MOUNT ALLISON UNIVERSITY

Improving the Contrast of Neutron Interferometry Phase Measurements Using Online Bayesian Markov Chain Monte Carlo Methods (Super Tentative Crappy Title)

by

Thomas Alexander

A thesis submitted in partial fulfillment for the degree of Bachelor of Science with Honours

in the
Faculty of Science
Department of Physics

February 2014

Declaration of Authorship

I, Thomas Alexander, declare that this thesis titled, 'THESIS TITLE' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: ______________________________

Date: ______________________________

"Such is the vastness of his genius that he can outwit even himself."

Steven Erikson

MOUNT ALLISON UNIVERSITY

Abstract

Faculty of Science
Department of Physics

Bachelors of Science with Honours

by Thomas Alexander

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor…

Contents

List of Figures

List of Tables

Abbreviations

t	transmitted beam amplitude coefficient
r	reflected beam amplitude coefficient

Physical Constants

$$\text{Speed of Light} \quad c \quad = \quad 2.997\ 924\ 58 \times 10^{8}\ \frac{m}{s}$$

Symbols

k	quantum wave number	m^{-1}
v	velocity	ms^{-1}
ω	angular frequency	rads^{-1}

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 Neutron Interferometry

1.1.1 History

Interferometry has long been a powerful tool for experimental physics. Its various forms have been used in the discovery of many historically significant results such as the Michelson-Morley experiment which showed that the speed of light was independent of inertial reference frames and experimental data in support of Bell's Inequality. [1][2]

The key concept of interferometry is the superposition of waveforms upon each other in order to deduce meaningful physical properties from the resultant combination. If one considers two waves of identical frequency than the waves when superimposed will combine constructively when in phase and de-constructively when out of phase. The technique of interferometry can be applied to many different experimental systems, the requirement being that the interferometry medium be described as a wave mathematically. Such systems that have been used in the past include electromagnetic waves, water waves, electrons and neutrons. Although electrons and neutrons classically are described as point particles the development of quantum mechanics allows that all matter is actually described by a waveform and therefore interferometry techniques may be applied to the electron and neutron waveforms. This paper focuses primarily on neutron interferometry.

The first Neutron Interferometer with slow neutrons was constructed by Maier-Leibnitz and Springer in 1962 and was effectively equivalent to a double slit experiment. However, their interferometer was not effective for measuring physical properties of materials. In 1965 the perfect single-crystal interferometer was theorized by Ulrich Bonse and Michael

Hart, however it was not until 1974 that their interferometer was made functional by Helmut Raunch and his student Wolfgang Treimer. Their interferometer used a single perfect crystal in which two horizontal slices were removed from the interior to form a three-blade interferometer.[3] **INSERT FIGURE**. Using the single-crystal design researchers Colella,Overhauser and Werner to perform the famous COW experiment which measured the phase shift due to the gravitational potential difference between two neutron beams separated by a small displacement in height.[4] Further experiments made such contributions to experimental physics such as the measurement of the Aharonov-Bohm effect and the the effect of the Earth's rotation on a quantum system.[3] It was quickly realized that neutron interferometry measurements provide an incredible level of accuracy and isolation in experimental measurements. This is due to the fact that the neutron has essentially zero electric charge and therefore does not feel the Coulomb force. Therefore for the case of slow neutrons there is no need to isolate for stray electric fields.

1.1.2 Application to Quantum Information

As the neutron interferometry provides a low-noise experimental system it provides an ideal test-bench for testing certain aspects of quantum information theory. Such an example was the use of a five-blade interferometer which allowed the quantum information encoded in the neutron waveform by using additional blades to exploit the symmetry of mechanical vibrations in the interferometer and decouple these modes.[5]. This is an example of encoding the information into a decoherence-free subspace and is a technique that may be applicable in future scalable quantum computation systems. Additionally it has been shown that neutron interferometers can be used for the generation of single neutron entangled states. [6] Additionally there is interest in the quantum discord of neutron interferometry systems and there application towards non-classical discord algorithms.[7]. It is unlikely that a scalable quantum computer will be realizable with neutrons due to their low interaction with other quantum systems.

