An Ultracold Neutron Source for TRIUMF
3rd Draft*

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1 Executive Summary

We propose the construction of the world's highest density source of ultracold neutrons (UCN) at TRIUMF. This source would 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 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 eventually run concurrently with ISAC. However, initially, the program would even have an international impact running when ISAC is turned off. Cost effectiveness (and timeliness) would be achieved by incorporating some of Masuda's equipment into the TRIUMF source. It would cost $1.4M CAD to make improvements to Masuda's setup and to produce a world-class facility at TRIUMF.

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).

*This document will be updated as more information becomes available, within the timescale relevant for the Fall 2007 decision-making process. Particularly, this relates to the "International Workshop: Ultracold Neutron Sources and Experiments" that will be held Sept. 13-14, 2007 at TRIUMF.

UCN sources are often characterized and compared by the limiting UCN density achieved ($\rho_{\rm UCN}$). The UCN source proposed for TRIUMF would have $\rho_{\rm UCN} = 1.8 \times 10^4$ 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 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 ILL n-EDM experiment.

However, 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 be competetive with

Location	Technology	critical energy E_c (neV)	storage time τ_s (s)	limiting density $\rho_{\rm UCN}$ (UCN/cm^3)
TRIUMF	spallation He-II	210	150	1.8×10^4
ILL Grenoble	reactor He-II	250	150	1000
SNS ORNL	CN beam He-II	134	500	430
Munich	reactor SD_2	250		10^4
NCSU	reactor SD_2	335		1300
PSI	spallation SD_2	250	888	2000
LANL	spallation SD_2	250	2.6	120

Table 1: Future UCN sources worldwide. The Los Alamos source is currently in operation on a testing basis. All other sources are proposed sources, including a future He-II source at the ILL reactor. The TRIUMF source figures are quoted for 5 kW average power delivered to the spallation source.

the projected highest density source, which is under development at the Munich FRM-II reactor.

Given this breakthrough in UCN production, a variety of new UCN experiments can be envisioned that would not have been possible with the previous 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 fundamental physics experiments:

- a precise measurement of the neutron lifetime,
- characterization of the recently discovered UCN quantum states in the Earth's gravitational field,
- a search for a non-zero neutron electric dipole moment,
- measurements of radioactive isotope scattering from a free neutron target.

Each project has its own physics interest and timeline, so that, in time, one could envision performing a series of UCN experiments at TRIUMF. Additionally, we envision applications of the UCN source to neutron absorption and scattering measurements, relevant for materials science applications in the study of nanofilms.

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

2.1 Neutron Lifetime

Measurements of the neutron lifetime at the sub-second level have recently been performed using the UCN rotor source at the Institut Laue-Langevin (ILL), Grenoble. 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.

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 well-known 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. Currently V_{ud} is most precisely determined from $0^+ \rightarrow 0^+$ nuclear decays. However, neutron lifetime experiments offer an independent check of the nuclear extraction, free of nuclear corrections.

