ABSTRACT

PALMQUIST, GRANT R. Design and Construction of the Ultracold Neutron Source at the NC State PULSTAR Research Reactor. (Under the direction of Dr. Paul Huffman.)

An ultracold neutron (UCN) source using solid deuterium is being constructed at the 1 MW PULSTAR nuclear reactor on the campus of North Carolina State University. The final stages of assembly and commissioning are underway. The overall design, status of construction, and benchmarking measurements are presented. The UCN source design is based on detailed simulations including MCNP, UCN transport Monte Carlo, and computational fluid dynamics (CFD) simulation of the cryogenic systems. The source will be useful for developing UCN technologies, including guides and detectors, and in support of current projects including measurements of neutron beta-decay asymmetry coefficients and the electric dipole moment of the neutron. The facility will also be available for testing new techniques using UCN in material and surface physics, as well as new fundamental physics measurements such as neutron lifetime and beta decay measurements. The expected experimental density of UCN/cm$^3$ in a storage volume will be competitive with currently available sources, including those at significantly more powerful reactors.

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Design and Construction of the Ultracold Neutron Source at the
NC State PULSTAR Research Reactor

by
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DEDICATION

To Wednesdays.
BIOGRAPHY

The author was born in Denver, CO, but moved to Raleigh within weeks. After graduating from W.G. Enloe High School, he attended North Carolina State University where he received Bachelor of Science Degrees in Physics and Applied Mathematics with Honors. Many years later he produced this document.
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Chapter 1

Introduction to Ultracold Neutron Physics

Ultracold neutrons (UCN) are currently of interest to the particle physics community as an alternative to beam-based experiments for precision fundamental measurements of the properties of the neutron. These include the ongoing search for the neutron electric dipole moment [1–4], reducing the uncertainty of the lifetime of the neutron [5–9], and measurements of the neutron beta-decay correlations [10,11]. The systematics that UCN experiments are subject to are often distinct from those of more traditional beam-based experiments. This allows these projects to be used as a crosscheck for other experiments, as well as being precision measurements in their own right.

To this end, there is a demand for user facilities that supply high densities of UCN for fundamental precision measurements and for use in developing technology and methods to improve the handling of UCN. A world class UCN source is currently being commissioned at the PULSTAR nuclear reactor on the campus of North Carolina State University that will be able to address the needs for small-scale experiments and development projects for larger efforts. This thesis will describe the current status of the source, elements of its design, and predictions for the performance and use of the facility.

This chapter will provide a brief overview of UCN physics and its place within in the broader field of fundamental neutron science. Chapter 2 will describe the methods of producing UCN, the current status of sources around the world, and the PULSTAR UCN source's place in the field. Simulations that were performed to predict the production and transport of UCN in the source, along with
computational fluid dynamics simulations to gauge its cryogenic needs, are presented in Chapter 3. Chapter 4 describes the design and construction of the source. Related work in characterizing the UCN source at the Research Center for Nuclear Physics (RCNP) cyclotron at Osaka University will be presented in Chapter 5. Finally, a summary of the current status, projected timeline, and probable uses for the source are described in Chapter 6.

1.1 Neutron Physics

Discovered by Chadwick in 1932 [12], the neutron is a neutral spin-\(\frac{1}{2}\) baryon with a mass of \((939.565379 \pm 0.000021)\) MeV/c\(^2\) [13] and a magnetic moment of \((-1.9130427 \pm 0.0000005)\)\(\mu_N\) [13]. It consists of one up and two down valence quarks. Free neutrons beta decay into a proton, an electron, and an electron antineutrino with a lifetime of \((880.0 \pm 0.9)\) s [13]. This process is mediated by a W\(^-\) vector boson and is solely a product of the weak interaction. This makes neutron beta decay an effective probe of weak interaction processes.

1.1.1 Neutron Energy Scales

Free neutrons are generally produced by fission processes — either in nuclear reactors or in spallation sources. The difference in energy of neutrons from, for example, a \(^{235}\)U fission and the highest energy UCN spans roughly 13 orders of magnitude. To simplify discussion of this large range of energies, common terms have emerged for various energy classes of neutrons. Neutrons from fission and spallation sources generally have energies in the MeV range and are referred to as Fast Neutrons. Epithermal neutrons are slower than fast, but have not been completely thermalized to the room temperature surroundings. Thermal neutrons are ones that have come to thermal equilibrium with their room temperature surroundings. These are crucial for maintaining chain reactions in nuclear reactors. Cold neutrons are generally created by thermalizing neutrons in cryogenic moderators and are widely used in material studies. Very Cold Neutrons (VCN) are lower energy than can plausibly be produced using cryogenic moderators, but are not slow enough to be stored in material bottles. UCN are generally defined as neutrons that totally internally reflect off of some materials via coherent
Table 1.1: Nomenclature for neutron energy scales. Approximate energies, velocities, wavelengths, and temperature ranges for different classes of neutrons.

<table>
<thead>
<tr>
<th>Class</th>
<th>Energy Range</th>
<th>Velocity (m/s)</th>
<th>Wavelength (Å)</th>
<th>Temperature (K)</th>
</tr>
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<tbody>
<tr>
<td>Ultracold</td>
<td>&lt; 350 neV</td>
<td>&lt; 8</td>
<td>&gt; 500</td>
<td>&lt; 4 × 10⁻³</td>
</tr>
<tr>
<td>Very Cold</td>
<td>350 neV to 0.05 meV</td>
<td>8 to 10²</td>
<td>500 to 40</td>
<td>4 × 10⁻³ to 0.5</td>
</tr>
<tr>
<td>Cold</td>
<td>0.05 meV to 25 meV</td>
<td>10² to 2 × 10³</td>
<td>40 to 2</td>
<td>0.5 to 290</td>
</tr>
<tr>
<td>Thermal</td>
<td>≈ 25 meV</td>
<td>≈ 2200</td>
<td>≈ 1.8</td>
<td>≈ 290</td>
</tr>
<tr>
<td>Epithermal</td>
<td>1 eV to 100 keV</td>
<td>1.4 × 10⁴ to 4 × 10⁶</td>
<td>0.3 to 10⁻³</td>
<td>1 × 10⁴ to 1 × 10⁹</td>
</tr>
<tr>
<td>Fast</td>
<td>&gt; 100 keV</td>
<td>&gt; 4 × 10⁶</td>
<td>&lt; 10⁻³</td>
<td>&gt; 1 × 10⁹</td>
</tr>
</tbody>
</table>

scattering from nuclei and may be stored. As $^{58}$Ni has the highest Fermi potential of any single material, 340 neV is typically taken as the upper energy limit for UCN. There is some variance in the exact definitions used for each category, but a general overview is given in Table 1.1.

### 1.1.2 Neutron Applications

The majority of facilities today produce neutrons that are used to probe the structure and properties of various materials using the quantum mechanical wave properties of the neutron [14, 15]. Many of the methods used with neutrons are similar to x-ray material characterization methods. Whereas the cross-sections of x-ray interactions are generally proportional to the atomic number of the element, neutron interactions with nuclei vary widely in strength across the periodic table. Perhaps most notably, hydrogen is nearly invisible using most x-ray techniques, but has a large, spin-dependent cross-section for neutrons. Various scattering, diffraction, and radiography techniques are available.

In addition to these studies, many facilities have programs aimed at understanding the fundamental properties of the the neutron. The neutron’s simplicity allows fundamental experiments to be performed without requiring extensive nuclear structure corrections that may introduce theoretical
uncertainty [16]. For example, the lifetime of the neutron is an important factor in calculations relating to Big Bang Nucleosynthesis [17]. This number, when paired with the beta asymmetry in neutron decay, may be used to calculate the $V_{ud}$ matrix element in the Cabibbo-Kobayashi-Maskawa (CKM) matrix of quark mixing. Non-unitarity of the CKM matrix would imply physics beyond the Standard Model [17, 18].

Historically, many of these experiments are performed with cold neutron beams (e.g. the PERKEO series [19–21] and the NIST Lifetime experiment [22, 23]). In more recent years, UCN experiments have begun to supplement, but not supplant, these experiments. The lower energies allow for longer measurement time in neutron lifetime experiments, or provide different handles on systematic effects for measurements of beta-decay asymmetries and the neutron electric dipole moment, for example.

### 1.2 Ultracold Neutrons

First observed in 1969 [24, 25], UCN are neutrons with energies low enough (typically $\lesssim 350$ neV) such that they can be reflected from a material surface at all angles of incidence. This corresponds to speeds of less than about 8 m/s or an effective temperature of less than a few millikelvin. Golub, Richardson, and Lamoreaux give an excellent overview of UCN properties in their book titled *Ultra-cold Neutrons* [26].

The defining property of UCN, reflection from materials, is a consequence of the UCN’s long de Broglie wavelength interacting with the comparatively small nuclei. The small energies of incident UCN (modeled as a plane wave) and the short range of the strong force ensure that s-wave scattering dominates. This lack of angular dependence leads to a scattered spherical wave that will appear, at long enough distances, as though it scattered off a hard sphere of radius $a$. To determine $a$ (referred to as the “scattering length”) this long range spherical wave function, $\Psi$, must be matched to the highly perturbed neutron wave function, $\Phi$, within the nucleus. If the nucleus is modeled as a spherical square well of radius $R$ and depth $V_0$, $\Phi$ at $r < R$ will be effectively sinusoidal. Enforcing the boundary
conditions $\Psi(a) = \Phi(a) = 0$ and $\Psi'(a) = \Phi'(a) = 0$ leads to

$$a = R \left( 1 - \frac{\tan KR}{KR} \right),$$

(1.1)

where $K = \sqrt{\frac{2m_n(E_n + V_0)}{\hbar^2}}$ is the wave number within the nucleus. When $a$ is positive, as it is for most nuclei, incident neutrons are repulsed by the nucleus despite the attractive potential inside. By extrapolating the effect to a large ensembles of nuclei bound together, an effective potential can be defined for the case when a neutron coherently scatters off a material. This potential, known as the Fermi potential, is given by

$$V = \frac{2\pi\hbar^2}{m_n Na}$$

(1.2)

for homogeneous materials, where $N$ is the number density of the material and the scattering length, $a$, takes into account that the nuclei are bound. Neutrons with kinetic energy below this potential will be reflected regardless of the neutron's angle of incidence.

Despite this reflection, the long wavelength of UCN does allow the nuclei to be sampled, leading to a possibility of loss through absorption or inelastic scattering. This can be characterized by a loss probability per bounce,

$$\mu(E, \theta) = 2f \sqrt{\frac{E \cos^2 \theta}{V - E \cos^2 \theta}},$$

(1.3)

where $f = \frac{\sigma_I}{2a\lambda_n}$ is the ratio between the real and imaginary part of the Fermi potential and $\sigma_I$ is the combined inelastic and absorption cross section [26]. In the case of an isotropic gas of UCN (e.g. in a storage bottle), this can be averaged over angle to obtain

$$\bar{\mu}(E) = 2f \left[ \frac{V}{E} \sin^{-1} \sqrt{\frac{E}{V} - \sqrt{\frac{V}{E} - 1}} \right].$$

(1.4)

The values given in Eq. 1.2 and Eq. 1.4 must be taken into account when materials for use with UCN are chosen.

Gravity of course effects neutrons at any energy, however, the effect is more prominent and can be quite useful with UCN. The standard gravitational potential, $V_0 = mg\hbar$, implies that a 1 m rise
corresponds to a 102 neV reduction in kinetic energy for the neutron. This effect can be exploited by using gravity to select a particular energy spectrum, to accelerate UCN to overcome the potential barrier of a foil on a detector, or even provide confinement of neutrons in the vertical direction, acting as the “top” of a material bottle.

Though electrically neutral, neutrons also interact with magnetic fields due to their magnetic dipole moment. This magnetic potential, \( V_m = -\vec{\mu} \cdot \vec{B} \), yields a 60 neV energy shift in a 1 T magnetic field. One can thus create a magnetic field geometry, for example, whereby one spin state may be trapped magnetically. This magnetic interaction also allows one to polarize UCN to nearly 100% by passing them through a strong (several Tesla) magnetic field. Further, RF techniques can be used to manipulate the direction of the neutron's spin axis using Larmor precession for either spin-flipping or precession phase comparison, both of which are done, for example, in the neutron electric dipole moment experiment [2].

1.2.1 Fundamental Physics Measurements with Ultracold Neutrons

The properties of UCN make them ideal for certain types of experiments. The ability to store neutrons in material or magnetic bottles allows UCN to be studied over longer periods compared to in-beam measurements, which can be important in measurements of the neutron lifetime [8, 9, 27]. Experiments searching for the electric dipole moment of the neutron take advantage of the long interaction time, as well as the random direction of movement in the magnetic field, thereby minimizing the \( \vec{v} \times \vec{E} \) systematic effect. [1, 2]. The ease of polarizing ultracold neutrons provides advantages in the measurement of spin-dependent parameters in neutron beta-decay whereby one has different systematic effects than in cold-beam experiments. These experiments include UCNA [10, 28] and UCNB. The incredibly low kinetic energies involved also allows for studies of gravitational quantum states [29, 30].

Using ultracold neutrons in fundamental physics experiments inherently involves accepting a substantially reduced fluence of neutrons as compared to cold neutron beam experiments. Typical cold neutron fluxes are around \( 10^9 \) cm\(^{-2}\)s\(^{-1}\) [31, 32] compared to \( \sim 10^4 \) cm\(^{-2}\)s\(^{-1}\) for UCN. However, this deficiency is offset in certain types of experiments by the significantly longer measurement times.
for each neutron. In cold neutron beams, a neutron typically spends milliseconds in the measurement volume, while a UCN can be stored in the measurement region for times as long as their beta-decay lifetime, \(880.0 \pm 0.9\) s [13]. For many measurements, these two methods compliment each other and allow different systematic effects to be explored.

While cold neutrons are often guided by reflection at oblique angles, UCN with kinetic energies below the Fermi potential of a material are reflected at all angles. The use of high Fermi-potential materials allows UCN to be guided and stored for lengths of time approaching the beta-decay lifetime. Commonly employed materials are \(^{58}\text{Ni}\) (340 neV), Be (252 neV), diamond-like carbon (220 neV) and Fomblin oil (106 neV). However, for each interaction with the walls of a container, there is a finite probability of the UCN being lost to upscattering or absorption. As shown in Eq. 1.3, the loss probability is dependent on both energy and angle of incidence. These effects will shape the energy spectrum and angular distribution of the UCN population as it travels through a system of guides.

UCN also may be transmitted through foils of lower Fermi-potential materials, e.g. aluminum (60 neV), but scattering and absorption may occur. Such foils are typically used as windows, allowing neutrons to pass from a production region into a separate measurement region for example.

Recent experiments are now replacing material walls with magnetic ones. Using either superconducting or permanent magnets, this approach allows one spin state to be stored without the complications of wall contact. However, care must be taken when this type of experiment is designed to ensure that there are no points in the storage volume with zero magnetic field. A neutron passing through such a point may lose its polarization and be accelerated into the wall by the very field meant to contain it.

The following sections give a brief overview of several types of UCN-based experiments that are presently underway.

**Neutron Lifetime Measurements**

The use of UCN in neutron lifetime experiments allows for measurement methods with different systematic effects than earlier beam experiments. Historically, the neutron lifetime was measured by
monitoring the rate of decays of neutrons in a well-defined volume as a cold-neutron beam passes through. While the number of neutrons passing through is large (e.g. \((1.5 \pm 0.1) \times 10^9\) neutrons/cm\(^2\)/s for the NIST experiment [32]), the time the neutrons spend in the volume is small (\(\sim 1\) ms), thus resulting in a small count rate. Ultimately, the derived lifetime is highly dependent on the precision of the measurements of the proton or electron count rate, the length of the trap, and the total neutron fluence through this experimental volume. In practice, the measurement of the neutron fluence is the most difficult of the three and limits present measurements using this technique.

The probability of any one neutron decaying while in the trapping region is proportional to the length of time it spends in the fiducial volume and is given by

\[
P_{\text{Decay}} = \frac{1}{\tau_n} \frac{L}{v},
\]

(1.5)

where \(\tau_n\) is the neutron lifetime, \(v\) is the neutron velocity, and \(L\) is the length of the volume. One measures the number of neutrons that decay, \(N_{\text{Decay}}\), relative to the total number of neutrons that pass through the volume, \(N_{\text{Total}}\). These are related by \(N_{\text{Decay}} = P_{\text{Decay}} N_{\text{Total}}\). By substituting this into Eq. 1.5, one obtains an idealized expression for the neutron lifetime,

\[
\tau_n = \frac{L}{v} \frac{N_{\text{Total}}}{N_{\text{Decay}}},
\]

(1.6)

The \(1/v\) dependence can be removed by exploiting the velocity dependence of the absorption cross-section of the material used as a detector for \(N_{\text{Total}}\). Due to this direct dependence, the accuracy of the determination of the total neutron fluence is critical and limits current experiments. For example, 3.0 s of the NIST beam lifetime experiment’s total systematic uncertainty (3.4 s) is due to effects that are related to counting the total neutron fluence [31].

UCN however provide two different ways experimenters can determine the neutron lifetime. The first, and more common technique, involves storing an ensemble of UCN for varied amounts of time and counting the surviving neutrons. This data can be fit to an exponential to extract the neutron
lifetime. The key systematic in this kind of measurement is the loss of neutrons through channels other than beta decay. The most precise measurements of this kind to date have been performed with material bottles coated with a Fomblin oil [1, 33]. Additional experiments using magnetic trapping or confinement of neutrons are underway and appear to have the promise of producing comparable results [5, 6, 34].

The other UCN lifetime technique allows one to measure neutron decays in real time. This is accomplished in one experiment, for example, by producing the UCN in superfluid 4He during a filling cycle, followed by counting decays via scintillation from the emitted betas in the helium bath [9]. An exponential curve can be directly fit to this data. Similarly to the aforementioned UCN method, other sources of neutron loss must be well understood.

