UCN Production and Analysis and Magnetic Stability Studies for the Future neutron Electric Dipole Moment Experiment at TRIUMF(?)

what is the subtitle?

by

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Abstract

text of the abstract

Acknowledgment

text of the acknowledgment

Dedicated to myself!!

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Chapter 1

Introduction

This thesis is focused on two important factors of successfully measuring the neutron Electric Dipole Moment (nEDM) at TRIUMF. Those include having a very stable magnetic field environment as well as a very high density Ultra Cold Neutron (UCN) source.

For the future nEDM measurement at triumf several types of shielding will be used. Magnetic shielding is vital to create a quiet magnetic environment. An important component of the magnetic shielding system is the large magnetic shields that are made of highly permeable materials. A prototype of such shields exists at the University of Winnipeg. the first half of the thesis is related on magnetic field stability studies on the prototype shields at the University of Winnipeg.

The The second half of the thesis is dedicated to the UCN production and analysis at TRIUMF using the vertical UCN cryostat which was previously used at RCNP (reference).

1.1 History of Fundamental Symmetries

Over the last few decades the interest in the invariance of the discrete symmetries have been increased. Such studies revealed the internal structure of the elementary particles and helped develop the underlying theories.

There are three significant symmetries in physics as Charge conjugation (C), Parity (P) and Time-reversal (T). C-symmetry simply decribes physical laws under a charge-conjugation transformation. Parity transformation, is simply the inversion of spatial coordinates and Time-reversal transformation is changing the direction of time. Tests of Charge C,P and T symmetries established the structure of the Standard Model (SM) [1].

In 1956, fall of discrete symmetries started with the famous $\theta - \tau$ paradox in the K-mesons decay. Yang and Lee suggested that the paradox is originated from a P violation in the weak interactions [2]. Immediately after, an experimental search was suggested by Ramsey for Parity violation in the β decay of Co-60. Within a few months, P violation was demonstrated by three different experiments [3–5]. After the observation of P violation, Landau showed that Electric Dipole Moments (EDMs) are forbidden by T symmetry [6] and then it was suggested that T symmetry should also be checked experimentally [7].

One of the most fundamental symmetries in physics is the CPT (Charge-Parity-Time) symmetry. The simultaneous operation of of C, P and T leaves the system unchanged.

	C	P	T
B	-	+	-
E	-	-	+
$\boldsymbol{\mu}$	-	+	-
d	-	+	-

Table 1.1: Symmetry properties of different components of the EDM Hamiltonian

To date there is no experimental evindence for CPT symmetry breaking. Because of the CPT invariance, breakdown of CP symmetry should be accompanied by violation of Time-reversal symmetry.

A finite EDM provides a good source of CP violation. EDMs caused by CP violation in the SM are negligible. But most extensions of SM such as supersymmetry naturally produces EDMs that are comparable to or larger than present experimental limits [8]. The search for EDMs can be traced back to 1950 when Purcell and Ramsey tested the possibility of finding EDMs for particles and nuclei. Smith, Purcell and Ramsey started an experiment to search for neutron EDM d_n and they achieved the upper limit of $d_n < 5 \times 10^{-20}$ e $\cdot$ cm [9]. Over the years the upper limit on the neutron EDM has been improved by many orders of magnitude. Measurement of particle EDMs provide some of the tightest constraints on extensions to the SM to probe CP violation. The most recent upper limit on the neutron EDM is found to be $|d_n| < 3.0 \times 10^{-26}$ e$\cdot$ cm [10].

1.2 Neutron Electric Dipole Moment

A permanent neutron electric dipole moment is an intrinsic property of a neutron. This fundamental property is a measure for the separation of positive and negative charges internal to the neutron. However no nEDM has been measured so far.

The interaction of a nonrelativistic neutron with the electromagnetic field can be descibed by the follwoing hamiltonian:

$$H = -\boldsymbol{\mu_n} \cdot \mathbf{B} - \mathbf{d_n} \cdot \mathbf{E} \tag{1.1}$$

where $\boldsymbol{\mu}_n$ is the magnetic moment of the neutron interacting with the magnetc field $\mathbf{B}$ and $\mathbf{d_n}$ is the electric dipole moment of the neutron interacting with the electric field $\mathbf{E}$.

