TRIUMF Ultracold Neutron Source

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1 Executive Summary

We propose the construction of the world's highest density source of ultracold neutrons (UCN) at TRIUMF. The truly high density that could be obtained at TRIUMF would allow a class of precision measurements to be conducted with significantly improved statistical and systematic uncertainties, and thus more significant results. This source would therefore make a major impact on studies of fundamental physics with UCN that would complement and enhance the ISAC program. A window of opportunity exists to capitalize on the successes of Y. Masuda's group at KEK and at RCNP, thereby allowing the TRIUMF project to surpass other proposed sources elsewhere. The technical requirements of a UCN source can be worked out so that the program would run concurrently with ISAC and μSR. Significant support for the UCN source would be requested from the Canada Foundation for Innovation (CFI) and from Japanese sources. Funding for physics experiments would be requested from a combination of NSERC, Japanese, and other international sources. Timeliness would be achieved by testing the UCN source components in Japan, and then installing at TRIUMF in 2012.

2 Introduction and Physics with Ultracold Neutrons

Ultracold neutrons (UCN) are neutrons of such remarkably low energies that they are totally reflected from the surfaces of a variety of materials. Hence, they can be confined in material bottles for long periods of time. Typically, UCN have kinetic energies less than 300 neV. Correspondingly, UCN are strongly affected by various fields, such as the Earth's gravitational field, and by strong magnetic fields (7 T).

UCN sources are often characterized and compared by the limiting UCN density achieved ($\rho_{\rm UCN}$). The UCN source proposed for TRIUMF would have $\rho_{\rm UCN} = 5 \times 10^4$ UCN/cm^3, which is at least a factor of 100 greater than any UCN source ever operated. Currently there is one UCN source in the world, at Institut Laue-Langevin (ILL) Grenoble, that is operating in production mode. The source at ILL typically achieves 40 UCN/cm^3 at the exit of the source. Typically 1-2 UCN/cm^3 is achieved in experiments, such as in the completed ILL n-EDM experiment (discussed in Section 2.1).

With the advent of superthermal sources of UCN, a new generation of UCN sources are under development at various laboratories (see Table 1). TRIUMF would surpass the projected highest

Location	Technology	critical energy E_c (neV)	storage time τ_s (s)	density in experiment $\rho_{\rm UCN}$ (UCN/cm^3)
TRIUMF	spallation He-II	210	150	5×10^4
ILL Grenoble	CN beam He-II	250	150	1000
SNS ORNL	CN beam He-II	134	500	150
Munich	reactor SD_2	250		10^4
NCSU	reactor SD_2	335		1000
PSI	spallation SD_2	250	6	1000
LANL	spallation SD_2	250	1.6	145

Table 1: Future UCN sources worldwide. The Los Alamos National Lab (LANL) source is currently in operation on a testing basis. All other sources are proposed (future) sources, including a future He-II source at the ILL reactor for the CryoEDM project. These are the Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL) for the n-EDM project there, the Munich FRM-II reactor (Forschungsneutronenquelle Heinz Maier-Leibnitz), the North Carolina State University nuclear reactor (NCSU), and the Paul-Scherrer Institut source (PSI). The TRIUMF source figures are quoted for 20 kW peak power delivered to the spallation source.

density source, which is under development at the Munich FRM-II reactor, by a factor of five. In addition, the pulsed nature of the proposed TRIUMF source would offer considerable advantages for reduction of background compared to a reactor source.

Given this breakthrough in UCN production, a variety of new UCN experiments can be envisioned that are now only possible with the new generation of sources. We have considered a variety of physics experiments that could be done with such a source. Emerging from these discussions, we have decided to focus in on the following possible physics experiments:

- a search for a non-zero neutron electric dipole moment,
- a precise measurement of the neutron lifetime,
- characterization of the recently discovered UCN quantum states in the Earth's gravitational field,
- measurements of radioactive isotope scattering from a free neutron target.
- development of new technology to study surface physics in nanofilms using ultracold neutrons.

Each project has its own physics interest and timeline, so that, in time, one could envision performing a series of UCN experiments at TRIUMF.

We now briefly describe the physics motivation and timeline for each experiment.

2.1 Neutron Electric Dipole Moment (n-EDM)

Electric dipole moments for fundamental particles are forbidden by time-reversal symmetry. The small amount of CP violation in the standard model leads to very tiny EDM's (for the neutron EDM, 10^{-31} e-cm). However, new sources of CP violation beyond the standard model are required to account for the observed baryon asymmetry of the universe (BAU). In many models of physics beyond the standard model, extra sources of CP violation are often present. Such models often naturally generate neutron EDM's at the 10^{-27} e-cm level [1]. The current experimental limit on the n-EDM is $d_n < 3 \times 10^{-26}$ e-cm [2]. The next generation of experiments at ILL, PSI, and SNS aim to constrain the n-EDM to the $10^{-27} - 10^{-28}$ e-cm level. The aim of an experiment at TRIUMF would be at the 10^{-28} e-cm level.

2.1.1 Experimental Principle

Neutron EDM measurements use Larmor precession under a static magnetic field ($\mathbf{H}_0$) and a static electric field ($\mathbf{E}$). The effect of an EDM is extracted upon electric field reversal. Here, the Hamiltonian is:

$$H = -(\mu \cdot \mathbf{H}_0 + \mathbf{d} \cdot \mathbf{E}),$$

where the magnetic dipole moment μ and the electric dipole moment $\mathbf{d}$ are aligned with the neutron spin $\mathbf{s}$. The effect of the Hamiltonian on the neutron spin is represented in terms of an S matrix as $S = \exp(-iHt/\hbar) = \exp(i(\mu \cdot \mathbf{H}_0 + \mathbf{d} \cdot \mathbf{E})t/\hbar)$. The phase shift $\mathbf{d} \cdot \mathbf{E} = \pm d_n E$ is measured by means of neutron polarimetry and hence the neutron electric dipole moment d_n is extracted.

2.1.2 Statistical and Systematic Uncertainties in EDM experiments

The statistical uncertainty on the EDM is given by $\delta d_n^{\rm stat} = \hbar/(2\alpha E t_c \sqrt{N})$. Here, α is the neutron polarization, t_c is the neutron precession time and N the total number of neutrons within the storage volume.

However, systematic errors that reverse sign with $\mathbf{E}$ reversal must also be carefully controlled. Systematic effects arise due to magnetic field instability $\delta d_n^{\rm syst} = \gamma \delta H_0 t_c$, due to changes in magnetic field induced by leakage currents $\gamma\delta H_{\text{leak}}t_c$, and due to motional magnetic fields in the rest frame of the neutron $\gamma(\mathbf{E}\times\mathbf{v}/c)t_c$. To correct for magnetic field instabilities, a "comagnetometer", a different nuclear species which samples the same fields as the neutrons experience, is often used.

In the highest precision experiments, an additional systematic effect must be considered which arises from magnetic inhomogeneity and relativity: the recently discovered geometric phase effect [3, 4, 5]. This effect arises due to a combination of magnetic field inhomogeneity and $\mathbf{E}\times\mathbf{v}/c$ effects for neutrons confined to a trap.

A transverse field $\mathbf{H}_{0xy}$ arises in the trap from magnetic field inhomogeneity. Neutrons see also the motional field, $\mathbf{H}_{\mathbf{v}} = \mathbf{E}\times\mathbf{v}/c$. In the rest frame of neutrons circulating in the trap, the overall field $(\mathbf{H}_{0xy}+\mathbf{H}_v)$ is seen as a rotating field, and the precession frequency is shifted by $(\gamma(H_{0xy}+H_v))^2/2(\gamma H_0 - v_{xy}/R)$ [6]. Here γ is the gyro-magnetic ratio of the neutron and R is the diameter of the bottle. This shift in frequency is called the Bloch-Siegert shift. The effect of the Bloch-Siegert shift depends on the rotation frequency of the neutron motion, $\omega_r = v_{xy}/R$ and the Larmor frequency $\omega_0 = \gamma H_0$.

However, neutrons propagating in one direction around the EDM cell will not experience the same Bloch-Siegert shift as neutrons propagating in the opposite direction. Additionally, the cross term between H_{0xy} and H_v changes sign upon $\mathbf{E}$ reversal. This results in a false EDM d_{afn}. The false EDM may be characterized as a function of the ratio ω_0/ω_r [3]. The false EDM for UCN, where the ratio ω_0/ω_r is very small, may be expressed as $d_{\text{afn}} = -\hbar/4\cdot(\partial H_{0z}/\partial z)/H_{0z}^2\cdot v_{xy}^2/c^2$. Nuclei N for the comagnetometer are also affected by the geometric phase effect. For the comagnetometer, the ratio ω_0/ω_r is large and $d_{afN} = -J_N\hbar/2\cdot(\partial H_{0z}/\partial z)\gamma^2R^2/c^2$, where J_N is the nuclear spin. When the magnetic field is corrected by means of the comagnetometer, the residual false EDM becomes $d_{afNn} = -J_N\hbar/4(\partial H_{0z}/\partial z)\cdot\gamma_n\gamma_N R^2/c^2$.

2.1.3 Previous experiments

In the previous ILL experiment, UCN were confined in a 50 cm diameter, 12 cm tall cell, in a 1 μT magnetic field and a 12 kV/cm electric field. The reported result for the neutron EDM was $d_n < 3\times10^{-26}$ e-cm, with the precision limited by statistics. The UCN density in the EDM cell was 0.7 UCN/cm^3.

A co-magnetometer of ^{199}Hg was used to sense the same field which the neutron spin experienced. Hence the magnetic field fluctuations were well normalized. Systematic errors associated with $\mathbf{E}$ reversal, were controlled to better than 10^{-27} e-cm.

However, for measurements at the 10^{-28} e-cm, the effect of the Bloch-Siegert shift becomes important. In the ILL experiment, the magnetic field gradient was controlled so that $\partial H_{0z}/\partial z <$ 3 nT/m and $d_{af\text{Hg}n} = 3.9\times10^{-26}$ e-cm. The false EDM was characterized as a function of the field gradient so that the systematic error could be reduced.

2.1.4 Future nEDM Experiments

The same group is preparing a new EDM measurement at ILL ("CryoEDM"). They will fill a double cell (24 cm diameter and 4 cm height for each cell) with UCN of density $\rho_{\text{UCN}} = 1000$ UCN/cm^3. The cell will reside in a superfluid helium (He-II) bottle. In this way, an electric field can be applied with lower leakage current. A superconducting magnetic shield will minimize systematic errors associated with field instability. For one cell, an electric field of 40 kV/cm will be applied while, for the other cell, no electric field will be applied. Neutrons in the second cell will hence be used as a magnetometer, but no co-magnetometer will be present in the measurement cell. Therefore the false effect of the Bloch-Siegert shift will be d_{afn} as described above. For the parameters of this experiment ($H_0 = 1\ \mu$T, and $\partial H_0/\partial z = 1$ nT/m), $d_{afn} = -1.1 \times 10^{-27}$ e-cm [3]. For measurements at the 10^{-28} e-cm, the field gradient will be reduced.

A group using the future UCN source at PSI is also preparing an n-EDM experiment. They will carry out a preliminary measurement at ILL with the previous EDM cell of ILL, and then a measurement of 5×10^{-27} e-cm at PSI from 2009 to 2010. The UCN density in the EDM cell will be 1000 UCN/cm^3. The experiment will employ several magnetometers outside the EDM cell to determine the magnetic field inhomogeneity. They will aim for a precision of 5×10^{-28} e-cm in measurements from 2011 to 2015 [7].