At present, there are several efforts to measure the neutron lifetime to greater precision and to improve our understanding of the systematic effects that limited previous measurements [7, 35]. While two future beam experiments are being developed (an improved version of the NIST lifetime experiment [36] and a pulsed beam approach at the Japan Proton Accelerator Research Compex [37]), the majority of effort is going into UCN storage lifetime measurements. These include continuations and improvements in ongoing experiments and new trap designs such as PENeLOPE [34] and the Los Alamos National Laboratory permanent magnet experiment [27].

**Neutron Beta Decay Asymmetry Experiments**

In addition to the studies of the neutron lifetime, UCN are now playing a more prominent role in measurements of neutron beta decay asymmetries. Precision measurements of the correlations between the UCN spin and the momenta of the proton, electron, and anti-neutrino, when coupled with the neutron lifetime, allows one to extract the $V_{ud}$ component of the CKM matrix as well as the axial vector coupling constant. One can then compare this value of $V_{ud}$ to the value extracted from measurements of the $0^+ \rightarrow 0^+$ nuclear lifetime to search for non-Standard Model physics. In recent years, experiments using UCN have begun yielding competitive results in this area that was previously dominated by cold beam-type experiments. The UCNA experiment, presently running at Los Alamos
National Laboratory, has successfully performed a precision measurement of the correlation between the neutron's spin and the direction of the emission of the electron (referred to as the “A” coefficient) \([10, 28]\). These measurements are continuing and will be of comparable precision to the cold-beam experiments.

Future plans for a measurement of the neutrino asymmetry coefficient, “B,” and the Fierz interference term, “b,” at the same source are being developed. The UCNB experiment will use a slightly modified version of the UCNA apparatus to detect the decay electron and proton coincidence and extract the neutrino momentum. The UCNb experiment, also at LANL, will measure the energy spectrum of the decay electrons using an integrating sphere of calorimeters surrounding a population of UCN \([38]\).

Experiments with UCN will continue to play a major role in this area for the foreseeable future and will compliment future cold neutron experiments. For example, the Nab experiment will measure both the Fierz interference term and the electron-neutrino correlation parameter, “a,” using the Fundamental Neutron Physics Beamline at the Spallation Neutron source at Oak Ridge National Laboratory \([39]\).

**Neutron Electric Dipole Moment Measurements**

As in neutron beta decay, experiments seeking to measure the neutron electric dipole moment have evolved from cold beams to utilizing UCN in order to minimize systematic effects. The Standard Model predicts the neutron to have an electric dipole moment of \(\lesssim 10^{-32}\) e·cm \([40]\). Any measured value larger than this would be a clear indication of excess CP violation and indicate physics outside the Standard Model. The measured CP violation in the B and K meson systems, as well as the observed baryon asymmetry in the universe, suggest a larger level of CP violation, thus motivating further EDM experiments. Experiments measuring the electric dipole moment of the neutron have been ongoing for over 50 years and have set an upper limit on its size of \(< 2.9 \times 10^{-26}\) e·cm \([41]\). While measuring an EDM on the scale of the Standard Model is well out of reach of current methods, the next generation of experiments using UCN will approach the limits that constrain theories that explain the cosmological
prediction of $10^{-28}$ e cm [40].

UCN offer several advantages for experiments measuring the neutron EDM. For example, UCN may be measured for hundreds of seconds, allowing the small effect of the EDM on the Larmor precision to compound over time. Another advantage is that, due to their small velocities, UCN are less effected by the “$v \times E$” effect in which the electric field in the lab frame is seen as a magnetic field in the frame of the particle. The effect of this field on the Larmor frequency of the neutrons is difficult to distinguish from the electric dipole moment that is being searched for.

There are currently several efforts underway to improve the limits on the neutron EDM using UCN. Two of these are based at the Institut Laue-Langevin (ILL): the Sussex-based CryoEDM [3], and a Petersburg Nuclear Physics Institute (PNPI) led experiment [42]. At the Paul Scherrer Institut (PSI), a room temperature experiment taking advantage of their solid deuterium UCN source is being performed [4]. A joint effort between TRIUMF and the RCNP will use neutrons extracted from a superfluid $^4$He source at TRIUMF that is based on the working source at the RCNP in Osaka, Japan. A new solid deuterium UCN source at the FRM-II reactor at the Technical University of Munich will be used for an experiment using co-magnetometers and SQUIDs to monitor magnetic fields in the measurement volume. At the Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) an experiment using a superthermal $^4$He source and a $^3$He co-magnatometer is being developed [2, 40].

The large number of experiments is commensurate with the importance of static electric dipole moments as probes into CP violation beyond the Standard Model and UCN based experiments are playing a major role in this field.

**Other Measurements**

In addition to the above mentioned experiments, UCN are increasingly being used in other types of experiments. For example, at the ILL, the GRANIT collaboration has developed a method for studying gravitational bound states of neutrons [29]. These techniques open a rare window into quantum mechanical behavior under gravity. Any deviations from the predicted values could be an indication of a short range "fifth force" [43]. Another proposed experiment using UCN will search for $n - \bar{n}$...
oscillations [44], which would place limits on a possible source of baryon number violation. The use of UCN for surface characterization of materials as well as studies of biological molecules have also been proposed [45]. Due to their minimal penetration depth, long wavelengths and the large neutron cross-section of hydrogen, UCN may be used, for example, to study the level of hydrogen contamination on surfaces.

1.3 Summary

The number and variety of fundamental and applied physics experiments utilizing UCN that are briefly described in this chapter demonstrate the need for sources of ultracold neutrons for further precision measurements and to probe for physics beyond the Standard Model. The PULSTAR UCN source will be well suited for smaller scale physics experiments and for supporting the larger scale experiments, such as nEDM at Oak Ridge National Laboratory and UCNA/B at Los Alamos National Laboratory.

Proposed experiments at PULSTAR include neutron lifetime and beta asymmetry measurements, systematic studies for the nEDM experiment, development of UCN production and transport technologies, and studies of material surfaces. As a medium-scale, university-based UCN source supplying high densities of UCN, the PULSTAR source will be a valuable addition to both North Carolina State University’s research efforts as well as the larger nuclear physics community. This source will open up new opportunities to the UCN research community.
Chapter 2

Ultracold Neutron Sources

Due to the demand for the production of greater densities of ultracold neutrons (UCN) for fundamental physics experiments, various types of sources have been developed over the last few decades. At present, a number of sources are in operation with several more being constructed. The PULSTAR UCN source will be ideally situated for small-scale fundamental physics experiments and for assisting in the development of larger scale UCN experiments.

Section 2.1 describes the methods of UCN production that are presently in use, including the classical approach of extracting the lowest energy part of a thermal spectrum (Section 2.3.1) and the "superthermal" approach (Section 2.3.2). The remainder of the chapter describes the current state of UCN sources around the globe and the PULSTAR UCN source's place within this context.

2.1 Production of Free Neutrons

Free neutrons must be liberated from nuclei to be studied or utilized. For most experiments that utilize UCN, this is achieved through nuclear fission or by bombarding neutron rich nuclei with high-energy particles. This second process is referred to as spallation.
Reactor Neutron Sources

While other fission processes are used as neutron sources ($^{252}$Cf, etc.), nuclear reactors are the most common fission sources used in UCN production because of the high densities of fast neutrons produced. As $^{235}$U undergoes fission, it produces an average of 2.42 free neutrons per fission event along with the daughter nuclei. Though many of these neutrons will interact with other $^{235}$U nuclei and induce further fission to sustain the reactor, some will inevitably escape the reactor core. Depending on the design of the reactor, these may be reflected back into the core, absorbed in shielding, or allowed to escape for other uses. This supplies a ready, constant source of neutrons that can be used for a UCN source. Heating caused by the neutrons and gammas from the fission processes must be compensated for in cryogenic UCN sources.

Spallation Neutron Sources

Free neutrons may also be produced by high energy collisions between a light particle, often protons, and a neutron rich nuclei such as tantalum, lead, or mercury. This is generally achieved using a particle accelerator (cyclotron, linac, etc.) with a stationary target. The Spallation Neutron Source (SNS), for example, uses 1 GeV protons incident on a mercury target.

Upon impact, the proton is momentarily incorporated into the target nucleus. This excited nucleus rapidly ejects high-energy particles in a cascade that excite other target nuclei. As these nuclei de-excite, lower energy neutrons, as well as protons, photons, and neutrinos are cast off in a process referred to as evaporation. Depending on the energy of the incident particle and the target material, 20–40 fast neutrons are emitted from several nuclei per impact.

2.2 Neutron Moderation

The energies of neutrons produced by both spallation and reactor sources are too high to efficiently convert to UCN via either spectral selection (for Maxwellian Sources) or the superthermal process. For example, the single-phonon channel for superfluid helium sources requires neutrons
with energies around 1 meV, as compared to an average of 4.8 MeV for prompt neutrons from $^{235}$U fission. For most applications, much of this energy must be dissipated before use. This is achieved by allowing the neutrons to scatter multiple times to come into thermal equilibrium with a bulk material. This is referred to as moderation and generally employs a material with a high neutron scattering cross-section, minimal absorption, and low atomic mass [47]. The utility of the first two properties are self-evident and the low atomic mass is important to minimize the number of collisions required to come into thermal equilibrium.

The energy loss per collision can be characterized using the “lethargy” parameter $u = \ln(E_0/E_n)$, where $E_0$ and $E_n$ are the neutron energy before and after the collision. While the neutron temperature is significantly higher than that of the moderator, the moderator atoms may be treated as motionless. Using simple kinematics and taking the average over all scattering angles (denoted by $\xi$), one can show that

$$\xi = 1 + \frac{(A - 1)^2}{2A} \ln \frac{A - 1}{A + 1},$$

where $A$ is the atomic mass of the moderator. The characteristic number of collisions ($n$) to moderate neutrons from their initial energy, $E_0$, to a final energy, $E_n$ is given by

$$n = \frac{\ln E_0 - \ln E_n}{\xi}.$$  

Due to this fact, for thermal moderation from $\approx 2$ MeV to $\approx 0.025$ eV, materials that are rich in hydrogen ($n \approx 18$) or deuterium ($n \approx 25$) are most common, as heavier materials require many more collisions (e.g. $n \approx 2200$ for $^{235}$U). In nuclear reactors, for example, the fuel elements are generally surrounded by light or heavy water to cool the neutrons and increase the efficiency of the interaction with the uranium as well as provide thermal cooling for the reactor core [46, 48].

The first stages of UCN sources are typically moderators designed to lower the energies of the produced neutrons first to thermal, and then cold energies (from $\approx 25$ meV down to $\approx 50$ $\mu$eV) to allow for more efficient conversion. Water and heavy water are commonly used for thermal moderation. Cryogenic materials such as liquid hydrogen (e.g. used at the NIST reactor [49]), liquid deuterium
(e.g. used at the ILL [50]), mesitylene, heavy water ice, and solid methane (e.g. used at the Indiana UCN source as well as proposed for the PULSTAR source) are used as cold moderators.

In the PULSTAR UCN source thermal moderation of neutrons from the reactor core will take place in a tank of D$_2$O that surrounds the entire source, including the cold moderator, UCN converter, and the associated vacuum volumes and cryogenic lines. The thermalized neutrons are more easily cooled by the cold source than the incident fast and epithermal neutrons from the core.

The PULSTAR UCN source will use a cup-shaped volume of solid methane as its cold source. Solid methane was considered as a cold source as far back as 1957 [51], but was considered problematic due to the potential build up of stored energy that occurs. Fast neutrons separate the methane, leaving CH$_3$ and H, which may recombine, suddenly releasing large amounts of energy and potentially vaporizing a portion of the methane (referred to as “burps” in the literature). These burps may either occur spontaneously or during warm-up phases. Later studies [52,53] have had mixed results in reproducing spontaneous burps, but definitely observe them during the warming process. To mitigate this, sources such as the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory annealed their methane moderator into a liquid state periodically to release any built-up energy [54].

For the PULSTAR UCN source design, the use of a solid methane cold moderator will be safe due to several factors. The gamma and neutron heating of the methane and its container should be $\sim 6$ W (see Section 3.1 for details). This relatively low heat load and the higher operating temperatures of the cold source as compared to the situations above will lead to a slower build up of stored energy. Occasional annealing in the liquid state will further mitigate any risks. Finally, should the methane turn gaseous, a check valve will release it into a large (946.4 L) ballast volume. Should the entire 1.4 L inventory vaporize, this ballast tank will still be at less than atmospheric pressure.

### 2.3 UCN Production

Ultracold neutron sources can be broadly categorized into two categories: Maxwellian and superthermal. Maxwellian sources take the low energy tail of a moderated neutron population, while superthermal sources exploit materials that have a high probability of inelastically scattering neutrons
into the UCN energy range. By either suppressing the upscattering rate or extracting the UCN before they gain energy, superthermal sources can produce much higher densities of UCN. The following section describe these two sorts of sources and give examples of sources that use these techniques.

### 2.3.1 Maxwellian Sources

Historically, it was assumed that due to phase space volume conservation, the only way to obtain UCN was from the low energy tail of a cold neutron energy spectrum \([\text{55}]\). While, in principle, reducing the temperature of the neutron population leads to an increase in the number of neutrons in the UCN energy range proportional to \(1/T_n^2\) \([\text{56}]\), in practice several limitations come into play. Perhaps most obviously, cooling a moderator to ever lower temperatures becomes increasingly difficult. This is exacerbated by the heating of the moderator by the source of the neutrons. Further, though it is often useful to consider the neutron energy spectrum as a Maxwellian distribution at a fixed temperature, complete thermal equilibrium with a moderator is never achieved. This is due to the limited time that the neutrons interact with the moderator and finite size of the moderator. Absorption of the neutrons by the moderator or container, neutrons escaping through the walls, and eventually neutron beta decay all prevent complete thermalization of the neutron population \([\text{57}]\).

Due to the limitations imposed by Liouville's theorem \([\text{55}]\), the phase space density of the neutron population cannot be increased by the influence of a conservative potential. Therefore any attempt to increase the spatial density of UCN will necessarily lead to spreading of the momentum distribution of the population compared to the distribution in the moderator. Despite these limitations, many successful sources have been constructed. Efficient extraction of UCN from the moderator is crucial to obtain useful densities for experiments. A vertical neutron guide is a common method of extraction from the moderator that offers several advantages. For example, UCN leaving the moderator will be accelerated by their transition across the Fermi potential at the moderator–vacuum interface. If the plane of this interface is horizontal, the energy boost will be in the vertical direction, giving the neutrons a more forward directed angular distribution as they travel up the guide. Further, the acceleration caused by the Fermi potential can be counteracted by the gravitational potential change
This vertical extraction method is used at the turbine source at the Institut Laue Langevin (ILL) in Grenoble, France. This source is the long-time UCN density record holder and has been the location of many UCN experiments over the past several decades \cite{50, 58}. This source, which has been operating since 1986, takes advantage of the 58.3 MW high-flux reactor with a liquid deuterium cold moderator. A fraction of the cold neutrons are extracted through a vertical, nickel-coated neutron guide of length 5 m. These neutrons then pass through two zirconium windows and enter a curved 13 m guide that leads into the neutron turbine.

Neutron turbines were originally developed at the FRM reactor in Munich \cite{59}. The cold neutrons are fed into series of curved, receding blades made of a material with a high Fermi potential in such a way that they collide with the blade at very shallow angles. The curved blade acts as a moving neutron guide. The neutrons are reflected several times and, upon exiting, have slowed by approximately twice the velocity of the receding blade through the doppler effect. The ILL turbine consists of 690 semi-circular blades 7.7 mm apart receding at 25 m/s. Though the density of neutrons at UCN energies is increased, the beam divergence also increases, satisfying Liouville’s theorem. On the order of $10^6$ UCN/s are available, with typical densities of 1–30 UCN/cm$^3$ realized in experiments.

### 2.3.2 The Superthermal Process of UCN Production

Golub and Pendlebury recognized that the production of UCN is not necessarily limited to the tail of a cold Maxwellian neutron population if a technique referred to as the “superthermal process” is employed \cite{60, 61}. This process relies on the fact that some portion of neutrons scattered from a material leave the majority of their kinetic energy behind in the conversion material. If these neutrons can be kept in this low energy state and prevented from thermalizing with the bulk material, a population of UCN can be produced. The two methods that were originally proposed were magnetic scattering from highly polarized nuclei and scattering from superfluid $^4$He \cite{57}. Both of these methods exploit the fact that upscattering of UCN is highly suppressed, allowing large populations to accumulate without thermalization. The magnetic scattering technique used the fact that neutrons anti-parallel to the field
could scatter and flip both the neutron and nuclear spins, decreasing the kinetic energy by increasing
the magnetic potential energy of both partners. Neutrons that were parallel could not spin flip due to
conservation of angular momentum. The superfluid helium approach relies on the Boltzmann factor
suppression of phonons in the cold helium [60]. Solid deuterium sources are commonly referred to as
superthermal despite the inability to suppress UCN losses as drastically as the previous methods. This
deficiency is overcome by allowing the UCN to quickly leave the deuterium volume before further
scattering occurs. Additional details of both helium and deuterium superthermal sources are provided
in the following two sections.

2.4 Superfluid Helium Sources

Superthermal helium sources rely on two properties of superfluid helium-4 (He-II). First, the phonon
dispersion curve of He-II only crosses the energy-momentum curve of the neutron at two points, 0 and
1 meV. This allows a 1 meV neutron (corresponding to a wavelength of 8.9 Å) to excite a single phonon
in the helium and transfer nearly all of its kinetic energy to the helium bath. Further, the reverse
(upscattering) process may be suppressed by a Boltzmann factor ($e^{-ΔE/kT}$) by keeping the temperature
low. Second, helium-4 is effectively transparent to neutrons when the helium-3 is removed. These
two factors allow the UCN population to only be limited by other loss mechanisms, such as wall
interactions, multi-phonon scattering processes, and $β$-decay.

To exploit the effective two-level system produced by the single-phonon interaction, monochro-
matic neutron beams at 8.9 Å, produced by Bragg diffraction or velocity selectors, are often used in
superfluid helium sources. This has the additional benefit of reducing cold neutron induced back-
grounds caused by the wider beam. Though the production rate rapidly drops off outside of the peak
wavelength, the effective width of neutron energies that can produce UCN via this single-phonon
process is governed by the ability to trap the down-scattered neutrons, i.e. the Fermi potential or
magnetic trap strength surrounding the production region [61]. Though the single-phonon peak is
the primary UCN production mechanism, multi-phonon processes can contribute up to $\sim 30\%$ of
the production if a broad-spectrum beam is used. This leads to a trade-off between the increased
production and the increased backgrounds. Recent experiments have shown production rates on the order of 1–5 UCN/cm³/s [62, 63].

