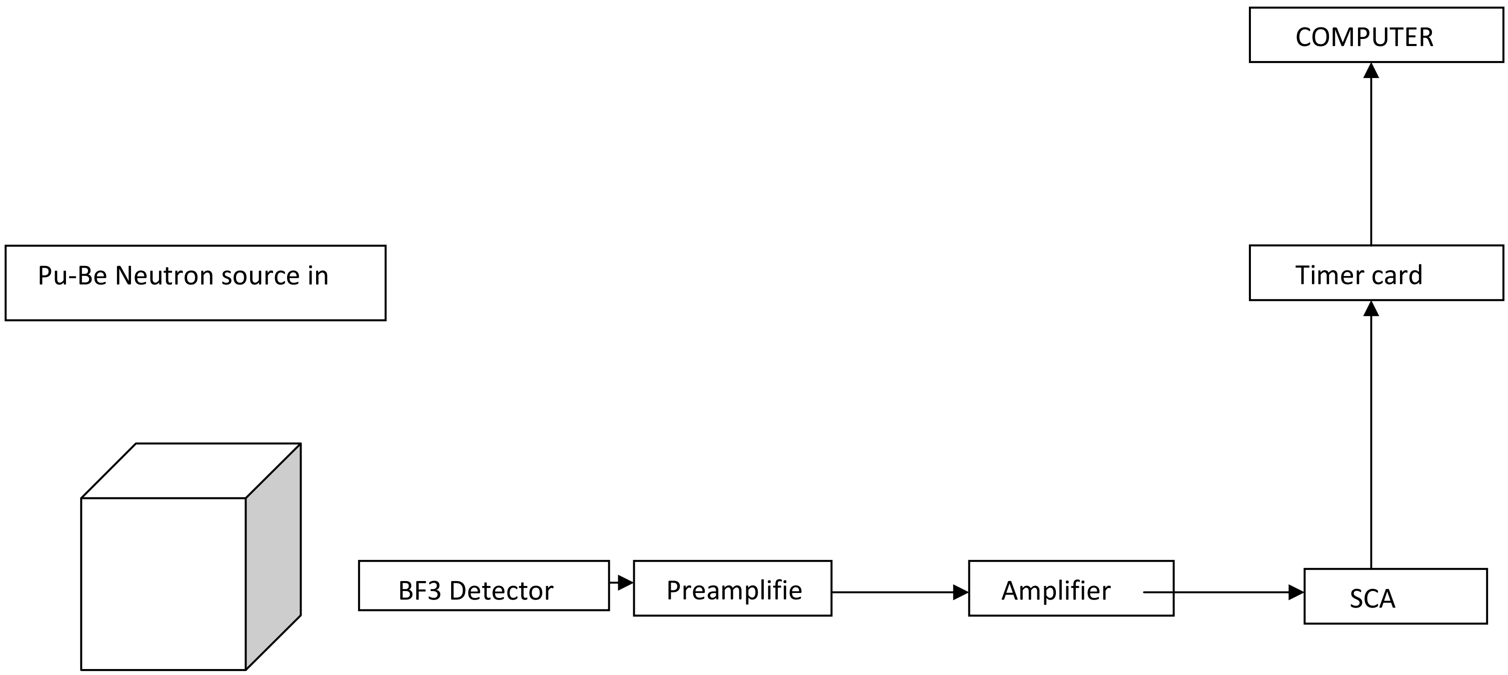

Fig.3.5 Schematic diagram of experimental setup with Pu-Be neutron source

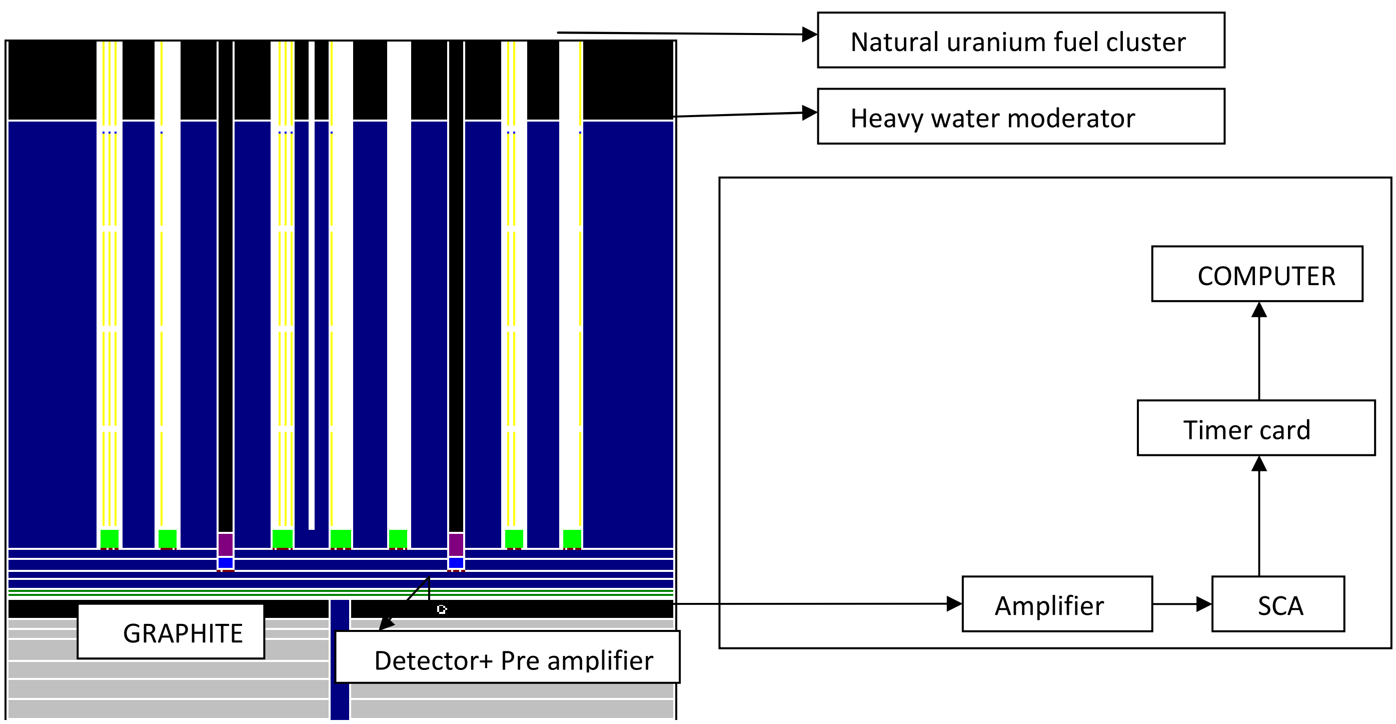

Fig.3.6 Schematic diagram of experimental setup with nuclear reactor

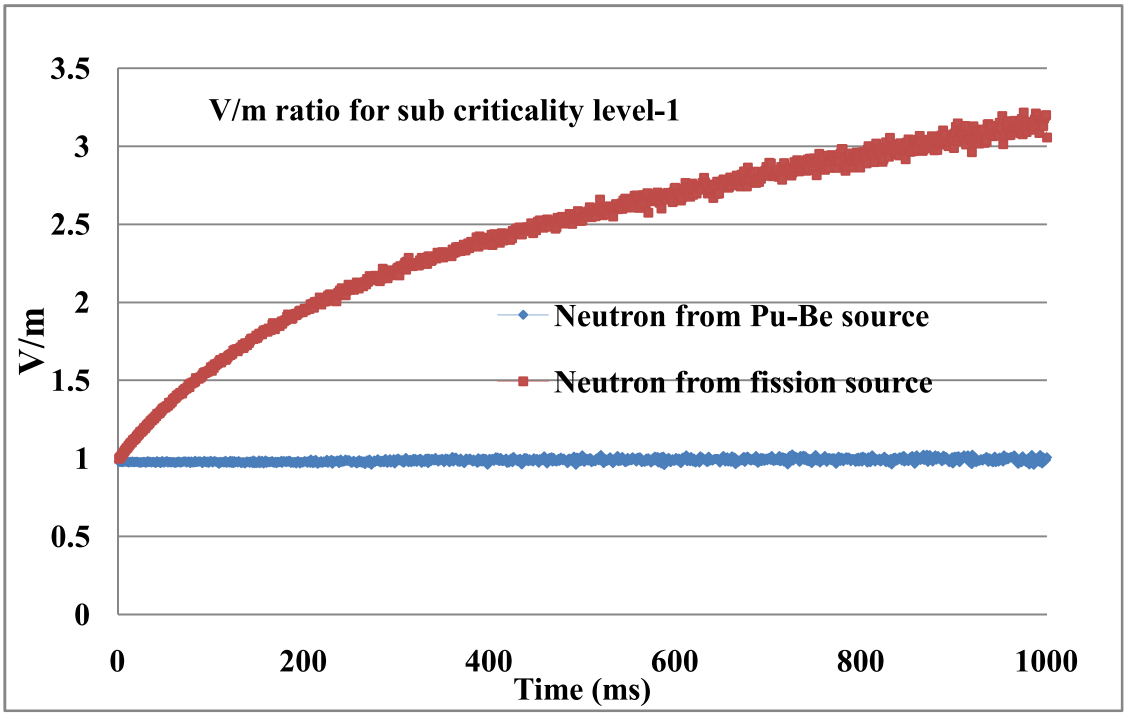

Fig. 3.7 Measured plot of V/m (sub-critical level-1)

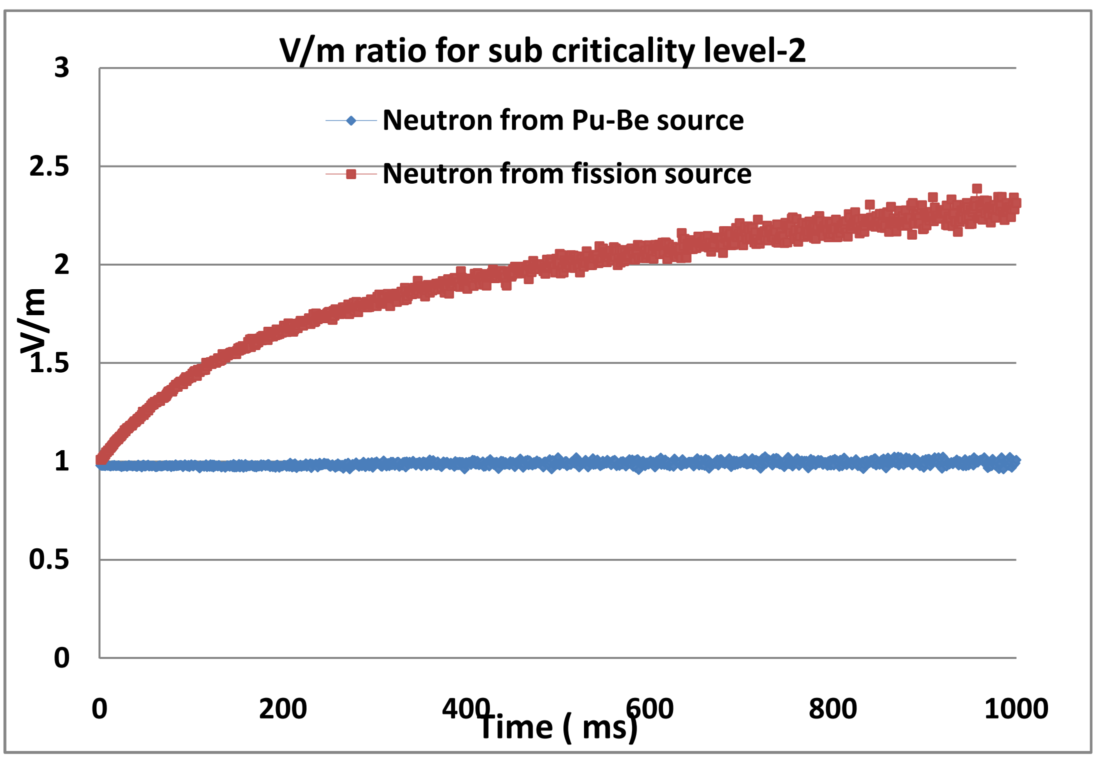

Fig. 3.8 Measured plot of V/m (sub-critical level-2)

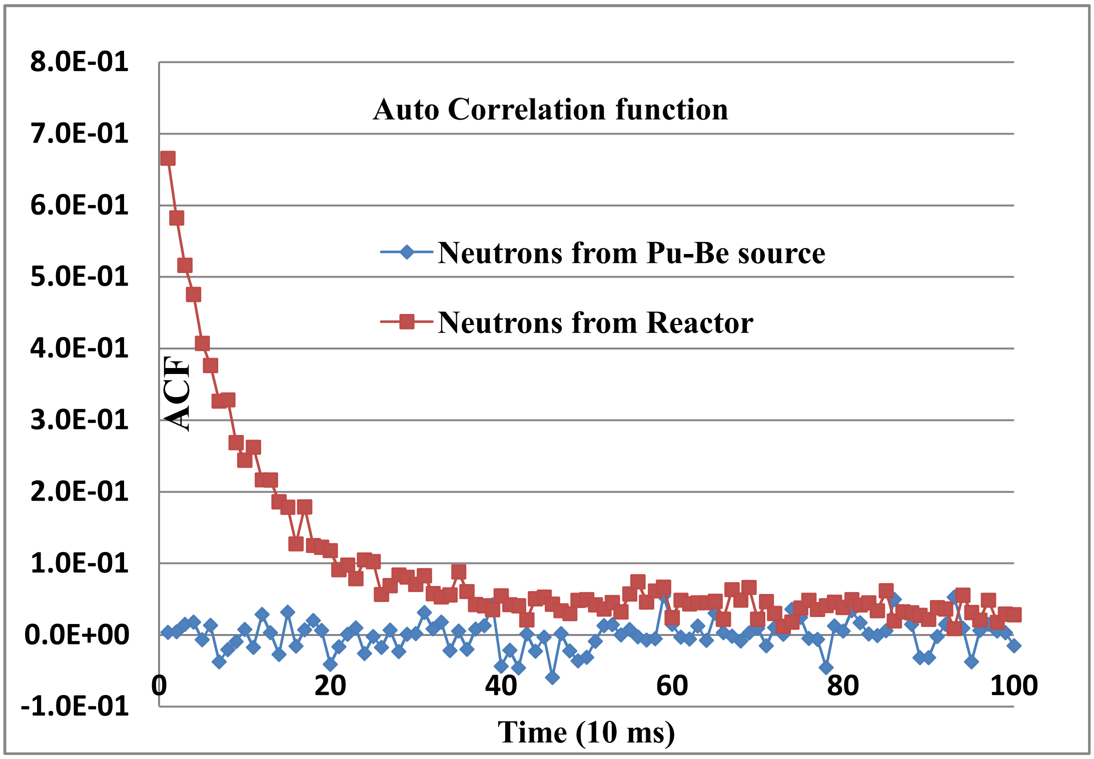

Fig. 3.9 Measured plot of Auto correlation function (sub-critical level-1)

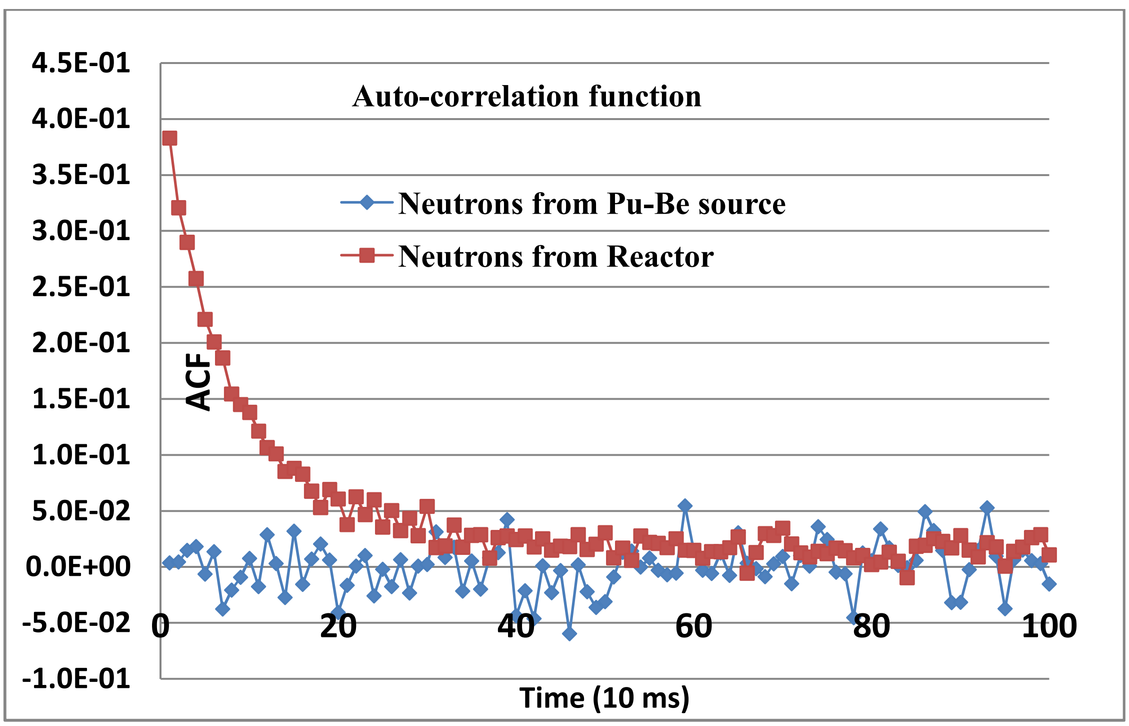

Fig. 3.10 Measured plot of Auto correlation function (sub-critical level-2)