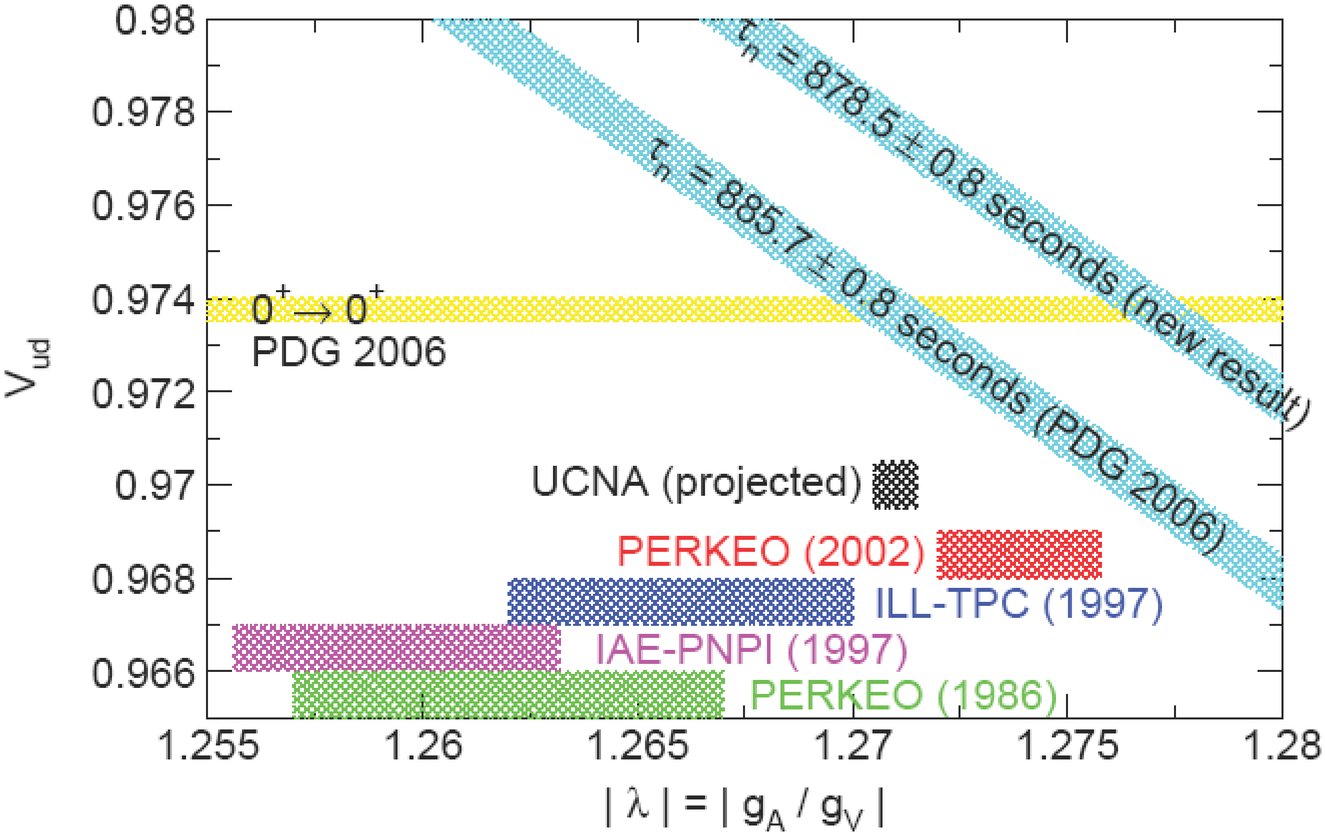

Figure 1: Current status of V_{ud}. Yellow horizontal band indicates current best determination by $0^+ \rightarrow 0^+$ nuclear beta-decay. Diagonal bands indicate current discrepancy in τ_n. Coloured bands at the bottom of the figure are to be interpreted as vertical bands indicating recent measurements of the beta-asymmetry in neutron decay.

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, and the average of all previous measurements [1]. Most of the systematic uncertainties arise from wall effects in these experiments. At TRIUMF, a magnetic trap would be used to confine the neutrons, thus removing such effects. While similar projects with vacuum trapping of UCN have been discussed in the context of experiments at LANL and PSI, they are as yet at a very premature stage relative to material traps.

An experiment performed at TRIUMF in the 2010 timeframe could build on the preliminary work done at LANL. This experiment would resolve the discrepancies observed at ILL. TRIUMF's superior UCN density would be instrumental in achieving the statistical error bar required.

2.2 Gravity Levels

Recently, a group at ILL has successfully observed the quantization of the energies of neutrons confined above a UCN mirror in Earth's gravitational field [2]. 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 [3].

The same group at ILL is mounting a more advanced setup 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, fast experiment at TRIUMF would have a large impact on the field.