The relatively low production rates are offset by the long lifetimes of UCN within the source that can be attained. The tightly bound \( ^4 \text{He} \) nuclei have no absorption cross-section for neutrons. This can be taken advantage of by minimizing the isotopic fraction of \( ^3 \text{He} \) within the source. Due to its Fermionic nature, helium-3 does not enter the superfluid state at the temperatures these sources are operated at. This fact facilitates its removal, allowing for significantly purer helium-4 UCN sources [64, 65].

Minimizing upscattering can also extend the UCN lifetime within the helium source. By keeping the helium temperature as low as is practical, the population of 1 meV phonons, which can upscatter UCN, can be nearly eliminated. This single-phonon upscattering process is suppressed by a factor of \( e^{-\Delta E/kT} \), which for a 300 mK source represents 18 orders of magnitude.

If losses due to the nature and geometry of the trapping region can be minimized, trap lifetimes approaching the neutron beta decay lifetime are feasible. Densities up to 55 UCN/cm³/s in an extraction user facility have been demonstrated [66] and for \textit{in situ} experiments higher densities are predicted.

\subsection*{2.4.1 Single Experiment Superthermal Sources}

Several purpose-built superthermal UCN sources have been constructed for dedicated use by single experiments. Due to He-II’s transparency to neutrons, the source and experimental volumes can be the same. Producing UCN in situ removes the losses associated with transporting the neutrons to a separate experimental volume. An example of this is the UCN lifetime experiment housed at the NCNR at NIST in Gaithersburg, MD [9]. This novel experiment uses 8.9 Å neutrons diverted from the fundamental physics beamline (NG-6) by an intercalated-graphite monochromator to produce UCN in highly isotopically purified superfluid \( ^4 \text{He} \). The \( ^3 \text{He} \) is removed via a heat-flush method described in references [64, 65]. The UCN are magnetically trapped in the helium in a potential well provided by an Ioffe-type superconducting magnet configuration [67]. The helium serves as both
the UCN converter and the detector. Electrons ejected during neutron beta decay ionize the helium and produce scintillation light. This extreme ultraviolet light is down converted to visible blue light using the organic wavelength shifter tetraphenyl butadiene (TPB) and detected with photomultiplier tubes. By counting the diminishing number of decays over time, the lifetime of the neutron can be deduced after accounting for other loss mechanisms in the trap. This method is fundamentally different from the beam-type neutron lifetime experiments (e.g. [22, 23, 68]) and does not depend on precise measurement of the total neutron fluence. A similar helium source is being developed as part of the nEDM collaboration for installation at the Spallation Neutron Source at Oak Ridge National Laboratory [2]. Other experiments using this approach, such as CryoEDM [3] at the ILL, produce the UCN in a separate cell from the experimental volume and transport these neutrons to the apparatus. This transport process introduces considerable losses. However, the benefits of reduced backgrounds from a separate production volume potentially offsets the reduced sensitivity from these losses.

2.4.2 RCNP

A spallation based superfluid helium source is presently running at the Research Center for Nuclear Physics on the campus of Osaka University. A lead spallation target is bombarded with up to 1 µA of 400 MeV protons, producing neutrons that are moderated by a 300 K D_2O thermal moderator and a 20 K D_2O cold neutron source. UCN are produced in an 8 L He-II converter. The measured production rate is 4 UCN/cm^3/s with a spectrum up to 210 neV, limited by the natural nickel walls [63]. In the future, this source will be relocated to TRIUMF in Vancouver, BC for use in a proposed nEDM experiment. Initial experiments characterizing this source using a gravitational spectrometer are described in Chapter 5.

2.5 Solid Deuterium

The use of solid deuterium was proposed by Yu et al. in 1986 [69] as a thin film and as a bulk converter by Serbrov et al. in 1994 [56]. Like superfluid helium sources, the neutrons in a solid deuterium source are prevented from coming to thermal equilibrium with the converter medium. Unlike helium
sources, the lifetime of UCN in the converter before being lost through upscattering or absorption is much shorter and the UCN must be extracted from the converter volume soon after production. This challenge is generally dealt by using compact volumes of solid deuterium that allow the neutrons to escape quickly into the guide system.

Neutron scattering in solid deuterium is significantly more complicated than in superfluid helium due to the anisotropy of the crystal, the diatomic structure, and the non-zero nuclear spin and absorption cross-sections. The mechanism of UCN production is a multi-phonon process with both coherent and incoherent contributions. To properly understand the interactions between neutrons and solid deuterium, the system must be considered at the atomic, molecular, and crystalline perspectives.

As deuterons are spin-1 particles, neutrons scatter off of them through singlet and triplet channels with scattering lengths of 0.975(60) fm and 9.53(3) fm respectively [70]. This yields a weighted average (coherent) scattering length, $b_{coh}$, of 6.674(6) fm and a weighted root mean square of the spin variations (the incoherent scattering length), $b_{inc}$ of 4.03 fm. These values correlate to cross-sections of $\sigma_{coh} = 5.592(7) \text{ b}$ and $\sigma_{inc} = 2.05(3) \text{ b}$. The absorption cross-section, which becomes important when optimizing the residency time of the UCN, is $\sigma_{abs} = 5.19(7) \times 10^{-4} \text{ b}$ [70].

As an isotope of hydrogen, deuterium forms diatomic molecules with an interatomic distance of 0.742 Å. The two spin-1 deuterons can combine into either ortho ($J = 0, 2$) or para ($J = 1$) states. Vibrational states are not relevant at low temperatures [71], but selection rules imply that the para state must have odd (anti-symmetrical) rotational quantum numbers. At temperatures low enough to solidify deuterium, one third of the molecules are in the para ($J = 1$) state, with the remainder in the ortho ($J = 0, 2$) state. Left alone, the ortho state is inaccessible to the para state, and this ratio remains stable. However, when neutrons scatter off the molecule, the para-deuterium may convert to ortho by imparting the energy differences into a neutron. This energy (7.5 meV) is more than enough to remove a neutron from the UCN regime [72]. To avoid this UCN loss mechanism, the para-deuterium must be converted into ortho before the crystal is formed. The conversion method used in the PULSTAR source is described in Chapter 4.
Solid deuterium is a hexagonally close packed molecular crystal with an intermolecular distance of 3.607 Å. Due to this anisotropic structure, a cold neutron gas will sample randomly oriented domains, making phonons capable of downscattering to the UCN energy scale readily available. Due to these effects, solid deuterium has both advantages and disadvantages compared to superfluid helium as a UCN source. The plethora of phonon energies that can contribute to downscattering compare favorably to the single energy slice available in helium. This leads to a significantly increased production rate. However, once the neutrons are converted to UCN, deuterium presents a challenge in the form of nuclear absorption. This leads to a UCN lifetime in the deuterium of only 150 ms, compared to the limit set by the beta-decay lifetime (880 ± 0.9 s), for helium. Despite the obvious problem this causes, it can be overcome. The source can be designed to have UCN residency times shorter than the lifetime of the neutron in the source by using a small volume of deuterium that is closely coupled to the downstream neutron guide system. Unlike in He-II sources, in this type of source there is little benefit to cooling a deuterium source below 5 K. This, coupled with the reduced radiation heat loads associated with a smaller volume source, significantly reduce the difficulty of the cryogenic design required for a source near a reactor or spallation target [69, 73, 74].

2.5.1 Los Alamos National Laboratory

A solid-deuterium UCN source is currently in operation at Los Alamos National Laboratory. The initial prototype [75–77] used a tungsten spallation target with pulsed 800 MeV protons incident from the Los Alamos Neutron Science Center (LANSCE) linear accelerator. The produced neutrons were contained within a 77 K beryllium box and moderated by a polyethylene cold source. A 240 cm$^3$ deuterium source produced densities of $(145 \pm 7)$ UCN/cm$^3$ in a simple bottle connected directly to the source [75–77].

The current version of the source [78] has been used to supply neutrons to the UCNA beta-decay asymmetry experiment [10, 28], for testing of the LANL neutron lifetime experiment [27], and to test components of the ORNL nEDM project. This source uses the same proton source as the prototype, with a different target, reflector, moderator, and convertor arrangement. The tungsten target currently

23
has a 2.5 cm by 2.5 cm square cross-section and a length of 12 cm and accepts ~ 50% more beam than the old cylindrical target. The target and the deuterium volume are surrounded by a room-temperature beryllium reflector embedded in ~ 1 m of graphite. The cold source is a 1 cm thick volume of polyethylene beads (T ~ 150 K depending on beam current) surrounding the deuterium volume. The cold neutron production was measured to be \((1.7 \pm 0.3) \times 10^{10} \text{ /cm}^2/\mu\text{A}\).

The 1500 cm\(^3\) (19.7 diameter, 5.7 cm high) cylindrical deuterium volume is located at the bottom of a 1 m guide coated with 200 nm of \(^{58}\text{Ni}\) and has “flapper” valve above the level of the deuterium which is only open while the beam is on target. As the beam is run in a pulsed mode with groups of 5 625 \(\mu\text{s}\) pulses at 20 Hz with 5.0 s of downtime between groups, the open flapper allows the UCN to exit the converter volume quickly during the pulses, but once closed prevents them from returning during the beam’s downtime. This is quite useful in a pulsed source, but does not provide any benefit in constant sources such as reactors. The neutrons are extracted through a horizontal guide at the top of the vertical source volume. This configuration of the source can deliver a density of \((52 \pm 9)\text{ UCN/cm}^3\) immediately outside the shield wall [78].

### 2.5.2 Paul Scherrer Institute

A new spallation, solid deuterium source is being commissioned at the Paul Scherrer Institute (PSI) in Switzerland with the intention of having ultimate densities on the order of 1000 UCN/cm\(^3\). 600 MeV protons from the cyclotron impact a target composed of lead-filled zircaloy tubes with an expected yield of 10 neutrons per proton. The beam is magnetically kicked in for 8 s out of every 800 s. These neutrons are thermalized in a D\(_2\)O moderator and converted to UCN in a 50 cm diameter container with up to 30 L of solid deuterium [79].

Presently the UCN source at PSI is in regular operation with a measured density of 30 UCN/cm\(^3\) at the experimental beam port. Various improvements, including optimization of the deuterium freezing process, are underway and it is expected that the UCN density can be increased by an order of magnitude or more [80].
2.5.3 Munich Mini-$D_2$ at FRM-II

A solid hydrogen moderated, solid deuterium UCN source is being constructed at the FRM II reactor at the Technische Universität München (TUM). The source is a 9 cm long, 6 cm in diameter, disk of solid deuterium situated 60 cm from the core of the reactor. Between the core and the converter a liquid deuterium cold source at about 40 K moderates the fast and thermal neutrons. A cold flux of $7 \times 10^{13}$ neutrons/cm$^3$ is expected in the converter. This will be directly coupled to a 7 m beryllium coated storage tube to extract the neutrons from the reactor volume. This source is expected to produce densities of $5 \times 10^4$ UCN/cm$^3$ in the source and a flux of $3 \times 10^6$ UCN/cm$^2$/s at the end of the storage tube. These expectations lead to UCN densities 2-3 orders of magnitude better than the ILL [81]. The sections of this source that are inside the reactor volume are scheduled to be installed during a shutdown in 2014.

2.5.4 Triga Mainz

At the pulsed TRIGA reactor in Mainz a solid deuterium source has been constructed near the reactor core inside of a radial beam tube. The UCN converter is 160 cm$^3$ of solid deuterium at 6 K with a solid para-hydrogen moderator. Recent measurements suggest a usable density of $25 \pm 3$ UCN/cm$^3$. With future improvements, including further moderator studies and UCN guides with higher transmission, a usable density of $\sim 100$ UCN/cm$^3$ is predicted [82].

2.6 The PULSTAR UCN Source

The North Carolina State University UCN source will utilize neutrons from the 1 MW on-campus nuclear reactor. A large amount of fast and thermal neutron leakage is characteristic in the design of the PULSTAR reactor. By installing a helium filled flight path, referred to as the "shielding box" and the "nose port," these neutrons will be transmitted to a volume within the biological shielding that will hold the UCN source. After extraction from the core, the neutrons will be moderated in heavy water and solid methane before they are converted to UCN in a solid deuterium converter. The deuterium
and methane will be cooled by liquid helium supplied by a dedicated liquefaction facility. $^{58}$Ni coated quartz guides will carry the UCN through the biological shielding to the experimental area. The entire source will be attached to a removable shielding block that can be pulled back for maintenance and testing. The general layout is shown in Figure 2.1 with an expanded view shown in Figure 2.2.

The PULSTAR UCN source will be a useful user facility for small scale experiments and the development of UCN technology. The following chapter discusses simulations of the neutron transport and cryogenic systems that were conducted during the design phase of this source. The design and construction of this source will be discussed in detail in Chapter 5.
Figure 2.2: An expanded view of the UCN source including, the solid deuterium and solid methane volumes (each surrounded by cooling channels), the first four UCN guides, the guide cooling channel, and the UCN window.
Extensive computer modeling was carried out during the source design phase to understand and optimize the cryogenic and neutronic properties of the source. The three major efforts were: neutronics modeling of the reactor core and UCN source using the Monte Carlo N-Particle Transport (MCNP)\(^1\) code; thermal and fluid flow simulations of the helium cooling loops and cryogenic moderators using ANSYS CFX\(^2\); and UCN transport simulations of the source and guides using Monte Carlo techniques.

MCNP was used to estimate the cold neutron flux in the solid deuterium, which is in turn used to estimate the UCN production rate. The neutron and gamma flux throughout the system is also used to predict source heating, the activation of source parts, and backgrounds in the experimental area.

ANSYS CFX was employed to assist in the design of the helium cooling loops for the solid deuterium UCN converter, the solid methane cold source, and the neutron guide housing. Geometries and flow rates were varied to ensure that there is adequate cooling power to counter heat loads from several sources, including conduction from the 300 K upper cryostat, radiative heating from the outer vacuum jacket and down the UCN guide, and nuclear heating from gammas and higher energy neutrons interacting with the source cryogens and construction materials.

An in-house Monte Carlo UCN transport code was used to explore UCN guide geometries and to optimize the UCN transport efficiency to the experimental region for different energy classes. This

\(^1\)http://mcnp.lanl.gov/
\(^2\)http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+CFX
UCN code was also used to assist in the analysis of the gravitational spectrometer experiment at the Osaka UCN source to account for non-gravitational effects of the spectrometer discussed in Chapter 5.

The following sections provide details about these simulations. Section 3.1 presents a summary of the MCNP simulations that were performed to predict the neutron flux in the source location. Sections 3.2 and 3.3 describe the cryogenic and UCN transport properties of the source respectively.

### 3.1 Overview of Neutronics Modeling

MCNP is a widely used FORTRAN Monte Carlo radiation transport code that was developed at Los Alamos National Laboratory. It is capable of modeling the transport of particles, such as neutrons, photons, and electrons, and their interactions with an extensive range of materials. Energy deposition and particle flux can be tallied at user defined points.

To predict the UCN production rate and estimate the heat loads in the source, MCNP was used to simulate the neutron and gamma fluxes from the reactor. This work was primarily carried out by Yanping Xu and Bernard Wehring [83], with more recent simulations performed by Eduard Sharapov and Graham Medlin. A brief overview is presented here for completeness since the neutronic and gamma heating are essential inputs to the cryogenic design given in Section 3.2.

#### 3.1.1 Early Xu and Wehring Simulations

The geometry used in early MCNP simulations of the source is shown in Figure 3.1. Since this was the design phase, the geometry used is similar, but not identical to the source as it is constructed. Despite these minor discrepancies, this work assisted in predicting the usable cold neutron flux at the source and the heat load placed on the cryogenic moderators and their housing from neutrons and gamma rays produced in the reactor core.

These simulations used a reactor core model that included 6% enriched uranium in the 5 fuel assemblies closest to the UCN source area, and 4% enrichment in the 20 remaining assemblies. In reality, the entire core is 4% enriched. This error was introduced by using outdated information, but it should not have a major effect on the results as most effects will be balanced out in a steady, critical
Figure 3.1: The geometry used in early MCNP simulations of the UCN source.

The reactor was modeled to be in a stable 1 MW configuration yielding a peak flux of $7.544 \times 10^{16}$ neutrons/s just outside the core. To reduce the attenuation of neutrons on their path to the UCN source, the water reactor pool between the core and the thermal column is displaced by filling the graphite-lined nose port with helium gas. The neutrons that reach the thermal column are then moderated to thermal energies by heavy water and then to cold energies with solid methane. The simulations predict a cold neutron flux in the solid deuterium volume of approximately $4 \times 10^{11}$ neutrons/cm$^2 \cdot$ s [83].

The neutrons and gammas that are absorbed by the source result in heat loads to the various components of the UCN source. The estimated radiation heating of components of the source
Table 3.1: The predicted heat loads by component from gammas and neutrons as calculated using MCNP [83].

<table>
<thead>
<tr>
<th>Component</th>
<th>Neutron Heating (mW/g)</th>
<th>Gamma Heating (mW/g)</th>
<th>Total Heating (mW/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Deuterium</td>
<td>3.23</td>
<td>1.24</td>
<td>4.47</td>
</tr>
<tr>
<td>Deuterium Chamber (Al)</td>
<td>0.033</td>
<td>1.52</td>
<td>1.55</td>
</tr>
<tr>
<td>Solid Methane</td>
<td>2.84</td>
<td>2.01</td>
<td>4.84</td>
</tr>
<tr>
<td>Methane Chamber (Al)</td>
<td>0.036</td>
<td>1.60</td>
<td>1.64</td>
</tr>
</tbody>
</table>

is shown in Table 3.1 and is used as input parameters for the thermal simulations described in Section 3.2. To accommodate differences in the simulated and as built geometries, the heat loads are scaled by mass, with the assumption that heating per gram of each material is unchanged.

A more detailed description of this work is found in Yan-Ping Xu's dissertation [83].

