PROJECT DESCRIPTION

1 Introduction

Ultra-cold neutrons (UCN) are playing an increasing role in nuclear physics investigations of the fundamental properties of the neutron and neutron decay. UCN source technology, as noted in the 2002 NSAC report, is advancing extremely rapidly, with U.S. groups taking the lead in a field dominated, up until 3 years ago, by European institutions. In particular, the superthermal source technique should permit several orders of magnitude gain in available UCN densities, and not only permit far superior measurements of quantites such as the neutron EDM and lifetime, where UCN already provide the best experimental values, but also in neutron angular correlations measurements, neutron-antineutron oscillations searches, spectroscopic studies of neutron decay, fundamental tests of quantum mechanics, and potentially cutting-edge neutron scattering applications as well.

We propose to construct a world-class, polarized ultra-cold neutron (UCN) source at a low-power, university research reactor. Our proposed source is extremely cost effective, supported by extensive, existing nuclear physics and nuclear engineering infrastructure (through the Triangle Universities Nuclear Laboratory, or TUNL, and the reactor program at NCState), and well-timed to provide support for the planned fundamental neutron physics efforts planned at the SNS and Los Alamos. This source would provide the ideal training ground for students interested in exploring fundamental and applied physics projects utilizing UCN, and would make possible a range of experiments in areas as widely varied as nuclear physics tests of the electroweak standard model and the dynamics of large biological molecules. Because of the very small heat load we anticipate for our cryogenic moderators, we can also experiment with UCN source configurations not practical near the core of a high power reactor or at a high-flux spallation target. We envision a program in which the physics and nuclear engineering departments at NCState jointly construct and participate in the research program at this facility. Strong interest in the nuclear/particle physics program has also been expressed at neighboring institutions (University of North Carolina at Chapel Hill and Duke), through TUNL.

Our source approach itself builds on the experience many members of our collaboration have had in the development of cold neutron and superthermal ultracold neutron sources. Our collaboration includes one of the inventors of the superthermal source concept[1, 2, 3], one of the members of the LANL-based group that have successfully constructed a prototype solid deuterium source coupled to a spallation target at LANSCE[4, 5, 6, 7] and the leader of the nuclear engineering group that produced a cold source at the University of Texas reactor[14, 15, 16, 17, 18, 19]. The LANSCE source recently set a world-record for the density of bottled UCNs produced by any means (the achieved density was roughly 3.5 times that of the bottled UCN density of 41/cm^3 produced at ILL[12]). Based on part on the success of this effort, a number of superthermal solid deuterium sources have been proposed at both reactor facilities (FRM II)[9, 10] and spallation targets (PSI and LANSCE)[11, 8]. Our facility will require almost no new overhead for the reactor program and, because of its close coupling to the nuclear physics program at TUNL and the materials science program at NCState, will immediately find use in a variety of projects.

The reactor facility at NCState features a 1 MW PULSTAR research reactor. One of the great strengths of our proposal is that we will have minimal impact on the operation of the reactor facility. The source we envision can be placed outside of the aluminum reactor vessel as an essentially independent entity, with no direct contact with the core coolant or support system. Utilizing a fast-neutron flux guide, we direct a large fraction of the flux over 100 keV...
away from the core, through the aluminum wall of the coolant vessel, and into our UCN source. The PULSTAR reactor is uniquely suited to this design, because of the relatively large neutron "leakage" flux exiting the core face. Thus we have almost no impact on the licensing and safety constraints key to the continued, trouble-free operation of the reactor itself. The PULSTAR reactor is operated on funds from the State of North Carolina, and given the recent re-licensing of the reactor for operation until 2017, we are in an ideal position to develop and take advantage of a solid deuterium source at this facility.

Finally, we note that our program is especially appropriate given the growth of neutron science at NCState. NCState is one of the six universities partnering with U.T. Batelle in the management of Oak Ridge National Laboratory. Our envisioned university-based program will provide training and support for personnel involved in cold neutron scattering efforts at Oak Ridge. The nuclear engineering program has already entered into a partnership agreement with Oak Ridge National Laboratory (ORNL), and is developing several different areas of cooperative research with ORNL. These areas of overlap with the neutron program at ORNL should result a tenure track hire fundamental neutron physics in the physics department (now being advertised) and a future tenure track hire in the nuclear engineering department.

2 Overview of a Science Program

NCState has very strong and active programs in several multi-disciplinary research areas including biochemistry/biophysics, materials/soft-condensed matter physics and low energy nuclear/particle physics. In each of these areas, there is intense activity both at NCState and at sister institutions in the research triangle: Duke and University of North Carolina. Although we plan an interdisciplinary research program, we note that a dominant part of our scientific emphasis will be nuclear physics (nuclear physics has traditionally played a leading role in the development of UCN applications). In particular, members of TUNL representing NCState, Duke and UNC are prepared to assist in the source construction and to build and launch pilot experiments as soon as the source becomes operational. The significance of the TUNL contribution will be touched on again in the next subsection.

Because of the extraordinary access that students and researchers will have to this source, the facility will serve as a valuable addition to the set of neutron facilities available in the U.S. We will be able to implement new, potentially time-intensive research projects without the pressure of efficiently processing the largest number of samples or competing with the largest nuclear physics collaborations. We can devote source time to investigating speculative guide technologies and new source materials, and we can involve students in every aspect of the design, construction and operation of the source and the experiments performed there. In what follows, we survey some of the measurement programs we are interested in pursuing and believe are possible at our proposed source.