A new n-EDM measurement employing a unique experimental technique is also in preparation for the SNS. The apparatus is based on the ideas of R. Golub and S. Lamoreaux. A schematic diagram of the proposed apparatus is shown in Fig. 1. A cold neutron beam from the SNS will

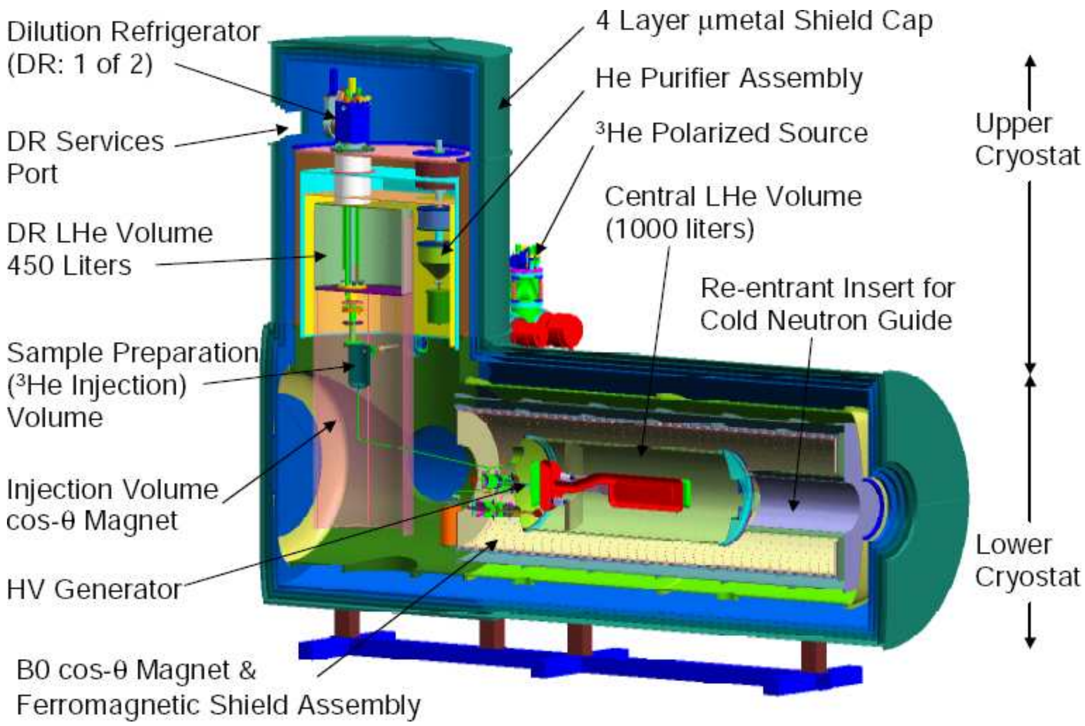

Figure 1: Schematic diagram of the proposed SNS EDM apparatus from Ref. [8]. The measurement volume consists of two cells of volume 4 L each.

impinge upon a volume of He-II (superfluid ^{4}He) creating 150 UCN/cm^3. The EDM measurement will be conducted in the same He-II volume. A small amount of polarized ^{3}He introduced into the superfluid ^{4}He will act as a co-magnetometer. A "dressed spin" technique will be used, where the neutron spin precesses with the same frequency as the ^{3}He spin. The neutron spin will be aligned with the ^{3}He spin, so that essentially no neutron captures will occur. Any small effect caused by a non-zero EDM will modulate the capture rate on **E**-reversal. The capture rate will be sensed by sensing the scintillation light produced by the capture products. The goal precision is 10^{-28} e-cm. Many technical challenges must be overcome for the experiment to be successful. The geometric phase effect for the ^{3}He magnetometer can be large compared with ^{199}Hg, but is mitigated because of collisions with the surrounding ^{4}He [4, 5]. Measurements at the SNS will begin in 2013 [9].

2.1.5 Plans for TRIUMF

We envision that any n-EDM effort at TRIUMF would occur after the completion of this new round of n-EDM measurements at ILL, PSI, and SNS, in the time frame of 2015 and beyond. It is difficult to say at this time which of these differing techniques would be shown to be the most successful by that time, and which would be best able to use the increased statistical precision which would be possible at TRIUMF. One possible scenario for the initial and fast completion of an EDM project at TRIUMF would be to simply move one of the devices from e.g. ILL or SNS, similar to the initial PSI strategy. To take advantage of the higher density at TRIUMF for systematic error reduction, a new and significantly smaller measurement cell would need to be designed.

The TRIUMF UCN source project has already attracted a number of collaborators who are experts in the n-EDM experiment at SNS: B. Filippone, R. Golub, T. Ito, E. Korobkina, M. Hayden, and B. Plaster. R. Golub in particular was instrumental in the successful completion of the previous generation of n-EDM searches, and has been a leader in the design of the SNS EDM project. It is envisioned that this nucleus of individuals, supplemented by very interested parties from Japan and Canada would grow into the eventual EDM collaboration for TRIUMF. We anticipate that a proposal for an EDM experiment at TRIUMF would be generated in the 2010 time frame.

2.2 Neutron Lifetime

Precise measurements of the neutron lifetime are of physics interest for two reasons:

1. The neutron lifetime is an essential parameter for Big-Bang Nucleosynthesis (BBN) calculations, and is currently the dominant uncertainty for accurate BBN predictions [10].

2. The neutron lifetime can be used, in combination with measurements of angular correlations in neutron decay, to extract the CKM matrix parameter V_{ud}. V_{ud} is the most precisely measured, large parameter in the CKM matrix and is useful for a variety of tests of the unitarity of the CKM matrix. Lack of unitarity would signify new physics beyond the standard model. Currently, V_{ud} is most precisely determined from $0^+ \rightarrow 0^+$ nuclear decays. UCN lifetime experiments offer an independent check of the nuclear extraction, free of nuclear corrections. The current status of V_{ud}, focusing on neutron experiments, is shown in Fig. 2.

Measurements of the neutron lifetime therefore have similar physics goals as many of the fundamental symmetries and nuclear astrophysics experiments conducted at ISAC.

Currently there is a seven sigma discrepancy between the most recent precise measurement of the neutron lifetime (878.5 ± 0.8 s, [11]), and the average of all previous measurements (885.7 ± 0.8 s, [12]). The most recent precise measurements have been performed in traps formed by the mean Fermi potential of material walls [13, 14] or material walls in combination with gravity [11]. The largest systematic uncertainties in these experiments arise due to effects of the interactions of the UCN with the material walls of the trap. At TRIUMF, a magneto-gravitational trap would be used to confine the neutrons, thus removing such effects. While similar projects with magnetic trapping of UCN have been discussed in the context of experiments at LANL [15], and elsewhere [16, 17, 18], they are as yet at a very premature stage relative to material traps.

The new magnetic trap experiments have identified an important new systematic effect specific to magnetic traps: marginal trapping of UCN energies larger than the trap depth. The marginally

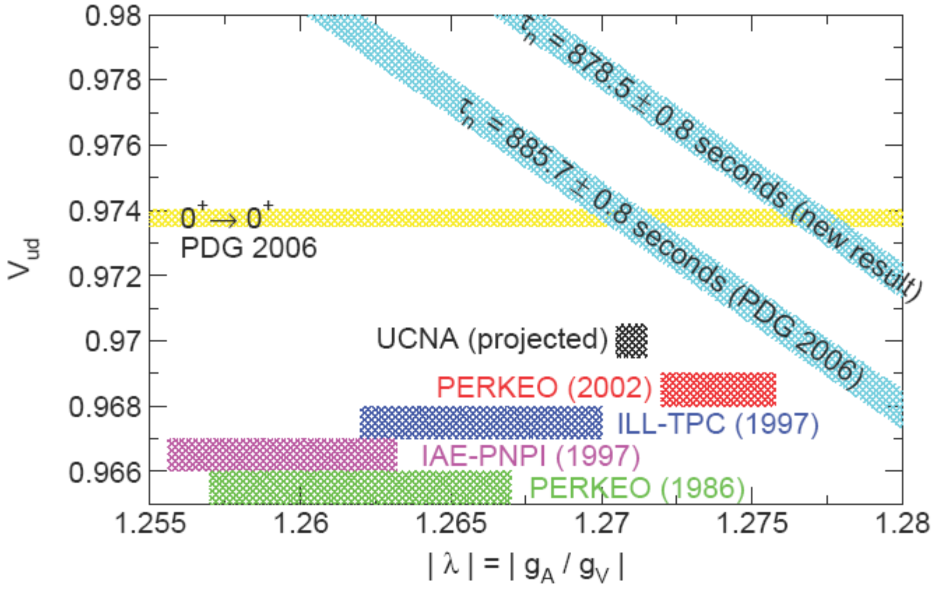

Figure 2: Current status of V_{ud}. Yellow horizontal band indicates current best determination by $0^+ \to 0^+$ nuclear beta-decay. Diagonal bands indicate current discrepancy in τ_n. Coloured bands at the bottom of the figure are to be interpreted as vertical bands indicating recent measurements of the beta-asymmetry in neutron decay.

trapped UCN can escape from the trap with timescales similar to the neutron lifetime, potentially giving a large systematic effect. These UCN must therefore be removed from the trap rapidly so that measurements of the UCN lifetime can be performed. The LANL trap design deals with this problem by introducing chaotic neutron orbits within the trap so that the marginally trapped UCN rapidly sample their allowed phase space and escape. An experiment performed at TRIUMF could build on the preliminary work done at LANL.

2.2.1 Experiment Design

The magneto-gravitational trap from LANL [15] is designed to contain so-called field-repelled neutrons, i.e., neutrons in a positive-energy eigenstate of the spin-field interaction. Fig. 3 shows the proposed open-top magneto-gravitational bowl trap with two independent magnetic-field-generating components: high-strength neodymium-iron-boron (NdFeB) permanent-magnet (PM) Halbach arrays [19, 20] that form the open-top bowl-shaped trap surface, and a enveloping set of current-carrying window-frame coils outside of the bowl. The PM arrays produce a field in the trap volume that is approximately 1 T at the surface and falls off exponentially in normal distance from the PM array surface with a characteristic length of about 1 cm; the PM field is the main confining field of the neutrons. The effective trap volume is 0.6 m^2. The window-frame coils produce a field of approximately 0.05-0.1 T that is everywhere perpendicular to the dominant component of the PM-array field and performs two essential functions: first, to guarantee that the trapped neutrons never encounter a zero field magnitude, and second, to guide the decay electrons to the detectors at the two ends of the trap. Under these conditions, neutrons with kinetic energy less than $|\mu_n B|_{\max}$, where μ_n is the neutron magnetic moment and $|B|_{\max}$ is the maximum trap-surface field, are per-

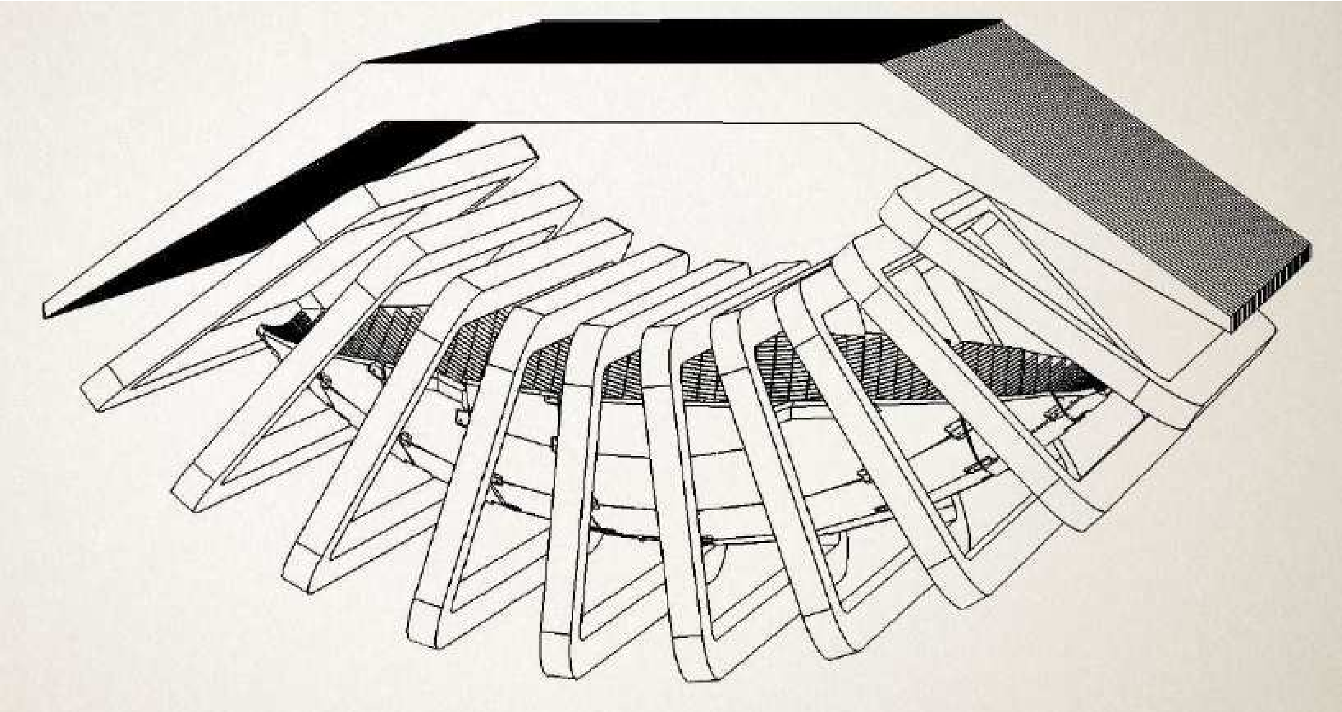

Figure 3: LANL-designed UCN trap, showing iron yoke, guide-field coils, and permanent-magnet bowl [15]. The vacuum chamber, which contains the bowl, but is inside the guide-field coils, and the detectors that are placed in the space between the end guide-field coils and the yoke, are not shown. The bowl depth is 0.5 m.

fectly reflected from the field near the trap surface, and if their kinetic energy at the bottom of the trap is also less than mgh, where h is the trap height, they would stay in the trap for an effectively infinite time, except for their natural decay.

