Continued from the "Quality of the Research or Technology Development" Section.

1.6 International Reviews of CSUNS

As a part of the planning process for CSUNS, J.W. Martin has presented the CSUNS project to review committees four times over the past year, and has organized two collaboration meetings.

The UCN source project was recently reviewed by the TRIUMF Experimental Evaluation Committee (EEC) for subatomic physics (March 2008). Presentations were made by J.W. Martin, Y. Masuda, and W.D. Ramsay from the CSUNS collaboration. The EEC concluded that "a high density UCN source will support a fundamental physics program at TRIUMF well into the future, thus maintaining the strong tradition at the laboratory of a broad program of measurement of nuclear interactions, nuclear structure, nuclear astrophysics, and fundamental symmetry tests. Like the latter it will furthermore bridge the gap between particle and nuclear physics." The strong endorsement resulted from a great deal of enthusiasm from the EEC about the project.

The project was presented again by J.W. Martin to the Advisory Committee on TRIUMF (ACOT) on May 9, 2008. This committee also gave a highly favorable review to the project. The membership of both ACOT and the TRIUMF EEC includes some of the most well-known nuclear and particle physicists in the world. The membership of ACOT includes representatives from the National Research Council Canada (NRC) and from NSERC.

2 Importance of Pursuing the Proposed Research Activity at this Time

The project is timely because the technology to produce the world-record density of UCN has only been demonstrated successfully in in the past decade. This field of research has recently been opened up by new innovations, and now that it has been, the experiments we've described above, themselves innovative, can 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 Y. 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 implement this infrastructure successfully in Canada and make it function as a world-class facility. The Japanese commitment to the infrastructure project in terms of human resources will also be huge, as will their extended contributions once the infrastructure is up and 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 funding and experimental 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 expertise 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 LANL UCN source. M. Gericke was a leader in CN experiments at LANL and is a leader in experiments planned for SNS. The new ideas of these two 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 to CFI.

The 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 partly 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. For a review of the possible experimental concepts that are being pursued, see Ref. [22]. The goal of these experiments is to solve the currently existing 6.5 sigma discrepancy offered by the most recent precise measurement. Our proposal would address this quandary with a new measurement with significantly reduced systematic and statistical uncertainties. However, it is important to conduct that experiment 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 LANL, 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 immediately, 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 will benefit from conducting the neutron lifetime experiment first, implementing a full n-EDM experiment in the future at CSUNS.

The gravity experiment would be conducted subsequent to the neutron lifetime effort and 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 delivered to the experiment, 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 increase 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 delivered to experiments, such as in the completed ILL n-EDM experiment.

A new generation of superthermal UCN sources are under development at various laboratories. For a list of these sources, please see Table 1 (below). 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 expect that our technology, ultimately, 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 ^{4}He	210	150	10,000–50,000
ILL Grenoble	CN beam ^{4}He	250	150	1000
SNS ORNL	CN beam ^{4}He	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 Laboratory (LANL, NM, USA) 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 (Institut Laue-Langevin, Grenoble, France) for the CryoEDM project. These are the Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL, TN, USA) for the n-EDM project there, the Munich FRM-II reactor (Forschungsneutronenquelle Heinz Maier-Leibnitz, Munich, Germany), the North Carolina State University nuclear reactor (NCSU, USA), and the Paul-Scherrer Institut source (PSI, Villigen, Switzerland). 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.

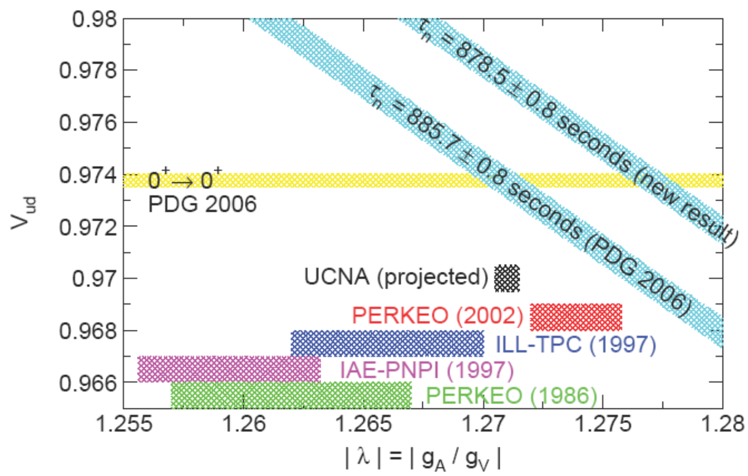

Figure 1: Current status of V_{ud}. The thin horizontal band indicates the current best determination by $0^+ \to 0^+$ nuclear beta-decay. Diagonal bands indicate the current discrepancy between the two most recent measurements of the neutron lifetime τ_n which both use UCN confined to material traps. The thick 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 LANL UCN source.