2.1 Particle and Nuclear Physics

This facility presents an ideal opportunity to perform research and development for some of the more challenging and higher profile measurements currently being envisioned for fundamental neutron research, such as the neutron EDM[20] and neutron-antineutrino (Nνbar) oscillations searches[21]. In addition, somewhat smaller scale measurements, such as placing new limits on the time-reversal symmetry (T) invariance in beta-decay would be very competitive with our envisioned UCN fluxes. Both of these experiments probe extensions to the standard model of particle physics and are complementary to the direct searches for new interactions/particles planned at
future high energy accelerator facilities. For these and other nuclear physics measurements, the presence of the TUNL facility ensures that the necessary infrastructure to construct large pieces of equipment and carry out these experiments is at hand. In this section we describe an approach to utilizing UCN to measure T invariance in beta-decay and the development of a test facility for the neutron EDM project. Because the primary obstacle to improved limits in NNbar experiments is the available UCN flux, we discuss a practical approach to this problem in our subsection on source development.

One method to probe T invariance in neutron decay is to measure the angular correlation between the neutron spin (J), the momentum of the emitted electron following beta-decay (p_e), and the momentum of the recoiling proton (p_p), usually expressed as: \(-DJ \cdot (p_e \times p_p)\). These measurements provide the most stringent limits for leptoquark and some contact interaction extensions to the standard model, and provide a very clean extraction of the complex couplings responsible for T non-invariance. Thus, they are complimentary in many respects to the EDM measurements discussed below.

A measured, non-zero value for the D coefficient in either of the two ongoing measurement programs would indicate the presence of a T violating interaction outside the standard model[23, 24]. These measurement programs are projected to achieve ultimate sensitivity levels at roughly the 10^{-4} level. Our proposed technique with UCN has the potential of improving over their projected limits by an order of magnitude in just one month of running at the PULSTAR facility, and should ultimately provide a crude detection of the final state effects in this angular correlation measurement[22].

As a part of our work for the UCNA collaboration at Los Alamos, we have developed a superconducting polarizer/spin-flipper magnet system for UCN (supported by NSF MRI grant PHY0049018). UCN can be polarized by passing them through a large magnetic field (one of the spin states lacks the energy to overcome the large potential barrier produced by the \(\mu \cdot B\) interaction, where \(\mu\) is the magnetic moment of the neutron and \(B\) is the magnetic field). After passing through this high field region, the UCN are essentially 100% polarized. While the “wrong” spin neutrons are rejected by the high field region, the “right spin” UCN are strongly accelerated into the high field region. If we place the Al foil in a guide at the center of the magnet, simulations indicate the accelerated right spin neutrons will pass almost unimpeded through the foil, whereas if no magnetic field is used, the transmission through the foil is reduced at least a factor of three (for a practical foil thickness). Such a geometry should permit us to produce a general purpose, polarized source of UCN which can be coupled to any experiment we wish to conduct.

In our proposed approach, UCN are polarized by passing them through a high field polarizer and then loaded into a cell designed to permit the measurement of this angular correlation for a very large fraction of the decays. This is accomplished by effectively making the walls of the cell into an array of proton detectors and detecting the decay beta’s after they pass through the cell walls and into a surrounding array of segmented plastic scintillators. Although such an approach has never before been attempted with UCN, similar experiments have been performed on 19Ne, where the cell geometry has provided large decay rate enhancements and has provided improved protection against certain classes of systematic errors.

The decay rate we achieve in this experiment depends critically on the quality of the UCN guides we utilize. At ILL, experiments mounted directly to the rotor source achieved 66% of the limiting density of 60 UCN/cm^3, but the ILL EDM experiment, mounted through over 6 m of guide with several right angles, foils, valves, etc., achieves densities roughly one tenth of this. As a part of our UCNA project, we have also developed a quartz guide tube coated with diamond-like carbon which reduces guide transmission losses (over those reported for the EDM experiment[25]) by a factor of roughly 7. Our projected increase of a factor of 20 in limiting density
over ILL together with improved guide technology should produce enormous gains in available UCN density. For an interesting D coefficient measurement, however, modest improvements over the available density at ILL are sufficient. With UCN densities in our 50 liter bottle of only 20 UCN/cm$^3$, the decay rate (achievable at ILL with our new guides) would be roughly 1000/s. At the projected UCN densities for the PULSTAR source, the decay rates could be up to 50 times higher. This would permit, in principle, a limit after 10 days of running of $D \leq 5 \times 10^{-5}$ (this limit is the result of detailed Monte-Carlo studies with the PENELOPE electron transport code to determine the sensitivity of this geometry).

We note that our current research program has already produced the critical technique required to detect the recoil protons emitted after the neutron decays. Our detector systems utilize remarkably tough, ultrathin, large polyimide foils with a secondary electron emitting material evaporated on the exit face of the foil. Protons can be accelerated through a modest potential (25 kV) and then pass through these foils, emitting 10-12 secondary electrons on average from the material on the exit face. These foils are very easy to make, are robust, withstand pumpdowns and can withstand temperatures up to about 400 C. Our detector development efforts have resulted in patent applications for the basic foil technology. More details of our proposed approach can be found on the weak interactions website at NCState university (http://www.physics.ncsu.edu/weakint/index.html).