The properties of the Hamiltonian under discrete symmetries is summarized in table. 1.2. Based on this, the first term is CP-even and T-even and the second term is cp-odd and T-odd where both terms are CPT-invariant. Therefore, a nonzero EDM may exists if both Parity and Time-reversal symmetries are broken.

1.2.1 Baryon Asymmetry of the Universe

The neutron EDM provides a highly sensitive diagnostic for CP violation which is an important element for the observed baryon asymmetry in the universe. The dominance of matter over antimatter in the universe can be characterized by [11]

$$\eta = \frac{n_b - \bar{n_b}}{n_\gamma} \simeq 6 \times 10^{10} \tag{1.2}$$

where n_b is the number of baryons, $\bar{n_b}$ is the number of anti-baryons and n_γ is the number of photons in the Cosmic Microwave Backgorund.

It is possible to assume that maybe the universe is baryon symmetric in a very large scale and it is split into regions that are made of only baryons or anti-baryons. If that was the case, an excess of gamma rays in between these separated regions was expected due to annihilation. But, even in the least dense regions of the space, there is hydrogen gas cloud.

Sakharov criteria

There are three ingredients needed to create baryon asymmetry known as Sakharov conditions [12]:

- Baryon number violation
- C(Charge) and CP(Charge-Parity) violation
- Departure from thermal equilibrium.

The first condition is obvious which means in a reaction, if the net baryon number is zero, there would be no baryon asymmetry. In the reactions that violate baryon number, if there is no C and CP violation, the net baryon number would be zero [13]. The third condition is essential for a net nonzero baryon asymmetry since the equilibrium average of B vanishes. Sakharov suggested that baryogenesis took place immediately after the big bang, at a temperature not far below the Planck scale of 10^{19} GeV, when the universe was expanding so rapidly that many processes were out of thermal equilibrium [14].

1.2.2 The nEDM Measurement Technique

1.2.3 neutron Electric Dipole Moment Status Worldwide

The most recent neutron electric dipole moment measurement at ILL found that be $d_n < 3.0 \times 10^{-26}$ e·cm (90% CL) [10]. The new ^{199}Hg EDM measurement constrains the nEDM better than direct nEDM measurements, $d_n < 1.6 \times 10^{-26}$ e·cm although subject to uncertainty from Schiff screening [15].

There are several ongoing experiments seeking to measure the nEDM. Most groups are aiming initially for an improvement of the uncertainty on d_n to the 10^{-27} e·cm level, ultimately improving to the 10^{-28} e·cm level over time.

The PSI nEDM measurement aims for a measurement at the 5×10^{-28} e·cm level [16]. (Add some detail about how they are going to measure it, what their technique is, reactor or spallation, solid deuterium or superfluid helium)

The nEDM collaboration at SNS plans to measure $d_n \approx 2 \times 10^{-28}$ e·cm, two orders of magnitude improvement from the current limit [17]. (Add some detail about how they are going to measure it, what their technique is, reactor or spallation, solid deuterium or superfluid helium)

The room temperature nEDM measurement at Munich also aims for nEDM measurement of 10^{-27} e·cm level, and is a world leader in active and passive magnetic shielding [18–21]. (Add some detail about how they are going to measure it, what their technique is, reactor or spallation, solid deuterium or superfluid helium)

(I am sure there are other places as well. They should be included here).

The nEDM experiment at TRIUMF is aiming for a determination of nEDM at the 10^{-27} e·cm level. A key factor for success is a unique high density ultracold neutron (UCN) source. The TRIUMF's approach is unique in a sense that it is the only place that is comibining a spallation method with superfluid helium for UCN production. Another novel feature is a dual comagnetometer (^{129}Xe and ^{199}Hg) to characterize systematic errors.

1.3 Ultracold Neutrons

(This section needs to be expanded) Ultracold neutrons (UCN) are neutrons with kinetic energy $\lesssim$ 300 neV corresponding to velocity $\lesssim$ 8 m/s or temperatures $\lesssim$ 3 mK. Because of their low energy, UCN can be reflected from many materials under arbitrary angles of incident and therefore, it makes UCN storable in a material bottle. UCN are subjected to all four fundamental forces in the following ways [22–25]:

1.3.1 Ultracold Neutrons Interaction with Fundamental Forces

The Gravitational Interaction:

The interaction of UCN with the earth's gravitation field is described by

$$V_g = mgh \tag{1.3}$$

where

$$mg = 102 \text{ neV/m} \tag{1.4}$$

which is comparable to the UCN kinetic energy. This means a UCN of energy 200 neV can rise by at most 2 m.

