Continued from the previous pages.

2 Importance of Pursuing the Proposed Research Activity at this Time

The project is timely because the technology to produce the ultracold neutrons has only been demonstrated successfully in in the past decade. This field of research is one that has been waiting to be opened up, and now that it has been, the experiments we've described above, themselves innovative, can now be conducted. From the discoveries made by those experiments, new breakthroughs will be made in the field of fundamental physics that otherwise could never have been made.

The technology proposed for the UCN source is one that has only ever been demonstrated in Japan. The expertise of Yasuhiro Masuda and the Japanese collaborators will be crucial to bring about the successful completion of the fully functioning UCN source. They are in fact supplying the completely functioning UCN source to Canada as an in-kind contribution. The responsibility of the Canadian group will be to successfully implement this infrastructure in Canada and make it function as a world-class facility. The Japanese commitment to the infrastructure project in terms of manpower will also be huge, as will their extended contributions once the infrastructure is up an running and experiments are being conducted. It is therefore very important that the Canadian counterparts be able to pursue this project on a timescale consistent with the aims of the Japanese researchers on the project. The aim of both is consistent: to create the highest density source of UCN in the world.

An additional aspect of the timeliness question is the availability of Canadian manpower to successfully complete such a project. Though this will be addressed in more detail in the "Researchers" section, we comment briefly on it here. Two new researchers in fundamental neutron physics have recently joined the Canadian system. These are J. Martin from U. Winnipeg (the spokesperson and project leader of CSUNS) and M. Gericke from U. Manitoba. J. Martin was a leader in the first, and to date most impressive, demonstration of the superthermal technique, at the similar Los Alamos National Lab UCN source. The new ideas of these two young researchers which they have brought with them to Canada has already changed the landscape in Canadian subatomic physics. It is their combined efforts that have led to this innovative proposal through the CFI.

The experimental schedule for the initial experiments to be conducted at CSUNS is also determined, partially, by time considerations. We envision our initial flagship experiment to be the neutron lifetime experiment. This is primarily because a variety of other neutron lifetime experiments are in preparation across the world, not all of them using UCN sources to achieve their aims, and only one using a technique remotely similar to the magneto-gravitational trap we've described here. The goal of these experiments is to solve the currently existing 6.5 sigma discrepancy offered by the most recent precise measurement. While our proposal would certainly answer this quandary, it is important that that experiment be conducted with the highest priority in the short term to have the largest possible impact. A prototype apparatus is also under construction at this time at Los Alamos National Lab, and the effort is therefore mature enough to consider an experiment employing the significantly increased UCN densities that would be available in Canada.

In tandem we would use a second UCN beamline to conduct R&D related to the n-EDM experiment. Though having the highest possible scientific priority, n-EDM efforts in Canada would be too premature to consider at this time, as technical developments towards several of the ongoing efforts at other laboratories have not yet been completed. Such efforts also generally require a significantly expanded collaboration size, and we will require time to form such a collaboration. We therefore feel we can only benefit from placing the n-EDM effort farther in the future in the CSUNS timeline.

The gravity experiment would be conducted subsequent to the neutron lifetime effort and also in tandem with ongoing n-EDM work. This experiment, while technically easier than the n-EDM effort, would also benefit from more time to mature into a coherent experimental plan.

General issues associated with experiment approval and scheduling are discussed in the "Management Plans" section.

3 Complementarity to other research or technology development

Infrastructure that can produce UCN, similar to CSUNS, exists or is being planned at other facilities in the world. CSUNS represents the evolution of such infrastructure to the highest UCN density possible with the current technology.

The UCN source proposed for TRIUMF would produce a density of 10,000 UCN/cc, which is a factor of 100 greater than any UCN source ever operated. In a future upgrade, the source would use a liquid deuterium cold moderator, giving a factor of five in UCN density, resulting in 50,000 UCN/cc. 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/cc at the exit of the source. Typically 1-2 UCN/cc is achieved in experiments, such as in the completed ILL n-EDM experiment.