Fig. 3.11 Experimental setup with neutron generator

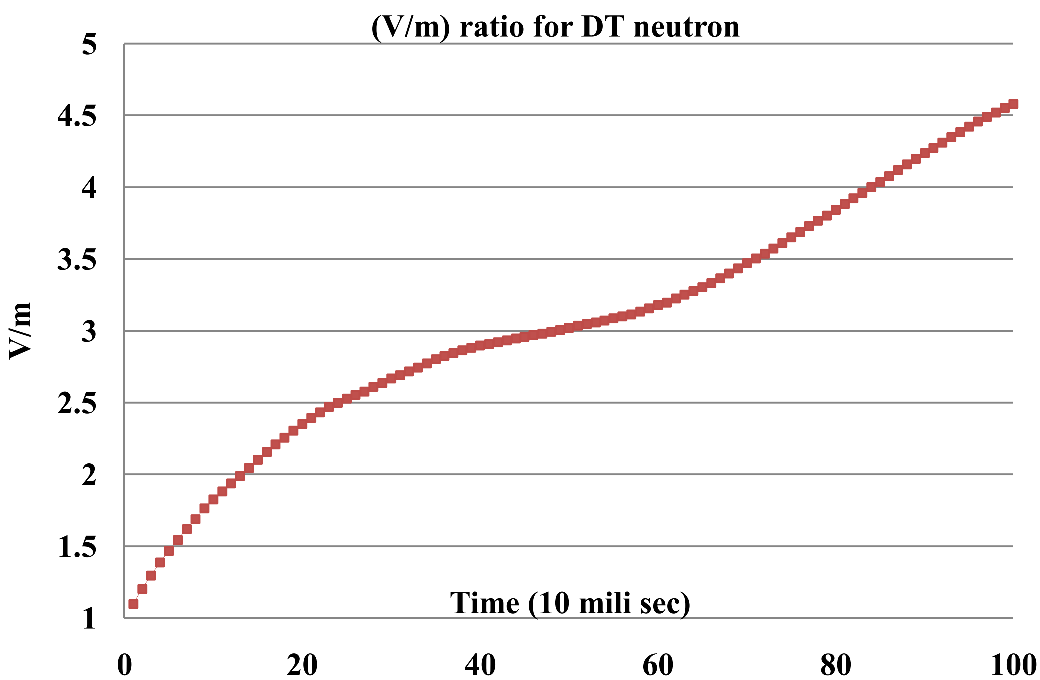

Fig. 3.12 Measured Feynman alpha profile of DT neutrons

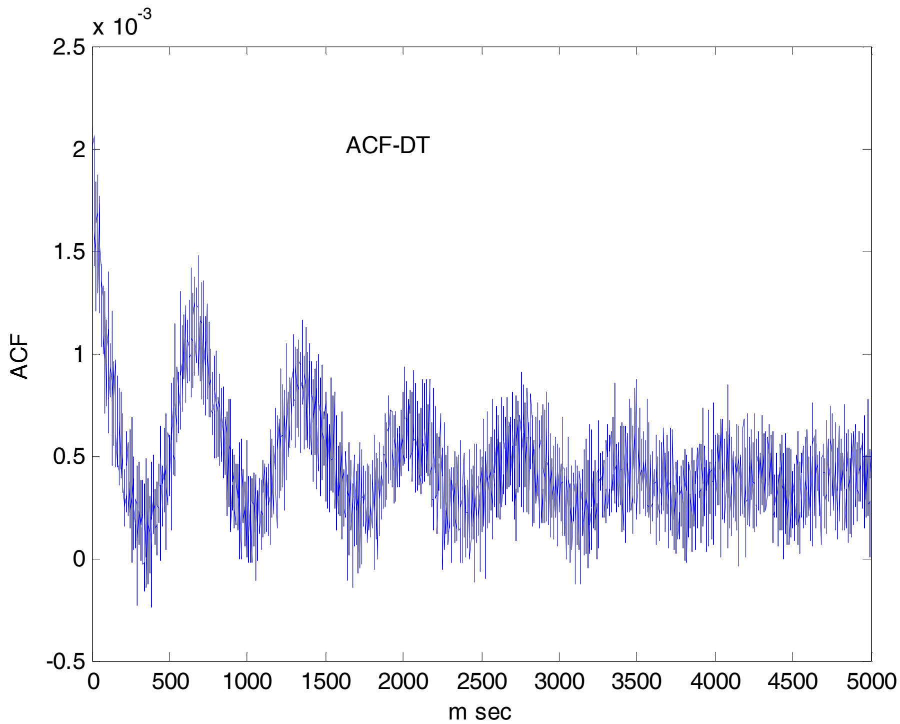

Fig. 3.13 Measured Auto correlation profile of DT neutron

Fig. 3.14 Schematic for [(R+A)-A] analysis

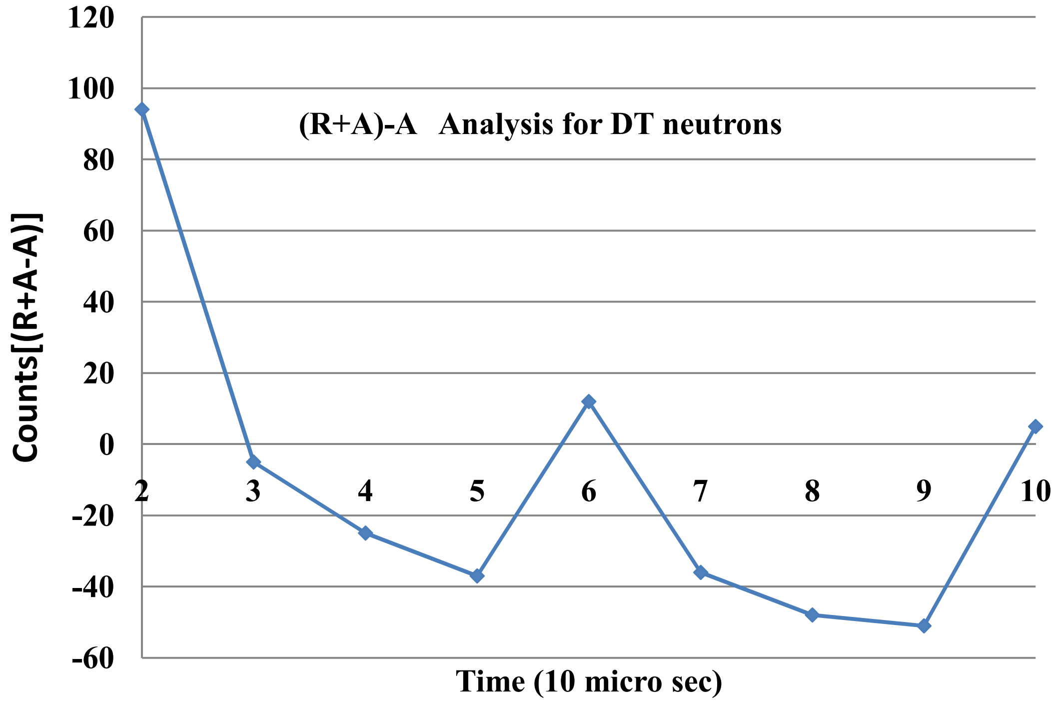

Fig. 3.15 Plot for [(R+A)-A] analysis

Chapter-4

Measurement of reactivity in heavy water reactors

4.1. Introduction

India has an interest in the development of accelerator driven systems (ADS) for utilizing its vast thorium reserves. Among the various reactor design being considered for this purpose, the heavy water moderated thermal accelerator driven system is one of the option (Degweker et al., 2013). The requirement of reactivity measurement in the context of ADS was discussed in Chapter-1. Among several methods used for reactivity measurement, the advantages of noise methods were discussed in Chapter-2. The present chapter will describe our study on reactivity measurement in a heavy water system using noise methods.

Measurement of sub-criticality using neutron noise methods in heavy water reactors is not as straight forward as in light water and fast reactors. The reason is that in fast and light water reactors, the prompt neutron life time is very short (~ 1micro sec to tens of micro seconds) while delayed neutrons appear on the time scale of precursor half lives which range from a little less than a second to few tens of seconds. Therefore there is no overlap between the correlations due to prompt neutron chains and those due to delayed neutrons in these types of reactors. By carrying out measurement & data analysis on a time scale of a few micro seconds to hundreds of micro sec (prompt neutron decay times), we can estimate α in these systems. Delayed neutrons hardly contribute and their contribution can be completely ignored. This makes the analysis simple and straight forward in fast and light water systems. The prompt neutron lifetime is about 0.5-1 ms in heavy water systems (Hanson A.L. 2006) which implies that the inverse of the prompt neutron decay constant ranges from tens of ms to about one hundred ms which is about the same as the lifetime of the short lived precursors. This results in significant overlap between the correlations due to prompt and delayed neutrons (including delayed photo neutrons). Consequently the prompt neutron kinetics cannot be separated from the delayed neutron kinetics. Therefore, in the case of heavy water reactors one must include the contribution of delayed neutrons/ delayed photo neutrons for a complete and correct analysis of the data. While experiments have been carried out, in the past, to measure the sub-criticality of a nuclear reactor and various other kinetic parameters using neutron noise methods (Misawa T., Shiroya S. et al., 1990; Kuramoto et al., 2007; Lee E, Park D. et al., 2010) there has been relatively less work done in the experimental determination (Gotoh Y. 1964; Behringer K., Phildius J. et al., 1975) of sub-criticality in heavy water systems using neutron noise methods.

In the present chapter, we describe noise based experiments for determination of sub-critical reactivity in the critical facility (CF) at Trombay. The CF is a zero power natural uranium fuelled and heavy water moderated reactor which was commissioned for the validation of the physics design of the advanced heavy water reactor being developed in India. (Raina V.K. et al., 2006). Measurements were carried out at different levels of sub-criticality by varying the moderator height. The measurements employed the time stamping data acquisition system described in Chapter-3. As stated before, the main advantage of such a system is that it permits analysis by any of the reactor noise methods using the same data set. We describe the analysis by the variance to mean (Feynman alpha) and the Auto correlation methods in this chapter. The effect of delayed neutrons/delayed photo neutrons has been taken into account in the data analysis treating the delayed neutrons in six groups. Results obtained using the simpler model of one delayed group are also presented.

Calculations of the reactivities and kinetic parameters were carried out using the in-house developed diffusion theory code KINFIN (Singh K.P. et al., 2009). The reactivity of the core was calculated at all those levels of sub-criticality for which measurement was carried out. Kinetic parameters like effective delayed neutron fraction and adjoint weighted prompt neutron generation time were also calculated. These quantities are required as input parameters in the data analysis. Measured reactivities are compared with the calculated values.

4.2. Experimental detail

4.2.1 Critical facility

The critical facility (CF) is a research reactor for carrying out various reactor physics experiments. It is a 100 W thermal reactor fuelled with natural uranium clusters and moderated by heavy water. The CF consists of a vertical cylindrical tank filled with heavy water in which the fuel clusters and all other reactivity/control devices are suspended from top. There is a graphite reflector below the reactor tank. The tank can be filled with heavy water moderator up to the required critical height. A schematic diagram of the critical facility is given in Fig. 4.1.

The core consists of 61 fuel clusters arranged in a square lattice of pitch 245 mm. The core is laid out in a 7×7 array with three positions added on each side and an absorber rod. Out of the total 62 positions, 55 positions are loaded with natural uranium fuel clusters, 6 positions accommodate the shut-off rods and one position in the reflector region is used for the absorber rod. A schematic layout of the reference core is given in Fig. 4.2. The fuel cluster consists of the 19 natural uranium pins in three concentric rings in an aluminum guide tube (Fig. 4.3). The clad material of the fuel pin is aluminum. The bottom of the guide tubes has structures such as springs and other components which provide support to the fuel cluster from the bottom. Since the reactor power is very low (100 W), no cooling arrangement is provided. The effective core radius is 108 cm with a 57 cm thick heavy water radial reflector (Fig 4.4 & 4.5). The moderator height for the critical core is 226.7 cm, which includes an axial (bottom) heavy water reflector thickness of 30 cm.

4.2.2 Experimental setup

The BF_3 neutron detector tube used in the experiment was placed in an easily accessible location available in the bottom graphite reflector region. The sensitivity (counts per second per unit neutron flux in n /cm-sq/sec) of the detector was 35 counts per second per unit flux. The associated electronics was placed outside the reactor cavity. A schematic of the experimental setup is similar to what was there in the testing of data acquisition system and it is shown in Fig. 3.6 of Chapter-3. The BF_3 detector tube is configured in the proportional region with a HV of 1700 Volt. The detector tube is coupled to a pre-amplifier and the pre-amplifier output is transmitted to a spectroscopic amplifier for pulse shaping. The amplifier output is connected to a single channel analyzer (SCA) which also serves as a discriminator. The output of the SCA is a TTL pulse that is fed to the data acquisition system described in Chapter-3. Neutron counts are registered with their time stamps in each set of the experiment corresponding to different levels of sub-criticality.

The reactivity is varied by adjusting the level of the heavy water in the reactor tank. The reactor was operated at six levels of heavy water corresponding to six levels of sub-criticality. Neutron counts were collected at each level of heavy water. A waiting time of about half an hour was provided between each change of water level and collection of data so as to stabilize the system at that level of reactivity.

4.3. Data analysis

Neutron counts were registered with their time stamp for long time duration in the format shown in Table 3.1 in Chapter-3. The size of a typical data set is a few hundred MB**.** The data was analysed by two neutron noise methods, namely the Feynman alpha and the Auto correlation function methods.

4.3.1 Feynman alpha method

The Feynman alpha method was discussed in detail in Chapter-2. Using this method, one measures the prompt neutron decay constant (α) by fitting the measured relative variance to Eq. (2.16). The sub-critical reactivity can be inferred from the measured value of decay constant as given in Eq. (2.17) provided the value of effective delayed neutron fraction (β) and prompt neutron generation time (Λ) are known . These two Eqs. (2.16 & 2.17) given in Chapter-2 are sufficient for obtaining the sub-criticality provided the prompt and delayed neutron time scales are very different and therefore clearly separable. As mentioned earlier, this is not the case in heavy water moderated reactors and one has to include the contributions from delayed neutrons/ delayed photo neutrons. Accounting for the contribution of delayed neutrons makes the analysis more involved. To account for the effect of delayed neutrons, the following expression (Williams MMR 1973) for the relative variance must be used.

$$\frac{V}{m} = 1 + 2\varepsilon\frac{\overline{\nu(\nu-1)}}{(\overline{\nu})^2}\sum_{i=0}^{J}\frac{A_i G(\alpha_i)}{\alpha_i}\left(1-\frac{1-e^{\alpha_i t}}{\alpha_i t}\right) \tag{4.1}$$

Where in conventional reactor kinetics parlance *G(p)* is the zero-power transfer function, viz.

$$\frac{1}{G(p)} = \mathrm{p}(\Lambda+\sum_{i=1}^{J}\frac{\beta_i}{\lambda_i+p}) - \rho \tag{4.2}$$

and Ai are the residues of the transfer function.

$$G(p) = \sum_{i=0}^{J} \frac{A_i}{p+\alpha_i} \tag{4.3}$$

In these expressions, α_0 is the root of the in-hour equation corresponding to the prompt neutron decay constant, and α_1 , α_2 ……..α_J are the roots corresponding to the first, second …jth delayed neutron group. β_i and λ_i are the delayed neutron fractions and decay constants of delayed neutron precursors respectively of the i^{th} delayed neutron group.

To get the relative variance of counts, we repeatedly record the number of counts Z_i in several time intervals, each of the same duration, *t* (gate length). Because of the fluctuations inherent in the various nuclear processes, the number of counts is a random variable and each of these counts (Z_i) is different. The variance and the mean of these counts are calculated and the ratio of variance to mean is obtained as follows.

$$\frac{V}{m} = \frac{\frac{1}{N}\sum_{i=1}^{N} Z_i^2 - (\frac{1}{N}\sum_{i=1}^{N} Z_i)^2}{\frac{1}{N}\sum_{i=1}^{N} Z_i} \tag{4.4}$$

The process is repeated for different gate lengths over a range of values of *t* which is of the order of the inverse of α.

As discussed in Section 4.2.2, neutron counts were recorded in a single shot for each level of sub-criticality. To get the variance and mean for a time interval of length *t*, the entire data record was divided into n equal segments each of length *t*. The number of counts falling in each segment was obtained and the ratio of variance to mean of these counts was calculated using Eq. (4.4). This value of V/m corresponds to an interval length equal to *t*. The procedure was repeated varying the interval length (*t*) to get the V/m values as a function of the time interval *t*. The V/m ratios were thus obtained for time interval lengths starting from 1 mili sec up to 1 sec in steps of 1 mili sec. The time interval range chosen is of the order of the inverse of the prompt neutron decay constant (α_0). A typical plot of V/m Vs counting interval is shown in Fig. 4.6 & 4.7. The statistical errors in the estimates of V/m are indicated by error bars, with the maximum error being about 0.037. It has been pointed out by Pal (1963) that the samples of neutron counts collected in consecutive intervals are not independent (which is also true in case of time stamped/list mode data), the variance estimated using Eq. (4.4) is likely to have a bias. This bias has been studied in detail by Pazsit (2008). To ensure that our results are bias free, the bias in our estimates was calculated using the following input parameters. α=15 sec^{-1}; gate width (T)=1000 mili sec (Max gate width taken in the plot Fig. 4.6); n=1800 (Typical data collection time is 30 minutes) and time advancement θ=0. The bias was found to be 3.97e-5 which has a negligible distortion on the empirical variance. The bias is also very small compared to the statistical error and is therefore neglected.

The measured values of V/m were fitted to Eq. (4.1) to obtain the reactivity (ρ) and detector efficiency (ε). The fitting procedure adopted was as follows. Theoretically calculated values of the prompt neutron generation time (Λ=0.798 mili sec) and effective delayed neutron fraction (β=0.0075) were used in the analysis and hence in the set of Eqs. (4.1), (4.2) and (4.3), all variables were treated as known except the detector efficiency (ε) and the reactivity (ρ). Guess values for these two unknowns were selected in a range which was decided on the basis of approximate estimates for these two quantities. With six groups of delayed neutrons, the in-hour equation (obtained by equating the right hand side of Eq. (4.2) to zero) gives rise to a polynomial equation of seventh degree in p. For the guess value of ρ, this in-hour equation was solved to get the values of the seven roots ($-\alpha_0$ to $-\alpha_6$). Here α_0 corresponds to the prompt neutron decay constant and the others correspond to the decay constant corresponding to the six groups of delayed neutrons. The values of these roots were used in Eq. (4.2) to obtain the seven values of $G(\alpha_i)$, ($i=0,6$). Substituting these values one by one in Eq. (4.3) gives us a set of seven linear equations which can be solved to get the values of A_i. These values of α_i, $G(\alpha_i)$ and A_i along with the guess value of ε were used to calculate the 'theoretical' V/m using Eq. (4.1), for each of the values of the time interval t and thus a theoretical value of V/m was obtained. The sum of the squares (i.e. the sum over all time intervals for which empirical estimates of V/m were made) of the difference between the 'theoretical' [(Eq. (4.1)] and measured values of V/m Eq. (4.4) was calculated. This procedure was repeated for all the guess values of ρ and ε in the selected range and those which gave the lowest sum of the squares were chosen as the best estimates of reactivity (ρ) and detector efficiency (ε).

The contribution of delayed neutrons was treated using delayed neutrons in the six groups in the analysis. The contribution of delayed photo neutrons was also accounted. According to the 9 energy group photo neutron data (Bernstein S. et al., 1947), two of the photo neutron groups having half lives of 41 and 2.5 sec are close to the two of the delayed neutron groups having half lives of 55 and 2.3 sec respectively. Hence the delayed photo neutron fractions of these two groups were added to the delayed neutron groups having the half lives of 55 and 2.3 sec. The half lives of photo neutrons in other groups are in the range of 2.4 min to 12.8 days and are far from the time scale of interest in the analysis and hence were ignored.

An approximate treatment based on a single group of delayed neutrons was also carried out to assess if this simplifying assumption is acceptably accurate. The same overall procedure was used in the case of one group of delayed neutrons; in this case we get only two roots, one corresponds to the prompt neutron and other corresponds to the delayed neutrons. One group values of the delayed neutron fraction (β) and the precursor decay constant (λ) were obtained by a weighted averaging over the six group data.

4.3.2 Auto correlation function method

This method is similar in principle to the Rossi alpha method, but data analysis is different. Here we talk about the Auto correlation function (ACF) Φ of the number of neutrons in the system at a given time (t) with that at a later time (τ). The Auto correlation function according to the point reactor model was described by Eq. (2.18)-(2.20) in Section 2.3.3 of Chapter-2. To include the effect of delayed neutron in the data analysis we have to go beyond the discussion given in Chapter-2. For that we re-write the expression of Auto covariance function (ACV) as given in (Williams MMR 1973).

$$\Phi'(\tau) = \varepsilon \frac{\overline{\nu(\nu-1)}}{(\overline{\nu})^2} \sum_i A_i G(\alpha_i)\, e^{-\alpha_i \tau}\,) \tag{4.5 a}$$

In practice we do not observe $N(t)$, but rather the detector count rate $Z(t)$ which is related to $N(t)$ as $Z(t) = \epsilon\lambda_f N(t) + \xi(t)$. The term $\xi(t)$ is a random variable resulting from the fact that there is a random error associated with the detection process referred to as detector noise. Under certain assumptions, it is possible to show that the effect of the detector noise is to add a delta function to the Auto covariance function.

$$\Phi'(\tau) = \epsilon\lambda_f \overline{N}(\delta(\tau) + \varepsilon \frac{\overline{\nu(\nu-1)}}{(\overline{\nu})^2} \sum_i A_i G(\alpha_i)\, e^{-\alpha_i \tau}\,) \tag{4.5 b}$$

$G(\alpha_i)$ and A_i are the transfer functions and their residues as defined in equations (4.2) and (4.3). The discretised form of Eq. (2.18) can be written as follows.

$$< N(t)N(t+\tau) >= \frac{1}{n}\sum_{i}^{n}(N_i - \overline{N})(N_{(i+k)} - \overline{N}) \quad (4.6)$$

Where N_i represents the number of neutron counts in the i^{th} bin and $\overline{N}$ is the average neutron counts. If each bin is of size Δt, then τ (time lag) $=k\Delta t$.

Since neutron counts were available with their time stamps, the sequence of neutron counts was divided in bins of equal width (Δt) of 10 mili sec such that N_i is the number of neutron counts in the i^{th} bin and $\overline{N}$ is the average neutron counts. The Auto covariance function is obtained for a range of values of τ from these neutron counts using equation (4.6). Two bin widths were tried viz., 1 ms and 10 ms. The bin width of 10 ms resulted in better statistics compared to the 1 ms bin width. A typical graph of ACV Vs time delay is shown in Fig. 4.8 & 4.9. The statistical errors in the estimates of ACV are indicated by error bars, with the maximum error being about 0.020.

The best estimates of the reactivity (ρ) and the detector efficiency (ε) were obtained by a least square fit of the ACV data to Eq. (4.5 a), the theoretical model. The procedure adopted for least square fit and the input parameters used for calculating the transfer functions and its residues was the same as described in the preceding section for the Feynman alpha method.

4.4. Theoretical calculations

The theoretical calculations were performed by the traditional deterministic approach consisting of lattice cell calculations followed by few group core calculations. The details of the reactor core taken for the modelling have been given in Section 2.1. At the first level, a set of three group homogenized diffusion theory parameters were generated for the fuel cells using the transport theory lattice code WIMSD in conjunction with the 69 group WIMS library. Three group parameters were also obtained for the heavy water and graphite reflector regions.

This was followed by a three dimensional simulation of the reactor core using the few group three dimensional diffusion theory code KINFIN (Singh K.P. et al., 2009). The code has the capability to solve the adjoint equation as well, and thereby to evaluate the point kinetics parameters like the prompt neutron generation time and the effective delayed neutron fractions. The reactor core and the surrounding reflector were represented using more than 16000 mesh points. While in the X-Y plane 572 mesh points (lattice pitch is 24.5 cm) were used to represent the core and radial reflector, 28 levels were used in the axial direction from the bottom reflector up to the level of the heavy water moderator**.** Different mesh sizes were chosen to represent fuel and reflector regions.

The direct and adjoint flux distributions were obtained and used to derive the adjoint flux weighted prompt neutron generation time (Λ) and the effective delayed neutron fraction. These were found to be 0.798 mili secs and 0.0075 respectively. It may be mentioned that the neutron generation time thus obtained is quite different from the infinite lattice value which is about 0.5 ms . The sub-critical reactivity was calculated at different moderator levels after adjusting for the offset at the observed critical height. The theoretically calculated values of the sub-critical reactivity are summarised along with the experimental results in Tables 4.1 and 4.2.

4.5. Results and discussion

The sub-critical reactivity was obtained by fitting the measured V/m data to the Feynman Y function and the measured ACV data to the Auto covariance Eq. (4.1) & (4.5 a) respectively. The value of the efficiency obtained in the fitting was found to be 1.28e-4 (± 3.5%). The calculation was done considering six groups of delayed neutrons and was repeated with one group of delayed neutrons. The measured values of the reactivity were compared with the calculated values obtained using the diffusion theory code, KINFIN. A comparison of measured results based on Feynman alpha analysis with the theoretically estimated values is given in Table 4.1. Table 4.2 shows a similar comparison based on Auto correlation function analysis. The results are shown graphically in Figs. 4.10 & 4.11.