2.3 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 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 [4]. The current experimental limit on the n-EDM is $d_n < 3 \times 10^{-26}$ e-cm [5]. 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 SNS group in particular is aiming at a determination of the n-EDM at the 10^{-28} e-cm level, by using a unique new experimental technique. The experiment involves production of UCN in superfluid He in a CN beam. However, the EDM measurement *itself* is also conducted in the same volume of superfluid. Hence, all detection and many of the techniques involved are geared towards the highly specific experimental situation where the entire experiment is conducted within the superfluid. The SNS experiment would not commence data taking until 2014.

While the current limit from ILL is dominated by statistical uncertainties, the next generation of experiments will encounter new systematic uncertainties. For example, a new systematic error was uncovered in the ILL experiment, the so-called "geometric phase" effect [6, 7] arising when trapped particles experience magnetic field inhomogeneity in the presence of an electric field.

An experiment at TRIUMF would have the advantage of higher UCN densities thus reducing statistical uncertainties. However, the higher density additionally would allow the EDM trap size to be reduced. This would thereby reduce the size of the geometrical phase effect, and would potentially reduce several other systematic effects.

For TRIUMF, we would also view n-EDM work as prototyping for an even larger effort at a future high-intensity UCN source at JPARC. Such developments could occur in tandem with the lifetime or gravity experiments mentioned above.

2.4 r-process

The possibility of using a free neutron target, formed from an open-ended UCN bottle, was investigated by Lothar Buchmann. The experiment would take radioactive beams from ISAC, post-accelerate them, and store them in a ring containing an internal UCN target. The target would resemble an open-ended material trap, where the circulating ions would pass through the open ends. UCN would be leaked into the side of the target. The setup would therefore resemble internal gas jet targets used at storage rings elsewhere.

A recoil separator would be used to collect reaction products. 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 for ^{123}Sn - neutron reactions.

This challenging project would be an effort for the far future (beyond an n-EDM measurement, for the 2015 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.

2.5 Materials Science and Nanofilms

We additionally wish to develop a program in collaboration with materials science groups to explore the feasibility of nanofilms studies involving UCN. Devices similar to neutron scattering and reflectometry employed historically in CN experiments can also be envisioned for UCN. For example, it has been shown in recent work by Korobkina *et al* [8] that (n,γ) and UCN loss rates on surfaces are sensitive to low-energy excitations of hydrogen contained in 10 nm nanofilms.

The ease of polarizing UCN for the same types of measurements would open up the possibility of studying magnetic thin films.

Korobkina *et al*, and others, have pointed out that such studies are always limited by the UCN densities achievable in the experiment. The UCN density at TRIUMF would therefore enable more detailed studies and new experimental setups to be envisioned.

2.6 Statement on Time Scales

Not all experiments listed above would occur on the same time scale. We envision an initial flagship experiment, which would be either the 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 would be a superthermal source based on downscattering of cold neutrons (CN) in superfluid He-II [9]. Fig. 2 displays a schematic of the proposed UCN source. Neutrons would be