Limits on the neutron EDM (together with limits on the atomic EDM in Hg) place some of the most stringent limits on new T violating interactions, and are particularly sensitive, for example, to T violation induced by supersymmetric and left/right symmetric extensions to the standard model. UCN experiments place limits on the presence of the EDM by searching for a change in the spin-precession rate of the neutron in the presence of very strong, homogenous electric fields. An experiment based on the technique proposed by Golub and Lamoreaux[26] is being developed with a collaboration centered at Los Alamos. Several members of our group (Golub, Korobkina) are also members of this collaboration and are actively contributing to this effort.

Because the limiting density of our source is well over 1000 UCN/cm$^3$ and we have access to improved guide technologies, our proposed facility would be an invaluable testbed to develop ideas in the years before the full experiment is to be run, since UCN should be available at our facility year-round, on demand, and at very low cost. We envision our source as being a general-purpose source of polarized UCN (the technique for polarizing the UCN is discussed below) and with such a facility we could then study UCN storage times, UCN spin-relaxation rates, the interaction between polarized UCN and polarized $^3$He, and perform in-depth studies of the He scintillations and the after-pulse technique for discriminating between neutron signals and gamma backgrounds. Without a detailed design of the test facility, an accurate estimate of the polarized UCN densities available in a liquid He filled bottle is difficult to make, but 100 UCN/cm$^3$ is a conservative and probably achievable goal. Such a facility would also be completely free from the usual cold neutron generated backgrounds.

2.2 UCN Scattering Instruments and Materials Studies

As an example of the incentive to develop UCN scattering as a technique for studies of condensed matter we call attention to two of the most important problems in current molecular biology; protein folding and enzyme action. The study of both of these problems requires the ability to study slow motions of relatively large objects. In the language of neutron scattering spectroscopy this requires low Q (momentum transfer) and low $\omega$. Phase space arguments, first advanced by Meier-Leibnitz, indicate that there are significant advantages in such cases to work with lower energy neutrons (see refs.[27, 28] for a discussion of this point and the present and future uses of UCN in scattering applications). For example, the time scales in protein folding are of the
order of microseconds while typical UCN energies correspond to de Broglie frequencies of $10^7$ Hz so that one can work with rather poor relative resolution in comparison to other methods. With the huge improvements in available UCN density expected with the new North Carolina State UCN source the investigation of techniques to exploit this inherent advantage of UCN become ever more promising.

While conventional techniques of neutron scattering continue to improve, e.g. neutron resonance spin echo and a range of new spin echo techniques based on thin magnetic films, the coming increase in UCN density means that there is a good chance that the inherent advantages of UCN scattering can be made to pay large dividends perhaps in combination with one of these techniques. A research program to investigate the various possibilities of UCN scattering and to build an optimized spectrometer should thus be given the highest priority.

Another area of recent activity which shows the promise of UCN for materials science applications is the neutron absorption and scattering work being performed to evaluate the surfaces of various materials. These studies have shown sensitivity to remarkably small concentrations of hydrogen (e.g. able to discriminate cases where only 2 monolayers of hydrogen exist on the surface probed by the UCN)[29]. Moreover, UCN scattering and absorption probes have almost no impact on the surface layer, whereas the highest resolution ion backscattering analysis for surface content has a resolution limited to roughly 10 nm and usually destroys the analyzing layer. UCN also permit the experimenter to probe surface dynamics by monitoring the upscattering rate of UCN in contact with the surface, probe for the presence of surface potential inhomogenities[30], pinholes in multilayers and various coatings[31],nanoparticles weakly bound on surfaces[32] and surface contaminations other than hydrogen by monitoring the characteristic gamma rays emitted upon capture.

Both a quasielastic scattering spectrometer and the surface interactions work could be carried out in a straightforward fashion with a superthermal source at NCState. One member of our team (R. Golub) has extensive experience in the development of cold neutron scattering instruments, and would lead efforts to develop a spectrometer. Another member, E.Korobkina, is actively involved in further developing the UCN absorption/interaction technique on various substrates over a wide range of temperatures with a recently commissioned ultrahigh vacuum cryostat[33]. This apparatus together with the gamma-detectors already available at PULSTAR reactor for gamma radiation analysis with thermal neutrons provides a unique opportunity to develop powerful cryogenic variant of this method.

2.3 UCN source and technology development

All of the members of our collaboration have devoted some of their research careers to the development of neutron sources, and we see numerous possibilities for new source geometries to explore at NCState. For example, in addition to the proposed solid deuterium source, we have evaluated the performance, in principle, of a superfluid He source within our cold premoderator[36]. Such a source has the potential to produce significantly greater than $10^5$ UCN/cm$^3$ if it is coupled to a volume for the UCN characterized by long (greater than 100s) storage times. These sources will find greatest applications for experiments which can be conducted when closely coupled to the superfluid He bath used to produce the UCN.