1.1.3 Application to Quantum Fundamentals

Neutron interferometry has played a large role in experimentally gathering information on the fundamental behaviour of quantum systems. Such as the Aharonov-Bohm effect, the effect of gravity,quantum discord and verifying Bell's Inequality. [3][4][7][2]. More recently researchers at the Institute for Quantum Computing are designing an experimental neutron interferometer that is equivalent to a triple-slit experiment in the search for third order interference effects that are theoretically non-existent but if found may be evidence of new quantum theories.[8]

1.1.4 National Institute of Standards and Technology

The majority of the work presented in this thesis applies directly to the neutron interferometry setup at the National Institute of Standards and Technology in Gaithersburg, MD. The neutrons are produced at the NIST Research Reactor and extracted via a dual-crystal parallel-tracking monochromator with energy of $4 - 20meV$. They are fed along wave-guides to the isolated interferometry setup. NIST has three,four and five blade perfect single-crystal interferometry assemblies although we focus on solely the three blade assembly. Neutron detection is provided by ^{3}He detectors or by high resolution position-sensitive detectors.[9][10] **INSERT FIGURES**.

1.2 Bayesian Markov Chain Monte Carlo Methods

Chapter 2

Theory

2.1 Neutrons

2.1.1 Particle Description of Neutrons

The neutron is a subatomic hadron particle that is present in the nucleus of every atom except ^{1}H. The neutron is composed of two down quarks and a single up quarks. This composition gives a neutral electric charge for the neutron making it an ideal candidate for sensitive experiments, however the downside is that neutrons are much more difficult to manipulate. The neutron is also therefore a fermion and by the Pauli exclusion principle only a single neutron is allowed in each quantum state. The free neutron is unstable and undergoes beta decay with a lifetime of just $881.5 \pm 1.5s$. The neutron has a rest mass of approximately $939.56Mev$. Free neutrons are produced using either neutral fission or fusion although in practical experiments fission is almost always used. At the NIST Research Reactor free neutrons are produced from the fission of ^{235}U.

2.1.2 Thermal Neutrons

Neutron interferometry utilizes thermal neutrons which are free neutrons that follow a Boltzmann distribution. The neutrons at NIST are found in the kinetic energy range of 4-20meV around room temperature of $T = 293.15K$. This gives gives neutron velocities of $875 - 1956\frac{m}{s}$ which gives $v << c$ and therefore relativistic affects do not play a role. Therefore thermal neutrons are in near thermal equilibrium with their surroundings. Neutrons are decelerated to a thermal state in the reactor by collisions with neutron moderators in the reactor. From de Broglie relations the wavelength of thermal neutrons is approximately $\lambda = \frac{h}{p} = 2.0\text{-}4.5\mathring{A}$. After being emitted form the NIST reactor the neutrons follow a wave-guide and using a wave splitter are sent into individual labs. As the strongest known phase space density of a neutron source is around $10^{-}14$ it can be safely assumed that the probability of two neutrons interacting inside the wave-guide or interferometer is sufficiently low that it can be disregarded and therefore detected neutrons have no correlation between each-other.

2.2 Neutron Interferometry

The Neutron interferometer is similar to other forms of interferometry in which an incoming wave is split and than allowed to interfere at a later point which allows the two wave paths to be compared. The modern day neutron interferometer is functionally equivalent to an optical Mach-Zender (MZ) interferometer.

2.2.1 Mach-Zehnder Interferometer

The MZ utilizes a half-mirror to split the incoming electromagnetic wave and the resultant two beam paths are refocused on a second beam-splitter. The two interfered waveforms exit the second beam-splitter and are incident on two detectors that can be visualized as Detector 1 & 2 in fig(2.1),

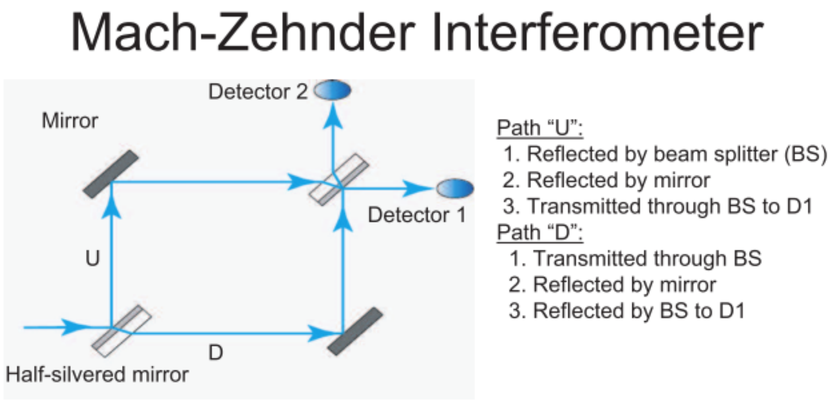

FIGURE 2.1: The Mach-Zehnder interferometer

As reflection results in a phase shift of π and assuming transmission through the half-mirrors results in a phase shift of δ we easily calculate the phase differences of the two paths at the two detectors. At detector 1 and path U there is a total of two reflections and a single transmission which results in a phase shift of $2\pi + \delta$. Similarly for path D the phase shift is also $2\pi + \delta$. therefore at detector 1 there is constructive interference. At detector 2 path U has a phase of $2\pi + 2\delta$ and path D has a phase of $\pi + 2\delta$. Therefore at detector 2 there is destructive interference.[**?**]