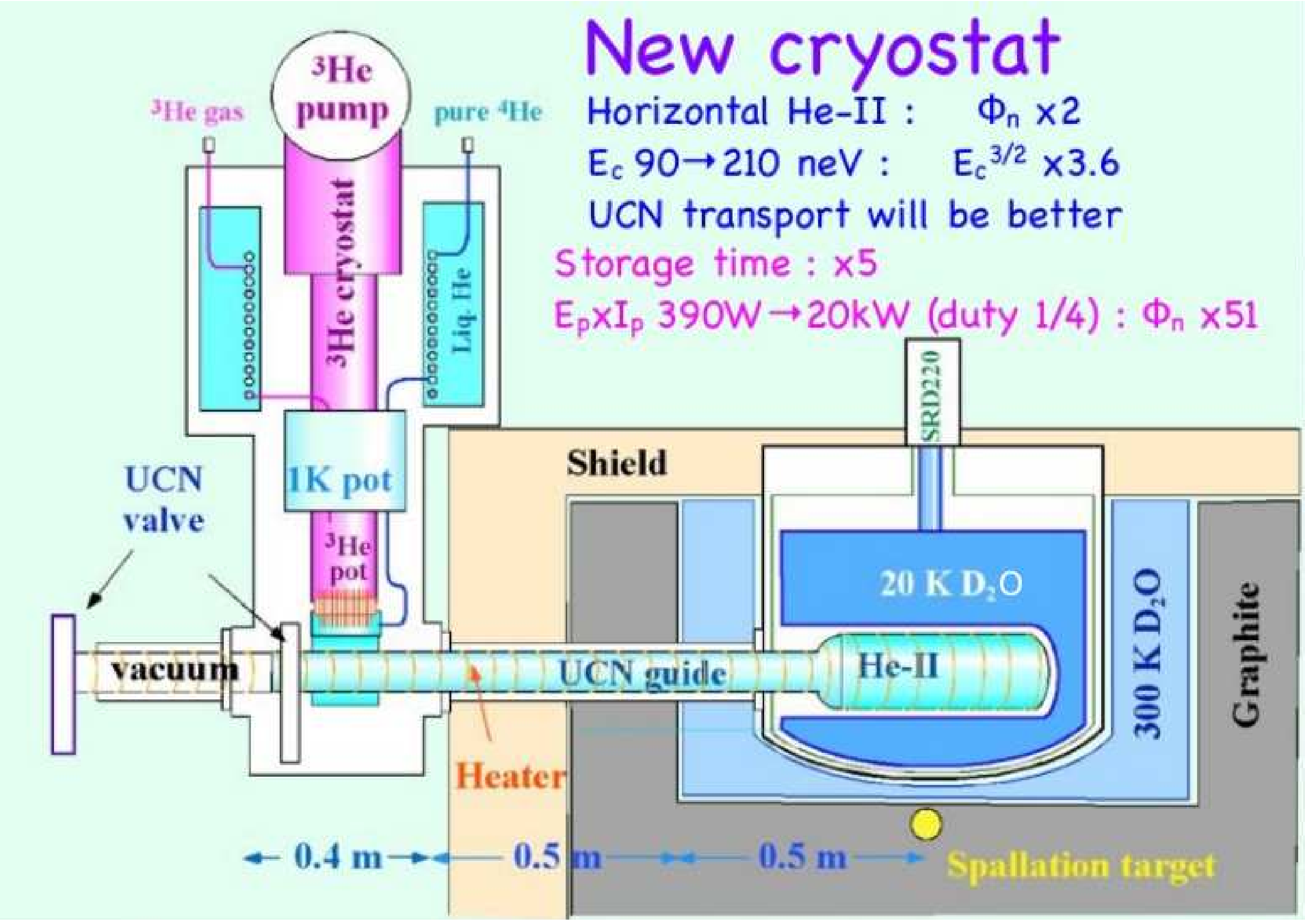

Figure 2: Proposed UCN source for TRIUMF.

liberated from a spallation target of either Pb or W. The neutrons would be moderated and reflected in surrounding cold D_2O. The resultant CN would then downscatter in the superfluid He-II and would be transmitted horizontally through a series of valves to experiments.

This source technology has been developed by Masuda's group at RCNP, Osaka. At RCNP, 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.

Incremental changes to the RCNP source would result various factors of increase for the eventual 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 would result in an increase in UCN density by a factor of 51.

The developments at TRIUMF would also be regarded as a step towards the even higher intensity beam that would be available at future spallation sources such as JPARC. In the UCN source envisioned for TRIUMF, it is hard to sustain instantaneous beam powers in excess of 20 kW without a significant increase in the cooling power to the He-II UCN source. This is also true of the superthermal solid D_2 source at Los Alamos. Demonstration of a working UCN source would therefore be an important step towards a truly high-intensity third generation superthermal UCN source employing higher beam power in a second target station at JPARC.