Another possibility is to develop a solid oxygen superthermal source[37]. Such a source functions primarily through the cold neutron couplings to magnon excitations in solid oxygen, and seems to be most effective when the oxygen is held at around 2 K. These sources offer potentially greater than a factor of 10 improvement in UCN production rates over solid deuterium, and thus would be very useful for NNbar experiments[34, 35] and neutron beta-decay experiments.
Exploring source and moderator possibilities such as solid oxygen are time-intensive projects, and difficult to conduct at production-oriented facilities such as our National Laboratories. We note that this source material was first theoretically evaluated as a part of the thesis research for Chien-Yu Liu, then a graduate student in our group.

Finally, our hope is that the NCState source could provide invaluable support to the UCNA program already funded and underway at Los Alamos. As noted earlier, projects such as guide development and the evaluation of UCN detector systems could be carried out at NCState, preserving the available UCN flux at Los Alamos for projects requiring all of the available flux of UCN at LANL. Because we plan to construct a polarized source, we can also maintain a research development program to optimize polarization-preserving guide coatings for UCN. The development of these coatings is a critical part of the UCNA collaboration’s research program, and requires a serious investment of beam time and resources. This has necessitated a sequence of experiments at ILL which might be much more efficiently, thoroughly and inexpensively pursued at the NCState facility.

3 Overview of the Source

Our design strategy was to utilize, whenever possible, the most conservative performance numbers available. The design effort can be split into two broad areas: estimations of the cold neutron flux produced in the vicinity of our solid deuterium moderator, and estimations of the performance of the solid deuterium source when immersed in the expected cold neutron flux. The first of these efforts was accomplished through a detailed model of the reactor core, coolant and shielding structures utilizing a MCNP (version 4B) model of the reactor facility. This code has been extensively validated for reactor criticality and neutron moderation applications[13]. The second of these efforts was accomplished using established models of neutron interactions with solid deuterium, and the experience gained from the construction of the LANSCE source[4, 5, 6, 8, 38, 7].

As mentioned in the introduction, we place within the coolant vessel a beryllium or graphite-lined flux guide, which directs a large fraction of the neutron flux exiting from the reactor face to the wall of the reactor vessel (2 cm, Al wall), see Fig. 1. Beyond the aluminum wall, we position a tank filled with D₂O which serves as a thermal moderator for the fast neutrons. Within this we place a nested set of cryogenic moderators. The outermost layer is a 1 cm thick, cylindrical volume of solid methane at a temperature of 22 K, see Fig. 2. Within this is our solid deuterium UCN converter, held at a temperature below 5 K. The cryostat vessels are constructed of aluminum. The inner guide is a 58Ni-coated Al guide, attached to a very thin stainless steel guide, also coated with 58Ni.

The predicted average cold neutron flux within the solid deuterium volume is (1.02 ± 0.04 × 10¹² ncm⁻²s⁻¹) (uncertainties are statistical) with a peak at a temperature of 2.5 meV (about 31 K). This CN flux generates, within the SD2 volume of our 18 cm guide, a total UCN current of 3 × 10⁷/s. For a reasonable UCN lifetime within the solid deuterium, this results in a limiting density of about 1,300 UCN/cm³ (see Sec. 6). This is 100 times greater than the useful densities at the world’s strongest source at present, at the Institut Laue-Langevin in Grenoble, France, and 10 times greater than the highest UCN densities achieved through any technique[5, 6, 7].

The flux surviving to the mouth of our guide beyond the biological shielding is roughly 1 × 10⁷ UCN/s, more than enough for a variety of experiments, some of which are described in our description of the science program, Sec. 3. In what follows, we present a summary of the model of the reactor core (including our treatment of the criticality and possible upgrade scenarios),
Figure 1: Top view of the reactor core, flux guide and one configuration for the UCN cryostat used in MCNP models of the source performance. The yellow regions are H\(_2\)O, the blue regions are D\(_2\)O, and the gray regions are Be. For clarity, in this figure we depict a horizontal cryostat. The UCN densities and production rates we quote for this proposal are for a vertical cryostat (see Fig. 2).

the cold neutron flux calculation, and the UCN production rate, limiting density and transport calculations.

4 The reactor core and the thermal neutron flux

As we will show, our design requires almost no modification to the existing reactor facility, and provides world class performance as a UCN source with only modest investments in capital equipment and manpower.

The principal of operation behind the PULSTAR reactor is uniquely well suited to our approach of implementing a cold neutron source, in that a relatively heavy loading of the \(^{235}\)U low enrichment fuel pellets (4% enriched) and a low H to \(^{235}\)U ratio provides for relatively a large leakage rate of neutrons from the faces of the core. Calculations of existing core geometries are in rough agreement with the neutron flux measured using foil detectors. The fluxes calculated in this fashion we take to be reliable at the 30% level.