### 3.1.2 Recent MCNP Simulations

A further series of simulations is underway to model the geometries used in the neutron flux experiments described in Section 4.2.1. This comparison can be used to evaluate the quality of the simulations and look for potential issues in the materials or assumptions that were used. Using this benchmark, the final source geometry can be benchmarked, providing greater confidence for simulations of possible future modifications. The results as of early 2013 are shown in Figure 3.2. Unfortunately, a correction factor of 0.6 must be applied to the simulated points to produce agreement with the experimental data. Additional simulations are being conducted to understand the discrepancy. A possible contributor could be the uncertainty of the thickness of water between the reactor core and the shielding box.

### 3.2 Thermal and Fluid Flow Simulations

Thermal and fluid flow simulations of the liquid helium and cryogenic moderators were carried out using ANSYS CFX. These simulations were aimed at ensuring that the required temperature
distributions for UCN production were attainable with the available helium flow from the liquefier, coupled with the radiative and nuclear heat loads. The Linde 1430 liquefier is capable of supplying 17 L/hour or, with liquid nitrogen pre-cooling, 47 L/hour.

The source is cooled by three parallel cooling loops, one containing mostly liquid helium for the solid deuterium chamber and two with gaseous helium for the solid methane chamber and upper neutron guide. Each flow rate can be controlled independently, allowing each loop to be simulated separately. Figure 3.3 shows the locations of the three regions of interest.

The deuterium temperature distribution was optimized to ensure that the entire volume could be kept at 5 K and that the freezing process would lead to a nearly cylindrically shaped source at the bottom of the deuterium volume while minimizing freezing on the upper walls. The largest simulation effort was directed towards understanding the temperature distribution in the solid deuterium and the helium flow path and rate that could achieve it. A series of flow geometries were simulated to explore their cooling properties.

The methane must be carefully liquified and frozen into the container from the bottom to avoid...
blocking the gas lines. This is achieved with the assistance of heaters that are attached near the top of the volume.

The neutron guide housing cooling loop is intended to minimize heating from the room-temperature upper cryostat to the deuterium volume. The simulations were carried out to model the temperature distribution that could be achieved while varying the helium flow rate.

### 3.2.1 Computational Fluid Dynamics

ANSYS CFX, a computational fluid dynamics (CFD) software package that can be used to model fluid flow and heat transfer in user-definable geometries, was used to optimize the cooling processes of the solid deuterium, methane, and neutron guide housing for the UCN source. It uses unstructured, variable sized meshing techniques to conform to complex shapes for accurate results. The flexible nature of these meshes allows for more precise simulation of position sensitive regions, such as boundary layer flow of helium, while leaving the mesh coarser in other regions, such as the bulk of the solid deuterium, to save computational time.
The shape and size of the meshing in heat and fluid flow simulations must be carefully considered to ensure that accurate results can be obtained while minimizing computational time. The mesh defines the location of the points where the desired properties are calculated, and the connections between these points. All but the earliest simulations were meshed using ICEM CFD\(^3\).

The default mesh shape is unstructured tetrahedral. This type of mesh is randomly grown with each of the mesh points connected to four others. The characteristic size of the mesh is user defined, but the mesher adjusts the size to conform to the shape of the volume. This mesh type was used for all of the volumes that were modeled with the exception of the boundary layers of the helium which were meshed with a series of triangular prisms. Prisms allow for higher aspect ratios than tetrahedral elements and can therefore have a very fine scale normal to the boundaries without increasing the number of mesh elements as much as would be required using tetrahedra. This resolution is required to capture the complex fluid dynamics near wall interfaces [84].

### 3.2.2 Solid Deuterium UCN Converter Simulations

Heat transfer from the solid deuterium source material through the aluminum housing to gaseous helium was modeled using ANSYS CFX. We optimized both the helium flow pattern and rate so that the deuterium crystal will grow uniformly from the bottom of the cryostat, minimizing the amount that freezes on the guides and upper cryostat, and that the solid deuterium source temperature is held at approximately 5 K. To satisfy these requirements, we designed a geometry with a uniform temperature gradient across the deuterium volume with the highest temperature corresponding to the upper walls of the source volume.

The actual UCN source will use a mixed flow of liquid and gaseous helium and the latent heat of the phase change will provide additional cooling power. Unfortunately, limitations in ANSYS CFX only allowed us to use a pure gaseous flow. The simulations therefore provide an overestimate of the helium flow rates that will be required since the latent heat is not included. If we assume that all of the liquid helium vaporizes while cooling the deuterium, a 0.2 g/s mass flow and a 30% liquid mixture,

\(^3\)http://www.ansys.com/Products/Other+Products/ANSYS+ICEM+CFD
Table 3.2: The temperature dependent properties of gaseous helium obtained via power law fits to existing experimental data [85].

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity</td>
<td>$(−2 \times 10^{-6} T^2 + 8 \times 10^{-4} T + 5.6 \times 10^{-3})$ W/m/K</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$(5270 + 5.87 \times 10^7 T^{-6})$ J/kg/K</td>
</tr>
<tr>
<td>Viscosity</td>
<td>$5.023 \times 10^{-7} T^{0.647}$ Pa s</td>
</tr>
</tbody>
</table>

Table 3.3: The temperature dependent properties of aluminum [86]. Early runs were conducted with a constant thermal conductivity without knowing what alloy of aluminum would be used. After aluminum 6061 was decided upon, a temperature dependent model of that alloy was employed.

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (Early Runs)</td>
<td>40 W/m/K</td>
</tr>
<tr>
<td>Thermal Conductivity (Al 6061)</td>
<td>$(−0.661 + 1.49 T)$ W/m/K</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$(9.2 \times 10^{-4} T^3 + 5 \times 10^2 T)$ J/kg/K</td>
</tr>
</tbody>
</table>

this would yield an additional 1.24 W of cooling power. In practice, this additional cooling will lead to a reduced helium flow rate.

The thermodynamic properties of solid deuterium, aluminum, and gaseous helium vary as a function of temperature in the region of these simulations (~5-15 K). Initially, constant values were used for the thermal conductivity, specific heat, and viscosity to simplify the simulations. The extent of the temperature ranges involved made this inadequate and the temperature dependent functions listed in Tables 3.2, 3.3, and 3.4 were incorporated into the simulations. These functional forms were a result of power law fits from available sources [85–89].

Table 3.4: The temperature dependent properties of solid ortho-deuterium [87–89].

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (Early Runs)</td>
<td>14 W/m/K</td>
</tr>
<tr>
<td>Thermal Conductivity (Later Runs)</td>
<td>$(1.7 \times 10^{-3} T^4 - 0.1 T^3 + 2.15 T^2 - 20.6 T + 75)$ W/m/K</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$(0.1125 T^2 + 300 T^3 + 27.5 T^4)$ J/kg/K</td>
</tr>
</tbody>
</table>
Geometries

The general design parameters of the deuterium source were held fixed while the cooling geometry was varied. The geometry was required to allow for growing the deuterium crystal from either liquid or vapor phase. Further, a symmetric distribution of the cooling power is desirable to produce a uniform, symmetric crystal. The bottom of the crystal should receive the bulk of the cooling power in case the crystal does not contact the walls.

The solid deuterium was modeled as an 8.5 cm radius cylinder with a volume of 1 L. The deuterium was assumed to be in thermal contact with the aluminum housing on the bottom and sides of the cylinder. This is surrounded by an aluminum shell 2 mm thick on the sides and 5 mm thick on the bottom. A 4 mm diameter aluminum pin extending into the middle of the deuterium was included in early simulations in an attempt to uniformly cool the center of the deuterium, though this was removed in later geometries and the final design. Outside of the aluminum is a volume containing flowing cold helium gas. The helium flows in from the bottom of the geometry through a curved 6 mm ID tube and sprays onto the center of the bottom of the aluminum assembly. The helium volume is 1 cm deep on the bottom of the assembly and 4 mm thick on the sides. After entering the volume the helium flows up the side of the aluminum cylinder and exits at the top through either one or three holes. A series of aluminum structures protruding into the helium volume were modeled in an attempt to distribute the flow and cooling evenly across the deuterium. These included straight and curved fins on the bottom of the geometry, a diffuser on the helium inlet, and baffles on the side of the container.

All of the simulations used gaseous helium that enters at 4.5 K. The base pressure in the helium volume was initially set to 1 atm, but was raised to 1.4 atm after receiving the specifications of the helium liquefier system. Heating is applied throughout the aluminum (1.6 mW/g) and deuterium (1.014 W or 4.15 mW/g) volumes to simulate nuclear heating from neutrons and gammas from the reactor interacting with the aluminum and deuterium in the source (see Table 3.1). An additional 2 W of heating is applied to the top of the aluminum shell to simulate heat conduction from the upper cryostat and guide systems. This was calculated separately in finite element simulations of the source.
shell using COSMOS (since renamed SolidWorks Simulation)\(^4\).

The mesh size is on the order of 1 mm with the exception of the bulk of the deuterium where a larger mesh of up to 10 mm is used. Thin sections of the geometry have automatically been given a smaller mesh size.

The initial geometry conformed to the general description above with a few variations. Specifically, it had three evenly spaced outlets the at the top, “long” fins seen in Figure 3.4, and the 4 mm pin protruding into the center of the deuterium.

**Study of the Mass Flow Dependence**

In the first set of simulations, the helium mass flow was varied from 0.2 g/s to 1.5 g/s to test the variation and range in cooling power and heat transfer coefficient. Note that 1 g/s corresponds to a flow rate of 29 L/hr. The cooling power, minimum temperature, and maximum temperature of the deuterium were determined for the initial geometry and are shown in Table 3.5. Not surprisingly, the higher the mass flow, the lower the temperature of the deuterium. 0.2 g/s corresponds to the amount of liquid helium that would be required to remove 4 W of heat through the latent heat of evaporation. As these calculations assume that the helium is already gaseous, this flow rate is higher than will be required when the latent heat of vaporization is taken into account.

For the remaining simulations, based on these results, we chose a mass flow of 0.6 g/s due to the fact that this yielded enough cooling power to maintain a minimum temperature of \(\sim 5.6\) K with a small temperature gradient across the deuterium. Large temperature gradients in the deuterium would make the warmer parts of the source less effective for producing UCN. These mass flows are within the capabilities of the liquefier and should not require liquid nitrogen pre-cooling.

Using this flow rate we then tried to optimize the temperature distribution on the bottom surface. The design has vertical aluminum fins to direct the helium flow and we varied the length to test the effect on the temperature distribution in the solid deuterium.

\(^4\)https://www.solidworks.com/sw/products/simulation/thermal-analysis.htm
Figure 3.4: The helium volume of the long fin (left) and short fin (right) geometries. The helium flow enters from the tube at the top left and flows up through the center of the volume. The voids show the locations of the fins. The aluminum pin in the center of the deuterium can also be seen. The long fins are 6.9 cm by 3.25 mm by 7 mm deep, starting 1 cm from the center. The short fins are 3.5 cm by 3.25 mm by 7 mm deep starting 3.5 cm from the center.
Table 3.5: The results from varying the helium mass flow through the initial geometry.

<table>
<thead>
<tr>
<th>Mass Flow (g/s)</th>
<th>Heat Transfer Coefficient (W/m²)</th>
<th>Minimum Deuterium Temperature (K)</th>
<th>Maximum Deuterium Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>116.7</td>
<td>7.79</td>
<td>8.24</td>
</tr>
<tr>
<td>0.4</td>
<td>203.6</td>
<td>6.19</td>
<td>6.57</td>
</tr>
<tr>
<td>0.6</td>
<td>289.1</td>
<td>5.64</td>
<td>5.97</td>
</tr>
<tr>
<td>1.0</td>
<td>433.6</td>
<td>5.20</td>
<td>5.48</td>
</tr>
<tr>
<td>1.5</td>
<td>594.5</td>
<td>4.98</td>
<td>5.22</td>
</tr>
</tbody>
</table>

Long Fins vs. Short Fins

The above runs used a geometry that had an array of eight “long,” radial fins as shown in Figure 3.4. We also ran with a set of shorter fins, also shown in Figure 3.4, to change the flow patterns and observe the effect on the heat transfer coefficient. Shortening the fins led to an increase of the minimum deuterium temperature from 5.6 K for long fins to 5.9 K for the short fins. This is most likely due to the constriction on the flow caused by the long fins near the inlet. The concentration of cooling power at the center of the bottom of the deuterium container provided by the longer fins was preferable and this geometry was used in the following simulations. As discussed below, further improvements to the fins were made in the final design.

One Outlet vs. Three Outlets

A uniform crystal growing from the bottom of the chamber is the preferred shape, but an asymmetric temperature distribution could lead to a strangely shaped solid during crystal growth. Thus one wants to ensure a uniform temperature distribution along the sides as well as the bottom. Some early calculations were performed using one 3 mm diameter outlet near the top of the helium volume. The single helium outlet at the top naturally led to the helium preferentially flowing to one side of the volume, giving an asymmetric temperature distribution of the inner aluminum housing and thus the deuterium as well. To minimize this asymmetry, two additional outlets were added to the geometry,
each 120 degrees from the others. This not only corrected most of the thermal asymmetry, but also led to a strong reduction in both the temperature and gradient across the deuterium (a range of 6.6 K to 8.2 K for one outlet compared to 5.6 K to 6.0 K for three). However, this approach was later deemed impractical due to the assumption that all three exits would have to have identical flow rates. These three exits holes were approximated by adding a circular baffle around the cylinder that allows helium flow to the upper cylinder in three places, as described in the final geometry below.

**Spiral on the Vertical walls**

While optimizing the cooling along the side wall, we explored a geometry with a thin spiral around the outside of the vertical walls that forced the helium to flow through a specific path to a single exit. This led to a notable reduction of the deuterium temperature from a range of 5.6 K to 6 K for the three outlet geometry to a range of 5 K to 5.2 K. It unfortunately also reintroduced fairly clear asymmetries in the deuterium temperature due to the single exit path. This issue was most clear near the entrance to the spiral near at the bottom. This could lead to non-ideal crystal growth, including growth from the wall and not the center and irregular crystal shapes. We chose not to incorporate this into the final design due to these temperature gradients.

**Deuterium Not Attached to Vertical Wall**

As mentioned above, in some crystal growth configurations, the deuterium will pull away from the wall due to thermal contraction or grow from the center of the bottom of the cup shaped deuterium container. Thus a set of simulations was performed in which the deuterium was not thermally connected to the vertical wall. As shown in Figure 3.5 the majority of the cooling power is concentrated near the helium inlet. Due to this fact, only minimal temperature changes were observed.

The void in the center of the deuterium in Figure 3.5 is the aluminum pin. We concluded that the thermal conductivity in the deuterium allowed for a crystal to be grown from vapor using only the cooling from the flat plate. The cooling is strongest above the inlet and is not well transmitted by the pin. This led to its removal.
Figure 3.5: The temperature profile of a cross-section of the deuterium in the case where the deuterium is not in contact with the aluminum side wall.
Figure 3.6: A view of the helium inlet in the deuterium container geometry. The diffuser and the mixing chamber are shown.

**Diffusers**

In an attempt to evenly distribute the helium flow and increase the heat transfer near the inlet, a flat plate diffuser was added to the geometry and modeled. The design of the diffuser was guided by discussions presented in the book *Heat Exchanger Design* by Arthur P. Fraas [90]. The diffuser is shown in Figure 3.6 and consists of a flared inlet and a flat plate positioned 1 mm from the top of the helium volume. The thin flow volume maximized the heat transfer in this area. Unfortunately, this geometry resulted in a highly asymmetric temperature distribution across the solid deuterium. This was caused by the directed flow which came out of the flared end of the curved inlet pipe. The changes discussed below to the fins and inlet geometry, as well as the addition of baffles near the helium outlet ameliorate this issue. The flat plate diffuser remains in the final design.

**Final Design**

Using the results of the simulations discussed above, a final design for the deuterium housing was determined. The diffuser lead to a high heat transfer coefficient near the inlet, but created an asymmetric flow. This was due to the inlet pipe approaching horizontally before curving upwards to meet the geometry, directing the flow towards one side. This was counteracted by creating a small mixing chamber below the inlet to the helium volume proper, as seen in Figure 3.6. The flow is
Figure 3.7: The helium volume deuterium system in the final design from the Top (Top Left), Side (Top Right), Cross-section (Bottom Left), and the Bottom (Bottom Left). The helium inlet is in the center of the bottom and the outlet is protruding from the side. Note the spiral fins in the bottom and the baffles in the sides.

less directed after exiting the chamber and spreads more evenly over the bottom of the deuterium container.

A central inlet coupled with symmetric outlets clearly leads to more even cooling across the deuterium. Due to design constraints, one outlet is more practical. To give the same effect as the multiple outlet geometries, a ring with a number of breaks in it was placed below the outlet. The breaks are positioned to maximize the symmetry of the cooling.

The fin geometry was changed to be four spiral channels in order to ensure even cooling across the bottom and minimize the vortices that form in unrestricted flow. The exits of these channels and the exit breaks in the ring above are placed to reduce the asymmetry in the temperature. These changes are shown in Figure 3.7. The resulting helium flow in this design is shown in Figure 3.8. These changes were successful in minimizing asymmetries in the deuterium temperature distribution and providing efficient heat transfer from the helium to the deuterium, as shown in Figure 3.9.
Figure 3.8: The flow of helium through the deuterium system in the final design viewed from the bottom. The helium enters through the diffuser on the bottom and is guided through spiral channels to the sides. The baffle on the side then evenly distributes the cooling power as the helium flows to the exit.
Figure 3.9: The temperature profile of a cross-section of the deuterium in the final geometry.
In the near future, the power of the reactor will be increased from 1 MW to 2 MW. To ensure that our cooling system will be adequate to handle the increased heat loads, all of the nuclear heating values and the mass flow of the helium were doubled. This resulted in a helium mass flow of 1.2 g/s, which is well below the predicted capacity of the liquefier. An acceptable temperature distribution could still be maintained.

Conclusions

This series of simulations in the helium flow volume guided the final design of the actual UCN source, which is almost identical to final simulation design.