With the advent of superthermal sources of UCN, a new generation of UCN sources using this technology are under development at various laboratories. For a list of these sources, please see Table 1 (in the attached pages). The table indicates that CSUNS would exceed the capabilities of all planned future UCN sources worldwide. It is important to note that all the sources that would come close to being competitive with CSUNS are future sources that are under development at this time. Additionally all the other sources use different technologies to the one proposed for CSUNS. We believe that it is our technology, ultimately, that will prove the most successful of all future projects worldwide. A comparison of the proposed infrastructure to those planned projects will be given in the "Need for the Infrastructure" section.

In section 2, we also commented on the complementarity of our neutron lifetime effort to other efforts worldwide, and the relationship to scheduling that experiment as the first flagship experiment in our program. Our experimental proposal is a technique suited explicitly for a very high density source of UCN, and is complementary to all other proposed experiments. It also would have the capability, ultimately, to exceed the capabilities of all other proposed experiments, given the very high densities of UCN that would be available at CSUNS.

Figures and Tables

Location	Technology	critical energy E_c (neV)	storage time τ_s (s)	density in experiment ρ_{UCN} (UCN/cc)
TRIUMF	spallation He-II	210	150	10,000–50,000
ILL Grenoble	CN beam He-II	250	150	1000
SNS ORNL	CN beam He-II	134	500	150
Munich	reactor SD_2	250		10,000
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. The range indicated for the TRIUMF source results from use of differing cold moderator materials, as discussed in the text.

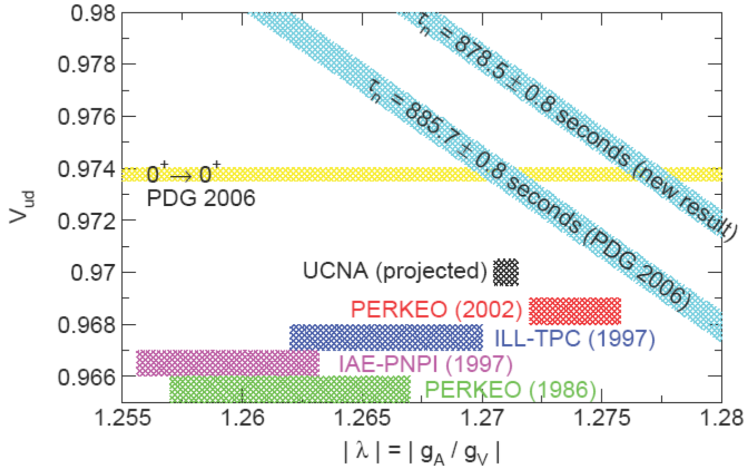

Figure 1: Current status of V_{ud}. Yellow horizontal band indicates current best determination by $0^+ \to 0^+$ nuclear beta-decay. Diagonal bands indicate current discrepancy between the two most recent measurements of the neutron lifetime τ_n which both use UCN confined to material traps. Coloured bands at the bottom of the figure are to be interpreted as vertical bands indicating recent measurements of the beta-asymmetry in neutron decay. The most precise of these, labelled UCNA is an ongoing measurement being conducted at the Los Alamos UCN source