We make optimal use of this neutron flux by directing it outside the reactor coolant vessel using a Be or graphite channel pressurized with He. To ensure a minimum impact to the heating characteristics of the core, we leave a 1 cm buffer layer of H\(_2\)O between face of the core and a lead shield (2 cm thick) at the entrance to our Be flux channel. With this configuration (H\(_2\)O layer and lead shield) and using tilted control rods, we are able to maintain the nominal reactivity for the PULSTAR facility at present. Table I lists the results of reactivity simulations carried out with MCNP to evaluate the impact of various modifications to the performance of the core.
<table>
<thead>
<tr>
<th>Change in Base Case Source Design</th>
<th>CN flux</th>
<th>reactivity</th>
<th>heat(mod)</th>
<th>heat(chmb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>reduce radius of D$_2$O, 64 to 40 cm</td>
<td>-21%</td>
<td>+0.40$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>remove He from flux channel</td>
<td>+2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>replace Be in flux channel with graphite</td>
<td>-11%</td>
<td>-0.35$</td>
<td>+10%</td>
<td>+20%</td>
</tr>
<tr>
<td>remove Pb shield from core face</td>
<td>+1%</td>
<td>-0.90$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>add 2cm thickness to Pb shield at D$_2$ tank</td>
<td>-11%</td>
<td>-10%</td>
<td>-20%</td>
<td></td>
</tr>
<tr>
<td>replace 6% fuel with 4%</td>
<td>-13%</td>
<td>-1.30$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>control rods banked</td>
<td>-7%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Table I lists the effects to the cold neutron flux at the site of our SD$_2$ source, the reactivity of our core ("dollars" indicate the fractional change in the neutron multiplication parameter, $k$), and the heating rate for our cryogenic moderators—the methane cold source and SD$_2$ UCN source—and the chamber walls of the cryostat.

The Be or graphite channel will be placed within an Al container and then immersed in the reactor coolant. The void region will be filled with He gas at one atmosphere, to partially offset the external water pressure and to avoid neutron losses through absorption in the buffer gas. As a safety precaution, the walls of this container will be roughly 1.25 cm thick, i.e. more than enough to hold off the one atmosphere overpressure on the outer surface of the vessel. In fact, a similar, evacutable channel was installed in the University of Buffalo PULSTAR reactor facility, providing us with a practical guide to realizing this element of the source. The Be, however, may represent a significant component in the equipment budget of the source. There is only a modest (11%) reduction in the UCN source performance if we use graphite instead of Be for the flux channel, providing us with a low cost alternative should the Be cost prove prohibitive. Just outside of the reactor vessel wall is a 1.2 m x 1.2 m access port (the thermal column) into which we place a D$_2$O moderator vessel and within which we position our solid deuterium source.

The fast neutrons moderated by the room temperature D$_2$O are further moderated by the solid methane cold neutron jacket. Because the heating rates in our UCN source and CN jacket are so small (8.5 mW/g and 10 mW/g respectively), we can immediately profit from higher neutron fluxes. Thus, one obvious path to consider is an upgrade of the reactor output power and thus its neutron flux. The University of Buffalo PULSTAR reactor can, once again, serve to guide us, because it operated at twice the thermal power (2 MW) and was otherwise almost identical in design. We developed a detailed simulation of the appropriate core geometry for this upgrade and verified that it can result in essentially a factor of 2 increase in the CN flux. We consider this upgrade path a very attractive possibility, and will pursue it with other sources of funding.

From the point of view of our UCN source performance, except for the possible increase in thermal power and neutron flux by upgrading to 2 MW, the performance improves only slightly through further optimization of the core configuration. Additional improvements at the 10 to 20 percent level can be obtained by replacing existing graphite reflectors with Be reflectors and removing the lead from reactor face.

5 Cold Neutron Flux: a Solid Methane Moderator

Our design, which places the cryogenic moderators roughly a meter away from the core face, provides us with a many possible choices of cryogenic moderator. This is primarily because the radiation field produces heating from all sources (gammas, betas, neutrons) for the cold neutron moderator of 5.6 W and for the Al cold neutron moderator chamber, only 6.0 W. This represents
Figure 2: The source cryostat consists of an outer vacuum jacket, followed by an inner jacket cooled to about 22 K by a closed cycle refrigerator and an inner cryostat cooled by liquid He. The solid deuterium rests inside a short length of $^{58}$Ni coated guide tube.

![Diagram of cryostat](image)

Figure 3: The cold neutron spectrum predicted in the volume occupied by the SD$_2$ converter material, as predicted by MCNP.

![Graph of cold neutron flux](image)

a total heat load of 11.6 W, easily dealt with at 22 K by commercial, closed cycle refrigerators (the Sumitomo SHI 6K refrigerator unit, for example). Moreover, the specific heating in our cold moderator of 10 mW/g is much smaller than any other proposed reactor source, and frees us to use moderators which provide extremely high cold neutron yields at the expense of being relatively “fragile” materials, which degrade in higher radiation fields. One such material is solid methane, which we have selected for our preliminary source design.

The solid methane moderator used for our pilot study is composed of 558 g of methane, is 1 cm thick and is held at 22 K, for which a detailed scattering kernel is available. The cooling is accomplished by a commercially available closed-cycle refrigerator system (see Sec. 5). The scattering kernel has been checked in at least one instance[39]. Our modeled value for the cold
neutron source within our cryostat is \((1.02 \pm 0.04) \times 10^{12} \text{cm}^{-2} \text{s}^{-1}\), roughly a factor of four greater than a converter of the same size containing liquid hydrogen. The cold neutron spectrum is depicted in Fig. 3, and is peaked at about 31 K.