Neutrons are fed into the trap with a mechanically operated trap door at the bottom of the trap. The upper surface of the trap door is covered with a Halbach linear PM array in such a way that when the door is closed, the combination of the trap-door PM array and the PM arrays on trap surface around the door opening forms a continuous Halbach array without gaps. The trap door will be opened and closed by an actuator below the bottom of the trap. Calculations have shown that forces on the trap door are manageable from the point of view of the mechanical actuator (on the order of about 800 Newtons in the worst-case position). Quasi-trapped neutrons are removed during the filling/cleaning phase of operation by a neutron-absorbing cleanout surface that is lowered to a height that is approximately 5-10 cm below the top of the bowl. The cleanout surface is then withdrawn to a level above the top of the trap after the trap door is closed and before counting of neutron decays for the lifetime measurement is started. In order to facilitate removal of quasi-trapped neutrons, the bowl has shallow inclination angles on one side and at both ends that force neutrons to acquire a large vertical velocity component at some point along their trajectories and then reach a sufficient height to strike a cleanout absorber. Moreover, chaotic orbit behavior is induced by ripple in the permanent-magnet field.

2.2.2 Plans for TRIUMF

Individuals who have participated in the design of this experiment and in the initial phase of construction of the experiment at LANL have joined the TRIUMF UCN effort: J.D. Bowman, B. Filippone, T. Ito, and B. Plaster. It is anticipated that other interested parties would join the effort upon approval of a UCN source for TRIUMF. The neutron lifetime experiment would have a shorter timescale than the EDM measurement, and is therefore a candidate for the first fundamental physics experiment to use the UCN source at TRIUMF.

A measurement of the neutron lifetime with precision < 1 s, but performed in a magnetic trap free of the systematic uncertainties which hinder material traps, would be a very exciting achievement for this field. Such an experiment could be completed at TRIUMF in the 2013 timeframe. TRIUMF's superior UCN density would be instrumental in achieving the < 1 s statistical error bar required.

2.3 Gravity Levels

Recently, a group at ILL has successfully observed the quantization of the energies of neutrons confined above a UCN mirror in the Earth's gravitational field [21]. The experiment is an interesting application of quantum mechanics to micron-sized quantum states. The experimental result has been used to place limits on modifications to the short-range (10 μm) behavior of gravity. The result therefore has impacted theories involving micron-scale extra dimensions. The result has also been used to constrain axion models [22].

The same group at ILL is mounting a more advanced setup (the GRANIT experiment) where they would attempt to excite resonant transitions between gravitational levels in a UCN bottle, achieving better resolution in the level spacing and hence placing tighter constraints on theories.

These experiments are limited in their scope by the UCN density available at ILL. TRIUMF therefore would have a distinct advantage for a new experimental effort. Additionally, this is a relatively new avenue of research in the UCN community, and much progress is being made rapidly. A timely experiment at TRIUMF would have a large impact on the field.

A large group of Japanese collaborators, led by S. Komamiya, has expressed interest in conducting a gravity levels experiment at TRIUMF. The group is currently developing neutron detectors with a spatial resolution of order microns to directly observe the height distribution of neutrons confined above the mirror in the experiment. This new technology, combined with the high fluxes of UCN available at TRIUMF, would enable a new precision test of gravity and a search for extra dimensions. The experiment would take one year to complete. Since the design of this experiment and the main detector are underway, and owing to the short run time for the experiment, this experiment is therefore also a candidate to be one of the first fundamental physics experiments to be conducted using the UCN source at TRIUMF.

2.4 Surface Nanoscience

The possible fields of UCN application to condensed matter studies are based on their unique properties of extremely low energies and long wavelength. This means high sensitivity to slow motions and low energy excitations. A number of attractive possible applications of UCN to condensed matter, including for instance, study of slow motion of large biological molecules were reviewed at ILL quite a long time ago [23, 24, 25] but the experimental development was hindered by the low density of UCN available at the UCN sources of that era. The advent of higher density UCN sources combined with new ideas for UCN instruments is therefore primed to revolutionize this field. For example, a new method, UCN inelastic scattering reflectometry, presented below, can extend UCN applications to one of the most exciting new scientific fields: surface nanoscience. The use of UCN to probe surfaces has some very promising applications: from smart materials to nanotechnology machines [26, 27]. Though the field is still in its infancy, there is a rapidly growing worldwide user community as technology improves.

2.4.1 UCN inelastic scattering reflectometry (UCN ISR)

The UCN inelastic cross section $\sigma_{ie}(T)$ is closely related to the excitation spectrum of molecules and is very sensitive to the hydrogenous component of the surface layer [28]. Briefly, $\sigma_{ie}(T)$ is an integral of the temperature independent excitation spectrum $g(\omega)$ with temperature dependent density of states and Debye-Waller factor. At low temperatures, corresponding to the lowest possible excitations, the temperature dependance of $\sigma_{ie}(T)$ is extremely sensitive to the molecular motions, such as vibrations and rotations or tunneling between rotational wells, where only one or a few states can be thermally excited. As an illustration, Fig. 4 shows the UCN upscattering cross section σ_{ie} as a function of temperature. At lower excitation frequencies ω_0 the cross section rises more steeply.

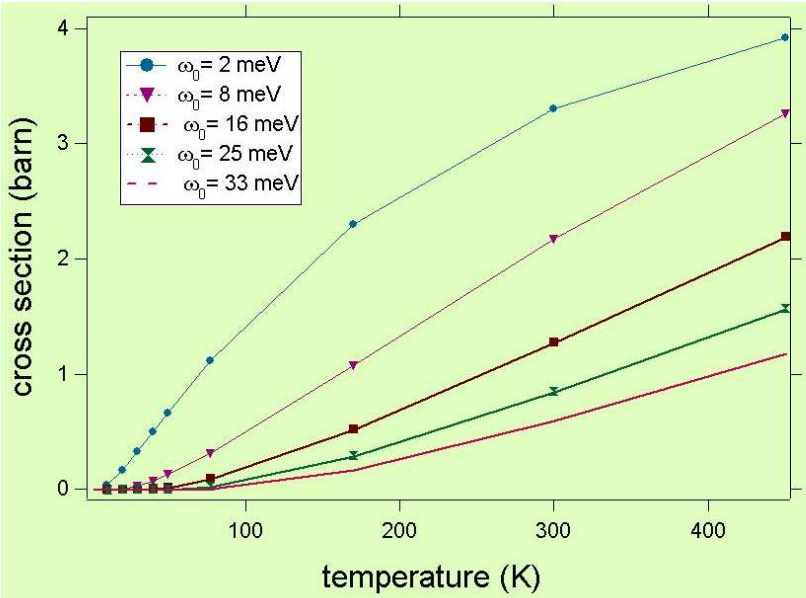

Figure 4: UCN upscattering cross section, $\sigma_{ie}(T)$, calculated for a harmonic oscillator with frequencies from 33 down to 2 meV.

The study of $\sigma_{ie}(T)$ has been compared to the measurement of the specific heat but with selective "contrast" given to hydrogen excitations.

The basic procedure in UCN ISR is to measure the temperature dependence of the UCN upscattering loss rate using two techniques simultaneously. The first technique is the storage time technique, where the number of neutrons surviving storage in a material bottle containing the sample is recorded for various trapping times. The second technique is the prompt (UCN,gamma) technique that provides an independent value for the UCN upscattering rate as well as data about the surface density of hydrogen in the film [29]. The combination of two techniques improved control on systematic uncertainties thereby significantly increasing the sensitivity to σ_{ie}. With the impressive UCN density of the proposed UCN source at TRIUMF even a single monolayer of hydrogen would be detectable, meaning hydrogen surface densities down to 10^{15} atom/cm^2 could be studied.

As described in Ref. [28], the sensitivity is not limited by the hydrogen bulk contamination of the substrates, because the excitation spectrum of such hydrogen is rather high and amplitude of scattering is suppressed by the mass of the substrate. The sensitivity may be limited only by a surface contamination of the substrate, which can be rendered negligible using a UV/ozone cleaning technique [30].

The design of a prototype cryostat was carried out at Hahn-Meitner Institute, Germany, in 2001-2004. In 2004 a prototype of the new cryogenic UCN bottle was successfully tested with UCN at ILL. The prompt (UCN,gamma) technique was developed in Kurchatov Institute, Moscow, and was used for several studies at ILL. At present the NCSU team (E. Korobkina, R. Golub, L. Clarke) is working on the design modifications required to study so-called "artificial molecular rotors", a field where L. Clarke is one of the leading specialists.

2.4.2 Artificial Molecular Rotors and UCN ISR

Moving and rotating molecules are everywhere around and inside us. Artificial molecular rotors are synthetic molecules designed specially towards desired rotational functionality, such as reducing friction on a surface, doing work (nanomachines), or storing information in particular rotational positions [31]. For instance, a team working at the University of Colorado recently developed the first computer-generated model of a tiny, waterwheel-like molecular rotor that can rotate only in one direction at different speeds in response to changes in the strength of an applied electrical field [32]. Since computational dynamics allow one to calculate excitation spectra and, thus, $\sigma_{ie}(T)$, such objects are very attractive to study with UCN ISR. The difference between theory and experiment is expected to come from properties of real substrate and intermolecular interaction.

A team at NCSU, led by L. Clarke, is working with self-assembled monolayers of surface-mounted artificial molecular rotors, in the two-dimensional random regime. They are studying the fundamental motions of these materials, including possible phase transitions, with hope to develop surface "smart" materials. Smart materials are a class of systems which respond autonomously and automatically to external stimuli. One technological challenge that smart surfaces may address is controlled permeability [33]. For instance, controlled drug delivery (from a vessel with different permeability in different pH, temperature, or chemical environments) would enable drug dosing customized to the particular biomedical conditions of each patient. Coating the surface of a drug delivery vessel with a temperature-responsive thin film might be one approach to realize this application. Permeability through a self-assembled monolayer-coated porous glass differed at temperatures above and below a monolayer phase transition (related to intramolecular rotational motion) [34].

At present, rotational motion in self-assembled monolayers is studied in the Clarke group using sensitive, surface-specific, dielectric spectroscopy (4 - 400 K), provided that the molecules have some dipolar nature and the substrate is dielectric [31]. UCN ISR would be a complementary technique where measurements could be applied to both polar and non-polar hydrogen-containing molecules, on semiconducting and conducting substrates. As a proof-of-concept, a short self-assembled monolayer of molecular rotor molecules, SiO_3CH_2Cl (where the CH_2Cl group is terminal), would enable comparison of information from the two methods. Dielectric spectroscopy measures molecular dynamics via changes in the dissipation factor versus temperature, where a peak in the dissipation factor is observed when the molecular reorientation rate is similar to that of the applied electric field. By altering the temperature and frequency of the measurement, the reorientation barrier can be determined. UCN can probe frequency of the torsional ground state splitting averaged over the sample surface, which is very sensitive to the strength of the well potential [35].