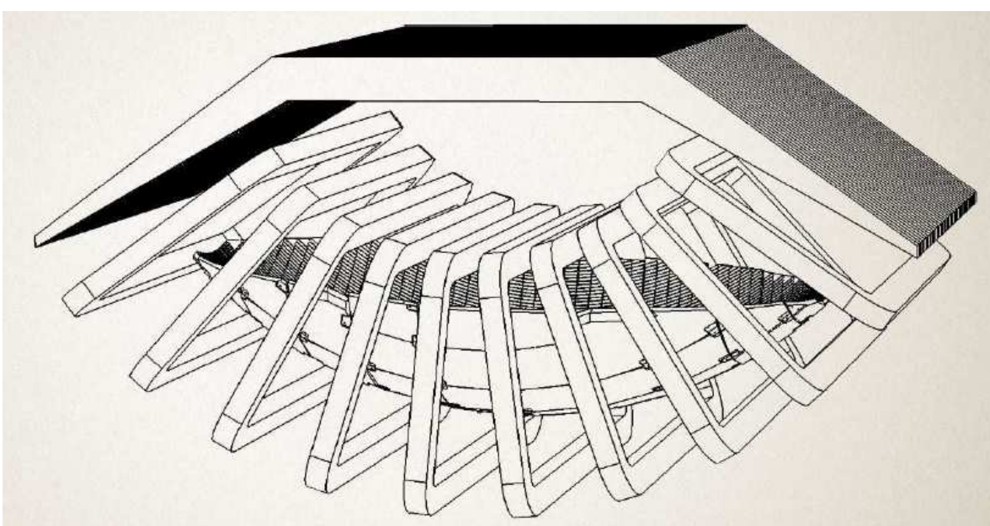

Figure 2: LANL-designed UCN trap, showing iron yoke, guide-field coils, and permanent-magnet bowl [6]. The vacuum chamber, which contains the bowl, but is inside the guide-field coils, and the detectors that are placed in the space between the end guide-field coils and the yoke, are not shown. The bowl depth is 0.5 m.

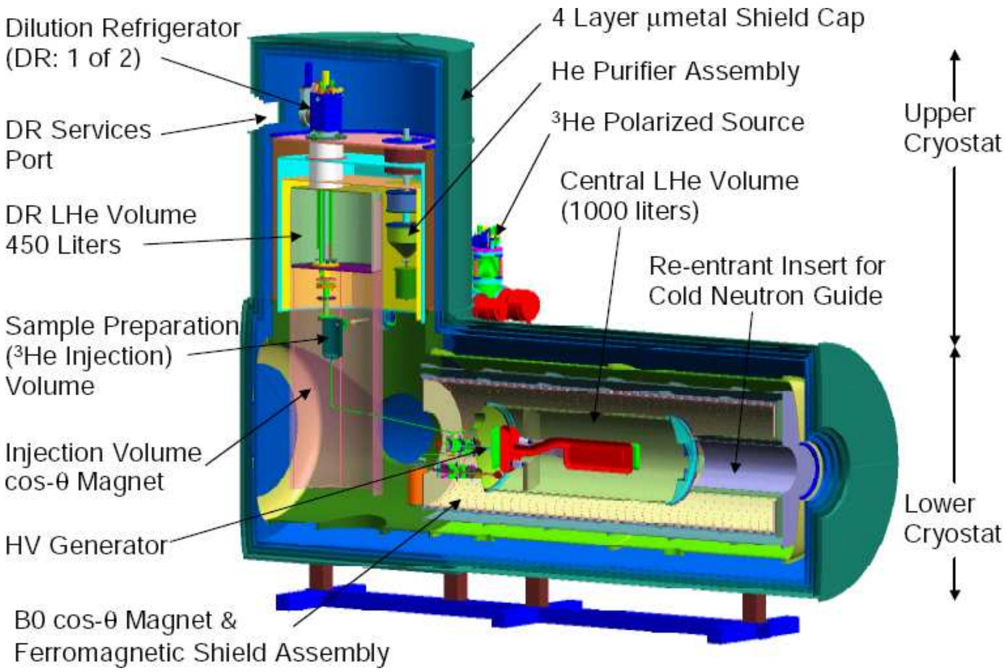

Figure 3: Schematic diagram of the proposed SNS EDM apparatus from Ref. [21]. The measurement volume consists of two cells of volume 4 L each.

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[19] 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.

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

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

3.2 Spallation solid deuterium sources

The existing LANL source and the future Paul-Scherrer Institut (PSI) source use solid deuterium SD2 as the UCN source material. The Los Alamos source is currently in operation in a testing mode. In SD2, the UCN storage lifetime is only 24 ms at 8 K. The small value of the storage lifetime for this type of source arises from a combination of phonon up-scattering (40 ms), up-scattering from para-D2 molecular states (100 ms), and nuclear absorption (150 ms) [23]. Therefore these sources use a storage bottle which is separated from SD2 by a UCN shutter. The shutter is opened briefly when a beam pulse arrives so that UCN are extracted to the storage bottle. Despite these lifetime and transport problems, SD2 has the advantage of having a large number of phonon states available from which CN can scatter, thus giving rise to a larger UCN production rate. The difficulty for these sources is to get the UCN out of the SD2 as efficiently as possible before the UCN are lost, and then not allow the UCN to move back into the volume of SD2 again. Another issue for a solid source is ice quality, and significant R&D at LANL, Mainz, Munich, and PSI has gone into achieving crystalline deuterium for optimal UCN production. Such considerations are of no concern for superfluid 4He technology.