The Weak Interaction:

UCN decay via

$$n \longrightarrow p + e^- + \bar{\nu}_e. \tag{1.5}$$

with a lifetime of 880.3 ± 1.1 S [26]. UCN can be bottled for times comparable to this time.

The Electromagnetic Interaction:

Although a neutron is electrically neutral, it possesses a magnetic dipole moment which interacts with a magnetic field **B** by the interaction

$$V_m = -\boldsymbol{\mu}_n \cdot \mathbf{B} \tag{1.6}$$

where

$$|\boldsymbol{\mu}_n| = 60 \text{ neV/T}. \tag{1.7}$$

UCN of anti-parallel spin to the magnetic field (high field seeker) have negative V_m, accelerate toward higher fields and are attracted and UCNs with parallel spin (low field seeker) have positive V_m and are repelled. If the UCN spin adiabatically traces the magnetic field, it will be fully polarized which can be achieved by passing UCN through a strong ~ 6 T magnetic field.

The strong Interaction:

The strong interaction governs the UCN interaction with material walls. It can be described by the Fermi potential V_F which arises from the coherent elastic scattering from nuclei. The highest known value ($V_F = 335$ neV) is measured for ^{58}Ni and it sets the upper limit of the UCN kinetic energy, since UCN are normally defined by the property of total reflection from materials.

1.3.2 Superthermal Sources of Ultracold Neutrons

Chapter 2

Future nEDM Measurement at TRIUMF

2.1 Magnetic Stability Requirements

2.1.1 Active Shielding

2.1.2 Magnetically Shielded room

2.1.3 Passive Shielding

2.2 High Voltage EDM Cells

2.3 Dual Comagnetometer

An introduction about the long term nEDM effort at TRIUMF, what the plan is, when it will start (roughly). I guess I can probably get this information from some proposals. I am not sure how much detail should go here.

How the EDM experiment is actually done, talk about different components of the system. Here is where I talk about the Ramsey cycle ...

nEDM measurement systematic effects: This is where I talk about the GPE and ... . Basically here is to kind of motivate that we need to have stable magnetic fields and we need lots of neutrons.

Introduction to the magnetic stability requirements at TRIUMF. What I mean is that there is 400 μT background field at TRIUMF. Hopefully we have a field map of the area soon(?).

From ouside in: Magnetically shielded room, what is the status of that, are we going to have it? when? How good is it going to be compared to the other ones worldwide? Why is it designed that way? What is the design? Drawings of it. General question: Some of these are about things that will happen in the future and I have not worked on them. Should they even go to my thesis? I feel I have to say a little about this since my thesis is nEDM related and it is part of it.

Passive shieldings: Again same questions as above, motivate for the next chapter

Say what will be discussed in the two coming chapters

what else?

Chapter 3

Temperature Dependence of Magnetic Permeability(?)

3.1 Shield Coupled Coils

3.1.1 Spherical Geometry

3.1.2 Cylindrical Geometry

3.2 Method one: Measurement with (How did I used to call it???)

3.3 Method two: Measurements with a transformer

This chapter I think should be very similar to the paper. It should be just the extended version of that with more detail (not a lot more though! It means I should not include every single data that I took!)

Motivation: Why are we interested in the temperature dependence of mu. The idea of coupling the field of an internal coil to the shield and that is because the shield act as a return yoke. Then it makes sense to have a stable shield so that the internal field does not change. And then explain that one of the factors are actually the changes in the temperature that affects the magnetic permeability.

The main part of this has to be about the measurements, explain the technique, show several picture of the setup. Look at the long version of the paper on github to remember what we did and why and then include the data that made sense.

Another relevant part is to make the connection between these measurements and the actual changes in the B field and for that I have to include the simulations. An explanation of the OPERA simulations and FEMM. Explain what each one is and what I did.