6 The Ultra-Cold Neutron Source

The UCN converter is composed of 200 g of solid deuterium, frozen by vapor deposition in the bottom of a liquid He-cooled UCN guide, coated with \(^{58}\text{Ni}\). The bottom surface of this guide may be ridged to ensure better thermal contact between the SD\(_2\) and the cooling surface (our thermal loads are so small this may not be necessary). The SD\(_2\) itself is 4 cm thick and 18 cm in diameter. There is a thermal break just above the cooled region of the guide, coupling the coated Al cryostat to thin-wall, stainless steel guide, also coated with \(^{58}\text{Ni}\) (modest gains can be had by replacing the stainless steel guide beyond the thermal break with Al or Be guide, but we are not pursuing this at present). One of the great strengths of our approach is that the heating rates are so low that our cryostat can be adequately cooled with flowing He liquid. Given our MCNP-modeled heat loads to the entire liquid He-cryostat of 5 W (this results in about 71 hour of liquid He consumption), we can almost certainly achieve temperatures down to 2 K for the solid deuterium cryostat, however we assume only 5 K temperatures for our discussion here. An optimized approach to the cryostat will be developed with D. Haase, the cryogenic target specialist at TUNL.

The motivation behind reducing the temperature of our cryogenic moderator to around 5 K is to reduce UCN losses inside of the solid deuterium source. The theoretical limit for the UCN densities produced within the source and any experimental volume attached to the source is given by:

\[
\rho_{UCN} = R \tau_{SD},
\]

where \(\rho_{UCN}\) is the density of UCN, \(R\) is the UCN production rate, and \(\tau_{SD}\) is the lifetime of a UCN in the solid UCN deuterium. Clearly, this limiting density is a function of the production rate and the lifetime of UCN.

The production rate for UCN is given by the formula in Liu et al. [38] (note that we assume the para-deuterium concentration in the source is 1.5\%, a fact which affects the production rate very little, but has a large impact in determining \(\tau_{SD}\), and is calculated by folding the predicted cold neutron spectrum (Fig. 3) with the cross-section. In our case, the solid methane converter provides ample cold neutron flux, and the production rate is about \(3 \times 10^7\) UCN s\(^{-1}\) continuously being generated within the solid deuterium. About \(1 \times 10^7\) s\(^{-1}\) survive to be useful in an experiment outside of the biological shielding, as modeled by UCN transport codes produced to model UCN transport for the Los Alamos SD\(_2\) source. Furthermore, this fraction of surviving UCN was predicted for standard \(^{58}\text{Ni}\)-coated guides; some improvement is expected if we utilize our diamond-like carbon coated guides. We note that our source is still reasonably thick (4 cm) whereas the scattering length in solid deuterium due to incoherent elastic scattering is 8 cm. Thus, modest gains may also be had by increasing the volume of SD\(_2\) used in our source.

The limiting density can only be predicted by specifying the lifetime of UCN in the solid deuterium. Here the longest lifetimes which have been measured are about 30 ms. The UCN lifetime is actually determined by at least four different sources:

\[
1/\tau_{SD} = 1/\tau_{\text{photon}} + 1/\tau_{\text{para}} + 1/\tau_{\text{H abs}} + 1/\tau_{\text{D abs}},
\]

with \(1/\tau_{\text{photon}}\) the loss rate due to upscattering UCN from phonons which exist in the solid, \(1/\tau_{\text{para}}\) the loss rate due to molecular upscattering from para-deuterium molecules in the solid deuterium, \(1/\tau_{\text{H abs}}\) is absorption on hydrogen and \(1/\tau_{\text{D abs}}\) is the absorption rate for neutron on
Figure 4: The UCN upscattering cross section vs. temperature of the solid D$_2$. The one phonon annihilation cross section in an ortho-D$_2$ solid (solid curve) and in a para-D$_2$ solid (dashed curve) are plotted. The dashed-dagger line is the temperature independent UCN upscattering cross section involving the J=1→0 relaxation not coupled to phonons in a para-D$_2$ solid.

deuterium. Ultimately, the lifetime is limited by the last of these, the absorption rate (through the (n,γ) process) on deuterium. This limiting lifetime is about 150 ms. Between 4 and 5 K, the loss rate due to upscattering of UCN off of phonons present in the solid deuterium falls to a level which is about the same as the loss rate due to absorption, reducing the lifetime to about 75 ms (at 2K the lifetime should be above 100 ms), see Fig. 4. It is possible to almost eliminate the absorption losses on hydrogen using pre-purified deuterium, and the para-fraction can be controlled in at least two different ways. Note that we ignore the contribution to the lifetime coming from guide wall losses here. Our experience with $^{58}$Ni coated guides indicates that this should be reasonable for system lifetimes up to roughly 10 seconds (for guides in contact with SD$_2$). However this still leaves the experimenter with the challenge of controlling the upscatter of UCN of para-deuterium molecules.

Molecular deuterium is found in two separate sets of rotational states, corresponding to “ortho-deuterium” and “para-deuterium,” determined by the exchange-symmetry of the total, molecular nuclear spin. Because both nuclei have integral spin (I = 1), the overall exchange symmetry should be consistent with Bose statistics. For total molecular spin I = 0 or I = 2, corresponding to ortho-deuterium[40] this implies the rotational spin states must be even (J = 0, 2, 4,...). For odd molecular spin, I = 1, this implies odd rotational spin states (J = 1, 3, 5,...). The significance
Figure 6: A sample Raman spectrum, clearly showing sensitivity of these measurements to para-contaminants. The peak at 132 Angstroms is due to para-deuterium, and is shown to be greatly reduced in the blue and green curves, where the D₂ gas is first passed through a paramagnetic converter cell held near 18 K.

of this is that the molecules freely rotate in cryogenic solid deuterium, and the conversion rate between para- and ortho- states is extremely slow, implying that, even at temperatures of 4 to 5 K, one expects to have both J = 0 and J = 1 molecular rotational states in solid deuterium. If one takes no steps to prevent it, one can freeze solid deuterium with the room temperature concentration of para-deuterium (33%), resulting in 33% of the solid being in the J = 1 molecular rotational state.