A number of simplifications were made to facilitate the calculations. The helium was treated as an ideal gas which is not accurate for temperatures below 8 K. If we take into account the change in enthalpy from the inlet temperature (4.5 K) to the outlet temperature (5 K) we get an approximate value for the cooling power of 2.4 W (4 J/g at 0.6 g/s). This is slightly above the cooling power we see from the ANSYS calculations.

The actual apparatus will most likely have a mixture of liquid and gaseous helium. This will increase the cooling power due to the latent heat of the evaporating helium. For a 0.2 g/s mass flow and a 30 % liquid mixture, this will yield an additional 1.24 W of cooling power. This may lead to a reduction in the flow required for cooling the converter.

With the knowledge gained from these simulations we are confident that our final design will effectively and evenly cool the solid deuterium UCN converter. This will facilitate the formation and maintenance of a high quality crystal leading to more efficient UCN production.
3.2.3 Methane Moderator Simulations

The cup-shaped methane cold neutron moderator surrounds the deuterium volume and heat exchangers. It is cooled with helium gas from the phase separator via a dedicated flow channel. The locations of the methane and its cooling loop are shown in Figure 3.3.

The temperature of the solid methane will be varied to maximize the UCN production. To produce UCN, cold neutrons are down-scattered by single phonon interactions in the solid deuterium crystal. Because of this, matching the cold neutron energy spectrum to the phonon spectrum is crucial. The UCN production cross-section has been measured for various cold neutron energies \cite{91}, but these values are not in agreement with theoretical predictions. The cooling system for the methane moderator will allow the temperature to be varied to test where UCN production is maximized.

Simulations using ANSYS CFX were conducted to optimize the cooling of the methane moderator. The primary parameters of interest are the temperature distribution in the solid methane, the heat transfer coefficient of the helium/aluminum interface and the pressure drop of the helium across the heat exchanger.

Geometry

The geometry used in these simulations consisted of a 9 mm thick cylindrical shell of methane surrounded by a 2 mm layer of aluminum both inside and out. A 5 mm thick volume of flowing helium was simulated outside of the aluminum housing. The helium is injected via an inlet tube running from the top to the bottom of the geometry. The helium then flows across the bottom of the source guided by a set of fins that distribute the flow as seen in Figure 3.10. The flow is then guided to the outlet at the top of the geometry through a 20 mm wide channel that reciprocates up the side of the cylinder, shown in Figure 3.11. The geometry is divided by a vertical symmetry plane to reduce computation time. The entire geometry is 125 mm in radius and 185 mm in height. Some shorter geometries were used to accelerate computation. Due to meshing issues, a helical helium channel up the side of the methane container was not simulated at the full height.

In these simulations, the helium gas enters at 5 K at a variety of mass rates up to 0.06 g/s. The
Figure 3.10: The helium volume of the methane cooling loop viewed from the bottom. Only half of the volume was simulated for efficiency.
Figure 3.11: The helium volume of the methane cooling loop viewed from the bottom. Only half of the volume was simulated for efficiency.
higher temperature of the methane allows the use of gaseous helium from the phase separator to cool the cold moderator. In the constructed source the mass rate will be adjusted to optimize the temperature of the methane and thus optimize the cold neutron production for conversion. To simulate nuclear heating, 1.52 W or 1.7 mW/g was applied uniformly to the aluminum and 1.49 W or 5 mW/g were applied to the solid methane. All mass flow and bulk heat loads (see Table 3.1) are one-half that of the real source due to only half of the cylinder being simulated.

The simulations of the initial geometry showed sufficiently uniform cooling and no significant changes were made to the design. This was largely due to the incorporation of the information obtained in the simulations of the deuterium volume.

The temperature of the methane is quite uniform in all of cases, e.g. the temperature distribution shown in Figure 3.12. The coolest spot is near the helium inlet as expected. The helium flow and heat transfer coefficients seem to be adequate for our purposes. Heaters may be used during the freezing process to force the condensate to grow from the bottom.

**Pressure Drop Simulations**

Due to concerns about the flow restriction in the initial cooling of the methane volume, a separate set of simulations were performed to determine the pressure drop that would result from injecting 300 K helium. These simulations used the same geometry as the thermal modeling (shown in Figure 3.10 and Figure 3.11). Table 3.6 illustrates that due to the low mass rate, this effect was minimal. This effect is more important in other parts of the cryogenic system.

**Table 3.6:** The pressure drop of 300 K helium from the inlet to the outlet of the methane geometry.

<table>
<thead>
<tr>
<th>Mass Flow (g/s)</th>
<th>Pressure Drop (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.0559</td>
</tr>
<tr>
<td>0.04</td>
<td>0.219</td>
</tr>
<tr>
<td>0.06</td>
<td>0.493</td>
</tr>
</tbody>
</table>
Figure 3.12: The temperature distribution of the methane in the aluminum 2024 case with 0.02 g/s helium flow. The temperature varies between 23 K and 26 K.
3.2.4 Neutron Guide Housing Cooling Simulations

A third cooling loop is used to cool the neutron guide housing near the top of the elbow (see Figure 3.3). This is included to minimize the heating of the deuterium from the upper cryostat and to ensure a smooth temperature gradient along the source elbow. This region is thermally decoupled from the deuterium by the zircaloy thermal break. A final set of simulations were performed to determine the mass flows required to maintain sufficient cooling to this area. As with the methane cold moderator, gas-phase helium from the phase separator is used for cooling the neutron guide.

Geometry

The geometry consisted of five reciprocating turns of helium surrounding a 2mm thick aluminum tube of OD 90 mm. The rectangular helium channels were 3 mm thick radially and 10 mm wide. There was a 2 mm gap between the channels. The inlet and outlet were 7.5 mm in diameter. Figure 3.13 shows this geometry. All of the cooling lines are on the outside of the guide housing.

Heat loads were applied to the outer circumference and edge of the aluminum away from the source, as well as its bulk. The outside circumference received 10 W of heating from blackbody radiation, the downstream edge received 1 W, and the volume as a whole received 1 W to simulate nuclear heating. Two mass flows were simulated initially: 0.035 g/s and 0.05 g/s. Later simulations were done with mass flows of .018 g/s and .036 g/s, corresponding to a total cryogen consumption of 1 and 2 liquid liters of helium per hour in the full geometry. (All of these heating and mass flow values are half of the real values since only half of the geometry was simulated.) The results for the 0.018 g/s and 0.036 g/s simulations are shown in Figure 3.14. These results suggest that the available cooling power will be adequate.

Analytic Calculations

Simple calculations using the enthalpy and specific heat were performed to estimate the average outflow temperature of the helium. Using a power law approximation of the enthalpy taken from the NIST Chemistry Webbook [85] of \(5.51 T^{-4.568} \text{ J/g}\) and a mass flow of 0.018 g/s, the outflow temperature
Figure 3.13: The helium volume (Yellow) and aluminum guide vacuum chamber (Grey) of the neutron guide cooling loop. Only half of the volume was simulated for efficiency. The UCN source is to the right.
with 12 W of heating is 126 K. For a mass flow rate of 0.036 g/s, the average outflow temperature would be 66.3 K. Using the specific heat above from Table 3.2 \((5.2705 + 58754 T^{−6}) \text{ J/g/K}\) and integrating from 5 K to \(T_{OUT}\), the outflow temperature for 12 W of heating and 0.018 g/s mass flow is 130.78 K. For the 0.036 g/s case, the average outflow temperature would be 67.53 K. The discrepancy between the two methods is likely due to fitting issues and small pressure changes.

### 3.2.5 Conclusions of the Computational Fluid Dynamics Simulations

The three sets of simulations described above were crucial for the design of the cryostat and cooling loops. The simplifications that were made (such as the use of only gas in the deuterium simulations and the geometry simplifications in the methane and neutron guide simulations) should not affect the cooling process significantly. These results suggest that the Linde 1430 helium liquefier output of 0.6 g/s (or 1.6 g/s with liquid nitrogen pre-cooling) will be sufficient to provide the necessary cooling power the UCN source requires.
3.3 UCN Transport Simulations

Once the UCN are created, they must be extracted from the deuterium and transported to the experimental area to be of any utility. In order to characterize the performance of the source, this UCN transport must be well understood. As the UCN are created throughout the deuterium with isotropic trajectories and a \( v^2 \, dv \) energy distribution, there are an infinite number of paths that the UCN may take. A fraction of these paths result in UCN escaping and entering into the experimental area, while the rest are lost via a variety of mechanisms. The paths are affected by gravity and interactions with materials including scattering in bulk media (the deuterium and aluminum foil); specular and non-specular reflections from the walls, deuterium, and foil; and energy change due to the change in Fermi potential when entering or exiting a bulk medium. The UCN may also be lost through absorption and up-scattering from materials, beta decay, and by escaping the guide volume.

Due to the complex, stochastic paths UCN take through the guides, it is impractical to attempt to solve this analytically. To address this issue, simulations of the transport of UCN were conducted using a custom Monte Carlo C code that was initially developed by Albert Young and Adam T. Holley of NCSU [92]. This code uses an analytical approach to solving quartic equations to simulate the parabolic trajectories of UCN as they travel through a user defined geometry. The code was applied to both the PULSTAR UCN source, as described in the following sections, as well as to the characterization of the Osaka superfluid helium source, as outlined in Section 5.3.1.

One of the major motivations for creating this code was to ensure that guide geometries could be changed easily without major edits to the code. Geometries are defined in two files that are separate from the main code that are referred to as the “regions” file and the “connections” file. The regions file contains a list of numbered volumes, either cylinders or rectangular solids, and their physical characteristics. These characteristics include: the region’s dimensions; its orientation in space; the Fermi potential for UCN of both the walls and the bulk; probabilities for loss and non-specular bounces when the neutron collides with the wall; magnetic field gradients in the region and a wall depolarization probability to allow for spin tracking; a mean free path for scattering in the bulk; a bulk
absorption rate; flags to adjust how the specularity, wall losses, and bulk propagation are handled; and a flag to have the region be treated as a detector. The connections file defines how all of the regions are connected and contains flags for special handling of the connections including: making the plane a monitoring detector; handling connections between different sizes of guides; forcing all neutrons passing the plane to be absorbed; and flipping the neutron’s spin.

The information taken from these two files is used to construct the geometry. The lengths of the regions are assumed to be lines along the center of the region and regions that meet at an angle are automatically joined by extending the region on the obtuse side of the angle and trimming the acute side so that the two regions are flush without extending into each other. The plane where the two regions meet is referred to as a “cut-plane.”

UCN are generated across a plane in a chosen region with a $v^2 \, dv$ velocity distribution with a set maximum velocity. Each neutron is randomly directed either isotropically or with a forward directed cosine-weighted distribution. In the PULSTAR source simulations, this plane is randomly placed in the deuterium volume for each UCN to simulate production throughout the volume.

After being generated, each UCN is assumed to move in a parabolic trajectory under gravity. This is simulated using an analytical quartic solver [93] to find every intersection between the parabola and the region that contains the UCN, including the cut-planes where the region connects to the adjacent volumes. These roots are then refined using Newton’s method. The solution with the smallest positive time is taken to be the physical one. Before continuing, a random number is generated to check if the UCN underwent beta decay during this time period, in which case the neutron is eliminated. If this intersection is at a cut-plane, the neutron is moved to the next region and a new solution is found.

If the intersection is with a guide wall, several processes are simulated. The perpendicular UCN energy is checked against the Fermi potential of the wall to determine if the neutron penetrates the guide and is lost. A routine was added for the case where the perpendicular energy is above the Fermi potential to give a reflection probability calculated for a one-dimensional quantum mechanical barrier. Next, other wall loss mechanisms are accounted for with the loss probability defined in the regions file. In the original code this was done with a uniform loss probability, but the code was
upgraded to use Ignatovich's method in which the loss probability is weighted by the perpendicular velocity as $2\eta \frac{u_{perp}}{v_{lim}}$, where $\eta$ is the loss probability from the regions file, $u_{perp}$ is the UCN's velocity perpendicular to the wall, and $v_{lim}$ is the limiting velocity derived from the Fermi potential [94].

If the UCN is not lost through either of these processes, it is reflected from the wall into a new trajectory. Using the specularity probability in the regions file, the bounce is determined to either be specular or non-specular. In specular bounces, the angle of incidence is equal to the angle of reflection. Non-specular bounces are redirected in a random direction that is cosine weighted around the wall's perpendicular. If the UCN polarization is being tracked, a check for wall depolarization is made against the depolarization parameter in the regions file. After this, a new parabolic trajectory is generated and the process is repeated.

Bulk materials, including the solid deuterium and aluminum foils in the PULSTAR source geometry, can be handled in the code. When a UCN moves from a region of lower Fermi potential to a region with a higher potential, the same processes that are used for wall bounces are used. If the UCN is moving from a higher to a lower potential, the component of the UCN's velocity perpendicular to the interface is boosted by the energy difference. Quantum mechanical reflections in both cases were added to make the handling of foils more realistic.

Scattering and absorption in bulk materials can also be implemented. The scattering mean free path is input in the regions file. Scattered neutrons are isotropically redirected. Absorption is handled by adding an absorption rate for the UCN in the material to the regions file. These rates were calculated from absorption cross-sections for 2200 m/s ($\sigma_{2200}$) taken from the ILL Neutron Data Booklet [70] using the equation

$$A_{abs} = \sigma_{2200} \frac{2200}{v_{ucn}} N v_{ucn}, \quad (3.1)$$

where "$N$" is the numerical density. This will be velocity independent.

The output file from the code is a list of "events," including the initial parameters when the neutron is created, bounces, transitions between regions, and the end of the trajectory. Each event includes the time, location, and velocity of the neutron as well as information that is specific to the event type, such as the type of bounce or the reason the UCN was lost. Irrelevant information can be suppressed.
Figure 3.15: The geometry used in the Monte Carlo UCN transport simulations. The breaks between cylinders are an artifact of the visualization script and are not present in the simulations.

to limit the file size.

3.3.1 General PULSTAR UCN Guide Geometry

The simulated UCN source consisted of a series of cylindrical guide sections joined together at specified angles to form the serpentine path required to extract the UCN from the converter while minimizing line-of-sight streaming of neutrons and gammas from the core in to the experimental area. The general layout is shown in Figure 3.15. Both the deuterium container and the guide surfaces are modeled as being coated with Nickel-58, having a Fermi potential of 350 neV and loss per bounce probability of $2 \times 10^{-4}$. The deuterium is treated as a bulk medium with potential of 106 neV, an absorption rate of 40 s$^{-1}$, and specularity at the deuterium-nickel interface of 0.5. The kinetic energy boost from the transition from the bulk medium to the vacuum above is handled and assumed to be normal to the plane representing the top of the deuterium volume. Scattering lengths were simulated where noted. The specularity of the UCN guides was varied across the simulations but was generally assumed to be high, with a typical value of 97 % used in most simulations. The modeling of the metal foil used in the UCN window is described below.
3.3.2 Guide Geometry Studies

A cylindrical ring of zircaloy separates the aluminum surrounding the deuterium and that surrounding
the upper UCN guides in order to provide a thermal break between the two. During construction, it
was discovered that the thickness of the weld on the zircalloy section of the cryostat would prevent the
use of 17 cm diameter guide for the section nearest to the deuterium. Because of this, it was decided
to go to a 16 cm diameter guide in the lower section immediately above the deuterium. The geometry
then had the vertical section above the source using a 16 cm diameter guide with the elbow staying
at 17 cm. After the elbow there would be 16 cm guides. The UCN transport code is ill equipped to
deal with this geometry due to the cylinder size changes between guides that meet at an angle. This
lead to very high “non-physical” losses. It is not clear if these losses arose from the gap, or if it was a
non-physical limitation of the code.

Assuming a uniform distribution of UCN across the area of the guides, a transition from 16 cm
to 17 cm diameter guides along a straight path would lead to an 11.5 % loss rate of neutrons. This
number will increase as the angle between the two increases. It is unclear how reliable these results
were due to the high level of non-physical losses.

The 16 cm diameter geometry with the 17 cm diameter elbow would certainly have less trans-
mision due to the two size changes from smaller to larger (above the D2) and from larger to smaller
(after the elbow). Due to these issues and concerns about the about losses, the 17 cm guides were
abandoned, leaving 16 cm guides throughout the source. There is still a small bottleneck at the gate
valve located outside the biological shielding. At this point the guides will narrow to 15 cm ID.

3.3.3 Foils

The deuterium source and the first four guide sections in the vertical elbow are in a separate vacuum
volume that is surrounded by the outer vacuum chamber. This is required to insulate the cryogenic
sections of the source and to ensure that the flammable cryogens do not mix with air. The UCN are
created in this inner volume, but must pass through a window separating this volume from the outer
vacuum chamber that houses the guides that transport the neutrons out of the source and to the
experimental area. A second vacuum break may be placed between the exit of the UCN guide at the thermal column door and any experimental UCN volume provided by the user.

The UCN windows consist of metal foils that must be strong enough to hold vacuum while allowing for good UCN transmission. A combination of low Fermi potential and low bulk absorption in the window material is required for efficient UCN transmission. Two materials considered are zirconium and aluminum. Zirconium has a Fermi potential of 76 neV, compared to aluminum's 54 neV, and an absorption cross-section at 2200 m/s of 0.185(3) b compared to 0.231(3) b for aluminum [70]. Using Eq. 3.1, these cross-sections can be converted into the absorption rates the code uses, yielding 2981 s$^{-1}$ for zirconium and 3049 s$^{-1}$ for aluminum. The comparable absorption rates and lower Fermi potential for aluminum would seem to make it a clear choice, but the higher tensile strength of zirconium allows for thinner foils, effectively reducing the absorption loss.

A series of simulations to compare the effects of foils of the two materials on UCN transmission were performed. The results of these simulations are shown in Figure 3.16. Not that the zirconium foils show slightly better transmission for comparable strength foils. Ultimately aluminum foils were chosen for the source design however, due cost and ease of manufacturing.

Simulations were also performed to compare a single foil vs. two foils. As can be seen in Figure 3.17, there was little difference between the two cases. This implies that the primary loss was due to the Fermi potential as opposed to the bulk absorption.