Chapter 4

Current UCN Facility at TRIUMF

The current vertical UCN cryostat at TRIUMF is the same UCN cryostat developed and tested at RCNP, Japan between 19xx and 2012(?) [27, 28]. In 2016, the cryostat was shipped to triumf for further UCN experiments. These experiments were essential for better understanding of the cryostat and design of the next generation UCN source. The vertical source was modified to fulfill the safety requirements at TRIUMF (find where and what those are.) The current location of the vertical source is at the meson hall experimental area. A picture of the UCN facitity is shown below.

The unique feature of the UCN source at TRIUMF is the combination of spallation neutrons and superfluid helium for UCN production. This will be discussed in detail in the following sections.

4.1 UCN beamline

TRIUMF's proton beam is provided by a 520 Mev cyclotron. The 120 μA beam (BL1A) enters the meson hall. This amout of current creates a lot of heat load on the vertical crystat which makes its operation impossible since it was designed for a maximum of 40 μA beam on target. As a result, only part of this beam should go to the UCN experimental area.

The microstructure of BL1A is in pulses with approximately 1 ms periods of beam followed by a 50-100 μs periods of no beam. This is shown in Fig. (4.1)(cite Nick Christopher's report). A kicker magnet kicks away 1/3 of the beam to BL1U. For most of the UCN data taking, the beam was on for 1 min and off for 4 min. These times are adjustable.

After the kicker magnet, the septum magnet bends the beam to the target and the quadropoles focus the beam to the target.

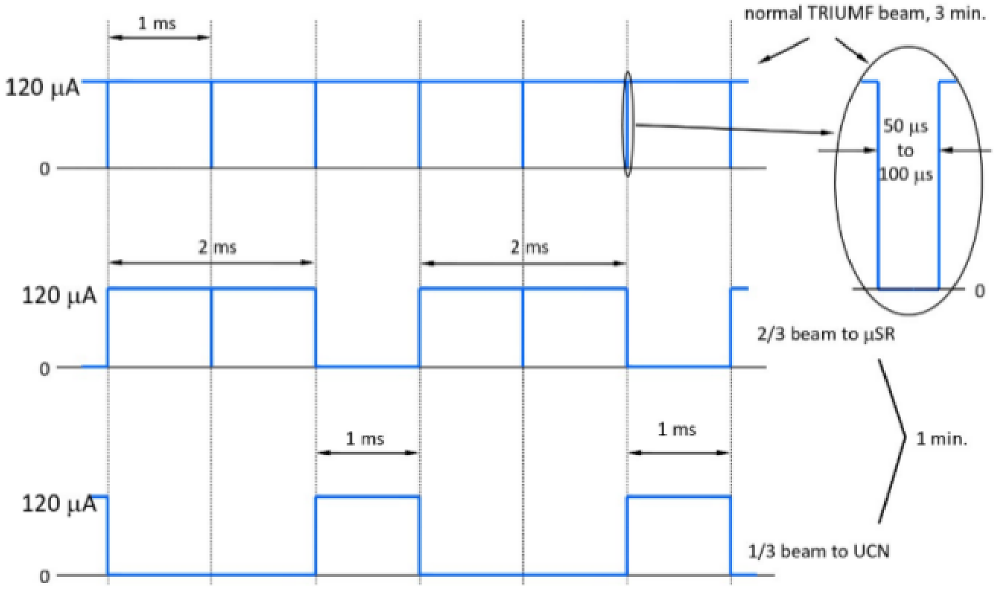

Figure 4.1: UCN beam structure. The top graph shows the 120 μA BL1A in 1 ms period of beam followed by a 50-100 μs of no beam. The middle graph shows the same beamline when the kicker magnet is on. The bottom graph shows the 1/3 of the beam that goes to the UCN area.

4.2 Radiation Sheilding

4.3 Vertical UCN Source at TRIUMF

4.3.1 D_2O Moderator

4.3.2 Helium Circulation

4 Kelvin Reservoir

1 Kelvin Pot

^{3}He Pot

Isopure Helium

4.4 Stages of UCN Production In The Source

At TRIUMF, UCN is produced in three stages: spallation, moderation and conversion. Each stage is explained below. Fig. (4.2) shows a schematic of this process.