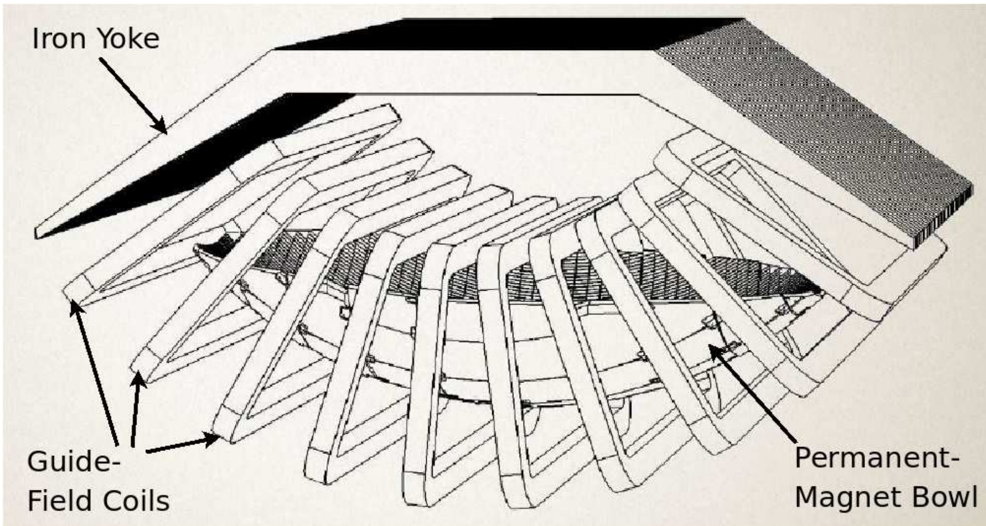

Figure 2: LANL-designed UCN trap, showing iron yoke, guide-field coils, and permanent-magnet bowl [6]. The vacuum chamber, which contains the bowl, but is inside the guide-field coils, and the detectors that are placed in the space between the end guide-field coils and the yoke, are not shown. The bowl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