4 Interface Issues and Required Infrastructure

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

4.1 Pulsed Beam

Low-intensity cw beam could be used to initially commission the UCN source. However, pulsed beam, similar to the running condition at RCNP, would eventually be required. The primary purpose for pulsed beam is to achieve low background rates for UCN counting experiments. Additionally, low backgrounds are often required for the types of sensitive physics experiments that would be conducted at TRIUMF. As noted in previous sections, pulsed spallation sources can give rise to improved backgrounds over cw reactor UCN sources, because experiments can occur when the beam is switched off.

Pulsed beam (one minute on, three minutes off) can be achieved at TRIUMF in various ways. We have considered the following options:

1. The ion source can be operated in a pulsed mode. However, in this mode, sole user status for UCN would be required. The reason for this is primarily because this type of operation conflicts with ISAC target requirements for beam stability (and other users). Sole user status before shutdowns would be acceptable, as UCN requires lower intensity beam than ISAC.

2. The beam could be diverted to a beam dump elsewhere, while UCN experiments take data with beam "off" to the UCN source. This would require the construction of fast kicker to permit switching, and a well-shielded beam dump to minimize backgrounds in the experimental hall. Fast kickers, much like the one required for UCN, have recently been constructed at TRIUMF for use at PSI, and further development is being pursued in the context ILC R&D [10]. The kicker would therefore be built making use of in-house expertise at TRIUMF. Potentially, the former TISOL beam dump on BL4A could be used as the dump. If the TISOL dump was found to be unsuitable (potentially due to shielding or beam current limitations), another larger beam dump could be constructed. A suitable time for such construction to occur would be simultaneous with construction for ISAC on BL4N (actinide targets). This solution would completely decouple UCN from any conflicts with ISAC BL2A, or from any other currently existing cyclotron users.

3. Gerardo Dutto has suggested possible schemes which would achieve beam pulsing on a given cyclotron beam port while decoupling that port from another. In these schemes, beam distributions would be separated inside the cyclotron either vertically or radially. Stripping foils, say

at 2A and 4A, would then be positioned to extract the two different distributions separately. The cyclotron pulser duty cycle would then be modulated, to provide cw smooth average intensity for ISAC (2A) while the 1/4 duty cycle pulsed displaced beam component would be extracted down 4A. A kicker magnet would likely still be required in order to eliminate small amounts of spurious beam coming from 4A during the 3/4 time fraction. However, the high intensity dump in #2 above would be reduced to a low intensity dump, with substantial simplification and cost savings. Although this is possible in principle, its design feasibility should be further investigated and confirmed through cyclotron beam dynamics studies, simulations, and tests.

We regard the requirement of pulsed beam to be the most important interface issue for UCN at TRIUMF. We therefore propose to initially accept sole user status for times when we require pulsed beam operation.

Low-intensity cw beam (no pulsing) during commissioning would be acceptable for many tests, and possibly for some experiments. It is also possible that incremental improvements in shielding of the UCN spallation target, or local shielding, could improve the maximum acceptable cw current to UCN experiments.

In tandem with such operation, we strongly support G. Dutto's suggestion to proceed with a feasibility study of partial pulsing using vertical or radial deflections of orbits within the cyclotron. This plan will require a study by the beam dynamics group, with dedicated manpower and some beam development time. Such studies might also be useful for other experiments besides UCN.

Additionally, we propose that meetings with the relevant parties in accelerator group be initiated as soon as possible. These meetings would be to further discuss these plans and to discuss other options we might have overlooked in our initial work during the Aug. 1-3 townhall meeting.

In the event that simultaneous cw/pulsed beam extraction from the cyclotron were unsuccessful, a large additional beam waste dump and kicker magnet would then eventually be constructed within the period of 2010 and beyond.