At the LANL source, an 800 MeV proton beam is used for spallation neutron production off a tungsten target. The SD2 is a disk 7.8 cm in diameter and 5 cm in height. Typically a 30 uC pulse of protons is delivered to the source for one second in every fifteen [24]. The short lifetime in the SD2 is not an issue for the LANL source because the UCN flow continually through the UCNA experiment, which is a polarized neutron beta-asymmetry experiment. I.e. the source is not optimized for density. In the UCNA experiment, if the UCN were stored, they would depolarize at an unacceptable rate on collisions with the cell walls. Despite this, a world-record density of 145 UCN/cc was achieved in the prototype source, which served as the first and to date most impressive validation of the superthermal production technique [25]. In the UCNA apparatus, densities of 1 UCN/cc are typically achieved, giving rise to neutron beta-decay rates of 10 Hz.

The PSI UCN source will be driven by a 600 MeV proton beam at 2 mA, operated at low duty-cycle. A proton beam pulse of 4 s every 400 s will be to fill a 2 m^3 storage bottle. The volume of SD2 is a disk 50 cm in diameter and 15 cm tall. UCN will be transported from the bottle to an EDM cell, where the expected UCN density is 1,000 UCN/cc. The construction of the UCN source will be complete in 2009 [19]. 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 SD2. Note also that though the instantaneous beam power is large, the duty-cycle of the source is 1%; 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.

3.3 Reactor SD2 sources

The Munich FRM-II reactor, a 20 MW reactor, will also have a UCN source employing SD2. A prototype UCN source for this project was constructed at the 100 kW TRIGA reactor in Mainz where 8 UCN/cc were obtained in a volume of 10 L. In that experiment, UCN with energies below 250 neV were trapped. This is expected to be improved to a density of 10,000 UCN/cc at FRM-II. However, the timescale for the development at Munich is not clear. It is a project that would likely be pursued more vigorously once the PSI UCN source is complete. There is considerable collaborative effort between the two groups in their pursuit of an electric dipole moment experiment.

A reactor SD2 source is also planned which would use the NSCU TRIGA reactor (1 MW in power), which would deliver a UCN density of 1000 UCN/cc.

3.4 Superfluid 4He sources employing cold neutron beams

These sources are used in cases where the source material can potentially also be used as the experimental volume. They are therefore not accessible as UCN user facilities like CSUNS; however, they use the same superfluid 4He UCN source. Unlike CSUNS, they will have a relatively smaller cold neutron flux, since they are stationed at cold neutron beamlines instead of close to a spallation target.

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/cc.

A large US group, working at the SNS, is also constructing a superfluid 4He UCN source for the SNS EDM measurement. The cold neutron flux is smaller than ILL. The UCN density is expected to be 150 UCN/cc in the EDM cell [20].

3.5 Accessibility, Complementarity and Sharing

We regard the projects described in the previous section as our sister projects. We will share knowledge with these projects through collaborative effort and through publications in journals.

Our project, similar to the original ILL rotor source and the PSI and Munich projects, would be operated as a UCN user facility. While the experiments proposed here could be conducted at other high-density sources such as PSI and Munich, we note the complementarity of our project with theirs. We use a different technique for producing the UCN (superfluid helium). It is well established in the UCN community that our technique would work, and that the technique should be pursued with high priority. Up until now, this has only been the Japanese group and the effort would now expand into Canada. Another aspect of complementarity is that there is absolutely zero overlap in our scientific collaboration with either the PSI or Munich collaborations. We note that fundamental neutron research historically in North America has not been competitive with research in Europe (the lack of an analogous facility to ILL is evidence of this) although facilities are improving with the advent of the SNS (in Tennessee). With this proposal we are addressing this serious lack of infrastructure in basic science in North America. We note that we do envision a close collaboration with individuals also conducting research at SNS, which is an entirely different cold neutron beam facility compared to CSUNS.