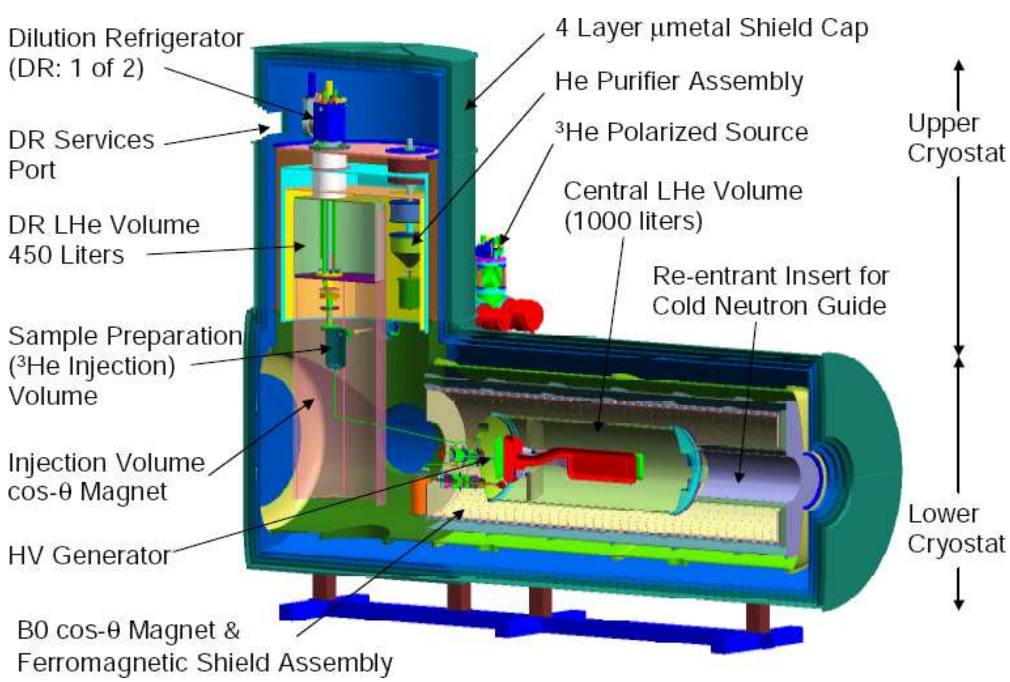

Figure 3: Schematic diagram of the proposed SNS EDM apparatus from Ref. [21]. The measurement volume consists of two cells of volume 4 L each.

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Continued from the "Need for the Infrastructure" Section.

3.2 Spallation solid deuterium sources

The existing LANL source and the future PSI source use solid deuterium (SD2) as the UCN source material. The LANL 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) [25]. 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 getting the UCN out of the SD2 efficiently before the UCN are lost, and then not allowing 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 [26]. 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 designed for high density, but for a continual flow of neutrons through the apparatus. In the UCNA experiment, if the UCN were stored, they would depolarize at an unacceptable rate due to 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 [27]. 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 an even lower duty-cycle than the LANL source. 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 will be 1,000 UCN/cc. The construction of the UCN source will be complete in 2009 [19]. The UCN source at PSI, despite having a larger instantaneous beam power than TRIUMF, will use a shorter pulse structure because of the shorter UCN lifetimes owing to the use of SD2. Note also that though the instantaneous beam power will be large, the duty-cycle of the source is 1%; the time-averaged beam power (12 kW) will not be so different from the CSUNS project (5 kW). The low duty cycle at PSI must also be enforced because of the tremendous heat load implied by the very intense beam.

It is interesting to attempt to compare our project with these other spallation source projects. At TRIUMF, a 40 uA proton beam will be used, which is a factor of 50 less intense than the 2 mA beam used at PSI. Consequently, the instantaneous beam power at TRIUMF will be smaller, and the cooling, shielding, and safety requirements on the spallation target will be simpler relative to PSI. We therefore prefer to compare our facility, in terms of safety and shielding, to the existing LANL UCN source, which was designed for 40 uA proton beam at 800 MeV. Indeed shielding calculations performed by experts at TRIUMF have given good agreement with the shielding actually in use at LANL (and are presented in the Budget Justification section). TRIUMF also has experience in dealing with more challenging spallation target projects than ours, such as the ISAC targets which operate routinely at 100 uA and high duty cycle.

The reason for the necessary disparity between the instantaneous beam power at PSI vs. TRIUMF is simply in the choice of SD2 vs 4He for UCN production. Since the 4He does not strongly capture or upscatter UCN, the TRIUMF source can be operated at lower currents allowing a large density of neutrons to build up. SD2 sources, on the other hand, must quickly pulse the proton beam, then isolate any UCN produced from the SD2 as quickly as possible, usually with a valve directly above the SD2. Our technology is therefore highly complementary to the SD2 project, and we believe that, in terms of UCN density it will prove superior.

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 operational. There is considerable collaborative effort between the two groups in their pursuit of an n-EDM 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 superfluid 4He 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 n-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 n-EDM measurement. The cold neutron flux is smaller than ILL. The UCN density is expected to be 150 UCN/cc in the n-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. We note the complementarity of our project with those of PSI and Munich (which seem the most likely to be operational when our UCN source would first be operated). 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. Until now, this technique has only been attempted by the Japanese group. 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