4.2 Floorspace and Shielding

We propose to house the UCN source in Proton Hall, in the general area of BL4A (TISOL area).

Several issues must be dealt with in order to achieve this:

1. The floorspace required for UCN must be designed so as not to conflict with the electron linac (SCRF) project. The UCN source is approximately an 8m x 8m shielded bunker. Additionally we would require space for two experiments, combined requiring a similar amount of floorspace. Most electronics and essential services could be located outside the hall in the former TISOL area. We note that in the event the SCRF project does not require a ring (an option discussed at the townhall meeting), the potential for floorspace conflicts is reduced considerably. A figure indicating the initial required floorspace for UCN is shown in Fig. 3. Fig. 3 is intended primarily to indicate the area of the UCN source and experiments. Shielding, and general beamline layout would be modified to be consistent with electron linac requirements.

2. Steel shielding could be used in place of concrete to reduce the size of the shield package for the UCN source.

3. Many beamline elements from BL4A can be reused to construct an appropriate beamline for UCN, and as would be consistent with electron linac space requirements.

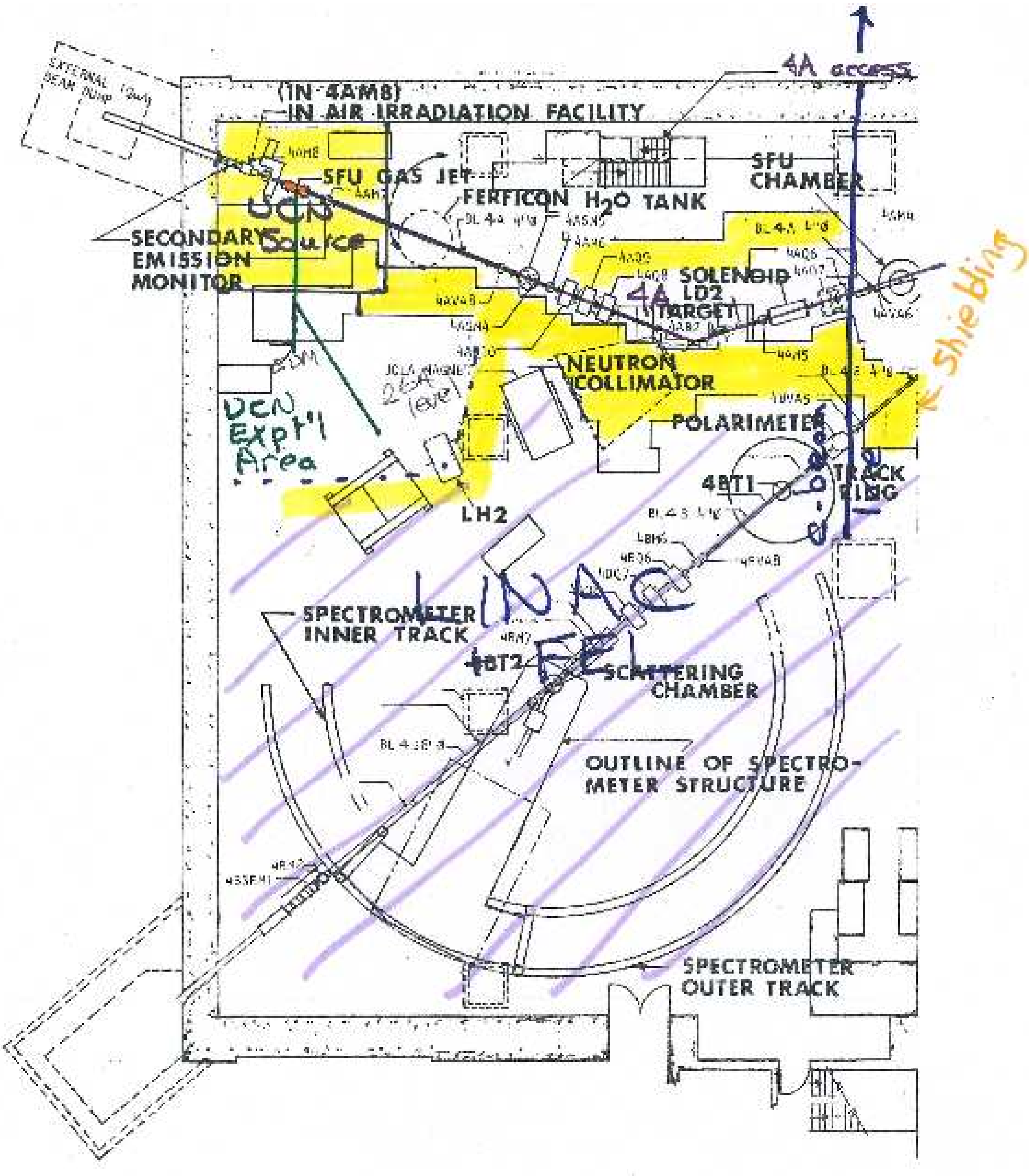

Figure 3: Initial UCN source layout concept. Yellow areas indicate shielding. UCN source and experimental as indicated. Electron linac (+FEL) space indicated by hatched area in lower portion of figure. Shielding passthrough for electron linac to dump and ISAC indicated by arrow on upper right-hand side of figure.

We therefore do not foresee any conflicts that could be regarded as “show-stoppers” for the UCN project. Quite the contrary, we envision that low cost, fast construction of a UCN source in Proton Hall is achievable. We strongly desire to pursue this option.

4.3 Future Developments Beyond 2010

For 2010 and beyond the top priority for UCN would be the development of an independent pulsed beam in Proton Hall, as mentioned previously.

However, another potential conflict exists in that on this same timescale, BL4 is planned to be used to drive the future ISAC actinide targets. On such a timescale, UCN would be in competition for proton beam originating from this port. In this vein, we have considered several options :