The geography of teams working in the field of artificial molecular rotors is spread all over the world, including the US, Japan, Germany, Netherlands, Czech Republic, and China. Hence, a potentially large international user base exists.

2.5 Rapid Neutron Capture process (r-process)

The dream of a free neutron target raises the possibility at TRIUMF of colliding radioactive beams with neutrons to study interactions that could never be accessed before. A possible experimental setup is shown schematically in Fig. 5. The experiment would take radioactive beams from ISAC,

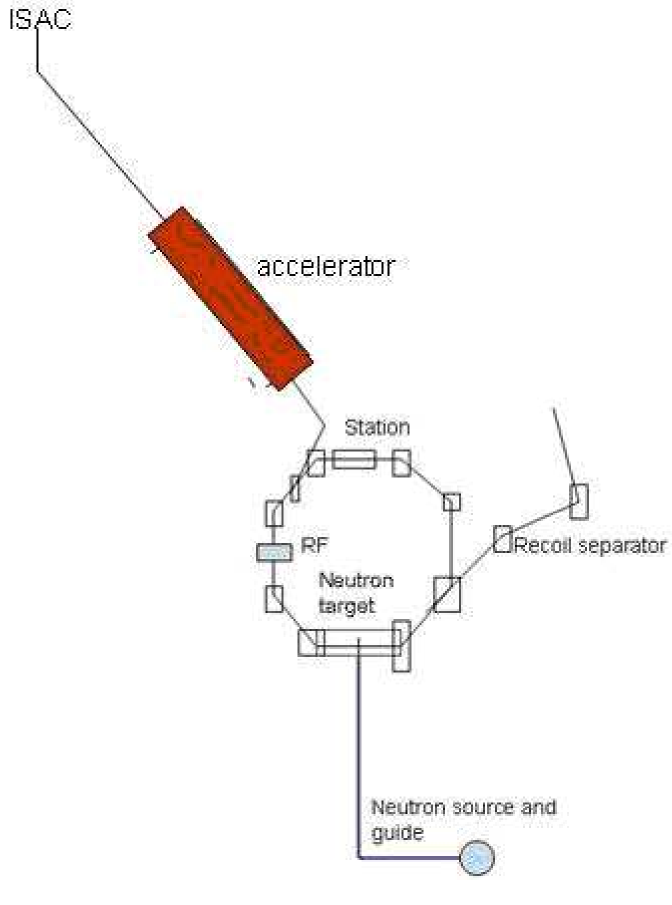

Figure 5: Schematic layout of a possible neutron target facility. The neutron target is made from UCN guided into a bottle for storage, intersected by the radioactive beam from ISAC. The radioactive beam has been accelerated to energies of 50-600 keV/u and injected into the storage ring. Reaction products of radiative neutron capture are detected in a recoil mass separator, An RF cavity allows for an energy sweep. “Station” labels a possible experimental station to do physics with radioactive stored ions independent of the UCN source.

post-accelerate them to energies of 50-600 keV/u (corresponding to r-process temperatures) and store them in a ring containing an internal UCN target. The UCN target would resemble an open-ended material trap, where the circulating ions would pass through the open ends, but may also include magnetic confinement. UCN would be leaked into the side of the target. The setup would therefore resemble internal gas jet targets used at storage rings elsewhere. However, no electronic effects are present and the beam does not get slowed down, nor are charge exchange effects present.

A recoil separator would be used to collect reaction products of neutron radiative capture. Other gamma and beta detectors around the UCN target could also be envisioned. Event rates on the order of tens per hour could be achieved, e.g. for the double magic nucleus ^{132}Sn - neutron capture reactions. It is envisaged that TRIUMF with the proposed electron linac and the additional proton beamline will provide copious quantities of fission produced radioactive ions close to the N=80 shell closure.

This challenging project would be an effort for the far future (beyond an n-EDM measurement, for the 2020 TRIUMF plan). However, it is important to note that, if constructed, it would truly be a one-of-a-kind facility in the world. Such a facility would open up a whole new field of nuclear physics research, previously inaccessible due to the lack of a free neutron target.

2.6 Experimental Schedule

Not all experiments listed above would occur on the same time scale. We envision an initial flagship experiment, which would be either the neutron lifetime, or the gravity experiment. In tandem we would use a second UCN beamline to conduct R&D related to the n-EDM experiment, and related to nanofilms research. In the far future, we could consider the experiments employing ions stored in a ring containing an internal UCN target.

3 Ultracold Neutron Source

The UCN source technology proposed is a superthermal source based on downscattering of cold neutrons (CN) in superfluid He-II [36]. Fig. 6 displays a schematic of the proposed UCN source. Neutrons would be liberated by proton-induced spallation from a tungsten target. The neutrons are moderated in room temperature heavy water and then 20 K liquid deuterium down to cold neutron energies. The moderator system is surrounded with a graphite reflector. The cold neutrons are down-scattered by phonons in superfluid ^{4}He (He-II) to ultracold neutron (UCN) energies. Heat is removed via heat conduction in the He-II to the ^{3}He cryostat and the ^{4}He-^{3}He heat exchanger. UCN are transmitted horizontally through a series of valves to experiments.

This source technology has been developed by Y. Masuda's group in Japan. At the Research Center for Nuclear Physics (RCNP) Osaka, a 1 μA, 390 MeV proton beam is used to drive the UCN spallation source. The source is operated at 1 μA for one minute, followed by three minutes with beam off (1/4 duty cycle). The beam off time has been found to be crucial in order to conduct sensitive UCN counting experiments in an environment free of backgrounds. The UCN density achieved at RCNP is 10 UCN/cm^3.

Incremental changes to the RCNP source would result in various factors of increase in UCN production for the UCN source at TRIUMF. However, it is primarily the increased beam power at TRIUMF that would lead to the creation of truly high densities of UCN. At TRIUMF, the UCN spallation target would be operated at 40 μA and at 500 MeV. Since UCN production scales by beam power, this results in a predicted increase in UCN density by a factor of 51.

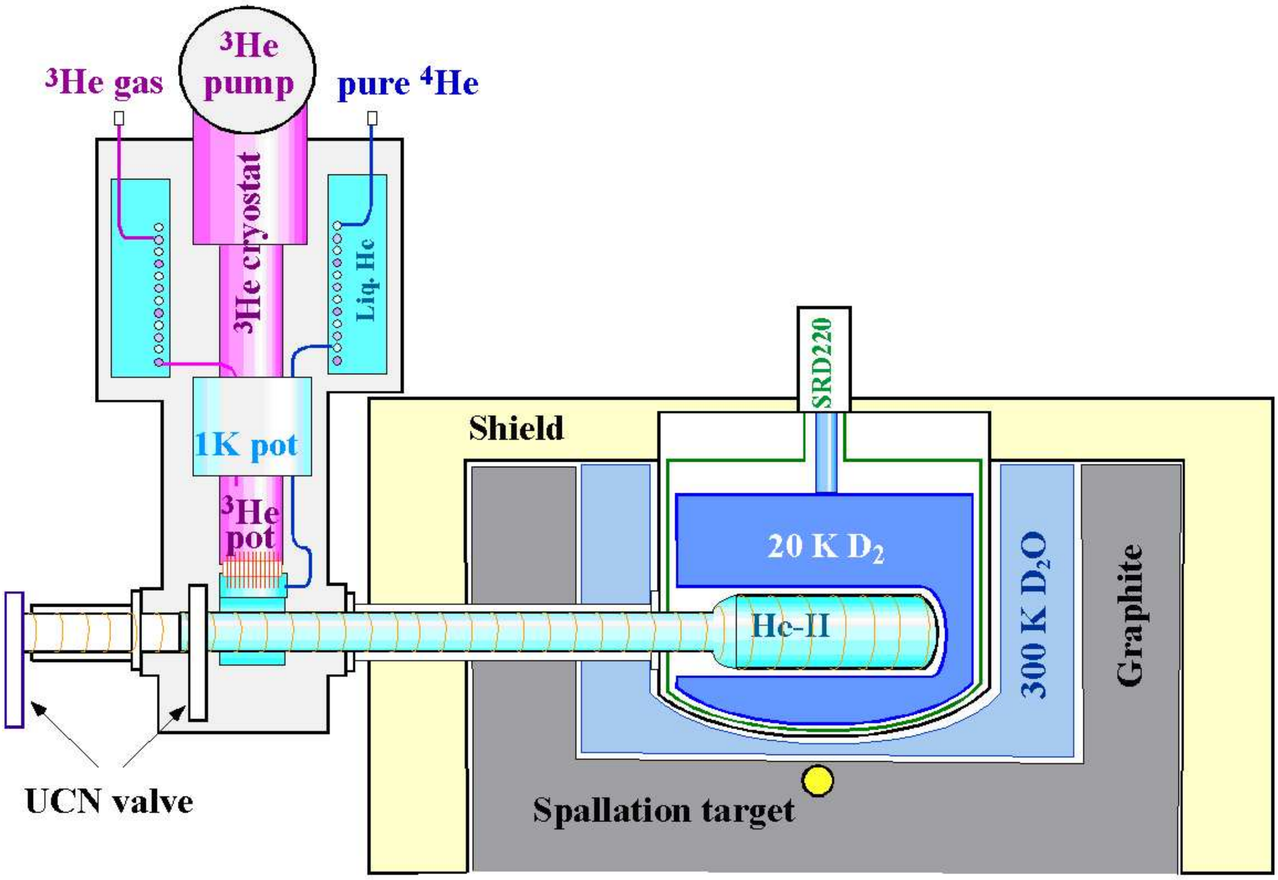

Figure 6: Schematic diagram of the He-II spallation UCN source for TRIUMF.

3.1 UCN Production

A new generation of UCN sources is being developed at many institutes in the world (see Table 1 for a summary). In the previous UCN source, the turbine source at ILL, the UCN density was limited by Liouville's theorem. The new UCN sources use phonons for neutron cooling, and are free from the phase space limitation of the neutrons themselves. The UCN density ρ_{UCN} in the source is represented as $P_{\mathrm{UCN}}\tau_s$ in terms of the production rate P_{UCN} and the UCN storage lifetime τ_s in the source volume. The production rate is given by $P_{\mathrm{UCN}} = \int\int \sigma(E\mathrm{in} \rightarrow E_{\mathrm{UCN}})\phi(E_{\mathrm{in}})N dE_{\mathrm{in}} dE_{\mathrm{UCN}}$ where the down scattering cross section is $\sigma(E_{\mathrm{in}} \rightarrow E\mathrm{UCN})$, the incident cold neutron flux is $\phi(E_{\mathrm{in}})$, the nuclear number density in the source material is N and the integrals are over the incident neutron energies E_{in} and final UCN energies E_{UCN}. For UCN production, higher cold neutron flux is therefore preferable. However, with higher CN flux comes a higher heat load, which is dominated by capture γ's. The UCN storage lifetime is limited by phonon up-scattering, which strongly depends on temperature, and the lifetime would be severely affected if the heat transport out of the source material couldn't be dealt with. After production, UCN are extracted to a UCN guide and a storage bottle for experiments. Extraction efficiency from the source material to the UCN guide and transport efficiency to the storage bottle are important parameters to obtain higher UCN density for experiments.

3.2 Summary of Other New Generation Sources

A list of new generation sources was presented in Table 1 and we refer the reader there for a summary.

The existing Los Alamos UCN source and the future PSI source use SD_2 as the UCN source material. In SD_2, the value of τ_s is only 24 ms at 8 K. Therefore these sources use a storage bottle which is separated from SD_2 by a UCN shutter. The value of τ_s arises from a combination of phonon up-scattering (40 ms), an up-scattering from para-D_2 (100 ms), and nuclear absorption (150 ms) [37]. The shutter is opened briefly when a beam pulse arrives so that UCN are extracted to the storage bottle.