Tables and Figures

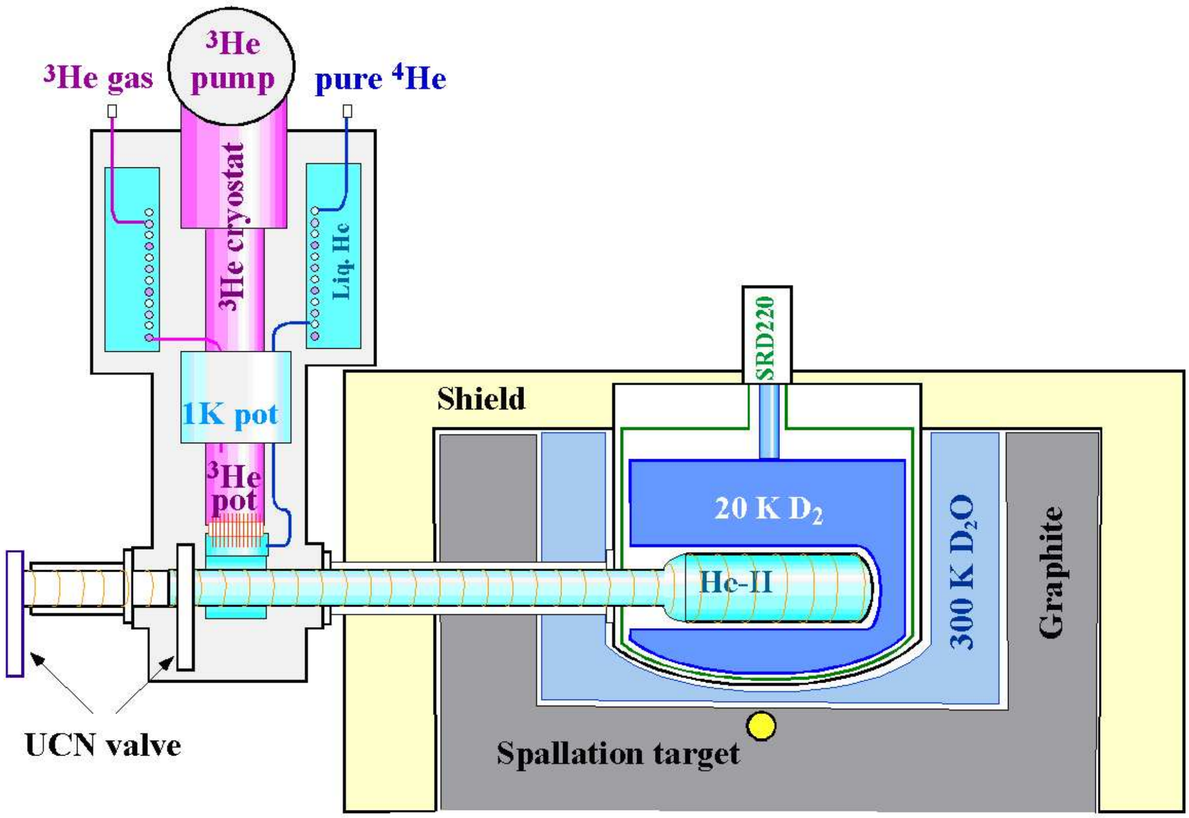

Figure 4: Schematic diagram of the superfluid 4He spallation UCN source for TRIUMF. The beam direction in the figure is into the page, i.e. an end-on view of the cylindrical spallation target is shown. Neutrons produced by spallation are moderators in surrounding D_2O and graphite, thereby becoming cold neutrons. Cold neutrons are downscattered to ultracold temperatures by phonon production in the superfluid 4He (He-II) volume. The ultracold neutrons are then transported out to experiments through guide tubes and a series of UCN valves.