The J = 1 state has an excitation energy of 7 meV, or about 84 K. If a UCN collides with a para molecule, it can remove all of this excitation energy, resulting in a much larger upscattering cross section than for the normal J = 0 ortho-deuterium at 5 K. The increase in the upscatter (loss) cross-section is about a factor of 50 for the excited para-molecules. To control this loss mechanism, one must facilitate para- to ortho- conversion, which can be done with a para-magnetic material held at temperatures near the triple point[5, 6, 37]. Absolute measurements of the para- to ortho-ratio can be performed using rotational Raman spectroscopy using a low power laser[37, 41] (see Figs. 5 and 6) Controlling this loss mechanism was first quantitatively explored at LANSCE, in a collaboration coordinated by C. Morris and also containing investigators on the proposal. The para-fraction will also spontaneously convert to the ortho- phase, at a rate of about 0.06% per hour when D₂ is cryogenically stored in the solid state. If the effects of radiation can be neglected, this may result in the elimination of para- contaminants in our source on a timescale of days if the D₂ gas is first passed through a para-magnetic catalyst.

The small heating rate and relatively weak radiation field in which we place our solid deuterium has a significant positive impact on the performance of our source. Not only does the weak radiation field ensure that there should be very little ortho- to para- regeneration through ionizing radiation (compared to more intense sources), but it also makes possible running our source at comparatively lower temperatures, down to near 2 K. The He expenditure rate at these temperatures is only slightly higher than at 4 K, and can result in significant increases in our system lifetime (as much as a factor of two). We note that, if it should become necessary, slightly more complex designs with ridged bottom surfaces to ensure greater SD₂ surface area in contact with the LHe cooling, forced LHe or supercritical He cryostat designs can be implemented.

A solid deuterium source requires a fairly elaborate gas handling system for the D₂ gas. The LANSCE system contained palladium membrane to clean the D₂, flow meters to monitor the
gaseous D₂ introduced to the vacuum, a cryogenic, para-magnetic catalyst, and a dry scroll pump as parts of the system. It is depicted in Fig. 7. Using this system, we were able to produce SD₂ with para/ortho ratios of 1.5%, which results in 43 ms lifetimes at 5K when all absorption due to H₂ is removed. We feel that significantly better lifetimes (and therefore higher densities) will be achievable in our source, however, because we should be able to cool our SD₂ well below 5 K and at these low radiation fluxes our para-populations may well relax to their thermal equilibrium values.

7 The Polarizer/Spin-Flipper

As mentioned in previously, we plan to polarize the UCN by passing them through a superconducting magnet with a strong magnetic field region. The \( \mu \cdot B \) interaction provides a potential barrier (60.3 neV/T) to one of the neutron spin states. To produce these fields and to permit high efficiency spin-flipping, we developed such a magnet in cooperation with an industrial partner (American Magnetics, Inc.). The field profile is depicted in Fig. 8, where the polarizing magnetic field will have a maximum value of 7T. This ensures a nominal 100% polarization of UCN with 60 neV greater than the maximum energy UCN we plan to bottle in our experimental geometries.

The AFP procedure we wish to follow is a variant of a well-known and often-used technique for flipping nuclear spins. The basic idea is for the UCN to pass through a magnetic field region where the longitudinal field, \( \mathbf{H}_0 \), is very gradually decreasing, and passes through a field of 1 T at the center of the AFP volume. An r.f. field, \( \mathbf{H}_1 \), is generated within this volume which rotates
in the plane orthogonal to \( \mathbf{H}_0 \) at the spin precession frequency of the neutron (\( \omega \approx 1.9 \times 10^8 \) rad/sec) in a 1 T field. In a frame rotating in synchronism with the r.f. fields ("the rotating frame"), the neutron experiences an effective magnetic field given by \( \mathbf{H}_e = (H_0(z) - H_T)\hat{z} + H_T\hat{x} \), where here we assume \( H_0(z) \) lies along the z axis, and the \( H_T \) term arises from the transformation to the rotating frame (see Abragam[42] for a detailed discussion of AFP), and corresponds to the resonance field strength of 1 T. As the neutron spin moves along the z axis, \( H_0(z) \) passes from values above 1 T to below 1 T, and the direction of the \( \mathbf{H}_e \) changes from parallel to the z axis to antiparallel to the z axis. If the rate of change of \( \mathbf{H}_e \) is slow enough, the neutron spin will "follow" \( \mathbf{H}_e \) in the rotating frame, adiabatically maintaining the same projection along the effective magnetic field axis. Because the projection of the neutron spin along the effective field axis is conserved, almost no depolarization occurs during the spin flip.