1. Construction of a new beam port (BL5) and shielding, with a new line going exiting the existing cyclotron vault in a westerly direction. Such a line has been shown to fit in a Proton Hall schematic with space for an electron linac.

2. innovative foil designs for BL4, which might permit a septum magnet to separate beams from the same foil.

3. a fast kicker on BL4 so that beam can be delivered to UCN and ISAC simultaneously.

Further discussions, detailed costing of each option, and possibly discussions of other options would be required before a decision on the most expedient solution would be reached.

4.4 Liquid Helium

The UCN source requires a source of LHe to operate. The consumption is at the level of 200 L/day during operation. We would recover all helium to a liquifier source on the TRIUMF site. At such low consumption rates, even dewar operation could be used for initial tests.

5 Collaboration and Required Funding

Thus far groups at TRIUMF, KEK, and at Canadian universities have taken an interest in the project. Groups at the University of Winnipeg and the University of Manitoba have taken a leadership role in the development of the Canadian collaboration.

We envision attracting other external collaborators in the context of the “International Workshop: UCN Sources and Experiments” held Sept. 13-14, 2007 at TRIUMF. The program of the workshop focuses on 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. Complementarity with reactor, and pulsed spallation CN sources will also be discussed. Additionally, the fundamental physics and materials science experiments planned for these sources will be discussed.

We anticipate that, given the advantages presented at TRIUMF, a new international group of physicists would conduct UCN experiments at TRIUMF.

5.1 Construction of the UCN source

5.1.1 Capital Equipment

The estimated cost for the UCN cryostat is $1.4M CAD. Included within this cost is essentially all the elements displayed on Fig. 2, 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 D_2O
- a ^{4}He isotopic purification system

Since many of these parts could be recycled from the existing source at RCNP, we regard this estimate as an overestimate of the likely costs associated with the source apparatus itself.