At Los Alamos, an 800-MeV proton beam is used for spallation neutron production off a tungsten target. The number of neutrons produced by the spallation reaction per proton is 13.3 n/p at 800 MeV [38]. The UCN production rate is $P_{\rm UCN} = 4.66 \times 10^2$ UCN/cm^3/μC [40]. The SD_2, is a disk 7.8 cm in diameter and 5 cm in height. Typically a 30 μC pulse of protons is delivered to the source for one second in every fifteen [39]. The short lifetime in the SD_2 is not an issue for the LANL source because the UCN flow continually through the UCNA apparatus, which is a polarized neutron beta-asymmetry experiment. Were the UCN stored, they would depolarize rapidly on the cell walls. Despite this, a world-record density of 1.45×10^2 UCN/cm^3 was achieved in the prototype source, which served as the first and to date most impressive validation of the superthermal production technique [40]. In the UCNA apparatus, densities of 1 UCN/cm^3 are typically achieved, giving rise to neutron beta-decay rates of $\sim$10 Hz.

The PSI UCN source will be driven by a 600 MeV proton beam at 2 mA. The number of neutrons per proton is 8.6 n/p at 600 MeV. The cold neutron flux in the SD_2 is expected to be $\phi_n = 2.6 \times 10^{13}$ n/cm^2/s. The UCN production rate is expected to be 2.9×10^5 UCN/cm^3/s [37]. The volume of SD_2 is disk shaped: 50 cm in diameter and 15 cm tall. The SD_2 is also partially used as a cold neutron moderator. Gaseous ^{4}He is introduced into the SD_2 vessel to improve the thermal contact between the SD_2 and the vessel wall. The extraction efficiency from the SD_2 is expected to be 10% [37], resulting in a UCN production rate of 2.9×10^4 UCN/cm^3/s. UCN will fill a 2 m^3 storage bottle which has a storage lifetime of 6 s. A proton beam pulse of 4 s every 400 s will be used when filling. After filling, the density in the bottle is anticipated to be 2000 UCN/cm^3 [42]. UCN will be transported to an EDM cell, where the expected UCN density is 1000 UCN/cm^3. The construction of the UCN source will be complete in 2009 [7]. The UCN source at PSI, despite using a larger instantaneous beam power, uses a shorter pulse structure because of the shorter UCN lifetimes owing to the use of SD_2. Note also that the duty-cycle of the source is 1%, and hence the time-averaged beam power (12 kW) is not so different from the TRIUMF source (5 kW). The low duty cycle at PSI must be enforced because of the tremendous heat load implied by the very intense beam.

The Munich FRM-II reactor, a 20-MW reactor, will also have a UCN source employing SD_2. A prototype UCN source at the TRIGA reactor in Mainz where 8×10^4 UCN were obtained in a source volume of 10 liter at $E_c = 250$ neV with reactor operation at 100 kW. This is expected to be improved to a density of 10^4 UCN/cm^3 at FRM-II.

The Sussex-RAL group is constructing a He-II UCN source in the H53 CN beamline at the 60 MW ILL reactor for the CryoEDM experiment. After construction of a more intense CN beamline (which will branch off the H172 beamline), the UCN density anticipated in the EDM cell is 1000 UCN/cm^3.

SNS is also constructing a He-II UCN source for an EDM measurement. The cold neutron flux is smaller than ILL. The UCN production rate is expected to be 0.3 UCN/cm^3/s and the density 150 UCN/cm^3 in the EDM cell [9].

3.3 The current UCN source at Osaka

The TRIUMF UCN source will be based on the source of Y. Masuda, which is currently installed at the Research Center for Nuclear Physics (RCNP), Osaka University, in Osaka, Japan. A picture of the source is shown in Fig. 7. The source uses a Pb spallation target and the UCN production

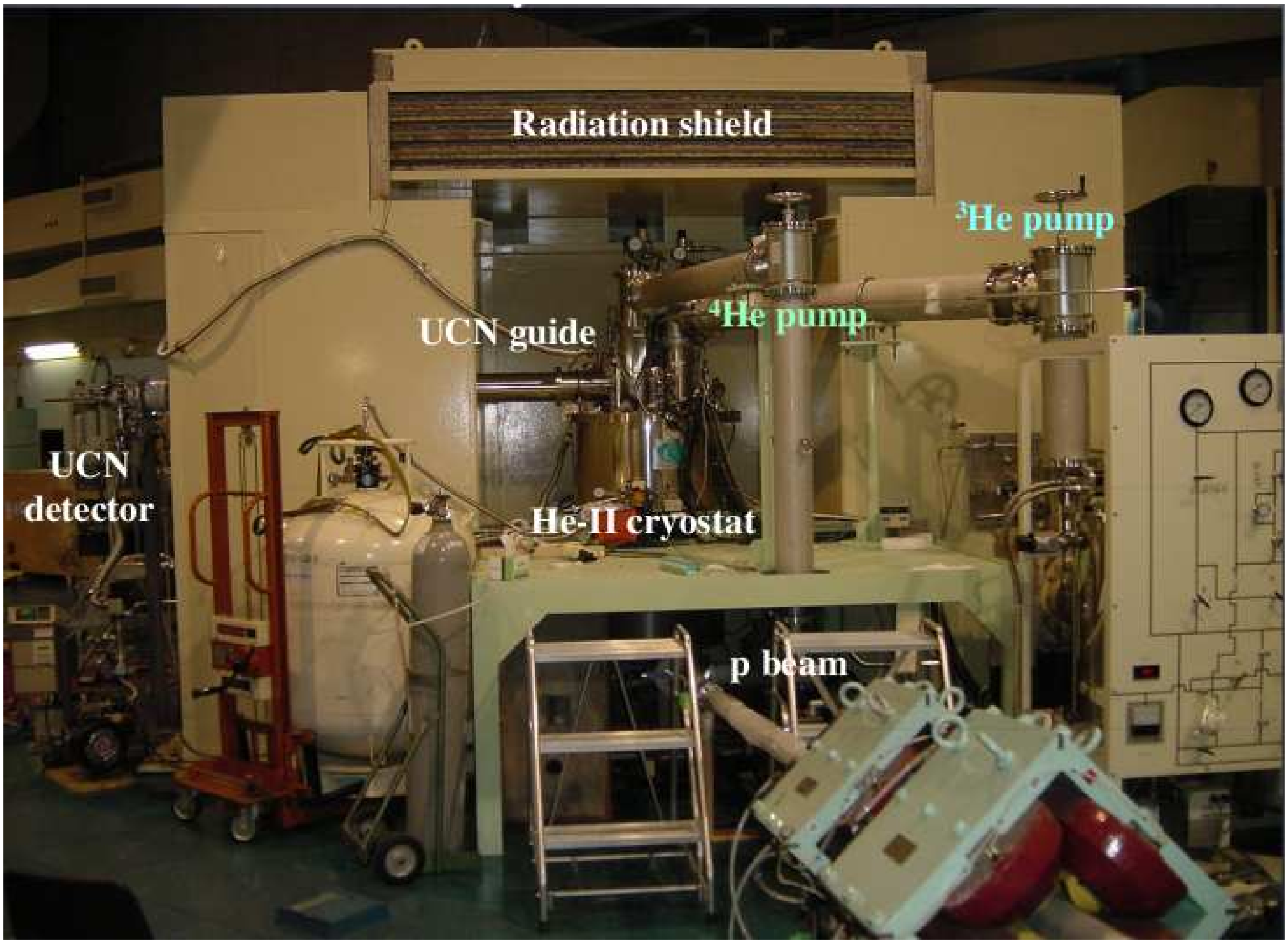

Figure 7: Y. Masuda's UCN source at Research Center for Nuclear Physics, Osaka.

material is superfluid ^{4}He (He-II).

The number of spallation neutrons produced per proton in a lead target is 4.4 n/p at the 390 MeV available at RCNP. The UCN production volume is a 10 liter vessel containing He-II, located within a 20 K heavy water vessel, in turn located within a 300 K heavy water vessel. The cold neutron flux in the He-II was estimated by means of a Monte Carlo N Particle (MCNP) based code, and found to be $\phi_n = 1.5 \times 10^{10}$ n/cm^2/s at a proton beam power of 390 MeV $\times$ 1 μA assuming the 20 K heavy water behaves as an ideal gas. The cold neutron flux at higher energies is larger in the 20 K heavy water than in cold neutron guide, and so multi-phonon down-scattering contributions become larger for UCN production. Including multi phonon down-scattering, the production rate becomes $4 \times 10^{-9}\phi_n/\mathrm{cm}^3/\mathrm{s}$ [43]. No data exist for the form factor of solid heavy water for neutron scattering, but the neutron temperature is expected to be 80 K in 20 K solid heavy water, so the cold neutron flux decreases to 0.2×10^{10} n/cm^2/s [44]. As a result, the UCN production rate is expected to be 4-8 UCN/cm^3/s in the He-II. This was found to be consistent with an experiment conducted at RCNP in 2007. UCN were extracted from the He-II to a vertical UCN guide of 1.2 m height and transported to an experimental port through a horizontal UCN guide of 3 m length. At the experimental port, the UCN density was 10 UCN/cm^3 at $E_C = 90$ neV. E_C is the maximum UCN energy, determined by the properties of the guide material used. The total number of UCN is expected to be 1.2×10^6 assuming the 36 liter bottle that was used. The volume includes the He-II bottle of 10 liter and the UCN guides. The UCN storage lifetime was 30 s. As a result a UCN production rate in He-II is obtained to be 4 UCN/cm^3/s, consistent with the theoretical prediction. The result shows that the UCN losses upon extraction from the He-II and transport through the UCN guides are not large.

3.4 TRIUMF UCN Source Parameters

At TRIUMF, the 500 MeV proton beam will be used and 40 μA peak current is desired. The number of neutrons per proton in a tungsten or Pb target, is 6.7 n/p. The configuration of the He-II in the spallation neutron source will be altered from the present vertical arrangement at RCNP to the horizontal arrangement displayed in Fig. 6. In this way, the cold neutron flux in the He-II will be doubled simply by decreasing the average distance of He-II from the spallation target. The cold neutron flux for the TRIUMF source will therefore be $\phi_n = 6.7/4.4 \times 40 \times 2 \times 1.5 \times 10^{10}$ n/cm^2/s $= 1.8 \times 10^{12}$ n/cm^2/s. The UCN production rate is expected to be $P_{\mathrm{UCN}} = 0.37 - 0.73 \times 10^4$ UCN/cm^3/s in the 10 liter He-II volume. The phonon up-scattering lifetime τ_{ph} will be 610 s at 0.8 K, which is comparable to the β-decay lifetime $\tau_\beta = 886$ s. Assuming the wall collision lifetime of 300 s results in an overall storage lifetime of 164 s. We therefore expect a UCN density in the He-II of $0.55 - 1.1 \times 10^6$ UCN/cm^3, where a somewhat more conservative storage lifetime of 150 s was assumed. If we include the He-II volume outside the cold moderator, the UCN density becomes $0.27 - 0.55 \times 10^6$ UCN/cm^3. After the production, UCN are extracted into a horizontal UCN guide, and then transported to an experimental volume. UCN loss upon extraction from He-II is negligibly small. The UCN density at the experimental port is expected to be $\rho_{\mathrm{UCN}} = (0.4 \times 10^4\ \mathrm{UCN/cm^3/s})/(4\ \mathrm{UCN/cm^3/s}) \times 150\ \mathrm{s}/30\ \mathrm{s} \times 10\ \mathrm{UCN/cm^3} = 0.5 \times 10^5\ \mathrm{UCN/cm^3}$ at $E_c = 90$ neV. The transport efficiency without the vertical guide is better. Therefore, the UCN density at the experimental port should exceed 5×10^4 UCN/cm^3.

The comparison of some of the parameters of this source to the rest of the world's UCN projects is summarized in Table 1.

The cold neutron flux we can accept is limited by γ heating as discussed more generally in Section 3.1, because the UCN storage lifetime is limited by phonon up-scattering. This contribution to the lifetime strongly depends on temperature, and varies as $1/T^7$ for He-II. According to a MCNP simulation, the power deposited by γ heating in the He-II is 8 W for 20 kW proton beam power. Fortunately, this heat can be quickly removed by making use of the excellent thermal properties of superfluid helium to transfer the heat rapidly to a ^{3}He cryostat and through a heat exchanger. As a result, the heat is transferred to ^{3}He gas via ^{3}He vaporization, and then removed by ^{3}He pumping. The latent heat of ^{3}He is 35 J/mol. The cooling power of the ^{3}He pumping is represented as the product of the latent heat of vaporization times the vapor pressure times the pumping rate divided by RT, where R is the ideal gas constant. The saturated vapor pressure of ^{3}He is 3 Torr at 0.8 K.