### 3.3.4 Deuterium Lifetimes and Scattering

The presence of hydrogen and para-deuterium in the converter, as well as the process by which the deuterium is frozen (effecting the quality and consistency of the crystal structure), can effect the elastic and inelastic scattering rates in the converter. These effects are represented in the simulations by the bulk material absorption rate and the mean free path. A collaborator, Jonathan Coburn, ran a series of simulations using the UCN transport code to explore the effect of these two parameters on the survival of the UCN that are produced. The mean free path was varied between 1 cm and 6 cm, while the UCN lifetime was varied between 25 ms and 75 ms. Though the higher values are desirable,
Figure 3.16: Comparison of the neutron transport through aluminum (200 micron, 54 neV) and zirconium foils (50 micron, 76 neV) to the case where no foil is present. 100,000 simulated neutrons were propagated, with the results scaled to the predicted $10^7$ UCN/s below the Be cutoff (252 neV).
Figure 3.17: Comparison of the neutron transport through one and two zirconium foils (50 micron, 76 neV) to the case with no foil. 100,000 simulated neutrons were propagated, with the results scaled to the predicted $10^7$ UCN/s below the Be cutoff (252 neV).
values of 4 cm and 50 ms are safer estimates due to imperfections in the crystal [76,81,95]. Figure 3.18 shows the expected trends for increasing mean free path and lifetime in the deuterium. However, it should be noted that for mean free paths above 4 cm (the thickness of the deuterium) there appears to be diminishing returns.

### 3.3.5 Conclusions of the UCN Transport Simulations

Monte Carlo UCN transport simulation based on UCN production rates calculated by MCNP were used calculate the effects of various design choices on the UCN population available for experiments. Though many parameters will need to be measured to fully model the source, a simulation with the parameters listed in Table 3.7 was performed to give a representative spectrum of UCN that can be delivered to the experimental area. The resulting energy spectrum and distribution of propagation direction at the exit from the biological shielding are shown in Figure 3.19 and Figure 3.20. At the
Table 3.7: The parameters for a representative simulation of the final geometry of the UCN source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid Deuterium Source</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermi Potential</td>
<td>106</td>
<td>neV</td>
</tr>
<tr>
<td>Mean Free Path</td>
<td>4</td>
<td>cm</td>
</tr>
<tr>
<td>UCN Lifetime</td>
<td>25</td>
<td>ms</td>
</tr>
<tr>
<td><strong>Guides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermi Potential</td>
<td>350</td>
<td>neV</td>
</tr>
<tr>
<td>Specularity</td>
<td>97</td>
<td>%</td>
</tr>
<tr>
<td><strong>Aluminum Foil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>200</td>
<td>µm</td>
</tr>
<tr>
<td>Fermi Potential</td>
<td>54</td>
<td>nm</td>
</tr>
<tr>
<td>UCN Lifetime</td>
<td>0.33</td>
<td>ms</td>
</tr>
</tbody>
</table>

At the end of the guide system, the UCN are largely forward directed. The lack of UCN with energies below 40 neV is due to the rise of the guide system not entirely counteracting the 102 neV energy boost imparted by the Fermi potential of the deuterium. Neutrons with energies above the guide Fermi potential (350 neV) are present due to higher effective potential for neutrons reflected at oblique angles.

Monte Carlo UCN transport simulations can be used to predict the spectrum of UCN that will be delivered to the experimental area. Further characterization of the solid deuterium and UCN guide systems will allow for improved simulation parameters.
Figure 3.19: The simulated energy spectrum of UCN at the exit from the thermal column. The parameters are shown in Table 3.7. A total of 15987 neutrons with energy below the Fermi potential of Be (252 neV) compared with 121308 UCN produced in that energy range.
Figure 3.20: The simulated energy spectrum and angular distribution of UCN at the exit to the thermal column. The parameters are shown in Table 3.7. The vertical axis represents the cosine of the angle between the velocity of the neutron and the axis of the beam line.
Source Design and Construction

The UCN source is located in the thermal column of the PULSTAR reactor. The thermal column is a large void (120 cm × 120 cm × 200 cm) inside the biological shielding facing the core and accessible through a rolling steel and concrete door. Neutrons from the core transit a helium-filled flight tube and exit the reactor pool through the aluminum liner into the thermal column and the UCN source. The UCN source consists of a heavy water thermal moderator, a solid methane cold moderator, and a solid deuterium UCN converter. Once the neutrons are slowed to UCN energies, they are guided through the biological shielding to the experimental area. The entire source, including the moderators, guides, and shielding is attached to the thermal column door to allow the source to be removed from the biological shielding for maintenance.

The general design decisions that were made and methods of construction will be discussed in this chapter. Section 4.1 discusses the general philosophy behind the source design. The PULSTAR reactor and the extraction of neutrons from the core will be described in Section 4.2. The design of the moderators and converter is explained in Section 4.3. The necessary systems for maintaining the low temperatures required by the cold moderator and UCN converter are discussed in Section 4.4 and Section 4.5. Finally, the UCN guide system is described in Section 4.6.
4.1 Design Philosophy

The source was designed with the goal of maximizing the number of usable UCN for experiments while allowing for access to the source for maintenance and upgrades. To accomplish this, UCN production must be maximized while minimizing neutron losses during transport to the experimental area. Production is maximized by placing the source as close to the reactor core as feasible. The size, shape, quality, and location of the converter and moderators must be optimized to maximize production while avoiding losses from the converter. Though the solid deuterium converter produces UCN via a single down-scattering event, further scattering events are undesirable, as they may lead to up-scattering or absorption of the UCN.

The three important parameters for minimizing losses during the transport of the UCN from the source to the experimental area are the Fermi potential, loss rate, and specularity of the guides. High Fermi potential guides allow higher energy, and therefore more, UCN to be used in experiments. The loss rate on guides is due to penetration through thin coatings, up-scattering, and absorption. These effects can also be mitigated by reducing the number of bounces the UCN undergo during transport. Using large diameter guides reduces these frequency and total number of wall interactions on average. The specularity of the guides refers to the probability that a UCN will reflect with an angle identical to the angle of incidence. Surface roughness on the guide can lead to randomization of the reflection angle, leading to less efficient transport and a higher probability of the UCN returning to the deuterium source where it may be lost.

4.2 Neutron Extraction from the Reactor Core

The UCN source will take advantage of the 1 MW PULSTAR nuclear reactor facility on the campus of North Carolina State University. The PULSTAR reactor is a light-water reactor that uses 4% $^{235}\text{U}$ enriched fuel. The fuel is sintered UO$_2$ pellets in zircaloy tubes arranged in fuel assemblies consisting of $5 \times 5$ arrays. Twenty-five of these assemblies are arranged in a $5 \times 5$ array to form the core. Water surrounds the fuel elements and acts as a forced convection coolant as well as a neutron moderator.
and reflector. This geometry and enrichment leads to a relatively large leakage of fast and thermal neutrons from the core as shown in Figure 4.1. This neutron leakage and the opportunity to place the UCN source in close proximity to the core in a underutilized area, referred to as the thermal column, makes this facility ideal for our purposes.

To utilize the neutrons that leak from the reactor core, they must transit a section of the reactor pool and penetrate through the pool liner into the thermal column area. Prior to the construction of this UCN source, two pieces of equipment were installed in this path. One was a set of rotating exposure ports used primarily for neutron activation analysis and the other was a graphite-filled aluminum container called the “nose piece.” The losses in this configuration, or with just pool water in this volume, would be unacceptable.

To solve this problem, the exposure ports were relocated and the “nose piece” was replaced by two helium-filled aluminum boxes, referred to as the “shielding box” and the “nose port.” Both volumes effectively displace the reactor coolant and shielding water to allow the maximum number of fast

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**Figure 4.1:** The neutron flux distribution in and around the PULSTAR reactor core. Note the thermal and fast flux outside of the core [96].
Figure 4.2: The shielding box and nose port installed next to the reactor core. The shielding box is shown without the flexible tubing used for filling it with helium.

and thermal neutrons to reach the UCN source. In addition, both can be flooded with water from the reactor tank to also act as neutron shutters when the UCN facility is not operating to minimize the activation of source parts and reduce the radiation dose to personnel near the facility and in the thermal column during maintenance. This is accomplished using flexible tubes that run to the surface of the reactor pool to allow the two volumes to be filled with helium gas, displacing the water. The effect of the helium filled voids in these volumes on the reactivity of the reactor has been measured and is within the acceptable limits for operation. The installed shielding box and nose port are shown in Figure 4.2.

The shielding box is a 45 cm × 45 cm × 10 cm aluminum box placed 10 mm from the core and containing a 2.54 cm thick sheet of lead filling the volume closest to the core. The lead sheet shields
the UCN source from core gammas that would induce an unacceptable heat load while only minimally reducing neutron flux. The shielding box is installed in the previous location of the rotating exposure ports.

The nose port is a replacement for the nose piece, which was previously part of the thermal column facility. This replacement component is filled with graphite except for a central 45 cm × 45 cm × 70 cm void. The graphite acts as a reflector for the neutrons passing through the nose port. Further, graphite slabs were installed between the sections of the 5.08 cm supporting aluminum web just inside the thermal column with the same area left open in the center. This effectively extends the nose port past the pool liner and into the thermal column. A schematic of this geometry can be seen in Figure 3.1.

4.2.1 Neutron Flux Measurements

A series of gold-foil activation measurements were performed to determine the thermal neutron flux rates in the location of the cold source. For these experiments an aluminum “test tank” was constructed that was similar, but not identical to the heavy water tank that will be used in the source. This tank had a cylindrical well near the front to simulate the void where the UCN source will be located and a rectangular channel through the center along the axis of the thermal column to insert the foil holder. This layout is shown in Figure 4.3. Seven gold foils were placed 5.08 cm apart with the closest one located 2.54 cm from the front of the tank. Every second one was coated in cadmium due to its high thermal neutron absorption cross-section. This allowed for an estimation of the fraction of epithermal and fast neutrons through comparison with the bare foils. In all cases the foils were irradiated for 30 minutes with the reactor running at 100 kW.

Experiments were conducted using this basic setup in various permutations. These included running with both light and heavy water with the well in the tank oriented both towards and away from the reactor. The shielding box was removed for some runs to see its effect on the thermal neutron flux.

During irradiation, the reaction $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ predominates. $^{198}\text{Au}$ decays into $^{198}\text{Hg}$ with a lifetime of 3.81 days via $\beta^-$ emission, followed by a 411.8 keV gamma with a probability of 0.9554. By
counting these gammas at a later time and accounting for the elapsed time, the thermal flux can be calculated. The addition of the cadmium covered foils allows the epithermal fraction of the flux to be calculated. This is a standard method for calculating thermal neutron flux [97].

In the most relevant test, the well was lined with acrylic to simulate the methane in the cold source and the tank was only partially filled with D$_2$O, leaving a 7.62 cm void at the top to simulate the neutron guides. The schematic is shown in Figure 4.3. The average thermal flux across the well was $5.2 \times 10^{11}$ n/cm$^2$s. The results for each individual foil are shown in Table 4.1. These results are comparable to the MCNP calculations discussed in Chapter 3.

### 4.3 Moderation and Conversion

The source uses a three-step process to moderate and convert the fast and thermal neutrons to UCN. First, heavy water moderates the neutrons from the reactor to thermal energies. A solid methane cold moderator then further moderates these thermal neutrons to cold energies. Finally, the cold neutrons
Table 4.1: The gold-foil flux results from the configuration shown in Figure 4.3, normalized to 1 MW of reactor power. Foil locations are measured from the front of the test tank.

<table>
<thead>
<tr>
<th>Foil Location (cm)</th>
<th>Neutron Flux ($10^{11}$ n/cm²s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.54</td>
<td>5.62</td>
</tr>
<tr>
<td>12.7</td>
<td>4.37</td>
</tr>
<tr>
<td>22.86</td>
<td>3.82</td>
</tr>
<tr>
<td>33.02</td>
<td>3.59</td>
</tr>
</tbody>
</table>

are converted to UCN in the solid deuterium source. The physics of these processes is described in Chapter 2.

During downtime and maintenance, the heavy water and cryogenic moderators are stored outside of the thermal column. The gaseous cryogens (methane and deuterium) are handled by a gas panel located above the thermal column. This allows for storing, purification, para-to-ortho conversion of the deuterium, and loading and purification of the methane. Due to the methane’s low cost, it is disposed of after use. The heavy water is stored in a raised tank along the wall near the thermal column. The following sections discuss the design and operation of the moderation systems.

### 4.3.1 Heavy Water Thermal Moderator

After passing through the reactor liner into the thermal column, the neutrons enter a 800 L aluminum tank containing the heavy water that surrounds the UCN source. In this volume, shown at the left of Figure 3.1, the neutrons are moderated to thermal energies.

The D$_2$O is stored in a raised, rectangular storage tank outside of the reactor biological shielding when the source is not operating. The storage tank is connected to the source D$_2$O tank by two 9.525 mm (nominal 3/8") diameter tubes through an unused beam tube that connects to the thermal column. The water is gravitationally fed to the source or returned to the storage tank using a peristaltic pump. The tube connected to the top of the storage tank leads to the top of the inside of the source tank to allow the air to be transferred when the water is moved in a closed loop, thereby preventing both
the loss of heavy water and providing containment of the tritium contaminates to avoid personnel exposure. The level of the water in the storage tank is measured using an Omega LVU32 ultrasonic level meter. Unfortunately, due to the minimum distance required by the level meter, the level can only be read out once the level drops 17.8 cm below the top. The total heavy water inventory is 717.6 L with a measured initial tritium contamination of 0.056 $\mu$Ci/ml for a total of 40.2 mCi as of March 11, 2010. This activity will increase when the $D_2O$ is exposed to the neutron flux in the thermal column, but will remain under 0.5 Ci. The Annual Limit on Intake (ALI) for tritium per year is 80 mCi, making a serious accident implausible.

4.3.2 Solid Methane Cold Moderator

A cup shaped volume of solid methane, held at a temperature between 20 K and 40 K, surrounds the deuterium converter and moderates the thermal neutrons down to cold energies (0-10 meV). MCNP calculations predict a cold neutron flux of $5 \times 10^{11}$ n/cm$^2$s in the solid deuterium.

The methane for the cold moderator is supplied from high-pressure cylinders through the methane manifold box into the methane ballast tank. The amount of gas transferred into the tank is determined by the volume of the methane required to fill the methane moderator at the triple point plus enough gas to maintain a pressure above the triple point in the fill line and the gas handling system. A flow meter is used to monitor the gas flow into the cryostat.

Helium and other gases may be added in small amounts to improve moderation. A 30 L gas bottle is attached to the gas handling system and can be used for measurement. This smaller volume allows for a more precise measurement of the amount of additional gas supplied to the cold source.

For safety reasons, the methane is never stored after use. It is exhausted to the reactor's (disused) outer ventilation stack through the flammable exhaust line by a Varian SH110 scroll pump. Nitrogen from a high-pressure cylinder is supplied to the outlet side of the pump to ensure that the mixture stays below the flammability limit as well as ensuring that flammable gases are not left in the line.

The methane ballast tank serves a secondary purpose as a relief volume for the cryostat. In the event of an unexpected warm up or pressure rise in the cryostat, a 2 bar burst foil allows the over
pressure gas to flow to the ballast tank through a 2.54 cm (nominal 1 inch) tube.

### 4.3.3 Solid Deuterium UCN Converter

Cold neutrons are converted to UCN in a cylindrical 1 L (200 g) solid deuterium volume situated inside the methane moderator (see Figure 3.1). This volume is shared with the first four neutron guides and is open to the deuterium tank during operation. The deuterium freezes onto the $^{58}$Ni-coated aluminum bottom of the cryostat. This area is the coldest area of the cryostat due to the arrangement of the helium cooling lines and the thermal isolation, as described in Section 4.4. The predicted UCN production rate is $0.8 \times 10^4 - 1.5 \times 10^4$ n/cm$^3$s (see section Section 3.1).

An extensive gas handling system is required to condition the deuterium gas for efficient UCN production. Clean, pure ortho-deuterium with minimal contamination of hydrogen is necessary to maximize the production rate and reduce losses while the UCN remain in the converter volume.

To begin the process, either pure deuterium from a high-pressure cylinder or deuterium from the storage tank (pressurized with a KNF diaphragm pump) is introduced into the processing line. This gas is passed through a liquid nitrogen trap before being sent through a Mr. Hydrogen brand palladium filter [98]. The purified deuterium is then sent to the Para to Ortho converter.

The converter is a volume machined from a copper block contained in a vacuum jacket and cooled with the cold plate of a cryopump. Incoming deuterium is cooled by the return gas in a counterflow heat exchanger. The para-deuterium is then converted to ortho-deuterium using one of two possible materials, Ferric Oxide Hydroxide or Oxysorb (Chromium (VI) Oxide). The two materials are currently being tested. The physics of these processes is explained in Section 2.5.

The apparatus is equipped with a sampling line to allow for testing of the deuterium. An in-house Raman spectrometer is used to measure the rotational states of the deuterium. The para-ortho ratio and the hydrogen contamination can be measured. The panel, shown in Figure 4.4, is arranged to allow the components used to condition the deuterium to be bypassed if they are not required due to the desired operation.
Figure 4.4: The gas handling panel for the methane and deuterium located on a shelf above the thermal column. The panel is arranged to allow components to be bypassed if they are unnecessary. The manifolds connecting to the cryostat are seen at the left edge of the picture.
4.4 Cryostat Design

The cryostat consists of an outer vacuum jacket and the deuterium and methane volumes, the first four sections of the UCN guide, and the associated cooling loops that it contains. This is all contained within the D$_2$O tank, as shown in Figure 4.5.

Construction materials for the cryostat were chosen to minimize neutron absorption in the source and to allow personnel near it without a long cool down period. In addition, many materials, including plastics, degrade quickly in high radiation fields. These considerations severely limited our construction material choices.