It can be seen that there is a significant improvement when delayed neutrons are treated in six groups compared to one group analysis. The six group analysis results are closer to the calculated values in both the methods. Overall, the calculated values are in agreement with the measured ones within an error band of 0.5 mK, except for one point in the case of measurement by the Feynman alpha method at the moderator level of 211.6 cm. The agreement between theoretical estimates and results of measurement by the Auto correlation function method is somewhat better as against the measurements by the Feynman alpha method. A possible reason is that the Feynman alpha method is an integral method which is influenced more by the long lived precursors, whereas the Auto correlation function is a differential method for which the effect of delayed neutrons is less.

Measured and fitted values of V/m are shown in Fig. 4.6. The prompt neutron component of the fitted function is also shown in this figure. To understand the importance of delayed neutrons, we present the plots separately showing the contribution of each of the six groups of delayed neutrons to the V/m in Fig.4.7. Similar plots for Auto correlation function methods are shown in Figs. 4.8 & 4.9. It can be seen that in the Feynman alpha method (Figs.4.6 & 4.7), the prompt neutron component gets saturated quite early and it is the contribution of delayed and delayed photo neutrons which causes the total value of V/m continue to increase much longer.

Table 4.1: Comparison of calculated and measured values of reactivities using Feynman alpha method

S. No	Moderator level (cm)	Reactivity (-mK)		
		Calculated	Measured (± 0.4) (6 group)	Measured(± 0.4) (1 group)
1	219.6	1.15	1.10	0.60
2	218.4	1.86	2.20	1.10
3	217.6	2.34	2.40	1.20
4	215.6	3.57	3.14	2.90
5	213.6	4.84	5.29	3.10
6	211.6	6.14	6.99	4.50

Table 4.2: Comparison of calculated and measured values of reactivities using Auto correlation function method

S. No	Moderator level (cm)	Reactivity (-mK)		
		Calculated	Measured ($\pm$ 0.16) (6 group)	Measured($\pm$ 0.16) (1 group)
1	219.6	1.15	1.22	0.7
2	218.4	1.86	2.35	1.4
3	217.6	2.34	2.61	1.7
4	215.6	3.57	3.72	2.8
5	213.6	4.84	4.81	4
6	211.6	6.14	6.31	5.5

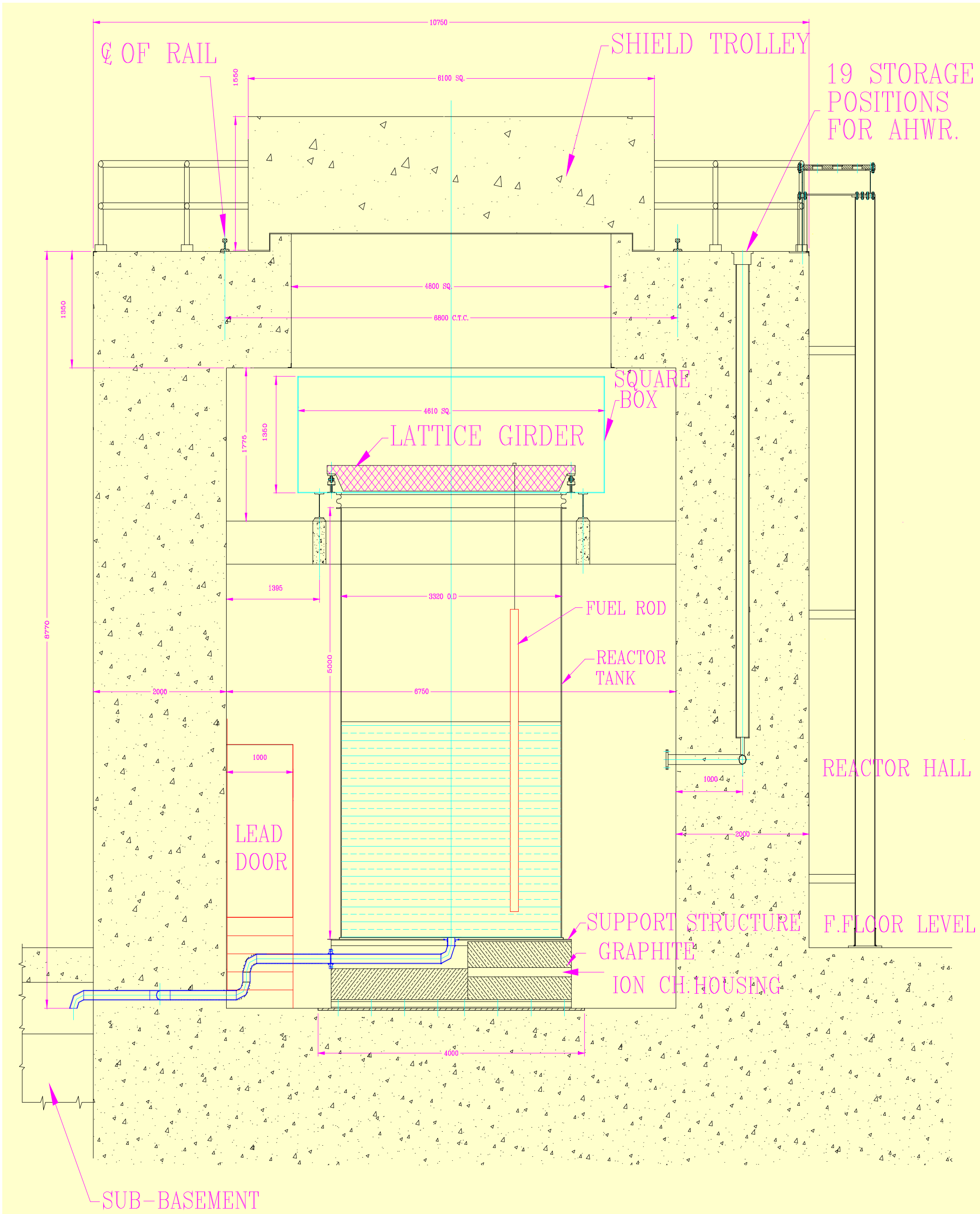

Fig.4.1 Sectional view of reactor block of critical facility

	1	2	3	4	5	6	7	8	9
A			**56**	**16Cu**	**17Cu**	**18Cu**	**57**		
B		**38Cu**	**36**	**41**	**42**	**43**	**35Cu**	**40Cu**	
C	**58**	**29Cu**	**10**	**S1**	**11**	**S4**	**12**	**48**	**AR**
D	**28Cu**	**55**	**13**	**2**	**3**	**4**	**14**	**49**	**20Cu**
E	**30Cu**	**53**	**S5**	**5**	**1**	**6**	**S2**	**50**	**21Cu**
F	**33Cu**	**52**	**15**	**7**	**8**	**9**	**24**	**51**	**19**
G		**32Cu**	**25**	**S3**	**26**	**S6**	**31**	**37Cu**	**61**
H		**34Cu**	**44**	**45**	**46**	**47**	**39Cu**	**54Cu**	
J			**59**	**22Cu**	**23Cu**	**27Cu**	**60**		

	Nat. uranium clusters within
	Nat. uranium clusters with average
	Nat. uranium clusters with average
	Additional natural uranium clusters
	Cadmium Shut off rods
	Cadmium absorber rod

Lattice pitch =245 mm; Diffusion coefficient : 1.103 cm
Absorption cross section: 3.877E-03 $cm^{-1;}$ Diffusion Length: 16.87 cm

Fig. 4.2 Core map of critical facility

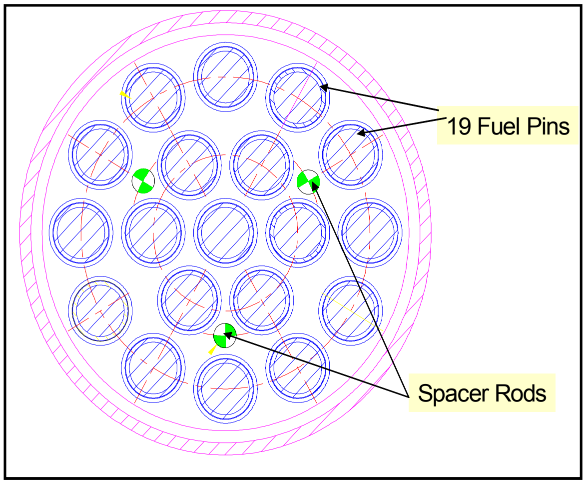

Fig. 4.3 View of 19 pin fuel cluster

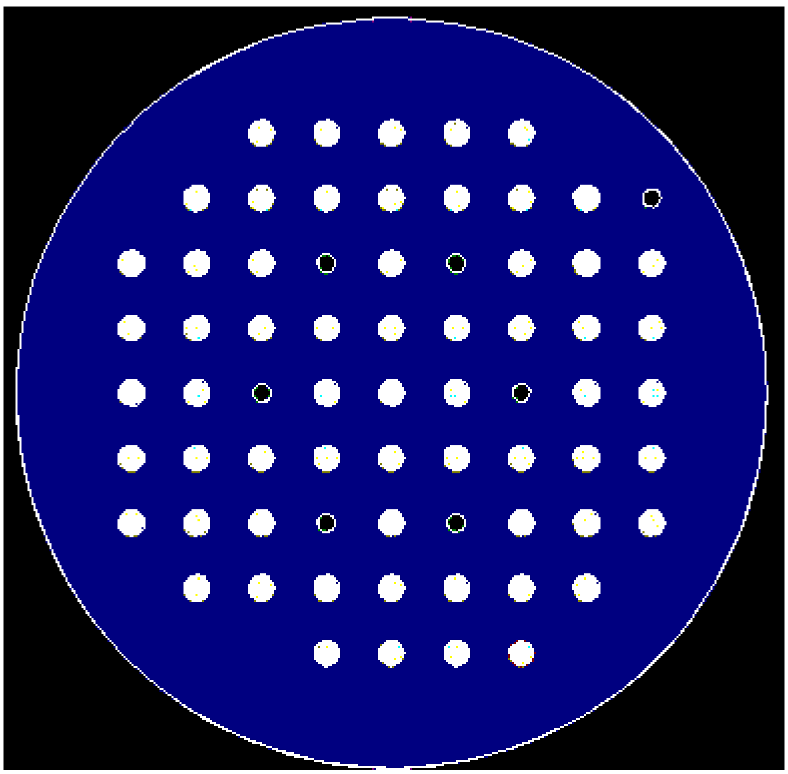

Fig. 4.4 Plan view of reactor tank of critical facility

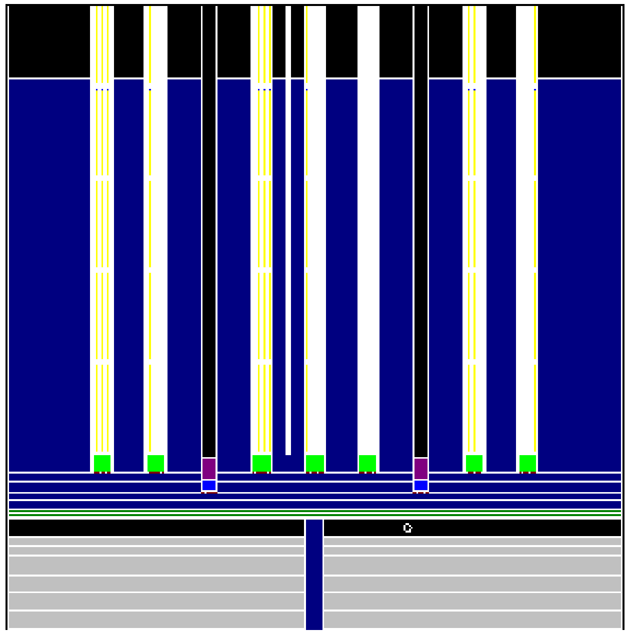

Fig. 4.5 Side view of reactor tank and bottom reflector region of critical facility

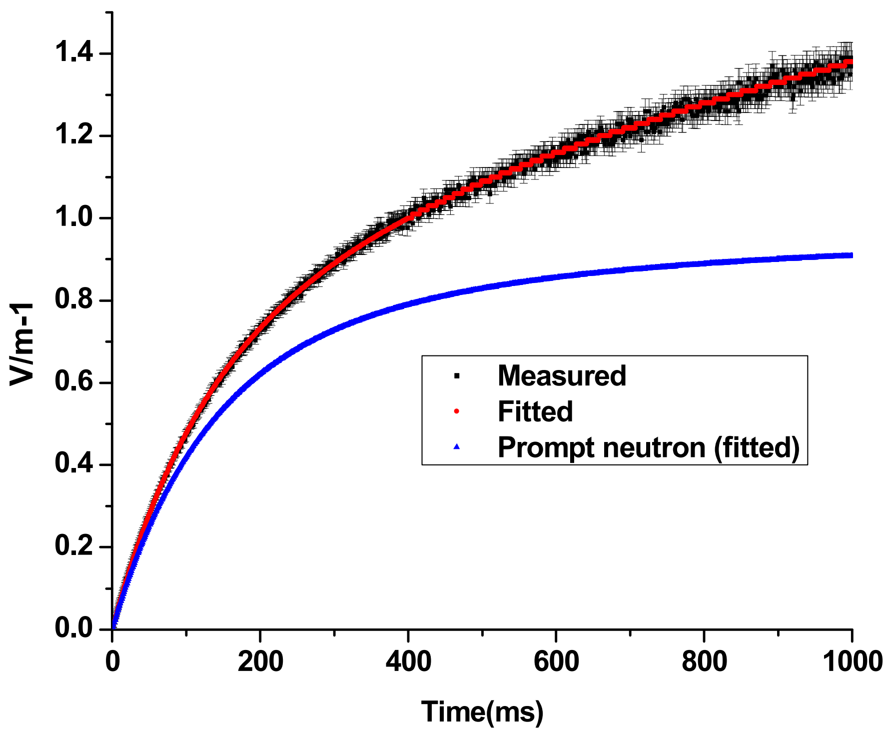

Fig. 4.6 Measured and fitted Feynman functions along with the prompt neutron component.

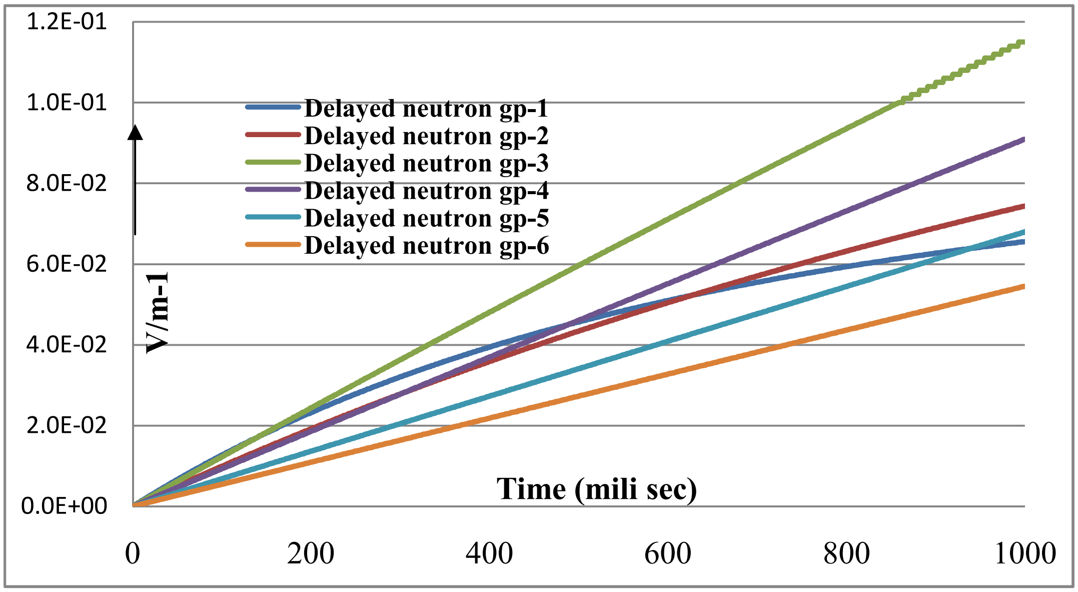

Fig. 4.7 Individual delayed neutrons group contributions in the fitted Feynman function

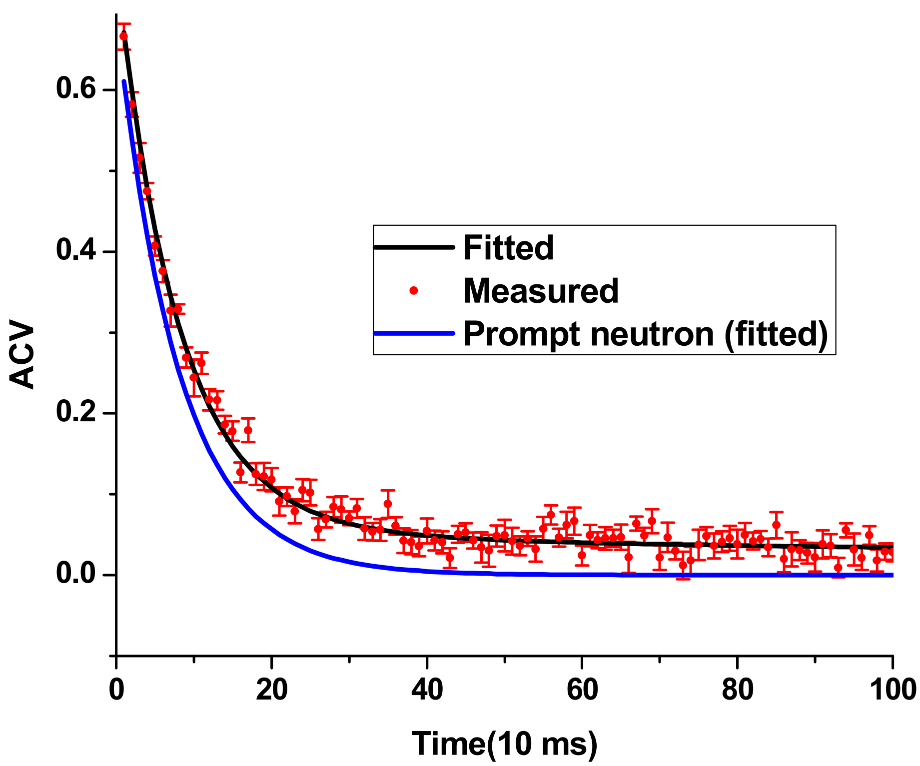

Fig.4.8 Measured and fitted Auto covariance function with the prompt neutron component.

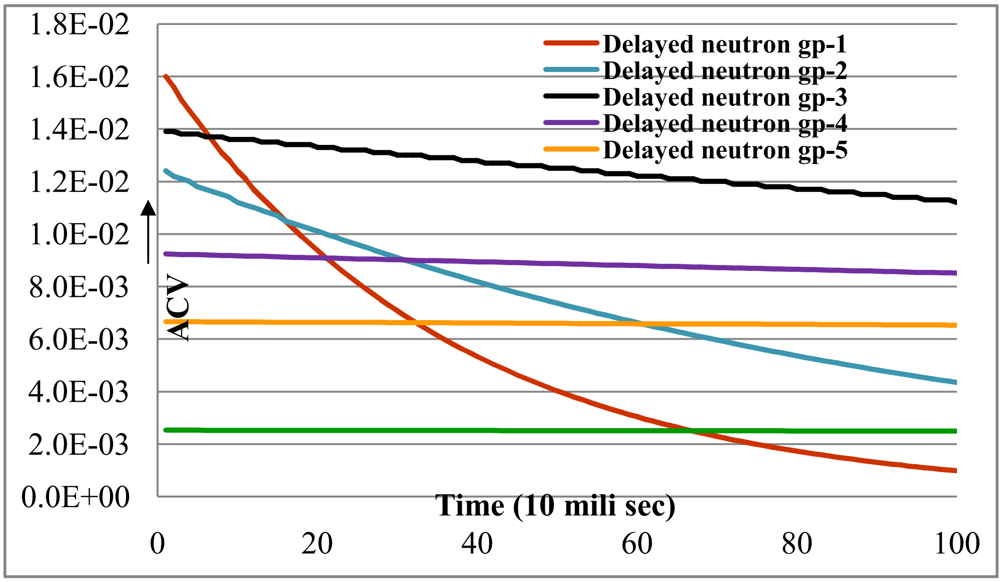

Fig. 4.9 Individual delayed neutrons group contributions in the fitted Auto covariance function

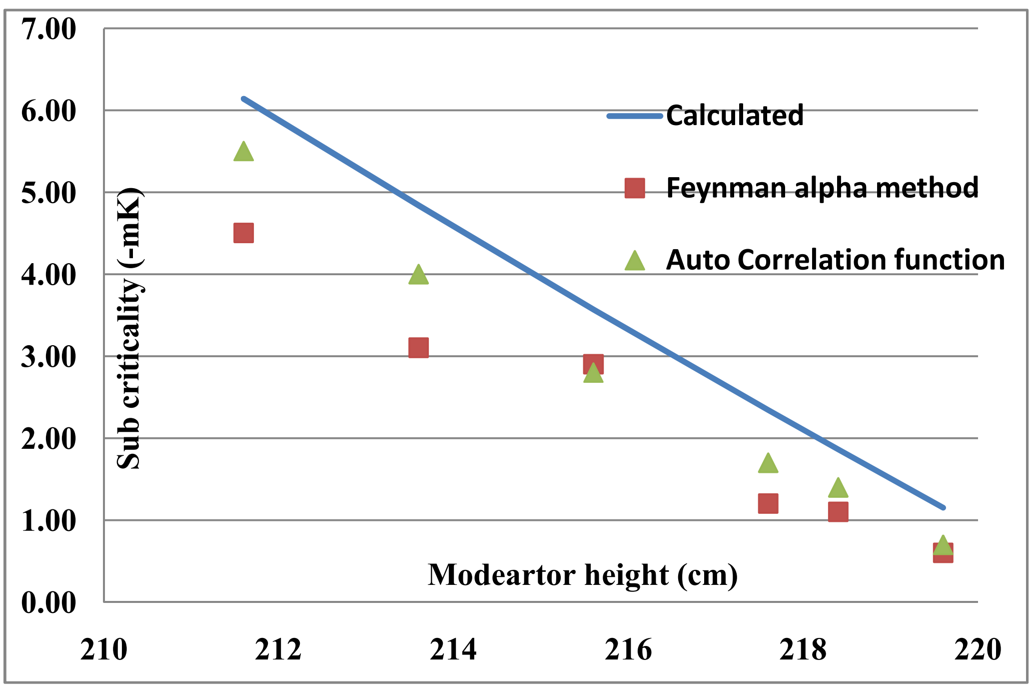

Fig. 4.10 Comparison of the theoretical estimates of reactivity with measurements using one group delayed neutron analysis.