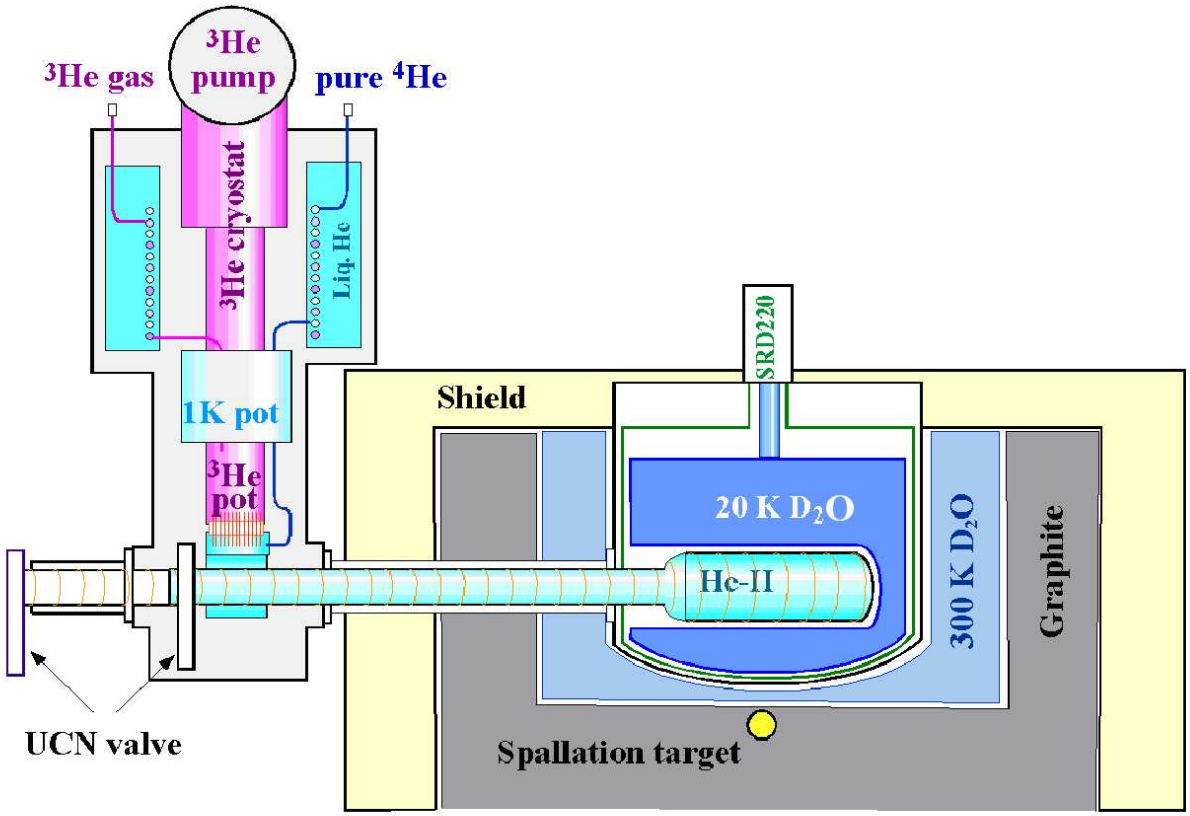

Figure 4: Schematic diagram of the superfluid 4He spallation UCN source for TRIUMF. The beam direction in the figure is into the page, i.e. an end-on view of the cylindrical spallation target is shown. Neutrons produced by spallation are moderated in surrounding D_2O and graphite, thereby becoming cold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