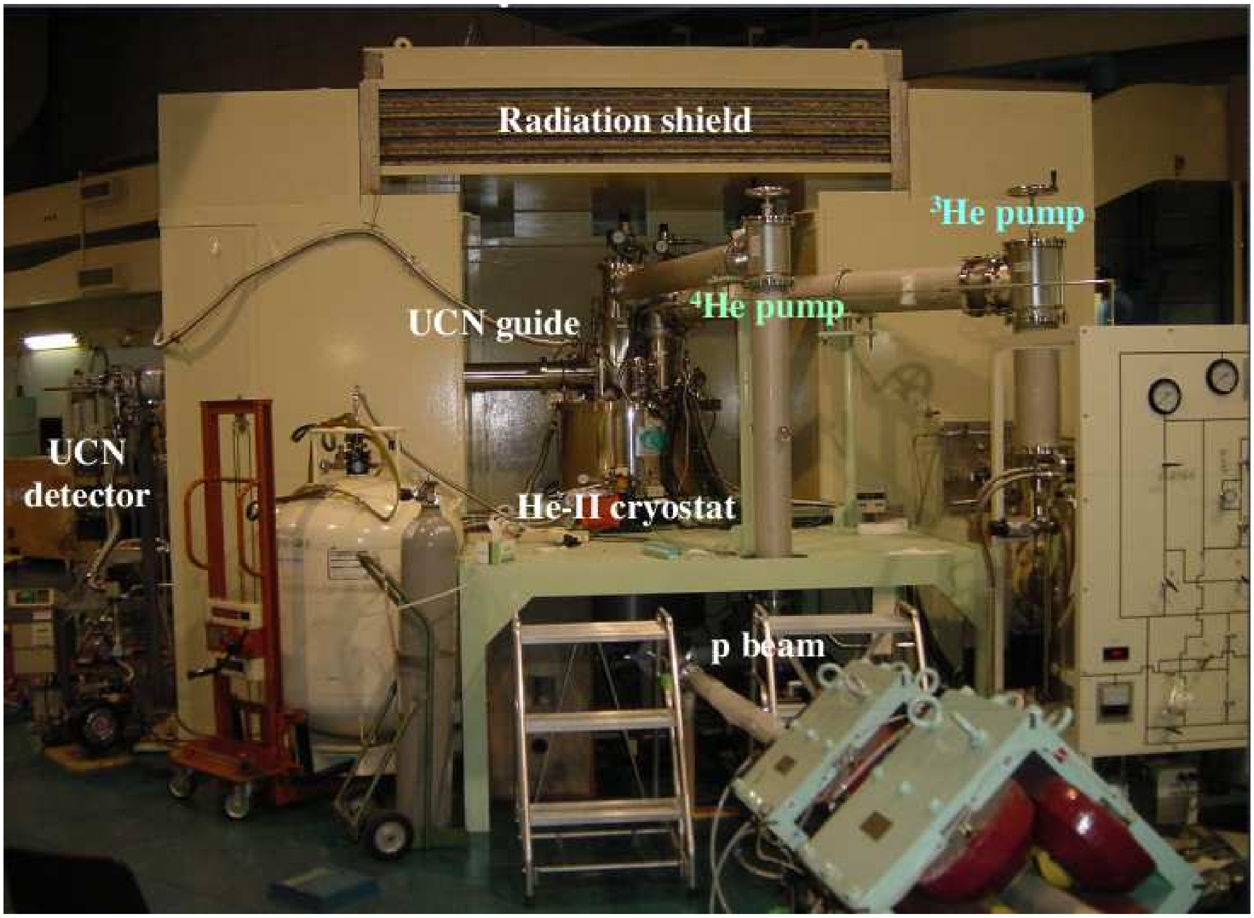

Figure 5: Y. Masuda's UCN source at Research Center for Nuclear Physics, Osaka.

References

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

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

[24] 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.

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

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

Report on UCN workshop at TRIUMF

Many of the collaborators that have signed on to the CSUNS project were attracted in the context of the "International Workshop: UCN Sources and Experiments" which was held Sept. 13-14, 2007 at TRIUMF [28], and was supported jointly by TRIUMF and NCSU/TUNL (Triangle Universities Nuclear Laboratory). The organizing committee was chaired by J.W. Martin. 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 in Canada.

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. In Canada, 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. Additionally, a UCN surface physics apparatus was discussed and new applications in nanotechnology "molecular rotors" were reported. Such innovation might also one day be pursued at CSUNS. Overall, the workshop was an astounding success, and confirmed that the CSUNS project is on the right track.

Partnership with Acsion Industries

The University of Winnipeg has partnered with Acsion Industries, a company based in Pinawa, Manitoba. The company will assist the CSUNS collaboration in the design and optimization of the neutron moderation for the UCN source. They have copious experience in this, having designed nuclear reactors in the past which are very similar in nature. They will also assist us in training of highly qualified personnel in the computer modelling simulations which they will write in order to achieve this task. Acsion Industries will maintain intellectual property rights over the software developed, but will provide access to the software for the collaboration as an in-kind contribution. The intention of the company is to use the project to build their own expertise in the area of neutron transport, and to potentially market the software and their expertise to other interested parties, for example, those designing nuclear reactors for power generation.