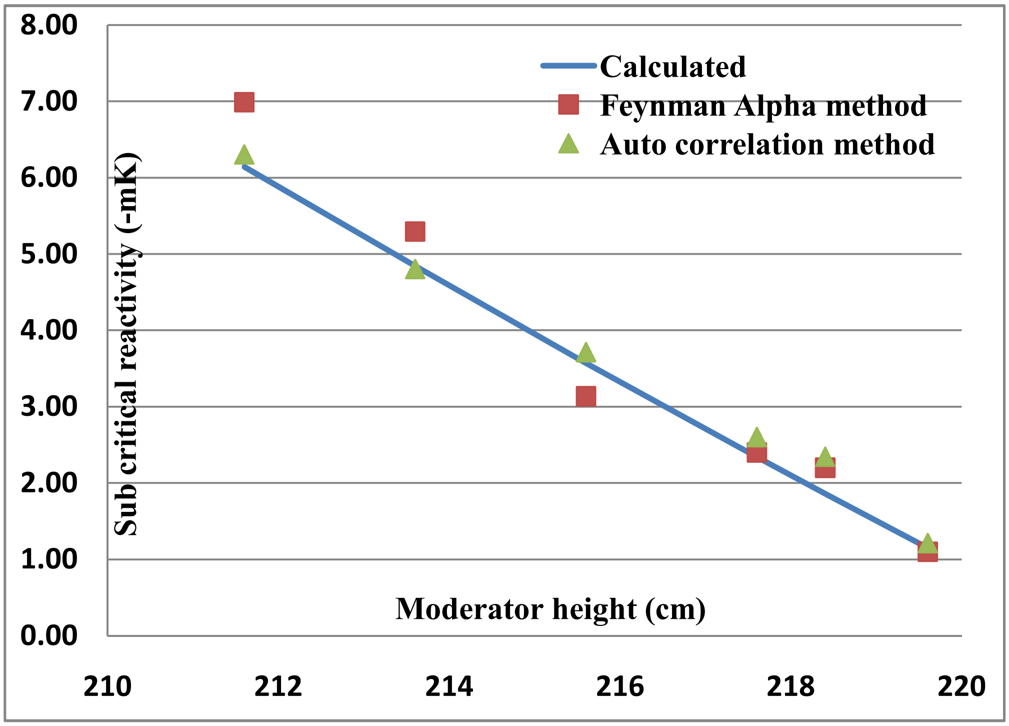

Fig. 4.11 Comparison of the theoretical estimates of reactivity with measurements using six group delayed neutron analysis.

Chapter-5

Theoretical basis of the method for mitigation of spatial effects in reactivity measurement of sub-critical systems

5.1 Introduction

As discussed in earlier chapters, accelerator driven systems (ADS) are drawing attention due to their enhanced safety features, and as a possible solution for nuclear waste management. Accurate monitoring of sub-critical reactivity is an important safety requirement for such systems. Therefore, development of methods for measuring the reactivity of sub-critical system in the context of ADS is an ongoing topic of research around the world. Methods for reactivity measurement in sub-critical systems by deterministic as well as by noise methods are plagued by problems of spatial dependence of the results and is a major issue that requires additional studies. Spatial effects are more prominent in the systems far from criticality. Development of a method for mitigation of spatial effects is one of the major contributions of this thesis and is described in the present chapter and in Chapter-6. The method was demonstrated by carrying out an experiment in the source driven sub-critical facility BRAHMMA. The sub-critical reactivity of the facility is more than 100 mK, and hence it is well suited for studying spatial effects.

The present chapter describes the theoretical basis of the idea proposed to mitigate spatial effects in measurement of reactivity in sub-critical systems. It also discusses the theoretical modelling of the core carried out as part of the preparatory work for implementing this idea in the experiment. The modelling includes calculations carried out to obtain the higher modes required for planning the location of detectors in the experiment. Various kinetics parameters such as reactivity, prompt neutron generation time and effective delayed neutron fraction were also calculated as these parameters go as input in the data analysis. The calculations were carried out using a diffusion theory based code KINFIN (Singh et al., 2009). The sub-critical facility BRAHMMA (Sinha Amar et al, 2015) is described in this chapter. Details of the experimental work (including preparatory work related to neutron detectors and instrumentation), data analysis, results and outcome of the experiment will be described in the next chapter.

5.2 Spatial effects

5.2.1 Background

The spatial effect is also viewed as the presence of higher harmonics (other than the fundamental mode) in the neutron distribution. The effect is particularly significant for deep sub-critical systems (Rugama et al., 2002, Rana and Degweker 2013). In the experiments carried out for measuring the reactivity, the reactivity value is inferred from the measured value of the prompt neutron decay constant of the fundamental mode. The presence of higher modes causes the decay curve in pulsed neutron experiments, and the Auto correlation function in noise measurements, to consist of multiple exponentials rather than a single exponential corresponding to the decay constant of fundamental mode. Thus the measurement of the prompt neutron decay constant in deep sub-critical systems is affected by the presence of higher modes, and appears as a contamination or error in the results. Hence, obtaining the reactivity from such measurements with multiple modes is not a straightforward task. If this modal contamination is not carefully accounted for, faulty conclusions regarding the reactivity might be drawn.

With regard to noise based reactivity measurements, several theoretical studies have been carried out recently (Yamamoto 2011; 2014, Munoz Cobo J.L. et al., 2011; Rana and Degweker, 2013; Singh K.P and Degweker, 2014) to address the problem associated with modal contamination. However, there has been little experimental work done in this direction. In one of the experimental studies carried out (Carl Berglof et al., 2011) the effect of higher modes was accounted for by using a multi exponential fitting. The difficulty of extracting multiple decay constants from a noisy data set is fairly obvious. In another effort in this direction (Mate Szieberth et al., 2015), reactivity measurements were performed by varying the detector position and fitting the noise descriptors to two alpha modes at each detector location. The best estimate for the prompt neutron decay constant was derived from these measurements corresponding to the position where the least bias was expected from higher mode, i.e where both the alpha values are closest to one another .

5.2.2 Mitigation of spatial effects

This thesis describes a new and better approach to address the problem of modal contamination in noise experiments in deep sub-critical systems. This involves locating the detectors in such a manner that contributions from higher modes are eliminated from the measurements rather than taking the effect of higher modes into account in the data analysis after the measurement. In the context of pulsed neutron experiments, this is relatively simple and placing a single detector located at the common zero of the first set of higher symmetric modes can eliminate a large number of modes, (all higher anti symmetric and the first set of higher symmetric modes) provided the source is located at the centre of a symmetrical reactor. In this arrangement the contributions from the anti symmetric modes cancel out and hence these modes are automatically eliminated (Rana and Degweker, 2013).

In noise experiments however, the situation is different. It was shown by Rana and Degweker (2013), that the Auto correlation function of a single detector located at a common zero of the first higher symmetric set of modes, has contamination due to the first set of anti-symmetric modes, and that this contribution does not cancel out by simply locating the source at the centre as in the pulsed neutron experiment. To effect this cancellation it is also necessary to have a set of detectors located at each of the (eight) intersections of the zeros of the first set of symmetric modes and use the combined output of such a system of detectors for noise analysis. With such an arrangement, the Auto correlation function is expected to contain contributions almost entirely due to the fundamental mode. The effect was derived mathematically and was also demonstrated using a Monte Carlo based noise simulator by Rana and Deggweker (2013) and is discussed in greater detail in Section 5.2.3.

However there has been no experimental confirmation of this effect. In this thesis we present an experimental demonstration and apply it to carry out measurement of the fundamental prompt neutron decay constant α that is practically free from any contamination due to higher modes. The experiment involved placing detectors symmetrically in the core at the common zeros of first set of higher symmetric modes and using the combined output of these detectors for noise analysis. We also show that placing a single detector at the correct position (common zeros of first set of higher symmetric modes) does not give satisfactory results thereby indicating that such a placement does not eliminate the higher modal contamination.

5.2.3 Theoretical basis of spatial effects

The mathematical models of noise descriptors like Feynman alpha and Rossi alpha generally described in texts book (Williams M.M.R., 1973) assume a point model, that in the context of noise analysis is strictly valid for an infinite homogeneous medium and an infinite sized detector distributed throughout the medium. To account for a finite sized medium, localized source and detector, other heterogeneities commonly occurring in reactors, and for the variation of cross sections with neutron energy, a space-energy dependent theory is required. A general formalism based on the stochastic transport equation (Pal, 1958 and Bell, 1965) is commonly used. Using an expansion of the flux and adjoint in terms of the alpha eigen functions, multimodal formulae for the Rossi alpha and Feynman alpha can be obtained (Munoz Cobo et al, 2011; Rana and Degweker, 2013). Often reactor assemblies have various symmetries such as one or more reflecting planes passing through the centre. In such situations, the diffusion (or transport) equation has eigen functions (modes) that are either symmetric or anti symmetric with respect to these planes. The sub-critical assembly (described in detail in Section 5.3) used in our experiment has such symmetry planes viz. the x-z and y-z planes and an approximate symmetry about the x-y plane.

A source placed at the centre is located essentially at the intersection of the zeros of the anti symmetric modes (of the adjoint equation). Such a source produces a symmetric flux and all anti symmetric modes are absent. The fundamental mode is symmetric and contributes together with higher symmetric modes to the flux distribution. Now if a detector is placed at the intersection of the zeros of the next symmetric modes, it will 'sense' a zero contribution from these modes. Such a detector largely responds to the fundamental mode alone. Such a location is ideal in the case of the pulsed neutron experiment.

In the noise experiment, the correlated part of the Auto correlation function would be expected to decay like the prompt neutron population in a pulsed neutron experiment. However as shown by Rana and Degweker (2013), the Auto correlation function of such a detector has contamination due to the anti-symmetric modes. To effect this cancellation it is also necessary to have a set of detectors located at each of the eight intersections of the zeros (one in each octant) and use the combined output of such a system of detectors. With such an arrangement, the ACF is expected to contain contributions almost entirely due to the fundamental mode. For the sake of completeness, we summarise the main arguments that lead to this conclusion. For the purpose of the discussion we choose the Rossi alpha function

It was shown by Rana and Degweker (2013) as well as by others (Munoz Cobo et al., 2011) that the Rossi alpha function can be written as follows.

$$
\begin{aligned}
P(t_1, t_2)\delta t_1 \delta t_2 \\
&= \left(\delta t_1 \int \Sigma_{d1}\varphi(\mathbf{r}, \mathbf{\Omega}, E) d\mathbf{r} d\mathbf{\Omega} dE\right)\left(\delta t_2 \int \Sigma_{d2}\varphi(\mathbf{r}, \mathbf{\Omega}, E) d\mathbf{r} d\mathbf{\Omega} dE\right) \\
&+ \overline{\nu(\nu-1)} \int \Sigma_f \varphi(\mathbf{r}, \mathbf{\Omega}, E)\left(\delta t_1 \int \frac{\chi(E')}{4\pi} G_{z_1}(\mathbf{r}, \mathbf{\Omega}', E', t, 1,1) d\mathbf{\Omega}' dE'\right)
\end{aligned}
$$

$$
\mathrm{x}\left(\delta t_2 \int \frac{\chi(E')}{4\pi} G_{z_2}(\mathbf{r}, \mathbf{\Omega'}, E', t, 1,1) d\mathbf{\Omega'} dE'\right) d\mathbf{r} d\mathbf{\Omega} dE \qquad (5.1)
$$

where G_{z_1} (or G_{z_2}) is the first derivative of Rossi alpha PGF evaluated at $z_1 = 1$ ($z_2 = 1$) and is simply the solution of the adjoint transport equation with the detector at time t_1 and (or t_2) acting as an instantaneous source. The G_{21} and G_{22} are Green's functions representing the expected number of counts [due to a single neutron released at $(\mathbf{r}, \mathbf{\Omega}, E)$] in delta function detectors $\Sigma_{d1}\delta(t - t_1)$ and $\Sigma_{d1}\delta(t - t_2)$ at times t_1 and t_2 respectively. The first term in Eq. (5.1) is simply the product of the count rates at δt_1 and δt_2 and forms the uncorrelated part while the second term involves a spatial integral of the product of the stationary reactor power and the spectral weighted neutron importance for the detector at the times t_1 and t_2. Now a single detector located in one of the octants would cause the importance functions to have symmetric and anti symmetric components. Since the product of two anti symmetric functions is symmetric, and the power distribution is symmetric, the integral does not give a zero contribution for anti symmetric modes even though the source is located symmetrically. On the other hand if we have a symmetric arrangement of 8 detectors (one in each octant), then the first set of anti symmetric modes are completely absent from the corresponding adjoint function and hence they do not contribute. Since the detectors are located at the intersection of zeros of the next higher symmetric modes, these modes also do not contribute to the functions G_{z_1} and G_{z_2}. Thus the first set of anti symmetric and symmetric higher harmonics are absent in these functions and hence do not contribute to the Rossi alpha function. In other words most of the contribution comes from the fundamental mode and gives us a single exponential decay in the correlated part of the Rossi alpha function.

5.3 Description of the BRAHMMA sub-critical assembly

Keeping the research and development for ADS in mind, several countries started experimental studies in sub-critical assemblies/test facilities such as MASURCA (Soule et al., 2004); , YALINA (Gohar et al., 2009, 2010), KUCA (Pyeon et al., 2007, 2008) and GUINEVERE (Uyttenhove et al., 2011). As a part of the ADS programme in India, a sub-critical experimental facility BRAHMMA (Berylium Reflected And High density Moderated Multiplying Assembly) has been recently commissioned (Sinha Amar et al., 2015) at the Bhabha Atomic Research Centre (BARC), India

The sub-critical assembly consists of metallic natural uranium rods as fuel. The fuel pin radius is 1.72 cm and the length is 130 cm which includes 100 cm of active fuel length and 15 cm of end cap on either side. High density polyethylene (HDPe) is used for the moderator and the core is reflected by beryllium oxide (BeO) bricks. The assembly is made from high density polyethylene sheets stacked together in a rectangular parallelepiped through which holes (channels) are drilled to accommodate the fuel rods. A maximum of 160 fuel channels are available. The fuel rods are arranged in a 13 X 13 square lattice with a 48 mm pitch (centre-to-centre distance between two fuel rods). One of the unique features of the core is the use of BeO as reflector. Beryllium oxide has excellent properties as reflector material and also makes the system compact. The core is surrounded (on four sides perpendicular to the incident beam) by beryllium oxide of 200 mm thickness. The core is finally surrounded by an outer layer of 50 mm of borated polyethylene (1% boron by weight) followed by 1.5 mm of cadmium to isolate the system from scattered neutrons from the surrounding walls. The central 3X3 lattice positions (144 mm X 144 mm) are cut out to form the cavity for inserting the neutron source. The sub-critical assembly is shown in Figs. 5.1 and experimental arrangement of the detectors is shown in fig. 5.2.

5.4 Modelling of the sub-critical assembly

5.4.1 Code used for the calculation

KINFIN code (Singh K.P et al., 2009) was used as a computational tool in calculations carried out prior to the experiment. The code solves the multi group neutron diffusion equation using the finite difference technique. The code has capability of solving direct and adjoint multigroup neutron diffusion equation in variable number of energy groups. It can find adjoint flux weighted kinetic parameters like neutron generation time, effective delayed neutron fraction etc.

It can also solve the time dependent multi group neutron diffusion equation by direct integration method. The code uses a rectangular variable mesh in the X-Y directions. One, two and three dimensional models can be easily represented by using appropriate boundary conditions. The code has the capability of determining the fundamental and higher modes of the multi group neutron diffusion equation using either the conventional mode elimination scheme or the method based on sub-space iterations.

5.4.2 Calculation of modes

The sub-critical core was modelled using the diffusion theory based code discussed above. The core along with the surrounding reflector region was represented using 17x17x28 mesh points (Fig. 5.3). At the lattice level, 3-group homogenized nuclear cross sections for the fuel lattice cells were generated using the multi group transport theory lattice code WIMSD in conjunction with a 69 group WIMS library. WIMSD is a multi-group neutron transport theory lattice code used widely for estimation of lattice parameters. At the core level, the neutron fluxes were calculated in three energy groups (10 MeV-0.821 MeV, 0.821 MeV-0.625 eV and 0.625 eV-0) using KINFIN.

Calculation of higher modes of the few group diffusion equation was carried out to decide the detector locations inside the core so that the effect of the higher modes can be minimized. Nine modes were calculated, λ eign values of five modes are given in Table-5.1. The idea is that effect of the symmetric modes in the prompt neutron decay constant measurement can be minimized by placing the detectors at the intersections of the zeros of the symmetric modes as discussed above. Contribution of the anti-symmetric modes can be removed by placing the source at the centre and the detectors at 8 symmetrical locations with respect to the centre of the core (one in each octant), and adding the signal from these detectors. The higher symmetric mode in the axial direction is shown in Fig.5.4a. 3-D surface plot equivalent to Fig. 5.4a is shown in Fig. 5.4b. The X-axis of the plot represents mesh number (mesh size is 5 cm) in the core along the axial direction and the Y axis of the plot shows the normalized neutron fluxes in the Y-Z plane of the core for all the lattice (A-M) positions at a given location in X-direction of the core. The zeros of this mode were found at 18.5 cm on both the sides from the centre. The higher symmetric mode in the radial (X-Y) plane is shown in Fig. 5.5a. 3-D surface plot equivalent to Fig. 5.5a is shown in Fig. 5.5b Numerical values corresponding to this symmetric mode in the radial plane at a fixed position in the axial direction (z) are given in Table-5.2. It can be seen from Table-5.2 that meshes in the central region (marked in color) have all negative values while the remaining meshes outside the central colored region have positive values. Therefore, meshes on the boundary of these two regions contain the zeros of the symmetric mode and these zeros lie on a circle in the plane perpendicular to the core axis (z-direction). Meshes marked with red color on the boundary have values which are about an order of magnitude lower than the values of nearby meshes; hence these red marked positions can be considered to be the zeros of the symmetric mode in the radial plane and detectors may be placed in these locations. This modal analysis was used in deciding the detectors locations such that the modal contamination can be minimized in the experiment. The experimental arrangement of the detectors will be discussed in the next chapter.

5.4.3 Adjoint function and kinetics parameters

The kinetic parameters like effective delayed neutron fractions and prompt neutron generation time is required to infer the reactivity from the measured value of prompt neutron decay constant. The calculated value of k_{eff} is also required for a comparison with the experimentally estimated value. The code used in the calculation has the capability to solve the adjoint equation as well, and thereby to evaluate the adjoint flux weighted kinetics parameters. Adjoint flux weighted prompt neutron generation time (Λ) and the effective delayed neutron fraction were calculated and were found to be 58.3 micro seconds and 0.0077 respectively. The calculated value of the k_{eff} was found to be 0.887. Thus the reference value of the prompt neutron decay constant works out to be 2310 sec^{-1}.