Therefore a pumping speed of 1×10^4 m^3/h applied to the ^{3}He at 3 Torr removes a heat of 17 W. To further reduce the heat load, a cold neutron filter will be developed, to reduce the capture rate and hence γ heating. The Bragg condition forbids low energy neutrons passing through a solid material except at cold neutron energies, explaining the principle behind the CN filter, which would be a material placed between the cold moderator and the He-II volume to screen out neutrons that are not cold.

Therefore, we estimate that the heat loads expected for instantaneous 20 kW beam power are well in hand for TRIUMF.

The UCN source requires a source of liquid helium to operate. The consumption is at the level of 200 L/day during operation. We would recover all helium back to a liquifier. A potential advantage of the meson hall location (discussed later on) is the availability of liquid helium from a dewar in the hall.

3.5 UCN source costs

Y. Masuda has already made a request to Japanese funding agencies for $2.4M CAD, over the next four years, for the main components of the UCN source itself. These include mainly those items displayed schematically in Fig. 6, which are:

- the ^{3}He cryostat
- a ^{3}He gas circulator
- pumps
- the He-II bottle (UCN production volume)
- UCN guides to the experimental port
- a GM cryostat for the 20 K LD_2
- a ^{4}He isotopic purification system

Several additional costs related to the UCN source were not included in his request, such as: the cost of the moderator materials themselves (although some quantity is available from the previous RCNP source), the cost to construct the kicker, septum and beamline for UCN, and the cost of radiation shielding blocks (though some would be available from TRIUMF) and the remote handling system.

In the following section, we discuss these additional infrastructure items required to complete the project at TRIUMF.

4 UCN Facility at TRIUMF

In this section, we comment on infrastructure needs for UCN. Primarily, these relate to space, beam, shielding, remote handling, and cryogenics needs.

4.1 Location

Many possible locations for the source have been suggested, namely, the proton hall, the beamline 1A TNF, a separate UCN hall, and the meson hall. At the present time, the most appropriate site seems to be the meson hall. The UCN facility would be installed after the completion of PiENu on M13 and would replace M13 and M11. Meson production targets and beamlines located downstream (M15, M9, and M20) could remain unaltered.

One of the primary reasons for this choice of location is the ability to periodically switch on the beam onto the UCN target in a one minute on, three minutes off fashion. The reason a pulsed beam is required is to achieve low background rates for UCN counting experiments. Low backgrounds are often required for the types of sensitive physics experiments that would be conducted at TRIUMF. Pulsed spallation sources can give rise to improved backgrounds over continuous reactor UCN sources, because experiments can occur when the neutron source is switched off.

The beam pulsing could be achieved at TRIUMF in a variety of ways, but the mechanism proposed for the meson hall is to periodically kick a fraction of the meson hall beam from beamline 1A to UCN. The rest of the time, the beam would be avaialable to other users in meson hall, most of the beam being dumped in the TNF dump at the end of the 1A line.

The presence of the TNF dump contributes to the attractiveness of the meson hall location. Additionally, a great deal of pre-existing infrastructure exists: existing BL1A shielding, a cryogenic plant (for the M9 solenoid), easy access to remote handling hot cells for servicing, and an existing 50 T crane for shielding blocks.

Fig. 8 shows a possible layout in the meson hall. Beam would be delivered to the UCN source by a kicker and septum system, which will be described in the next section. A beamline would be constructed to divert the 500 MeV, 40 μA protons onto the spallation target of the UCN source. The spallation target (either W or Pb) would be cooled by flowing either gaseous helium or liquid water. Substantial shielding and a remote handling system for the target is required. Experimental space at the level of 6×12 m^2 is required for experiments.

4.2 Beam Delivery to UCN

The beamline shown in Fig. 8 is based on the work of J. Doornbos reported in Ref. [45]. Located upstream and downstream of the 1BVB2 dipole are new fast kicker magnets, indicated by K1 and K2. Together, they deflect the proton beam by 10 mr, offsetting the beam by 65 mm at the start of a magnetic septum. The septum then bends the beam by a further 115 mr, displacing the beam from the BL1A axis by 220 mm at the dipole 1UB1. This dipole deflects the beam by a further 15 degrees. The final dipole magnet, 1UB2, deflects the beam by 45 degrees. Following 1UB2 are steering magnets to position the beam accurately on a tungsten spallation target at the centre of the UCN source. An initial optics study for this configuration is also reported in Ref. [45].

Regardless of the location of the UCN facility, an important consideration is to minimize the impact on other TRIUMF users. In the meson hall, after the conclusion of PiENu, this will be almost exclusively μSR users. We have conducted initial meetings with individuals involved in μSR, primarily J. Brewer, D. Fleming, and S. Kreitzman. The results of these meetings indicate that the scheme proposed for beam delivery to UCN can be accomodated for almost all data-taking modes of μSR, with a maximal 7% of the beam being delivered to UCN simultaneous with μSR operation.

The macrostructure of the beam delivery solution is described pictorially in Fig. 9. The normal

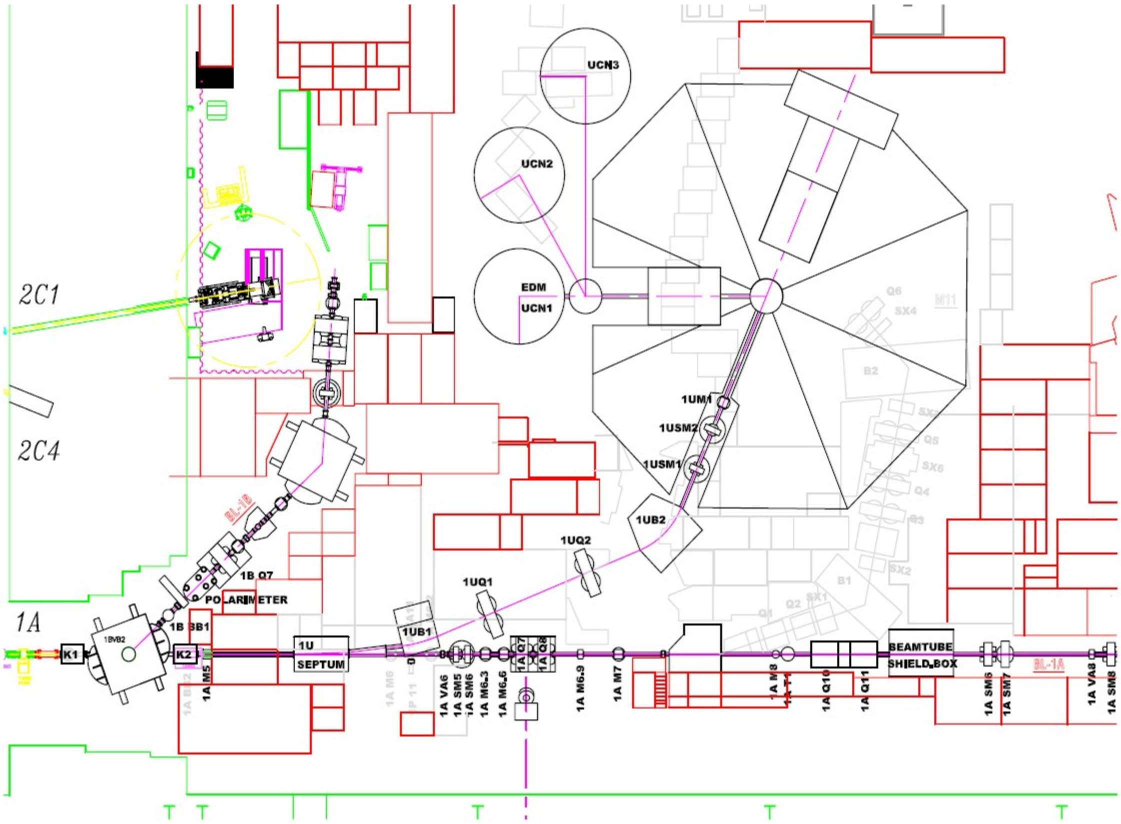

Figure 8: Possible location of the UCN facility in the meson hall. In this scenario, both M11 and M13 would be decommissioned. The beamline layout shown is based on TRIUMF design note TRI-DN-08-3.

time structure of the TRIUMF proton beam is shown on the top panel of Fig. 9. A 1 kHz pulser in the injection line interrupts the beam once per millisecond for a short time of 10 μs to 40 μs. The exact time of the beam-off gap can be adjusted by the operators, and this is normally done in relation to tuning for ISAC. These short gaps of zero beam do not affect μSR users. The important consderation for μSR is that the rest of the beam be stable.

In operation, the UCN source would typically take beam for 1 minute, then receive no beam for a further 4 minutes, during which time the ultra-cold neutron experiments would take data. Private communications with Mike Barnes suggest that it should be possible to build fast kicker magnets with rise and fall times on the order of a few μs and a flat-top of 1 ms or more [46]. The proposed beam sharing scheme assumes the use of ~ 5 μs risetime fast kickers that turn on during the brief beam-off interval, direct beam to the UCN source for 1 ms, then turn off in the next beam-off interval. By adjusting the duty cycle, one can vary the split between UCN and downstream users. The lower two panels of Fig. 9 illustrate a 2:1 split, for example 80 μA to downstream users and 40 μA to UCN. This scheme makes no change to the beamline 1A optics and does not affect the instantaneous beam current to other users. The missing 1 ms "buckets" should not be noticed by μSR experiments except for a small reduction in total counts. In this example, with UCN taking one-third of the beam, one-fifth of the time, would impact beam delivered to downstream users at the 7% level.

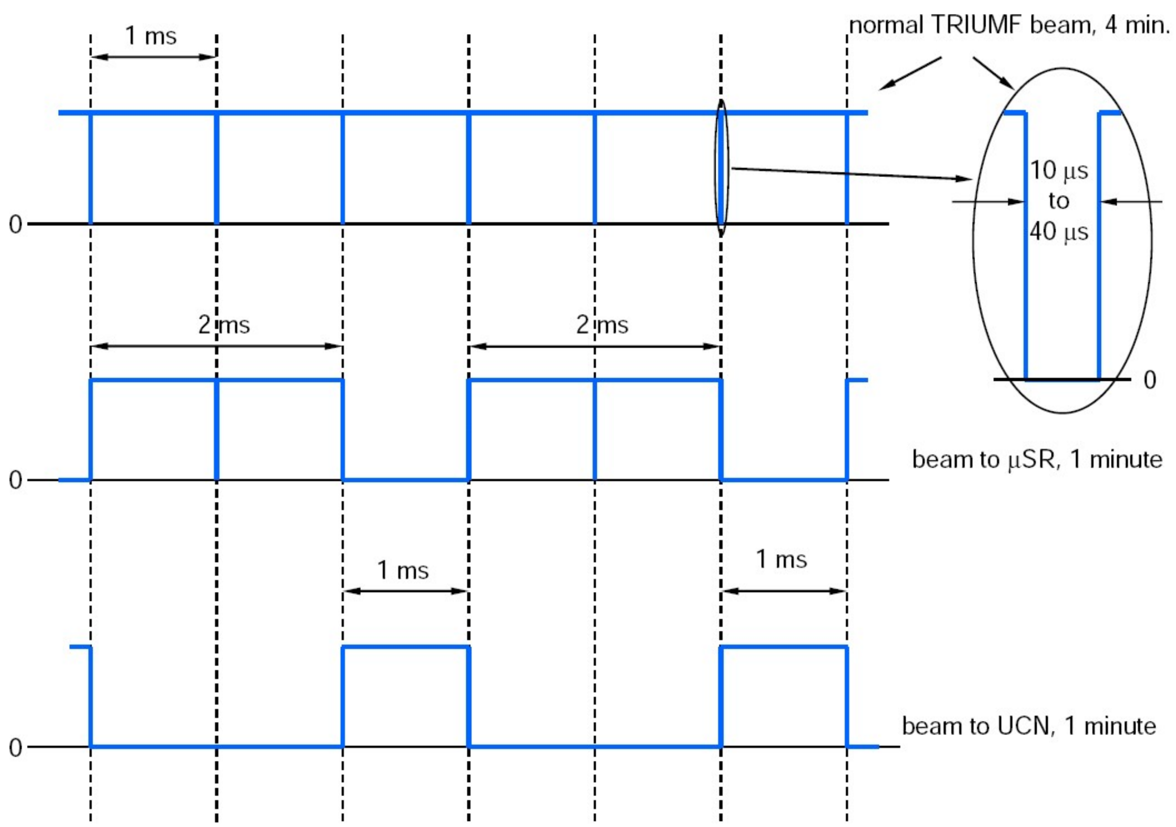

Figure 9: Method of sharing the proton beam between the UCN source and other meson hall users. Every 4 minutes, the UCN source will take a minute of beam in the form of a 1 ms burst every 3 ms. The instantaneous beam current is not affected and the total loss of integrated beam to downstream users is about 7%. The exact details of the time division will depend on what specifications are achievable for the fast kicker magnets.