Our magnet's field is tailored in the center of the magnet to produce a 1 T field with a gradient smaller than .006T/m, which should ensure adiabatic fast-passage spin-flipping efficiencies greater than 99.97% (Monte Carlo calculation). We have tested our planned rf resonators at ILL[37] and recent tests of the rf spin-flipper technique have demonstrated, for CN beams, efficiencies greater than 99.9%. [43]

8 Other Possible Configurations for the NCState Source

As mentioned previously, we have also identified a core configuration already implemented in the Buffalo reactor facility which should permit us to double the thermal power and the available neutron fluxes from our reactor. Because of our low heating rates, this should result in a straight gain of a factor of two in our UCN production rates. Through our optimization of this source design, we also evaluated a number of other geometries for our source. From these investigations we concluded that we can place two sources side-by-side within our D\(_2\)O moderator tank and only lose, within each UCN converter volume, between 20% and 30% of the cold neutron flux we predicted for a single source. Because such a modification does not impact the reactor at all, expanding to more than one source would be quite straightforward.

We also evaluated inserting a source in a large guide tube and placing it very close to the face of the reactor. In this geometry, we were able to achieve 50% greater production rates, but at a cost of more than double the heating rates. Higher heating rates, more restricted access to the source, and licensing considerations all suggested that our flux channel approach was the more optimal path.

9 Comparison with Other Sources

Constructing our source at the PULSTAR facility provides us with unprecedented access to our source and measurement apparatus, in sharp contrast to the somewhat inflexible and heavily constrained environments at the large laboratory facilities in the US (LANSE) and abroad (PSI, KEK), and large reactor facilities such as the FRM II reactor in Munich. Students and researchers can exercise direct control over the reactor and the source, and will have the flexibility to develop and adapt the source to applications of interest.

Although our planned source will provide somewhat lower densities than some of the planned facilities, there are a number of caveats which work to the advantage of the PULSTAR facility. Perhaps most important is the very weak radiation fields and heating we anticipate in our cryogenic materials. This is in sharp contrast to the proposed source at the FRM II reactor, with at least 20 times the heating rate per gram of SD\(_2\) in their source. Thus, although they predict very high UCN
densities (greater than 10⁴ UCN/cm³), this relies on very small para-deuterium contaminations, smaller than 1% which may be impossible to achieve. Our projected densities of 1,300 UCN/cm³ rely on a more relaxed requirement of 2% para-contamination, and we have much smaller radiation fields to contend with. Because the FRM II source requires a supercritical, flowing He cooling system inserted near the core of this much higher power reactor, it is an expensive and elaborate project, also in sharp contrast to our small, liquid He bath-cooled source placed outside of the PULSTAR reactor vessel.[9]

The proposed PSI source should produce densities comparable to the PULSTAR source (2,400 UCN/cm³) and requires coupling a 590 MeV proton beam to a spallation target. The massive size of this facility and large volume of SD₂ (30 liters) require a significant investment in cryogenics, shielding and remote handling equipment. Access to the cryostat will be limited and significant changes to the guides and environment closely coupled to the source will also be somewhat challenging.[11, 44]

The LANSCE UCN source, already under construction, should provide up to about 1000 UCN/cm³ and is a complementary source to the one we plan to construct at the PULSTAR facility. Although these sources have comparable performance, the PULSTAR source will provide support for activities at LANSCE and should also provide an excellent tool to investigate aspects of neutron beta-decay and UCN interactions with materials not planned for the LANSCE source.[45]

Finally, there is a source planned for operation at a university-based 50kW TRIGA reactor near Mainz. This program will operate in pulsed mode (as opposed to our CW mode of our reactor) and appears to have significantly smaller time-averaged production rates, but comparable peak densities. This source will also be used as a test facility to develop an optimized approach to the FRMII reactor mentioned above.[10]

There are also several superfluid ⁴He UCN sources being planned (at the SNS and KEK). These sources can potentially provide UCN densities in excess of 10⁵ UCN/cm³, but rely on very long UCN lifetimes in their measurement apparatus to achieve these densities. Thus we see solid deuterium sources as being useful for the very short holding time experiments (neutron beta-decay angular correlations studies and solid state studies) that we plan to perform at the PULSTAR facility. In fact, we may well be able to implement a superfluid He source at the PULSTAR facility. Our initial estimates, recently published in Physics Letters[36], indicate we should produce densities which are competitive (and may be higher) than the sources at SNS and KEK.

10 Previously Supported Research

We cite heavily from the research performed during our last support period (in which we developed a superthermal SD₂ source) in Sec. 6 of this proposal. This work has resulted in the establishment of a new world record UCN density (145 ± 7 UCN/cm³) and several publications [4, 7, 38], conference proceedings[5, 6] and numerous talks. We have also evaluated the impact of multphonon production on superthermal He source[36] and performed three separate studies of UCN depolarization[46, 47], the last of these depolarization studies established the our diamond-like carbon coatings are at least factor of three better than any previous guide material for depolarization. In the last support period we also completed studies of anomalous positron production in heavy-ion collisions[48], Rb polarization in He vapor-filled cells below 2K[49], the atomic physics of spin-exchange polarization in high pressure cells[50, 51, 52, 53] and P non-invariance in neutron capture and epithermal neutron scattering,[54, 55, 56, 57, 58, 59]