Table-5.1: Eigen values of sub-critical assembly BRAHMMA

Modes	Eigen values
1	0.8867
2	0.8247
3	0.8034
4	0.8039
5	0.7547

Table-5.2: Fluxes of symmetric modes in the radial (X-Y) plane in sub-critical assembly

	1	2	3	4	5	6	7	8	9	10	11	12	13
A	6.71E+07	7.72E+07	7.39E+07	6.00E+07	4.21E+07	2.77E+07	2.23E+07	2.77E+07	4.21E+07	6.00E+07	7.39E+07	7.72E+07	6.71E+07
B	7.72E+07	8.64E+07	7.82E+07	5.69E+07	3.16E+07	1.18E+07	4.41E+06	1.18E+07	3.16E+07	5.69E+07	7.82E+07	8.64E+07	7.72E+07
C	7.39E+07	7.82E+07	6.33E+07	3.48E+07	3.43E+06	-2.00E+07	-2.85E+07	-2.00E+07	3.43E+06	3.48E+07	6.33E+07	7.82E+07	7.39E+07
D	6.00E+07	5.69E+07	3.48E+07	4.62E+05	-3.38E+07	-5.74E+07	-6.55E+07	-5.74E+07	-3.38E+07	4.62E+05	3.48E+07	5.69E+07	6.00E+07
E	4.21E+07	3.16E+07	3.43E+06	-3.38E+07	-6.67E+07	-8.48E+07	-8.97E+07	-8.48E+07	-6.67E+07	-3.38E+07	3.43E+06	3.16E+07	4.21E+07
F	2.77E+07	1.18E+07	-2.00E+07	-5.74E+07	-8.48E+07				-8.48E+07	-5.74E+07	-2.00E+07	1.18E+07	2.77E+07
G	2.23E+07	4.41E+06	-2.85E+07	-6.55E+07	-8.97E+07				-8.97E+07	-6.55E+07	-2.85E+07	4.41E+06	2.23E+07
H	2.77E+07	1.18E+07	-2.00E+07	-5.74E+07	-8.48E+07		**CENTRAL CAVITY REGION**		-8.48E+07	-5.74E+07	-2.00E+07	1.18E+07	2.77E+07
I	4.21E+07	3.16E+07	3.43E+06	-3.38E+07	-6.67E+07	-8.48E+07	-8.97E+07	-8.48E+07	-6.67E+07	-3.38E+07	3.43E+06	3.16E+07	4.21E+07
J	6.00E+07	5.69E+07	3.48E+07	4.61E+05	-3.38E+07	-5.74E+07	-6.55E+07	-5.74E+07	-3.38E+07	4.63E+05	3.48E+07	5.69E+07	6.00E+07
K	7.39E+07	7.82E+07	6.33E+07	3.48E+07	3.43E+06	-2.00E+07	-2.85E+07	-2.00E+07	3.43E+06	3.48E+07	6.33E+07	7.82E+07	7.39E+07
L	7.72E+07	8.64E+07	7.82E+07	5.69E+07	3.16E+07	1.18E+07	4.41E+06	1.18E+07	3.16E+07	5.69E+07	7.82E+07	8.64E+07	7.72E+07
M	6.71E+07	7.72E+07	7.39E+07	6.00E+07	4.21E+07	2.77E+07	2.23E+07	2.77E+07	4.21E+07	6.00E+07	7.39E+07	7.72E+07	6.71E+07

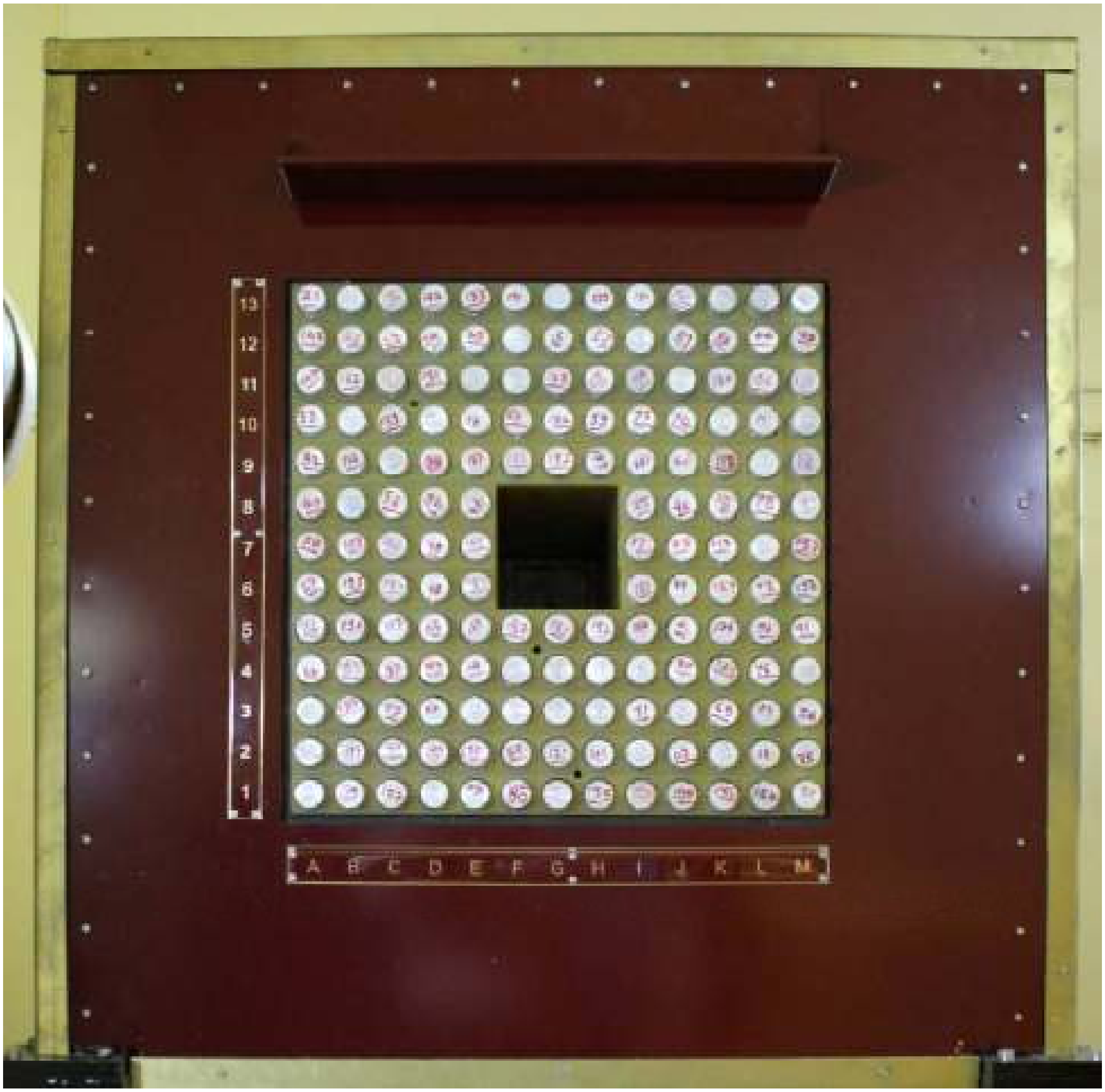

Fig. 5.1 View of BRAHMMA sub-critical assembly

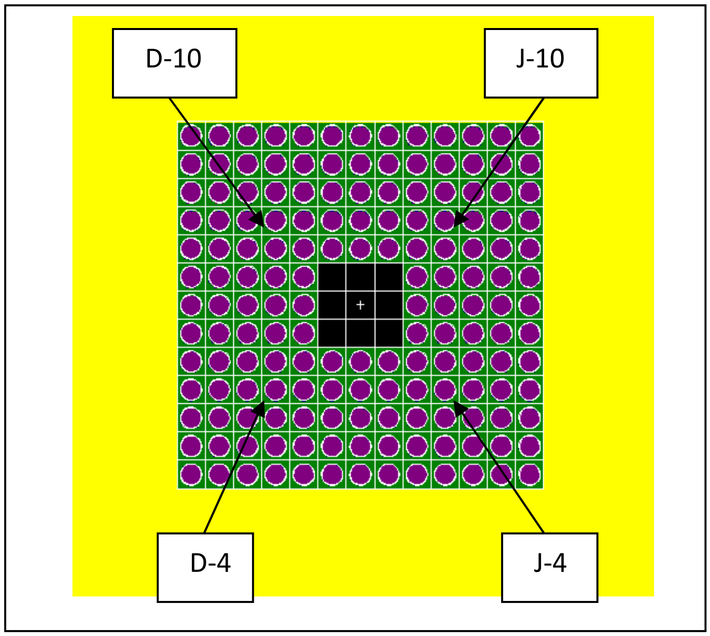

Fig. 5.2 Experimental arrangement of detectors

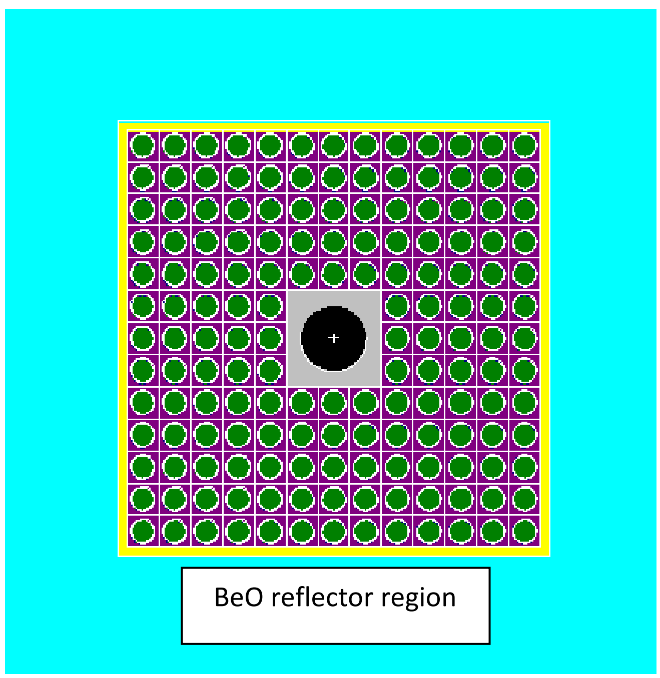

Fig. 5.3 Modelled cross sectional view of BRAHMMA

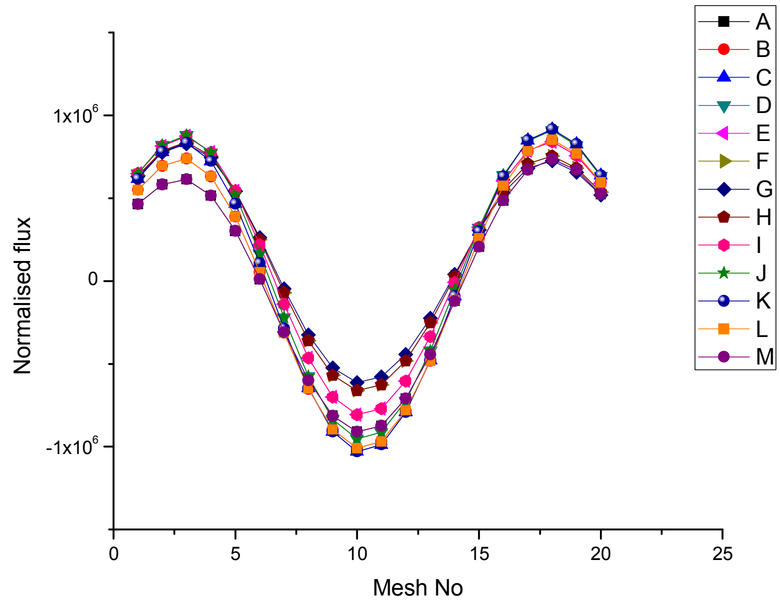

Fig. 5.4a First higher symmetric mode in the axial direction

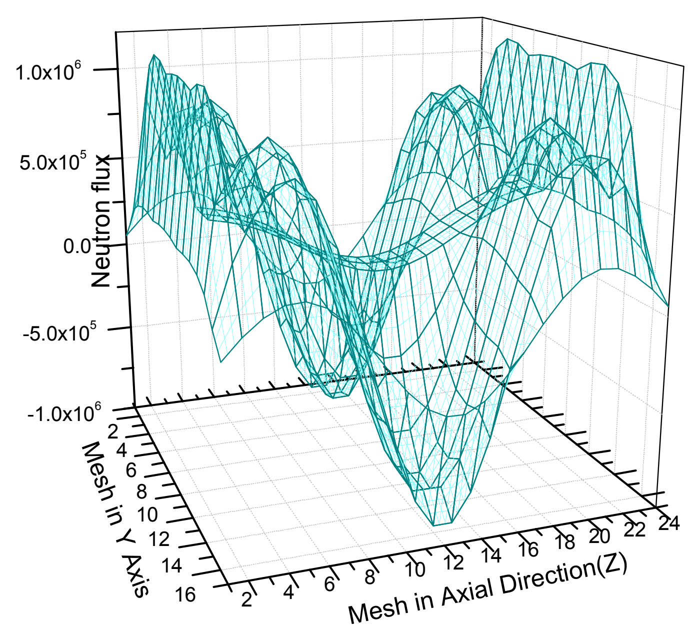

Fig. 5.4b 3D surface plot of first symmetric mode in axial (Z) direction (Y-Z plane)

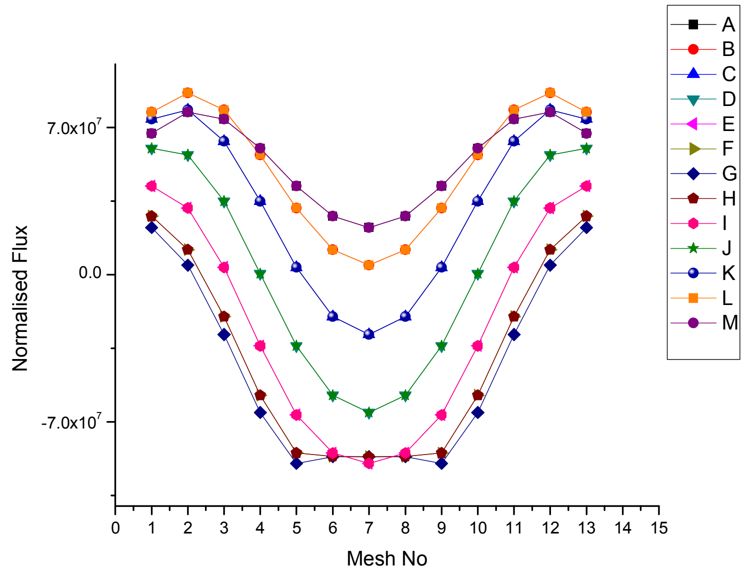

Fig. 5.5a First higher symmetric mode in the radial (X-Y) plane

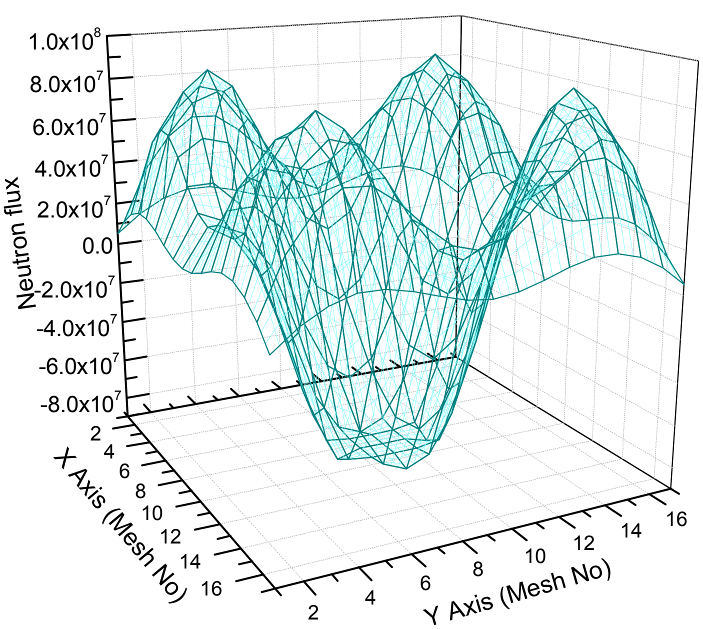

Fig. 5.5b 3D surface plot of first symmetric mode in horizontal (X-Y) plane

Chapter-6

Measurement of reactivity in BRAHMMA

This chapter describes the experiment and its results carried out to measure the reactivity of the sub-critical system BRAHMMA. The experiment was carried out to demonstrate the mitigation of spatial effects in reactivity measurement of deep sub-critical systems using noise methods. The neutron detectors were placed on the location decided on the basis of modal analysis described in the Chapter-5. The in-house developed data acquisition system (Kumar, Ali Yakub et al., 2015) was employed to collect the data in the experiment. The data was analysed using two noise methods namely, the Variance to mean (Feynman alpha) and the Auto correlation methods. The measured value of the reactivity was compared with the theoretical results and was found to be in good agreement.

6.1 Experimental setup

6.1.1 Description of the equipment used

The equipment required for carrying out the experiment is made up of four main components, viz., the sub-critical assembly, a neutron source, the detectors & associated electronics and the time stamping data acquisition system. Many of these systems have been described in earlier chapters. The data acquisition system was described in Chapters-3 in connection with the development with this crucial piece of equipment for noise related experiments. A description of the sub-critical assembly was given in Chapter-5 as it was required for numerical modelling.

In this chapter we limit ourselves to discussing the source and the detector & associated electronics.

6.1.2 Neutron source

An Am-Be neutron source was used in the experiment as an external neutron source and was placed at the centre of the core. At a source strength of ~ 1.0e+4 n/sec, the count rate was in the range of 1000 cps. DT accelerator based neutron source was also available. As described in Chapter-3, the statistical properties of DT neutron source were studied experimentally and were found to be different from Poisson source. Use of non-poisson source calls for complicated mathematical data analysis since expressions of the noise descriptor is different in case of the non-Poisson source (Degweker, 2000, 2003). Moreover the main purpose of the experiment was to study the modal (spatial) effects and to demonstrate the method proposed for mitigation of these effects. Therefore, the Am-Be source (Poisson source) was deemed to be adequate for this purpose. .

6.1.3 Neutron detectors

A few penetrations (few mm dia.) in the high density polyethylene moderator region are available for inserting miniature detectors for the flux measurements. However detectors of such miniature size are too small to give adequate detection efficiency for noise measurements. Moreover the special detector arrangement worked out in the previous chapter required placement of detectors in at least 8 locations for suppressing the most significant contributions from higher modes. It was therefore decided to accommodate the detector in the fuel rod locations by removing four fuel rods. (The reactivity effect of the removal of these rods was estimated and found to be small about ~ 5 mK). Therefore, the diameter of the detectors was chosen to be slightly less than the fuel rod diameter so that they could be accommodated in the space created by removal of the fuel rods. The length of the detector was chosen to be 10 cm so that detectors have good sensitivity and at the same time can be considered to point detectors as they are small compared to the core length. Therefore, a detector having a diameter less than 3.44 cm and a length of 10 cm was chosen. Helium gas filled detectors were procured as they have good sensitivity even for the small size. Other detectors like BF_3 gas filled or Boron coated detectors have a lower sensitivity for the given size of the detector. A cross sectional view of the detector is shown in Fig. 6.1. The characteristic plateau curve was obtained for all the detectors for the purpose of HV application. A typical characteristic plateau is shown in Fig. 6.2. The technical details of the detectors are as follows.

General Properties

Filling gas	He^3
Gas pressure (Torr)	3800
Cathode material	SS
Maximum length (mm)	174.8
Effective length (mm)	100.0
Maximum diameter (mm)	25.4
Effective diameter (mm)	24.38
Connector	HN

Operating temperature range (C)	-50 to +100
Effective volume (cc)	50.65

<u>Electrical Properties</u>

Recommended operating voltage (V)	1000
Operating Voltage range (V)	900-1300
Maximum plateau slope (%/100 volts)	1
Maximum resolution (%/FWHM)	10
Capacitance (pf)	8
Weight (grams)	85
Thermal neutron sensitivity	18
Efficiency of the detector	**0.01**

6.1.4 Electronics

The nuclear instrumentation used for the signal processing in the experiment includes a charge sensitive pre-amplifier, spectroscopy amplifier and a single channel analyzer to apply a suitable discriminatory bias to remove the noise. A signal adder module named as 'Junction Box' was developed which was used to add the signals from all the detectors. This model was tested for its performance by using an Am-Be neutron source, and the performance was found satisfactory. The developed 'neutron pulse time stamping data acquisition system' was employed for data collection in the experiment. The development and testing of this system was described in Chapter-3. The details of the electronics modules used are the same as described in Chapter-3.

The dead time is an important parameter of the electronics used in the neutron noise experiment. The specifications of the electronics modules were chosen in such a way that the dead time of the system should be reasonably small. The dead time of the system used in this experiment was deduced by obtaining the time interval distribution of neutron counts. The time bin width for obtaining this distribution was chosen to be 0.5 micro sec. The time interval distribution of neutron counts obtained in this way is shown in Fig 6.3. It can be seen that upto 2 micro sec there are no counts, after which they increase rapidly. The rise though rapid, is not instantaneous, which indicates that the dead time is of the paralysable kind. Thus the dead time of the system is found to be 2 micro sec. The count rate in the main experiment is maintained at about 1000 cps which is low enough to need practically no dead time correction.

6.2 Detector configurations used in the experiment

Eight helium gas filled neutron detectors were used in the experiment. The combined TTL signal from all the detectors was fed to the neutron pulse time stamping data acquisition system (Kumar, Ali. Y. et al., 2015). Four sets of experiment were carried out using a different number of detectors in various configurations. These neutron detector locations in the core were decided on the basis of the modal analysis of the core discussed in previous chapter.

In the first two configurations, eight detectors were used (four in each axial plane) and the axial locations of the detectors was chosen based on the zeros of the axial modes at $z = \pm 18.5\ cm$. In the X-Y planes there are a number of locations as per Table-5.2 of Chapter-5 which shows the first radial mode. The first choice, called R1 consists of locations D-4, D-10, J-4 and J-10 (Fig. 5.2 in Chapter-5) in the radial (X-Y) plane. These locations represent the zeros of the symmetric mode in the radial plane hence this arrangement of the detectors will minimize the contribution from the radial mode, and by ensuring azimuthally symmetric locations, the higher azimuthal modes will also be eliminated. Thus, there are a total of eight detectors (four in each of the $z = \pm 18.5\ cm$ planes). This configuration is referred to Case 8-DET-R-1. In this configuration, each of the two sets of four detectors were placed at intersection of the zeros of the symmetric mode in the axial direction and also at symmetric locations with respect to the centre. Adding the signal from these two sets of detectors will eliminate the contribution from all axial anti-symmetric modes. This arrangement will therefore eliminate the modal contamination in measured neutron decay constant from first higher symmetric mode and all higher anti-symmetric modes. The contribution from the second and higher symmetric modes is expected to be small.

Another configuration (R-2) with eight detectors consists of B-7, L-7, G-2 and G-12 locations in X-Y plane. Axial location is same as was in earlier configuration ($z = \pm 18.5\ cm$). This configuration is referred to as Case 8-DET R-2. This is expected to perform similar to the configuration 8-DET R-1.

The third configuration consists of only four detectors placed at B-7, L-7, G-2 and G-12 locations in one of the axial planes and is referred to as 4-DET-R2. In this configuration, axial anti-symmetric modes were present (which were eliminated in case of 8 detectors due to the addition of signals) and hence significant modal contamination is expected. The fourth configuration has only one detector in the lattice location C3 and is referred to as 1-DET-C3.