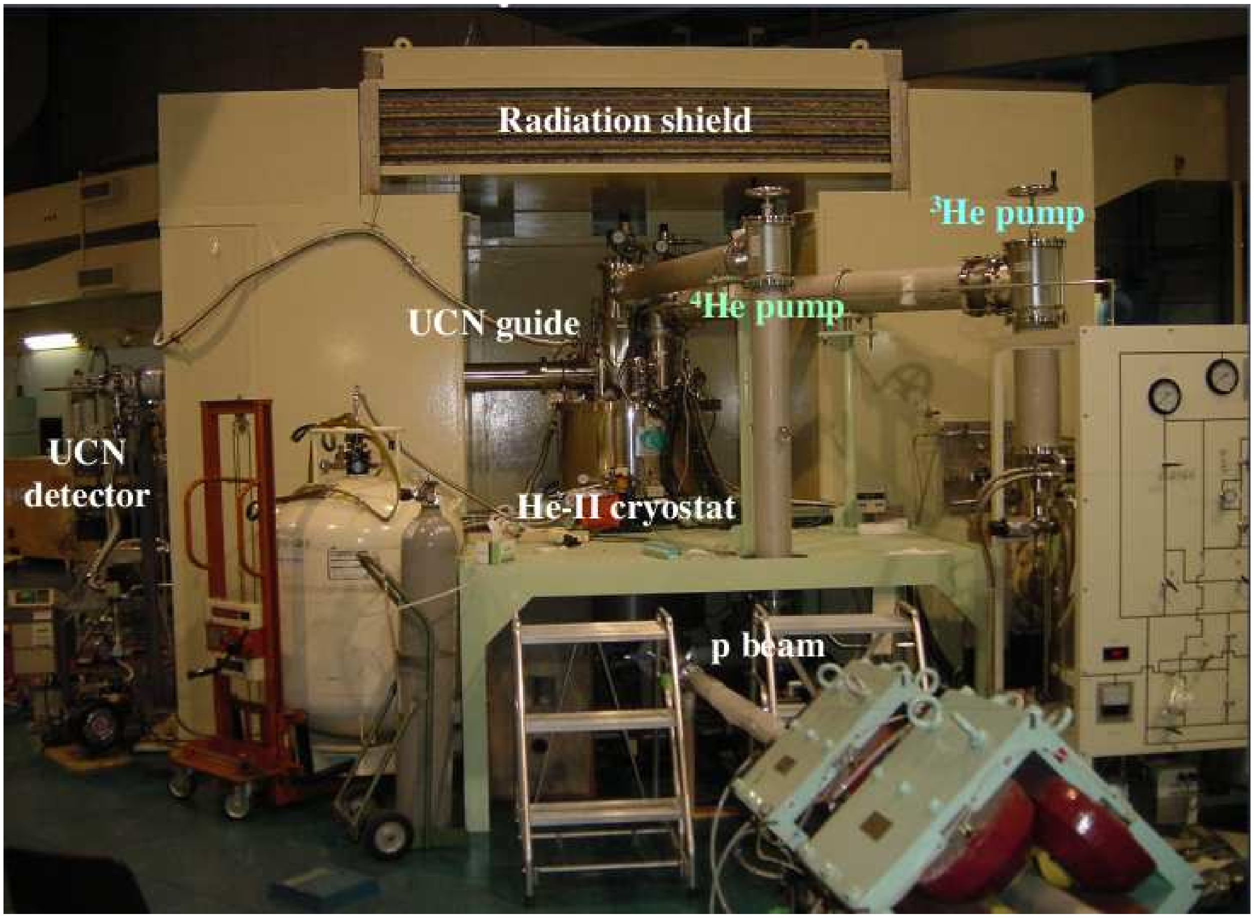

Figure 5: The existing Japanese UCN source at the Research Center for Nuclear Physics at Osaka University, Osaka, Japan. The source has demonstrated the feasibility of a superthermal source of UCN based on production in superfluid helium. It will serve as the basis for the UCN source in Canada.

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Continued from the "Collaborations and Partnerships" section.

Advanced Applied Physics Solutions Inc. (AAPS) is a wholly owned, not-for-profit subsidiary of TRIUMF supported through the Government of Canada's Networks of Centres of Excellence Program. Technology transfer for research results would be pursued through this NFP organization.

3 Steps to Strengthen Collaborations and Partnerships

Full membership in TRIUMF for U. Manitoba is pending. Associate membership may be extended to U. Winnipeg. Full membership entitles universities to bridged faculty positions where a portion of the faculty's salary is paid by TRIUMF. In return, the faculty member conducts research at TRIUMF. It is possible that a future bridged position (TRIUMF-Manitoba) would support the fundamental symmetries discipline, and would therefore increase Canadian support for the experiments conducted at CSUNS.

Winnipeg HQP would be trained by Acsion Industries thereby strengthening this new partnership.

Once CSUNS would receive funding, there would be a renewed effort to recruit more collaborators for the physics experiments to be conducted there (neutron lifetime, gravity levels, and n-EDM).

3.1 UCN workshop at TRIUMF

Another aspect of strengthening collaboration between our collaborators and beyond is through international conferences and workshops. Many of the collaborators who 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 4He, 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 n-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.

4 Importance of the Infrastructure to Collaborations and Partnerships

The infrastructure will bring together people and institutions with a common goal: the creation of a world-leading facility in fundamental neutron physics in Canada.

Large, international collaborations of this sort are the norm in the field of subatomic physics. We have made use of a typical management structure that makes these types of collaborations succeed. Additionally, we have assembled a team of world experts from Canada, Japan, and the US who are all committed to the success of the project, and we have partnered with TRIUMF and with Acsion Industries to make the project a reality. With such strong commitments, we therefore are confident that this infrastructure project will be a great success.

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.