The 1 in 3 duty cycle requires a large average current in the kickers and their fast power supplies. Such power supplies may be difficult (or at least expensive) to obtain. If the beamline 1A current could be increased, the kicker duty cycle could be reduced. The optimum solution can only be identified when more detailed kicker designs are available.

4.2.1 Beamline Magnet Costs

For the beamline shown in Fig. 8, the kicker magnets (K1 and K2), the septum, and the two dipoles (1UB1 and 1UB2) will be new. The quadrupoles 1UQ1 and 1UQ2 can be re-used from M20. Existing M11 power supplies should be suitable for the quadrupoles and for the dipole 1UB1, but 1UB2 is a higher power magnet and will need either a new supply, or power from a beamline 1B supply. Based on the cost of the TRIUMF 2AB1/2 dipole, the dipoles will probably cost about \$100 k each with about the same for the power supplies if we can't re-use existing supplies. The septum is more specialized and may be more expensive, depending on how rad-hard it must be. The septum downstream of T1 was several $\times$ \$100 k due to its exceptional radiation hardness. The main cost of K1 and K2 will probably be in their special fast pulsed power supplies. If, on the

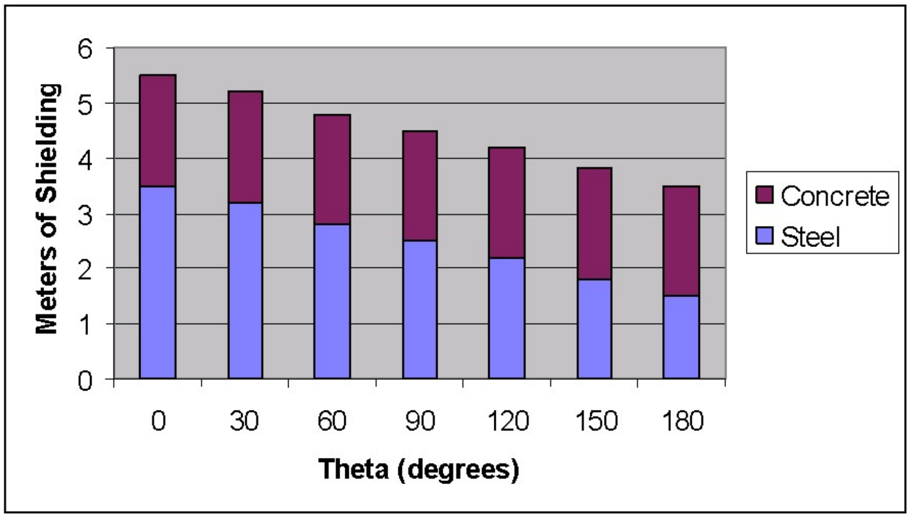

Figure 10: Shielding required for a 40 μA, 500 MeV proton beam incident on a thick tungsten target. The design dose rate is 3 μSv/hr immediately outside the shielding.

average we allow \$250 k for each of the magnets and the same amount for installation, it would cost \$2.5 M for the installed magnets.

4.3 Shielding

Fig. 10 shows the results of shielding calculations by Anne Trudel [47]. In these calculations, the assumptions were a 40 μA, 500 MeV beam proton beam stopping in a tungsten target 1.5 m from the floor. The effect of the neutron moderators around the tungsten target was not estimated; the calculation simply assumes that the target is surrounded by 0.5 m of empty space in all directions. The thicknesses displayed in Fig. 10 reduce the dose rate immediately outside the shielding to less than 3 μSv/hr. This is comfortably below the 10 μSv/hr guideline for low occupancy areas such as walkways. Integrating the shielding gives 125 m^3 of steel and 375 m^3 of concrete. This does not take into account the "blockiness" of the steel and concrete, and in practice we will need somewhat more. For the cost estimates presented below, a somewhat arbitrary 20% is added, giving 150 m^3 steel and 450 m^3 concrete.

In a previous TRIUMF design note from 1989 [48], removable concrete shielding was found to cost \$800/m^3. Correcting to 2008 dollars using the Consumer Price Index gives \$1200/m^3. The same design note shows \$11,900/m^3 for steel plate blocks for M20. "Off-grade steel ingots" for M20 were \$8000/m^3. Allowing for inflation we should allow at least \$12,000/m^3 for new steel. It is, however possible to obtain slightly radioactive recycled steel much more cheaply. In 1997, TRIUMF obtained 99 10-ton blocks from Scientific Ecology Group for approximately \$10k, or only \$80/m^3. The cost was completely dominated by shipping, as SEC wants to dispose of the steel and only charges \$1 per 10-ton block. It has been confirmed that these blocks are still available for one dollar per block [47]. Shipping will be more expensive due to much higher fuel costs, but even allowing a factor of three to four, we should be able to obtain recycled steel for ~\$300/m^3. How much will be available when we need it is unknown, so we consider this range of possibilities.

4.4 Other Infrastructure Needs

The heart of the UCN production equipment including source, refrigerators, cryogenics etc. was discussed in Section 3.5. However, moderator costs were not included in the cost estimate presented there. The moderator will be some combination of graphite and heavy water and/or liquid deuterium (see Fig. 6). The cost for the moderator and associated systems might be in the range \$1M to \$3M.

Additionally, it has been assumed that liquid helium would be available from a pre-exisiting cryogenic plant available in meson hall (used for cooling the M9 solenoid), and hence the cost of a helium liquifier has not been included in our estimates.

There will also be a need for remote handling equipment, beamline stands, vacuum boxes and all the smaller hardware such as pipes and bellows. Much, but likely not all, of that is covered by the \$1.25 M we have allowed for "installation".

Remote handling would be accomplished by removing the concrete shielding blocks, then pulling a custom-made target assembly out through a hole in the steel shielding by crane. The activated section of the target handling assembly would then be placed into a cask for safe removal from the area, or transported to hot cells available in meson hall, which is a distinct advantage of the meson hall location [49].

In addition, it is likely that two more beamline monitors will be required at $\sim$\$10 k each.

4.5 Engineering Support

In addition to costs for hardware and outside contracts, the project will require manpower support from TRIUMF. A very important early task is engineering, design, and prototyping of the kicker magnets for beam sharing. Mike Barnes estimates we would need an engineer, designer and technician at 50% for about 2 years, i.e. 3 FTE-years [46]. It will also be important for TRIUMF engineering to study the details of the beamline re-build and to prepare detailed cost estimates, probably taking $\sim$1 FTE-year. Should the project proceed, we would need a project engineer, project manager, design office support and technical support from beamlines technicians and riggers during installation. The total number of FTE-years required has not been estimated at this time.

4.6 Summary of Infrastructure Costs

Table 2 summarizes some of the major costs for the new facility. Shielding costs for the spallation target may be significant. Note that we can save some \$1.7 M by using slightly radioactive recycled steel instead of new steel. More detail on the items in the table and on other costs are covered in the following sections.

4.7 Planning for Canada Foundation for Innovation Request

The Canadian collaboration intends to make a request for funding for this project through the Canada Foundation for Innovation (CFI) New Initiatives Fund (NIF) in 2008. The request is envisioned to be pursued with University of Winnipeg as the lead institution. An initial proposal to the University of Winnipeg for the university's internal CFI process is due April 14. A notice of intent to apply will be due to CFI on June 30, 2008. The final proposal is due October 3, 2008. Hence there is a need to complete design studies and costing for the UCN source rapidly throughout

Item	Unit Cost	Total
UCN source apparatus		\$2.4M
5 magnets	\$250 k each	\$1.25 M
Installation	\$250 k per magnet	\$1.25 M
Moderator		\$ 1 M - \$3 M
150 m^3 steel	\$300/m^3 - \$12000/m^3	\$45 k - \$1.8 M
450 m^3 removable concrete	\$1200/m^3	\$540 k
Grand Total		\$6.5 M - \$10.2 M

Table 2: Summary of some of the major costs for the UCN facility. "Installation" includes such things as outside contractors for water and power.

the summer of 2008. Support will be required from TRIUMF for successful completion of those studies.

In the cost structure of CFI grants, CFI normally supplies 40% of the overall project cost. Funds from other sources must match the 40% contribution of CFI. The cost structure that we envision for the approximate \$10M overall project is 40% CFI, 40% Japanese funding sources, and 20% TRIUMF. It is for this reason that equipment costs for items likely to be supplied by funding from Japanese sources (e.g. the UCN source and moderators) are included in the tables in previous sections: such in-kind contributions will need to be reported to CFI.

As mentioned previously, funding for physics experiments would be pursued at a later date (2009 and beyond) and would come from a combination of Canadian (NSERC), Japanese, and other international sources.

4.8 Summary of Timeline to First Experiments

The M13 area is currently committed to the PiENu experiment. In what is written below, we assume that the M13/M11 area would be made available to UCN in the timeframe of 2012.

Prior to 2011, the collaboration would primarily support the development of Masuda-san's source at RCNP in Japan for TRIUMF. From 2012 onward, the successfully commissioned source would be moved from RCNP to TRIUMF for installation. Work at this time at TRIUMF would involve the reconfiguration of the area, the construction of the UCN beamline and shield package.

Initial commissioning of the beamline, with UCN source installed, would then take place, along with initial UCN production experiments. We anticipate several months for such experiments. Such experiments use one inexpensive UCN detector as the primary detection scheme. Simultaneous with this first run, measurements of gamma and fast neutron rates would also be conducted using standard detectors in the experimental area, relevant for UCN experiments.

After that time, in 2013, the first physics experiment (likely either the neutron lifetime or gravity levels experiment) would be conducted. The funding request for the physics experiment would be made to NSERC, and other international funding bodies, would be made in 2009-10. Construction and commissioning of the initial experiment could potentially be completed in 2012. A production run could then occur in 2013.

EDM experiment funding would be sought in 2010. First runs with EDM equipment could be conducted as early as 2014, depending on the solution taken for the experimental apparatus.

4.8.1 Design and Construction of UCN Source

Where we anticipate needing assistance from TRIUMF in the next year to two years is in the accurate costing of the remainder of UCN source infrastructure items not already requested by Masuda-san. In order to succeed, this assistance is needed to generate an adequate technical design. We are grateful for the assistance thus far of experts at TRIUMF. However, a realistic overall design involving the TRIUMF engineering and radiation safety groups must eventually be pursued to address this issue.

This would include the design of the spallation target itself, and the volumes (on Fig. 6) external to the cryostat, namely the 300 K D_2O vessel, the graphite reflector, and shielding and remote handling. We anticipate three months of designer time required to complete the design of these elements. Additionally, the detailed design of the UCN beamline, from kicker, to septum magnet, to dipoles and quadrupoles and monitors, up to the spallation target itself, would be required.

The design and fabrication of the UCN cryostat would be completed by the Japanese collaborators (in communication with TRIUMF). Delivery of the cryostat to RCNP would require one year from concept to successful completion of initial cooldown, based on the previous experience of Y. Masuda.

Integration of the completed parts of the apparatus would require a significant investment from TRIUMF in terms of manpower and time. Once the UCN source construction is complete, we anticipate one to two staff scientists being able to operate the source.