A 1 μA proton beam hits the Tungsten target and creates spallation neutrons. Spallation is referred to a nuclear reaction where high energy particles interact with atomic nucleus. The target is surrounded by several blocks of lead and graphite to slow down the ultrafast neutrons. The fast neutrons get reflected from these blocks and enter the warm D_2O moderator (300 K) and become thermal neutrons with an energy of 0.025 eV and the speed of 2.2 km/s.

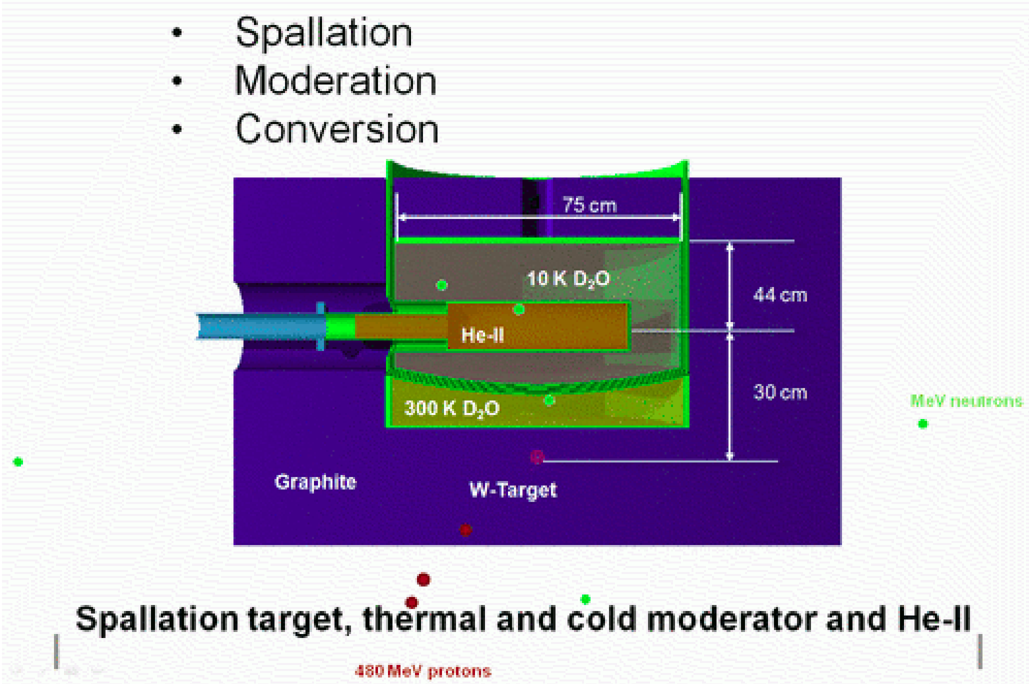

Figure 4.2: blah

Iced heavy water at 20 K is used as a cold moderator. After passing through the warm D_2O, thermal neutrons enter the the cold moderator and become cold neutrons.

The last stage is when these slow neutrons enter the superfluid helium at 0.84 to 0.92 K. UCN is produced as a result of phonon transitions inside the superfluid helium as discussed in section 1.3.2.

4.5 D_2O Solidification

The D_2O vessel has a capacity of 100 L. At first, 14 L of liquid D_2O gets injected to the vessel. This is followed by adding 11 L of D_2O to the vessel over 8 times. After filling up the vessel, Gifford McMahon refrigerators solidify the heavy water and further cool it down to 10 K. The process of icing the heavy water takes about 6 days and cooling it down takes another XXX days.

4.6 Data Acquisition System

Here talk about the EPICS and PLC and put pictures. I can also use stuff from student's reports.

4.7 UCN Detectors

Talk about how each detector works.

4.7.1 ^{6}He Detector

4.7.2 ^{6}Li Detector

Chapter 5

UCN Production and Detection

Put the rate equations here.

5.1 UCN Counts Measurement

5.2 Storage Lifetime Measurements

5.3 Heater Tests of The Source

5.4 Detector Comparison

Using the rotary valve

5.5 Background Measurements

With Ni foil

5.6 UCN guide Transmission Measurements

Chapter 6

Conclusion

Appendices

Appendix A

Some Appendix

The contents...
testing my bibliography[10]

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