The degree of modal contamination can be studied by analyzing the results of the four sets of the experiment corresponding to the different detector configurations.

6.3. Data analysis

The data analysis was carried out by two different noise methods namely Feynman alpha and Auto correlation function method. The method and procedure of data analysis were discussed in earlier Chapters (2, 3 and 4) in detail. Before starting the data analysis by any method, it is important to see the stability of the collected data. Here stability means the stability of the count rate throughout the count collection time. There may be shifts/fluctuations in the count rate during the experiment. There may be several reasons for this instability like poor stability of electronics, spikes in the power supply or change in the other experimental conditions. The stability of the count rate was tested by obtaining the count rate (cps) by processing the entire time stamped data through a FORTRAN program. The profile of count rate over the data collection time is observed before processing it further for the data analysis. As an example, Fig.6.4 shows the count rate profile of counts collected over a period of 200 sec. The Y axis shows the normalized count rate. It can be seen from the figure that there is a shift in the count rate profile after about 1000 sec. This type of unstable count rate is not acceptable and therefore is not suitable for the analysis and hence the data is rejected. An example of data set with stable count rate is shown in Fig. 6.5. The effect of instability in the count rate is reflected clearly in the Feynman alpha curve obtained using stable and unstable data set. Profiles of the relative variance for both the data sets are shown in Fig.6.6. It can be seen that there is a remarkable difference between the profiles of the relative variance corresponding to the stable and unstable data sets. The shift in the count rate in the unstable data set causes a continuous increase in the V/m curve, while the V/m curve of the stable data set behaves properly; it gets saturated on its characteristic time scales.

6.3.1 Feynman alpha method

The prompt neutron decay constant is estimated by fitting the measured relative variance to Eq. (2.16) of Chapter-2. The sub-critical reactivity ρ can be inferred from the measured value of neutron decay constant provided the delayed neutron fraction (β) and the neutron generation time (Λ) are known.

As mentioned before, this equation is valid in the point model of reactor noise. We have eliminated the effect of higher modes by placing the detectors at suitable locations as discussed in the Section 6.2. In the present experiment the hydrogenous material high density polyethylene is the moderator, the prompt neutron decay constant is much larger than the decay constants of the fastest decaying delayed neutron precursor and hence we can safely ignore delayed neutron contributions on the prompt neutron decay time scale that is of interest for measuring alpha. This is in contrast to the case of heavy water reactors discussed in Chapter-4. Hence we use the set of equations discussed in Chapter-2 for analysis and are reproduced below.

$$\frac{V}{m} = 1 + \varepsilon \frac{\overline{\nu(\nu-1)}}{(\overline{\nu})^2(\rho-\beta)^2}\left(1 - \frac{1-e^{-\propto t}}{\propto t}\right) \tag{6.1}$$

$$\propto = \frac{\rho-\beta}{\Lambda} \tag{6.2}$$

Neutron counts were registered with their time stamp for a long time duration (T) in one shot in the format shown in Table 3.1 of Chapter-3. To get the variance and mean for a time interval of length t, the entire data record was divided into n equal segments each of length t. The number of counts falling in each segment was obtained and the ratio of variance to mean of these counts was calculated using Eq. (4.4) of Chapter-4. This value of V/m corresponds to an interval length equal to t. The procedure was repeated varying the interval length (t) to get the V/m values as a function of the time interval t. The V/m ratios were thus obtained for time intervals length starting from 50 micro sec up to 5 mili sec in steps of 50 micro sec for all sets of the experiment. The range of time interval chosen is of the order of the inverse of the prompt neutron decay constant (α^{-1}). The maximum statistical error in the V/m is estimated to be 0.0026. The measured values of V/m were fitted to the Eq. (6.1) to obtain the prompt neutron decay constant. The reactivity value was inferred from Eq. (6.2) using the calculated values of β and Λ.

If the sampling of the neutron counts is not independent (which is true in case of time stamped/list mode data), it may result in a bias in the estimated variance as discussed earlier in Section 4.3.1. The bias factor for the present experiment was estimated using the following input parameters: α= 2.31 sec^{-1}; width T=5000 micro sec (Max gate width taken in the V/m analysis.); n=360000 (Typical data collection time is 30 minutes); and θ=0. The bias factor was thus found to be 2.65e-7 which has a negligible impact on the empirical variance.

6.3.2 Auto correlation function method

This method is similar in principle to the Rossi alpha method, but the data analysis is different. The Auto correlation function and Auto covariance functions were described in Section 2.3.3 of Chapter-2 [Eq. (2.18-2.20)]. These equations are reproduced below for easy reference.

$$\Phi(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{+T} dt(N(t)(N(t+\tau) \qquad (6.3)$$

$$\Phi'(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} dt((N(t) - \overline{N})((N(t+\tau) - \overline{N}) \qquad (6.4)$$

According to the point model of reactor noise, the Auto covariance function is given by

$$\Phi'(\tau) = \epsilon\lambda_f \overline{N}(\delta(t) + \varepsilon \frac{\overline{\nu(\nu-1)}}{2\Lambda(\beta-\rho)} e^{-\alpha\tau}) \qquad (6.5)$$

Eq. (6.3) represents the Auto correlation function of the number of neutrons in the system at a given time (t) with that at a later time (τ). Eq. (6.4) shows the Auto covariance function which is obtained by subtraction of the DC component of the neutron signal. The discretised form of Eq. (6.4) is reproduced below.

$$< (N(t) - \overline{N})(N(t+\tau) - \overline{N}) >= \frac{1}{n} \sum_i^n (N_i - \overline{N})(N_{i+k} - \overline{N}) \qquad (6.6)$$

where N_i represents the number of neutron counts in the i^{th} bin and $\overline{N}$ is the average of the neutron counts. If each bin is of size Δt, then the time lag τ =kΔ t.

The stored time stamped sequence of neutron counts was divided in bins of equal width (Δ t) of 50 micro sec such that N_i is the number of neutron counts in the i^{th} bin and $\overline{N}$ is the average neutron counts. The Auto covariance function is obtained for a range of values of τ using Eq. (6.6) from the measured data for all sets of the experiment and is shown in Fig. 6.7. The maximum statistical error is about 5.66e-6 which is less than 4 %. The Auto covariance measurements are fitted to Eq. (6.5) to extract the prompt neutron decay constant. The use of Eq. (6.5), which is strictly speaking valid for the point model, may be justified using the same argument that was given in the case of the Feynman alpha, in Section 6.3.1.

According to the second term in Eq. (6.5), the plot of the Ln of ACV Vs the time interval between bins, is expected to be a straight line. The Ln of measured ACV was fitted to the straight line and the prompt neutron decay constant is obtained from the slope. This statement is true if the system has one alpha value i.e. only the fundamental mode. If higher modes have a significant effect on the neutronics of the system, Eq. (6.5) will have to be modified to have multiple exponential terms and in that case, Ln of ACV will deviate from the straight line. Therefore, it is straight forward to study the modal effect in the system qualitatively by analysing the plot of Ln (ACV) Vs time and it is easy to obtain the decay constant by doing the liner fit of the plot. The plot should be a straight line if modal contamination is absent.

6.4. Results and discussion

Data analysis of all sets of experiment was carried out by the Feynman alpha and the Auto correlation function methods. The level of modal contamination among the different sets of experiment can be analyzed qualitatively by examining the shape of the curve in Fig. 6.7, which shows the plot of Ln (ACV) Vs time lag for each set of experiments. One can see that the Ln (ACV) Vs time for 8 detectors in case of both the radial configuration R1 and R2 is almost straight . It shows that the contribution of higher modes was minimal on placing the 8 detectors at the proper locations as discussed in Section 6.2 regarding the experimental setup. In the case of 4 detectors the Ln(ACV) curve deviates slightly from a straight line. Moreover, the slope of the fitted straight line is somewhat greater than what was obtained in the cases 8-DET R-1 and 8-DET R-2. This can be attributed to the fact that on removing one set of four detectors from one axial side, the contribution from the axial anti-symmetric mode appears which was getting cancelled (in the 8 detector case) due to the addition of the detector signals from both the sides. In case of the single detector, the Ln(ACV) curve is not at all straight. It shows that the ACV for the case of a single detector contains multiple exponentials due to significant contributions from the higher modes.

The values of the prompt neutron decay constant are obtained by fitting the Ln(ACV) curve to a straight line, and are given in Table-6.1. In the case of four detectors the alpha value is significantly different from the reference value. And in the case of a single detector it is far away from the reference value. These numbers are therefore consistent with the qualitative analysis described above.

The summary of the fitting of Auto covariance function to the single exponential term is given in Table-6.2. It can be seen that error in the fitted value of slope (alpha value) is slightly more in case of 4 detector case in comparison to 8 detector case. In single detector experiment, the error in fitted value of slope is significantly large in comparison to 8 or 4 detector case. Values of 'sum of residuals square' and 'Adj. R Square' are also following the similar trend. This shows that as one move from single detector case to 4 or 8 detector cases, modal contamination reduces and consequently this increases the validity of single exponential model and hence the quality of fitting improves

In spite of substantial reduction in modal contamination by strategic placement of the detectors and combining their output as described above, even in the best case, the modal contamination could not be removed completely. One reason is that only the contribution of the first set of symmetric and all anti-symmetric higher modes could be removed. The contribution from other higher symmetric modes though small was still present in the measured data. Another reason is that the only positions available for placing the detectors were the fuel positions while the zeros may not necessarily present at these positions. This will cause small contributions from modes that are sought to be fully eliminated.

In the case of the Feynman alpha method, the level of modal contamination among the different sets of the experiment can be analyzed qualitatively by observing the shape of the curves in Fig 6.8, 6.9, 6.10. The figures show the plot of Y (V/m-1) Vs gate width value for various sets of the experiment. It also includes the reference curve of Y value. Fig. 6.11 shows the deviation of Feynman alpha curves from reference for all sets of the experiment. One can see that the Y curve in Case 8-DET R-2 lies on the reference Y curve within the error bars. The reference Y curve was generated using the reference value of prompt neutron decay constant. It shows that the contribution of higher modes was minimal when 8 detectors were placed at the correct locations as described in the Section 6.2. In the case of 4 detectors, the measured Y curve deviates from the reference curve slightly, while in the case of a single detector, it deviates significantly from the reference curve. In both the latter cases the deviation is greater in the short time interval region but the Y curve agrees with the reference curve in the saturation region. This deviation in the high frequency region can be understood due to modal contamination from the higher (fast decaying) modes in the case of one and four detectors. Another reason as mentioned earlier is that the only positions available for placing the detectors were the fuel positions while the zeros may not necessarily present at these positions. This will cause small contributions from modes that are sought to be fully eliminated.

The values of the prompt neutron decay constant were obtained by fitting the measured Feynman Y values to the Eq. (6.1) and are given in the Table-6.1. The comparison among the values of alphas for various cases is similar to what was seen in the case of analysis by the Auto correlation function method. In the case of four detectors, the alpha value is significantly different from the reference value and in the case of a single detector; it is further away from the reference value. The results are consistent with the qualitative analysis carried out above by observing the Feynman alpha plots. The results obtained by the Auto correlation function method are consistent with the ones obtained by the Feynman alpha method in all sets of the experiment.

In results obtained by auto correlation analysis, it can be seen that in case of 8 detector case (R1 & R2), upper bound of deviation between measured and reference value of alpha is less than 12 %. This deviation is about 17% and 35 % in case of 4 detectors and single detector respectively. The trend is similar in the results obtained by Feynman alpha analysis. Thus, the effect of modal contamination is least in case of 8 detector configuration and maximum in case of single detector; the pattern of deviation is as per the theoretical expectations. Apart from modal contamination, other errors like statistical one are also are the components the deviation between measured and reference value of alphas. Therefore it can be concluded that the modal contamination effect could be mitigated significantly by employing the proposed method.

Based on the autocorrelation and Feynman alpha method for 8 detectors case (R1 & R2), measured average value of alpha comes out to be 2.52 $msec^{-1}$. This value of alpha along with the calculated values of prompt neutron generation time and delayed neutron fraction can be used to infer the reactivity of the sub-critical system using Eq.(3). The sub-critical reactivity inferred works out to be 139 mK which corresponds to a K_{eff} of 0.878. This value of K_{eff} is in good agreement with the value obtained by calculations described in section 2.3. It also matches well with the values of K_{eff} measured in the other experiment carried out by area ratio and slope fit method (deterministic method) (Sinha Amar etal., 2015).

Table-6.1: Measured value of the prompt neutron decay constant for all sets of experiments

Exp. set	Prompt neutron decay constant α ($msec^{-1}$)		
	Auto correlation	Feynman Alpha	Reference
8 DET-R1	2.58 ± 0.056	2.62 ± 0.023	2.31
8 DET-R2	2.44 ± 0.068	2.46 ± 0.027	
4 DET-R2	2.70 ± 0.082	2.66 ± 0.025	
1 DET-C3	3.11 ± 0.145	3.58 ± 0.44	

Table-6.2: Detail of fitting of Auto covariance function for all sets of the experiment

Configuration	Fitting Parameters	Value (± Standard error)
8 Det-R1	Intercept	-6.751± 0.0400
	Slope (micro sec^{-1})	-0.00258± 5.71E-5
	Sum of residuals square	0.1445
	Adj. R Square	0.9898
8 Det-R2	Intercept	-6.962± 0.048
	Slope	-0.00244 ± 6.85E-5
	Sum of residuals square	0.2082
	Adj. R Square	0.9836
4 Det	Intercept	-8.188± 0.0575
	Slope	-0.00270±8.20E-5
	Sum of residuals square	0.2984
	Adj. R Square	0.9809
Single detector	Intercept	-7.678±0.1019
	Slope	-0.00311±1.453E-4
	Sum of residuals square	0.9359
	Adj. R Square	0.9559

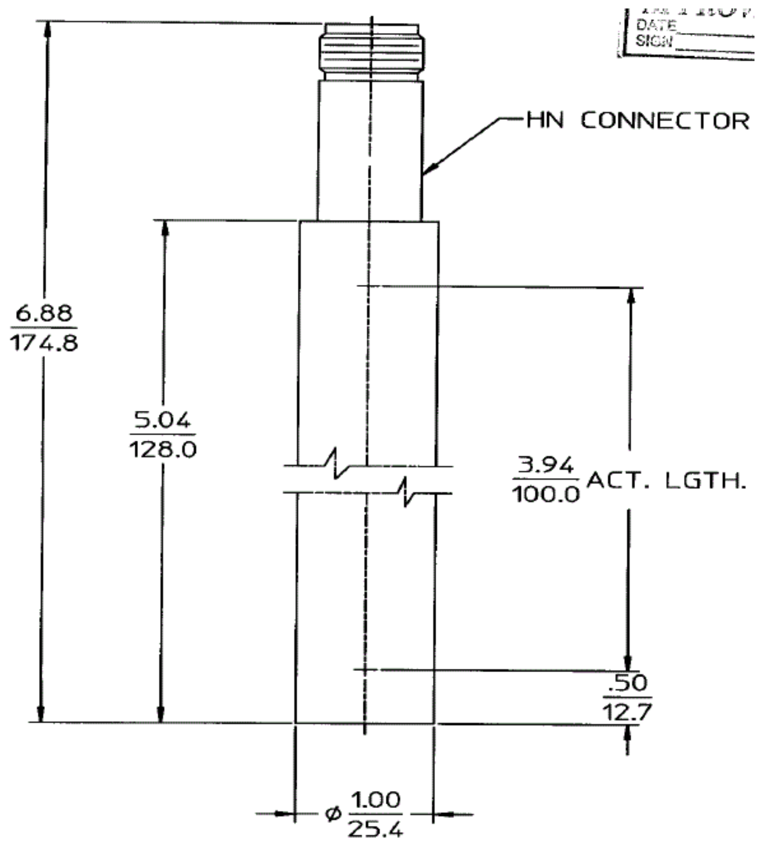

Fig. 6.1 Cross sectional view of the helium detector

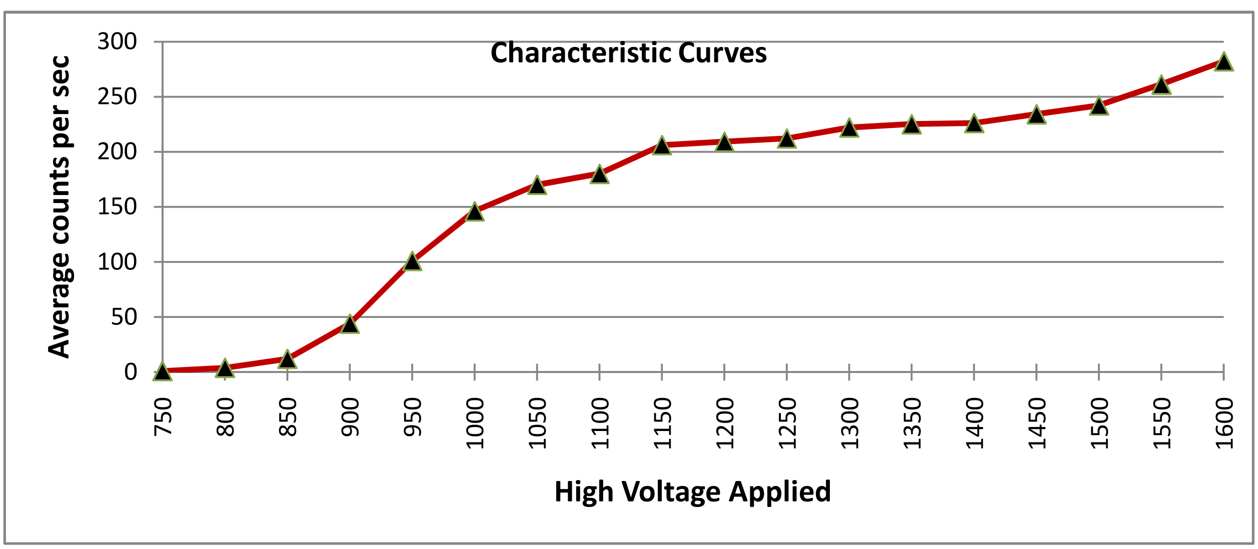

Fig. 6.2 Characteristic curve showing the variation of counts with applied voltage.