A memorandum of understanding between Acsion and the University of Winnipeg has recently been signed which outlines these issues. The budget in that MOU will be discussed in the Financial Module.

References

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

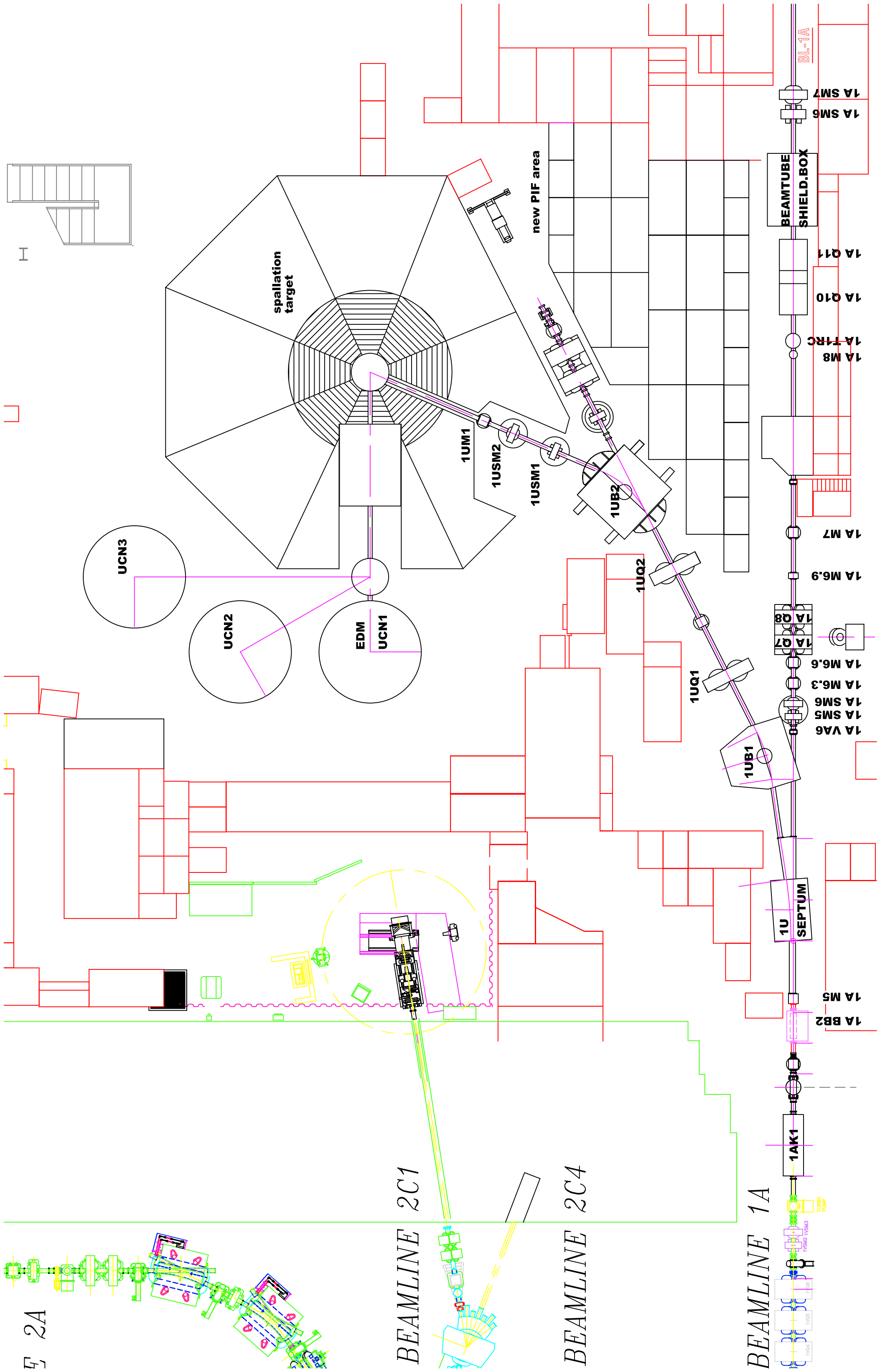

Figure 6: Floorplan indicating the location of the UCN facility in the Meson Hall at TRIUMF.