The source is primarily constructed out of aluminum due to its short half life when activated.
by neutrons. Natural aluminum is nearly all $^{27}\text{Al}$ which may be activated through several channels, but the most relevant process for personnel safety is $^{27}\text{Al}(n,\gamma)^{28}\text{Al}$ and $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$. The cross-section of the $^{28}\text{Al}$ reaction is 231 millibarns for thermal neutrons. $^{28}\text{Al}$ decays to $^{28}\text{Si}$ via a 4.64 MeV $\beta^-$ ($\tau=2.24$ min) followed by a 1.78 MeV $\gamma$ ($\tau=475$ fs). The $^{24}\text{Na}$ reaction has a peak cross section of 121.2 millibarns and a lifetime of 14.96 hours, decaying by emitting a 5.52 MeV $\beta^-$ and a series of gammas [70]. The remaining neutron activation modes have significantly lower thermal cross-sections or are very short-lived. The Institut Laue-Langevin Neutron Data Booklet recommends a cool down period of just 21 minutes after 1 day in a thermal flux of $1 \times 10^7$ neutrons/s/cm$^2$ [70]. This short activation lifetime allows work on the source to be performed in a reasonable time period after the reactor is shut down. The more conventional construction material choice of stainless steel would require either significantly longer cool-down periods or larger radiation doses for personnel.

The outer vacuum jacket is manufactured in three sections that reside inside the D$_2$O tank. The lowest section is a centrifugally cast aluminum cylinder with a curved bottom. This surrounds the methane and deuterium volumes and the first UCN guide. Above this are two welded aluminum pieces containing the remaining UCN guides in the elbow. The top piece protrudes through the D$_2$O tank and has three openings for the helium and gaseous cryogens to pass through. This vacuum is shared with the volume for the remaining UCN guides out to the thermal column door.

The methane moderator volume hangs outside deuterium volume by aluminum threaded rods. It contains 1.4 L of solid methane when operating. A cup-shaped volume of methane is surrounded by a helium channel (see Section 3.2.3 and Section 4.5.2).

The innermost volume is shared by the deuterium UCN convertor and the first four sections of guides. A 200 $\mu$m aluminum foil serves as a UCN window to separate this volume from the outer vacuum jacket and the downstream guides.

4.4.1 Thermal Isolation

Due to the required temperatures in the lower cryostat and the need to have the extraction guides at room temperature, heat conduction must be minimized. The large thermal conductivity of the
aluminum that comprises the bulk of the cryostat is unacceptable without modification. Two design elements that are included to decrease the heat load are a ring of zircalloy above the deuterium and titanium mesh supports to break the thermal link to the outer vacuum body.

**Zircaloy Ring**

The inner cryostat includes a section of zirconium alloy (∼1.5% tin) directly above the frozen deuterium volume. Zircaloy was chosen due to its poor thermal conductivity (13.41 W/m/K at 300 K [99] compared to 205 W/m/K for aluminum 6061 [100]). This helps create a thermal break between the solid deuterium which must be below 18 K, and the rest of the volume where deuterium freeze out must be minimized to reduce the UCN losses on the neutron guides. This specially constructed zircalloy ring was explosively bonded to two rings of aluminum to allow it to be welded to the rest of the cryostat.

**Powder Sintered Mesh Supports**

The inner vacuum volume is separated from the outer volume with three titanium-alloy (Ti₆Al₄V) mesh supports. These supports were specially constructed using an electron beam powder sintering technique in the NCSU Mechanical Engineering department. The effective cross-sectional area of the connection between the inner cryostat and the room temperature components is minimized while maintaining a high mechanical strength. The minimal contact area coupled with the low thermal conductivity (1.67 W/m/K at 30 K [101] compared with 41.1 W/m/K for Al 6061 [100]) isolates the cryostat from the room temperature vacuum jacket. Figure 4.6 shows four sample versions of the supports.

**4.5 Liquefier Commissioning and Operation**

Due to the low temperatures required for the deuterium and methane in the source, constant liquid helium flow is required to supply the cooling power required to counteract the heating from the reactor and the upper, room temperature, sections of the source. The solid deuterium UCN converter, solid
Figure 4.6: The Ti$_6$Al$_4$V sintered powder support structures. The thin connecting sections reduce thermal conductivity while maintaining strength.
methane cold neutron source, and the neutron guide are cooled by a closed loop helium liquefaction facility. This includes a Linde 1430 helium liquefier, a 500 L helium dewar, a phase separator to supply the three cooling loops, and recovery systems for both low-pressure and high-pressure storage.

4.5.1 Helium Liquefier

The helium is liquefied into the dewar using a Linde 1430 with an RS compressor. The component names in the following reference the piping and instrumentation diagrams (PID) shown in Appendix A. The liquefier, dewar and surrounding area are shown in Figure 4.7.

The helium liquefier uses a series of heat exchangers cooled by the returning cold gas, isentropic expansion engines, and isenthalpic Joule-Thompson expansion valves. The helium is initially pressur-
ized by the RS compressor to \( \sim 17.2 \) bar and sent to the vacuum-insulated cold box of the liquefier. If liquid nitrogen is being used to precool the helium, the flow is split with part of the gas flowing through the first main heat exchanger (E30) while the remainder is cooled with counter flowing nitrogen boil off in E81. The flows are then joined and cooled in E83 by liquid nitrogen. If precooling is not being used, all of the gas is sent through E30.

After the following heat exchanger (E31), the helium flows through a charcoal absorber to remove trace contaminants and then split once again. A portion is sent through the first expansion engine and exhausted to the cold side of the heat exchangers between E32 and E33 at atmospheric pressure. The remaining helium is sent through two more heat exchangers (E32 and E33) and a charcoal absorber before being split between the second expansion engine (E39) and the final heat exchanger (E34). The first flow is sent to the cold side of the heat exchangers while the flow through E34 is again purified in a charcoal absorber and then expanded through a Joule-Thomson expansion valve (JT307).

The liquefied portion is delivered to the dewar while the remaining cold gas is returned to the cold side of the heat exchanger. This flow is combined with cold gas returned from the deuterium cooling loop, the boil-off from the dewar and, further upstream, the gas from the expansion engines. The combined gas flow is warmed to nearly room temperature while cooling the incoming gas and is finally returned to the suction line of the RS compressor to begin the cycle again. This facility is capable of producing 17 L/h (47 L/h with liquid nitrogen precooling) of liquid helium into the dewar.

During normal operation, the liquefaction facility will operate in a closed loop by reliquefying the helium that is returned from the cryostat. When the liquefier is initially started, previously used helium is drawn from the high-pressure storage and must be run through a purification process in the liquefier cold box. This process uses a pair of heat exchangers (E60 and E62) that are cooled by \( \sim 20 \) K gas taken from the main heat exchanger. Impurities are condensed in the purifier, which can be operated with up to 10 percent air. The purifiers may be regenerated by pumping and heating them.

In the event of helium loss or insufficient inventory in the helium storage, purchased pure make-up helium from a 12-bottle bank on the loading dock may be liquefied without purification.
4.5.2 Helium Cooling Loops

The helium flow from the dewar is split into three cooling loops using a gravitational phase separator located just outside the thermal column door. The liquid is used to cool the deuterium while the gas flows through the other two cooling loops. All of the returned helium is reliquified into the dewar during normal operation. Simulations for the helium flows and temperature distributions are described in Section 3.2.

The liquid flow from the phase separator is used to cool the solid deuterium. This helium enters the cooling volume directly underneath the center of the deuterium. The flow then spirals outward and flows around the sides of the deuterium container. During the freezing process, this arrangement ensures that the central bottom of the cryostat is the coldest surface for the deuterium to freeze onto and assists in preventing frozen deuterium from adhering to the upper walls of the cryostat. The return flow from this cooling loop can be either used in a cold return mode (via valve VJD) or heated to be recovered for later use.

The methane cooling loop takes gas from the phase separator and flows around the outside of the methane volume in a spiral. The methane temperature is adjusted by controlling the return gas flow using a proportional solenoid valve and by using heaters attached to the volume. Gas returning from this loop is heated and routed to the suction line of the RS compressor via VTRM to be reliquified.

The neutron guide is also cooled with gas flow from the phase separator. Keeping the upper cryostat at ~100 K minimizes the heat load on the methane and deuterium from the room temperature neutron guides. Helium returned from this loop is heated and combined with the methane loop return to be reliquified.

All three return loops are heated and diverted from the RS compressor suction line to the helium recovery system through VTD and VTC when the liquefier is shut off.

4.5.3 Helium Recovery

The scarcity and expense of liquid helium made it cost-prohibitive to supply the source with remotely liquefied helium and then vent the used helium into the atmosphere. During normal operation, all of
the helium that is returned from the cryostat, as well as any boil-off from the dewar, is recovered.

Normal boil-off from the dewar is used to actively cool the helium delivery tube from the liquefier and then joins the cold gas returning from the solid deuterium cooling loop that is fed into the liquefier's cold return port. This gas is inserted part way through the heat exchangers in the cold box and is rel liquefied.

Helium gas returned from the methane and neutron guide cooling loops is sent through a bank of heaters capable of supplying up to 2000 W of power. The flow of this return gas from the methane and neutron guide cooling loops is regulated using proportional valves to control the flow and cooling of these systems. This warmed helium is then either sent to the RS compressor to be rel liquefied or sent into the helium recovery and storage system. A schematic of the system is shown in Figure A.1 in Appendix A.

At the end of a source run it will be necessary to recover the helium gas from all sources for future use. The returned gas from the deuterium loop is diverted from the liquefier cold return, heated, and combined with the neutron guide and methane cooling loops return gas. This gas joins with dewar boil-off and is recovered to storage. This is done in two stages. The recovered gas is first sent through a Quantum Technologies J-20 low pressure compressor and stored in two 378.5 liter (nominal 100 gallon) repurposed propane tanks. If the pressure rises above 6.9 bar (100 psi), a Jordair G120-3EV high-pressure compressor turns on and sends the helium into high-pressure storage.

The high-pressure storage consists of 36 standard 300 cubic foot gas bottles in 3 12-bottle banks. This helium can be rel liquefied through the purification process in the liquefier cold box.

4.6 UCN Guides

The UCN will be guided away from the solid deuterium converter and to the experimental area using 16 cm inner diameter (2 mm wall thickness), $^{58}$Ni-coated quartz guides that are being produced in collaboration with Virginia Polytechnic Institute and State University (VT) using a specially constructed electron beam evaporation facility for coating tubes. $^{58}$Ni is often used for UCN guides because it has the highest Fermi potential of any single material at 335 neV [26]. Quartz glass tubing was chosen as a
substrate due to its low surface roughness and low absorption of higher energy neutrons. The low surface roughness leads to higher guide specularity and therefore higher guide transmission [102].

4.6.1 Guide Preparation

To ensure close fitting in the source, and thus minimize neutron loss, the guides were laser cut by Scientific Glass International to the correct lengths and angles. The dimensions of the guides immediately above the source are shown in Figure 4.8.

The cut guides were prepared for coating using a process developed by R. Mammei, M. Makela, and R. B. Vogelaar [102]. First, the guides were sonic cleaned in acetone and methanol for 5 minutes each and thoroughly rinsed with deionized water. Following this, they were etched in a solution of 5 % HF (50 % concentration electronic grade), 3 % HCl, 1 % HNO₃, and water for 10 minutes, followed by three baths of deionized water for 10 minutes each. The HF removes approximately 1 micron of the quartz guide surface and reduces the surface roughness to less than 0.5 nm. The HCl and HNO₃ are used to remove any metal impurities that were on the guide [103].

The guides were then thoroughly rinsed with flowing deionized water and dried on the outside with Kimwipes® and on the inside using a PVC stick with clean room wipes on the end. From this
point forward nothing, except for the clean room wipes, was allowed to touch the inner surface or cut edges of the guide to avoid contamination that might lead to delamination.

The etched, rinsed, and dried quartz guides were then placed in a custom built vacuum oven and pumped overnight. The oven was heated to 200 °C for 24 h, followed by 400 °C for 24 h and then was allowed to cool. This process is to remove hydrocarbons and water that remain on the surface [102].

### 4.6.2 Guide Coating

The guides were coated using a MDC single pocket electron beam gun that was modified to increase the distance it extends into the vacuum chamber. This design was further changed after initial use showed that the thermal expansion of the copper high voltage leads could vertically deflect the e-beam assembly significantly and cause it to interfere with smaller diameter guides [102].

This e-beam evaporation was performed in a custom 3 m long, 40.64 cm diameter vacuum chamber with a rotating and translating guide carriage. Other ports on the vacuum chamber allow for a water-cooled crystal monitor for observing the deposition rate, a quartz lamp to heat the guide, and a thermocouple to monitor the temperature inside the chamber.

An alumina crucible liner filled with $^{58}$Ni was prepared in a nearby bell jar e-beam evaporator. Due to the magnetic nature of nickel and the irregular pieces of $^{58}$Ni, the control of the e-beam location and spread that this evaporator is capable of allowing for a more even and consistent melting of the nickel. Alumina crucible liners were used instead of graphite due to the formation of nickel carbide observed in previous coatings [102].

The guides were held in place using springs that were hooked to a frame, shown in Figure 4.9, that was attached to the carriage that rotates and translates around the electron beam assembly. The guide motion is driven by two computer-controlled stepper motors that are coupled to the carriage via an aluminum rod through a feedthrough in the end of the chamber. Springs were used to minimize the force put on any single point of the fragile quartz glass while still holding the guide centered around the e-beam and gripping tightly enough to ensure uninterrupted rotation. Previous methods have resulted in guide breakage.
Once the guide, e-beam, and $^{58}\text{Ni}$ were in place, the coating chamber was pumped overnight, reaching pressures in the mid-$10^{-6}$ Torr range. The guide was then baked using the quartz lamp at $\sim 80 ^\circ \text{C}$ for 1 hour while translating and rotating the guide over the lamp. This baking helped remove any remaining contaminants and prevented residual gas from condensing on the guide during the coating process. Higher temperature baking was desirable, but thermal expansion of the guide carriage leads to rough guide translation and rotation. The lamp was left on during the coating process.

The standard procedure for coating was to push the guide to the end of the chamber out of the deposition plume and the e-beam current was slowly ramped up until the crystal monitor began to register deposition on the order of 3 Å/s to 5 Å/s. The high voltage could be adjusted to center the beam spot in the crucible. However, the design of this e-beam head unavoidably led to some of the beam hitting the front and back of the crucible liner. Once a stable deposition rate is reached the guide is translated over the e-beam head at a rate of 2.6 cm/min and rotated at 12 rpm to ensure even coverage on the guide. Multiple coating passes were made until the thickness was estimated to be adequate, usually $\sim 180$ nm. A coated guide is shown in Figure 4.10.
Figure 4.10: A $^{58}$Ni coated quartz guide just after it was removed from the e-beam chamber. The guide was bagged in an argon environment immediately following this.
The guide blocked the crystal monitor while it is being coated, so the deposition rate could only be measured between passes. This led to some uncertainty in the coating thickness. To give a direct measurement of the coating thickness, small (approximately 1 cm by 2 cm) pieces of silicon wafer were attached to the outside of the end of the guide. Aluminum foil was wrapped around half of each of these to give a clean edge for profilometry. When the desired thickness was reached according to the crystal monitor estimate, the chamber was vented with argon and one of these “witness strips” was pulled. Using a Dektak profilometer, the thickness was measured and further coating was done if necessary.

The procedure outlined about above was generally followed, but a failure mode was discovered while doing test coatings in which the coating rate would rapidly rise from a steady and acceptable value up to over 30 Å/s while the crystal monitor was obscured by the guide. Due to the geometry, this could not be discovered until the guide passes out of the way of the crystal monitor. Both the fast coating rate and the thick coatings that this led to raised concerns about delamination during thermal cycling of the guides due to the internal stress in the coating and the differential contraction between the quartz substrate and the nickel. The cause of this problem is not fully understood, but visual inspection of the crucible while coating often showed lighter and darker areas of the molten nickel. A possible explanation of the rapid change in evaporation rate is that an oxide layer on the top of the nickel moved on the surface away from the area where the e-beam was focused and led to a strong plume of over-heated nickel. This effect seemed to be mitigated by ramping the beam current well past what was required for the desired coating rate in an attempt to “burn off” the oxide layer and then ramp back down to the required current.

This process was added to the procedure, but unfortunately did not eliminate the problem entirely. The first and third guides from the bottom of the cryostat were coated during a single session and there was drastic increase in the coating rate while the crystal monitor was blocked. The thickness measured on the witness strips showed that the coating was significantly thicker (∼350 nm on guide 1 and ∼225 nm on guide 3) than the target of 180 nm. To test for delamination, guide 1 was slowly cooled using a Sumitomo RDK-415D cryocooler. The guide was held in an aluminum inner vacuum
volume connected to the first stage of the cryocooler by pure aluminum strips and copper braid. The
temperature of the inner vacuum can was monitored. No delamination occurred during this process.

4.7 Conclusions

The design of the PULSTAR UCN source faced a number of novel challenges including construction
of a cryogenic vacuum chamber in a radiation environment and the use of flammable cryogens inside
the biological shielding of the reactor. These concerns needed to be addressed without compromising
the UCN production and transport characteristics of the source. Through choices of materials and
methods, a strong, safe UCN source is being constructed.
Osaka UCN Source Characterization

Once the PULSTAR UCN source is operational it will be necessary to characterize the fluence, limiting density, and energy spectrum of the UCN produced. This will allow the source to be compared to other UCN user facilities. In an effort to develop techniques to perform these measurements and gain experience with other UCN sources, a series of measurements using a gravitational spectrometer were taken at the UCN source at the Research Center for Nuclear Physics (RCNP) cyclotron at Osaka University in collaboration with the Masuda group. This chapter will describe these experiments and the analysis of the results.

5.1 Experimental Overview

The gravitational spectrometer measurements were performed from April 30, 2008 through May 7, 2008 with a shutdown on May 3 for an open house at the facility. This UCN source uses spallation neutrons produced by a 400 MeV proton beam from the cyclotron impacting a 5 cm diameter by 20 cm cylindrical lead target. The beam current was varied between 100 nA and 1 µA. These neutrons were then thermalized and cooled by room temperature liquid and 10 K solid heavy water moderators. A fraction of the cold neutrons were then converted to UCN in a superthermal, superfluid 4He source, as described by Masuda et al. [63, 104]. A shutter at the exit of the source UCN guide remained closed
while the beam was on target and was either opened immediately after the beam shuts off or at a later time to measure the lifetime of the source. The beam time, beam current, storage time after beam shutoff, and spectrometer height were varied and the UCN that were transmitted through the spectrometer were measured using a $^3$He detector positioned after a 59.8 cm drop below the horizontal axis of the spectrometer to ensure that the UCN had enough energy to penetrate the detector's aluminum window.