However, several additional costs were not included in this figure, such as: the cost of the D_2O itself (although some quantity is also available from the RCNP source), the cost to reconfigure BL4A as may be necessary, and the cost of radiation shielding blocks (which we also assume would dominantly come from TRIUMF stock).

Given the potential savings in recycling RCNP equipment and TRIUMF shielding blocks, we therefore regard $1.4M CAD as an accurate estimate of the capital equipment expenses associated with the UCN source and BL4A. This cost is also consistent with costs incurred at RCNP (Masuda) and at LANL (the UCN source for the UCNA experiment) in the construction of their respective UCN sources.

We view these costs as the minimum to initiate a program of UCN production experiments. It is not at this time clear what fraction of these costs would go into a CFI request, and what fraction would come from Japanese funding sources.

5.1.2 Time and Manpower Required to Construct UCN Source

Here we comment on the timescale and manpower to complete the UCN source fabrication. We envision redesign of the UCN cryostat to take three months. This would involve communication of two physicists with a cryogenic engineer.

Fabrication, reconfiguration, and reconstruction of the UCN cryostat would then occur. This work could be done at TRIUMF or in Japan. This stage would take six months. In the case of RCNP, the fabrication of the UCN cryostat was subcontracted to a private company. In the case of the TRIUMF, the same approach would likely be taken.

Once the UCN cryostat is fabricated, initial cooldown tests would be performed at the private company. This would require three people traveling to the manufacturer for periodic tests. We anticipate some debugging would occur, requiring potentially another three months of work.

Delivery of the cryostat to TRIUMF would therefore require one year from concept to successful completion of initial cooldown. Installation at TRIUMF could then occur.

In parallel with these developments (possibly occuring in Japan, or in North America) preparations for the arrival of the cryostat would occur at TRIUMF. This would include the design of the spallation target itself, and the volumes (on Fig. 2) external to the cryostat, namely the 300 K D_2O vessel, the graphite reflector, and shielding. We anticipate three months of designer time required to complete the design of these elements. Any required fabrication could be then be completed in six months. Installation would require three months. Thus one year would also be consistent with the requirements for preparations of the relevant area of the Proton Hall at TRIUMF.

Any small amount of reconfiguration of the 4A line could also be completed along a similar timescale.

Initial commissioning of the beamline, with UCN source installed, would then take place, along with initial UCN production experiments. We anticipate one month for such experiments. Such experiments use one inexpensive UCN detector as the primary detection scheme. However, 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.

5.2 Timeline, Funding, and First Experiments

Once successful commissioning is complete, the source would be available for the UCN experiments discussed in Section 2.

The existing Canadian collaboration would like to proceed with a CFI request in 2008. Details of the request would depend on the CFI programs available at that time. However, given the opportunity, the funds for a significant fraction of the initial UCN source would be requested.

Funds would be in hand by early 2009. Construction and initial commissioning would then be complete by early 2010.

We would at that time begin to conduct our initial flagship physics experiment. The costs associated with the physics experiment are hard to estimate at this time. However, the funding request would be made to NSERC in either 2008 or 2009, so that commissioning of the initial experiment could be completed by 2011. A production run could then occur in 2012.

In addition to the initial source costs, we can envision several other future upgrades to the apparatus, for which funds could be requested beyond the 2010 timeframe. These would include, for example, those infrastructure needs indicated in Section 4.3. Costs for such developments have not been estimated at this time. We view those developments as requiring potentially significant rearrangements of Proton Hall, and therefore as desirable to complete on a timescale consistent with ISAC's actinide targets.

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. The cost for the UCN source is \$1.4M CAD. Funding for the source would be requested from CFI in 2008. Commissioning of the source, and achievement of the world record UCN density, would be completed in early 2010. A first flagship physics experiment would be completed in 2012 using the new world-class UCN facility at TRIUMF.

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