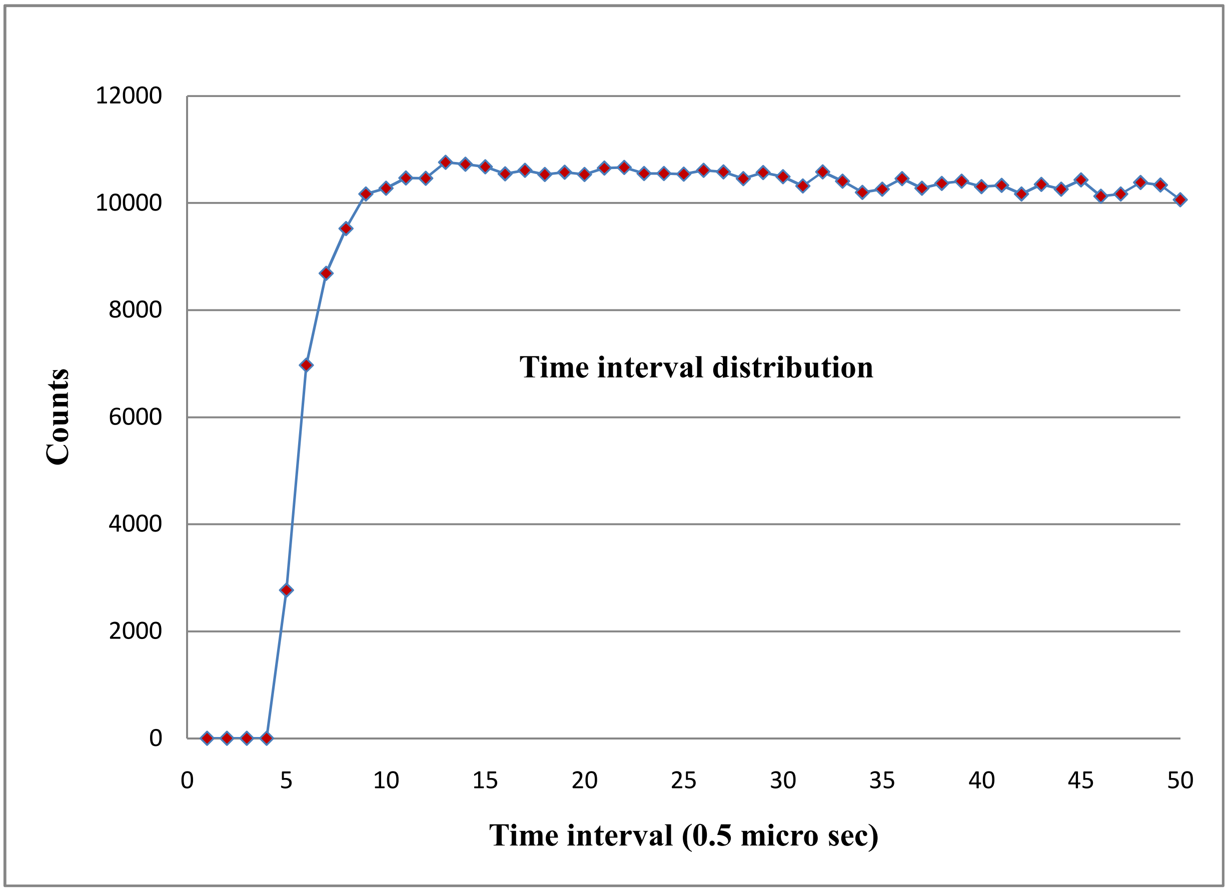

Fig. 6.3 Time interval distribution of counts

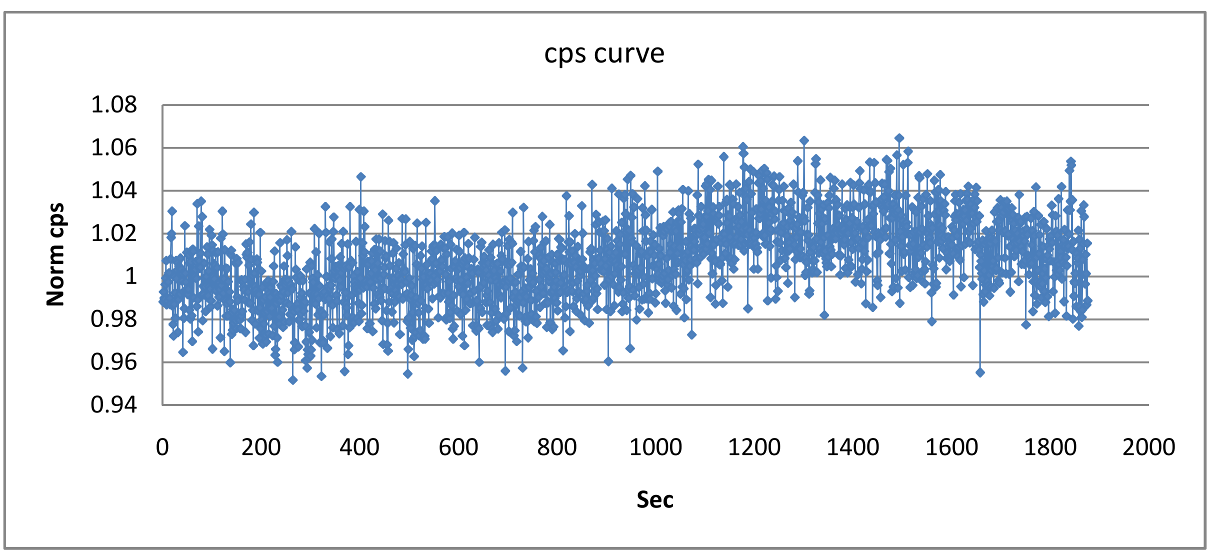

Fig 6.4 Data with unstable count rate

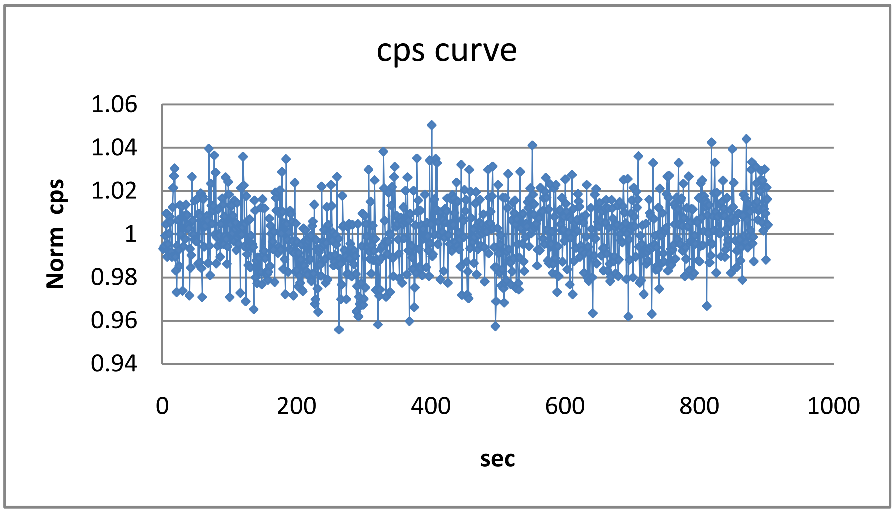

Fig. 6.5 Data with stable count rate

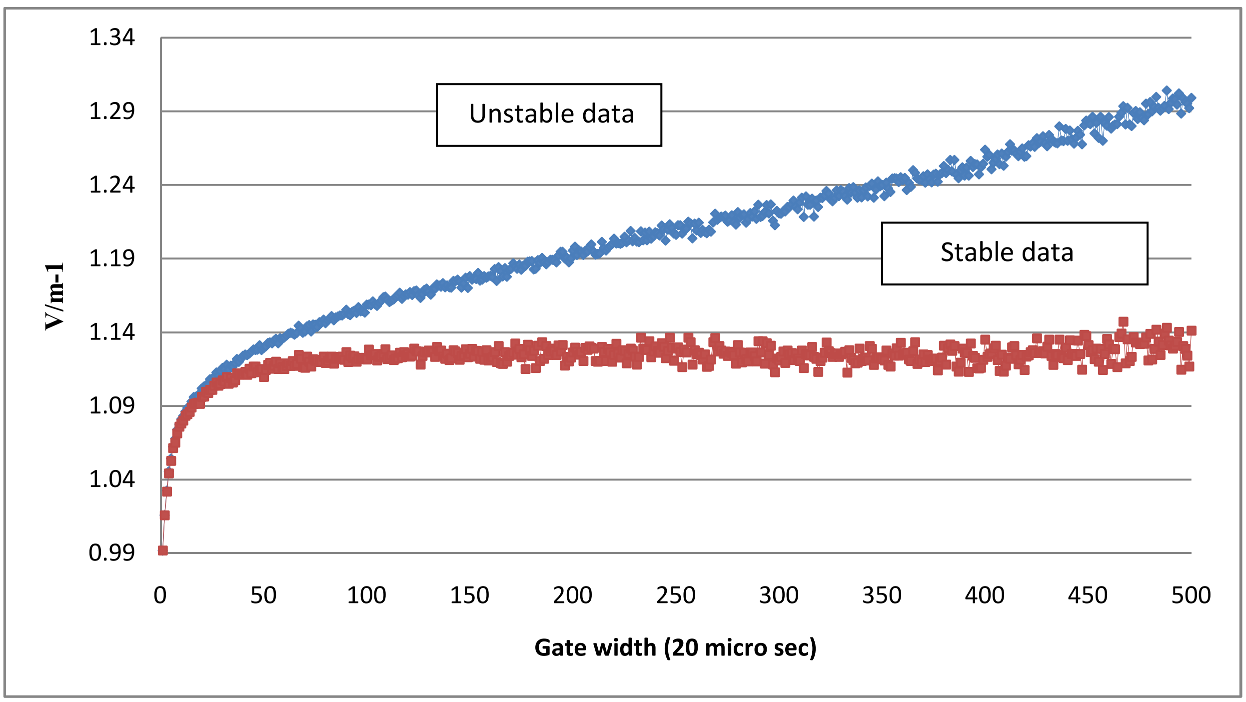

Fig. 6.6 Effect of unstable count rate on the relative variance

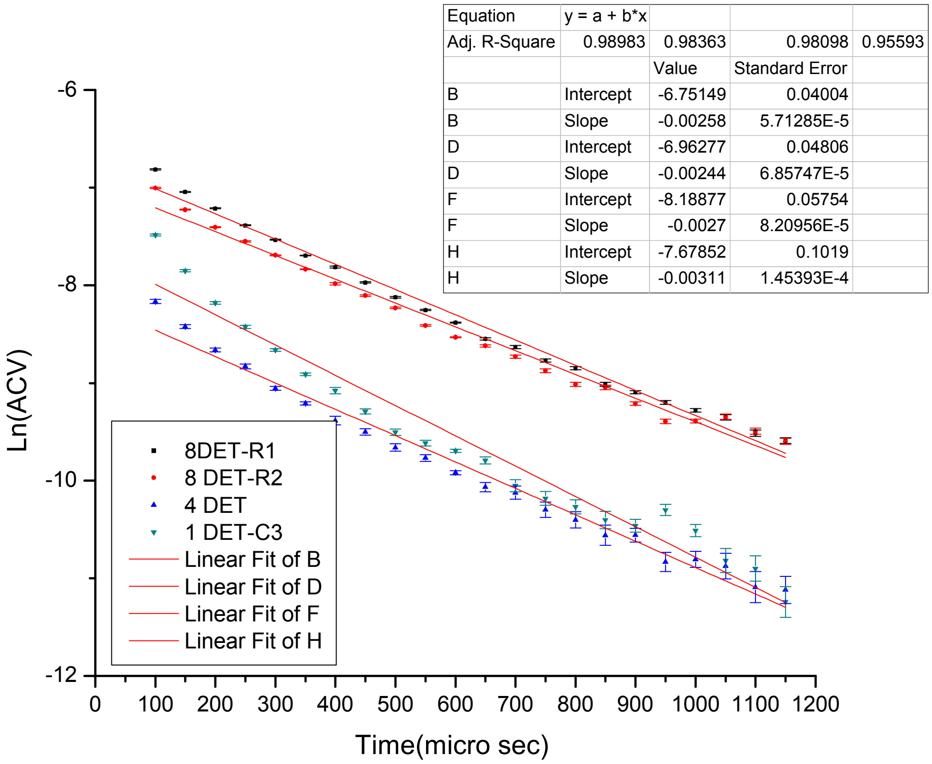

Fig. 6.7 Measured and fitted Auto covariance function for all sets of the experiment.

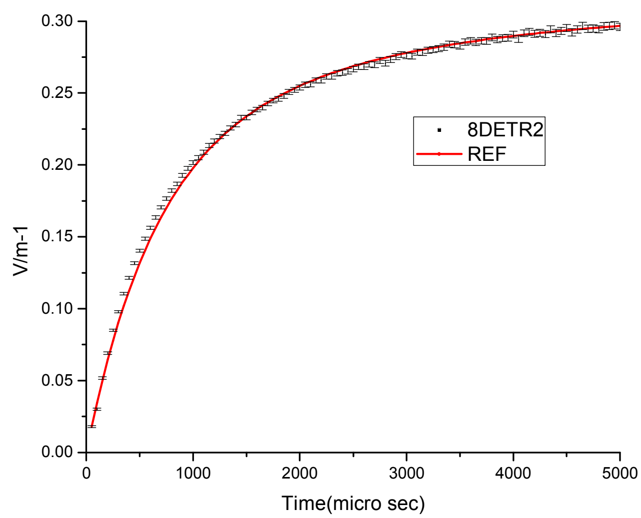

Fig. 6.8 Measured and reference Feynman alpha plot for set 8-DET-R2

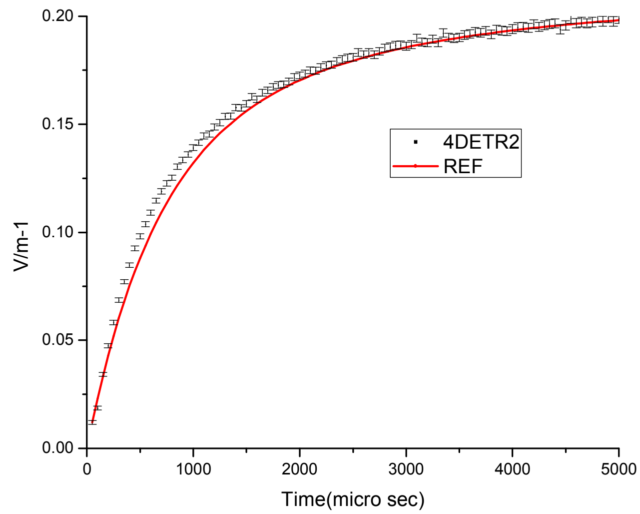

Fig. 6.9 Measured and reference Feynman alpha plot for set 4-DET-R2

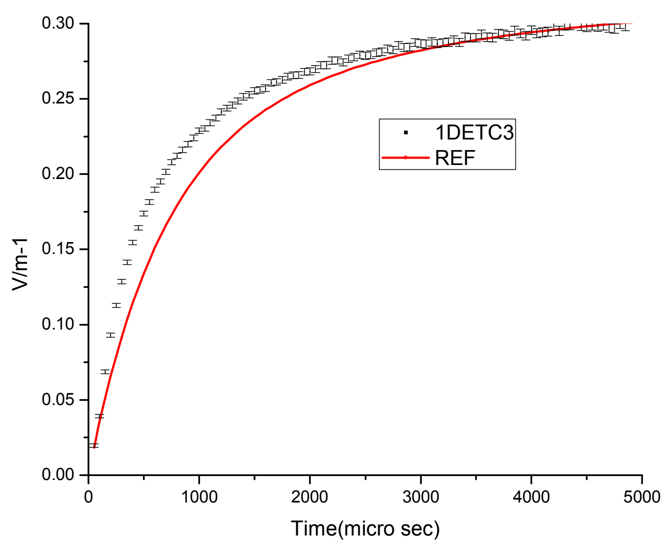

Fig.6.10 Measured and reference Feynman alpha plot for set 1-DET-C3

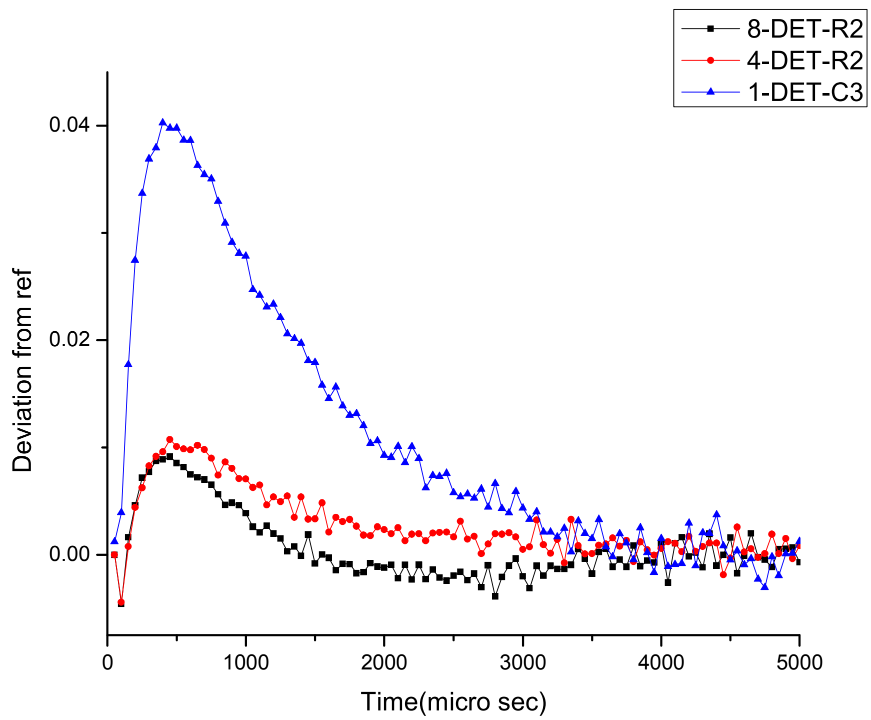

Fig.6.11 Deviation of Feynman alpha curves from reference for all sets of the experiment

Chapter-7

Summary and conclusions

Problems associated with the application of neutron noise methods for measurement of sub-criticality of accelerator driven systems (ADS) have been studied experimentally. The studies include space dependent effects in reactivity measurement, the contribution of delayed neutrons in such measurements & the non-Poisson character of the accelerator based neutron source. The experiments were carried out in two reactors. One of these is the critical facility which is a zero power heavy water moderated reactor which was used to study the effect of delayed neutrons on sub-criticality measurements. The other is the BRAHMMA (Berylium Reflected and High density polyethylene Moderated Multiplying Assembly), a highly sub-critical assembly that was used for studying spatial effects in reactivity measurement. A 14 MeV D-T neutron source was used to study the statistical properties of an accelerated based neutron source. The development of a "neutron pulse time stamping data acquisition system" was a necessary & significant part of the preparatory work for these experiments. The data acquisition system was developed for application to reactor noise analysis and may also be used in passive neutron assay (PNA). Traditionally the electronics modules that are used to acquire data in neutron noise and passive neutron assay experiments are specific to the method of analysis. Hence only one type of analysis can be carried out with the data set acquired using conventional electronics. The measurements have to be repeated with different electronics if one wants to employ another method for the analysis. The system developed by us registers each neutron count with its time stamp which provides the entire time history of neutron counts permitting analysis by any of the methods of neutron noise and passive neutron assay. The system was tested on two types of neutron sources. The statistical properties of these two sources were studied and were found to be consistent with the expected statistical character of the sources. This provided the necessary validation of the data acquisition system.

As mentioned above, the space dependence of noise in sub-critical systems, specially in highly sub-critical systems, and its impact on sub-criticality measurements was studied. The experiments were carried out in the BRAHMMA sub-critical assembly which is sub-critical by more than 100 mk. Eight numbers of helium gas detectors were used and their combined output was fed to the time stamping data acquisition system described above. An attempt was made to minimize the spatial effects by placing the detectors at strategically chosen locations. These detector locations were obtained on the basis of detailed modal calculations for the sub-critical system. The data analysis was carried out by two different noise methods namely the Feynman alpha method and the Autocorrelation function method. The measurements were compared with the calculations.

The second problem mentioned above was the study of the contribution of delayed neutrons and delayed photo neutrons in the measurement of sub-critical reactivity in heavy water moderated reactor. We have interest in this problem since heavy water moderated reactors constitutes most of the power generating reactors in India and also one of the options for future ADS in India. Measurement of the kinetic parameters using noise methods in such systems is difficult because prompt and delayed neutron time scale is not distinctly different. Hence long time correlations due to delayed and delayed photo neutrons have to be analyzed together with the correlations due to prompt neutrons due to the significant overlapping between the two. This makes the data analysis more cumbersome and involved.

Measurement of reactivity was done at various levels of sub-criticality. The data analysis was done by two noise descriptors namely Feynman alpha and Autocorrelation function method and delayed neutrons/ delayed photo neutrons were treated in six group.

One of the principal differences between reactor noise in ADS and traditional reactors lies in the characteristics of the external source. There are reasons to believe that the accelerator produced neutron source cannot be assumed to be a Poisson process (Rana and Degweker 2007). An immediate consequence of this is that the commonly used approaches in traditional reactor noise theory are not applicable to the study of reactor noise in ADS. A new theory has been developed for describing reactor noise in ADS (Degweker 2000, 2003). The third problem studied in the thesis is related to this feature of reactor noise in ADS. The time stamping data acquisition system was applied to study the statistical properties of accelerator based neutron source. Several descriptors were studied on short and long time scales & these were found to be different from that of Poisson sources.

The main conclusions of our studies are as follows.

The "neutron pulse time stamping data acquisition system" developed as part of this work is a very versatile tool for the noise analysis and related applications. The system was used successfully in all our experiments for noise analysis by various methods, thus demonstrating its utility. It represents a major advance for future noise and PNA measurements.

The mitigation of modal contamination using the proposed method was demonstrated successfully and the experiment in BRAHMMA confirms our theoretical expectations based on an earlier theoretical work on the subject. The experiment was carried out in three sets where one detector, four detectors and eight detectors were used in each set of measurements with varying degrees of modal contamination (expected on theoretical grounds) in each set of measurement. The observed degree of modal contamination was along the theoretical expectations, being least for the 8 detector case and most for the single detector case. The measured value of the prompt neutron decay constant with eight detectors was found in agreement with the calculated value. The value of K_{eff} inferred from this measurement of decay constant was found in good agreement with the calculated value in this work and also with the K_{eff} value obtained in another experiment carried out in BRAHMMA using a different method.

The measured values of reactivity at each level of sub-criticality in the heavy water moderated reactor were found to be in fairly good agreement with the theoretical estimates only when the analysis included the effect of delayed neutron/delayed photo neutrons. The reactivity could be extracted from a study of correlations within an error band of 0.5 mK. The experiment showed the importance of including the delayed neutrons in noise analysis in such situations.

As a third outcome of the work done in this thesis the statistical properties of DT accelerator based neutrons were found to be different than that of a Poisson source. This finding supports our belief about the character of noise in ADS.

Scope for future studies

Presently the time stamping data acquisition system has only one channel available for acquisition. However it has a capability to acquire data using 8 channels simultaneously. The provision for data acquisition using more than one channel will be provided in future; such an extension of the system capability will be useful in cross correlation measurements where two or more outputs (eg. detector and source signal) can be registered with their time stamp.

There is a proposal to introduce SEU in some of the fuel rods in BRAHMMA. This will enable us to study sub-criticality measurement methods at different level of sub-criticality. Regarding the work carried out in the heavy water reactor, measurements can be carried out at deeper levels of sub-criticality. The method for mitigation the space effects demonstrated in BRAHMMA can be applied in these experiments. As regards the experimental confirmation of the non-Posisson characteristic of the neutron source in context of the ADS, more convincing experimental studies can be carried out using other types of accelerator based sources in continuous as well as pulsed modes of operation.

References

Abanades A. et al., (2002), Results from the TARC experiment: spallation neutron phenomenology in lead and neutron-driven nuclear transmutation by adiabatic resonance crossing, Nucl. Instr. Meth. A, 478(3), 577.

Abderahim H. A., (2005), Myrrha Project-ADS Related R&D and Nuclear Data, DAE-BRNS National Workshop on Nuclear Data for Reactor Technology and Fuel Cycle, Mumbai, India.

Abderrahim H. A. et al., (2001), MYRRHA: A multipurpose accelerator driven system for research & development, Nucl. Instr. Meth. A, 487.

Albrecht R. W., (1962), The Measurement of Dynamic Nuclear Reactor Parameters using the Variance of the Number of Neutrons Detected, Nucl. Sci. Eng., 14, 153.

Anderson J., Chernikova D., Pázsit et al., (2012), Two-point theory for the differential self-interrogation Feynman-alpha method, Eur. Phys. J. Plus 127 (8).

Andriamonje S. et al., (1995), Experimental determination of the energy generated in nuclear cascades by a high energy beam, Physics letters B, 348, 697-70.

Avery R., (1958), Theory of coupled reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, vol. 12. United Nations, Geneva, pp. 182–191.