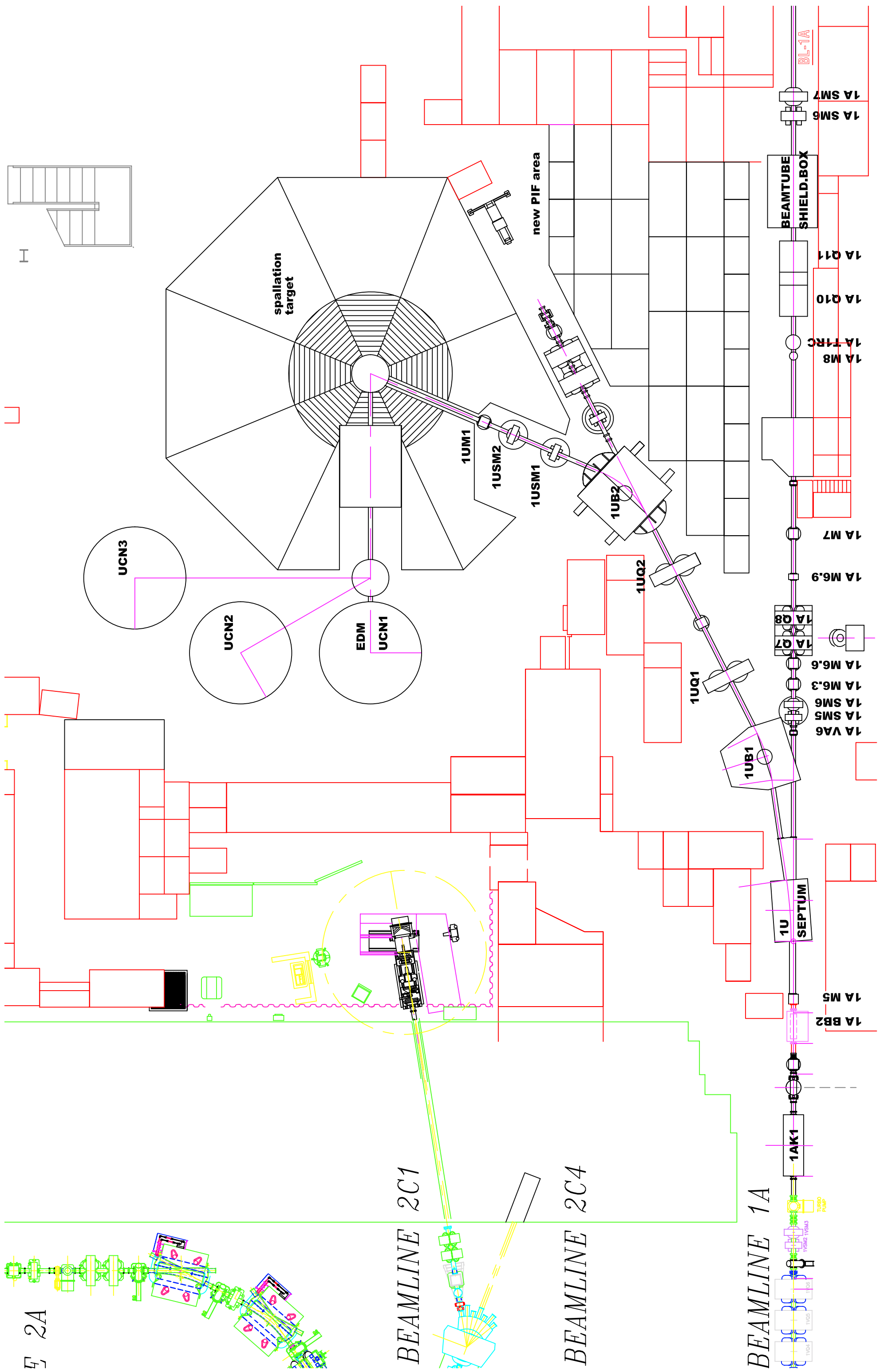

Figure 6: Floor plan indicating the location of the UCN facility in the Meson Hall at TRIUMF. Beamline 1A projects east from the cyclotron. The kicker magnet 1AK1 would divert beam northward into a new beamline and onto a spallation target. The UCN source would be located directly above the spallation target. UCN guide tubes would deliver the world's highest UCN density to physics experiments is indicated schematically by the circular areas labelled UCN1-3. For scale, the diameter of each circle is 3 m.