The gravitational spectrometer consisted of a series of 8.1 cm diameter stainless steel neutron guides that could be rotated around the axis of the UCN source guide at various angles from horizontal up to the vertical position shown in Figure 5.1. UCN with kinetic energies below the gravitational potential of the peak of the spectrometer could not travel through the spectrometer. This spectrometer allowed for up to one meter (corresponding to 102 neV) of height change. The dimensions are shown in Figure 5.2. By taking measurements at different spectrometer heights the number of transmitted neutrons with sufficient energy can be measured with the lowest energy UCN being eliminated with each increase in height. This is referred to as an integral spectrum. The difference in UCN transmitted at two heights corresponds to the number of UCN in a particular energy band. For example, the difference between the 40 cm and the 30 cm heights corresponds to the UCN with energies between 30 neV and 40 neV. This is referred to as the differential spectrum.

As UCN are produced in the source, they are held in the helium and the attached UCN guide that penetrates the shielding. The $^4$He is nearly transparent to the UCN, but the interactions with the walls of the source and the adjacent guide can lead to losses through tunneling, absorption, and upscattering off the guide material and any contaminants on the surfaces. These losses are more probable for higher energy UCN, leading to a softening of the spectrum for longer production times. By varying the length of time the beam is on target and measuring the transmission through the spectrometer at various heights, the effect of the source and guides on the shape of the spectrum can be observed.
Figure 5.1: The gravitational spectrometer. UCN enter from the shielding wall on the left. The He-3 detector is on the right after a drop.
Figure 5.2: The dimensions of the gravitational spectrometer used in the simulations. Neutrons are produced in the source at the bottom left and detected using a detector mounted to the far right end. The real source container (lower left) has a curved top and bottom. The spectrometer section is shown in the vertical (largest barrier) orientation. This section can be rotated into or out of the plane of the page to lower the barrier potential. All dimensions are in meters and all bodies are cylindrical.
Due to an apparent vacuum leak in the system, the source neutron storage lifetime got shorter over the course of the experiment. The lifetime measured in the horizontal orientation (0 neV barrier) began at \((28.7 \pm 0.38)\) s at 9:14 on Apr 30. This value is about 10 s longer than the lifetime after the open house, making the early runs difficult to analyze due to the difficulty of separating this effect from the effect of the height of spectrometer. Because of this problem we focus our data analysis on the runs after the open house when began pumping the spectrometer more often to reduce this effect.

### 5.2 Experimental Data

The experiment consisted of a series of runs in which the UCN source was filled and then allowed to empty through the spectrometer, which was fixed at some height above horizontal. The UCN that successfully traversed the spectrometer were counted using a \(^3\)He detector attached to a vertical neutron guide at the end of the spectrometer, as shown in Figure 5.2. The typical run consisted of a period of time when the proton beam was on the lead spallation target and UCN were produced in the source. During this period the UCN shutter was closed, confining the UCN to the source volume and the attached guide through the shielding wall. Any detector counts during this period were disregarded. After the proton beam was shut off, the UCN shutter remained closed for a set amount of time to allow the UCN to sample the source volume and walls. Once the shutter was opened, the UCN were free to travel through spectrometer, though only neutrons with sufficient kinetic energy to surmount the gravitational potential imposed by the spectrometer could reach the detector. For each spectrometer height, source filling time, and source storage time, several runs (generally 10) were taken and later combined to improve the statistics. Each run was then normalized to the average proton beam current to account for fluctuations in the rate of UCN production.

We focused on the runs after the open house due to the decaying source lifetime. These runs are summarized in Figures 5.3 through 5.5 with each point representing one set of measurements with the same spectrometer height, beam time, and storage time. Beam time refers to the length of time the proton beam was on target and UCN are being produced. Storage time refers to the time between when the proton beam shut off and when the UCN valve opens. This was varied to measure
the effective lifetime of the source. Though pumping more regularly slowed the degradation of the source lifetime it did not eliminate it. The analytical method used to account for the changing lifetime is described in Section 5.3.

The two graphs in Figure 5.3 have all of the different beam times with 0 and 10 seconds of storage. Figures 5.4 and 5.5 show the same data plotted for single beam time (10 s, 20 s, 40 s, and 60 s) and all of the different storage times. All of the UCN count rates are normalized to the average beam current.
Figure 5.3: All of the analyzed runs in which the UCN shutter was opened immediately after the beam shut off (left) and 10 s after shut off (right). The horizontal axis represents the minimum neutron energy required to pass through the spectrometer, e.g. 40 neV implies that the spectrometers apex was raised 40 cm above horizontal. The vertical axis is the number of UCN counted in the $^3$He detector normalized to the average beam current. The four data sets represent different lengths of time that neutrons were accumulated in the source volume while the proton beam was on target.
Figure 5.4: All of the analyzed runs with 10 s (left) and 20 s (right) of proton beam. The horizontal axis represents the minimum neutron energy required to pass through the spectrometer, e.g. 40 neV implies that the spectrometers apex was raised 40 cm above horizontal. The vertical axis is the number of UCN counted in the $^3$He detector normalized to the average beam current. The two data sets on each graph represent different lengths of time that neutrons were held in the source after the beam was shut off. These plots contain the same data shown in Figure 5.3.
Figure 5.5: All of the analyzed runs with 40 s (left) and 60 s (right) of proton beam. The horizontal axis represents the minimum neutron energy required to pass through the spectrometer, e.g. 40 neV implies that the spectrometers apex was raised 40 cm above horizontal. The vertical axis is the number of UCN counted in the $^3$He detector normalized to the average beam current. The two data sets on each graph represent different lengths of time that neutrons were held in the source after the beam was shut off. These plots contain the same data shown in Figure 5.3.
5.3 Lifetime Calculations

As previously stated, the effective lifetime of neutrons within the source degraded over time. To account for this issue, the rate of decay of this lifetime had to be characterized. Two methods for this were proposed. First, with the spectrometer in the horizontal orientation (i.e. not energetically excluding any neutrons), comparing the data for several different storage times for the same UCN production time would directly produce a lifetime. Unfortunately, there was not enough data in the horizontal position to use the storage time to calculate the lifetime at both the beginning and end of the after open house runs. The alternative method relies on comparing runs with 0 s storage times for various beam times. If both constant production and loss rates are assumed while the beam is on, an effective source lifetime can be inferred. Using the beam time numbers, the source lifetime decayed from $19.39 \pm 1$ s to $16.97 \pm 1$ s between 23:15 on May 5 through 1:41 on May 7 (37 hours and 26 minutes).

We fit the 19.39s and 16.97s values linearly in time and obtain:

$$\tau_P(s) = -0.0018t + 25.63, \quad (5.1)$$

where $t$ is measured in minutes after the resumption of data taking after the open house at 17:29 on May 3.

The effect of this lifetime change can be clearly seen in the Figure 5.3. The pairs of points with the same parameters (spectrometer height and beam time) in the represent sets of data taken several days apart with the later runs invariably yielding fewer counts. To correct for the change in lifetime, we assumed that the production followed a linear build up in the source with exponential losses due to the source lifetime. Using Eq. 5.1, we can correct the lifetimes by multiplying by the following factor:

$$\frac{N_0}{N_P} = \frac{\tau_0(1 - e^{-\frac{t_b}{\tau_0}})}{\tau_P(1 - e^{-\frac{t_b}{\tau_P}})}, \quad (5.2)$$

where $t_b$ is the beam time in seconds, $\tau_0$ is the lifetime at the end of the open house (25.63 s), and $\tau_P$
is the lifetime calculated from Eq. 5.1 at the actual time of the run.

The corrected data is shown in Figure 5.6 along with 5th order polynomial fits. Higher-order polynomials did not improve the fit. The first derivative is forced to zero at zero energy to give a more physical spectrum. Recall that, due to the nature of the gravitational spectrometer, each point represents the number of UCN with the energy equal to or greater than the gravitational barrier energy (i.e. spectrometer height) it corresponds to. This may therefore be thought of as an "integral spectrum" of the UCN in the source.

The number of UCN in an energy region can be determined by taking the difference in counts between two points. For example, the difference between the number of neutrons that pass through the spectrometer in its horizontal (0 cm) and 10 cm orientations corresponds to the neutrons with between 0 neV and 10 neV of kinetic energy as they enter the spectrometer. The derivative of the integral spectrum thus gives the "differential spectrum," which corresponds to the number of UCN with a given energy. The differentiated fits are shown in Figure 5.7 and give the approximate shape of the differential spectra. Unfortunately, due to the nature of error propagation, the errors on the differential spectra are quite large. As such, Figure 5.7 is included for illustrative purposes only. Beyond the obvious increase in production at all energies for longer beam times, the peak energy shifts towards lower energy for longer production times. This is the expected softening of the spectra due to the higher loss rates for higher energy neutrons reducing their population over the longer times.

5.3.1 Osaka UCN Source Modeling

To assist in the analysis of the gravitational spectrometer data, a series of Monte Carlo UCN transport simulations were carried out to improve our understanding of secondary effects of the gravitational spectrometer beyond the simple gravitational potential energy cutoff. A variation of the code described in Section 3.3 was employed. The geometry used in these simulations is shown in Figure 5.2. This geometry is slightly simplified by removing the curved top and bottom of the helium source container and replacing them with flat surfaces.
Figure 5.6: The data with 0 s storage time after correction for the change in source lifetime over the course of the experiment. Polynomial fits are included for illustration. The first derivative at zero energy is forced to zero. This is physically reasonable since no neutrons that enter the spectrometer are excluded from the horizontal orientation.
Figure 5.7: The first derivative of the fits from Figure 5.6 illustrating the relative number of UCN for different beam times as well as the shape of the energy spectra.
Single Energy Simulations

The simulated UCN were produced at the beginning of the spectrometer in a forward-directed cosine-weighted angular distribution. Each run contained a single initial UCN energy at 20 neV intervals with $10^5$ UCN in each run. Eleven sets of simulations were performed with the spectrometer oriented in 10 cm increments from horizontal to vertical in the same positions that were used in the actual experiment. These simulations allow one to determine the transmission properties of the spectrometer for different energy ranges and allow for the effect of the spectrometer on the shape of the spectrum to be accounted for when inferring the UCN spectrum at the source. The results of these simulations are shown in Figure 5.8. The ratio of each curve in Figure 5.8 normalized to the horizontal configuration (0 cm) is shown in Figure 5.9.

If we assume that the difference between two curves above the spectrometer cutoff energy ap-
Figure 5.9: The simulated transmission fraction for each spectrometer height curve in Figure 5.8 normalized to the horizontal (0 cm) transmission. This shows the effect the spectrometer has on each energy region and the orientation of the spectrometer. The initial assumption that there is a sharp cutoff at the energy corresponding to the spectrometer height is an oversimplification.
proximates any distortions of the experimental spectrum caused by the spectrometer, we can correct the data using the ratio of the integrals of these simulated spectra above the cutoff energy. For each spectrometer height the simulated spectrum for both the 0 cm height and the appropriate height were integrated from the cutoff energy out to 200 neV. Figure 5.10 shows the after-open-house data multiplied by the ratio of these two integrals to correct for the effect of the spectrometer. Figure 5.11 shows the differential spectra implied by those fits.

5.4 Conclusions

The gravitational spectrometer is an excellent tool for measuring the integral spectrum of a UCN source. Unfortunately, when taking the difference in counts between two of the lowest heights, the
propagation of error leads to very large error bars compared to the absolute value of the result. Due to this effect, the differential spectrum obtained from this device is significantly more useful at higher energies. However, a separate experiment was performed by our collaborators at the RCNP for which the errors in the differential spectrum are improved at lower energies and magnified at high energies. This experiment consisted of a 206 mm ID vertical stainless-steel storage bottle with an adjustable polyethylene ceiling. By lowering the ceiling, UCN with sufficient energy to reach the height of the ceiling are absorbed. In contrast to the gravitational spectrometer, only the UCN below a maximum energy survive, reversing the error propagation issue. This other experiment is described in RCNP annual reports [105, 106]. By combining these two approaches the energy spectrum of a UCN source can be determined. After commissioning, understanding this energy spectrum for the PULSTAR UCN source will be necessary for experimenters to be able properly analyze the systematic effects that are correlated with the energy of the UCN.
Status and Future Directions

When it is completed, the PULSTAR ultracold neutron source will be a valuable tool for the UCN community. This concluding chapter will discuss the status and outlook for the source and describe several experiments that have been proposed to utilize it.

6.1 Current Status

As of this writing, the PULSTAR UCN source is being commissioned. Final cryogenic testing of the gas handling systems and the source itself using inert gases in place of the flammable cryogens are underway to ensure the safety of the system. During these tests the cryostat is operated outside of the biological shielding of the reactor. For these tests, neon is used in place of the deuterium and nitrogen replaces the methane. Condensing these materials into the cryostat allows for testing of the cooling systems, helium liquefier, and gas moderator handling systems. These tests have shown that these systems are sufficient to run the source and have shown minor opportunities for improvement before the source is operated with the flammable cryogens.
6.2 Possible Experiments

The PULSTAR UCN source will be most useful for small-scale standalone experiments and in support of larger-scale efforts. The experimental area that is available makes the site unsuitable for experiments such as nEDM and UCNA/B without significant modifications to the facility, but will be able to support these experiments and help develop UCN technologies. Below, I outline several proposed experiments that could utilize UCN from this source. These experiments will follow the commissioning and characterization of the source itself.

6.2.1 Neutron Electric Dipole Moment Search

The first proposed experiment for the PULSTAR UCN source will be to characterize systematic effects that affect the nEDM experiment at ORNL. To accomplish this a small scale apparatus capable of holding a full-sized measurement cell for the nEDM experiment will be constructed to study the interactions of polarized UCN and polarized \(^3\)He in the detection volume, characterize the effects of the UCN trajectories on the geometric phase build up, and study \(^3\)He NMR imaging techniques. This project is currently being developed by the nEDM collaboration.

6.2.2 Neutron Lifetime

The PULSTAR UCN source may be utilized for a neutron lifetime experiment that is being developed at LANL [27, 107]. This experiment uses a Halbach-array permanent magnetic container with an additional holding field supplied by external electromagnetic coils. This arrangement allows for the storage of one spin state of UCN and eliminates zero-field areas that can lead to UCN losses caused by Majorana spin flips. The trap volume is supplied with UCN through a trap door in the bottom of the magnet array. By emptying the trap (through the same trap door) and measuring the remaining UCN after varying holding times, the lifetime of the neutron can be inferred. In order to avoid systematic effects generated by these marginally-trapped neutrons (i.e. neutrons with sufficient energy to escape the trap that remain inside in certain orbits) the trap is constructed with minimal symmetry and a
polyethylene surface can be lowered into the trap to eliminate the highest energy neutrons. Recent measurements have demonstrated a trap lifetime of $860 \pm 19$ s [107].

6.2.3 $\beta$ Asymmetries

A measurement of the $\beta$ decay triple-correlation coefficient, “$D_1$,” utilizing the PULSTAR UCN source has also been proposed. This coefficient represents the correlation between the neutron spin, the electron momentum, and the anti-neutrino momentum and can act as a probe into CP-violating extensions to the Standard Model [108]. The anti-neutrino momentum will be inferred from the proton recoil momentum. The small maximum kinetic energy of the proton ($\sim 720$ eV) will be detected using LiF on fluorinated polyimide foils that are presently being developed at North Carolina State University and the Triangle Universities Nuclear Laboratory. These foils can be coated with diamond-like carbon or beryllium to reflect UCN. The decay electron can traverse the foil with minimal energy loss, while the proton can be detected from secondary electrons produced in the impact [109]. This small scale experiment would be well-suited for the PULSTAR UCN source.

6.3 Development of UCN Technologies

Further developing the techniques used in constructing UCN guides will allow for greater UCN densities in future experiments. The PULSTAR UCN source will be well suited for experiments to characterize the transmission properties of prototype and production guides. The high UCN density, flexible running schedule, and access provided by this source will allow for efficient characterization of various types of UCN guides.

The properties of the solid deuterium in the UCN source are critical to maximize production and UCN losses inside the deuterium. The PULSTAR UCN source can be used to characterize the effects on UCN output of these properties and methods. For example, monitoring and adjusting the freezing process will provide information about the crystalline structure of the solid deuterium and its effects on UCN production. This information will be useful for optimizing the source, as well as to the UCN community at large.
6.4 Conclusions

The PULSTAR ultracold neutron source is presently nearing completion and will provide the UCN community with a new apparatus for small scale experiments and development of UCN technologies. As the construction and commissioning of the source nears completion, the first experiments are being planned.

The design, construction, and simulations described in this document represent an attempt to maximize the number of UCN available to experimenters. This will soon be tested during the first UCN production runs. Initial testing will include optimization of the solid deuterium condensation process and varying of the cold neutron spectrum by changing the methane temperature to maximize UCN production. Characterization of the UCN spectrum, using methods similar to those described in Chapter 5, will assist future facility users in planning and designing their experiments.

When completed, the PULSTAR UCN source will be a valuable tool for future fundamental physics experiments and for the development of UCN technologies.


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[80] D. Ries on behalf of the PSI UCN project team. Status of the source for ultracold neutrons at the Paul Scherrer Institute, September 2013. Presented at the Physics of Fundamental Symmetries and Interactions — PSI2013 conference.


APPENDIX
Appendix A

Helium Liquefier Drawings

A.1 Liquefier Piping and Instrumentation Diagram

The liquefier Piping and Instrumentation Diagram (PID) (Figure A.1) shows all of the helium flow paths that are external to the Linde 1430 cold box. These include the Dewar; a simplified version of the cryostat; the helium return, recovery and storage systems; and external components of the liquefaction system such as the RS compressor. The flow diagram of the Linde 1430 is shown in Figure A.2.
Figure A.1: The Piping and Instrumentation diagram (PID) for the helium liquefaction and recovery system.
Figure A.2: The internal Piping and Instrumentation diagram (PID) for the Linde 1430 liquefier cold box.