2.2.2 Bragg Scattering

In neutron interferometry the crystal planes of the interferometer blades act as diffraction gratings. Incident waves that satisfy the Bragg condition 2.1 are coherently scattered.

$$n\lambda = 2dsin(\theta_b) \tag{2.1}$$

Where n is a positive integer, d is the distance between the atomic planes of the crystal lattice and θ_b is the angle between the incident beam and the atomic plane of the crystal. The amplitudes of the transmitted and the reflected beams are given by the coefficients t (transmitted) and r reflected.[**?**]

Chapter 3

Experimental Setup

3.1 The Neutron Interferometer

3.1.1 NIST

3.1.2 Reactor and Lab

3.1.3 Motors and Actuators

3.1.4 Sensors

3.2 NI-Engine

3.2.1 Design Requirements

3.2.2 Language and Library Choices

3.2.3 System Architecture

3.2.4 Documentation

3.3 Q-Infer

3.3.1 Interaction with NI-Engine

3.3.2 GPU Implementations of Likelihood functions

Chapter 4

Discussion

4.1 Application to Quantum Information

4.2 Application to Quantum Fundamentals

4.3 Application to Materials Science

4.4 Outside of Neutron Interferometry

Chapter 5

Conclusion

5.1 Contrast Improvement with MCMC Methods

5.2 The Experimental Setup

5.3 Application of Findings

Bibliography

[1] A. A. Michelson and E. W. Morley. On the relative motion of the earth and the luminiferous ether. *American Journal of Science*, 34:333–345, 1887. doi: doi:10.2475/ajs.s3-34.203.333. URL http://dx.doi.org/10.1007/s10701-010-9529-9.

[2] Yuji Hasegawa, Rudolf Loidl, Gerald Badurek, Matthias Baron, and Helmut Rauch. Violation of a bell-like inequality in single-neutron interferometry. *Nature*, 425, 2003. ISSN 6953. URL http://dx.doi.org/10.1038/nature01881.

[3] A.G. Klein. Adventures in neutron interferometry. *Foundations of Physics*, 42(1):147–152, 2012. ISSN 0015-9018. doi: 10.1007/s10701-010-9529-9. URL http://dx.doi.org/10.1007/s10701-010-9529-9.

[4] R. Colella, A. W. Overhauser, and S. A. Werner. Observation of gravitationally induced quantum interference. *Phys. Rev. Lett.*, 34:1472–1474, Jun 1975. doi: 10.1103/PhysRevLett.34.1472. URL http://link.aps.org/doi/10.1103/PhysRevLett.34.1472.

[5] D. A. Pushin, M. G. Huber, M. Arif, and D. G. Cory. Experimental realization of decoherence-free subspace in neutron interferometry. *Phys. Rev. Lett.*, 107:150401, Oct 2011. doi: 10.1103/PhysRevLett.107.150401. URL http://link.aps.org/doi/10.1103/PhysRevLett.107.150401.

[6] Yuji Hasegawa, Rudolf Loidl, Gerald Badurek, Stefan Filipp, Jürgen Klepp, and Helmut Rauch. Evidence for entanglement and full tomographic analysis of bell states in a single-neutron system. *Phys. Rev. A*, 76:052108, Nov 2007. doi: 10.1103/PhysRevA.76.052108. URL http://link.aps.org/doi/10.1103/PhysRevA.76.052108.

[7] Christopher J. Wood, David G. Cory, Mohamed O. Abutaleb, Michael G. Huber, Muhammad Arif, and Dmitry A. Pushin. Quantum correlations in a noisy neutron interferometer. Jun 2013. URL http://arxiv.org/abs/1304.6935.

[8] Cozmin Ududec, Howard Barnum, and Joseph Emerson. Three slit experiments and the structure of quantum theory. *Foundations of Physics*, 41(3):396–405, 2011.

ISSN 0015-9018. doi: 10.1007/s10701-010-9429-z. URL http://dx.doi.org/10.1007/s10701-010-9429-z.

[9] Neutron interferometry and optics facility. http://physics.nist.gov/MajResFac/InterFer/text.html. Accessed: 2014-01-27.

[10] Sam Werner. Neutron interferometry: From missouri to nist. http://webster.ncnr.nist.gov/nran/talks/Werner.pdf. Accessed: 2014-01-27.