5 Collaboration and TRIUMF UCN Workshop

Thus far groups at Canadian universities, TRIUMF, at KEK, at Japanese universities, and at institutions in the U.S. have joined the project. J.W. Martin (U. Winnipeg) is the collaboration spokesperson. Y. Masuda is the leader of the UCN source development project in Japan. W.D. Ramsay is the liaison to TRIUMF for the project. C. Davis (TRIUMF) is envisioned to become the UCN project manager, once the project is underway.

5.1 Canadian Grant-Eligible Collaborators

The Winnipeg/Manitoba/UNBC/TRIUMF group (the grant-elegible members on this proposal are J.W. Martin, C. Davis, M. Gericke, E. Korkmaz, S.A. Page, and W.T.H. van Oers) has successfully completed difficult parity-violation experiments at both TRIUMF and at Jefferson Lab. Additionally, with recent arrival of new faculty members (J.W. Martin and M. Gericke) the group has renewed its interest in fundamental physics with ultracold and cold neutrons. The group is currently involved in a large project to make the world's most precise determination of $\sin^2\theta_W$ from e-p elastic scattering. Additionally, J.W. Martin has been a leader in detector development in the UCNA project at LANL. M. Gericke, S.A. Page, and J.W. Martin are involved in future experiments at the SNS (Spallation Neutron Source, Oak Ridge, TN), as well, primarily neutron beta-decay and parity-violating neutron hadronic weak interactions. J.W. Martin and M. Gericke each have successfully obtained funding from the CFI Leaders Opportunity Fund (LOF) for laboratory grants for detector fabrication and testing facilities at their respective universities.

M. Hayden from SFU is a leader in UCN production in superfluid He and has recently authored a paper in PRL on the characterization of ^{3}He impurities in superfluid ^{4}He. This paper is related to the development of the SNS n-EDM project. He is also an expert on NMR techniques and on novel magnetic field sensors (SQUID's) used in such experiments.

L. Buchmann (TRIUMF), has been the main proponent of the potential use of this UCN source as a free neutron target. He has been instrumental in the development of the physics case and facilities case. He is currently a collaborator on the DRAGON and TUDA projects at TRIUMF.

5.2 Japanese collaborators

The KEK and other Japanese collaborators have generally been involved in the development of Y. Masuda's UCN source at RCNP. In terms of physics experiments, these collaborators view the neutron EDM experiment as their top priority. New collaborators, mainly from Tokyo (S. Komamiya and collaborators), have joined this effort more recently, with the goal of eventually completing a neutron gravity-levels measurement at TRIUMF.

5.3 US collaborators

R. Golub (NCSU) has been one of the main proponents of the field of UCN physics over the past several decades, and in the development of superthermal sources of UCN. He has expressed a strong desire to participate in the development of Masuda's spallation-driven UCN source at TRIUMF, and has also expressed a strong belief that this will result in the world's highest density UCN source. He has been involved in many of the most important experiments performed using UCN over the past 30 years, for example, previous measurements of the neutron EDM at ILL.

E. Korobkina (NCSU) is an expert on UCN production and storage experiments. She has designed the UCN ISR apparatus, and collaborates on the SNS EDM project, and the NCSU Pulstar reactor UCN source project. L. Clarke (NCSU) is the group-leader of the NCSU in surface nanoscience, whose research focuses on artificial molecular rotors.

J.D. Bowman (ORNL) is a recipient of the prestigious Bonner prize of the APS. He is the main proponent of the magneto-gravitational UCN lifetime experiment.

B.W. Filippone (Caltech), T.M. Ito (ORNL), and B. Plaster (U. Kentucky) have most recently brought about the successful completion of the first round of physics measurements with the UCNA apparatus. They are also all collaborators on the SNS EDM project, and work primarily on the inner detector system and the magnetic field system.

5.4 Report on UCN workshop at TRIUMF

Many of these collaborators were attracted in the context of the "International Workshop: UCN Sources and Experiments" which was held Sept. 13-14, 2007 at TRIUMF [50], and was supported jointly by TRIUMF and NCSU/TUNL. The program of the workshop focused mainly on the comparison of our eventual UCN source at TRIUMF with those proposed at other institutes world-wide: ILL, FRM-II (Munich), NCSU, LANL, PSI, KEK, and Mainz. Several sessions were held where opinions of the community were solicited, specifically in relation to the project at TRIUMF. The consensus arose from the worldwide UCN community that a spallation-driven superthermal source of UCN, based on production from superfluid He, should be pursued. Currently, the only group in the world working on such technology is Y. Masuda's group in Japan. TRIUMF, with its availability of high-current proton beam, is therefore uniquely poised to take advantage of this new development in UCN source technology.

Fundamental physics and materials science experiments planned for these sources were also discussed. While the top priority for the field is the precise determination of the neutron EDM, the gravity and UCN lifetime experiments were regarded as excellent and timely physics goals. The free neutron target interacting with radioactive species stored in a ring was regarded as representing a whole new subfield of nuclear physics, while being unique in that such experiments could only be conducted at TRIUMF. The UCN surface physics apparatus was discussed and new applications in nanotechnology "molecular rotors" were reported. Overall, the workshop was an astounding success, and confirmed that the TRIUMF UCN project is on the right track.

6 Conclusion

The world's highest density UCN source would be constructed at TRIUMF, building on the successes of Masuda's group at KEK and at RCNP. The source would be used for a variety of fundamental physics and materials science experiments, complementary to those currently being conducted at TRIUMF. Funding for some of the source has already been requested from Japanese funding sources in Fall 2007. A Canadian contribution for most of the remaining infrastructure would be requested from CFI NIF in 2008. The UCN source would be developed and tested at RCNP until 2011, and reconfiguration of the M13/M11 area would commence for UCN would occur in 2012. This would be followed by installation of the UCN source. Commissioning of the source, and achievement of the world record UCN density, would be completed in 2012-3. A first flagship physics experiment would be conducted in 2013 using the new world-class UCN facility at TRIUMF.

References

[1] S. J. Huber, M. Pospelov and A. Ritz, Phys. Rev. D **75**, 036006 (2007).

[2] C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006).

[3] J.M. Pendlebury et al., Phys. Rev. A **70**, 032102 (2004).

[4] S.K. Lamoreaux and R. Golub, Phys. Rev. A **71**, 032104 (2005).

[5] A. L. Barabanov, R. Golub, and S. K. Lamoreaux, Phys. Rev. A **74**, 052115 (2006).

[6] N.F. Ramsey, Phys. Rev. **100** (1955) 1191.

[7] B. Lauss, "Status of the Ultra-cold Neutron Project and the Neutron EDM Experiment at the Paul Scherrer Institut", presentation at "Neutron Experiments" meeting, JPARC, Japan, March 6, 2008.

[8] SNS EDM pre-proposal, M. Cooper and S.K. Lamoreaux spokespersons, available from http://p25ext.lanl.gov/edm/edm.html.

[9] T. Ito, "Overview of the Fundamental Neutron Physics Program at SNS-FNPB", presentation at "Neutron Experiments" meeting, JPARC, Japan, March 6, 2008.

[10] G. J. Mathews, T. Kajino, and T. Shima, Phys. Rev. D 71, 021302(R) (2005).

[11] A. Serebrov et al., Phys.Lett. B 605, 72 (2005).

[12] W.-M. Yao et al. (the Particle Data Group), J. Phys. G **33**, 1 (2006).

[13] W. Mampe et al., Phys. Rev. Lett. 63, 593 (1989).

[14] S. Arzumanov et al., Phys. Lett. B 483, 15 (2000).

[15] P. L. Walstrom, J. D. Bowman, S. I. Penttila, C. Morris, and A. Saunders (in preparation).

[16] P. R. Huffman et al., Nature 403, 62 (2000).

[17] V. F. Ezhov et al., J. Res. Natl. Inst. Stand. Technol. 110, 345 (2005).

[18] R. Picker et al., J. Res. Natl. Inst. Stand. Technol. 110, 357 (2005).

[19] J. C. Mallinson, IEEE Transactions on Magnetics, Vol. MAG-9, No. 4, Dec. 1973, p. 678.

[20] K. Halbach, Nucl. Instrum. Meth **187**, 109 (1981).

[21] V. V. Nesvizhevsky *et al.*, Nature **415**, 297 (2002).

[22] S. Baessler, V. V. Nesvizhevsky, K. V. Protasov and A. Y. Voronin, Phys. Rev. D **75**, 075006 (2007).

[23] R. Golub, D.J. Richardson and S.K. Lamoreaux, Ultra-cold Neutrons, (Adam Hilger:Bristol 1991).

[24] R. Golub, Rev. Mod. Phys., **68**, 329 (1996).

[25] A. Michaudon, "The use of Ultra-cold neutrons for condenced matter studies", Los Alamos National Lab report, LA-13197-MS, May 1997.

[26] V. Balzani, A. Credi, and M. Venturi, Molecular Devices and Machines: A Journey into the Nano World; WILEY-VCH, Weinheim, Germany, 2004.

[27] W.R. Browne, B.L. Feringa, Making Molecular machines work, Nature nanotechnology, Vol 1, October 2006, p. 25-35.

[28] E. Korobkina, R. Golub, J. Butterworth, P. Geltenbort, and S. Arzumanov, Phys. Rev. B **70**, 035409 (2004).

[29] S. Arzumanov, L. Bondarenko, P. Geltenbort, E. Korobkina, V. Morozov, Yu. Panin, A. Fomin, and S. Chernjavsky, Nucl. Instrum. Meth. A **440**, 690 (2000).

[30] J.R. Vig, J. Vac. SCi. Technol. A **3**, 1027 (1985).

[31] G.S. Kottas, L.I. Clarke, D. Horinek, and J. Michl, "Artificial molecular rotors", Chem. Rev. **105**(4) pp. 1281 - 1376 (2005).

[32] D. Horinek and J. Michl, "Surface-mounted altitudinal molecular rotors in alternating electric field: single-molecule parametric oscillator molecular dynamics", Proc. Natl. Acad. Sci. USA, 102, 14175 (2005).

[33] Y. Chen, Y. Liu, H. Fan, H. Li, B. Shi, H. Zhou, B. Peng, Journal of Membrane Science **287**, 192-197 (2007).

[34] Y. Okahata, A. Katsuhiko, O. Shimizu, "Porous glass plate immobilized with the adsorbed monolayer of dialkylsilane amphiphiles. Permeation control by a phase transition of the adsorbed monolayer," Langmuir **2**, 538-5240 (1986).

[35] A. Huller, J. Raich, "Torsional ground state splitting for tetrahedral molecules", J. Chem. Phys. **71**(9), 3851-3860, (1979)

[36] Y. Masuda *et al.*, Phys. Rev. Lett. **89**, 284801 (2002).

[37] F. Atchison *et al.*, Phys. Rev. C **71**, 054601 (2005).

[38] K. Tesch, Rad. Prot. Dosim. **11**, 165 (1985).

[39] M. Makela, "The Ultracold Neutron Source at LANSCE," presentation at the International Workshop on UCN Sources and Experiments Sept. 13-14, 2007, TRIUMF, Vancouver, BC.

[40] A. Saunders et al., Phys. Lett. B **593**, 55 (2004).

[41] "The UCNA Experiment: Recent Progress towards a Measurement of the Beta Asymmetry using Ultracold Neutrons", A. Young, presentation at "Neutron Experiments" meeting, JPARC, Japan, March 6, 2008.

[42] The PSI UCN website, http://ucn.web.psi.ch/ .

[43] E. Korobkina, R. Golub, B. W. Wehring, and A. R. Young, "Production of UCN by downscattering in superfluid ^{4}He", Phys. Lett. A **301**, 462-469 (2002).

[44] K. Inoue and Y. Kiyanagi, J. Nucl. Sci. Technol. **11-5**, 228 (1974).

[45] J. Doornbos, "Proton Beamline to UCN Source", TRIUMF design note TRI-DN-08-3 (2008).

[46] M. Barnes, private communication.

[47] A. Trudel, private communication.

[48] "TRIUMF shielding cost experience", TRIUMF design note TRI-DN-89-D26 (1989).

[49] E. Blackmore, private communication.

[50] The workshop agenda and presentation materials shown at the workshop are available from http://www.triumf.info/hosted/UCN/agenda.htm.