Babala D.,(1966), Report KR-114.

Babala, D. (1967), Point-reactor theory of Rossi-alpha experiment, Nucl. Sci. Eng., 28, 237.

Baeten P. and Abderrahim A., (2003), Reactivity monitoring in ADS application to the MYRRHA ADS project, Prog. Nucl. Energy, Vol,43,1-4,pp 413-419.

Bécares V., Villamarín D. et al.,(2013), Validation of ADS reactivity monitoring techniques in the Yalina-Booster sub-critical assembly, Annals of Nuclear Energy 53, 331–341.

Behringer K. and Wydler P.,(1999), On the Problem of Monitoring Neutron Parameters of the Fast Energy Amplifier, Annals of Nuclear Energy 26, 1131.

Behringer K., Phildius J. and Seifritz W., (1975), Ann. Nucl. Energy, Vol.2, 399-403.

Bell G. I., (1965), On the stochastic theory of neutron transport, Nucl. Sci. Eng., 21, 390.

Bell G.I., (1965), Nuclear Science and Engineering, 21, 390.

Bell G. I. and Glasstone S., (1970), Nuclear Reactor Theory, Van Nostrand Reinhold, New York.

Bennett E. F., (1960), The Rice formulation of pile noise, Nucl. Sci. Eng., 8, 53.

Bernstein S., Preston W.M., Wolfe G. and Slattery R.E., (1947), Yield of Photo-Neutrons from ^{235}U Fission Products in Heavy Water, Phys. Rev. 71, 573.

Billebaud A. et al., (2009), The GUINEVERE Project for Accelerator Driven System Physics, International conference GLOBAL 2009, The Nuclear Fuel Cycle: Sustainable Options and Industrial Perspectives, Paris, France.

Brikhoff G., (1985), Monitoring of plutonium contaminated waste, Commission of European Commmmunities EUR-10026.

Birkhoff G., Bondar L., and Coppo N., (1972), Variable Dead time Neutron Counter for Tamper Resistant Measurements of Spontaneous Fission Neutrons, Eurochemic Technical Report EUR-4801e.

Boehnel K., (1978), Determination of Plutonium in Coincidence Method, KFK2203, Karlsruhe, (54/4252), 489.

Bohnel K., (1975), Report KEF-2203.

Borgwaldt H. and Stegeman D., (1965), Nucleonik, 7, 313.

Bruno Rossi (1944).

Burger J.R., (1969), USAEC Report WAPD-TM-855.

Busch R.D., Spriggs G.D., (1994), Preliminary results of a Rossi-alpha experiment on the University of New Mexico's AGN-201 reactor. Trans. ANS, 459.

Carl Berglöf, Manuel Fernández-Ordóñez et al., (2011), Auto-correlation and Variance-to-mean measurements in a subcritical core obeying multiple alpha-modes Annals of Nuclear Energy 38, 194–202.

Carl Magnus Persson et al., (2005), Analysis of reactivity determination methods in the sub-critical experiment Yalina, Nucl. Instr. Meth. A, 554, 374.

Carta M. and D'Angelo A., (1999), Sub-criticality level evaluation in accelerator driven systems by harmonic modulation of the external source, Nucl. Sci. Eng., 133, 282.

Chernikova D., Wang Z., Pázsit I. et al., (2014), A general analytical solution for the variance-to-mean or Feynman-alpha formulas for two-group two-point, two group one-point and one-group two-point cases. Eur. Phys. J. Plus, submitted for publication.

Cohn C.E., (1960), Nucl. Sci. Eng. 7, 472.

Cohn C.E., (1962), Reflected-reactor kinetics. Nucl. Sci. Eng. 13 (1), 12–17.

Courant E. D. and Wallace P. R., (1947), Fluctuations of the Number of Neutrons in a Pile, Physical Review, 72(11), 1038.

Croft S., Henzlova D., et al., (2014), The optimum choice of gate width for neutron coincidence counting, Nuclear Instruments and Methods Physics, Vol., 764,11,322-329.

Croft S., Henzlovaa D., Haucka D.K., (2012), Extraction of correlated count rates using various gate generation techniques: Part I theory, Nuclear Instruments and Methods in Physics Research A 691,152–158.

Degweker S.B., (1989), Ann. Nucl. Energy 16,409.

Degweker S. B., (1994), A forward equation for stochastic neutron transport, Ann. Nucl. Energy, 21(9), 531.

Degweker S. B., (2000), Some Variants of the Feynman Alpha Method in Critical and Accelerator Driven Sub-critical Systems, Ann. Nucl. Energy, 27(14), 1245.

Degweker S. B., (2003), Reactor Noise in Accelerator Driven Systems, Ann. Nucl. Energy, 30(2), 223.

Degweker S. B. and Rana Y. S., (2007), Reactor Noise in Accelerator Driven Systems-II, Ann. Nucl. Energy, 34(6), 463.

Degweker S. B. et al., (2010), Neutronic Studies for Thorium Utilization in Accelerator Driven Systems, International Workshop on Accelerator Driven Sub-critical Systems and Thorium Utilization, Virginia Tech, Blacksburg, Virginia.

Degweker S. B. and Rana Y. S., (2011), The Langevin Approach to Reactor Noise in Accelerator Driven Systems, Nucl. Sci. Eng., 169, 296.

Degweker S.B., Singh P. et al., (2013), Accelerator Driven system for thorium utilization in India, International thorium energy conference, Oct 27-31, CERN, Switzerland.

Degweker S.B. et al., (2016), On the relation between Rossi alpha and Feynman alpha methods**,** Annals of Nuclear Energy 94 (2016) 433–439.

Dragt J.B., (1966b), Reactor noise analysis by means of polarity correlation, Nukleonik, 8 (4), 225.

Dytlewski N., Krick M.S. and Ensslin N., (1993), Measurement variances in thermal neutron coincidence counting, Nuclear Instruments and Methods in Physics Research A327, 469-479.

Feynman R.P., (1944) Unpublished.

Feynman R. P. et al., (1956), Dispersion of the neutron emission in U^{235} fission, J. Nucl. Energy, **3**, 64.

Gohar Y. et al., (2004), Accelerator-Driven Sub-critical assembly: concept development and analyses, The RERTR-2004 international meeting on reduced enrichment for research and test reactors, Vienna.

Gohar Y., Aliberti G., Bolshinsky et al., (2009), YALINA booster subcritical assembly conversion. Trans. Am. Nucl. Soc. 101, 39–40.

Gohar Y. and Smith D. L., (2010), YALINA Facility A Sub-Critical Accelerator-Driven System (ADS) for Nuclear-Energy Research Facility Description and an Overview of the Research Program (1997-2008), ANL-10/05.

Gotoh Y., (1964), Measurement of neutron life time in a D_2O system by neutron fluctuation, Journal of nuclear science and technology, 1, No 6, p.193-196.

Hanson A.L et.al, (2006), Calculation of the Prompt Neutron Lifetime in the NBSR, Nuclear science and enginering: 153, 2632.

Hashimoto K., Ohya K. et al., (1996), Experimental investigation of dead time effect on Feynman alpha method, Ann. Nucl. Energy, 23, 1099.

Hill D.J, Ragland W. A. and Roglans J., (1994), The EBR-II probabilistic risk assessment: Lesson learned regarding passive safety, Reactor Analysis Division, Argonne National Laboratory. (ANL/RC/CP/81828).

IAEA report (1999), on the preliminary fact finding mission following the accident at the nuclear fuel processing facility in Tokaimura, Japan.

IAEA Report (2004), nuclear safety review for the year 2003.

Imel G. et al., (2004), The TRADE source multiplication experiments, PHYSOR 2004.

Jacquesson J. J., (1963), Phys 24, 112-116A.

Jammes Christian C. et al., (2006), Absolute Reactivity Calibration of Accelerator-Driven Systems, PHYSOR-2006.

Kadi Y. and Adonai Herrera-Martı´nez, (2006), Energy amplifier systems: simulation and experiments in the field, Nucl. Instr. Meth. A, 562, 573–577.

Kapoor S. S. (2001), Roadmap for development of Accelerator Driven Sub-critical Reactor Systems, BARC/2001/R/00.

Karam R.A., (1964), Measurement of Rossi-alpha in reflected reactors. Trans. ANS 7 (2), 283.

Keepin G. R., (1965), Physics of Nuclear Kinetics, Addison Wesley, Reading, MA.

Kitamura Y. Yamauchi H. et al., (2004), Experimental investigation of Variance to mean formula for periodic and pulsed neutron source, Ann. Nucl. Energy, 31,163-172.

Kitamura Y. et al., (2006), Calculation of the stochastic pulsed Rossi-alpha formula and its experimental verification, Prog. Nucl. Energy, 48, 37.

Kitamura Y. Taguchi K. A., Yamamoto et al., (2006), Application of variance-to-mean technique to sub criticality monitoring for accelerator-driven sub critical reactor, International Journal of Nuclear Science and Technology, vol. 2, no. 3, pp. 266 – 284.

Kumar Rajeev and Degweker S.B., **(2011),** Reactor Physics Experiments in PURNIMA Sub Critical Facility Coupled with 14 MeV neutron source, 2nd international conference on ADS and thorium utilization, Dec. 11-14, Mumbai, India.

Kumar Rajeev, Ali Y. and Degweker S.B. et al., (2015), Development and Testing of Neutron Pulse Time Stamping Data Acquisition System for Neutron Noise Experiments, Nuclear Instruments and Methods in Physics Research A770,8–13.

Kumar Rajeev, Degweker S.B., **Singh K.P. et al., (2016 a),** Measurement of Sub-critical Reactivity in a Heavy Water Reactor by Neutron Noise Methods Using a Time Stamping Data Acquisition System, Annals of nuclear Energy,87, 720-727.

Kumar Rajeev, Degweker S.B. et al.,(2016 b), Measurement of Reactivity in Source driven deep Sub Critical System using Neutron Noise Methods. **(***Communicated to Annals of nuclear Energy***).**

Kuang Z. F. and Pazsit I., (2000), A Quantitative Analysis of the Feynman-alpha and Rossi-alpha formulas with Multiple Emission Sources," Nucl. Sci. Eng., 136, 305.

Kuramoto R.Y.R., Santos A., Jerez R. et al., (2007), Absolute measurement of β_{eff} based on Feynman-α experiments and the two-region model in the IPEN/MB-01 research reactor. Ann. Nucl. Energy 34, 433–442.

Lee E. Park D. and Choi H., (2010), Experimental Determination of Sub criticality at Subcritical PWRs in Korea, Annals of Nuclear Energy, pp. 1601-1608.

Lambert K. and Leake J., (1979), A Comparison of the VDC and Shift Register Neutron coincidence Systems for - Assay, Nuclear Materials Management VII (4), 87.

Lestonea J.P., Pecosa J.K. et al., (2002), Passive nondestructive assay of the plutonium content of spent-fuel assemblies from the BN-350 fast-breeder reactor in the city of Aqtau, Kazakhstan, Nuclear Instruments and Methods in Physics Research A 490, 409–425.

Máté Szieberth, Gergely Klujber, Jan Leen Kloosterman et al., (2015), Measurement of multiple alpha-modes at the Delphi sub critical assembly by neutron noise techniques, Annals of Nuclear Energy 75, 146–157.

Matthes., (1962), Nucleonik 4, 213

Matthes., (1966), Nucleonik 8, 87 .

Mihalczo J.T., (1974), Nucl. Sci. Eng. 53,393.

Mihalczo J. T. et al., (1990), Dynamic sub-criticality measurements using the Cf^{252} source driven noise analysis method, Nucl. Sci. Eng., 104, 314.

Misawa T., Shiroya S., Kanda K., (1990), Measurement of prompt decay constant and sub criticality by Feynman-a method, Nucl. Sci. Eng. 104, 53–65.

Moore M.N., (1963), Trans Amer. Nucl. Soc. 6(2), 213.

Munoz Cobo J.L. and Difilippo F. C., (1988), Noise and Nonlinear Phenomena in Nucl. Systems, Proc. NATO Adv. Res. Wksp. Plenum, NY.

Munoz Cobo J.L.et al., (2001), Sub-critical Reactivity Monitoring in Accelerator Driven Systems, Annals of Nuclear Energy, 28, 1519.

Munoz-Cobo J.L., Pena J., González E., (2008), Rossi-alpha and Feynmann Y functions for non-Poissonian pulsed sources of neutrons in the stochastic pulsing method:

Application to sub criticality monitoring in ADS and comparison with the results of Poissonian pulsed neutron sources, Annals of Nuclear Energy 35, 2375–2386.

Munoz Cobo J.L. et al., (2011), Feynman-α and Rossi-α formulas with spatial and modal effects, Annals of Nuclear Energy 38, 590–600.

Mukaiyama T. et al., (2001), Review of research and development of accelerator-driven system in Japan for transmutation of long-lived nuclides, Prog. Nucl. Energy, 38 (1-2) 107

Nifenecker H. et al., (2003), Accelerator Driven Sub-critical Reactors, IOP Publishing.

Orndoff J. D. (1957), Prompt neutron periods of met al critical assemblies, Nucl. Sci. Eng., 2, 450.

Osborn R.K. and Yip S., (1966), The foundation of neutron transport theory, Gordon and Breach, NY.

Pacilio N., Jorio V., Norelli F.et al., (1976), Towards a Unified Theory of Reactor Neutron Noise Analysis Techniques, Annals of Nuclear Energy, vol. 3, pp. 239-251.

Pacilio N., (1969), Reactor noise analysis in the time domain, USAEC Technical Monograph No TID 24512.

Pal L., (1958), On the theory of stochastic processes in nuclear reactors, II Nuovo Cimento, 7 (Suppl.), 25-42.

Pal L., (1962).

Pal L., (1963), Reactor science technology, 17, 395.

Pál L., Pázsit I., (2012), Two-group theory of the Feynman-alpha method for reactivity measurement in ADS. Sci. Technol. Nucl. Instal, 14.

Pazsit I., (1987), Ann. of Nucl. Energy, 14, 25.

Pazsit I. and Yamane Y., (1998a), The Variance-to-Mean Ratio in Subcritical Systems Driven by a Spallation Source, Ann. Nucl. Energy, **25(9)**, 667.

Pazsit I. and Yamane Y., (1998b), Theory of neutron fluctuations in source driven sub-critical systems, Nucl. Instr. Meth. A, **403**,431.

Pazsit I., Kitamura Y., Wright J., and Misawa T., (2005), Calculation of the Pulsed Feynman-Alpha Formulae and Their Experimental Verification, Ann. Nucl. Energy, 32, 986.

Pazsit I. and Pal L., (2008), Neutron Fluctuations: A Treatise on the Physics of Branching Processes,Elsevier Science Ltd., London, New York, Tokyo, page. 252.

Pluta P.R., (1962).

Profio A.E., (1976), Text book on Experimental reactor physics, John willy and sons**.**

Pyeon C.H., Hirano Y., Misawa et al., (2007), Preliminary experiments on accelerator-driven subcritical reactor with pulsed neutron generator in Kyoto university critical assembly. J. Nucl. Sci. Technol. 44 (11), 368–1378.

Pyeon C.H., Hervault M., Misawa T et al., (2008) Static and kinetic experiments on accelerator driven system with 14 MeV neutrons in Kyoto University Critical Assembly. J. Nucl. Sci. Technol. 45 (11), 1171–1182.

Raina V.K., Srivenkatesan R. et al., (2006), Critical Facility for lattice physics experiments for the Advanced Heavy, Water Reactor and the 500MWe pressurized heavy water reactors, Nuclear Engineering and Design 236, 758–769.

Raiveski V., (1958), Report CEA-917.

Rana Y.S., Singh Arun and Degweker S. B., (2013), Diffusion Theory Based Analogue Monte Carlo for Simulating Noise Experiments in sub-critical Systems," Nucl. Sci. Eng., 174, 245.

Rana, Y. S. and Degweker, S. B., (2009), Feynman Alpha and Rossi Alpha Formulae with Delayed Neutrons for Sub-critical Reactors Driven by Pulsed Non-Poisson Sources, Nucl. Sci. Eng., 162, 117.

Rana, Y.S. and Degweker, S. B., (2011), Feynman-Alpha and Rossi-Alpha Formulas with Delayed Neutrons for Subcritical Reactors Driven by Pulsed Non-Poisson Sources with Correlation Between Different Pulses, Nucl. Sci. Eng., 169, 98.

Rubbia C. et al., (1995), Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier, Report CERN/AT/95-44 (ET). Report-CERN/AT/95-44 (ET).

Rugama Y., Munoz-Cobo J.L., (2002), Modal influence of the detector location for the noise calculation of the ADS, Annals of Nuclear Energy 29, 215–234.

Saito K., (1967), Nucl. Sci. Eng. 28, 384.

Saito K., (1979), Source papers in reactor noise, Prog. Nucl. Energy, **3**, 157.

Shamzu Y., Naing W., (2005), Some technical issues on continuous sub criticality monitoring by a digital reactivity meter during criticality approach. J. Nucl. Sci. Technol. 42, 515–524.

Sher R. and Untermyer S.,(1980), The Detection of Fissionable Materials by Nondestructive Means. American Nuclear Society. Lagrange Park, Illinois.

Shimazu Y. and Tsuji M., (2001), Applicability of point reactor kinetic equations for sub criticality monitoring, Proc. Nuclear Society, Spring Meeting, Cheju, Korea.

Shimazu Y., Unesaki H. and Suzuki N., (2003), Sub criticality monitoring with a digital reactivity meter, Journal of Nuclear Science and Technology, vol. 40, no. 11, pp. 970-974, November.

Shvedov O. V. et al., (1997), ADS Program in Russia, Status report on Accelerator driven systems: Energy generation and transmutation of nuclear waste, IAEA-TECDOC 985, D.4, 313.

Sinha Amar, Roy Tushar et al., (2015), BRAHMMA: A compact experimental accelerator driven subcritical facility using D-T/D-D neutron source. Annals of Nuclear Energy 75 (2015) 590–594.

Singh K.P., Modak R.S., Degweker S.B. et al., (2009), Iterative schemes for obtaining dominant alpha-modes of the neutron diffusion equation, Annals of Nucl. Energy, 36, p.1086.

Singh K.P., Degweker S.B., (2014), Transport Theory Based Analog Monte Carlo for Simulating Noise Experiments in Subcritical Systems, Nuclear science and engineering 177, 126–140.

Sjostrand N. G., (1956), Measurements on a subcritical reactor using a pulsed neutron source, Arkiv for physic, 11(13), 233.

Soule R., Assal W., Chaussonnet P et al., (2004), Neutronic studies in support of accelerator-driven systems: the MUSE experiments in the MASURCA facility. Nucl. Sci. Eng. 148 (1), 124–152.

Srinivasan M., (1967), Nuckleonik, 10, 224.

Srinivasan M. and Sahni D. C., (1967), Modified statistical technique for the measurement of alpha in fast and intermediate reactor assemblies, Nukleonik, 9, 155.

Stacey W., (2001), Nuclear Reactor Physics, John Wiley & Sons, INC.

Swansen J.E. et al., (1982), report LA-9221-MS.

Swansen J.E., (1984), Report LA-9936-MS.

Talamo A., Gohar Y., Sadovich S., Kiyavitskaya H., Bournos V., Fokov Y., Routkovskaya C., (2013), Correction factor for the experimental prompt neutron decay constant. Annals of Nuclear Energy, 62, 421-428

Taninaka H., Hashimoto C. et al., (2010), Determination of lambda-mode eignvalue separation of a thermal accelerator driven system from pulsed neutron source,J. Nucl. Sci. Technol.,47,376.

Taninaka H., Hashimoto K., Pyeon et al., (2011 a), Determination of subcritical reactivity of a thermal accelerator-driven system from beam trip and restart experiment. J. Nucl. Sci. Technol. 48 (6), 873–879.

Taninaka H., Atsuko Miyoshi et al., (2011 b), Feynman alpha analysis for a thermal subcritical reactor system driven by an unstable 14 MeV neutron source, Journal of nuclear science and technology, Vol. 48, No. 9,p 1272-1280.

Toshihiro Yamamoto, (2011), Higher order mode analyses in Feynman-a method, Annals of Nuclear Energy 38, 1231–1237.

Toshihiro Yamamoto, (2014), Higher order mode analyses of power spectral density and Feynman-α method in accelerator driven system with periodically pulsed spallation neutron source, Annals of Nuclear Energy 66, 63–73.

Toshihiro Yamamoto, (2015), Higher harmonic analyses of the 252-Cf source driven noise analysis Method, Annals of Nuclear Energy 76, 521–529.

Tsuji M., Suzuki Y. et al., (2003), sub criticality measurement by neutron source multiplication method with a fundamental mode extraction, J. Nucl. Sci. Technol.,40 [3],158.

Uyttenhove W., Baeten P., Vanden Eynde et al., (2011), The neutronic design of a critical lead reflected zero-power reference core for on-line sub criticality measurements in Accelerator Driven Systems. Ann. Nucl. Energy 38, 1519–1526.

Uyttenhove W. et al., (2012), Detector positioning for the initial sub criticality level determination in accelerator driven systems, PHYSOR 2012.

Uhrig R., (1970), Random noise techniques in nuclear reactor systems, New York: The Ronald Press Company.

Veltman, B.P.T. and Kwakernaak H., (1961), Regelungstechnik 9, 357.

Williams M.M.R., (1973),Random processes in nuclear reactors, Oxford: Pergamon.

Wallerbos E.J.M. and Hoogenboom J.E., (1998), Ann. Nucl. Energy, 25, 733.

Wright J., (2005), Development and investigation of reactivity measurement methods in sub-critical cores, Thesis for the Degree of Licentiate of Engineering CTH-RF-190, Department of Reactor Physics Chalmers University of Technology.